DETAILED STUDY OF SELENIUM IN SOIL, WATER, BOTTOM SEDIMENT, AND BIOTA IN THE SUN RIVER IRRIGATION PROJECT, FREEZOUT LAKE WILDLIFE MANAGEMENT AREA, AND BENTON LAKE NATIONAL WILDLIFE REFUGE, WEST-CENTRAL MONTANA, 1990-92

By David A. Nimick and John H. Lambing, U.S. Geological Survey
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CONVERSION FACTORS, VERTICAL DATUM, ABBREVIATED UNITS, AND ACRONYMS

Multiply	By	To obtain
acre-foot (acre-ft)	1,233	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.028317	cubic meter per second (m^3/s)
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day
inch (in.)	25.4	millimeter (mm)
inch (in.)	2.54	centimeter (cm)
mile (mi)	1.609	kilometer
pound (lb)	453.6	gram (g)
square mile (mi^2)	2.59	square kilometer (km^2)

Temperature can be converted to degrees Celsius (°C) or degrees Fahrenheit (°F) by the following equations:

$$°C = 5/9\ (°F - 32)$$
$$°F = 9/5\ (°C) + 32$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD 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.

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 in sediment and biological tissues is reported in milligrams per kilogram (mg/kg) or micrograms per gram (μg/g), which are both equal to parts per million, or in percent, which is equal to parts per hundred.

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.

Abbreviated units and acronyms used in this report:

MCL	maximum contaminant level
mg/kg	milligram per kilogram
mg/L	milligram per liter
mm	millimeter
mV	millivolt
spp.	species
µg/g	microgram per gram
µg/L	microgram per liter
µS/cm	microsiemen per centimeter at 25 degrees Celsius
pCi/L	picocurie per liter
TU	tritium unit
WMA	Wildlife Management Area
NWR	National Wildlife Refuge
STR	salt-toxicity relation
CFC	chlorofluorocarbon
XRD	X-ray diffraction

Detailed Study of Selenium in Soil, Water, Bottom Sediment, and Biota in the Sun River Irrigation Project, Freezout Lake Wildlife Management Area, and Benton Lake National Wildlife Refuge, West-Central Montana, 1990-92

By David A. Nimick and John H. Lambing, U.S. Geological Survey *and*
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Abstract

Selenium and other constituents are adversely affecting water quality and are a potential risk to wildlife in several areas of the Sun River Irrigation Project, Freezout Lake Wildlife Management Area, and Benton Lake National Wildlife Refuge in west-central Montana. Selenium derived from Cretaceous shale and Tertiary and Quaternary deposits containing shale detritus is transported in the oxic shallow ground-water systems. Both irrigated and non-irrigated farming result in mobilization and discharge of selenium to wetlands. Selenium concentrations in the water of some drains and streams flowing to the wetlands commonly exceeded the aquatic-life criterion for chronic toxicity of 5 micrograms per liter. A saline seep that discharges to Priest Butte Lakes had the maximum selenium concentration of 1,000 micrograms per liter.

At Freezout Lake Wildlife Management Area, return flow from irrigated glacial deposits is the primary source of selenium and dissolved solids to all wetlands except Priest Butte Lakes, where ground water discharging from non-irrigated farm land is the primary contributor. Estimates of selenium loads indicate that Benton Lake generally receives more selenium in natural runoff from its non-irrigated basin than from the trans-basin diversion of water from Muddy Creek. Selenium discharged to wetlands is removed from water by biogeochemical processes and has accumulated in bottom sediment.

Selenium has accumulated in aquatic plants and invertebrates, fish, and water birds, particularly in wetland units that receive the largest selenium loads. Selenium residues in biological tissue from some wetland units exceeded biological risk levels. The highest selenium residues in biota commonly occurred in samples from Priest Butte Lakes, which also had the highest selenium concentration in wetland water. Selenium concentrations in all invertebrate samples from Priest Butte Lakes and the south end of Freezeout Lake exceeded the critical dietary threshold for water birds. Fish-age characteristics, population structure, and associated high selenium residues suggest that fish reproduction has been impaired in Priest Butte Lakes. With the possible exception of reduced juvenile survival at Priest Butte Lakes, water-bird reproduction generally has not been impaired.

Much of the selenium discharged to wetlands probably is accumulating in bottom sediment, predominantly in near-shore areas. Therefore, potential impacts to water quality and biota may be greatest near the mouths of inflows. Because the selenium discharged to wetlands becomes bound in insoluble forms, selenium likely will continue to accumulate in bottom sediment and biota rather than moving out of the wetlands through water releases.

INTRODUCTION

Concern has increased during the last decade about the quality of irrigation drainage—both surface and subsurface water draining irrigated land—and its potential effects on human health, fish, and wildlife. In 1983, incidences of mortality, physical abnormalities, and reproductive failures in waterfowl were discovered by the U.S. Fish and Wildlife Service at the Kesterson National Wildlife Refuge in the western San Joaquin Valley where drainage water was impounded. Selenium was detected in high concentrations in the drainage water, which came from irrigated land in the western San Joaquin Valley in California (Gilliom and others, 1989). In addition, potentially toxic trace elements and pesticide residues have been detected in other areas in western states that receive irrigation drainage (Sylvester and others, 1990).

Because of similar geologic and hydrologic characteristics in numerous irrigated areas of the western United States, there was concern that potentially toxic conditions related to selenium or other constituents in irrigation drainage might not be limited to the Kesterson area. To address this concern, the U.S. Department of the Interior (DOI) began the National Irrigation Water Quality Program in 1985 to determine whether irrigation-related problems existed at other DOI constructed or managed irrigation projects, national wildlife refuges, or other wetland areas for which the DOI has responsibilities. The program evolved into five phases (Engberg and Cappellucci, 1993): (1) Identification of potential problem areas, (2) reconnaissance investigations, (3) detailed studies, (4) planning, and (5) remediation.

Approximately 600 irrigation projects and major wildlife resource areas have been constructed or are managed in 17 western states by DOI bureaus. The reconnaissance investigations are designed to determine whether irrigation drainage (1) has caused or has the potential to cause harmful effects to human health or on fish and wildlife or (2) may limit the suitability of water for beneficial uses. The duration of the reconnaissance investigations was approximately 2 years. Detailed studies were initiated if the reconnaissance investigations indicated that potentially serious water-quality problems were related to irrigation drainage. The purpose of detailed studies is to gather sufficient information to provide the scientific understanding needed for development of plans to resolve identified problems. The purpose of planning is to develop and evaluate remedial alternatives in a coordinated manner with the public and appropriate Federal, State, and local agencies. The final phase involves implementation of remedial actions.

The Sun River area of west-central Montana was selected in 1986 for a reconnaissance study. The area encompasses the Bureau of Reclamation's Sun River Irrigation Project and two nearby wetland areas managed for wildlife. The two wetland areas—Freezout Lake Wildlife Management Area (WMA) and Benton Lake National Wildlife Refuge (NWR)—receive substantial quantities of irrigation return flow from the project. The reconnaissance study (Knapton and others, 1988) indicated that most sampling sites within the Greenfields Division and Fort Shaw Division of the Sun River Irrigation Project had constituent concentrations that were less than established criteria and standards for the protection of humans, fish, and wildlife. However, several sites within Freezout Lake WMA and Benton Lake NWR had selenium concentrations in water, bottom sediment, and biota that were moderately to considerably higher than regional background values or reference concentrations associated with biological risk. On the basis of the elevated concentrations of selenium, a detailed study was conducted in the Sun River area during 1990-92.

Purpose and Scope

The purpose of this report is to present the interpretive results from a detailed, process-oriented study of the extent, magnitude, sources, pathways, and potential fate of selenium and other constituents of concern associated with irrigation drainage in the Greenfields Irrigation Division of the Sun River Irrigation Project, Freezout Lake WMA, and Benton Lake NWR. Although selenium is the primary focus of the report, other constituents of concern also are discussed. Saline conditions prevalent in the many areas underlain by shale or shale-derived deposits are a possible source of biological impairment, and locally elevated concentrations of nitrate and other trace elements are of concern. Non-irrigated lands that contribute flow to the wildlife areas also were investigated during this study to evaluate relative inputs from both irrigated and non-irrigated source areas. Physical, chemical, and biological data were collected and analyzed to describe:

1. The concentrations of selenium in representative irrigated and non-irrigated soils near Freezout Lake WMA.
2. The flow paths of shallow ground water that discharges to wetlands, the distribution of selenium and dissolved solids in ground water, and the geochemical processes that control constituent concentrations between recharge and discharge areas.
3. The concentrations of selenium and other constituents in surface water draining irrigated and non-irrigated land and in wetlands.
4. The quantities of selenium transported to the wetlands from irrigated and non-irrigated source areas.
5. Selenium accumulation in bottom sediment of wetlands and the potential physical and chemical factors influencing the fate of selenium in wetlands.
6. The reproductive success of aquatic birds at Freezout Lake WMA and Benton Lake NWR

and correlations between hatching success and selenium residues in egg tissues.

7. The concentration of selenium in aquatic vegetation, aquatic invertebrates, fish, and water birds, and whether selenium residues have the potential to adversely affect the health of fish or birds utilizing aquatic habitats within the study area.
8. The potential acute toxicity of selenium and other constituent concentrations in water from seeps, streams, drains, and wetlands, based on laboratory aquatic-bioassay tests and a duckling-exposure study.
9. The processes and interrelations between the hydrogeochemical and biological systems that may aid the planning of any necessary remedial efforts.

Sampling of soil, ground water, and biota was concentrated in and near irrigated farmland and wetlands receiving irrigation drainage. Surface water was sampled throughout the study area, including areas managed for irrigation and wildlife, and adjacent nonirrigated land that contributes natural runoff to wetlands. Field and laboratory methods used for sample collection, processing, and analysis are described by Lambing and others (1994).

Data for the detailed study were collected from July 1990 through September 1992. Some additional data collected from other programs established prior to the detailed study are used in this report, including biological data for the wildlife areas and streamflow data for long-term streamflow-gaging stations. Data collected during this study, as well as data collected by the U.S. Fish and Wildlife Service in 1987-89, were compiled by Lambing and others (1994). This study was conducted by an interbureau team of scientists from the U.S. Geological Survey and U.S. Fish and Wildlife Service. Funding for the study was provided by the U.S. Department of the Interior.

Acknowledgments

The authors acknowledge with appreciation the many individuals who assisted in the study. Particular thanks for assistance are given to Donald G. Hultman, James E. McCollum, Stephen J. Martin, and the staff at Benton Lake National Wildlife Refuge; Jerry Nypen, Manager of the Greenfields Irrigation Division; and Frank G. Feist, Mark E. Schlepp, and the staff at Freezout Lake Wildlife Management Area. Much of the biological data were collected by Kristi L. DuBois and Robert A. Grove of the U.S. Fish and Wildlife Service, and Victoria L. Kurnat, Alison E. H. Perkins and Rachel E. White of the University of Montana. Peter Schendel of the Bureau of Reclamation provided technical assistance throughout the study. Appreciation is extended to the many landowners in the study area for allowing access to their property.

Description of Study Area

The Sun River study area (fig. 1) is located within Cascade, Chouteau, and Teton Counties of west-central Montana. Headwaters of the Sun River form along the eastern slopes of the Rocky Mountains from which the river flows eastward to its confluence with the Missouri River at the city of Great Falls. Irrigation water is diverted from the Sun River below Gibson Reservoir, which lies at the foot of the mountains. The irrigation water is conveyed by canals to several elevated prairie plateaus termed "benches." The largest of these benches served by the Sun River Irrigation Project is the Greenfields Bench.

The Sun River Irrigation Project has two major divisions. The smaller division, the Fort Shaw Irrigation Division, borders the lower Sun River and contains approximately 10,000 acres. The Fort Shaw Irrigation Division was not included in this study because Knapton and others (1988) concluded in their reconnaissance study that irrigation drainage from this division had little impact on biota. The other division is the Greenfields Irrigation Division, which consists of approximately 83,000 acres. The predominant irrigated crops are barley and alfalfa. Some of the irrigated land is used as pasture.

The study area encompasses a broad and diverse geographic area that includes several administrative units and hydrologic basins. In this report, the study area is subdivided into three areas—the Greenfields Irrigation Division of the Sun River Irrigation Project, Freezout Lake WMA, and Benton Lake NWR—to clarify data presentation and discussion.

Climate of the area is influenced by the topographic convergence of mountains and plains causing semi-arid conditions and variable temperatures. Harsh winters are often interrupted by warm air masses moving along the east slope of the Rocky Mountains resulting in mid-winter runoff from melting snow. Annual precipitation is about 12-15 in. and class-A pan evaporation, as estimated by the National Weather Service, is 57 in. About 80 percent of the annual precipitation falls from April through September (National Oceanic and Atmospheric Administration, 1982). Although the climate in this part of Montana is suitable for non-irrigated farming, water distribution made available by the Sun River Irrigation Project has resulted in parts of the area being converted to irrigated farming.

Greenfields Irrigation Division of the Sun River Irrigation Project

Almost two-thirds, or about 54,700 acres, of the irrigated land in the Greenfields Irrigation Division is on the Greenfields Bench (fig. 2). Irrigation within the Division also occurs on the Ashuclot Bench and in the Sunny Slope area. The Division contains about 600 farms. Water for the irrigation project is diverted from the Sun River and passes through a series of reservoirs and canals before distribution to fields. Most of the irrigation return flow from the Division drains into the Sun River, either directly from the south flanks of the irrigated benches or indirectly from the north and east flanks of the Greenfields Bench through the tributary Muddy Creek. A small part of the Division near the western edge of the Greenfields Bench drains to Freezout Lake WMA.

Construction of facilities within the Greenfields Irrigation Division began in 1913 and the first water was delivered in 1920. The main storage structure, Gibson Dam, is located on the upper Sun River and was constructed during 1922-29. Gibson Reservoir has an active storage capacity of about 105,000 acre-ft. Water is diverted about 3 mi downstream from Gibson Dam and flows by canal for approximately 10 mi to Pishkun Reservoir, an off-stream storage facility with a capacity of 46,300 acre-ft. From Pishkun Reservoir, water flows through a canal for 18 mi before entering the Greenfields Main Canal. This canal, with an initial capacity of 1,200 ft^3/s, extends 25.4 mi northeast across the Greenfields Bench, ending in a wasteway that flows to Muddy Creek. Approximately 300 mi of canals and laterals distribute water across the Greenfields Bench.

Irrigation return flow is the diverted water that is not consumed by evaporation or plant transpiration and that returns as inflow to a downgradient stream or lake. The two principal components of irrigation return flow are irrigation drainage and surface return flow. Irrigation drainage refers to the subsurface component of irrigation return flow and consists of irrigation water that percolates past the root zone in fields or leaks from canals. This water enters the shallow ground-water system and discharges to drains or streams. Surface return flow consists of unconsumed irrigation water that drains from the surface of irrigated fields and unused irrigation water spilled directly to drains.

Irrigation return flow from the Greenfields Irrigation Division persists throughout the irrigation season and continues after the irrigation season as aquifers discharge ground water to drains. Many drains carry some water during the entire year. Direct spills of excess supply water are common at the beginning of the irrigation season, when supply canals are being filled but little water is needed for irrigation. Direct spills also occur during and shortly after precipitation events, when scheduled applications of irrigation water are not needed. During times of direct spills, large volumes of water move through the canal system and drain to downgradient streams or wetlands. Late in the season, as water is utilized by crops, flow in irrigation drains decreases. After termination of irrigation deliveries, flow in drains is sustained at base-flow levels by discharge of residual irrigation drainage.

Irrigation return flow is supplied to Freezout Lake WMA by drains from three general areas: (1) the northwest corner of the Greenfields Bench, (2) the southwest corner of the Greenfields Bench, and (3) the area between the Greenfields Bench and Freezout Lake WMA. Much of the irrigation return flow from the northwest corner of the Greenfields Bench is intercepted by the North Supply Ditch that flows into Pond 1 of Freezout Lake WMA (fig. 2). The southwest corner of the Greenfields Bench drains directly to the south end of Freezeout Lake. Irrigation return flow from the area between the Greenfields Bench and Freezeout Lake discharges primarily to Freezeout Lake and Pond 5 of Freezout Lake WMA.

Supplemental water is supplied to Benton Lake NWR by trans-basin diversion from Muddy Creek. Water in Muddy Creek at the pump station, which is near the town of Power, consists almost entirely of irrigation return flow from the central and northeast parts of the Greenfields Bench.

Freezout Lake Wildlife Management Area

Freezout Lake WMA was established in 1952 and contains 12,000 acres of wetlands and uplands. The refuge is owned by the State of Montana, except for 435 acres of the main lake that are owned by the U.S. Fish and Wildlife Service; the entire area, however is managed by the Montana Department of Fish, Wildlife and Parks. The area was historically a natural closed basin that, at times, would go completely dry. With development of nearby irrigation and the contribution of irrigation return flow, the area of wetlands has increased and wetland stability has been sustained. The natural drainage area of Freezout Lake WMA is 71,500 acres, with the largest part consisting of rangeland and non-irrigated farmland west of Freezeout Lake.

About 4,800 acres, or 40 percent, of Freezout Lake WMA is maintained in wetlands. The wetlands

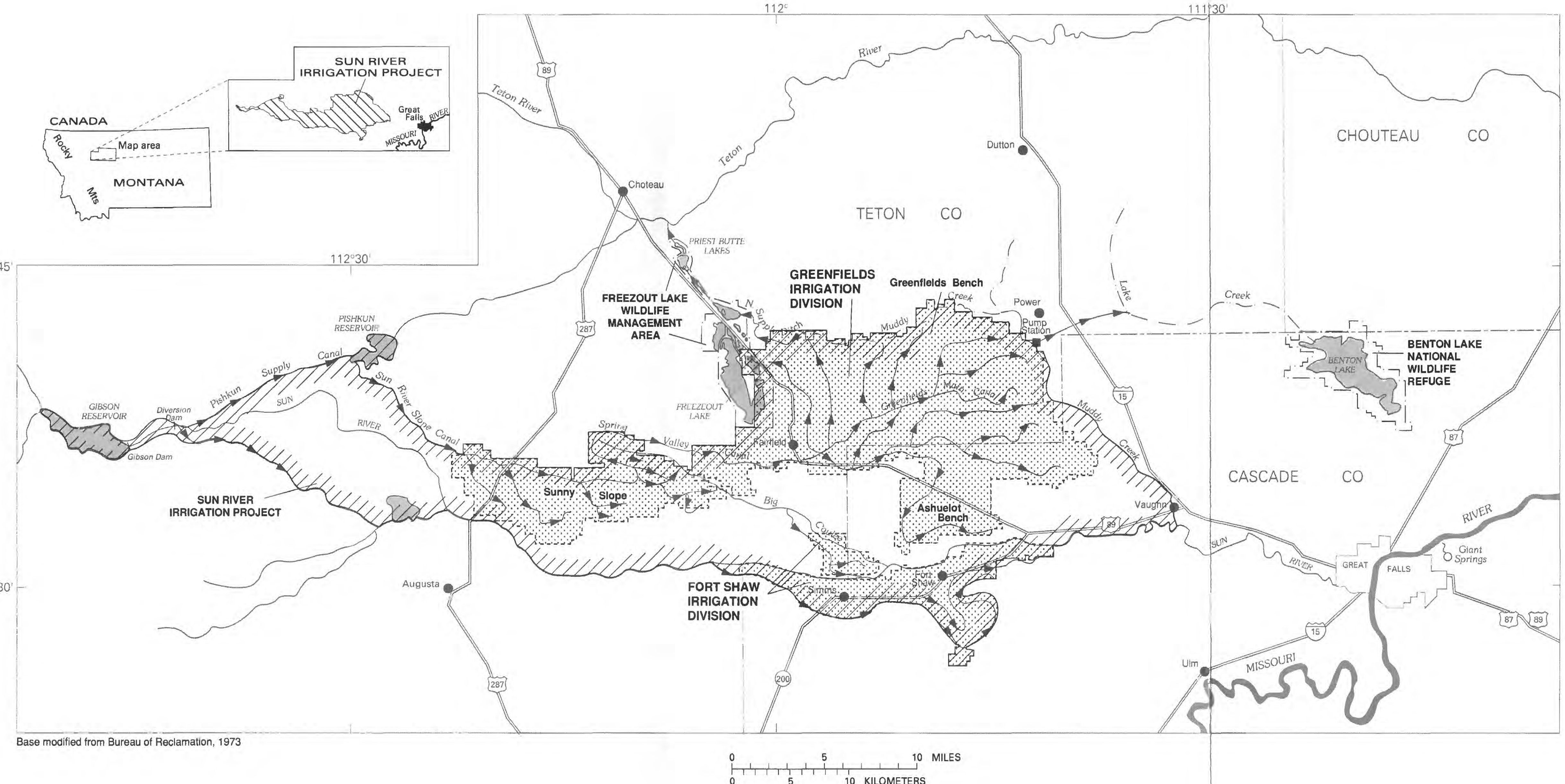


Figure 1. Location and selected features of the Sun River study area, Montana.

consist of six ponds (Ponds 1-6), Freezeout Lake, and two smaller lakes (Priest Butte Lakes) several miles to the north and connected to the southern complex by a canal (fig. 2). The principal sources of water for Freezout Lake WMA are (1) irrigation return flow from approximately 7,540 irrigated acres of the Greenfields Irrigation Division, (2) natural runoff from the surrounding basin, and (3) direct precipitation falling onto the water bodies.

Numerous drains carry irrigation return flow into the south and east sides of Freezout Lake WMA and several management options are utilized to distribute water to obtain optimal water levels in the wetlands. The North Supply Ditch discharges water into Pond 1. From Pond 1, distribution can be made to Ponds 2, 3, and 4, which, in turn, can drain to Freezeout Lake. Pond 5 is fed by several drains and can discharge into Pond 6 and then into Freezeout Lake. Water can be conveyed from Freezeout Lake to Priest Butte Lakes and then discharged through a control structure into the Teton River. The amount of water released to the Teton River is regulated for salinity by the Montana Department of Environmental Quality based on the dilution capabilities of the river. Releases from Priest Butte Lakes occur infrequently.

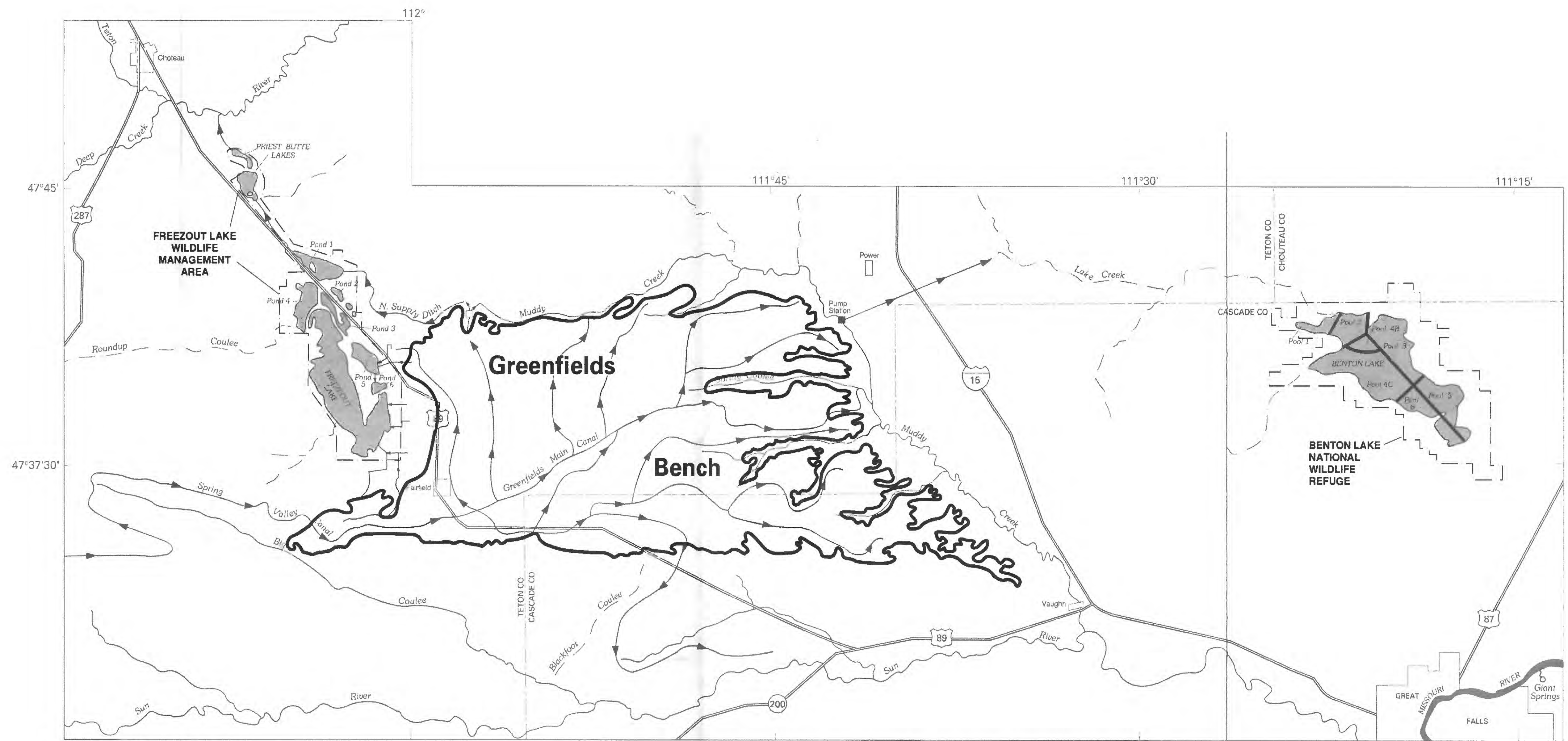
Freezout Lake WMA is primarily managed to promote waterfowl and upland game-bird production, game-bird hunting opportunities, and public viewing of the diverse wildlife that utilize the area throughout the year. This area is considered to be a key staging area along the Pacific Flyway during the spring and fall migration of water birds. It is estimated that up to a million waterfowl, including 300,000 snow geese (*Chen caerulescens*) and 100,000 tundra swans (*Cygnus columbianus*), have utilized this area during peak migration periods (Frank Feist, Montana Department of Fish, Wildlife and Parks, written commun., 1992).

Federally listed endangered bird species observed at Freezout Lake WMA include the trumpeter swan (*Cygnus buccinator*), bald eagle (*Haliaeetus leucocephalus*), and peregrine falcon (*Falco peregrinus*). Montana Natural Heritage Program bird species of special concern utilizing the area include the common loon (*Gavia immer*), American white pelican (*Pelecanus erythrorhyncos*), white-faced ibis (*Plegadis chihi*), and ferruginous hawk (*Buteo regalis*). Of the 158 bird species that have been observed at Freezout Lake WMA, 67 species, including 13 waterfowl and 24 other waterbird species, nest within the area. Waterfowl production has been estimated to be approximately 10,000 to 20,000 birds per year (Frank Feist, Montana Department of Fish, Wildlife and Parks, oral commun., 1992).

Benton Lake National Wildlife Refuge

Benton Lake NWR is managed by the U.S. Fish and Wildlife Service and 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 and the wetland area was divided into six units (Pools 1-6) by dikes (fig. 2). Before 1961, the amount of water in Benton Lake varied greatly seasonally and annually due to the large variability in the timing and amount of natural runoff. Provision for interbasin transfer from Muddy Creek, where flow is derived primarily from irrigation return flow from the Greenfields Bench, allowed for a larger and more stable wetland system. Water from Muddy Creek is pumped about 4 mi through a pipe over a 200-ft drainage divide to Lake Creek, flows down Lake Creek approximately 8 mi, and discharges into Pool 1 of Benton Lake. Both gravity flow through canals and pumping are used for distribution of water among the pools. In addition to water pumped from Muddy Creek, surface runoff from the non-irrigated basin and direct precipitation onto the wetlands constitute the other principal water sources to Benton Lake NWR. Benton Lake is in a closed basin.

Benton Lake NWR ranks as one of the top waterfowl-producing refuges in the nation. Annual duck production ranges from 8,000 to 40,000 ducks, primarily gadwall (*Anas strepera*), northern shoveler (*Anas clypeata*), blue-winged teal (*Anas discors*), cinnamon teal (*Anas cyanoptera*), northern pintail (*Anas acuta*), and mallard (*Anas platyrhynchos*). A flock of Canada geese (*Branta canadensis*) started in the 1970's now produces 300 to 400 goslings each year. Other water birds such as American avocets (*Recurvirosta americana*), marbled godwits (*Limosa fedoa*), willets (*Catoptrophorus semipalmatus*), Wilson's phalaropes (*Phalaropus tricolor*), American coots (*Fulica americana*), and eared grebes (*Podiceps nigricollis*) nest in large numbers on the refuge. Franklin's gulls (*Larus pipixcan*) nest in several large colonies containing a total of 10,000-15,000 nests. Benton Lake NWR is a significant stop-over area for many migratory birds and has been nominated for inclusion in the Western Hemisphere Shorebird Reserve Network. Up to 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.



Base from U.S. Geological Survey Choteau quadrangle, 1:100,000, 1984 and from Bureau of Land Management, Great Falls North quadrangle, 1:100,000, 1976

Figure 2. Location of Freezout Lake Wildlife Management Area, Greenfields Bench, and Benton Lake National Wildlife Refuge, Montana.

Geology

The geology of the study area (fig. 3) is characterized by gently dipping sedimentary bedrock overlain in many places by unconsolidated glacial and alluvial deposits. Bedrock in most of the study area is seleniferous marine shale of the Cretaceous Colorado Group. A second bedrock unit, the Upper Cretaceous Montana Group, is exposed along the western margin of the study area and consists of relatively non-seleniferous mudstone, siltstone, and sandstone. The important unconsolidated deposits in the study area are Tertiary (?) or Quaternary gravels underlying the Greenfields Bench and Quaternary glacial deposits near Freezeout and Benton Lakes. Many of the unconsolidated deposits are seleniferous because they contain detritus of the seleniferous marine shale.

Detailed geologic mapping has been completed only in the eastern half of the study area (Maughan, 1961; Lemke, 1977). In the western half of the study area, geologic information is available only from smaller-scale, regional maps (Mudge and others, 1982; Kleinkopf and Mudge, 1972). Colton and others (1961) mapped the extent of the last Pleistocene continental ice sheet and glacial Lake Great Falls. Mudge and others (1982), Lemke (1977), Maughan (1961), and Alden (1932) mapped glacial deposits in more detail. The extent of glacial deposits north of the Greenfields Bench was mapped during the present study.

The Colorado Group is exposed from west-central Montana north to Canada and underlies the study area east of Freezeout Lake. The unit is flat-lying to gently dipping and is best exposed in the many small drainages that dissect it. The Colorado Group consists of the Cretaceous Blackleaf Formation and Upper Cretaceous Marias River Shale (not mapped separately in figure 3). These formations are primarily dark gray shale with some interbedded siltstone, sandstone, and bentonite. The combined thickness of both formations is about 1,500 ft. Cobban and others (1976) and Maughan (1961) described the Colorado Group in detail. The Upper Cretaceous Montana Group is exposed west of Freezeout Lake. This unit consists of the Telegraph Creek Formation, Virgelle Sandstone, and Two Medicine Formation (Mudge and others, 1982). The Telegraph Creek Formation consists of marine mudstone, siltstone, and sandstone. The Virgelle Sandstone consists of marine fine-grained sandstone and forms the prominent cliffs west of Freezeout and Priest Butte Lakes. Rocks in the Two Medicine Formation are nonmarine, volcanic-rich mudstone and sandstone. Because of its limited exposure in the study area, the Telegraph Creek Formation is mapped with the Virgelle Sandstone in figure 3.

The Greenfields Bench is underlain by Tertiary (?) or Quaternary gravel deposited on eroded surfaces of the Colorado Group by the ancestral Sun River (Maughan, 1961). The moderately well sorted, poorly stratified gravel consists primarily of cobbles and pebbles of quartzite and argillite derived from rocks of Precambrian age exposed in the headwaters of the Sun River. In contrast, limestone and dolomite fragments are not common in the gravel despite the large area of exposure of these rocks in the Sun River drainage. The gravel probably contains relatively little detritus from the Colorado Group because this unit has limited surface exposure in the Sun River drainage. Caliche coatings as much as 0.5-in. thick are almost universal on the under surfaces of clasts. Locally, the gravel is cemented by caliche into conglomerate. Fine-grained wind-deposited material as much as 2 to 3 ft thick covers the gravel in most places. The Greenfields Bench consists of three terraces underlain by 10-60 ft of gravel. The Bench has remained topographically high relative to adjacent areas because the gravel veneer has protected the underlying shale from erosion. The contact of the gravel and shale around the periphery of the Bench commonly is marked by seeps and springs.

The late Pleistocene continental ice sheet extended south to the northern margin of the study area (Colton and others, 1961). Glacial drift associated with the ice sheet was deposited northeast of Benton Lake and east of Priest Butte Lakes. The deposits are primarily glacial till consisting of unsorted and unstratified clay, silt, sand, and some coarser fragments. Locally, glacial drift includes stratified sand and gravel alluvial deposits (Mudge and others, 1982; Lemke, 1977). The ice sheet dammed the ancestral Missouri River forming glacial Lake Great Falls (Colton and others, 1961). The lake covered many low-lying parts of the study area. Glacial-lake deposits near Benton Lake are primarily clay and silty clay and are as much as 100-ft thick (Lemke, 1977). Near Freezeout and Priest Butte Lakes, glacial-lake deposits consist of silty clay, clay, and some sand and generally are coarser where wave action selectively sorted surficial deposits. Between Freezeout Lake and the Greenfields Bench, lake deposits are mixed with colluvium derived from the gravel that caps the Bench. All glacial deposits presumably contain a large amount of shale detritus eroded by the ice sheet from the wide-spread exposures of the Colorado Group north of the study area.

Quaternary alluvium is present in valleys of major drainages. These deposits consist of unconsolidated fluvial silt, sand, and gravel and include alluvial-fan and slope-wash deposits.

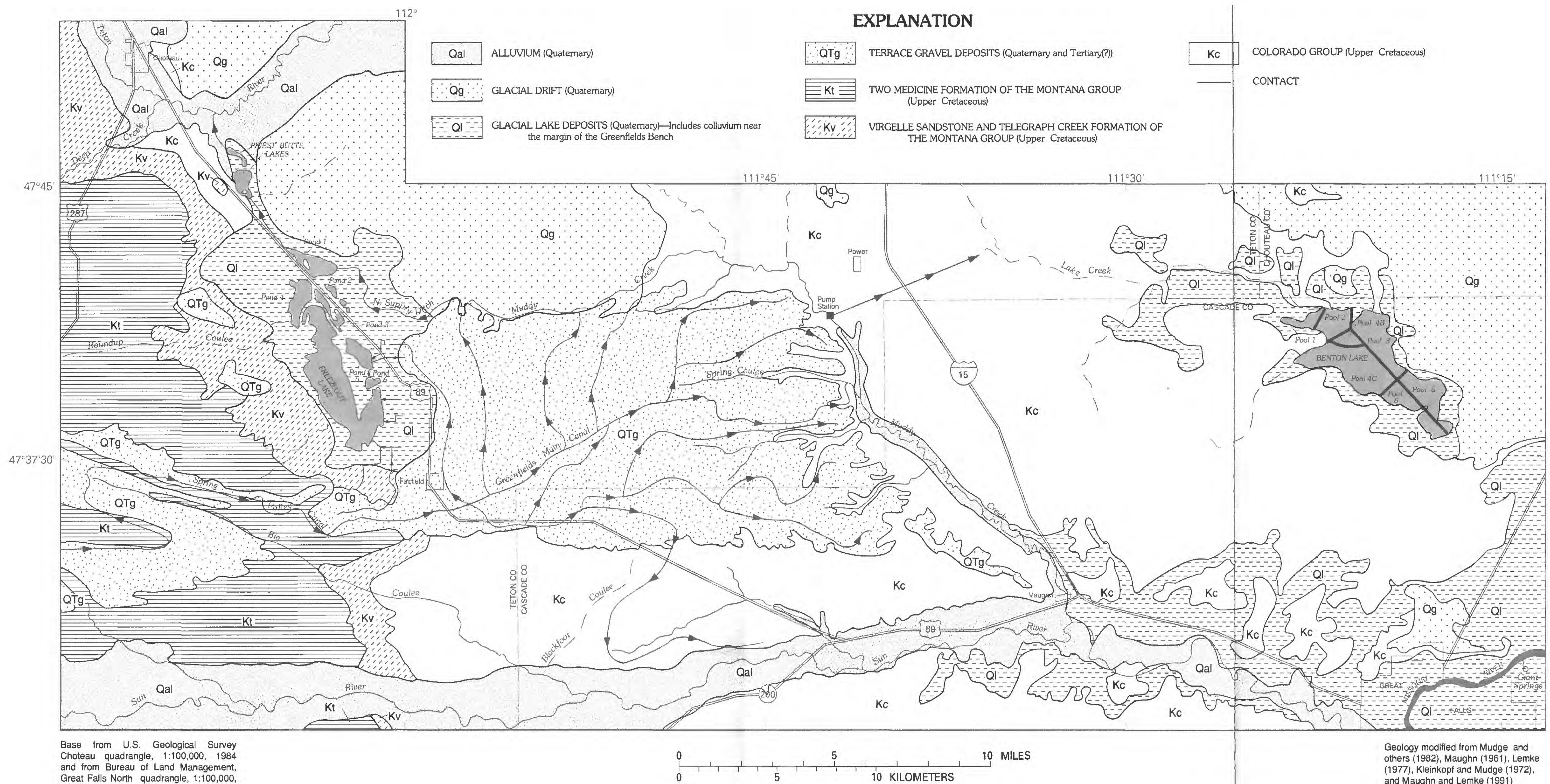


Figure 3. Geologic map of the Sun River area, Montana.

Data on the selenium content of geologic units in the study area are sparse. Selenium concentrations in drill-core samples of unweathered shale were determined for this study (Lambing and others, 1994, table 13). Twelve samples of the Marias River Shale from 4 boreholes near Freezeout Lake had selenium concentrations ranging from 1.5 to 3.0 µg/g. Eight samples from 3 boreholes penetrating the upper part of the Blackleaf Formation near Benton Lake had concentrations ranging from 0.3 to 1.1 µg/g. Prior to this study, no data had been reported for samples from the study area. Selenium concentrations for 10 samples of Colorado Group shale collected from several areas within 50 mi of the study area had concentrations ranging from 0.25-10 µg/g with a geometric mean of 1.3 µg/g (Donovan and others, 1981). All but two samples had concentrations greater than 0.5 µg/g. These values are similar to the values for unweathered shale samples collected for this study. Schultz and others (1980) determined selenium concentrations in 26 samples from the Montana Group collected from 4 localities within about 60 mi of the study area. Selenium concentrations in these samples ranged from less than 0.5 to 1 µg/g. Although the analytical method used was neither as sensitive nor as precise (Rader and Grimaldi, 1961) as methods available today, the analyses indicate that selenium concentrations in the Montana Group generally are much lower than selenium concentrations in the Colorado Group.

Selenium Biogeochemistry

Selenium is a trace element that is widely distributed in aquatic and terrestrial systems. Selenium biogeochemistry is complex because selenium occurs in several inorganic and organic forms and many physical and biological processes affect its concentration, mobility, and distribution. Because the range of concentrations that are beneficial to plants and animals is small, understanding the sources and transport mechanisms of selenium is important (McNeal and Balistrieri, 1989).

Concentrations of selenium in natural waters are controlled by processes such as mineral precipitation, adsorption, volatilization, chemical and bacterial reduction and oxidation reactions, and metabolic uptake and release by biota. The importance of each of these processes in controlling selenium concentrations in natural waters depends on which selenium species is present. Inorganic selenium species are selenate (SeO_4^{2-}), selenite (SeO_3^{2-}), elemental selenium (Se^0), and selenide (Se^{2-}). Oxidation-reduction potential (Eh) and pH are the most important factors controlling the chemical speciation and stability of selenium (McNeal and Balistrieri, 1989). Organic forms of selenium also are important in the biogeochemistry of selenium (Cooke and Bruland, 1987).

Selenate is the most mobile inorganic selenium species in natural water because chemical and physical processes generally do not limit its solubility. Selenate occurs in oxidizing environments, such as well-aerated streams, where it adsorbs weakly to particles and its salts are soluble. Therefore, most selenium transported in streams is dissolved selenate rather than some form of selenium adsorbed to suspended particles. Where oxidizing conditions exist, selenium also is easily leached from soil and transported to ground water.

Other inorganic selenium species are less soluble and, therefore, less mobile. Selenite is immobilized by either adsorption to metal oxides, clays, and organic particulates or by reduction to elemental selenium by chemical and biological processes. Elemental selenium is stable over a wide intermediate range of pH and Eh conditions and is insoluble in water. In strongly reducing conditions, selenide is the thermodynamically stable species. Selenide tends to substitute for sulfur in sulfide minerals or to precipitate as insoluble metal selenides, although limited selenium solubility in strongly reducing conditions has been demonstrated by Weres and others (1989). Ground water under reducing conditions normally does not contain dissolved selenium (Long and others, 1990; Weres and others, 1990). White and others (1991) observed negligible dissolved selenium in ground water with Eh values of less than 200 mV, measured semi-quantitatively with a platinum electrode. Because selenium generally is mobile only in oxidizing conditions, and because ferrous iron, manganese, and sulfide are dissolved species indicative of reducing conditions, selenium typically will not be present in ground water if any of these other constituents are present. Conversely, because dissolved oxygen and nitrate are dissolved species indicative of oxidizing conditions, selenium might be present in ground water if either of these constituents is present.

Organo-selenium compounds are part of selenium's biogeochemical cycle, although their chemistry is not well understood. Analytical techniques that can identify these compounds are difficult and not routinely performed and, therefore, the distribution and concentration of these compounds are poorly known. Cooke and Bruland (1987) demonstrated that methylated selenium species were a dominant form of dissolved selenium at Kesterson Reservoir and Salton Sea. Some methylated selenium compounds, such as dimethyl selenide, are volatile. Plants and soil microbes (commonly fungi) can convert elemental selenium to methylated forms if moisture, air, and organic matter are available (Karlson and Frankenberger, 1989, 1990; Frankenberger and Karlson, 1989). Bacteria in alkaline lake water (Thompson-Eagle and Frankenberger, 1991) and at the water-sediment interface (Cooke and Bruland, 1987) in aquatic systems also can produce volatile methylated selenium compounds. Some organo-selenium compounds are important selenium sinks in anaerobic sediments (Cooke and Bruland, 1987).

Habitats that tend to accumulate selenium most efficiently are shallow-water areas of standing or slow-moving water with low flushing rates (Lemly and Smith, 1987). Dissolved selenium can be removed from lake water and stored in sediment by several processes. The most important process leading to selenium accumulation probably is reduction and conversion to organic or elemental selenium by bacteria in surficial sediment (Oremland and others, 1990, 1991). Selenium also is removed from water and concentrated in surficial sediment through uptake by aquatic organisms or adsorption to suspended sediment and subsequent settling of the dead organisms and suspended sediment (Lemly and Smith, 1987; Weres and others, 1989, 1990). Seventy-five percent of all the selenium in an aquatic system may be in the upper few inches of bottom sediment, and most of the selenium in sediment is associated with organic matter (Weres and others, 1989; Tokunaga and others, 1991).

In contrast to accumulation, selenium can be removed from shallow aquatic systems by several processes. Selenium can be flushed from lakes by movement of water and sediment through the lake outlet. If surface water of wetlands recharges a ground-water system, dissolved selenium can be transported in the ground water if oxidizing conditions persist. Formation of volatile selenium compounds and subsequent release to the atmosphere also will remove selenium from aquatic systems. If sedimentation rates are high, selenium can be buried and effectively removed from the active biogeochemical zone of the aquatic system. Or, if shallow ponds go dry, selenium-enriched salts and exposed sediment can be removed by wind erosion. Although evaporation can concentrate dissolved selenium in lake water, removal processes generally are more active and selenium concentrations in lake water typically tend to decrease rather than increase (Lemly and Smith, 1987; White and others, 1991).

Biota can be exposed to selenium by several processes. Although anaerobic sediments are a sink for selenium in aquatic ecosystems, selenium continually cycles from sediment to water and biota and back into the sediment. Selenium in sediments can be released to water through oxidation enhanced by plant roots and microorganisms or through physical agitation of sediments by wind, currents, or the feeding activities of benthic invertebrates, fish, and water birds (Lemly and Smith, 1987). Conversion of reduced organic or elemental forms to methylated forms by microorganisms or plants also releases selenium to water where it is available to aquatic organisms (Weres and others, 1989; Karlson and Frankenberger, 1990). In perhaps the most important pathway of selenium exposure, selenium in bottom sediments can enter the food chain either through direct uptake by plant roots or ingestion of bottom sediment by detrital- and bottom-feeding organisms, or by consumption of these dietary items by fish and wildlife. Thus, although selenium concentrations can be very low in water, exposure to biota can continue to occur from selenium accumulated in bottom sediments.

Bioaccumulation of selenium in aquatic systems can cause selenium concentrations in aquatic organisms to be higher than concentrations in sediment by an order of magnitude or more. Selenium toxicity to fish and wildlife typically occurs through ingestion of lower trophic level organisms that have bioaccumulated selenium. Bioaccumulation may occur easily because selenium is an essential micronutrient and is chemically similar to sulfur (Lemly and Smith, 1987; Ohlendorf and others, 1993).

Considerable information regarding the occurrence and mobility of selenium in soils has been published in recent years. Much of this information is summarized by Severson and others (1991). In separate but related studies of selenium in soils of the San Joaquin Valley, Fujii and others (1988) and Alemi and others (1988) found that most of the soluble selenium was present as selenate, whereas most of the selenium adsorbed in the soil was selenite. This combination is particularly evident in soils that are slightly alkaline such as those generally present in the plains area of the western United States. In seleniferous areas, high selenium concentrations in soil and water commonly are accompanied by high salinity.

Reference Concentrations Used for Risk Assessment

Concentrations of constituents in water were compared to regulations and criteria established for the protection of human health or aquatic life. Exceedances of these reference concentrations could indicate potential risk to humans or aquatic organisms either by direct ingestion or ambient exposure. Environmental risk also is evaluated indirectly by comparison to local background concentrations to indicate whether ambient concentrations are elevated relative to natural conditions for the area.

Regulations for allowable concentrations of selected constituents in public drinking-water supplies have been established by the U.S. Environmental Protection Agency (1991) to protect human health. Primary Drinking-Water Regulations, which are reported as Maximum Contaminant Levels (MCL's), are legally enforceable for public drinking-water supplies.

Aquatic-life criteria for concentrations of selected constituents in water have been established by the U.S. Environmental Protection Agency (1986) to protect aquatic organisms from potential toxicity. Two levels of toxicity are designated by the criteria—acute and chronic. Acute toxicity is manifested by widespread death to large numbers of the aquatic population within a relatively short time as a result of rapid and large increases in contaminant concentrations. Chronic toxicity is manifested by suppression of normal biological functions over a long time as a result of contaminant concentrations that consistently exceed biological thresholds for impairment.

Drinking-water regulations and aquatic-life criteria for trace elements and nitrogen compounds are presented in table 1. Because the degree of toxicity to

Table 1. Drinking-water regulations and aquatic-life criteria for selected constituents in water

[All concentrations are in micrograms per liter (µg/L) unless otherwise noted. Abbreviation: mg/L, milligrams per liter. Symbol: --, no regulation or criterion]

Constituent	Maximum concentration established for indicated regulation or criteria			Hardness, as calcium carbonate (mg/L as $CaCO_3$)
	Primary drinking-water regulation[1]	Freshwater aquatic-life criteria[2]		
		Acute toxicity	Chronic toxicity	
Ammonia, total[3]	--	0.71-0.83 mg/L	0.12-0.13 mg/L	--
Arsenic	50	360	190	--
Barium	1,000	--	--	--
Cadmium	5	14	2.7	300
		24	4.0	500
		53	6.9	1,000
		83	9.5	1,500
		400	28	6,000
Chromium[4]	100	16	11	--
Copper	--	50	30	300
		81	47	500
		160	85	1,000
		230	120	1,500
		840	390	6,000
Nickel	--	3,600	400	300
		5,500	620	500
		9,900	1,100	1,000
		14,000	1,600	1,500
		45,000	5,000	6,000
Nitrite plus nitrate	10 mg/L	--	--	--
pH (minimum)	--	--	6.5 units	--
pH (maximum)	--	--	9.0 units	--
Selenium	50	20	5	--
Zinc	--	300	270	300
		460	410	500
		820	750	1,000
		1,200	1,100	1,500
		3,200	2,900	6,000

[1]U.S. Environmental Protection Agency, 1991.
[2]Hardness, in milligrams per liter as calcium carbonate, is used to calculate aquatic-life criteria for cadmium, copper, nickel, and zinc. Equations for hardness-dependent criteria are reported in U.S. Environmental Protection Agency (1986). Hardness concentrations shown represent the range of values commonly occurring in the study area.
[3]The ranges of aquatic-life criteria for ammonia are based on a temperature range of 0-25°C at pH of 9.0 (U.S. Environmental Protection Agency, 1986). The criteria listed are for total ammonia concentrations, as nitrogen, and are based on equivalent concentrations of un-ionized ammonia.
[4]Aquatic-life criterion is for hexavalent chromium (U.S. Environmental Protection Agency, 1986).

aquatic life from cadmium, copper, nickel, and zinc varies with the ambient hardness of water, toxic concentrations for these trace elements need to be calculated for each sample. However, to facilitate general comparison of potential toxicity among the sampling sites, hardness-dependent aquatic-life criteria are presented for five levels of hardness. These five levels approximate the median hardness of surface water at sites grouped by similar geology, land use, and hydrologic characteristics (table 2).

Concentrations of selenium in sediment and in the tissue of organisms that are food sources for fish, water birds, and ducks are compared to available reference concentrations for potential toxicity (table 3). In addition, selenium residues in the tissue of fish, bird eggs, water birds, and ducks are compared to reference concentrations that are indicative of levels at which

Table 2. Median hardness values for surface-water samples from areas of similar geology, land use, and hydrologic characteristics in the Sun River area, Montana

[Abbreviation: mg/L, milligrams per liter. Symbol: --, not applicable]

Water type	Principal geologic unit	Approximate median hardness (mg/L as $CaCO_3$)
Irrigation return flow	Quaternary and Tertiary (?) gravel	300
Natural runoff	Upper Cretaceous Montana Group	500
Irrigation return flow	Mixed gravel and glacial deposits	1,000
Wetlands	--	1,000
Irrigation return flow	Quaternary glacial deposits	1,500
Natural runoff	Quaternary glacial deposits and Cretaceous Colorado Group	6,000

Table 3. Selenium concentrations in food sources, animal tissue, and sediment related to safe background levels and potential biological impairment in some fish and water-bird species

[Concentrations in micrograms per gram dry weight. Symbols: <, less than; --, not applicable]

Matrix	Safe background concentration	Concentration threshold for potential biological impairment: Critical waterfowl dietary ingestion	Low water-bird hatchability	Reduced duckling survival	Reproductive inhibition in mallards	Reproductive failure or mortality in water birds	Reproductive failure or mortality in fish	Reference
Food sources								
Aquatic plant	<4	5	--	--	--	--	--	Skorupa and Ohlendorf (1991)
Aquatic invertebrate	<4	5	--	--	--	--	--	Skorupa and Ohlendorf (1991)
Fish	<4	5	--	--	--	--	--	Skorupa and Ohlendorf (1991)
Animal tissue								
Fish	2	--	--	--	--	--	12-24	Lemly and Smith (1987)
Water-bird embryo	<3	--	8	5.2	--	--	--	Skorupa and Ohlendorf (1991)
Water-bird liver	6	--	--	--	10.4	--	--	J.P. Skorupa, U.S. Fish and Wildlife Service, written commun., 1993
Sediment	--	--	--	--	--	4	4	Lemly and Smith (1987)

selenium bioaccumulation adversely affects growth, survival, or reproduction. Most of the biological reference concentrations in table 3 are compiled from the literature and are based on either laboratory toxicity tests conducted under controlled environmental conditions or field studies performed within the Central Valley of California. Exceedances of these concentrations in either dietary items or body burden of higher trophic organisms could indicate potential risk.

SOIL

Soils were sampled to determine the concentration and distribution of selenium and other elements in areas that contribute irrigation drainage or natural runoff to Freezout Lake WMA. Soils were not sampled in the eastern and central parts of the Greenfields Bench or in the Benton Lake basin. Depth-composited samples were collected from 40 sites (fig. 4) in irrigated farmland, non-irrigated farmland and rangeland, alkali flats, and a saline seep during late summer and fall of 1991. Additional samples of smaller, discrete depth intervals were collected at three sites. Soil samples were analyzed for total concentrations of selenium and other selected elements, water-extractable concentrations of selenium, and water-extractable specific conductance (soil salinity). Soil-sampling sites and soil data are listed in Lambing and others (1994, tables 1 and 6).

Soil-sampling sites were selected to represent various land uses and parent materials. To maximize detection of selenium sources near Freezout Lake WMA, sites were selected predominantly in irrigated land and areas with seleniferous parent material. Soil studies typically use a random-sampling design to prepare isoconcentration maps and to estimate landscape variability of constituent concentrations. However, in this study, a random-sampling approach was not utilized because of the small number of samples that were to be collected.

Geometric means and ranges of total concentrations of selenium and other elements in soils for this study and for a regional study of the western United States (Shacklette and Boerngen, 1984) are given in table 4. The non-random site selection in this study possibly biased the data; thus, direct comparisons with other studies may not be entirely valid. Also, samples from this study were composites from the surface to a depth of 3 ft or less, whereas samples for the regional study were subsurface samples collected at a depth of approximately 8 in. The geometric mean selenium concentration (0.4 µg/g) for this study is somewhat higher than the geometric mean (0.23 µg/g) for the western United States. Most geometric mean concentrations of elements other than selenium in the Sun River area are similar to those for the western United States.

The range of total-selenium concentrations (0.1-8.5 µg/g) measured in the 40 composite soil samples was relatively large. The predominant factor affecting concentrations appears to be parent material. Soils derived from glacial deposits had higher and more variable selenium concentrations, whereas soils derived from gravel or the Montana Group generally had lower and more uniform concentrations. Table 5 summarizes selenium data for soils by parent material and land use.

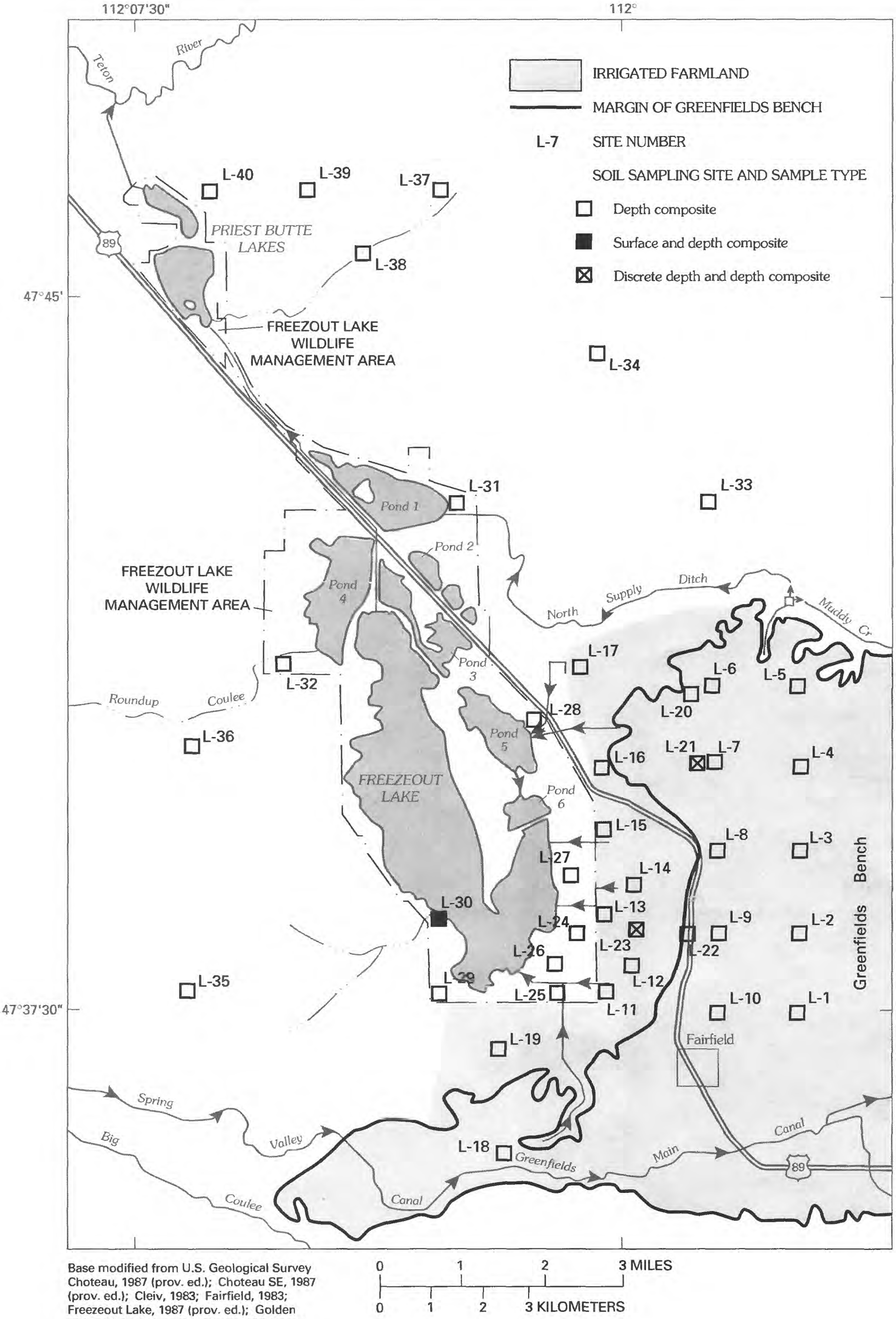
Soils Derived from Gravel

Soils of the Greenfields Bench are derived from gravel and the thin layer of wind-deposited material that commonly covers the gravel. These soils are unique in the study area because of their uniform texture and composition. Most of the sampled soils are clay loams (Lambing and others, 1994, table 1). All but one of the 13 sampling sites were irrigated. Flood irrigation was used at 12 sites and sprinkler irrigation was used at one site. Gravel soils are well drained and require more irrigation water than finer-grained soils.

The concentration of total selenium in 13 composite samples from gravel soils ranged from 0.1-0.4 µg/g with a geometric mean concentration of 0.2 µg/g (table 5). These concentrations are near the geometric mean for soils of the western United States (table 4) and are among the lowest concentrations for the different parent materials in this study. Likewise, water-extractable selenium concentrations were low (geometric mean of 0.007 µg/g) and accounted for only about 3 percent of the total selenium.

The highest water-extractable selenium concentrations in soils derived from gravel were in samples from five sites (L-5, L-6, L-7, L-20, and L-21) in the northwest corner of the Greenfields Bench (Lambing and others, 1994, table 6). Although the concentrations were relatively low, the geometric mean (0.010 µg/g) for these 5 samples is almost double the geometric mean (0.006 µg/g) for the other 8 samples of gravel-derived soils collected from other areas of the Bench. Although total-selenium concentrations did not vary substantially in soils throughout the Bench, a difference in the chemical form of selenium in the parent material or a difference in weathering rate may account for the higher concentrations of water-extractable selenium in soils in the northwest corner of the Bench.

Figure 5 illustrates total-selenium concentrations in samples of gravel-derived soil collected from site



Base modified from U.S. Geological Survey Choteau, 1987 (prov. ed.); Choteau SE, 1987 (prov. ed.); Cleiv, 1983; Fairfield, 1983; Freezeout Lake, 1987 (prov. ed.); Golden Ridge, 1987 (prov. ed.); Lowry, 1987 (prov. ed.); and Sevenmile Hill 1987 (prov. ed.) 1:24,000 quadrangles

Figure 4. Location of soil-sampling sites within or near the Greenfields Bench and Freezout Lake Wildlife Management Area, Montana.

Table 4. Geometric mean and range of concentrations for elements in soils of the Sun River area, Montana, and the western United States

[Abbreviations: µg/g, micrograms per gram. Symbols: <, less than; >, greater than; --, value not calculated]

Element	Sun River area[1]		Western United States[1] (west of 96th meridian) (Shacklette and Boerngen, 1984)	
	Geometric mean	Range	Geometric mean	Range
Aluminum, percent	5.9	4.2 - 7.2	5.8	0.5 - >10
Calcium, percent	5.1	2.7 - 13	1.8	.06 - 32
Iron, percent	2.3	1.6 - 2.9	2.1	.1 - >10
Magnesium, percent	1.6	1.2 - 2.4	.74	.03 - >10
Potassium, percent	1.7	1.1 - 2.0	1.8	.19 - 6.3
Sodium, percent	.94	.55 - 2.2	.97	.05 - 10
Arsenic, µg/g	--	<10 - 20	5.5	<.10 - 97
Barium, µg/g	510	68 - 960	580	70 - 5,000
Beryllium, µg/g	1	1 - 2	.68	<1 - 15
Chromium, µg/g	44	24 - 68	41	3 - 2,000
Cobalt, µg/g	9	7 - 10	7.1	<3 - 50
Copper, µg/g	17	13 - 23	21	2 - 300
Lithium, µg/g	34	25 - 57	22	5 - 130
Lead, µg/g	10	7 - 20	17	<10 - 700
Manganese, µg/g	350	270 - 450	380	30 - 5,000
Molybdenum, µg/g	--	<2 - 2	.85	<3 - 7
Nickel, µg/g	20	8 - 25	15	<5 - 700
Phosphorus, µg/g	710	400 - 1,400	320	40 - 4,500
Selenium, µg/g	.4	.1 - 8.5	.23	<.1 - 4.3
Strontium, µg/g	210	150 - 440	200	10 - 3,000
Uranium, µg/g	--	<100	2.5	.68 - 7.9
Vanadium, µg/g	82	55 - 150	70	7 - 500
Zinc, µg/g	69	39 - 96	55	<10 - 2,100

[1]Forty samples for Sun River area; more that 700 samples for western United States.

Table 5. Geometric mean and range of total-selenium concentration, water-extractable selenium concentration, and water-extractable specific conductance for depth-composite samples of soil derived from different parent materials in the Sun River area, Montana

[Abbreviations: µg/g, micrograms per gram; µS/cm, microsiemens per centimeter at 25 degrees Celsius; WMA, Wildlife Management Area. Symbol: <, less than]

Location (fig. 4)	Land use	Number of samples	Total-selenium concentration (µg/g)		Water-extractable selenium concentration (µg/g)		Water-extractable specific conductance (µS/cm)	
			Geometric mean	Range	Geometric mean	Range	Geometric mean	Range
		Soils derived from Tertiary (?) and Quaternary gravel						
Greenfields Bench	Irrigated[1]	13	0.2	0.1 - 0.4	0.007	<0.005 - 0.018	250	210 - 320
		Soils derived from Quaternary glacial-lake deposits						
East and south of Freezout Lake WMA	Irrigated	10	.5	.2 - 1.6	.039	.011 - .55	720	300 - 3,800
	Non-irrigated	5	.4	.1 - 1.1	.020	<.005 - .31	1,000	270 - 3,200
	Alkali flat	2	1.0	1.0 - 1.1	.099	.090 - .11	12,000	9,900 - 14,000
		Soils derived from Quaternary glacial drift						
North of Greenfields Bench	Rangeland	4	.5	.3 - 1.1	.008	.007 - .011	260	240 - 300
	Alkali flat[2]	2	3.1	1.1 - 8.5	.16	.12 - .21	2,800	870 - 8,700
		Soils derived from the Upper Cretaceous Montana Group						
West of Freezout Lake WMA	Rangeland	2	.2	.2 - .3	.005	<.005 - .010	250	160 - 390
	Alkali flat	2	.2	.2	.032	.023 - .044	8,400	7,400 - 9,600

[1]One site is non-irrigated.
[2]One site is a saline seep.

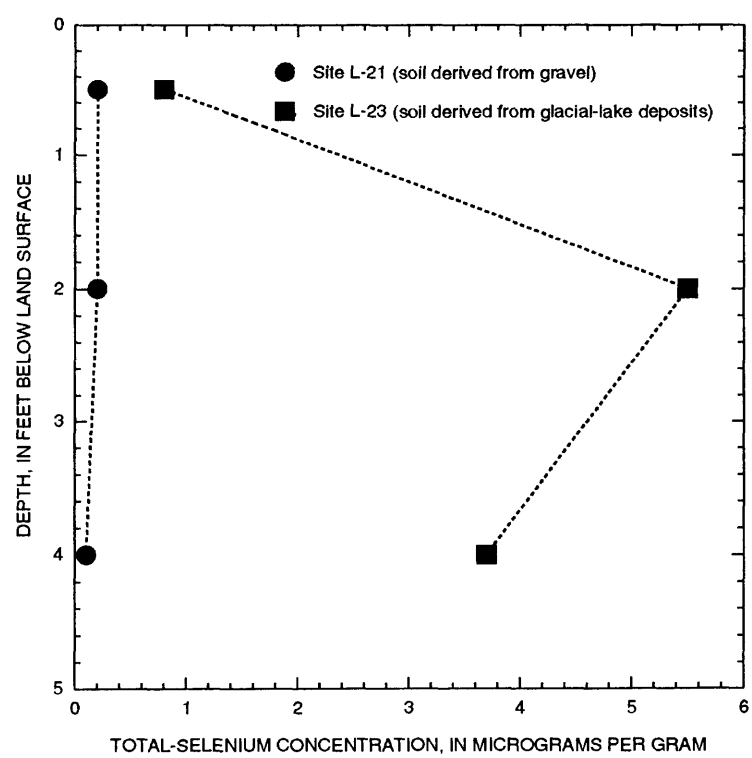


Figure 5. Total-selenium concentration in soil at discrete depths at sites L-21 and L-23, Greenfields Irrigation District, Montana.

L-21 at depths of 0.5, 2.0, and 4.0 ft. Low concentrations at each horizon indicate that selenium is not accumulating and probably is being removed at a constant rate from the top 4 ft of soil.

The consistently low concentration of total selenium in soil samples from the Greenfields Bench probably reflects the low selenium concentrations in the predominantly quartzite and argillite clasts of the gravels. However, the gravels probably contain some shale detritus, which slowly weathers and releases selenium as selenate. The soils are well drained and oxic. Therefore, any selenate that may form is rapidly removed by deep percolation of irrigation water. Larger quantities of soluble selenium may have been present prior to irrigation development. Although salts typically accumulate in soils in semi-arid areas like the study area because potential evapotranspiration is greater than average annual precipitation, most of these salts, if present, and any selenium in them, probably were flushed from the gravel-derived soils during the early years of irrigation.

Soils Derived from Glacial-Lake Deposits and Glacial Drift

Soils derived from glacial deposits are mostly clay loams or silty clay loams and were sampled at locations east and south of Freezeout and Priest Butte Lakes. Glacial-lake deposits occur in the area between Freezeout Lake and the Greenfields Bench whereas glacial drift is found east of Priest Butte Lakes and north of the Bench (fig. 3). Weathered shale of the Colorado Group underlies the glacial deposits. Soils on alkali flats derived from both types of glacial deposits were sampled and are discussed in a later section.

Total-selenium concentrations (0.1-1.6 μg/g) in composite samples of soils derived from glacial deposits were higher and exhibited greater spatial variability than concentrations in soils derived from gravel on the Greenfields Bench. Concentrations were similar in soils derived from glacial-lake deposits and glacial drift. Similarly, soils derived from glacial-lake deposits at irrigated and non-irrigated sites had virtually the same concentrations. Concentrations were variable from site to site, but no spatial pattern related to land use was evident.

Water-extractable selenium in soils derived from glacial-lake deposits had a higher geometric mean concentration (0.031 μg/g) and range (<0.005-0.55 μg/g) than soils on the Greenfields Bench. With less water percolating through, non-irrigated soils might be expected to accumulate more selenate in near-surface soluble salts and have higher concentrations of water-extractable selenium than in irrigated soils. However, concentrations were slightly higher in irrigated soils than in non-irrigated soils. Overall, water-extractable selenium made up about 5 to 8 percent of the total selenium in soils derived from glacial-lake deposits.

Water-extractable selenium concentrations in soils derived from glacial-drift (0.007-0.011 μg/g) were lower compared to concentrations in soils derived from glacial-lake deposits and were about equal to concentrations in gravel-derived soils on the Greenfields Bench. The reason for the lower water-extractable selenium concentrations in glacial-drift as compared to glacial-lake soil is not known.

The large variability of total-selenium concentrations with depth at site L-23 (fig. 5) indicates that selenium is being leached from the surface zone, which is reworked by farming, and accumulating in deeper zones. Similarly, Tidball and others (1991) found that concentrations of selenium in soils of the San Joaquin Valley of California were highest at depths of 66-72 in. and attributed the condition to leaching from upper soil zones. At site L-23, concentrations from the 2.0- and 4.0-ft horizons (5.5 and 3.7 μg/g, respectively) are comparatively high and inconsistent with the total-selenium concentration (0.9 μg/g) determined for a nearby depth-composite sample. The differences in concentrations between the discrete-depth and depth-composite samples, collected less than 50 ft apart, emphasizes that large horizontal and vertical variations in concentrations of soil selenium occur. For example, See and others (1992) and Naftz and Barclay (1991) reported large variability for total-selenium concentrations for soils in Wyoming. Glacial reworking of shale could have contributed to the selenium variability in glacial soils in the Sun River area.

The selenium in soils derived from glacial deposits probably came indirectly from shale of the Colorado Group, which was widely eroded by continental ice sheets. A study of trace elements in soils of the northern Great Plains of Montana (Williams and others, 1940) indicated that soils derived from the Colorado Group are enriched in selenium. A number of studies, such as See and others (1992), in the western United States also associate soil selenium with marine shale of Cretaceous age.

Soils Derived from the Montana Group

Soils derived from the Montana Group are calcareous loams. Concentrations of total selenium (0.2-0.3 μg/g) in composite samples were low and about the same magnitude as that for gravel-derived soils.

Water-extractable selenium concentrations (<0.005-0.010 µg/g) were low as well. Soils derived from the Montana Group are not irrigated in the study area.

Soils of Alkali Flats and Saline Seeps

Alkali-flat and saline-seep soils are discussed as a group because geochemical conditions in these non-irrigated areas are similar. The soils are clays or silty clays formed in fine-grained sediment deposited from either upstream drainages or possibly by sedimentation when water in Freezeout and Priest Butte Lakes was at a higher level. The water table is near land surface and plant growth typically is vigorous. The reducing conditions that likely are created by the saturated and organic-rich environment probably immobilize much of the selenium present. Therefore, soils in alkali flats and saline seeps might be expected to have higher selenium concentrations than coarser upland soils.

Five composite samples were collected from alkali flats around the perimeter of Freezeout and Priest Butte Lakes, where alkali flats are common, and one sample was collected about 2 mi east of Priest Butte Lakes from a prominent saline seep draining non-irrigated uplands. Sites L-30 and L-32 west of Freezeout Lake are in drainages receiving runoff from the Montana Group. On the east side of Freezout Lake WMA, drainage areas upstream from the three alkali-flat sites (L-28, L-31, and L-40) and the saline-seep site (L-38) are predominantly areas of glacial drift.

The total-selenium concentration of 8.5 µg/g measured in the saline-seep soil sample from site L-38 east of Priest Butte Lakes was the maximum for the study area and is about forty times greater than the geometric mean for soils of the western United States (table 4). This value, however, may not be unusual for soils at saline seeps in glaciated areas where drift has been derived principally from marine shale of Cretaceous age. Discharge of seleniferous ground water to the surface and subsequent evaporation probably promotes selenium accumulation in seep areas.

Total-selenium concentrations in alkali-flat soils were different on either side of Freezout Lake WMA and presumably reflect the selenium content of the sediment that accumulated in each area. The three soil samples from alkali flats formed on glacial deposits east of Freezout Lake WMA had relatively high total-selenium concentrations (1.0-1.1 µg/g) and water-extractable selenium concentrations (0.090-0.12 µg/g). In contrast, samples from alkali flats derived from Montana Group sediments west of Freezeout Lake had a total-selenium concentration of 0.2 µg/g and water-extractable selenium concentrations of 0.023 and 0.044 µg/g. These lower concentrations were similar to those in the Montana Group soils of rangeland west of Freezeout Lake and reflect the lower selenium concentrations in the Montana Group compared to the glacial deposits east of Freezout Lake WMA.

Based on one sample collected from the surface at site L-30 on the west side of Freezeout Lake, water-extractable selenium accumulates in salt crusts on alkali flats. During warm and dry periods, salts precipitate on or near the surface as soil moisture evaporates. Although total-selenium concentrations were essentially the same at site L-30 for the surface and depth-composite samples, water-extractable selenium concentrations were substantially different—0.47 µg/g for the surface sample compared to 0.023 µg/g for the depth-composite sample. Salt crusts from alkali flats on the east side of Freezout Lake WMA were not sampled but, because of high concentrations of total selenium in the soils, high concentrations of selenium presumably would be present in the surface salt crusts in this area as well.

Salts of selenium and other elements can be transported out of alkali flats by wind and water. Prevailing winds are from the west; thus, salts from alkali flats west of Freezout Lake WMA could be carried to the lakes. Surface material from alkali flats and saline seeps east of Freezout Lake WMA may be carried east, away from the wildlife area. Overland runoff from intense rains and snowmelt, however, could flush salts from alkali flats on either side to the lakes of the wildlife area.

GROUND WATER

Ground-water studies in the Sun River area were designed to determine the sources, pathways, and fate of selenium in water-bearing units that contribute drainage to wetland refuges. Salinity is a concern in the wetlands and, therefore, sources of dissolved solids also were studied. Because Freezout Lake WMA is the main wetland area that receives direct drainage from the irrigation project, ground-water investigations were focused on the small part of the Greenfields Irrigation Division that contributes irrigation drainage to Freezeout Lake and adjacent small ponds. Irrigation drainage that flows to Freezout Lake WMA discharges from two different ground-water systems: one system consists of terrace gravel underlying the Greenfields Bench and the other consists of glacial-lake deposits between the Greenfields Bench and Freezeout Lake. These ground-water systems have little, if any, interconnection, and the results of detailed investigation of each system are discussed separately. A secondary part of the investigation focused on the Benton Lake basin, primarily to provide reconnaissance information about the possible transport of selenium and dissolved solids within this non-irrigated basin.

Greenfields Bench

The Greenfields Bench consists of three gravel terraces deposited by an ancestral Sun River on an eastward-sloping, weathered shale surface of the Colorado Group. The gravel is composed of pebbles and cobbles up to 1 ft in diameter, is as much as 60-ft thick at the western end of the Bench, and is at least partly saturated throughout the Bench area. The gravel aquifer, which has been developed for domestic and municipal water supply, is isolated hydraulically by its topographic position well above the Sun River and Muddy Creek and by the less permeable shale of the underlying Colorado Group (Osborne and others, 1983). Water discharges from the gravel aquifer to several springs that existed prior to irrigation development, numerous irrigation-induced seeps located at the gravel-shale contact around the perimeter of the Bench, and irrigation drains on the Bench.

Ground-Water Flow and Water Levels

Irrigation-induced recharge turned the relatively dry gravel into a productive aquifer that now supplies water to domestic wells in all parts of the Greenfields Bench and to two public water-supply systems. Prior to irrigation development, very few wells existed on the Greenfields Bench and residents commonly hauled water to their farms because of the lack of adequate ground water. Most older domestic wells are shallow, hand dug, and gravel-lined, whereas wells completed in the past 40 years typically are deeper and steel-cased. A limited inventory of domestic wells was made by Osborne and others (1983). Additional wells were inventoried (fig. 6; Lambing and others, 1994, table 9) for this study to locate wells on the western Greenfields Bench for detailed water-table mapping and for collection of water-chemistry samples. Municipal water is provided to Fairfield from several wells south of the town (fig. 6) and to about 160 rural users north and east of the Greenfields Bench by the Tri-County Water-Supply System constructed in 1982. The infiltration gallery for the Tri-County system is about 5 mi north of Fairfield (fig. 6).

Few wells on the Greenfields Bench are completed in shale underlying the gravel because of poor water quality and low yields. Three wells completed in shale at the western edge of the Greenfields Bench (fig. 6) were drilled through gravel into shale only because the gravel at these sites was dry except perhaps for a few months during the irrigation season.

Test wells were completed at sites W-4 and W-5 on the Greenfields Bench (fig. 6) to collect ground-water samples and water-level data. At each site, two wells were completed with 4-in.-diameter polyvinyl-chloride (PVC) pipe with a 5- to 7-ft screened interval in the gravel. The shallower well (W-4A, W-5A) at each site was completed near the elevation of the seasonally low water table. The deeper well (W-4B, W-5B) was completed just above the gravel-shale interface. A third well (W-4C, W-5C) was completed with 2-in.-diameter PVC pipe in underlying shale at each site with the top of a 8- to 10-ft screen placed 21-33 ft below the gravel-shale interface. Well-construction and lithologic data are in Lambing and others (1994, tables 7 and 8).

Water in the gravel aquifer of the Greenfields Bench generally flows east and north toward Muddy Creek (fig. 7). However, under a small part of the Bench near Fairfield, ground water flows to seeps and drains that lead to Freezeout Lake. To determine the areal extent of the aquifer that contributes flow to Freezeout Lake, water levels were measured in domestic wells (Lambing and others, 1994, table 9). Measurements were made in January and February 1991 when ground-water levels were near a seasonal low and again during a 3-day period in early August 1991 when water levels were near a seasonal high. The August 1991 data were used to construct a water-table map (fig. 8) and to identify areas contributing to ground-water discharge to drains and seeps that flow to Freezeout Lake. One area of about 1,825 acres lies west of Fairfield. The other area is north of Fairfield in the northwest corner of the Bench and encompasses about 2,140 acres. Water-table contours (not shown) of the January-February 1991 data indicate that, although ground-water levels were lower and hydraulic gradients were less than in August 1991, the extent of the gravel aquifer discharging to Freezeout Lake was similar to the August 1991 areas.

The gravel aquifer receives substantial recharge from irrigation. Osborne and others (1983) estimated that recharge from irrigation in 1982 amounted to 56,770 acre-ft, or 39 percent of the irrigation water delivered to the Bench. Canal-ponding tests showed that canal seepage contributed 24,615 acre-ft, and detailed instrumentation of eight fields showed that deep percolation of water applied to fields contributed another 32,155 acre-ft. On-farm losses were high, partly because of the widespread use of flood irrigation on the Bench (85 percent of the area). Current

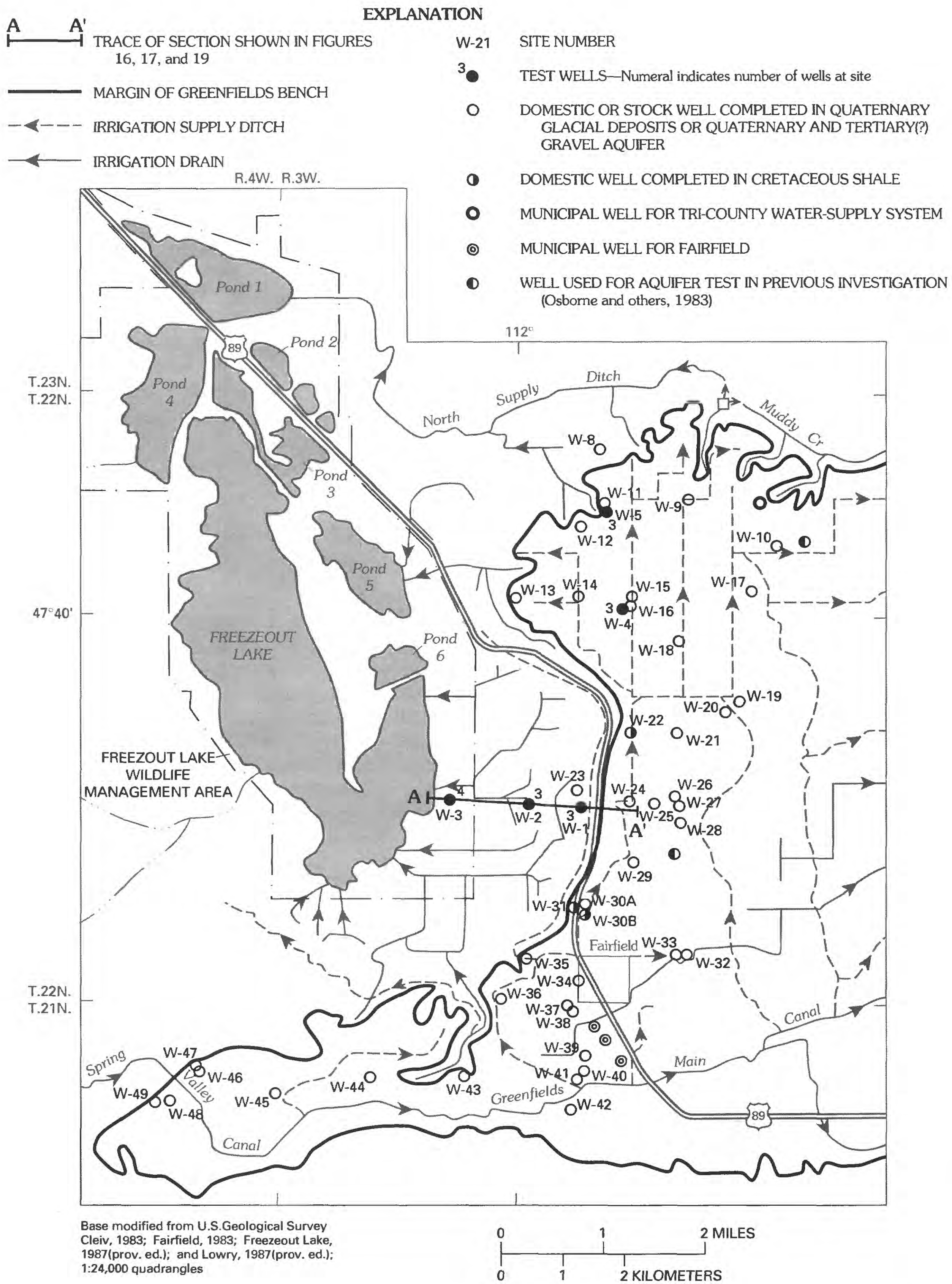


Figure 6. Location of wells on or near the western Greenfields Bench, Montana.

(1991-92) losses from irrigation probably are less than losses in 1982 because some canals have been lined, some flood-irrigation systems have been converted to sprinklers, and irrigation scheduling has been improved (Jerry Nypen, Greenfields Irrigation Division, oral commun., 1991).

The seasonal distribution of irrigation water has a large effect on water levels in the gravel aquifer (fig. 9 and 10). Ground-water levels quickly rise in response to irrigation water delivered to the Greenfields Bench in the spring. For example, during the study period, the irrigation system was activated on May 20, 1991, and April 13, 1992, and water-level rises were observed soon after. Irrigation continues through June and July and ground-water levels continue to rise. In August, when irrigation of malt-barley fields ceases, water levels generally start declining. Although irrigation of hay fields continues into September, water levels decline from their summer peak through the fall and winter until irrigation is started again the following spring. The continuous-record hydrograph for well W-4B (fig.10) shows intermediate water-level peaks that probably are caused by episodic flood irrigation of barley fields upgradient of the well. In dry years, such as 1992, some shallow, hand-dug wells go dry, and the Greenfields Irrigation District has imported irrigation water to the Bench earlier than necessary for irrigation needs for the express purpose of recharging the aquifer. The rise in water levels that occurred in spring 1992 after supply canals were filled with no concurrent irrigation of fields indicates that the canals leak.

Vertical hydraulic gradients measured in nested wells can be used to determine whether water is likely to flow between the shale and gravel. Based on water-level data from wells W-30A and W-30B (Lambing and others, 1994, table 9), a downward vertical gradient exists near the west margin of the Greenfields Bench, indicating that some recharge from the gravel aquifer to the underlying shale may be occurring. Similarly, near site W-5, vertical gradients were always downward from gravel to shale (fig. 10). However, the upward gradient that occurred for 6 of 12 months at site W-4 indicates that water in the underlying shale could provide recharge to the gravel aquifer in some areas when water levels in the gravel are near seasonal lows. Based on altitudes of the top of the shale reported by Osborne and others (1983) and measured at sites W-4 and W-5 during this study, a depression in the shale surface may exist near site W-4 that could be a contributing factor in the reversals in vertical gradient near site W-4. The extent of the area where vertical gradients fluctuate is not known. The fluctuating gradient observed at site W-4 could cause cyclic movement of water between gravel and shale, and, as discussed below, this cyclic movement could be important in mobilizing selenium.

Ground water moves quickly through the gravel aquifer. Osborne and others (1983) calculated hydraulic conductivities of the gravel aquifer of 730 and 1,310 ft/d using data from multiple-well aquifer tests at two sites near the west end of the Greenfields Bench (fig. 6). Horizontal hydraulic gradients in August 1991 varied from about 0.001 in the northwestern corner of the Bench in January-February 1991 to about 0.004 near Fairfield in August 1991. Assuming a porosity of 0.2 for the gravel (Heath, 1983) and using Darcy's Law, the average ground-water flow velocity would be between 3.7 and 26 ft/d, or between 0.25 and almost 2 mi/y. Based on these estimates of average flow velocity and the short flow paths, the residence time for ground water in the gravel aquifer generally is less than 10 years in the areas where ground water flows toward Freezeout Lake.

Ground-Water Age

Determining the age of ground water can help in understanding residence times and flow rates within an aquifer. The age is based on the time since the water entered the aquifer. In addition, age dates help determine how ground-water quality may have evolved and whether irrigation has had an effect on ground-water quality. Ground-water ages determined from concentrations of tritium and chlorofluorocarbons in ground-water samples support the conclusion based on physical hydrogeologic data that the residence time of water in the gravel aquifer is short.

Tritium is a radioactive isotope of hydrogen that is used as a tracer to estimate the age of ground water. Prior to 1953, precipitation contained about 3-5 TU. Because of the radioactive decay of tritium (half-life of 12.43 years), ground water recharged from precipitation that fell in 1940 and sampled in 1991 would contain about 0.3 TU, the minimum reporting level for tritium analyses performed for this project. Therefore, any ground water with a 1991 tritium concentration less than 0.3 TU is assumed to be more than 50 years old. Ground water recharged in 1953 would contain about 0.6 TU in 1991. Beginning in 1953 and continuing through the 1960's, testing of nuclear bombs introduced large quantities of tritium to the atmosphere. Generally, ground water that originated solely from precipitation that fell after 1953 would have a tritium concentration greater than about 12 TU in 1991. Ground water with a tritium concentration greater than 100 TU probably was recharged in the late 1950's, 1960's, or early 1970's, when atmospheric levels of tritium were at their peak.

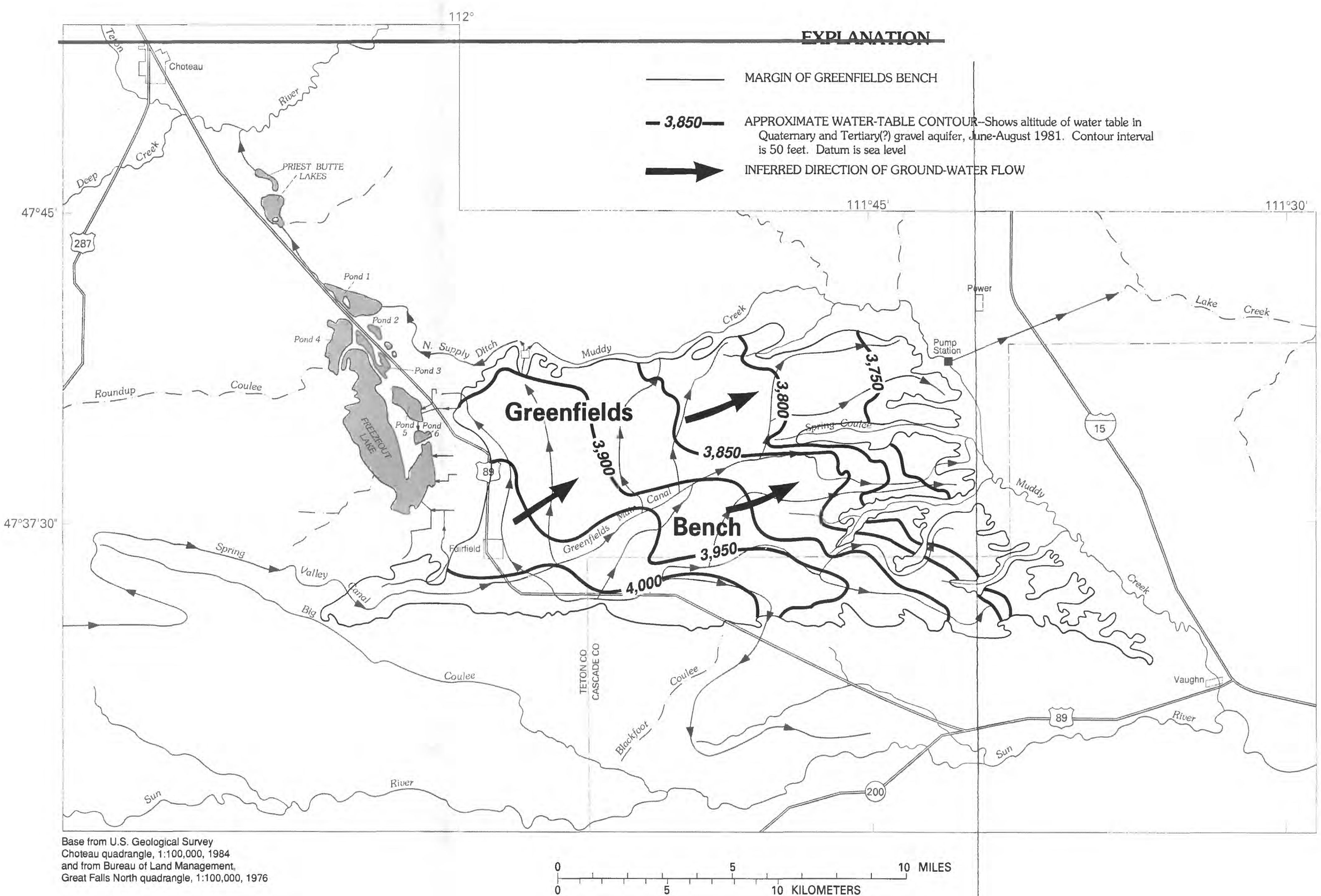


Figure 7. Approximate altitude and configuration of the water table based on data collected June-August 1981 from wells completed in the gravel aquifer of the Greenfields Bench, Montana. Modified from Osborne and others (1983).

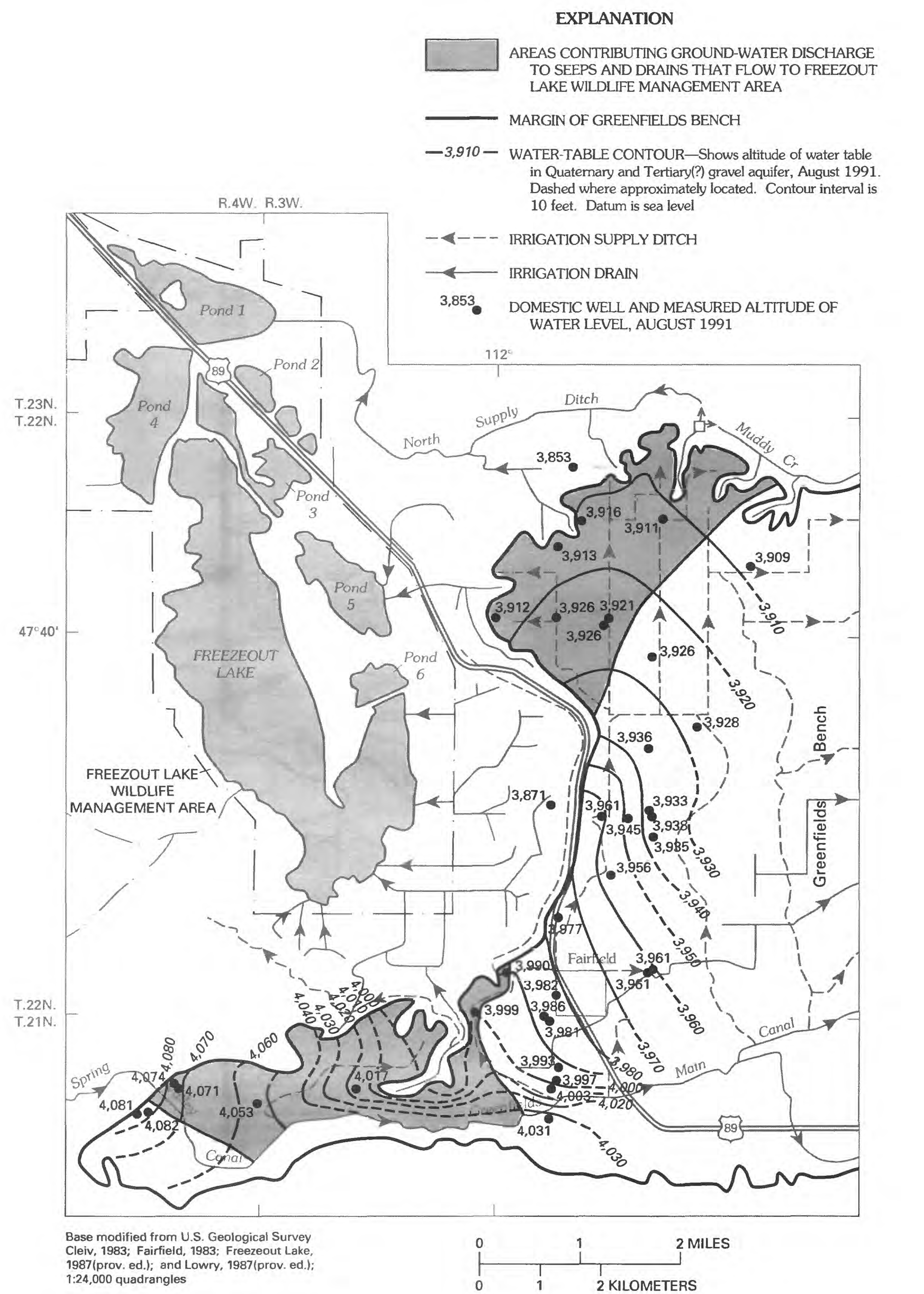


Figure 8. Altitude and configuration of the water table in August 1991in the gravel aquifer of the western Greenfields Bench, Montana.

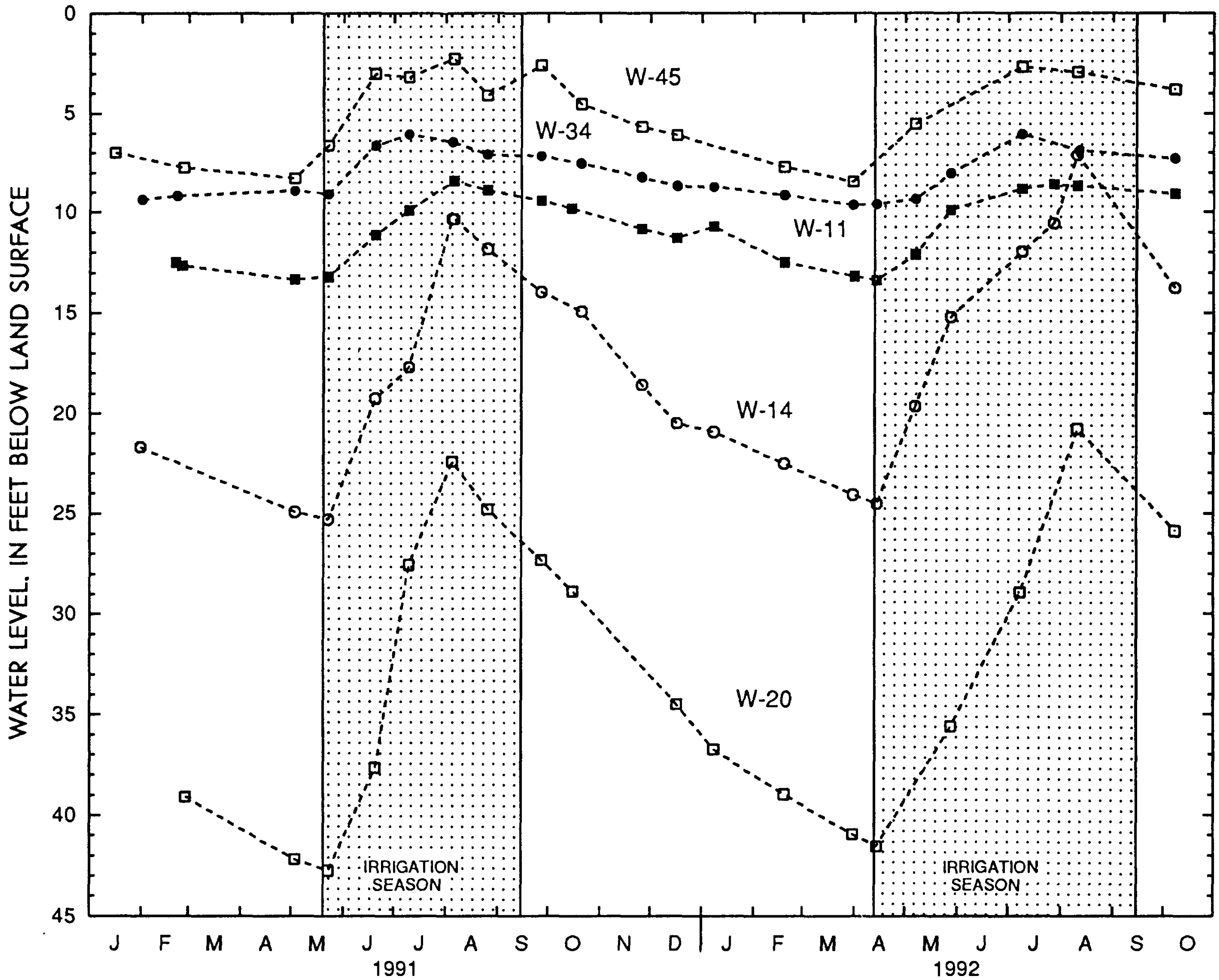


Figure 9. Hydrographs of domestic wells completed in the gravel aquifer of the western Greenfields Bench, Montana. Dashed line connecting symbols represents assumed water level during the time interval between measurements.

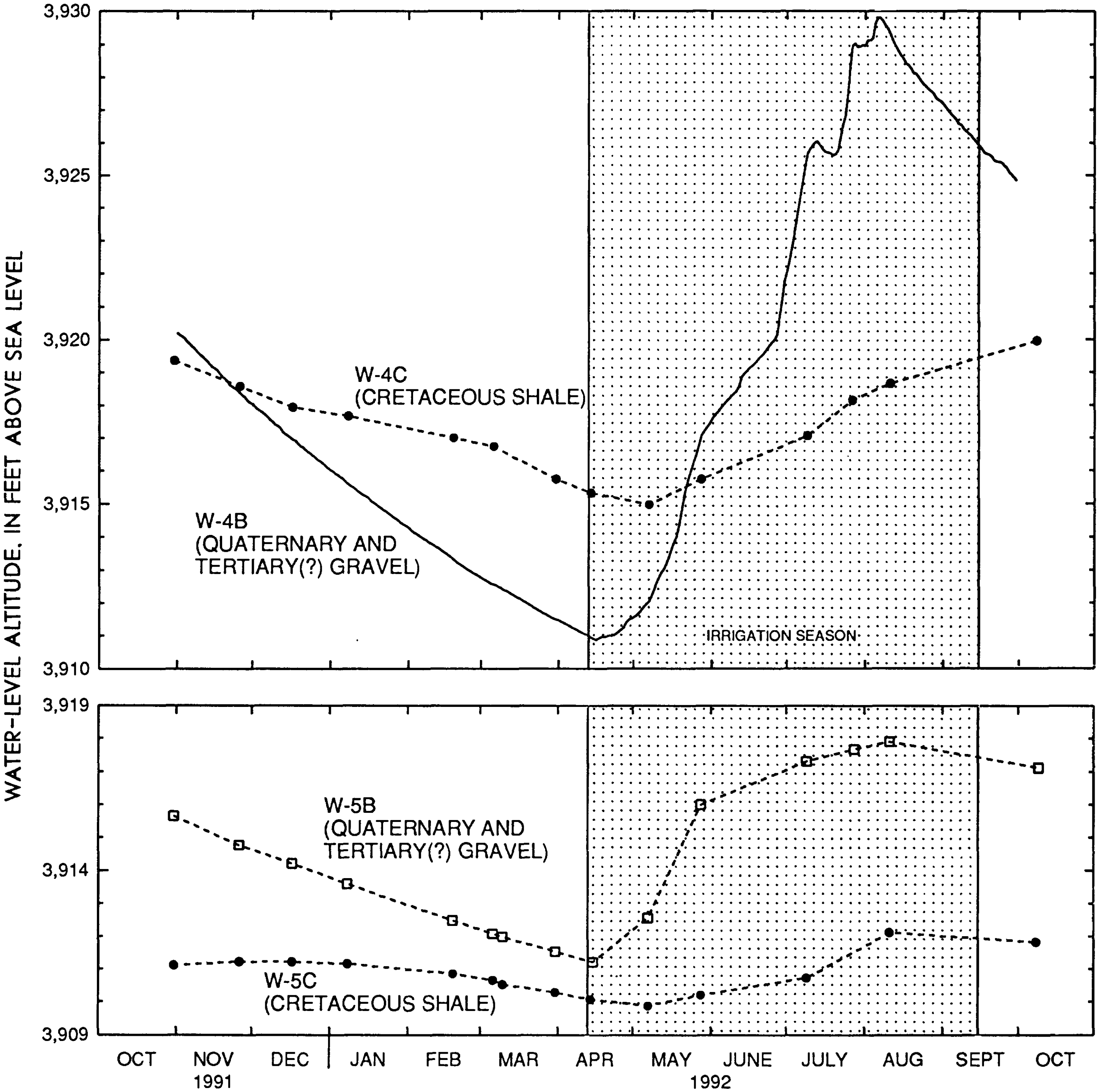


Figure 10. Hydrographs of test wells completed in the gravel aquifer or shale, western Greenfields Bench, Montana. Dashed line connecting symbols represents assumed water level during the time interval between measurements. The solid line for well W-4B represents continuous water-level data.

Determining the recharge date for water with tritium concentrations between 12 and 100 TU can be problematic. Possibilities include recharge during the mid-1950's before atmospheric tritium levels reached their peak, recharge during the 1960's if recharge rates were low and dispersivity was high, or recharge after the early 1970's. Similarly, tritium concentrations of 0.3-12 TU can indicate that recharge occurred soon after the initiation of atmospheric testing, that tritium in post-1953 water has dispersed into older water, or that pre-1953 and post-1953 water was drawn into the well while sampling (Robertson and Cherry, 1989). Other hydrogeologic data are needed to make reliable predictions about recharge dates for water when tritium is in these concentration ranges.

Tritium concentrations in ground water under the Greenfields Bench were determined in samples collected from four domestic wells in August 1991 and four test wells in April 1992 (fig. 11; Lambing and others, 1994, table 11). Tritium concentrations (18-23 TU) in samples from the gravel aquifer indicate that recharge to the aquifer occurred after 1953. Based on the rapid response of water levels to irrigation and the transmissive nature of the aquifer, the sampled water most likely post-dates the early 1970's and could even have been recharged a few years prior to sampling. In contrast, water samples from the two test wells completed in underlying shale had tritium concentrations of less than 0.3 TU, indicating that water in the shale in the northwest corner of the Bench is at least 50 years old.

The tritium concentration of 41 TU in a sample from well W-31 appears anomalous and was not considered in the discussion above. Although this well was completed in shale, the chemistry of the two water samples from the well suggest that a significant component of the water in the well may come from the gravel aquifer, perhaps because of the way the well was constructed. Concentrations of constituents such as sodium, sulfate, nitrate, and boron in the two samples from well W-31 are similar to concentrations in samples from nearby wells completed in gravel as compared to concentrations in samples from wells W-4C and W-5C, which were completed in shale.

Concentrations of chlorofluorocarbons (CFC's or Freons) in ground water also can be used to determine recharge dates. CFC's are stable synthetic compounds whose atmospheric concentrations have steadily increased since they were first manufactured in the 1930's. Detectable concentrations are present in post-1940 ground water or mixtures of older ground water and post-1940 water. CFC concentrations in recharge water are dependent on the atmospheric concentration of CFC's and the temperature of the recharge water. Recharge temperature can be estimated from the concentrations of argon and nitrogen in ground water. Recharge temperature for all CFC samples collected in this study was estimated from dissolved-gas concentrations determined in the sample from well W-1A. CFC and dissolved-gas analyses and estimates of recharge dates were made by Eurybiades Busenberg (U.S. Geological Survey, written commun., 1993) by methods described in Busenberg and others (1993).

CFC concentrations in the gravel aquifer were determined in samples collected in summer 1992 from wells W-4B and W-5B. These wells are in the northwest corner of the Greenfields Bench; W-4B is in the recharge area and W-5B is in the discharge area. Estimated recharge dates range from 1987 to 1992 (Eurybiades Busenberg, U.S. Geological Survey, written commun., 1993). Similar dates from recharge and discharge areas as well as the dates themselves support the conclusion drawn from tritium and hydrogeologic data that ground water moves quickly through the gravel aquifer.

Dissolved Solids in Ground Water

Water samples from 11 wells completed in the gravel aquifer were collected for chemical analysis (Lambing and others, 1994, table 11). The samples are representative of ground water in that part of the western Greenfields Bench where ground water flows to Freezeout Lake (fig. 8). Chemical changes that occur in this area as water moves from supply canals through the gravel aquifer to wells are a change from calcium bicarbonate irrigation water to magnesium bicarbonate ground water and an increase in dissolved-solids concentrations (table 6). Understanding the causes of these changes in major-ion chemistry is important not only because salinity is a concern in the wetlands receiving irrigation drainage but also because changes in major-ion chemistry along flow paths can provide insight into possible sources of selenium.

The increase in dissolved-magnesium concentrations probably is caused by exchange of the dissolved calcium in irrigation water for magnesium ions sorbed to clays. Clays, such as found in the Colorado Group and presumably as detritus in the gravel, can release magnesium and adsorb calcium (Nesbitt and Cramer, 1993; Osborne and others, 1983).

The range of dissolved-solids concentrations increased from 119-133 mg/L in samples from the Greenfields Main Canal (site S-1) to 194-530 mg/L in ground-water samples. This increase could be caused by several processes including evaporative concentration, mixing with water from the underlying shale, or leaching of salts within the gravel.

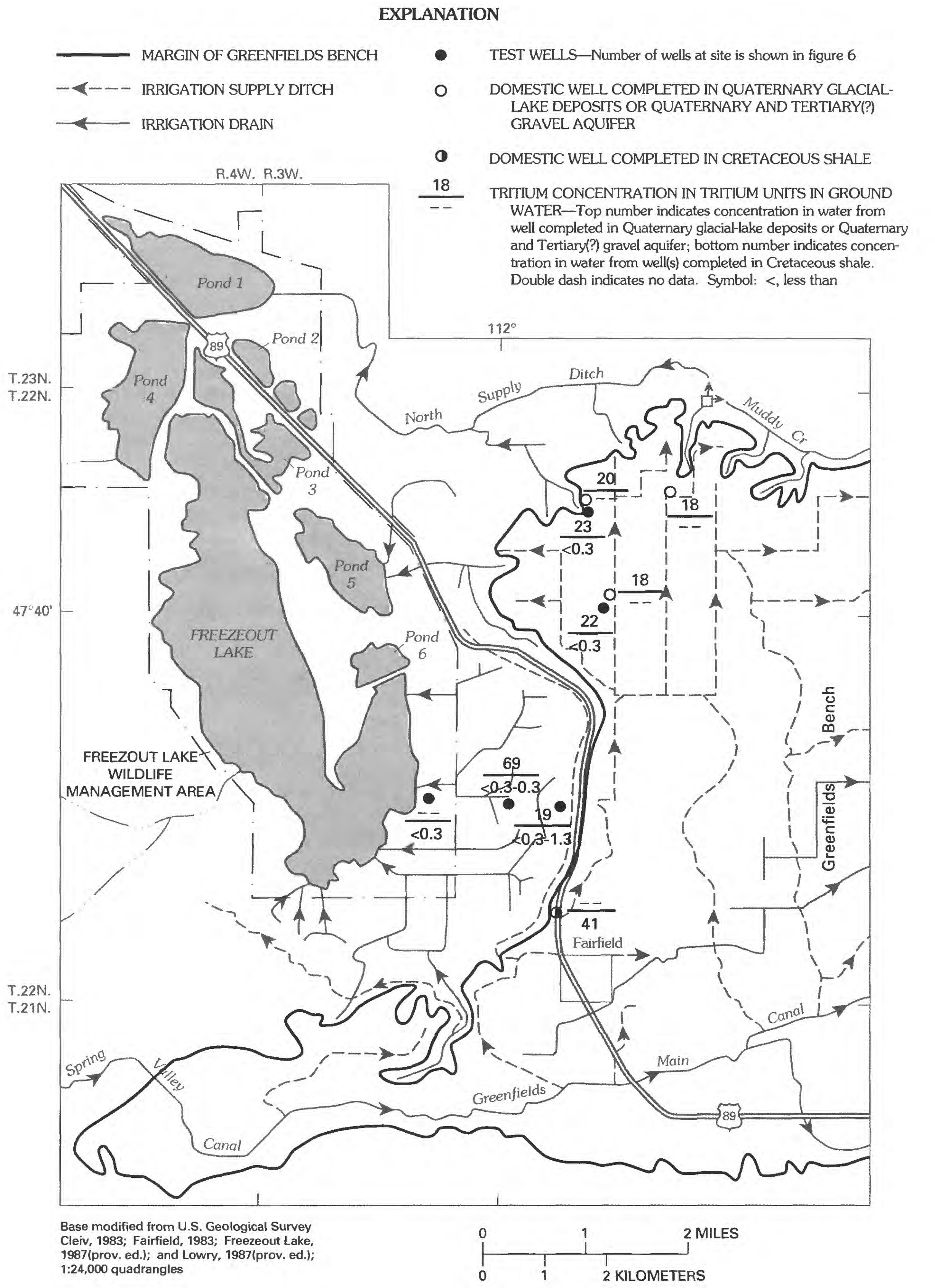


Figure 11. Tritium concentrations in ground water under the western Greenfields Bench and near Freezeout Lake, Montana.

Table 6. Concentrations of dissolved solids and selenium in surface water and in water from wells completed in the gravel aquifer, western Greenfields Bench, Montana

[Abbreviations: µg/L, micrograms per liter; mg/L, milligrams per liter. Symbol: <, less than]

Source of sample	Site number(s) (figs. 6 and 25)	Range of dissolved-solids concentrations (mg/L)	Range of dissolved- or total-recoverable selenium concentrations (µg/L as Se)
Greenfields Main Canal supplying irrigation water from the Sun River	S-1	119 - 133	<1
Domestic well completed in Quaternary and Tertiary (?) gravel aquifer	W-9, W-11, W-15 W-20, W-37 W-43, W-45	194 - 409	<1 - 12
Test well completed in Quaternary and Tertiary (?) gravel aquifer	W-4A, W-4B W-5A, W-5B	277 - 530	4 - 18
Irrigation drain or seep receiving drainage from Quaternary and Tertiary (?) gravel aquifer	S-2, S-10 S-14, S-15	[1]283 - 402	<1 - 16

[1]The range of dissolved-solids concentrations is for S-2 and S-15.

Evaporative concentration was examined as a possible cause of increases in dissolved-solids concentration by using ratios of stable isotopes of oxygen (oxygen-18/oxygen-16) and hydrogen (deuterium/hydrogen). These isotope data are reported as ratios, which are more precisely determined than abundances, and are reported as delta values in units of parts per thousand, or permil, relative to an arbitrary standard known as SMOW (standard mean ocean water) (Craig, 1961). This ratio is calculated as follows:

$$\text{delta}\chi \text{ (permil)} = \left(\frac{R_\chi}{R_{standard}} - 1\right) \times 1000,$$

where R_χ and $R_{standard}$ are deuterium/hydrogen or oxygen-18/oxygen-16 ratios of the sample and standard, respectively. For example, a sample with a delta oxygen-18 value of -10 permil is depleted in oxygen-18 by 1 percent, or 10 permil, relative to the standard. Delta deuterium and delta oxygen-18 values in hydrologic studies are typically negative because of the initial isotopic depletion that occurs as water evaporates from the ocean. Delta deuterium and delta oxygen-18 values in North American continental precipitation plot along a line described by the equation (Gat, 1980):

$$\text{delta deuterium} = 8(\text{delta oxygen-18}) + 6.$$

Delta deuterium and delta oxygen-18 values in ground water reflect the values in the precipitation that recharged the ground water unless some process or reaction causes the isotopes to be fractionated. Evaporation is one process that commonly affects delta deuterium and delta oxygen-18 values. As evaporation occurs, the remaining water becomes enriched with deuterium and oxygen-18 at different rates. Therefore, a plot of delta deuterium and delta oxygen-18 values in water affected by evaporation will deviate from the precipitation line and define a line having a slope less than 8. Ratios in North American continental precipitation and water samples from the gravel aquifer (fig. 12) were nearly the same indicating that little, if any, evaporation occurs as irrigation water recharges ground water. Therefore, based on the stable-isotope data, evaporative concentration probably is not the cause of the increase in dissolved-solids concentration in ground water.

A second possible cause of the increased dissolved-solids concentrations in water in the gravel aquifer is mixing with water from the underlying shale. Concentrations of dissolved solids in samples from two test wells completed in shale (W-4C and W-5C) were high, ranging from 2,780 to 3,450 mg/L, compared to a maximum of 530 mg/L in samples from the gravel aquifer. Water in shale also had high concentrations of sodium and sulfate, which are minor components in water from the gravel aquifer. If mixing is occurring, then the concentrations and the proportions of major ions in the gravel aquifer should change. Osborne and others (1983) noted a small increase in sulfate concentrations in ground water in the north-central and northeast part of the Greenfields Bench and attributed the increase to mixing with sulfate-rich ground water from underlying shale rather than geochemical reactions within the gravel. Their data also show a concurrent increase in sodium concentrations at the same sites

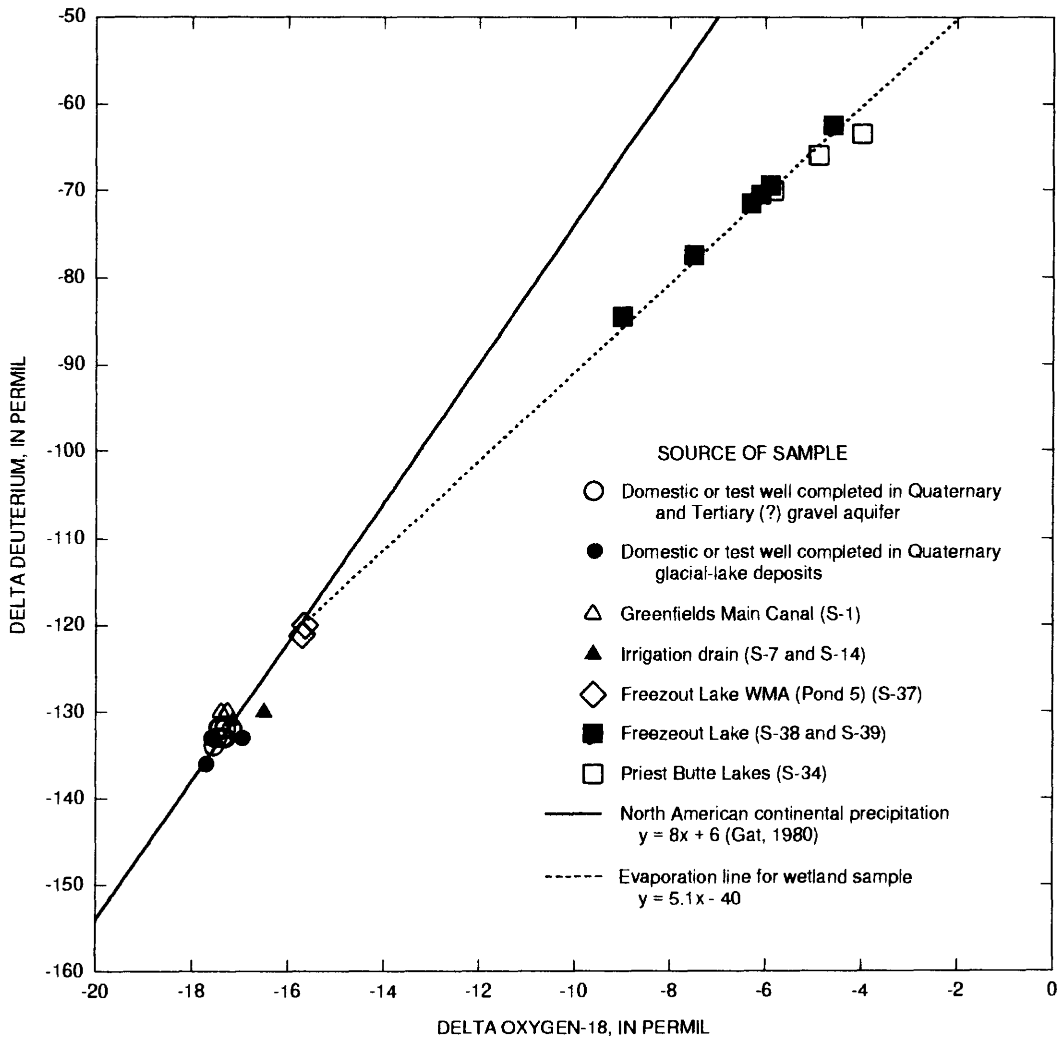


Figure 12. Relation of delta oxygen-18 and delta deuterium in selected surface-water and shallow ground-water samples from the Freezeout Lake area, Montana.

with increased sulfate concentrations. Upward flow probably would have to occur for most or all of the year to have a noticeable impact on the quality of the relatively fast-moving water in the gravel aquifer. Insufficient vertical-gradient data were collected to determine the extent of upward flow in the study area. Sodium and sulfate concentrations in samples from domestic and test wells completed in the gravel aquifer in the study area consistently were low, between 6.1-21 mg/L for sodium and 17-33 mg/L for sulfate, except for the pre-irrigation sample from well W-9. The higher concentrations (27 mg/L sodium and 41 mg/L sulfate) in the sample from well W-9 could indicate mixing with water from underlying shale. However, considering the water-quality data from most wells completed in the gravel aquifer, mixing with shale water probably is not a major cause of the increase in dissolved-solids concentrations between canal water and water in the gravel aquifer.

Another possible cause of increased dissolved-solids concentrations in the gravel aquifer is leaching of salts accumulated in the unsaturated zone. Prior to irrigation, evaporative salts almost certainly formed in the upper part of the gravel because potential evapotranspiration exceeds precipitation in this semi-arid area. Likely minerals that would have formed include carbonates, gypsum, and sodium and magnesium sulfates. In the first years of irrigation, most of the highly soluble salts, such as sodium and magnesium sulfates, probably were flushed out of the system and no longer influence ground-water quality. Similar flushing of soluble salts was reported by Fujii and others (1988) in irrigated fields in the San Joaquin Valley, California. However, the caliche coatings that are prevalent throughout the upper part of the gravel are composed of slightly soluble carbonate minerals that probably continue to dissolve and release calcium, magnesium, and carbonate to recharge water, thus increasing the dissolved-solids concentration in the ground water. Some of the increase in dissolved-solids concentrations also could be caused by ongoing weathering of other minerals in the unsaturated or saturated zone. In either circumstance, a larger increase in concentration would be expected in areas where recharge occurs primarily from water applied to fields as opposed to leakage from supply canals, because irrigation spreads water over a large area of unsaturated material. Canal leakage, on the other hand, funnels more water through a much smaller area. If some evaporative concentration occurs, it also would cause larger increases in water infiltrating through fields than canals. Although dissolved-solids concentrations varied from site to site, higher dissolved-solids concentrations seem to be associated with areas where recharge could come primarily from infiltration through fields, such as near sites W-4, W-20, W-37, and W-45. Lower dissolved-solids concentrations occurred in samples from areas where more recharge is likely to have come from direct infiltration from supply canals, such as near sites W-15 and W-43. Leaching of the carbonate minerals and ongoing weathering of other minerals in the unsaturated zone probably are the main cause of the increased concentrations of dissolved solids. These processes occur relatively slowly and ample source material is available such that major-ion concentrations in ground water in the gravel aquifer probably will not change appreciably for at least the next few decades.

The chemistry of ground-water samples from individual sites remained virtually unchanged between the irrigation and non-irrigation seasons, except at site W-9 where upward leakage from shale may affect water-quality during the non-irrigation season. Based on ground-water-quality data collected during three sampling periods between April 1981 and May 1982, Osborne and others (1983) also noted little seasonal variation in major-ion chemistry in samples from any site. With the exception of the increases in sulfate concentration noted previously, they discerned no major chemical change in ground water along flow paths. Based on these observations, they suggested that major chemical changes occur only in the unsaturated zone as water moves from supply canals to wells. They reasoned that some evolution of ground-water quality would be observed along flow paths, if chemical changes were occurring in the aquifer.

Selenium in Ground Water

Dissolved-selenium concentrations in 19 samples from the gravel aquifer ranged from <1-18 µg/L (Lambing and others, 1994, table 11) and were less than the MCL of 50 µg/L. This range of values is almost identical to the range of <1-19 µg/L reported by Osborne and others (1983) and Knapton and others (1988) for samples from 22 wells located throughout the Greenfields Bench (fig. 13). The combined data generally show that dissolved-selenium concentrations in ground water in most of the western third of the Bench were low (<3 µg/L) and that concentrations in ground water in the central and eastern parts of the Bench were slightly higher, ranging from 2 to 7 µg/L. However, the highest dissolved-selenium concentrations occurred in three areas. The first area is at the east end of the Bench where the concentration in a sample from one well was 19 µg/L. The second area is a small, non-irrigated area on the south edge of the Bench where concentrations (8-18 µg/L) in three samples were elevated, possibly because of a lack of dilution from irrigation-induced recharge. The third area is the northwest corner of the Bench, where concentrations in 13 samples collected from 7 wells for this study ranged from 2-18 µg/L (fig. 13). The higher concentrations in the northwest corner are anomalous for the irrigated part of the Bench, and are important because ground-water discharge from this area flows to Freezout Lake WMA.

Selenium commonly occurs in ground water only if nitrate is present (Weres and others, 1989; White and others, 1991), because redox conditions that are sufficiently oxidizing to favor nitrate stability also favor selenate stability. Selenate is the only highly soluble form of selenium and, therefore, selenium is removed almost completely from solution if selenate is reduced. Because selenate reduction is mediated by microbes that preferentially utilize nitrate as an electron acceptor over selenate (Oremland and others, 1989; Weres and others, 1989), selenate remains in solution as long as nitrate is present. In the study area, indicators of oxidizing conditions in the gravel aquifer were the high dissolved-oxygen concentrations and the general absence of dissolved iron and manganese in ground-water samples. Speciation analyses for August 1991 samples from wells W-4B and W-5B show that dissolved selenium occurred solely as selenate (Lambing and others, 1994, table 12).

Nitrate is pervasive in the gravel aquifer and concentrations generally are elevated relative to recharge water. Concentrations in 19 ground-water samples collected during 1991-92 ranged from 0.54-12 mg/L and most samples had values between 1 and 5 mg/L. A sample from one well (W-4A) exceeded the MCL of 10 mg/L. These nitrate concentrations are similar to those measured by previous investigators in samples from wells located mostly in the central and eastern part of the Greenfields Bench. Knapton and others (1988) reported nitrate concentrations between 0.46-6.4 mg/L in samples collected in 1986 from five wells. Nitrate concentrations ranged from 0.17-37 mg/L in 392 samples from 30 wells sampled in 1980 by Walther (1981), and mean concentrations of samples from 21 of the wells were between 1 and 5 mg/L. Fertilizers are the likely source of nitrates in ground water in this agricultural area. Malt barley, the primary crop on the Bench, reportedly is grown with heavy application of nitrogen fertilizers. In samples analyzed for this study and by Knapton and others (1988), nitrate concentrations tend to be lower in samples with lower dissolved-solids concentrations and could reflect a larger component of recharge from canals rather than fields, where fertilizers are applied.

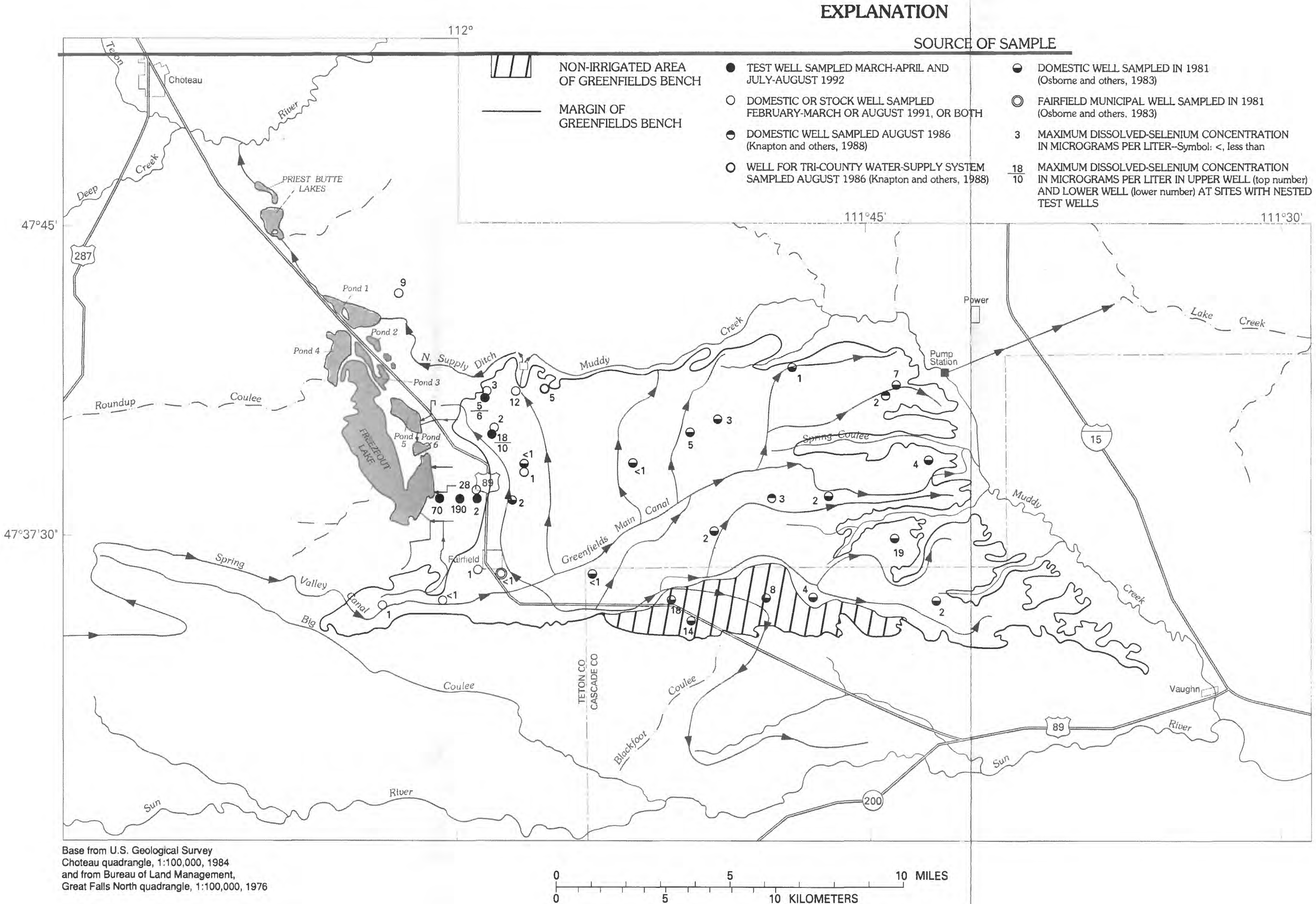
Concentrations of dissolved trace elements other than selenium were low and did not exceed applicable human-health criteria. Arsenic, cadmium, chromium, iron, and manganese concentrations were near or less than the minimum reporting level (Lambing and others, 1994, table 11). Copper and zinc occurred at low levels in samples from domestic wells and could have been introduced into samples from the metal well casing and distribution pipes.

Source of Selenium in Ground Water

Dissolved selenium in water in the gravel aquifer could be coming from dissolution of evaporative salts formed prior to irrigation, from the underlying shale, or from ongoing weathering of shale detritus in the gravel. Data from this study and from Osborne and others (1983) are useful for assessing the potential importance of each source.

Evaporative salts that accumulated in the unsaturated zone prior to irrigation seemingly would be a likely source of the selenium in water in the gravel aquifer. Sodium and magnesium sulfates would be the most likely of the evaporative salts to contain selenium (Presser and Swain, 1990; Presser and others, 1990). Once irrigation begins, these sulfate minerals are easily dissolved and transported to ground water. Although most selenium-containing salts probably have already been flushed from areas irrigated for many decades, these salts could still be a source of selenium in areas where little or no irrigation has occurred, where flow rates are slow, or where flow paths are long. If the dissolved selenium in the gravel aquifer comes from dissolution of evaporative salts, then selenium concentrations in ground water would be expected to increase with increasing sodium and sulfate concentrations. This correlation occurs with samples collected by Osborne and others (1983) from the central and eastern part of the Greenfields Bench where ground-water flow paths are relatively long (fig. 14), thereby indicating that evaporative salts could be an important source of selenium in these areas. In the northwest corner of the Bench, however, the higher dissolved-selenium concentrations in water in the gravel aquifer are accompanied by very slight or no increases in sodium and sulfate concentrations. Therefore, dissolution of evaporative salts probably is not a significant source of selenium in the northwest part of the Greenfields Bench.

Underlying shale could be a selenium source to the gravel aquifer in areas, such as site W-4, where upward hydraulic gradients occur. Total-selenium concentrations (1.2-4.8 µg/g, Lambing and others, 1994, table 13) are high in samples of shale from the Colorado Group at sites W-4 and W-5. However, despite the elevated solid-phase selenium concentrations, dissolved selenium did not occur in concentrations above the minimum reporting level (1 µg/L) in water from shale. Redox conditions in shale, as indicated by the presence of iron, manganese, and ammonia and the absence of nitrate in ground-water samples (Lambing and others, 1994, table 11), are less oxidizing than in the overlying gravel aquifer and presumably any selenium would be present as a reduced, non-mobile species. Therefore, in areas where water flows upward from shale to gravel all the time, sodium and sulfate but not selenium could move from shale to the gravel aquifer. However, selenium could be released from shale to the gravel aquifer in some areas by another mechanism—the cyclic, vertical movement of water in and out of the shale. During periods of downward gradients, water moving from the gravel aquifer into shale could temporarily create oxidizing conditions and mobilize reduced selenium species from the uppermost shale. These transitory conditions were not observed because they would occur in the uppermost shale above the zone where test wells were completed in the shale. When the gradient reverses and if oxidizing conditions still exist, dissolved selenium could be transported to the gravel aquifer. Cyclic movement of water across the gravel-shale interface probably would not cause much movement of sodium or sulfate from shale to the gravel aquifer because little net movement of water



Base from U.S. Geological Survey
Choteau quadrangle, 1:100,000, 1984
and from Bureau of Land Management,
Great Falls North quadrangle, 1:100,000, 1976

0 5 10 MILES
0 5 10 KILOMETERS

Figure 13. Maximum dissolved-selenium concentration in water samples from wells completed in the gravel aquifer of the Greenfields Bench or in glacial deposits near Freezeout Lake, Montana.

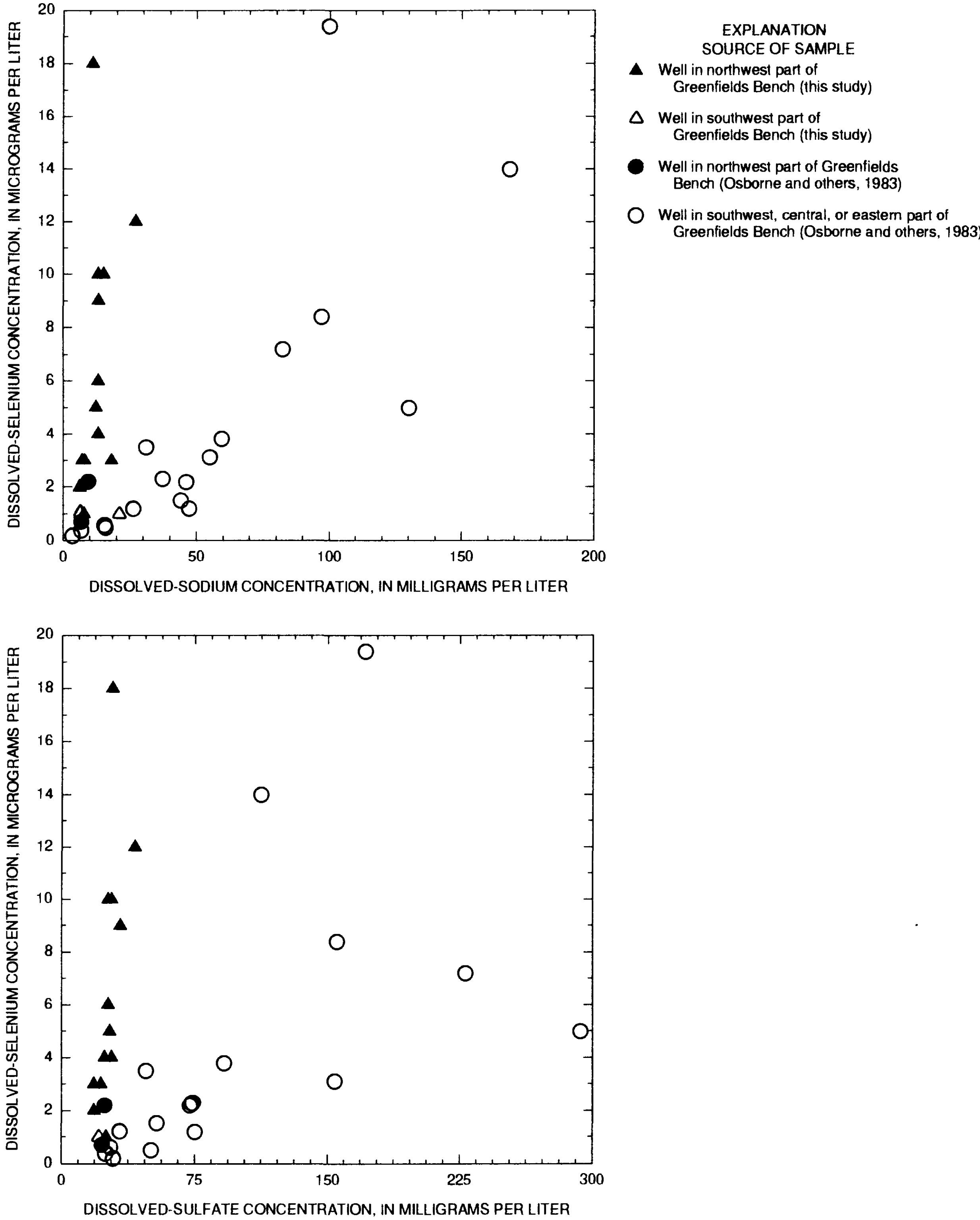


Figure 14. Relation of dissolved-sodium and dissolved-sulfate concentrations to dissolved-selenium concentration in water samples from the gravel aquifer of the Greenfields Bench, Montana.

would occur. Therefore, the combination of increased selenium concentrations with no associated increase in sodium or sulfate concentrations (fig. 14) that occurred in ground water in the northwest corner of the Greenfields Bench could be caused by cyclic water movement between gravel and shale. Few data exist to define the temporal and spatial distribution of vertical gradients. However, the highest dissolved-selenium concentrations in the gravel coincide with the one area (W-4) where fluctuating vertical gradients were measured (fig. 10). The high dissolved-selenium concentrations (9-18 μg/L) with no concurrent increase in sodium and sulfate concentrations in samples from wells W-4A and W-4B suggest that this mechanism could be important at this site.

The other possible selenium source is weathering of shale detritus in the gravel. Selenium probably is associated with organic or pyritic sulfur in the shale detritus. Oxidation of these materials could, therefore, release sulfate as well as selenium to pore water in the unsaturated zone. This reaction may explain the slight increase in sulfate concentration (fig. 14) that occurs with increasing selenium concentration in the wells in the northwest corner of the Greenfields Bench. Evidence that weathering of shale detritus is a selenium source can be inferred from several types of data, all of which are consistent with the conclusion of Osborne and others (1983) that the major processes affecting water chemistry in the gravel occur in the unsaturated zone. At site W-4, selenium concentrations in water samples from the two nested wells completed at different depths in the gravel aquifer provide evidence that the unsaturated zone is a source of selenium. Samples collected in spring 1992 prior to irrigation had similar dissolved-selenium concentrations (9 and 10 μg/L). However, samples collected after irrigation had raised the water table about 18 ft had different concentrations. The selenium concentration (18 μg/L) in a sample from the shallower well (W-4A) was almost twice the concentration (10 μg/L) in a sample from the deeper well (W-4B). Selenium released by weathering of shale detritus during low water-table periods would be flushed from the unsaturated zone after the onset of irrigation, either by infiltration of irrigation water or by the seasonal rise in the water table. Soil data also support the hypothesis of an unsaturated-zone source of selenium. The occurrence of elevated water-extractable selenium concentrations in soil samples from the same area in the northwest corner of the Greenfields Bench where dissolved-selenium concentrations in ground water are elevated suggests that selenium is leached from soil to ground water. The high water-extractable-selenium concentrations in soils in the northwest corner of the Bench could be caused by the occurrence of a larger proportion of shale detritus. However, total-selenium concentrations in soils derived from gravel were similar throughout the study area and, therefore, the amount of shale detritus probably is the same in all areas. Another explanation for the higher water-extractable concentrations in the northwest corner of the Bench could be the apparent greater use of sprinkler irrigation rather than flood irrigation in this area. The greater efficiency of sprinklers causes less water to infiltrate past the root zone and, therefore, constituents, such as selenium, released by weathering reactions would have higher water-extractable concentrations in soils and higher dissolved concentrations in pore water in areas irrigated by sprinklers.

In the northwest corner of the Bench, higher dissolved-selenium concentrations occur in ground-water samples with higher dissolved-nitrate concentrations (fig. 15). This correlation supports the hypothesis that selenium in ground water is derived from the unsaturated zone because the nitrate, presumably from fertilizers, travels through the unsaturated zone to ground water. In the southwest part of the Bench, elevated nitrate concentrations are not accompanied by higher dissolved-selenium concentrations. This may indicate that the unsaturated zone in this area has less solid-phase selenium available for leaching.

Although the evidence is not conclusive, the most likely source of the dissolved selenium in gravel in the northwest corner of the Greenfields Bench is shale detritus in the gravel, particularly shale detritus in the unsaturated part of the gravel. More data support this hypothesis than the other hypotheses. Based on major-ion data, dissolution of evaporative salts probably is not important in this area although it does appear to be an important selenium source in the central and eastern part of the Greenfields Bench. Underlying shale may contribute some selenium locally where the direction of the vertical hydraulic gradient alternates.

Area between the Greenfields Bench and Freezeout Lake

Irrigation occurs on 3,580 acres of glacial-lake deposits (fig. 3) east and south of Freezeout Lake. These deposits are as much as 20 ft thick and are less permeable than the gravel capping the Greenfields Bench. Numerous drains have been constructed to lower ground-water levels in irrigated areas underlain by glacial-lake deposits. Shale of the Colorado Group underlies the glacial-lake deposits.

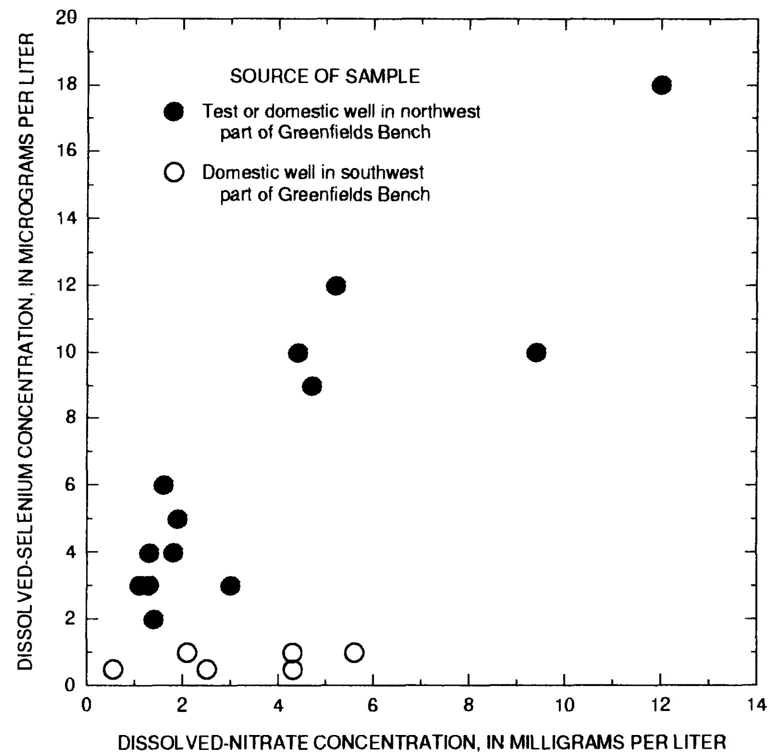


Figure 15. Relation of dissolved-selenium concentration to dissolved-nitrate concentration in water samples from the gravel aquifer of the Greenfields Bench, Montana. Dissolved-selenium concentrations less than the minimum reporting level (1 microgram per liter) are plotted as 0.5 microgram per liter.

Ground-Water Flow and Water Levels

Few domestic wells have been completed in glacial-lake deposits, probably because the chemical quality of the ground water makes it unsuitable for most uses. One well (W-23) used for stock water was inventoried and sampled (fig. 6). No domestic wells are completed in the underlying Colorado Group.

Ten test wells were installed in glacial-lake deposits and the underlying Colorado Group to determine horizontal and vertical components of flow and to study the evolution of ground-water quality and selenium transport. Well-construction and lithologic data are in Lambing and others (1994, tables 7 and 8). Nested test wells were placed at three sites (W-1, W-2, and W-3) along a line perpendicular to topographic contours (fig. 6, 16, and 17). Each test well was completed with 2-in-diameter PVC pipe and a screened interval 5-15 ft in length. Three wells were installed at site W-1, three were installed at W-2, and four were installed at site W-3. Wells with an "A" following the site designation were completed in glacial-lake deposits. Wells labeled with a "B" generally were completed in the upper weathered zone of the shale, which is 13-27 ft thick. Wells with "C" following the site designation were completed in unweathered shale. The screened interval of well W-3C straddles the transition from weathered to unweathered shale and another well, designated W-3D, was completed at greater depth in unweathered shale.

Water levels measured in the nested wells at sites W-1, W-2, and W-3 indicate the hydraulic gradients controlling ground-water flow in a section between the Greenfields Bench and Freezeout Lake (fig. 16 and 17). Irrigation is the primary source of recharge. The principal direction of ground-water flow appears to be toward Freezeout Lake. Most ground-water flow probably occurs in the glacial-lake deposits because these deposits are assumed to be more permeable than the underlying shale. The flow system is modified locally where ground water discharges to drains excavated in glacial-lake deposits. The thickness of the saturated zone in glacial-lake deposits is 10-18 ft in irrigated areas (sites W-1 and W-2) and only 1-2 ft in non-irrigated areas (site W-3) adjacent to Freezeout Lake.

Water levels (Lambing and others, 1994, table 10) in test wells completed in glacial-lake deposits respond to recharge from irrigation (fig. 18). The differences in the timing of water-level rises in wells

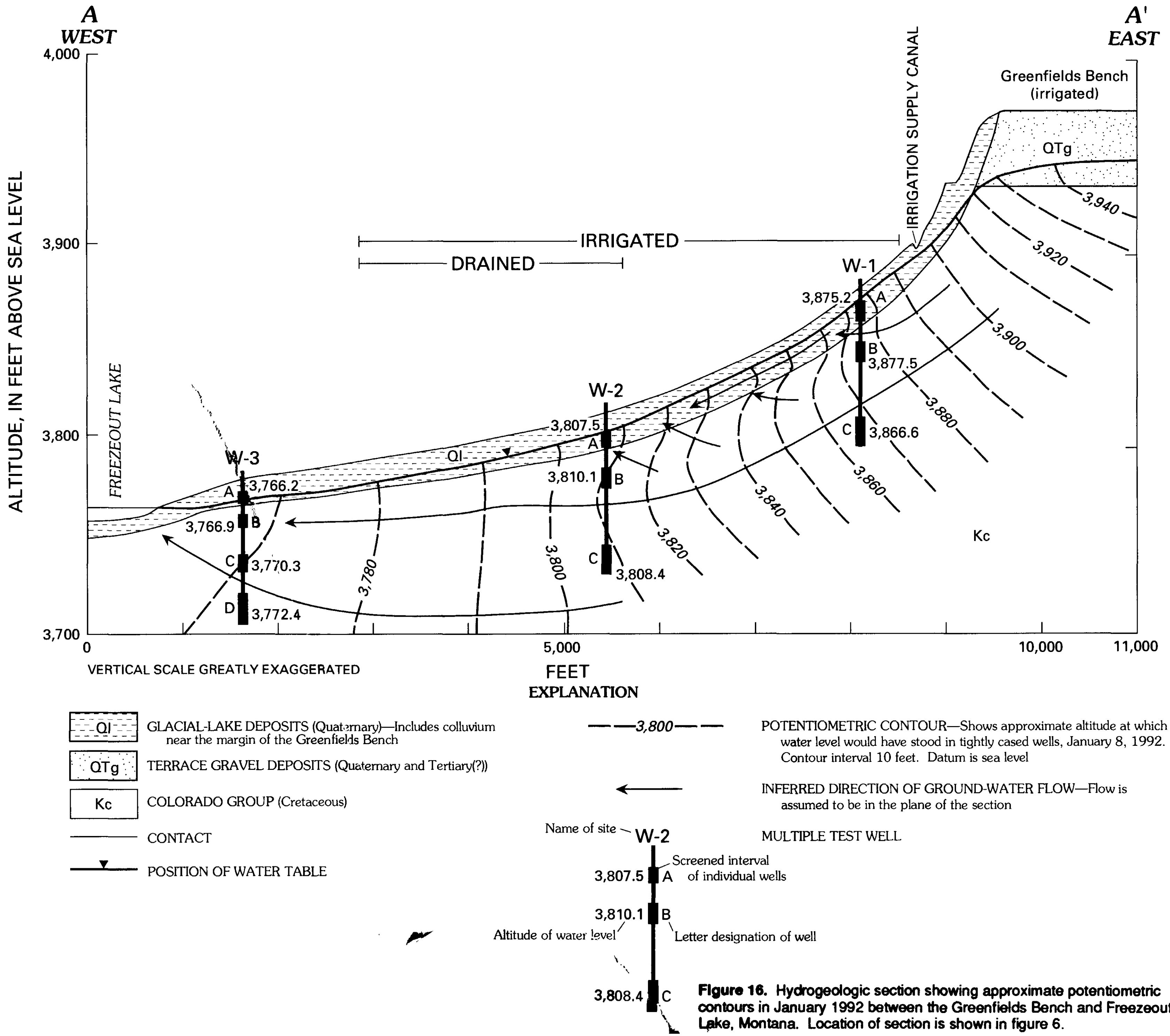


Figure 16. Hydrogeologic section showing approximate potentiometric contours in January 1992 between the Greenfields Bench and Freezeout Lake, Montana. Location of section is shown in figure 6.

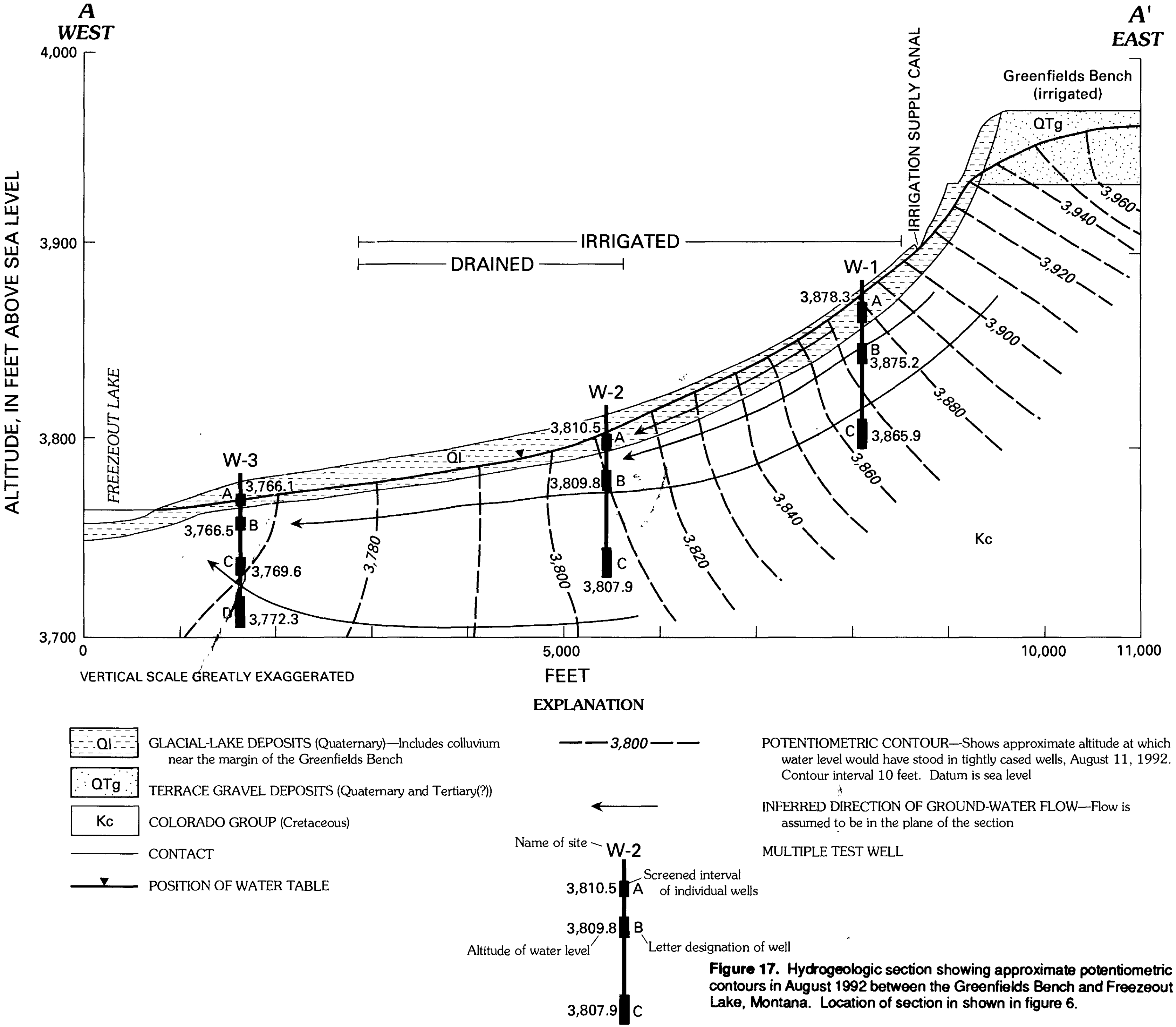


Figure 17. Hydrogeologic section showing approximate potentiometric contours in August 1992 between the Greenfields Bench and Freezeout Lake, Montana. Location of section in shown in figure 6.

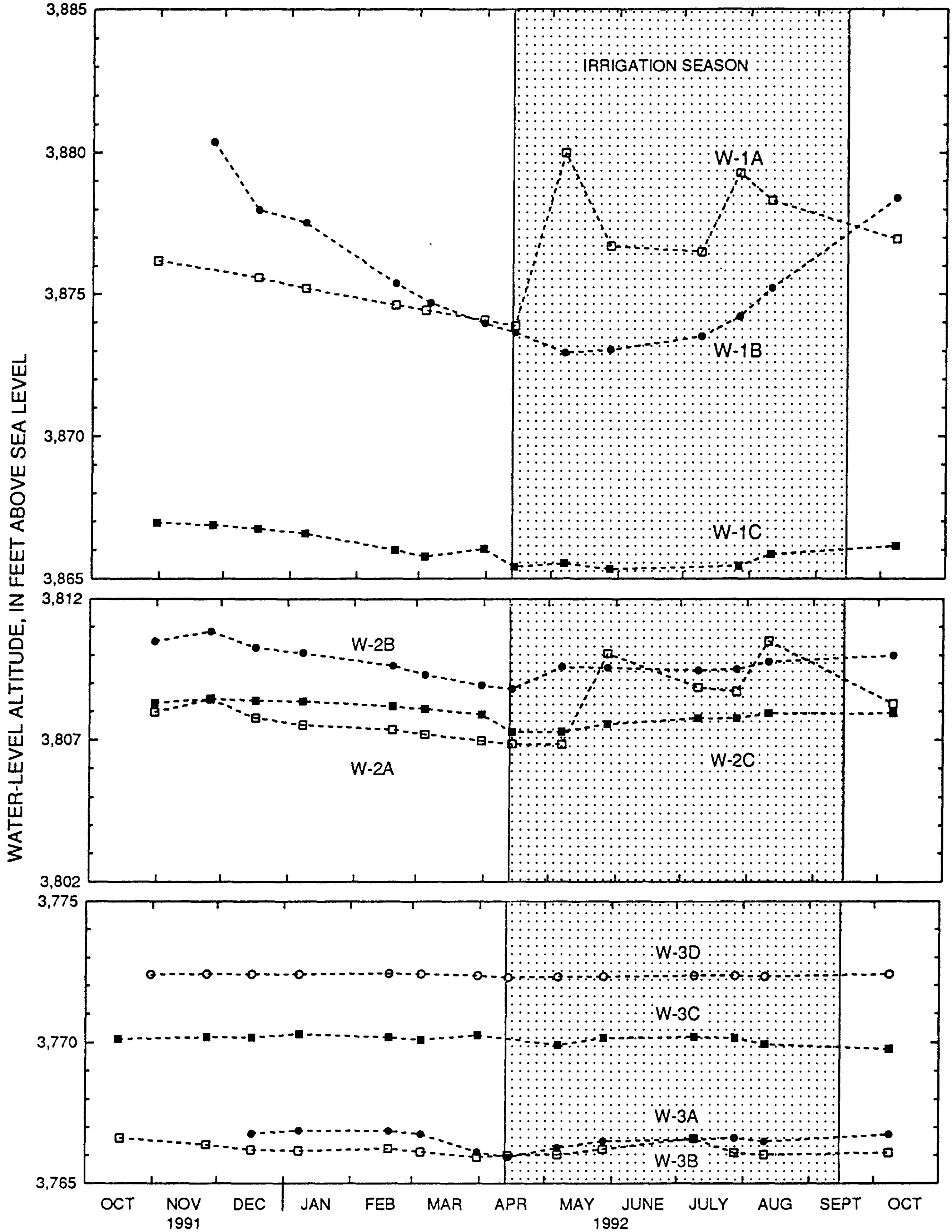


Figure 18. Hydrographs of test wells completed in glacial-lake deposits or shale between the Greenfields Bench and Freezeout Lake, Montana. Dashed line connecting symbols represents assumed water level during the time interval between measurements.

W-1A and W-2A in 1992 resulted from corresponding differences in the timing of the first application of irrigation water on fields immediately upgradient. Water levels in a stock well (W-23) also responded to irrigation but at a slower rate because no upgradient fields were irrigated and the only irrigation-induced recharge came from seepage from an upgradient supply canal. The wells at W-3 are in a non-irrigated area but are downgradient from an irrigated area. Small water-level fluctuations in wells W-3A and W-3B could reflect effects of upgradient irrigation or seasonal effects of recharge from precipitation.

Based on hydraulic gradients measured in nested wells, vertical ground-water flow can occur. At site W-1, the most upgradient well nest, the decrease in water level with depth during the irrigation season (fig. 17 and 18) indicates that irrigation water can recharge both glacial-lake deposits and shale. During the non-irrigation season, water-level relations in wells W-1A and W-1B reverse, indicating that water in weathered shale can flow upward to glacial-lake deposits. Hydraulic gradients also fluctuate at site W-2. During the non-irrigation season, discharge to a nearby drain lowers the water level in the glacial-lake deposits and causes an upward gradient from weathered shale (well W-2B) to the glacial-lake deposits (well W-2A). During the summer, irrigation recharge raises water levels in the glacial-lake deposits, reversing the gradient, and establishes a downward gradient through the profile. Without the drain, water levels probably would be higher in the glacial-lake deposits and the gradient would be downward throughout the year. At site W-3, heads increase with depth in shale and show that ground water could flow upward through shale to the surficial deposits. These head relations would be expected at site W-3 because Freezeout Lake probably is a regional ground-water-discharge area.

Ground-Water Age

Water samples were collected from most test wells between the Greenfields Bench and Freezeout Lake and analyzed for tritium and CFC concentrations to determine ground-water ages. Samples for tritium analysis were collected from all test wells except W-3A and W-3B. Samples for CFC analysis were not collected from slowly recovering wells (W-1A, W-2C, W-3A, and W-3B) requiring bailing because samples would have been contaminated by contact with the atmosphere. Tritium concentrations are shown in figure 11 and estimated ground-water ages are shown in figure 19. Ground water tends to be older in glacial-lake deposits than in the gravel aquifer probably because flow rates are slower, particularly in areas away from the Bench where glacial-lake deposits contain little coarse-grained colluvium.

Ground water near well W-1A probably represents the youngest water in the glacial-lake deposits owing to the proximity to an upgradient supply canal and the probable connection of the canal and ground water through relatively coarse-grained colluvium. The tritium concentration of 19 TU (Lambing and others, 1994, table 11) in a sample from well W-1A suggests that ground water at this site is either less than 20 years old or about 35 years old. However, the similarity in water quality to that in the gravel aquifer of the Greenfields Bench and the short flow path from an irrigation supply canal suggests that ground water here, as in the gravel aquifer of the Greenfields Bench, is less than 5 years old. Ground water in downgradient areas, where the glacial-lake deposits are finer grained and less permeable, is older. The tritium concentration (69 TU) in a water sample from well W-2A indicates recharge either in the mid-1950's or after the early 1970's. The recharge date estimated from CFC concentrations is the late 1970's (Eurybiades Busenberg, U.S. Geological Survey, written commun., 1993), and therefore, ground water near well W-2A probably is about 15 years old. Based on the longer residence times and shorter flow paths, flow rates are slower in the glacial-lake deposits than in the gravel.

Water in shale is older than water in glacial-lake deposits and, for the most part, is older than 50 years although water in the upper, weathered part of the shale could be slightly younger. The tritium concentration (1.3 TU) in the sample from well W-1B indicates a post-1953 recharge date, while the concentration (<0.3 TU) in samples from wells W-2B and W-3C indicates a pre-1940 date. Based on CFC concentrations, recharge dates for samples from wells W-1B and W-3C are the late 1940's or early 1950's (Eurybiades Busenberg, U.S. Geological Survey, written commun., 1993). Water in these wells likely could be a mixture of older (>50 years old) water and younger water that percolated down from the glacial-lake deposits. Samples from deeper wells completed in shale had tritium concentrations less than or equal to 0.3 TU and CFC recharge-date estimates of earlier than 1940 (Eurybiades Busenberg, U.S. Geological Survey, written commun., 1993). Therefore, water in unweathered shale probably is more than 50 years old.

Dissolved Solids in Ground Water

Major-ion concentrations (Lambing and others, 1994, table 11) varied spatially but not temporally in water samples from wells completed in glacial-lake deposits. The magnesium bicarbonate water in samples

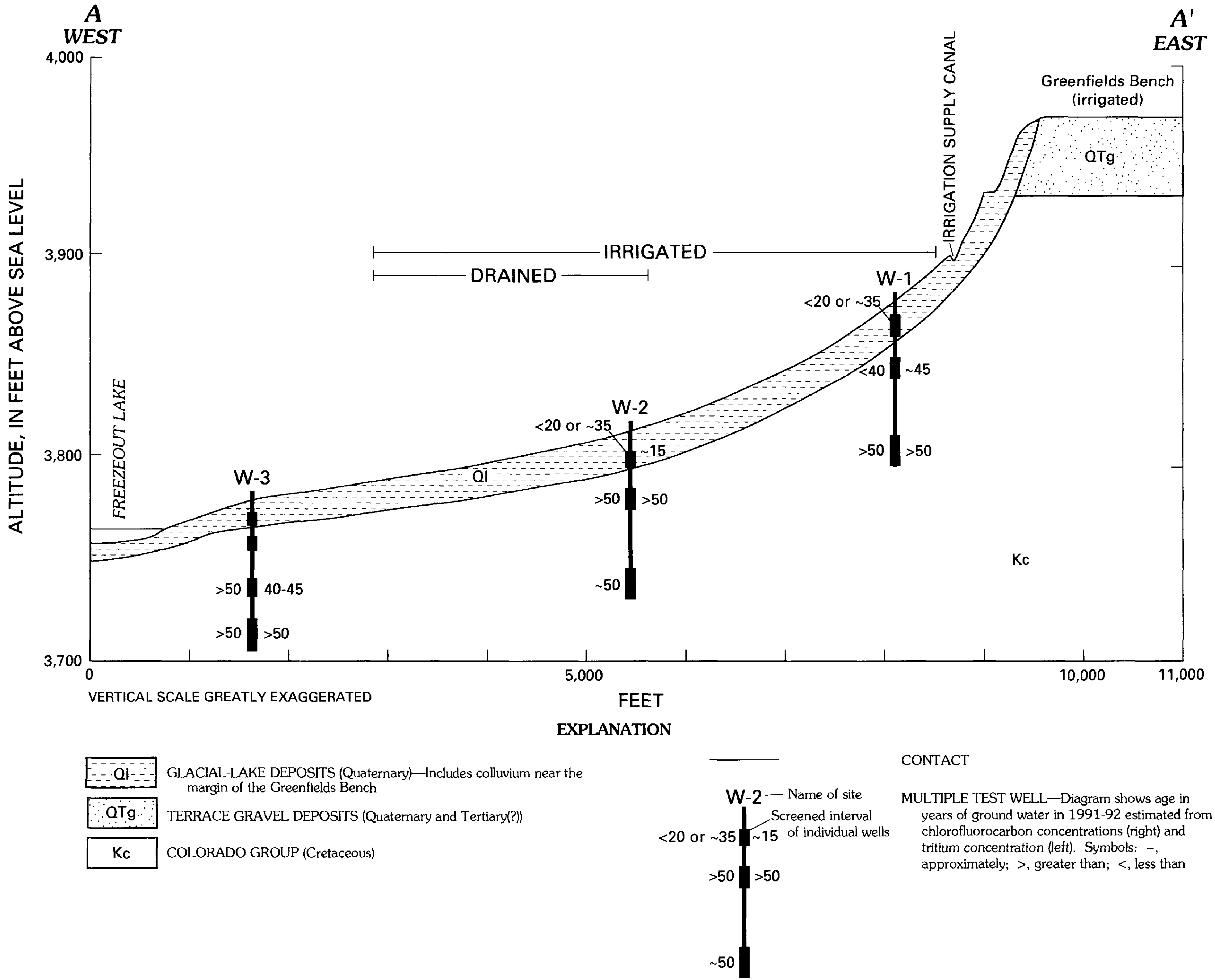


Figure 19. Hydrogeologic section showing ground-water ages estimated from chlorofluorocarbon and tritium concentrations between the Greenfields Bench and Freezeout Lake, Montana, 1991-92. Location of section is shown in figure 6.

from well W-1A was similar in composition and dissolved-solids concentration (375 mg/L) to water in the gravel aquifer of the Greenfields Bench and probably had a similar evolution. Water samples from wells W-2A and W-23 (fig. 6) had higher dissolved-solids concentrations (958-4,340 mg/L) and variable major-ion compositions that most likely reflect additions of solutes released from shallow evaporative salts that had accumulated prior to irrigation development. The specific conductance (30,500-31,400 µS/cm) of samples from well W-3A indicate that dissolved-solids concentrations may be higher under non-irrigated areas, probably because concentrations have not been diluted by addition of irrigation water. Based on isotopic data (fig. 12), evaporative concentration has not increased dissolved-solids concentrations in glacial-lake deposits.

The quality of water in shale underlying glacial-lake deposits varied greatly spatially, reflecting different geochemical environments within the shale. Water quality, however, did not change with time in samples from the same well. Samples from wells completed in weathered shale (W-1B, W-2B, W-3B, and W-3C) had mixed water types that contained sodium, magnesium, and calcium as cations and sulfate as the primary anion. Values of pH generally were slightly acidic (6.6-6.8) except at well W-3B, where samples had pH values of 7.4-7.5. Water in weathered shale has been affected by weathering reactions, which release sulfate and acid from pyrite and a variety of ions from silicate minerals. Mixing with water from glacial-lake deposits also probably affects water quality in weathered shale. Water samples from wells completed in unweathered shale (W-1C, W-2C, and W-3D) mainly had a sodium bicarbonate composition. Redox conditions in unweathered shale were reducing, as shown by the absence of dissolved nitrate and the presence of dissolved ammonia, iron, and manganese in water samples (Lambing and others, 1994, table 11). Sulfate concentrations were low, probably because of reduction to sulfide. Mixing with irrigation water probably does not occur in this zone. Ground water in shale near Freezeout Lake (wells W-3B, W3C, and W3D) contained chloride, which could have been derived from evaporite deposits possibly formed during the relatively warm and dry Altithermal period (4,000-7,500 years before present).

Selenium in Ground Water

Selenium concentrations in ground water in the area between the Greenfields Bench and Freezeout Lake are affected by source materials, residence time, and redox conditions. Selenium was detected in samples from glacial-lake deposits (fig. 13), where redox conditions were oxidizing, as indicated by the presence of dissolved oxygen and nitrate and the absence of dissolved iron and manganese. As expected, the only selenium species in these samples was selenate (Lambing and others, 1994, table 12). Selenium concentrations in ground-water samples from shale, where reducing conditions exist, were <1 µg/L, except in the sample from well W-3B. Based on the coexistence of dissolved selenite and selenate in a sample from well W-3B, redox conditions were transitional at this site.

Dissolved-selenium concentrations (1-2 µg/L) in samples from well W-1A were similar to concentrations in samples from the gravel aquifer. The coarse sand derived from gravel colluvium and sorted by ancient shoreline processes at this site probably contains little shale detritus. Little selenium is picked up by ground water in this area because flow rates likely are rapid and soluble evaporative salts probably have been flushed out by irrigation. In contrast, dissolved-selenium concentrations were higher in ground-water samples from irrigated areas farther downgradient and from non-irrigated areas. Dissolved-selenium concentrations in samples from well W-23 were 28 and 50 µg/L. The highest dissolved-selenium concentration (190 µg/L) in ground water in the Freezeout Lake-Greenfields Bench area was in samples from well W-2A. Samples from well W-3A, located near Freezeout Lake and in an area that may have received some irrigation between 1942 and 1978, had concentrations of 18 and 70 µg/L. In the area between the Greenfields Bench and Freezeout Lake, exceedance of the MCL of 50 µg/L for selenium occurred only in samples from these three wells.

Source of Selenium in Ground Water

Possible sources of dissolved selenium in glacial-lake deposits are the same as those identified for ground water in the gravel aquifer underlying the Greenfields Bench. Dissolution of pre-irrigation evaporative salts is a likely source of the selenium because sodium and sulfate concentrations increase as selenium concentrations increase (fig. 20). Because flow rates are slow, dissolved constituents derived from evaporative salts could still be in the glacial-lake deposits. Ongoing weathering of minerals within the glacial-lake deposits could also be contributing sodium, sulfate, and selenium to ground water. Glacial-lake deposits presumably contain more shale detritus than the gravel and, therefore, ongoing weathering would release more selenium to water in glacial-lake deposits than in the gravel of the Bench. The longer ground-water resi-

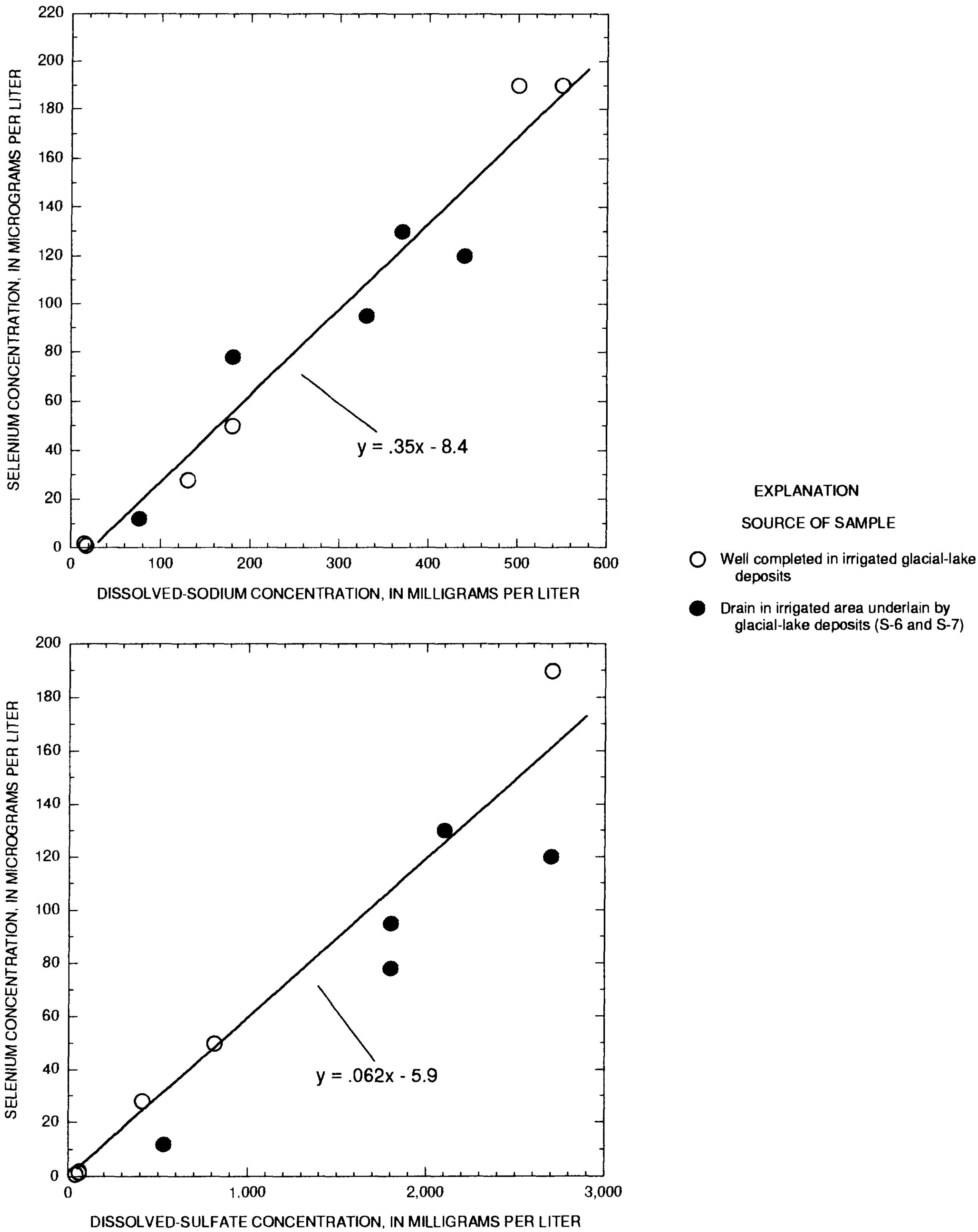


Figure 20. Relation of dissolved-sodium and dissolved-sulfate concentrations to dissolved-selenium concentration in ground water and total-selenium concentration in drains in irrigated glacial-lake deposits between the Greenfields Bench and Freezeout Lake, Montana.

dence times in glacial-lake deposits would allow dissolved major-ion and selenium concentrations to become higher than in the gravel aquifer.

Cyclic vertical movement of oxygenated water between glacial-lake deposits and shale also could contribute selenium to shallow ground water. This mechanism probably is not the principal source of selenium to ground water because the concurrent increases in sodium and sulfate concentrations would not be expected to occur. Water-level data from both sets of nested wells completed in irrigated areas (sites W-1 and W-2) show that the direction of the vertical hydraulic gradient changes seasonally. The likelihood of similar seasonal changes in the direction of the vertical gradient in other irrigated areas underlain by glacial-lake deposits is unknown.

Drill-Core Data

Chemical data (Lambing and others, 1994, table 13) from analyses of drill-core samples collected at sites W-1 and W-3 provide insight into chemical processes that affect selenium mobilization in glacial-lake deposits. Total-selenium concentrations varied with depth and lithology (fig. 21). Concentrations generally were intermediate in unweathered shale (1.8-3.0 µg/g), highest in weathered shale (2.4-9.3 µg/g), and lowest in the glacial-lake deposits (0.2-1.1 µg/g). Total-selenium concentrations in shale are typical of concentrations (0.25-10 µg/g) reported for Cretaceous marine shales in north-central Montana (Donovan and others, 1981). In weathered shale, the higher total-selenium concentrations probably resulted from accumulation of selenate transported to this zone by ground water from the upper part of the weathered shale or overlying glacial-lake deposits. Redox conditions in weathered shale probably were slightly reducing, as shown by the occurrence of dissolved selenite in a ground-water sample from well W-3B (Lambing and others, 1994, table 12). Selenate transported to this zone probably was reduced to selenite and subsequently adsorbed to clay minerals or iron oxyhydroxides. The maximum selenium concentration occurred lower in the weathered-shale zone at site W-1 than at site W-3, probably because recharge from irrigation has driven oxygenated water farther down into the weathered shale than has occurred at site W-3, where little irrigation has occurred. The original selenium concentration of glacial-lake deposits is unknown but could have been as high as the selenium concentration in the Colorado Group because the deposits are thought to have been derived, to a large extent, from the Colorado Group. Total-selenium concentrations in glacial-lake deposits are lower now, probably because some of the original reduced forms of selenium contained in shale detritus have been oxidized to soluble selenate and transported downward or laterally out of the deposits.

Supporting evidence for weathering reactions and redox conditions in glacial-lake deposits and shale comes from data for sulfur in drill-core samples (fig. 21; Lambing and others, 1994, table 13). The major forms of sulfur are sulfate, which is stable under oxidizing conditions, and sulfide and organic sulfur, which are stable under reducing conditions. Chemical analyses were performed to determine concentrations of total sulfur and sulfide. Based on the small difference between total sulfur and sulfide concentrations, little organic sulfur occurred in samples of unweathered shale. In glacial-lake deposits and weathered shale, where oxidation is likely to have partially or completely removed sulfides, the difference between the total sulfur and sulfide concentrations probably represents sulfate.

In unweathered shale, sulfur occurred almost entirely as sulfide, and sulfide concentrations were relatively constant vertically and laterally in samples from boreholes at sites W-1 and W-3 as well as sites W-4 and W-5 on the Greenfields Bench. These data indicate that unweathered shale probably had all of the sulfur originally deposited and that no oxidation reactions have occurred in the shale. In contrast, weathered shale and overlying glacial-lake deposits had essentially no sulfide, presumably because the original sulfide has been oxidized to sulfate. Much of the sulfate generated from sulfide oxidation most likely would have precipitated as gypsum and remained in the profile unless removed by ground water. At site W-1, essentially no sulfur, and therefore no sulfate, remains in the top 24 ft of the profile. Repeated flushing by irrigation water probably has dissolved any gypsum that had been stored in this zone. Gypsum was not detected by X-ray diffraction (XRD) in drill-core samples from 12-14 ft and 24 ft at site W-1 (Douglas McCarty, Dartmouth College, written commun., 1992). The absence of gypsum, and probably other soluble salts, in the upper 24 ft at site W-1 is consistent with dissolved-solids concentrations that do not increase as irrigation water flows through the shallow subsurface. Some sulfide and sulfate does remain at the 30-ft level near the transition zone between weathered and unweathered shale at site W-1. Gypsum was detected by XRD in the drill-core sample from 30 ft. In the upper, oxidized part of the profile at site W-3, much of the original sulfur remains, probably as sulfate in gypsum, which was identified at 10-12 ft in the one

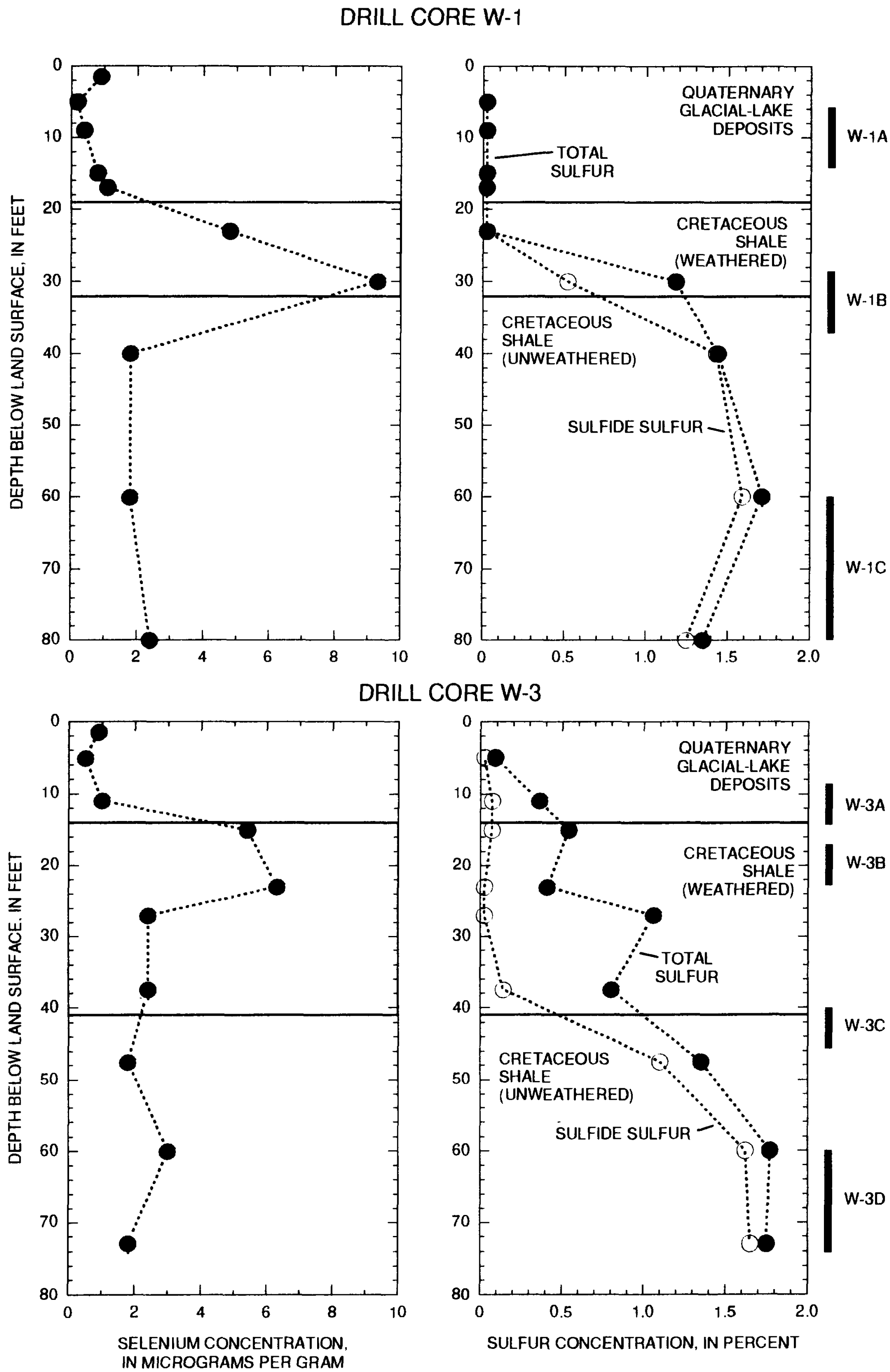


Figure 21. Selenium and sulfur concentrations in samples of glacial-lake deposits and shale between the Greenfields Bench and Freezeout Lake, Montana. Depths of the screened intervals of nested test wells completed at each site are shown on the right. Sulfur concentrations less than the minimum reporting level (0.05 percent) are plotted as 0.025 percent.

sample from this borehole analyzed by XRD (Douglas McCarty, Dartmouth College, written commun., 1992). When recharge occurs in this area, gypsum and probably other soluble salts can dissolve and increase the dissolved-solids concentration in ground water, as reflected by the high specific-conductance values (14,500-31,400 µS/cm) in water samples from wells W-3A and W-3B.

The sulfur profile at site W-3 may be representative of the pre-irrigation profile at site W-1. No drill-core samples were collected at site W-2, but selenium and sulfur profiles may be intermediate between those at site W-1, where irrigation of relatively permeable material has promoted flushing of the upper profile, and site W-3, where little irrigation has occurred.

Benton Lake Basin

Reconnaissance-level ground-water studies were conducted in the Benton Lake basin during 1990-92 (fig. 22). These studies were initiated to determine if seepage from Benton Lake to shallow ground water is a significant mechanism for removing selenium or dissolved solids from the wetland, to investigate the occurrence of selenium and salinity in shallow ground water, and to determine the relation between ground-water sources of selenium and salinity and surface water.

Saline seeps are common in the Benton Lake basin and in the northern Great Plains of Montana (Miller and Bergantino, 1983). Two seeps sampled by Knapton and others (1988, site 24 and 25, p. 62-65) on the south shore of Benton Lake are typical of the many seeps in the Benton Lake basin (Erich Gilbert, U.S. Fish and Wildlife Service, unpub. data). The alternate crop-fallow rotation widely used in this semiarid region causes increased areal recharge of precipitation to shallow ground water. Salts that had accumulated in the vadose zone under pre-farming conditions are dissolved by the increased infiltration and are transported to shallow ground water. Shallow ground water flows to local discharge areas on side slopes or in low-lying areas, where it evaporates and forms saline seeps (Halvorson and Black, 1974; Doering and Sandoval, 1976; Miller and others, 1981). Reclamation of seeps is a management goal of some local farmers. Reclamation can be accomplished by decreasing the amount of precipitation infiltrating through the root zone in the recharge area of a seep (Miller and others, 1981). Several farmers in the basin have installed shallow test wells with assistance from the Montana Salinity Control Association to gather water-level data for defining recharge areas to saline seeps. Except for wells (W-53 to W-56, fig. 22) just south of Benton Lake, these shallow test wells were not inventoried.

Ground-Water Flow

Glacial-lake deposits and glacial drift overlie shale in parts of the basin. Field reconnaissance during this study showed that isolated patches of glacial till or outwash not mapped by Lemke (1977) or shown in figure 3 occur in the basin. Although no wells completed in glacial deposits were found, ground water in glacial deposits could be the source of water to some saline seeps in the basin.

Colorado Group shale is the primary shallow water-bearing unit underlying much of the Benton Lake basin. Only limited ground-water development, primarily for stock water, has occurred in shale due to poor water quality and low yields. Drinking water is supplied to most residents of the basin by the Tri-County Water-Supply System. Prior to completion of the system, residents typically hauled water from Great Falls. Due to the sparsity of wells in the basin, insufficient water-level data were obtained to construct a potentiometric map; however, ground-water flow is assumed to generally follow the directions of surface drainage. Some deep wells have been drilled through the Colorado Group into underlying strata, primarily for petroleum exploration. Wells completed below the Colorado Group were reported to produce poor quality water.

The topographic position of the Benton Lake basin is higher than land to the east, making it plausible that ground water could flow eastward from the basin and discharge to wetlands between Benton Lake and the Missouri River. If Benton Lake is connected hydrologically to ground water flowing eastward, contaminants in Benton Lake could possibly discharge into the wetlands to the east. Any water that does percolate 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, most dissolved solids would be transported. Boreholes were drilled at the junction of the dikes separating Pools 3, 4C, 5, and 6 of Benton Lake (fig. 22) and at the northwest end of the dike separating Pools 3 and 4B to determine the lithology and thickness of underlying materials. Both holes were drilled to a depth of 80 ft through gray, silty clay lake-bed sediments. The borehole results are consistent with the observation by Lemke (1977) that the thickness of glacial-lake sediments exceeds 100 ft near Benton Lake. Based on the assumed low permeability of the lake-bed sediments, probably little water is lost from Benton Lake to ground water.

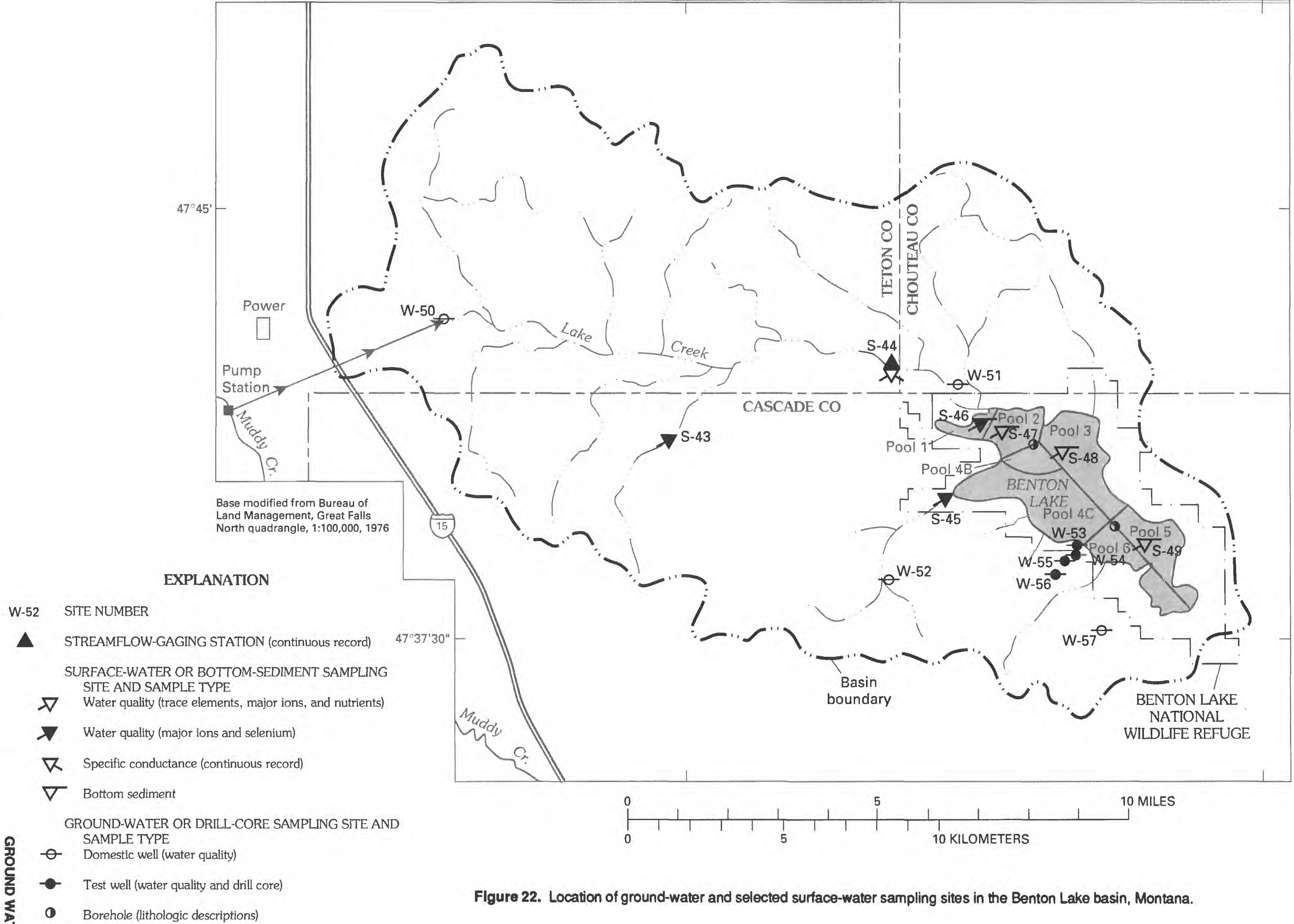


Figure 22. Location of ground-water and selected surface-water sampling sites in the Benton Lake basin, Montana.

Ground-Water Quality

Characterization of ground-water quality in the Benton Lake basin is based on samples from four domestic wells completed at depths of 27-177 ft in the Colorado Group and four test wells completed at depths of 13-80 ft in the Colorado Group (fig. 22; Lambing and others, 1994, table 9). The four test wells were installed approximately along a ground-water flow path upgradient of one of the saline seeps (Knapton and others, 1988) that discharge to Benton Lake.

Ground-water quality in the Benton Lake basin was poor. Ground-water samples can be divided into two broad groups according to source—deep and shallow (table 7). Water from two wells completed in deep (>100 ft) shale had sodium, sulfate, and bicarbonate as predominant ions. Chloride concentrations were relatively low, dissolved-solids concentrations were moderate (for the area), and pH was basic. Based on nitrate concentrations, redox conditions probably were reducing and consequently, even though the shale is seleniferous, dissolved-selenium concentrations were very low.

The proportion and amount of constituents in samples of shallow ground water were different from that of deep ground water. Samples of shallow ground water from wells less than 100 ft deep had both magnesium and sodium as predominant cations while sulfate was virtually the only anion. Higher concentrations of calcium, sulfate, chloride, and particularly magnesium contributed to much higher dissolved-solids concentrations than in deeper ground water. Due to lack of carbonate minerals, acid produced from oxidation of sulfides in the marine shale (Mermut and Arshad, 1987) is not completely neutralized and pH values (5.0-7.2) in shallow ground water, for the most part, were acidic. Nitrate concentrations were elevated, probably because cultivation causes increased oxidation of organic nitrogen in the soil (Kreitler and Jones, 1975) or because of fertilizer use. Based on nitrate and dissolved-oxygen concentrations, redox conditions were

Table 7. Water-quality characteristics in ground- and surface-water samples from the Benton Lake basin, Montana

[Major cations: Ca, calcium; Mg, magnesium; Na, sodium. Major anions: HCO_3, bicarbonate; SO_4, sulfate. Abbreviations: µg/L, micrograms per liter; mg/L, milligrams per liter. Symbols: <, less than; --, no data]

Site (fig. 22)	Well depth (feet below land surface)	Major cation(s)	Major anion(s)	Dissolved solids (mg/L)	Chloride, dissolved (mg/L as Cl)	Nitrate plus nitrite, dissolved (mg/L as N)	Selenium, dissolved or total-recoverable (µg/L as Se)	pH (standard units)
				DEEP GROUND WATER				
W-50	111	Na	HCO_3, SO_4	4,210	39	<0.1	1	9.1
W-52	160	Na	SO_4, HCO_3	2,350	14	.5	<1	7.7
W-57	[1]177	Na, Mg	HCO_3, SO_4	9,250	330	130	530	5.6
				SHALLOW GROUND WATER				
W-51	27	Mg, Ca, Na	SO_4	4,560	180	41	87	6.3
W-53	12	Mg, Na	SO_4	16,300	210	1.7	300	5.0
W-54	49	Mg	SO_4	17,600	210	20	270	6.7
W-55	59	Na, Mg	SO_4	10,400	220	13	200	7.2
W-56	78	Na	SO_4	9,660	300	3.9	19	7.2
				NATURAL SURFACE RUNOFF				
S-43	--	Mg, Na	SO_4	10,800-12,000	370-400	--	570-730	4.4-4.6
S-44[2]	--	Mg, Na	SO_4	6,630-13,400	280-480	5.9-75	62-160	5.1-6.6
S-45	--	Mg, Na	SO_4	12,200	580	--	18	8.5

[1]Depth of water-bearing zone is unknown. Based on the similarity of water-quality characteristics for this well and shallow ground water, the water-bearing zone of this well may be shallower than the well depth of 177 ft.

[2]Excludes samples collected when water was being pumped from Muddy Creek and the samples collected April 18-19, 1991, when streamflow was diluted by precipitation runoff.

oxidizing and consequently selenium concentrations were high. As has been found in other areas (Donovan and others, 1981; Weres and others, 1989; White and others, 1991), concentrations of selenium and nitrate were correlated in oxygenated ground water in the Benton Lake basin. The selenium in ground water presumably came from weathering of the Colorado Group shale, which had a selenium concentration range of 0.1-1.1 µg/g in drill cuttings from sites W-53, W-54, W-55, and W-56 (Lambing and others, 1994, table 13). High trace-metal concentrations were measured in acidic ground-water samples. Dissolved concentrations were as high as 100 µg/L for cadmium, 21,000 µg/L for manganese, and 4,900 µg/L for zinc in samples with pH values less than about 6 (Lambing and others, 1994, table 11). MCL's for cadmium, nitrate, and selenium were exceeded in some samples by large amounts.

Water quality in shallow shale in the Benton Lake basin was similar to ground-water quality in other parts of north-central Montana underlain by the Colorado Group. Samples from 53 wells completed in shale or overlying glacial deposits (Donovan and others, 1981) typically had a sodium magnesium sulfate composition and average concentrations of dissolved solids and selenium of 9,260 mg/L and 308 µg/L, respectively. The major difference between the north-central Montana samples and samples 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 few 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.

Oxygen and hydrogen stable-isotope ratios in samples from wells W-53, W-54, W-55, and W-56 plot close to the North American continental precipitation line (Gat, 1980) (fig. 23). Based on these isotopic data, the high concentrations of dissolved constituents in samples from these wells were derived primarily from mineral dissolution along the flow path rather than evaporative concentration of more dilute water. Schwartz and others (1987) reached the same conclusion based on similar isotopic data for shallow ground-water samples collected near saline seeps in southern Alberta. Based on tritium concentrations of 2.5-13 TU in samples from wells W-53, W-54, and W-55, ground water was derived from precipitation that infiltrated after 1953. These tritium and stable-isotope data support the widely accepted hypothesis (Halvorson and Black, 1974; Doering and Sandoval, 1976; Miller and others, 1981) that crop-fallow farming results in increased recharge and salt loading to shallow ground-water systems and consequent enlargement of the saline seep areas.

Although ground-water discharge maintains a small base flow in Lake Creek and some of its tributaries during the spring and fall and part of the summer, most ground water discharged to seeps and tributaries does not reach Lake Creek or Benton Lake because topographic gradients are small and evaporation rates are high, especially during warm months. Minerals precipitate as ground water evaporates in discharge areas. Slightly soluble minerals 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 minerals in the subsurface reduces the dissolved-solids load discharged at seeps. Efflorescent crusts consisting of highly soluble sodium and magnesium sulfate salts form on the surface of seeps and along channels (Whittig and others, 1982; Keller and others, 1986a,b). Most of the dissolved-solids and selenium load precipitated at the surface from ground water eventually is redissolved and transported to Benton Lake by surface flow.

Although formation of salts in the subsurface may reduce the dissolved-solids load transported 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 minerals. Two surface 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 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. High initial concentrations of selenium in water samples collected from Lake Creek on July 25, 1990, when pumped water from Muddy Creek flushed salts from the previously dry channel, provide evidence that the efflorescent salts that form in the basin contain selenium (fig. 24). The efflorescent salts are dissolved quickly and transported to Benton Lake either by precipitation runoff or by water pumped from Muddy Creek.

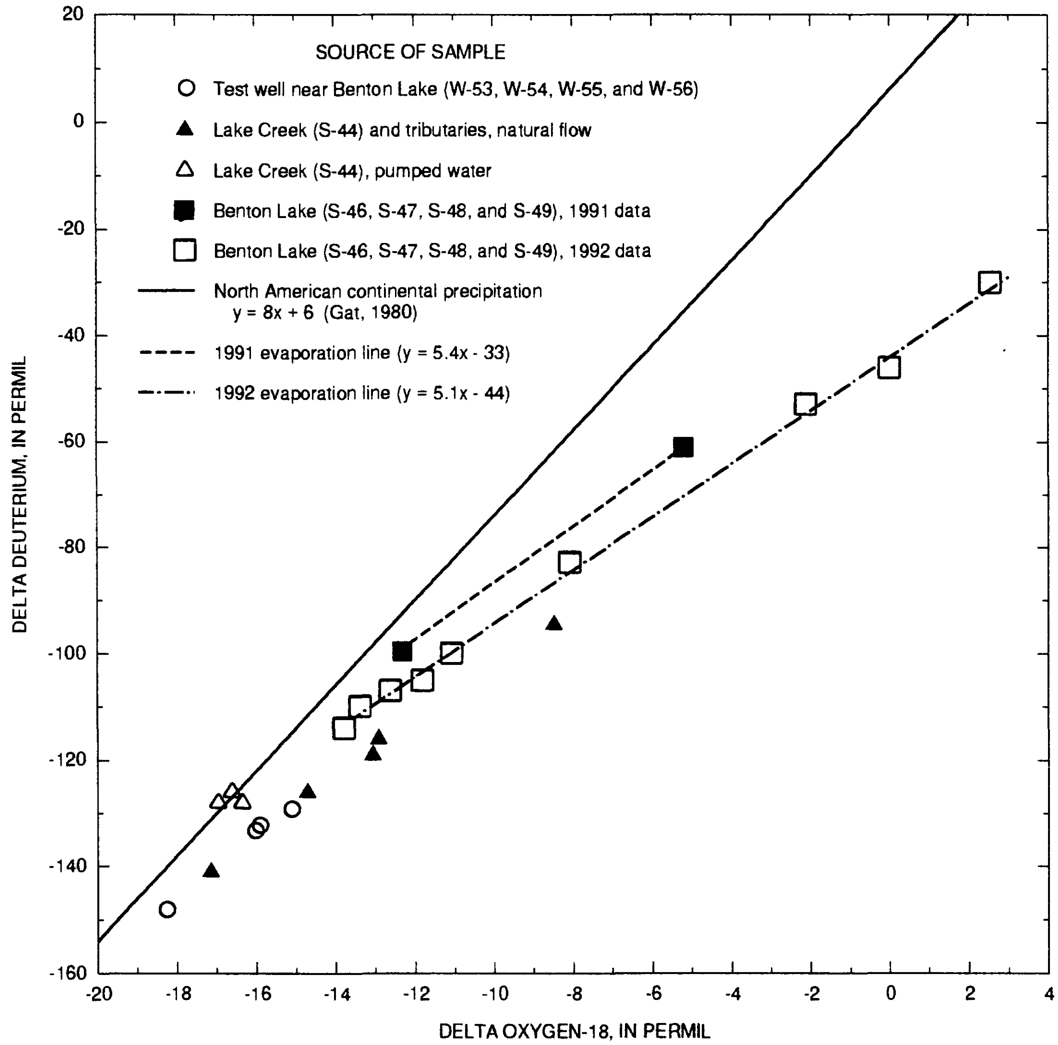


Figure 23. Relation of delta oxygen-18 and delta deuterium values in samples of ground water and surface water from the Benton Lake basin, Montana.

SURFACE WATER AND BOTTOM SEDIMENT

Surface water and bottom sediment were sampled at numerous sites (Lambing and others, 1994, table 3) to determine the magnitude and spatial variability of constituent concentrations in the Sun River area (fig. 25). Analytical results for samples collected during 1990-92 as part of this study are presented in Lambing and others (1994, tables 14, 15, and 20). Data for analysis of samples collected in 1986 as part of the reconnaissance study are presented in Knapton and others (1988, tables 15 and 16). Water-borne concentrations were compared to drinking-water regulations and aquatic-life criteria (table 1) to evaluate risk to human health and aquatic life. Selenium concentrations and quantities of flow in drains and natural streams were used to estimate selenium loading to wetlands. Load estimates were used to identify important source areas for selenium and to provide information to aid in the understanding of processes occurring in wetlands that affect concentrations in water, bottom sediment, and biota.

Hydrologic and Chemical Characteristics of Surface Water

Surface water in the study area includes irrigation supply water from the Sun River, irrigation return

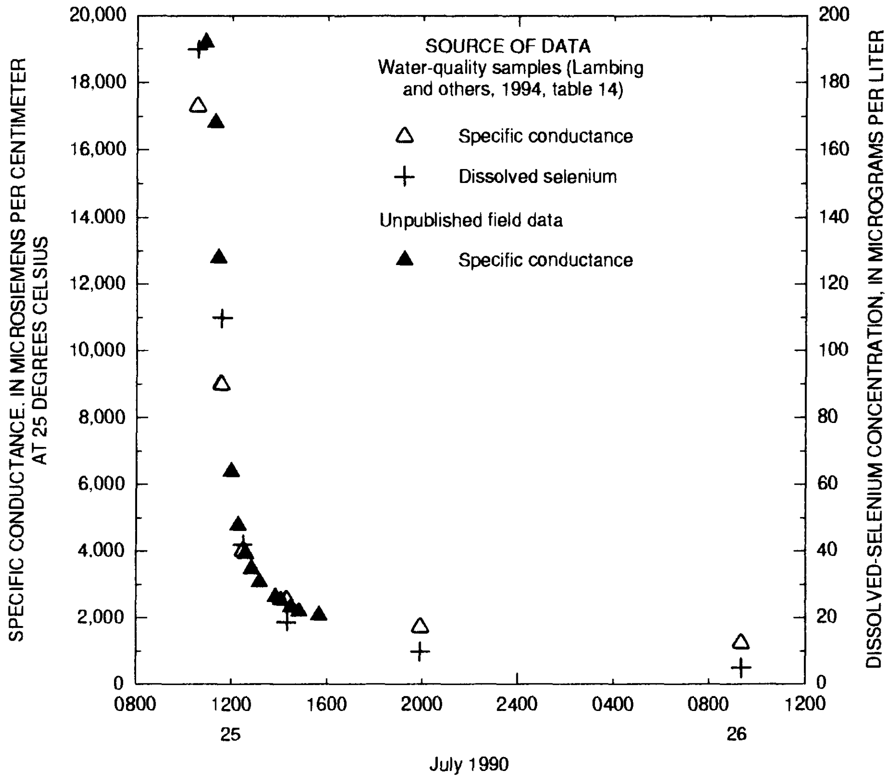


Figure 24. Specific conductance and dissolved-selenium concentration of water samples collected from Lake Creek (site S-44, fig. 22), Montana, as water pumped from Muddy Creek flushed salts from the channel. No flow occurred in Lake Creek for the 15 days prior to collection of the first sample. Streamflow was 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.

flow, natural runoff from non-irrigated land, and wetlands in the wildlife areas. Natural runoff from irrigated areas is included in return flow because runoff is a relatively small part of return flow. Irrigation return flow provides a relatively stable supply of water to wetlands every year, whereas natural runoff from non-irrigated areas is highly variable from year to year, depending on annual precipitation. The major wetlands in the study area receive surface inflows from multiple sources and are hydrologic sinks whose chemical characteristics are controlled in part by the variable quality and quantity of irrigation return flow and natural runoff.

Irrigation return flow derived from fields underlain either by gravel on the Greenfields Bench or by glacial deposits in off-bench areas (fig. 2 and 3) is routed through a network of drain canals to Freezout Lake WMA, Muddy Creek, and the Sun River. All irrigation return flow supplied to Benton Lake NWR is pumped from Muddy Creek. Natural runoff in streams and seeps comes from non-irrigated areas underlain by the Montana Group west of Freezout Lake WMA and glacial deposits or Colorado Group shale east of Freezout Lake WMA and in the Benton Lake basin.

Geology is a primary factor affecting spatial variability in chemical characteristics of surface water. Land-use practices, such as irrigated and non-irrigated (dryland) farming, also can significantly modify hydrologic conditions that, in turn, affect constituent concentrations and rates of chemical transport. To characterize the quality of water derived from different sources, sampling sites on irrigation drains, natural streams, and seeps have been grouped into the following five categories in order to evaluate chemical differences that are attributable to geologic or land-use factors:

Irrigation return flow:
- Gravel
- Glacial deposits (primarily glacial-lake deposits)

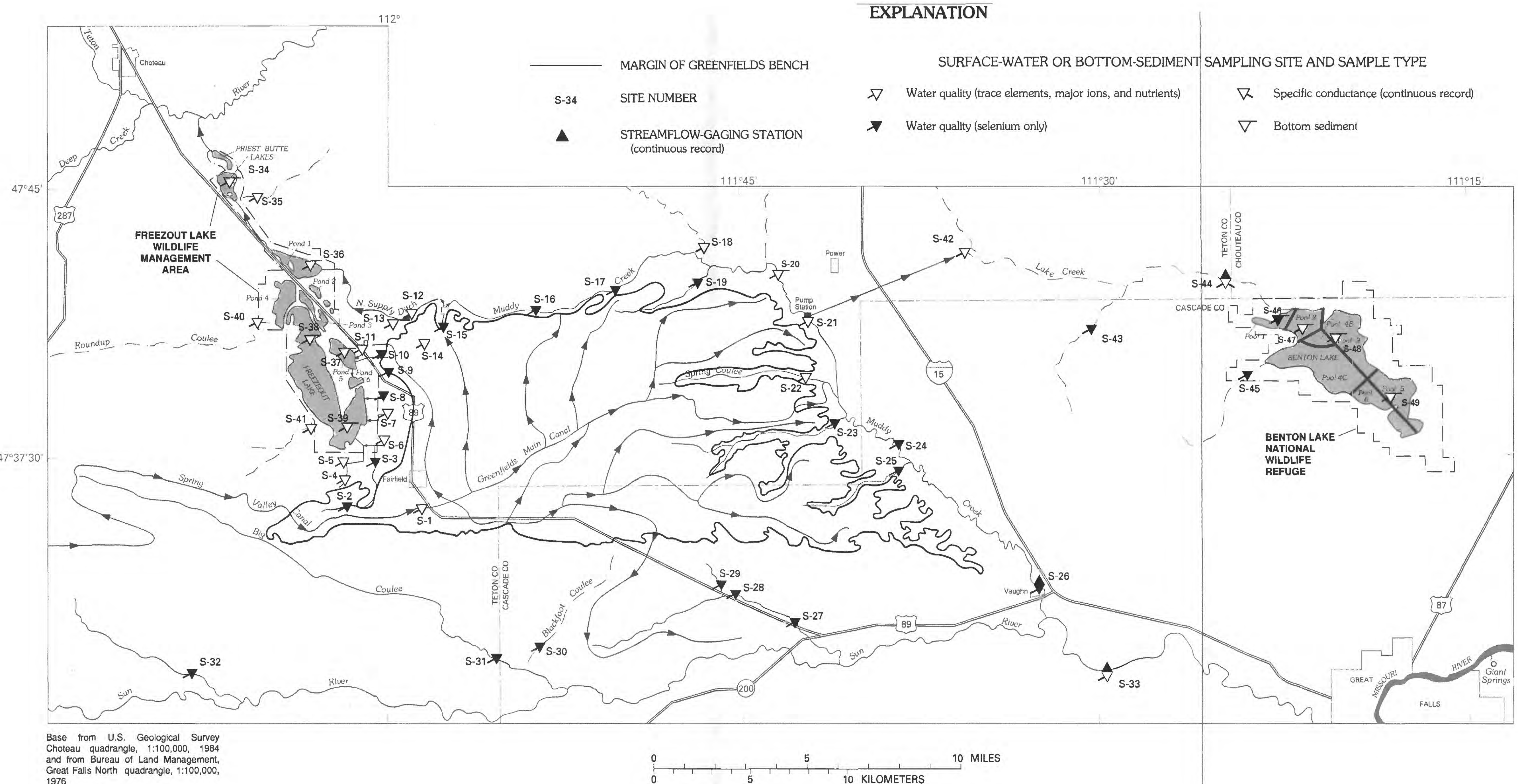


Figure 25. Location of surface-water and bottom-sediment sampling sites in the Sun River area, Montana.

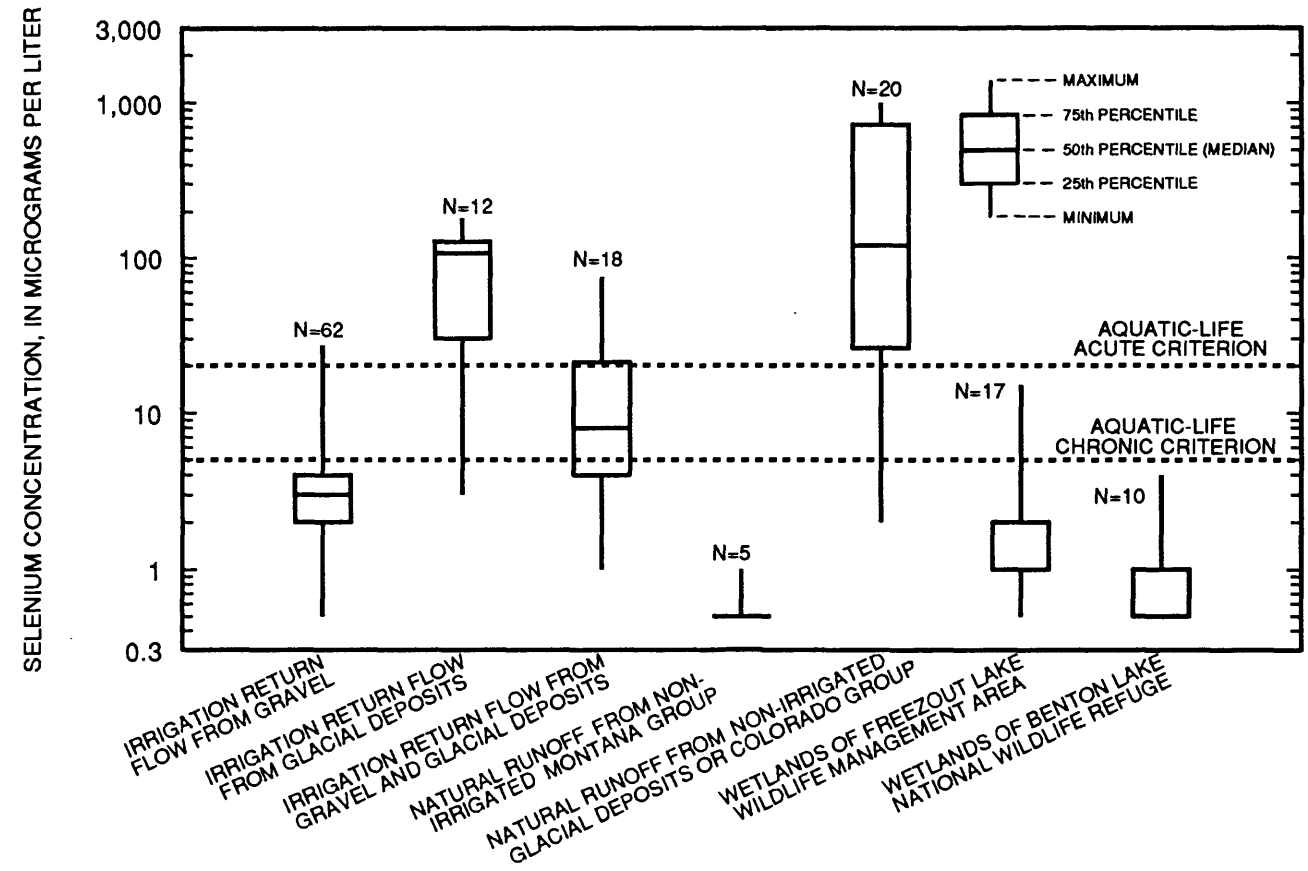


Figure 26. Selenium concentrations in surface water collected during 1986-92 from similar geologic and hydrologic environments in the Sun River area, Montana. Values plotted less than the minimum reporting level of 1 microgram per liter were estimated using a log-probability regression (Helsel and Cohn, 1988).

Gravel and glacial deposits
Natural runoff from non-irrigated land:
Montana Group
Glacial deposits or Colorado Group

Selenium concentrations in surface-water samples collected from each group during 1986-92 are summarized graphically using boxplots (fig. 26) to provide a general comparison among different hydrologic and geologic environments. Concentrations in wetlands of both wildlife areas also are shown for comparison. Aquatic-life criteria for selenium are plotted to indicate the magnitude and frequency of exceedances in surface water from each group of sites. The chemical characteristics of each group and factors contributing to variability are discussed in the following sections.

Selenium in surface water occurs almost entirely in the dissolved phase. A Wilcoxon matched-pairs, signed-rank test did not indicate a statistically significant difference between dissolved- and total-recoverable-selenium concentrations at a significance level of 0.05. Dissolved and total-recoverable concentrations were nearly equal over the wide range of selenium concentrations observed in the study area (fig. 27). Consequently, concentrations of both phases are considered essentially equivalent and distinctions generally will not be made in subsequent discussions and graphs in this report.

Greenfields Irrigation Division and Freezout Lake Wildlife Management Area

Spatial variability in the quality of irrigation return flow, natural runoff, and water in wetlands is influenced by the diverse geology and land use within the Greenfields Division, Freezout Lake WMA, and adjacent non-irrigated lands that drain to Freezout Lake WMA. To provide a reference for the spatial variability of water quality, median selenium concentrations measured during 1990-92 at surface-water sites representing various geologic and hydrologic features are shown in figure 28.

Irrigation Return Flow

The majority of irrigation water in the Greenfields Division is applied to the Greenfields Bench,

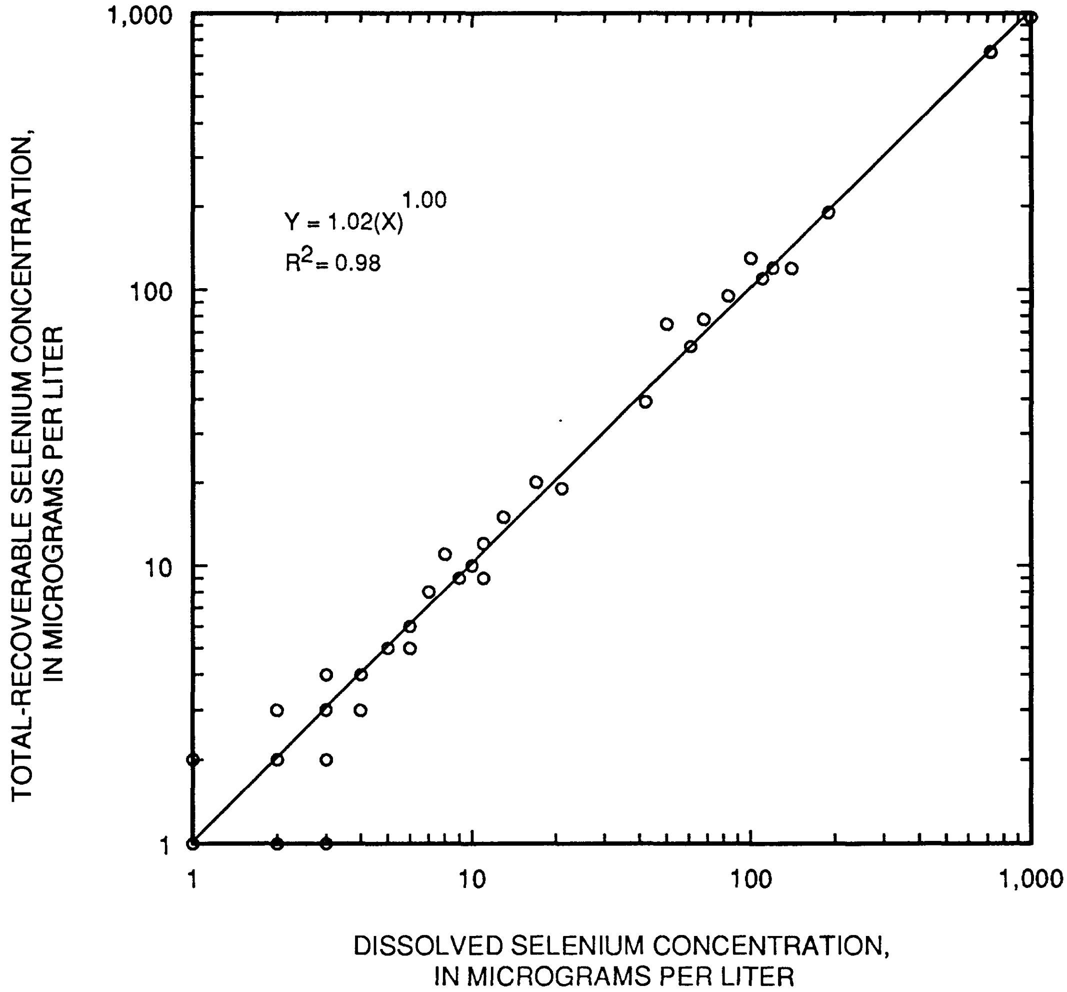


Figure 27. Relation of dissolved- (X) to total-recoverable (Y) selenium concentration in surface water from the Sun River area, Montana.

which is underlain by gravel. Most of the return flow from the Greenfields Bench drains either to Muddy Creek or the Sun River. Similar to ground-water drainage, surface water from two small parts of the Greenfields Bench drains to Freezout Lake WMA—an area in the southwest corner of the Bench south of Freezeout Lake and an area in the northwest corner of the Bench. An area of irrigated glacial deposits in low-lying fields between the Greenfields Bench and Freezeout Lake drains to Freezeout Lake. All water draining to Freezout Lake WMA from irrigated land in the Greenfields Division discharges either to Freezeout Lake or smaller ponds in the south part of the refuge. Priest Butte Lakes at the north end of the refuge receive no direct discharge from irrigation drains. Water from the north end of Freezeout Lake is conveyed by canal to Priest Butte Lakes.

Irrigation water supplied to the Greenfields Division by the Greenfields Main Canal (site S-1) was a calcium bicarbonate type with a dissolved-solids concentration of about 100-150 mg/L. Concentrations of all constituents were low. Selenium concentrations were less than the minimum reporting level of 1 µg/L. Water-quality characteristics of this site serve as a background reference for comparison with irrigation return flow.

The quantities of irrigation return flow and precipitation runoff vary substantially throughout the year. As a result, flow volumes in drain canals change seasonally. Maximum flow volumes typically occur during the early part of the irrigation season (May-June) when supply water is being flushed through canals, fields are being irrigated, and precipitation runoff is at a maximum. Minimum flows in drains generally occur 6-7 months after the end of the irrigation season (March-April) when surface runoff is sparse and base flow sustained by subsurface irrigation drainage is at a minimum.

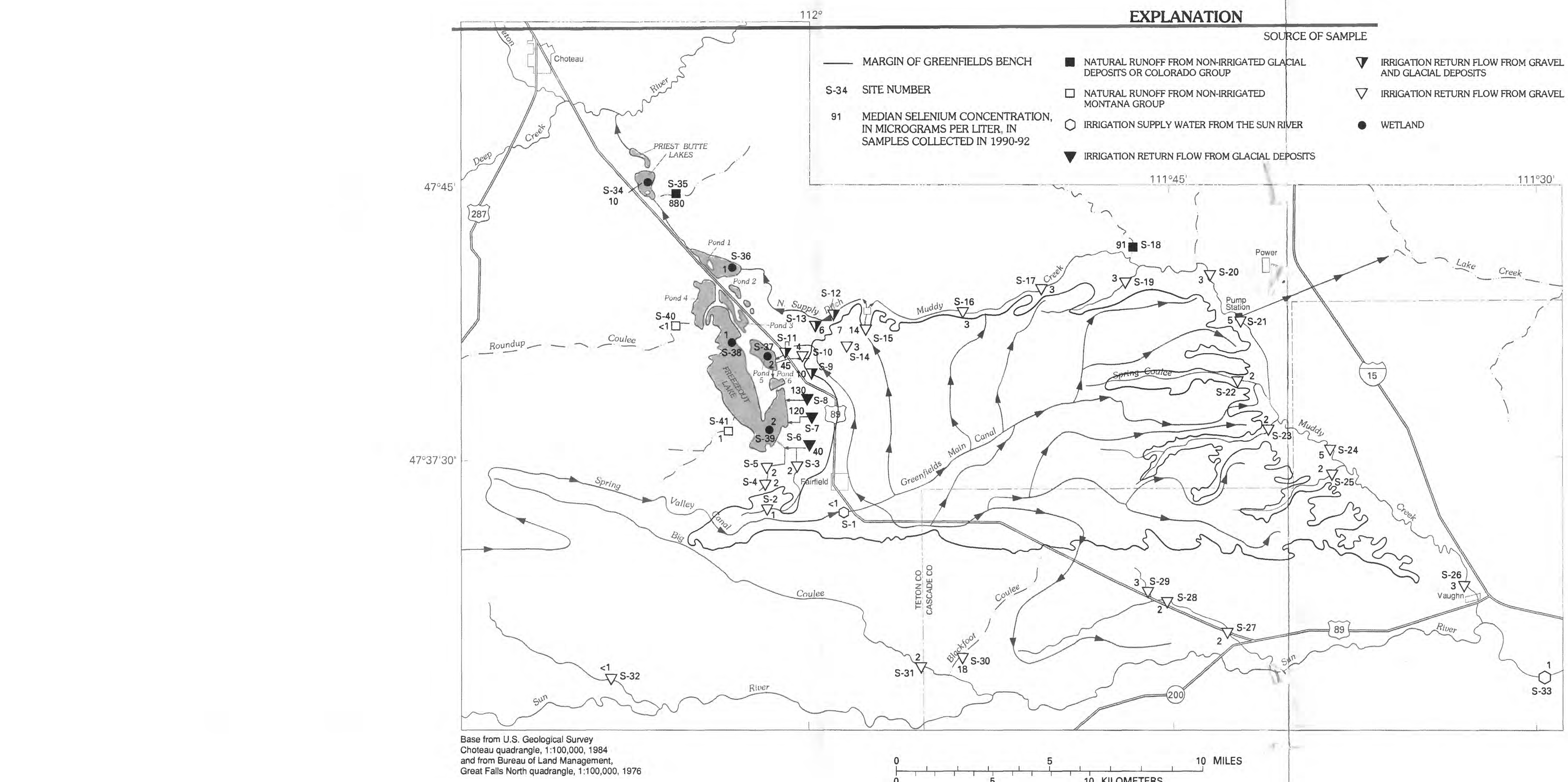


Figure 28. Median selenium concentration in surface water at selected sites within or near the Greenfields Irrigation Division and Freezout Lake Wildlife Management Area, Montana.

Concentrations of constituents in irrigation return flow also vary seasonally. Selenium concentrations in samples of irrigation return flow during the fall, spring, and summer of 1990-92 are plotted for four sites (fig. 29). The sites represent irrigation return flow from gravel, glacial deposits, and combined flows from gravel and glacial deposits or Colorado Group. Dashed lines connecting seasonal concentrations have been drawn to portray a hypothetical pattern of change based on rapid dilution effects upon delivery of large amounts of supply water to canals and irrigated fields and rapid increases in concentration upon termination of irrigation. These lines do not imply actual patterns, but rather are used to infer the relative differences between seasons and sources of irrigation return flow. Although concentrations differed substantially between the sites, similar seasonal patterns were evident for all sites.

Following the end of irrigation, selenium concentrations increase during the fall, winter, and spring as flow in drain canals decreases to base-flow levels. The concentration increase is due to the diminishing effect of dilution from direct spills of unused irrigation water and surface runoff. Because of sparse rainfall and seasonal termination of irrigation, flows in drain canals consist almost entirely of subsurface drainage from about October through April. Maximum concentrations commonly are attained during minimum base flow just prior to the start of the irrigation season (late April to early May). Upon delivery of irrigation water in the spring, the ground-water system is rapidly recharged and excess surface runoff and direct spills are quickly routed through the network of drain canals. During the period that direct spills combine with the ground-water components of irrigation drainage, constituent concentrations in drain canals are diluted significantly. Precipitation runoff can have similar diluting effects on water in drain canals over short periods of time. This abundance of supply water results in a seasonal minimum selenium concentration during the time that flows are highest. Minimum concentrations probably are maintained throughout the remainder of the irrigation season based on consistently low values measured at most sites during the summer. The cycle of increasing selenium concentrations begins again when irrigation deliveries are terminated in September.

Return Flow from Gravel

Irrigation return flow from the gravel capping the Greenfields Bench (figs. 3 and 28) was a magnesium-calcium bicarbonate type. The dissolved-solids concentration in 23 samples of irrigation return flow from gravel collected during 1986-92 ranged from 190-8,710 mg/L, with a median concentration of 414 mg/L. The median concentration represents about a threefold increase over the dissolved-solids concentration of supply water.

Selenium concentrations in 62 samples of irrigation return flow from gravel collected during 1986-92 ranged from <1-27 μg/L, with a median of 3 μg/L. Similar to dissolved solids, the median selenium concentration of 3 μg/L represents about a threefold increase compared to the selenium concentration in the supply water. Because concentrations generally were low, seasonal variability of selenium concentrations at most sites on the Bench was minor.

Elevated concentrations of selenium in irrigation return flow from gravel were observed in only a few localized areas. The maximum value of 27 μg/L was measured near the mouth of Blackfoot Coulee (site S-30), which is a natural stream that drains to the Sun River. The water in the coulee consists mostly of irrigation return flow from the southern edge of the Greenfields Bench and possibly from the Ashuelot Bench. Selenium concentrations in this coulee showed distinct seasonal differences, with high values (17-27 μg/L) occurring during base flow and low values (2 μg/L) occurring during the irrigation season. Part of the Blackfoot Coulee basin is underlain by shale that could be a source of selenium.

Most irrigation return flow from the Greenfields Bench flows toward the north and east to Muddy Creek (fig. 25), and constitutes most of the flow in the stream. Muddy Creek also drains a sizeable non-irrigated area (85,800 acres) north and east of the Bench that contributes relatively minor amounts of water, except during occasional precipitation runoff. Selenium concentrations ranged from 2-10 μg/L at six sites on Muddy Creek. Selenium concentrations in Muddy Creek generally increase in a downstream direction, especially during pre-irrigation base-flow conditions of March-April. Because irrigation return flow draining to Muddy Creek from the eastern edge of the Bench contained uniformly low selenium concentrations (fig. 28), the slight downstream increase of concentrations in Muddy Creek may result from the contribution of either ground water or ephemeral tributaries draining the non-irrigated area north and east of the Bench.

Irrigation return flow from gravel along the western edge of the Greenfields Bench that drains to Freezout Lake WMA had selenium concentrations that ranged from <1-16 μg/L. Spatial differences were evident, with selenium concentrations in 13 samples from the southwest corner of the Greenfields Bench ranging from <1-5 μg/L, with a median of 1 μg/L, and concen-

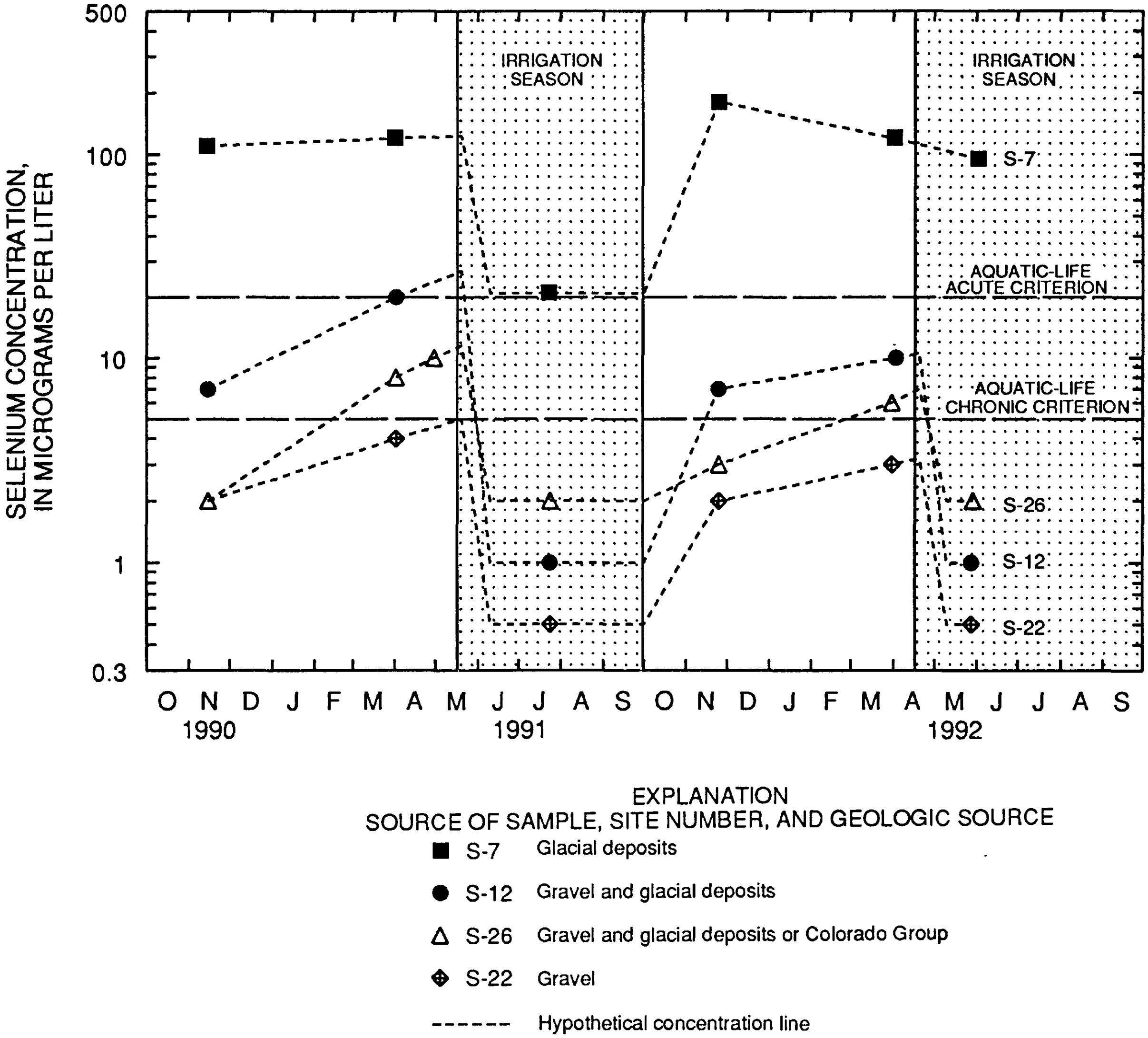


Figure 29. Hypothetical seasonal variation of selenium concentration in irrigation return flow from different geologic sources in the Sun River area, Montana. Symbols represent measured concentrations in samples collected on the various dates shown. Values less than the minimum reporting level of 1 microgram per liter are plotted as 0.5 microgram per liter.

trations in 10 samples from the northwest corner of the Bench ranging from 2-16 µg/L, with a median of 4 µg/L. The maximum concentration was measured at an irrigation-induced seep (site S-15) that discharges in the northwest corner of the Bench at the contact between gravel and underlying shale.

Similar water-quality characteristics for surface water and ground water sampled in the western part of the Greenfields Bench (table 6), provide evidence that water in drains and irrigation-induced seeps in this area is derived from water discharging from the gravel aquifer. Near the northwest corner of the Bench, water at sites S-10 and S-14 (fig. 25), had major-ion chemistry and selenium concentrations similar to samples from nearby wells (W-5A, W-5B, W-9, and W-11). The range of selenium concentrations was 2-16 µg/L in irrigation return flow from the northwest corner of the Bench and 3-12 µg/L in water from nearby wells. Near the southwest corner of the Bench, surface water from sites S-2 and S-5 had chemical quality similar to ground water from nearby wells W-43 and W-45, which are completed in gravel. Dissolved-selenium concentrations in surface water of this area ranged from <1-3 µg/L and were similar to concentrations (<1-1 µg/L) in ground water.

Irrigation return flow from gravel is used as a source of public drinking water at two sites (S-10 and S-20). Site S-10 is a developed spring discharging from the gravel aquifer of the Greenfields Bench. This supply is used at the headquarters office of Freezout Lake WMA. Site S-20 is on Muddy Creek near the town of Power. Stream water is pumped from this site to a settling pond and distributed to residents of the community. The maximum selenium concentrations at these sites (5-6 µg/L) were much lower than the MCL of 50 μg/L. However, no samples were obtained from Muddy Creek during short periods of significant runoff when natural flow from non-irrigated areas would have constituted a larger proportion of the streamflow. If selenium concentrations in natural flow respond similarly to that observed in Lake Creek (fig. 24) during initial periods of runoff, selenium concentrations in Muddy Creek near Power (site S-20) may increase and possibly exceed the MCL for short periods of time. No exceedances of MCL's were measured for the other constituents analyzed in irrigation return flow from gravel. Similar to selenium, brief exceedances of MCL's for other constituents potentially could occur at Muddy Creek near Power during runoff from non-irrigated areas north of the Greenfields Bench.

Concentrations of selenium in irrigation return flow from gravel at most sites on the Greenfields Bench were less than the aquatic-life chronic criterion of 5 μg/L. Exceedances of the criterion were measured only in Blackfoot Coulee, Muddy Creek, and the northwest corner of the Greenfields Bench. Because Blackfoot Coulee and Muddy Creek receive a small portion of natural runoff from areas underlain by shale, it is uncertain if the elevated selenium concentrations are derived from irrigated or non-irrigated sources. Of these three areas, the northwest corner of the Greenfields Bench is the only area where irrigation drainage is derived solely from fields underlain by gravel. Concentrations of all other constituents were less than aquatic-life criteria.

Return Flow from Glacial Deposits

All return flow from irrigated glacial deposits drains to the southeast part of Freezeout Lake or adjacent small ponds in the central and southern part of Freezout Lake WMA (fig. 2). The glacial deposits in this irrigated area are almost entirely glacial-lake deposits except in a small area near the upstream end of the North Supply Ditch where the deposits are glacial drift (fig. 3). The quality of irrigation return flow from the glacial deposits is represented by water from three drains (S-6, S-7, and S-8) that are located in the low-lying area east of Freezeout Lake and below the Greenfields Bench (fig. 25). Irrigation drainage at these three sites consists of water applied solely to fields underlain by glacial deposits (fig. 3 and fig. 28). Although other canals drain fields underlain by glacial deposits south of Freezeout Lake and below the northwest corner of the Greenfields Bench, they also carry drainage from irrigated gravel and thus were not used to characterize the chemistry of irrigation return flow from glacial deposits.

Irrigation return flow from glacial deposits had a magnesium-sodium sulfate composition. The dissolved-solids concentration in five samples of irrigation return flow from glacial deposits at sites S-6 and S-7 ranged from 1,090-4,060 mg/L, with a median concentration of 2,870 mg/L. This median represents about a twentyfold increase over the dissolved-solids concentration in supply water from the Greenfields Main Canal (site S-1).

Selenium concentrations in 12 samples of irrigation return flow from glacial deposits collected during 1986-92 at sites S-6, S-7, and S-8 ranged from 3-180 μg/L, with a median concentration of 108 μg/L. This median represents about a hundredfold increase over selenium concentrations in the supply water. Concentrations greater than 50 μg/L were measured in water from all three drains. Relatively large seasonal variability of concentrations was evident. The minimum selenium concentration of 3 μg/L was measured during rainfall runoff, which illustrates the effect of dilution from precipitation. Several concentrations less than 50 μg/L were measured during the irrigation season when return-flow volumes were at a maximum and probably consisted partly of direct spills that diluted concentrations. Selenium concentrations during periods of dilution remained moderately high (12-21 μg/L), indicating that the subsurface drainage had substantially elevated concentrations of selenium.

On the basis of specific conductance, major-ion chemistry, and selenium concentrations, irrigation return flow draining from the irrigated area between the Greenfields Bench and Freezeout Lake is derived primarily from ground water in glacial-lake deposits and not from the underlying shale. Data for samples from well W-1A are excluded from the comparison of water chemistry in glacial-lake deposits and drains because of possible leakage from a nearby irrigation canal. Specific-conductance values (1,420-5,190 μS/cm) of water from two wells completed in irrigated glacial-lake deposits (wells W-2A and W-23) (Lambing and others, 1994, table 11) were similar to those (844-5,310 μS/cm) from drains (sites S-6, S-7, and S-8) excavated in glacial-lake deposits east of Freezeout Lake. Major-ion chemistry in water from drains S-6 and S-7 and the two wells was mostly magnesium sulfate with sodium, calcium and bicarbonate in varying proportions. Shale probably is not a major source of water to drains because water in shale underlying the irrigated areas has a dissimilar major-ion composition.

Selenium concentrations in samples of irrigation return flow from glacial deposits (range of 3-180 μg/L, median concentration of 108 μg/L) were similar to dissolved-selenium concentrations in four ground-water samples from two wells (W-2A and W-23) completed in irrigated glacial-lake deposits (range of 28-190 µg/L, median concentration of 120 µg/L). The similarity in concentration ratios of sodium to selenium and sulfate to selenium (fig. 20) also supports the theory that water in these drains comes from glacial-lake deposits. The low dissolved-selenium concentrations (<1 µg/L) in ground water from wells W-1C, W-2C, W-3C, and W-3D completed in shale indicates that water in irrigation drains in the area between Freezeout Lake and the Bench is not derived from underlying shale.

Irrigation return flow from glacial deposits is not used as a domestic drinking-water supply. Therefore, the high selenium concentrations probably do not pose a human-health risk.

Selenium concentrations in irrigation return flow from glacial deposits exceeded both the chronic (5 µg/L) and acute (20 µg/L) aquatic-life criteria in about 90 percent of the samples. Although irrigation drains that carry water from glacial deposits are not major aquatic habitats, evaluating the quality of their water on the basis of aquatic-life criteria is relevant because of potential localized impacts to biota in the shallow near-shore areas of wetlands at the mouths of the drains. Incomplete mixing of drain inflows could cause an elevated concentration gradient extending some distance into Freezeout Lake. The greatest risk of adverse effects from ambient exposure or ingestion of water may be during seasonal base-flow periods (October-April) when selenium concentrations are at a maximum. No exceedances of aquatic-life criteria were measured for constituents other than selenium.

Return Flow from Gravel and Glacial Deposits

Drains in the two off-bench areas south of Freezeout Lake and below the northwest corner of the Greenfields Bench carry a mixture of water from both irrigated gravel and glacial deposits (fig. 28). Water quality in these drains is controlled by the quality and proportion of water from each source. Chemical characteristics typically are intermediate to those of the individual sources.

Mixed irrigation return flow from gravel and glacial deposits had a magnesium sulfate composition. The dissolved-solids concentration in nine samples of irrigation return flow from gravel and glacial deposits (sites S-9, S-11, S-12, and S-13) ranged from 337-6,920 mg/L, with a median concentration of 1,370 mg/L. This median concentration represents about a tenfold increase over the dissolved-solids concentration of supply water from the Greenfields Main Canal (site S-1). Selenium concentrations in 18 samples collected from these drains during 1986-92 ranged from 1-75 µg/L, with a median of concentration of 8 µg/L. Dilution of selenium concentrations by substantial volumes of irrigation drainage from gravel or direct spills of supply water results in a median concentration much lower than that of irrigation return flow from glacial deposits. The maximum selenium concentration of 75 µg/L in mixed irrigation return flow was measured in a drain to Freezout Lake WMA Pond 5 (site S-11) during pre-irrigation base-flow conditions in April.

Mixed irrigation return flow from gravel and glacial deposits is not used as a domestic-drinking water supply. Therefore, high selenium concentrations probably do not pose a human-health risk.

Selenium concentrations in mixed irrigation return flow from gravel and glacial deposits exceeded the aquatic-life chronic criterion in more than 50 percent of the samples and the acute criterion in 25 percent of the samples, thereby indicating potential risk to aquatic biota from ambient exposure or ingestion of water. Concentrations of other constituents did not exceed aquatic-life criteria.

Natural Runoff from Non-Irrigated Land

Streams and seeps that drain to Freezout Lake WMA from non-irrigated land potentially can impact water quality in the wetlands. Although water in these ephemeral and intermittent streams is described as "natural runoff" in this report, dryland farming occurs in much of the area and may affect water quantity and quality to varying degrees.

The quantity of natural runoff draining to the wetlands from non-irrigated areas is small relative to irrigation return flow in most years. However, substantial volumes of water can be contributed to the wetlands during major snowmelt or rainfall events. Precipitation runoff was rare during the study period and no high streamflows from non-irrigated areas were sampled. Consequently, most of the data for natural runoff represent either base flow or small to moderate runoff. Average annual precipitation at Fairfield during 1990-92 (10.9 in.) was 87 percent of the 30-year (1951-80) average of 12.5 in. (National Oceanic and Atmospheric Administration, issued annually).

Runoff from Montana Group

West of Freezeout Lake, two sites (S-40 and S-41) on streams which drain the sandstone and siltstone formations of the Montana Group were sampled during 1991-92. Natural runoff from the Montana Group had a sodium sulfate-bicarbonate composition. Dissolved-solids concentrations in three samples from the Montana Group ranged from 1,210-2,330 mg/L, and generally were lower than dissolved-solids concentrations in natural runoff from drainage basins underlain by glacial deposits or the Colorado Group.

No MCL's were exceeded for any constituent in natural runoff from the Montana Group. Selenium concentrations in five natural-runoff samples from the Montana Group ranged from <1-2 μg/L, with a median concentration of <1 μg/L. All selenium concentrations were less than the aquatic-life chronic criterion. The total-recoverable chromium concentration (15 μg/L) in one sample from the coulee southwest of Freezeout Lake (site S-41) exceeded the chronic criterion of 11 μg/L. No other criteria were exceeded.

Runoff from Glacial Deposits and Colorado Group

Samples of natural runoff from areas underlain by either glacial deposits or shale of the Colorado Group (fig. 3) were collected from a seep (site S-35) east of Priest Butte Lakes and an ephemeral tributary to Muddy Creek (site S-18) in the non-irrigated area north of the Greenfields Bench. The composition of natural runoff from these two sites was magnesium-sodium sulfate. The seep at site S-35 was the most saline surface-water site sampled in the study area; the dissolved-solids concentration ranged from 50,100-55,700 mg/L, with a median concentration of 52,600 mg/L. No dissolved-solids analyses are available for the tributary to Muddy Creek, but specific conductance ranged from 2,490-15,000 μS/cm. The higher value is about half the specific conductance of water at the seep. Surface water draining from these sites potentially could cause localized impacts to biota in receiving waters such as Priest Butte Lakes or Muddy Creek.

The maximum selenium concentration in the study area (1,000 μg/L) was measured in a sample from the saline seep (site S-35) that discharges to the east side of Priest Butte Lakes. The flow in this seep is relatively small (about 0.1-0.2 ft^3/s), but generally is sustained for most of the year. Fallowing of fields to increase soil infiltration of precipitation in this non-irrigated area probably accounts at least partially for the sustained flow and accelerated leaching of constituents from the soil (Miller and others, 1981).

Selenium concentrations in two samples from a tributary to Muddy Creek (site S-18) that drains non-irrigated land north of the Greenfields Bench were 2 and 180 μg/L. Both samples were collected during base flow, but the minimum concentration was measured several days after a runoff event. The maximum concentration was measured two months earlier, but after an extended dry period when the channel was thickly encrusted with evaporative salts. The large variation in selenium concentration indicates that salts precipitated along the bed and banks of stream channels are a significant source of selenium, but that they can be depleted temporarily by the flushing action of runoff. The initial stages of precipitation runoff probably transport a substantial amount of selenium as the surface salts are dissolved by rain and overland flow (fig. 24). After surface salts are flushed, concentrations may decrease with dilution from extended runoff. High selenium concentrations are reestablished during subsequent dry periods as discharge of poor quality ground water becomes the only source of flow. Evaporation can further increase concentrations in base flow as well as replenish the surface salts.

Although no exceedances of the MCL for selenium were measured in samples collected from Muddy Creek, water at the diversion to the public water supply for Power potentially could be affected by runoff from non-irrigated areas north of the Greenfields Bench that are underlain by glacial deposits and shale. Samples from site S-18 provide an indication of the chemical characteristics of tributaries draining this area and, therefore, it may be reasonable to assume that brief increases in concentrations of selenium and other constituents occur in these tributaries during runoff. The potential effect on the water supply of Power created by this infrequent natural runoff to Muddy Creek is uncertain, but it is probably temporary and partly alleviated by dilution from irrigation return flow from the Greenfields Bench.

The acute aquatic-life criterion of 20 μg/L for selenium was exceeded in all five samples from the seep east of Priest Butte Lakes (site S-35) by more than thirtyfold to fiftyfold. Although very high concentrations of selenium were measured at this site, none of the other trace elements exceeded aquatic-life criteria. One sample from the tributary to Muddy Creek (site S-18) also exceeded the acute aquatic-life criterion for selenium.

Wetlands of Freezout Lake Wildlife Management Area

Wetlands of Freezout Lake WMA receive the combined inputs of irrigation return flow, precipitation runoff from non-irrigated land, direct precipitation on the wetlands, and discharge from seeps. Irrigation return flow is the major source of sustained water supply to the wetlands. Although direct spills of irrigation supply water are provided only during the irrigation season, they can represent a substantial percentage of the annual water supply (Osborne and others, 1983). Precipitation runoff from irrigated lands is a small percentage of total runoff (Osborne and others, 1983). In some years, precipitation runoff from non-irrigated areas can provide substantial amounts of water, but the study period of 1990-92 was characterized by below-normal precipitation and runoff. Therefore, the effects of near- or above-normal precipitation runoff on the water-quality of wetlands are uncertain.

Evaporation causes the concentration of dissolved solids in the wetlands of Freezout Lake WMA to increase as water moves through the small ponds and Freezeout Lake in the central and southern part of the refuge toward Priest Butte Lakes (fig. 30). The major-ion composition was somewhat variable but generally was sodium-magnesium sulfate. Dissolved-solids concentrations in the smaller Ponds 1 and 5 (sites S-36 and 37) were similar to those in mixed irrigation return flow from gravel and glacial deposits. Based on samples collected in both the irrigation and pre-irrigation seasons, concentrations of dissolved solids in Ponds 1 and 5 were substantially less (median of 1,350 mg/L) than those of Freezeout Lake (median of 4,000 mg/L). The lower concentrations in these ponds may be due to their small volumes, which afford shorter residence times for evaporative effects and which respond more rapidly to large inputs of dilute irrigation return flow from gravel. The lack of substantial evaporation in Pond 5 is supported by stable-isotope data (fig. 12). Concentrations of dissolved solids (median of 7,860 mg/L) were highest in Priest Butte Lakes (site S-34), which

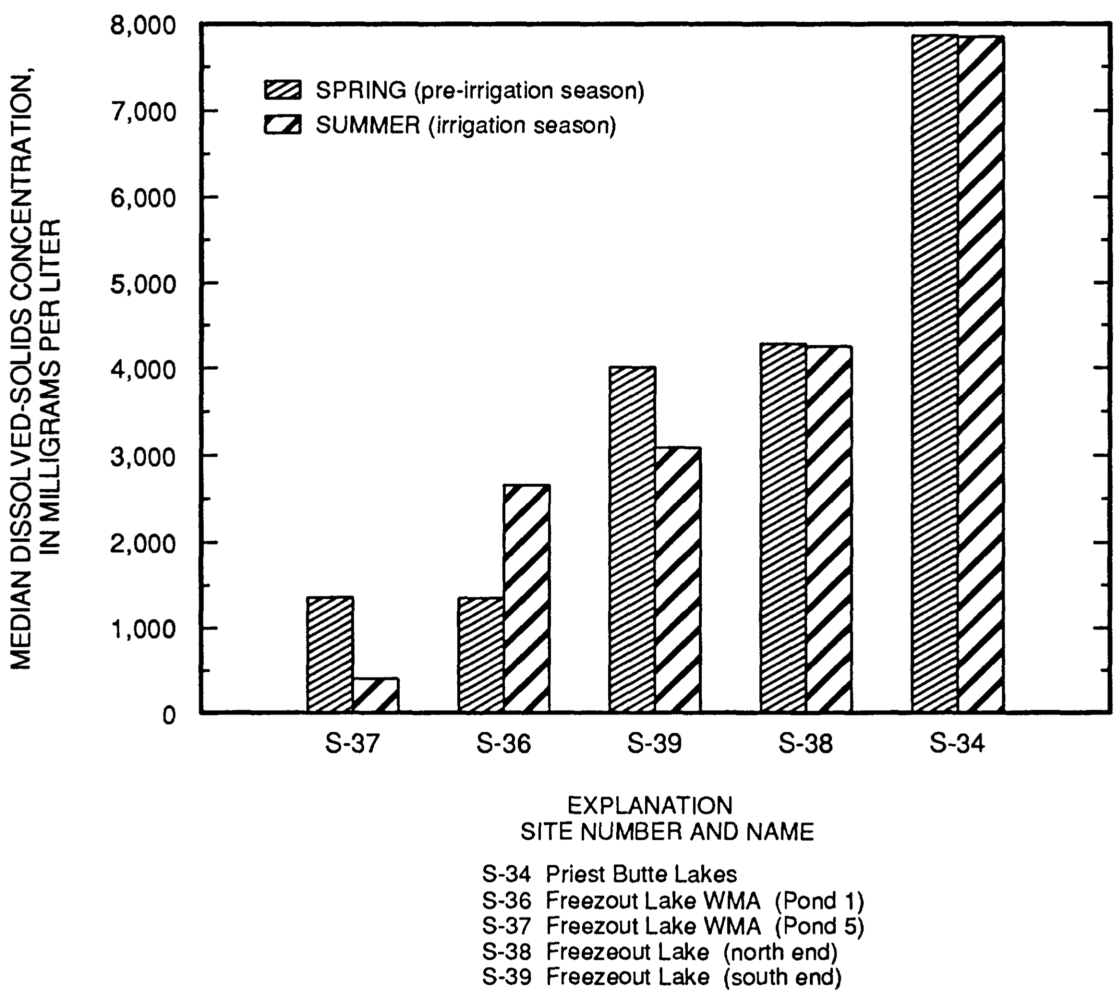


Figure 30. Median seasonal dissolved-solids concentration in water collected during 1991-92 from wetlands of Freezout Lake Wildlife Management Area, Montana. Sites are plotted in a general downstream direction.

are located at the downstream end of the interconnected pond system of the WMA. The primary water supply for Priest Butte Lakes comes from the north end of Freezeout Lake (site S-38) rather than from irrigation return flow. In general, dissolved-solids concentrations increase about twofold between the north end of Freezeout Lake and Priest Butte Lakes because of evapoconcentration and input from saline seeps.

Selenium concentrations in 13 samples from Freezeout Lake and the adjacent ponds in the central and southern part of Freezout Lake WMA were low, ranging from <1-2 µg/L. Similar to dissolved solids, the maximum selenium concentrations in the wetlands of Freezout Lake WMA occurred in Priest Butte Lakes. Selenium concentrations in four samples collected from Priest Butte Lakes during 1991-92 ranged from 9-15 µg/L, even though the water entering Priest Butte Lakes from the north end of Freezeout Lake had selenium concentrations of only 1 µg/L or less. The median selenium concentration of 10 µg/L in Priest Butte Lakes represents a tenfold increase over the primary supply water from the north end of Freezeout Lake. Unlike dissolved solids, increases in the concentration of selenium are not evident as water moves through the central and southern parts of Freezout Lake WMA. The sharp increase in selenium concentrations in Priest Butte Lakes, therefore, might result from additional selenium inputs rather than from evaporative processes.

Seasonal concentrations of selenium were examined in wetlands to identify possible differences related to inflow quantities of irrigation return flow. Median selenium concentrations during spring (pre-irrigation) and summer (irrigation) seasons at individual wetland sites in Freezout Lake WMA are illustrated in figure 31. Seasonal differences in selenium concentration

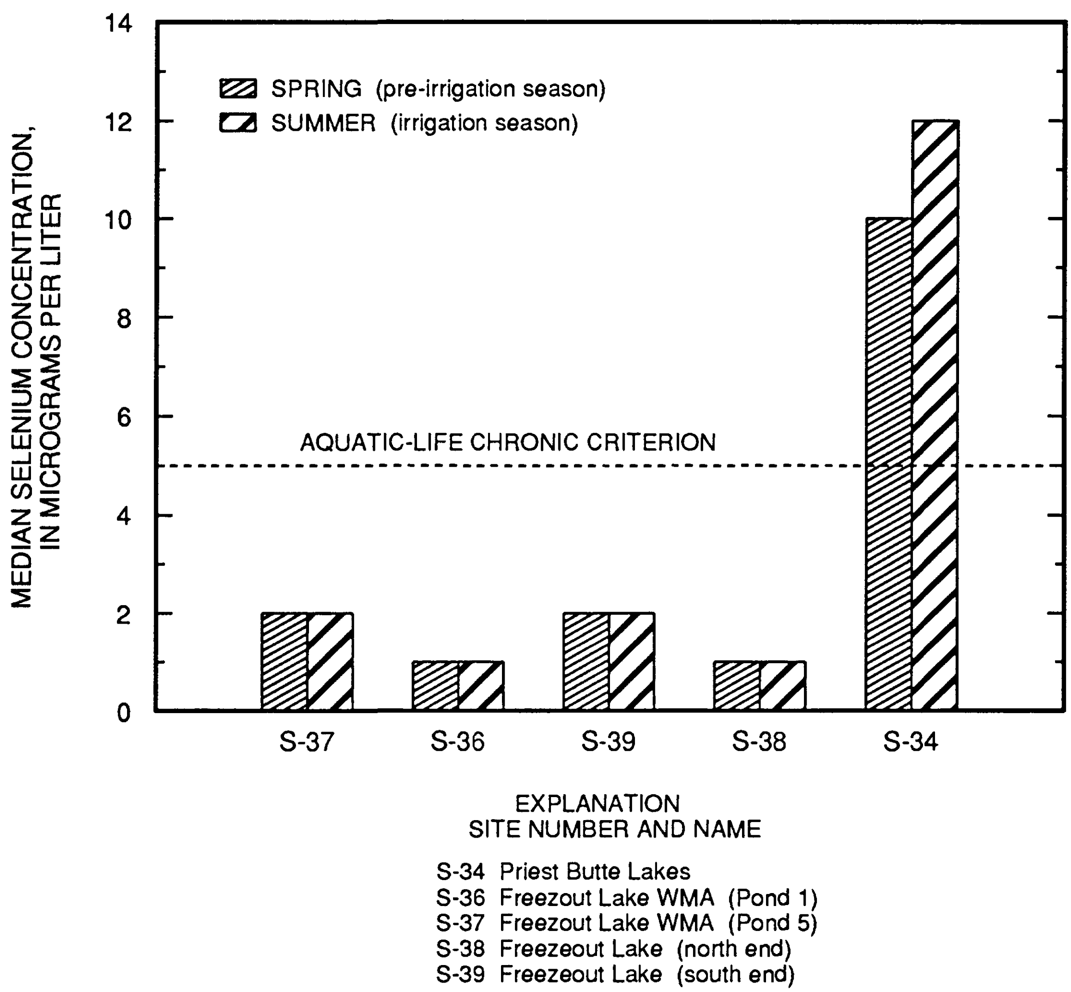


Figure 31. Median seasonal selenium concentration in water collected during 1991-92 from wetlands of Freezout Lake Wildlife Management Area, Montana. Sites are plotted in a general downstream direction.

were slight and showed no consistent pattern, even though the selenium concentration in several drains discharging to the wetlands was substantially higher during the spring pre-irrigation season when irrigation return flow consisted primarily of subsurface irrigation drainage. The consistently low selenium concentrations in the wetlands during hydrologically different seasons indicate that seasonally elevated concentrations in drains had minimal effect on the chemistry of water in the wetlands.

The only wetland in Freezout Lake WMA with selenium concentrations exceeding the chronic aquatic-life criterion was Priest Butte Lakes (site S-34). All samples from Priest Butte Lakes had concentrations exceeding the selenium chronic criterion of 5 µg/L, and the concentration in a sample in July 1991 (15 µg/L) was near the acute criterion of 20 µg/L. Almost all values of pH in the wetlands of Freezout Lake WMA were equal to or greater than the upper chronic criterion of 9.0, with a maximum pH of 9.9 in Freezeout Lake. The chronic criterion of 0.13 mg/L for ammonia was exceeded in one sample (0.20 mg/L) from Priest Butte Lakes in April 1991, but the median concentration for four samples (0.04 mg/L) was below the criterion.

Benton Lake Basin

Benton Lake receives natural runoff from the Lake Creek basin and small ephemeral tributaries draining the periphery of Benton Lake (fig. 22), water pumped from Muddy Creek, and direct precipitation on the lake. The pump station operated by the U.S. Fish and Wildlife Service commonly is used for up to several months each year to divert water from Muddy Creek (site S-21) through a pipeline over the drainage divide to the Lake Creek basin. This imported water flows down Lake Creek to Benton Lake NWR and supplements natural runoff to the wetlands. The amount of water pumped from Muddy Creek is variable from year to year and is governed, in part, by availability of funds in the refuge budget for electricity to operate the pumps. The quantity of natural surface runoff determines the need for pumped water and is evaluated annually. During the high runoff years of 1975 and 1978, no pumping occurred. Water from Muddy Creek typically is pumped to Lake Creek in late spring and again in late summer or early fall when natural runoff in Lake Creek is very small or absent.

Lake Creek

The drainage area of Lake Creek (61,400 acres) is about 66 percent of the total drainage area of Benton Lake (93,400 acres). On the basis of streamflow and pumping records, most of the water entering Benton Lake NWR during 1991-92 was pumped from Muddy Creek because of sparse runoff from the Benton Lake basin. Pumped water represented 94 percent of the flow conveyed past the gaging station on Lake Creek (site S-44) during the period. Streamflow in Lake Creek during periods of pumping generally ranged from 30-38 ft^3/s, compared to a typical base flow of 0.1 ft^3/s or less from natural runoff (Lambing and others, 1994, table 18). Average annual precipitation for 1991-92 at Great Falls was 14.2 in. compared to the 1951-80 long-term average of 15.2 in. Precipitation at Power, which is near the upper Lake Creek basin, averaged 12.6 in. for 1991-92 (National Oceanic and Atmospheric Administration, issued annually).

The water quality in Lake Creek during periods of pumping from Muddy Creek was very similar to the quality of irrigation return flow from gravel of the Greenfields Bench. The water in Lake Creek during pumping had a magnesium bicarbonate composition with a median dissolved-solids concentration of 420 mg/L. Selenium concentrations during pumping ranged from <1-3 µg/L, with a median concentration of 3 µg/L. No aquatic-life criteria were exceeded in samples from Lake Creek during periods that water from Muddy Creek was pumped to Benton Lake NWR.

During precipitation runoff in the upper Muddy Creek basin, a portion of the flow pumped to Lake Creek consists of runoff from the non-irrigated area north of the Greenfields Bench. This natural runoff may contain elevated selenium concentrations and thus temporarily cause increased concentrations in the water pumped to Benton Lake. No samples of pumped water from Muddy Creek were collected during times of runoff in the area north of the Greenfields Bench, but it is likely that periods of runoff from the ephemeral tributaries in the area would be short and presumably have little effect on the overall quality of water pumped to Benton Lake.

Natural runoff in Lake Creek is intermittent and had a magnesium-sodium sulfate composition. During periods of natural runoff, concentrations of constituents in Lake Creek generally were much higher than when pumped water was the primary or sole source of flow. Dissolved-solids concentrations in natural runoff ranged from about 1,000 mg/L during periods of snowmelt or rainfall runoff to about 13,000 mg/L during base flow (median of 9,920 mg/L). Values of pH in natural runoff from the Lake Creek basin (range of 5.1-6.6) were considerably lower than the pH (range of 8.3-8.9) in water pumped from Muddy Creek. Selenium concentrations in natural runoff ranged from 12 µg/L during precipitation runoff to 160 µg/L during base flow, with a median concentration of 90 μg/L. The water quality in Lake Creek during periods when precipitation runoff mixed with pumped water was characterized by concentrations intermediate to those of pumped water and natural runoff.

The low pH in natural runoff of the Lake Creek basin presumably results from acid produced by oxidation of sulfides in shale of the Colorado Group. However, some natural surface water in the basin is not acidic. Samples from a Lake Creek tributary (S-45) and a seep near Benton Lake (Knapton and others, 1988, site 24, p. 62) were alkaline, probably because these sites receive ground water from glacial drift rather than shale.

The quality of natural runoff in the Benton Lake basin is determined primarily by the quality of shallow ground water. Deep ground water probably is isolated from the shallow system, and discharge of deep ground water is not an important factor in generation of surface runoff. The connection between shallow ground water and surface runoff is supported by the similarity of major-ion composition, pH values, and concentrations of dissolved solids, nitrate, and selenium (table 7). The similarity in delta oxygen-18 and delta deuterium values (fig. 23) in samples of shallow ground water and Lake Creek base flow also demonstrate the probable connection between base flow and shallow ground water.

Constituent concentrations in natural runoff of the Benton Lake basin exceeded several aquatic-life criteria, sometimes by substantial margins. Although Lake Creek, ephemeral tributaries, and seeps in the basin generally do not support extensive aquatic communities, water from these sources potentially could impact biota residing in Benton Lake NWR. The acute criterion for selenium and the chronic criterion for ammonia were exceeded in more than 75 percent of samples of natural runoff from Lake Creek. A sample collected in 1986 from a saline seep (Knapton and others, 1988, site 25) that discharges directly to Benton Lake from non-irrigated farmland contained a zinc concentration of 19,000 μg/L that exceeded the acute criterion and a nickel concentration of 7,000 μg/L that exceeded the chronic criterion. Criteria for several trace elements also were exceeded in a tributary to Lake Creek (site S-43). Water from this site has low pH (about 4.5) and a sustained base flow of about 0.1-0.3 ft^3/s. Selenium concentrations at site S-43 (median of 660 μg/L) greatly exceeded the acute criterion of 20 μg/L in every sample. A water sample collected in 1986 at this site (Knapton and others, 1988) had constituent concentrations that exceeded acute criteria for chromium and zinc and the chronic criterion for cadmium.

Wetlands of Benton Lake National Wildlife Refuge

The water in Benton Lake has a magnesium-sodium sulfate composition. Dissolved-solids concentrations in 12 samples ranged from 516-7,740 mg/L, with a median of 2,090 mg/L. Higher concentrations occurred during the spring (pre-pumping) period and commonly decreased during the period when relatively dilute water was pumped into the refuge from Muddy Creek. A pattern of increasing salinity generally occurred in a general downstream direction from Pool 2 to Pools 3 and 5 (fig. 32); however, this pattern is irregular, possibly as a result of seasonal water-management operations. The greatest seasonal variability in dissolved-solids concentration was measured in Pools 3 and 5 of Benton Lake.

Based on stable-isotope data (Lambing and others, 1994, table 15; U.S. Geological Survey, unpub. data), surface water is affected by evaporation in the Benton Lake basin (fig. 23). Surface-water sites affected by evaporation plot closer to the upper right part of the graph and are enriched in deuterium and oxygen-18 relative to water not affected by evaporation. The delta deuterium and delta oxygen-18 values for samples from Benton Lake define evaporation lines for 1991 and 1992. If extended, these lines intersect the points representing pumped water in Lake Creek, thus indicating that pumped water probably was the primary source of the evaporated water in Benton Lake. This conclusion is supported by gaging records which verify that most of the inflow to Benton Lake in 1991 and 1992 was from pumped water.

Selenium concentrations in 14 water samples from Benton Lake ranged from <1-4 μg/L, with a median of <1 μg/L. Median concentrations in the wetlands of Benton Lake NWR (fig. 33) are much lower than those in the natural flows contributed by the Lake Creek basin and are even lower than the median selenium concentration (3 μg/L) in 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 inflows indicates that selenium is being removed from the water by biogeochemical processes.

In Benton Lake, pH was the only parameter that exceeded an aquatic-life criterion. The median pH was 9.3, with a maximum of 10.2 in Pool 2 (site S-47). Arsenic concentrations were elevated (range of 7-92 μg/L) in Pools 3 and 5 (sites S-48 and S-49) relative to the other pools of Benton Lake. The source of the arsenic is unknown, but the concentrations were below the chronic criterion of 190 μg/L.

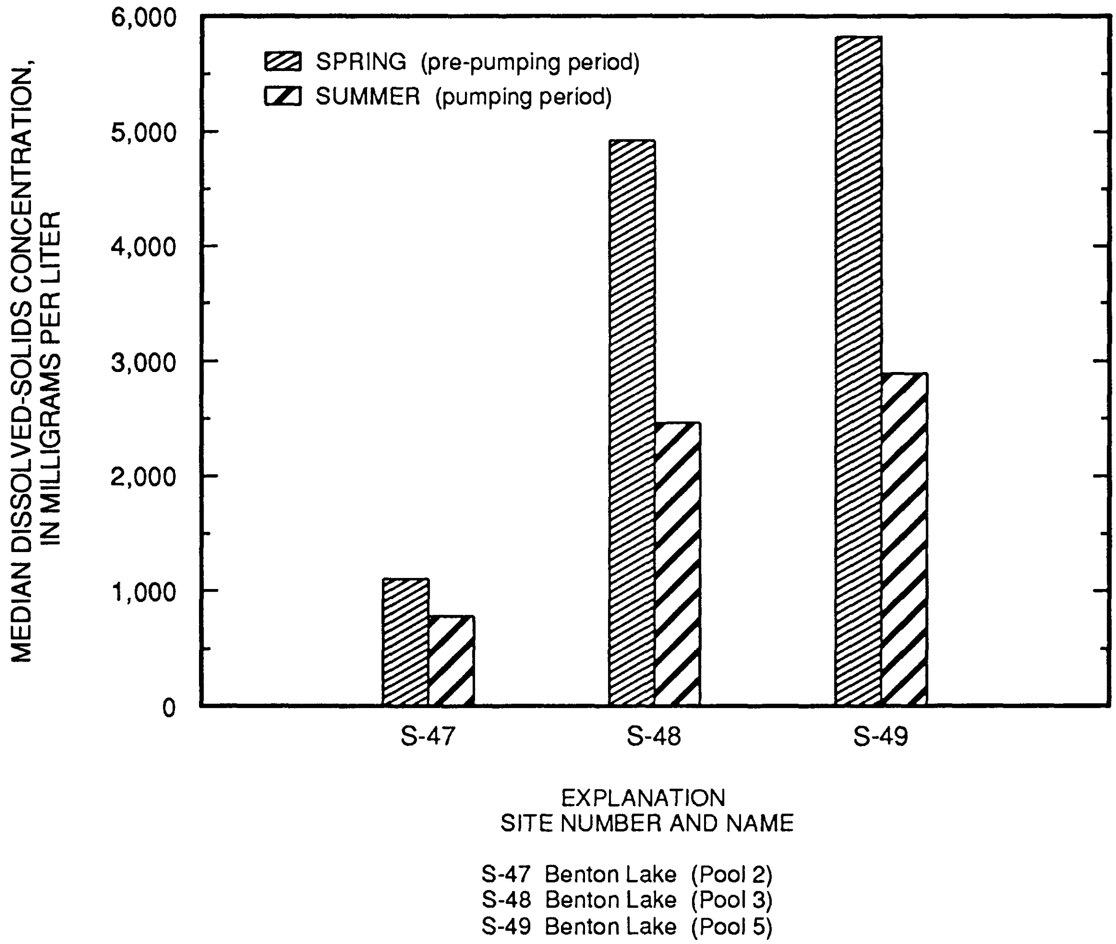


Figure 32. Median seasonal dissolved-solids concentration in water collected during 1991-92 from wetlands of Benton Lake National Wildlife Refuge, Montana. Sites are plotted in a general downstream direction.

Selenium Loads from Source Areas

Average annual selenium loads from all source areas contributing water to Freezout Lake WMA and Benton Lake NWR were estimated using available information for runoff quantities and water quality. Estimates were made for both irrigated and non-irrigated sources to provide a relative measure of loads derived from source areas of different land use and geology.

Freezout Lake Wildlife Management Area

Selenium loading to Freezout Lake WMA is only grossly estimated because of a lack of continuously recorded streamflow and water-quality data for the numerous drains and streams that discharge to the refuge. However, the estimates are informative in providing insight to the relative magnitude of selenium loads contributed from specific areas that represent various geologic settings and land-use practices.

Selenium Loads from Irrigated Land

Selenium loads from individual irrigated areas were estimated using seasonal averages for runoff quantities and selenium concentrations. The most distinct seasonal differences from a hydrologic perspective occur between the "irrigation" and the "non-irrigation" seasons. Therefore, the data used to estimate average flows and concentrations were segregated into the following two seasons—irrigation (May-September) and non-irrigation (October-April). The data were further segregated on the basis of geologic material underlying the irrigated land. Three subareas of irrigated land were evaluated that represent

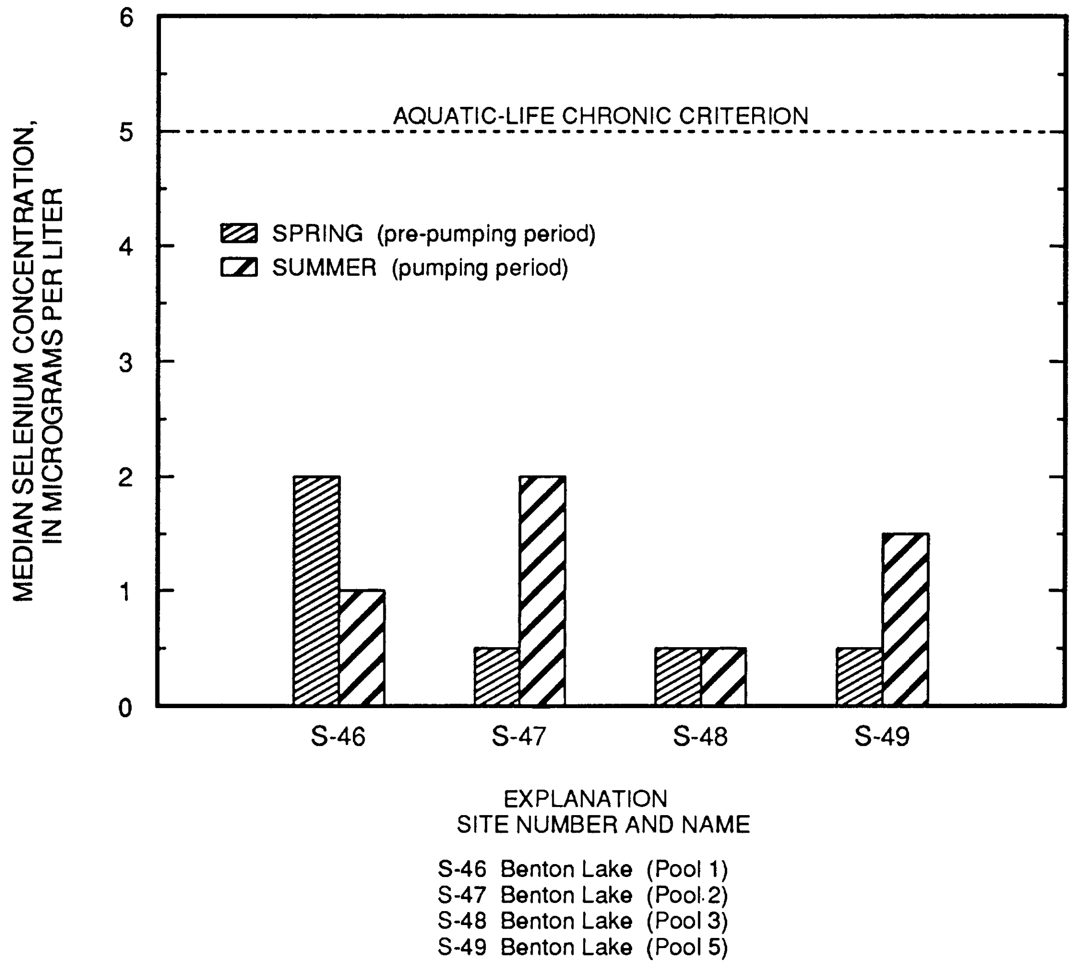


Figure 33. Median seasonal selenium concentration in water collected during 1991-92 from wetlands of Benton Lake National Wildlife Refuge, Montana. Sites are plotted in general downstream direction. Concentrations less than the minimum reporting level 1 microgram per liter are plotted at 0.5 microgram per liter.

different geologic materials and water-quality characteristics:

1. 1,820 acres underlain by gravel in the southwest corner of the Greenfields Bench,
2. 2,140 acres underlain by gravel in the northwest corner of the Greenfields Bench, and
3. 3,580 acres underlain by glacial deposits in the off-bench area south and east of Freezeout Lake.

Estimates of average annual irrigation-return-flow quantities and selenium concentrations for each season and geologic subarea were used to compute average annual selenium loading to Freezout Lake WMA from irrigated land. Estimates of average annual irrigation return flow from each subarea within the Greenfields Division were developed from data on total volume of irrigation water delivered to farms within a subarea and corresponding irrigation efficiency estimates (Jerry Nypen, Greenfields Irrigation District, written commun., 1993). Water-budget estimates for the Greenfields Bench (Osborne and others, 1983) were used to verify and refine the estimates of irrigation return flow. Estimated average annual irrigation-return-flow quantities were divided by the total irrigated acreage (Peter Schendel, Bureau of Reclamation, written commun., 1993) to determine a volumetric water yield, in acre-ft/acre, for each subarea. The average annual flow from each subarea was apportioned between each of the two seasons based on the relative magnitude of seasonal measurements of flow in irrigation drains made during1990-92.

Selenium concentrations used to estimate loads from each of the subareas were determined by segregating water-quality data by geologic setting. Numerous off-bench drains below the southwest and northwest corners of the Greenfields Bench carry irrigation return flow derived from both gravel and glacial deposits. Because the mixture of water draining from these two geologic sources displays wide variability in water-quality characteristics, the volumetric and chemical contribution from specific sources is difficult to determine. Therefore, selenium concentrations representative of each subarea were determined using data from sites that were known to drain only one geologic source. The geology-specific concentrations then were segregated by season to calculate average seasonal selenium concentrations for each subarea. Seasonal selenium concentrations and the corresponding seasonal irrigation-return-flow quantities were used to compute seasonal loads, which were summed to obtain an annual load for each subarea. Table 8 summarizes seasonal flow and selenium loading from each of the three irrigated subareas draining to Freezout Lake WMA.

Selenium Loads from Non-Irrigated Land

Estimates of selenium loads contributed to Freezout Lake WMA by natural runoff from non-irrigated land were made using limited data. Flow estimates were combined with available selenium concentrations from samples collected during 1991-92 to estimate annual selenium loads. The small number of samples and lack of samples representing high-flow conditions enable only gross estimates of selenium loading.

Average annual flow of natural streams draining basins west of Freezout Lake WMA (fig. 25) were estimated indirectly from channel geometry using methods described by Omang and others (1983). Flow estimates were made for the two primary non-irrigated basins draining to Freezeout Lake from the west—Roundup Coulee (site S-40) and an unnamed coulee draining the southwest part of the Freezeout Lake basin (site S-41). These two basins west of Freezeout Lake have a combined drainage area of 27,010 acres (42.2 mi^2). The estimated average annual runoff of Roundup Coulee (site S-40) is 280 acre-ft and that of the unnamed coulee southwest of Freezeout Lake (site S-41) is 160 acre-ft. The combined average annual flow (440 acre-ft) and drainage area (27,010 acres) for

Table 8. Estimated average annual selenium loads contributed to Freezout Lake Wildlife Management Area from irrigated land in the Greenfields Division of the Sun River Irrigation Project, Montana

[Abbreviations: acre-ft, acre feet; lbs, pounds; µg/L, micrograms per liter; I, irrigation season; NI, non-irrigation season. Symbols: <, less than; --, not applicable]

Location	Underlying geologic unit	Drainage area (acres)	Average seasonal flow (acre-ft)[1]		Average seasonal selenium concentration (µg/L)[2]		Average seasonal selenium load (lbs)		Average annual selenium load (lbs)	Average annual water yield (acre-ft/acre)	Average annual selenium yield (lbs/acre)
			I	NI	I	NI	I	NI			
Greenfields Bench, southwest corner	Quaternary and Tertiary(?) gravel	1,820	2,480	820	<1	2	3.4	4.5	8	1.8	0.004
Greenfields Bench, northwest corner	Quaternary and Tertiary(?) gravel	2,140	3,090	770	6	8	50	17	67	1.8	.03
Off-bench area south and east of Freezeout Lake	Quaternary glacial deposits	3,580	4,850	1,620	49	110	650	480	1,130	1.8	.3
TOTAL		7,540	10,420	3,210	--	--	703	502	1,205	--	--

[1]Flow estimates are based on a combination of 1991-92 irrigation statistics (Jerry Nypen, Greenfields Irrigation District, written commun., 1993) and hydrologic budget estimates for 1982 (Osborne and others, 1983).

[2]Concentration estimates are based on samples collected during 1986 (Knapton and others, 1988) and 1990-92 (Lambing and others, 1994).

these two basins results in an average annual water yield of 0.016 acre-ft/acre. Extrapolating this unit-area water yield to the entire drainage area of 45,700 acres west of Freezout Lake WMA results in a total annual runoff of 730 acre-ft. The selenium concentration in runoff from the west side of Freezeout Lake was assumed to be 1 µg/L, based on the range of concentration (<1-2 µg/L) in five samples from S-40 and S-41.

Estimates of natural flow from non-irrigated areas east of Freezout Lake WMA and north of the Greenfields Bench were extrapolated from sparse data for a nearby tributary to Muddy Creek (site S-18). Average annual flow and average selenium concentrations were extrapolated from this tributary because of areal proximity and similarity in geology, precipitation, and land use. An average annual water yield of 0.015 acre-ft/acre was estimated for the tributary to Muddy Creek using channel geometry methods (Omang and others, 1983) and applied to the drainage area of 23,700 acres contributing flow to Freezout Lake WMA. This computation results in an average annual flow estimate of 360 acre-ft from non-irrigated land east of the refuge, most of which flows to Pond 1. An average selenium concentration of 91 µg/L was computed on the basis of two samples (2 and 180 µg/L) collected during 1991. The estimates of average annual flow and selenium load from the non-irrigated area east of Freezout Lake WMA does not include the discharge from the seep (site S-35) east of Priest Butte Lakes.

The seep east of Priest Butte Lakes drains an area of 2,100 acres. Annual flow of the seep was estimated by averaging seasonal flow measurements made during 1991-92. Flow at this site was small (average of about 0.1 ft^3/s) but relatively constant throughout the year; thus, averaging of periodic flow determinations probably provides a reasonable estimate of average annual flow. The average annual flow converted to a unit-area water yield is 0.034 acre-ft/acre. This water yield is about double that of nearby non-irrigated land, presumably because of alternate crop-fallow farming in the basin that increases infiltration of precipitation. The average selenium concentration for five samples collected during 1991-92 was 880 µg/L.

A summary of estimated selenium loads contributed to Freezout Lake WMA from non-irrigated land is presented in table 9. Because of uncertainty associated with estimates based on ungaged flow determinations and limited water-quality data, the estimated loads in table 9 are intended only for relative comparisons to loads contributed from irrigation drainage. The total average annual selenium load to Freezout Lake WMA is 1,469 lbs; 1,205 lbs came from irrigated source areas (table 8) and 264 lbs came from non-irrigated source areas (table 9).

Relative Importance of Selenium Source Areas

The percentage of average annual selenium loads contributed from various source areas to Freezout Lake WMA is shown in figure 34. Return flow from irrigated land contributes an estimated 82 percent of the average annual selenium load to Freezout Lake WMA. Return flow from irrigated glacial deposits accounts for about 77 percent of the total annual load and is the single most important source of selenium contributed to Freezout Lake WMA. Although the volume of runoff from glacial deposits is slightly less than the runoff from irrigated gravel on the Greenfields Bench, sele-

Table 9. Estimated average annual selenium loads contributed to Freezout Lake Wildlife Management Area from non-irrigated land in the Sun River area, Montana

[Abbreviations: acre-ft, acre-feet; lbs, pounds; µg/L, micrograms per liter. Symbol: --, not applicable]

Location (fig. 25)	Underlying geologic unit	Drainage area (acres)	Average annual flow (acre-ft)	Average selenium concentration (µg/L)	Average annual selenium load (lbs)	Average annual water yield (acre-ft/acre)	Average annual selenium yield (lbs/acre)
West of Freezout Lake WMA	Upper Cretaceous Montana Group	45,700	730	1	2	0.016	0.00004
East of Freezout Lake WMA	Quaternary glacial deposits	23,700	360	91	90	.015	.004
Seep east of Priest Butte Lakes	Quaternary glacial deposits	2,100	72	880	172	.034	.08
TOTAL		71,500	1,162	--	264	--	--

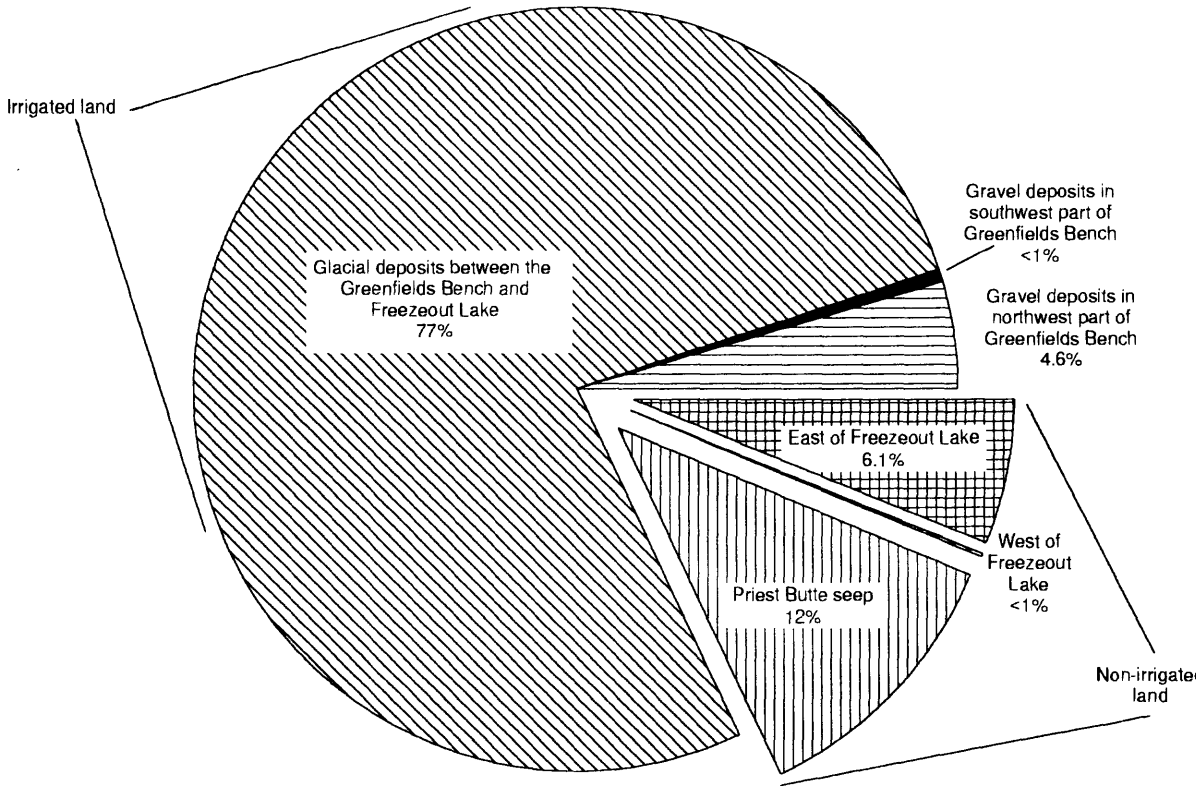


Figure 34. Percentage of total estimated annual selenium load discharged to Freezout Lake Wildlife Management Area, Montana, from irrigated and non-irrigated land.

nium concentrations in irrigation return flow from glacial deposits were 6-100 times greater than in return flow from gravels. Although dilution from direct spills lowers selenium concentrations during the irrigation season, selenium loads from irrigated glacial deposits are substantial during both the irrigation and non-irrigation seasons. Consequently, the selenium yield per acre is much higher from irrigated glacial deposits than from irrigated gravel on the Greenfields Bench. Return flow from irrigated land on the Greenfields Bench contributes only about 5 percent of the total selenium load to Freezout Lake WMA. Of this small amount of selenium derived from the Bench, almost 90 percent comes from the northwest corner, where selenium concentrations were higher than in the southwest corner (table 8).

Natural runoff from non-irrigated land contributes about 18 percent of the total selenium load to Freezout Lake WMA but only about 8 percent of the total inflow. Because of high selenium concentrations, the seep east of Priest Butte Lakes was the major source of selenium discharged to Freezout Lake WMA from non-irrigated land. The seep supplies almost 12 percent of the total selenium load to the refuge while contributing only 0.5 percent of the total inflow. Runoff from other non-irrigated land east of Freezout Lake WMA contributes about 6 percent of the total selenium load, whereas runoff from the non-irrigated area west of Freezout Lake WMA contributes only 0.1 percent.

Although information on selenium loads helps to identify the source areas contributing the most selenium to wetlands, data on selenium yields may provide a better understanding of the potential response to water management. Unit-area selenium yields, which are expressed as pounds of selenium produced per acre, are a function of both selenium content in geologic materials and the quantity of water moving through the soil and underlying materials. Selenium yields estimated in this study indicate that irrigated glacial deposits contribute from 10-75 times more selenium, per acre, than irrigated gravel under conditions of similar water yield (table 8). The selenium yield from the seep east of Priest Butte Lakes (table 9), which is in a non-irrigated area but also underlain by glacial deposits, is slightly higher than the yield from the northwest corner of the Greenfields Bench, even though water yield from the northwest corner of the Bench is 50 times greater than that of the seep (table 9).

Because return flow from irrigated land is the primary source of selenium loading to the wetlands of Freezout Lake WMA, an attempt was made to more clearly identify the annual loads transported to specific wetlands in the central and southern part of the refuge. The total load contributed from each irrigated subarea was apportioned among the individual wetlands on the basis of irrigated drainage area contributing flow to each wetland. A summary of estimated selenium loads discharged from irrigated land to specific wetlands of Freezout Lake WMA is given in table 10.

A generalized map showing the spatial distribution of estimated average annual selenium loads contributed to wetlands of Freezout Lake WMA from individual source areas is shown in figure 35. The annual loads contributed from irrigated land to Freezout Lake WMA are distributed among three primary wetland areas in generally similar quantities, with the south end of Freezeout Lake and Pond 5 each receiving nearly equal amounts of selenium (428 and 451 pounds, respectively). Pond 5 has a substantially smaller surface area (140 acres) than the south end of Freezeout Lake (650 acres) and therefore has less capacity to disperse the incoming selenium load. Pond 1, with a surface area of about 360 acres, receives an average of 326 pounds of selenium annually. The selenium loads entering individual wetlands can be informative in understanding subsequent processes affecting selenium concentrations in the water, bottom sediment, and biota of the wetlands.

Benton Lake National Wildlife Refuge

Selenium loads to Benton Lake NWR can be reasonably quantified because the majority of flow to the refuge is conveyed through Lake Creek. Long-term average annual natural runoff to Benton Lake from its drainage basin of 93,400 acres (146 mi^2) was calculated from lake-stage data collected by the U.S. Fish and Wildlife Service for the period 1970-91 (Stephen J. Martin, U.S. Fish and Wildlife Service, written commun., 1992). These data were collected after runoff events and were used in conjunction with stage-capacity curves of the Benton Lake pools to calculate total runoff into Benton Lake. Average annual long-term natural runoff from the entire Benton Lake basin was estimated to be 3,550 acre-ft. The reliability of this estimate is supported by a predictive equation, applicable to central and eastern Montana (Omang and Parrett, 1984), which resulted in a similar estimate of 3,110 acre-ft.

Based on the Lake Creek part (66 percent) of the total Benton Lake drainage area, the estimated average annual natural runoff for the 61,400-acre (96 mi^2) Lake

Table 10. Estimated average annual selenium load contributed to individual wetlands in the central and southern part of Freezout Lake Wildlife Management Area from irrigated land in the Greenfields Division of the Sun River Irrigation Project, Montana

[Abbreviation: lbs, pounds. Symbol: --, not applicable]

Wetland (fig. 35)	Surface area of wetlands (acres)	Irrigated gravel		Irrigated glacial deposits		Total selenium load to wetland (lbs)	Percent of total selenium load from irrigated land
		Drainage area (acres)	Selenium load (lbs)	Drainage area (acres)	Selenium load (lbs)		
Freezeout Lake (south end)	650	1,820	8	1,330	420	428	36
Freezout Lake WMA (Pond 1)	360	820	26	950	300	326	27
Freezout Lake WMA (Pond 5)	140	1,320	41	1,300	410	451	37
TOTAL	--	3,960	75	3,580	1,130	1,205	100

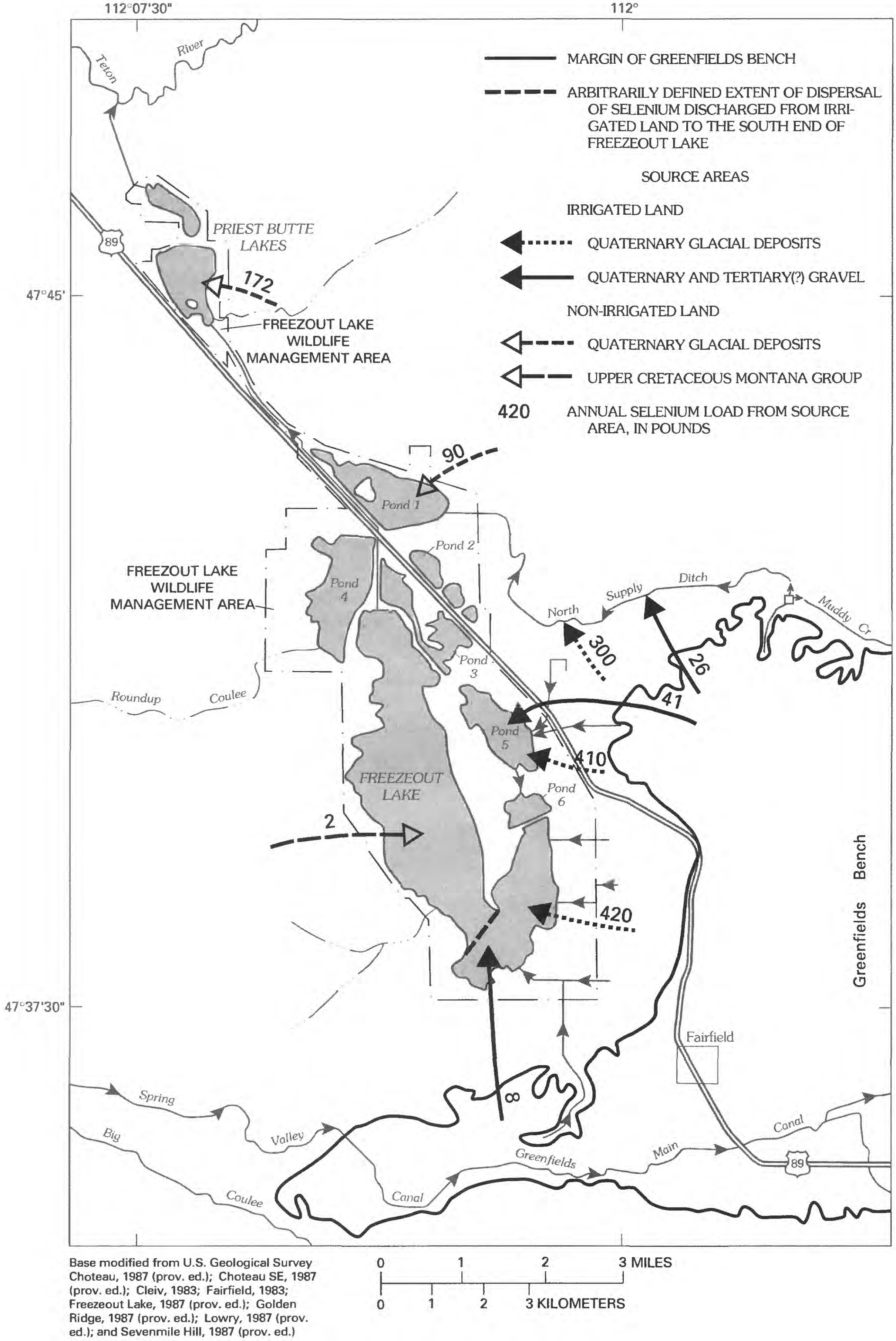


Figure 35. Areal distribution of estimated average annual selenium load discharged to Freezout Lake Wildlife Management Area, Montana, from irrigated and non-irrigated land.

Creek basin is 2,340 acre-ft. The average annual natural runoff measured for the 47,900 acres of drainage area at the Lake Creek gage (site S-44) during 1991-92 was much less (412 acre-ft) than the estimated long-term average runoff. Extrapolating the average quantity of natural flow measured at the Lake Creek gage during 1991-92 to the entire Benton Lake basin results in an estimated 803 acre-ft of natural runoff for the entire basin. Natural runoff for the study period therefore represented only 23 percent of the long-term average annual natural runoff to Benton Lake.

The average annual volume of pumped water during 1991-92 was 6,750 acre-ft, compared to the long-term average annual volume of 4,250 acre-ft estimated from pumping records of the NWR (Steve Martin, U.S. Fish and Wildlife Service, written commun., 1992). The volume of water pumped during the study period, therefore, was about 160 percent of normal.

Based on estimates of 3,550 acre-ft of natural runoff and 4,250 acre-ft of pumped water from Muddy Creek, long-term average annual inflow to Benton Lake is 7,800 acre-ft. Natural runoff constitutes, on average, about 46 percent of the total annual runoff to Benton Lake and pumped water constitutes about 54 percent. The proportions and magnitudes of natural runoff are highly variable from year to year. During 1991-92, natural runoff, on average, constituted only 10 percent of the total annual runoff to Benton Lake.

Because Lake Creek conveys about half of the natural runoff in the Benton Lake basin and all of the pumped water, selenium loads measured at the Lake Creek gage (site S-44, fig. 25) probably represent most of the total selenium load discharged to Benton Lake. However, some additional selenium is transported to Benton Lake by natural runoff from that part of the Benton Lake basin downstream from the Lake Creek gage. Selenium loads transported past the Lake Creek gage at site S-44 were quantified for the period of daily streamflow record (March 1991-September 1992).

A best-fit linear regression of log-transformed specific conductance and selenium concentrations (fig. 36) was developed using samples collected from Lake Creek during 1990-92. A record of daily mean specific

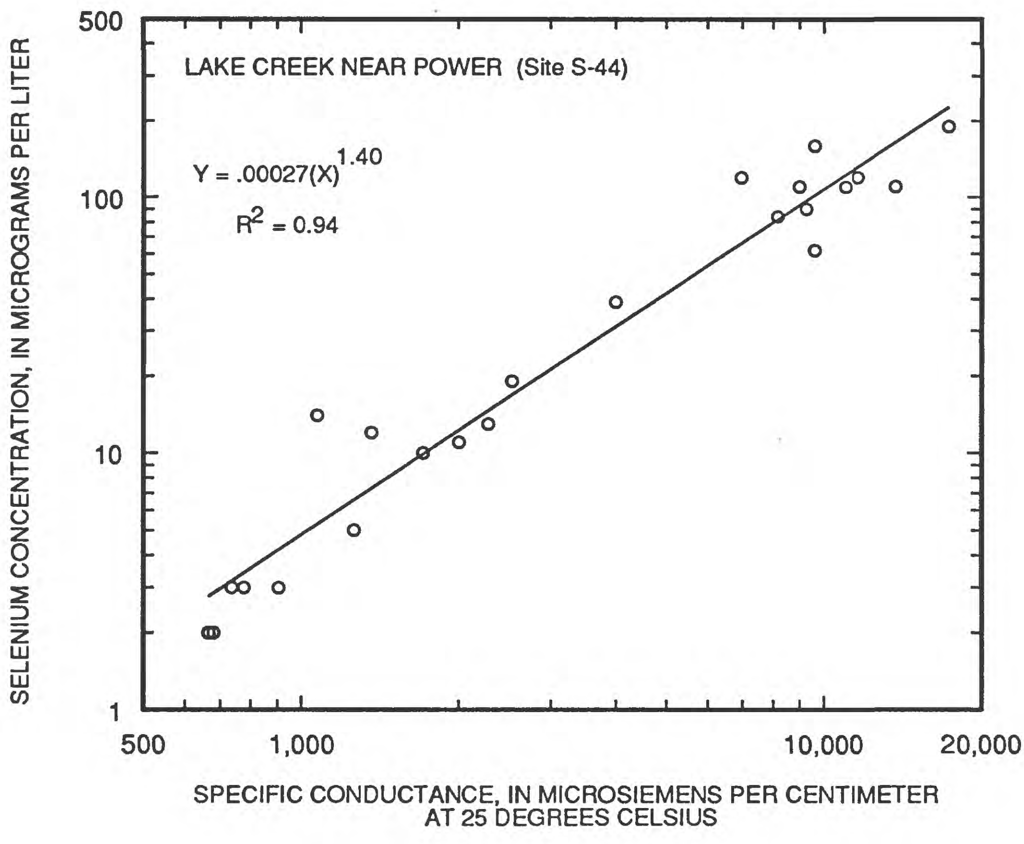


Figure 36. Relation of specific conductance (X) to selenium concentration (Y) in water collected during 1990-92 from Lake Creek near Power, Montana.

conductance was constructed for March 1991-September 1992 on the basis of periodic samples and an hourly recording conductivity meter (installed March 1992). The regression relation between specific conductance and selenium concentration was applied to the daily conductance record to estimate daily mean selenium concentrations. These estimated selenium concentrations were multiplied by daily mean streamflow and a units-conversion factor to compute daily selenium loads at the Lake Creek gage.

Daily selenium loads discharged to Benton Lake past the Lake Creek gage (site S-44) were summed for the period March 1991-September 1992. Pumping records for the NWR enabled segregation of natural-flow and pumped-flow periods so that selenium loads could be determined for each of the two sources of flow. Pumped water, which represented 94 percent of the total water volume passing the gage during 1991-92, consisted almost entirely of irrigation return flow from the Greenfields Bench. An average annual selenium load of 55 lbs was transported by pumped water past the Lake Creek gage during 1991-92. Natural runoff during 1991-92 accounted for only 6 percent of the total flow at the Lake Creek gage during the period, but contributed an average annual selenium load of 21 lbs. Extrapolating the 21 lbs of selenium transported by natural runoff past the Lake Creek gage to the total drainage area of the Benton Lake basin results in an average annual selenium load of 41 lbs contributed during 1991-92 by natural runoff. The estimates of average annual selenium load from pumped water (55 lbs) and natural runoff (41 lbs) results in an average annual load of 96 lbs of selenium entering Benton Lake during 1991-92.

Long-term estimates of natural runoff and pumped water volumes are based on 22 years (1970-91) of data. Long-term average selenium concentrations, however, are based on a limited number of samples collected during 1990-92. Because natural runoff was sparse during 1990-92, samples were collected predominantly during base flow when concentrations were high and flow volumes were minimal. To minimize bias of long-term load estimates, selenium concentrations for natural flow were discharge-weighted prior to averaging in order to account for variation of concentrations with flow magnitude. Long-term average selenium concentration in pumped water from Muddy Creek was assumed to be the same as the average concentration during the study period. A summary of estimated long-term average annual flows and selenium loads contributed to Benton Lake NWR is provided in table 11.

The average annual selenium load pumped from Muddy Creek during 1991-92 (55 lbs) was larger than the long-term average annual pumped load (35 lbs, table 11) because of increased pumping. The average annual load (41 lbs) transported by natural runoff in the Benton Lake basin during 1991-92 was substantially smaller than the estimated long-term average annual selenium load contributed by natural runoff (135 lbs). During 1991-92, natural runoff in the Benton Lake basin contributed only 43 percent of the total annual selenium load to Benton Lake NWR whereas natural runoff during 1970-91 is estimated to have contributed 79 percent of the total. Therefore, although data collected during 1991-92 indicate that irrigation return flow pumped from Muddy Creek was the largest contributor of selenium load to Benton Lake, long-term estimates for 1970-91 provide evidence that natural runoff from the non-irrigated Benton Lake basin is the major source of selenium loading to Benton Lake NWR.

Table 11. Estimated average annual selenium loads contributed to Benton Lake National Wildlife Refuge by natural runoff from the Benton Lake basin and water pumped from Muddy Creek

[Abbreviations: acre-ft, acre-feet; lbs, pounds; µg/L, micrograms per liter. Symbol: --, not applicable]

Source	Drainage area (acres)	Average annual flow (acre-ft)[1]	Average selenium concentration (µg/L)	Average annual selenium load (lbs)	Average annual water yield (acre-ft/acre)	Average annual selenium yield (lbs/acre)
Natural runoff from Benton Lake basin	93,400	3,550	[2]14	135	0.037	0.001
Water pumped from Muddy Creek	--	4,250	3	35	--	--
TOTAL	--	7,800	--	170	--	--

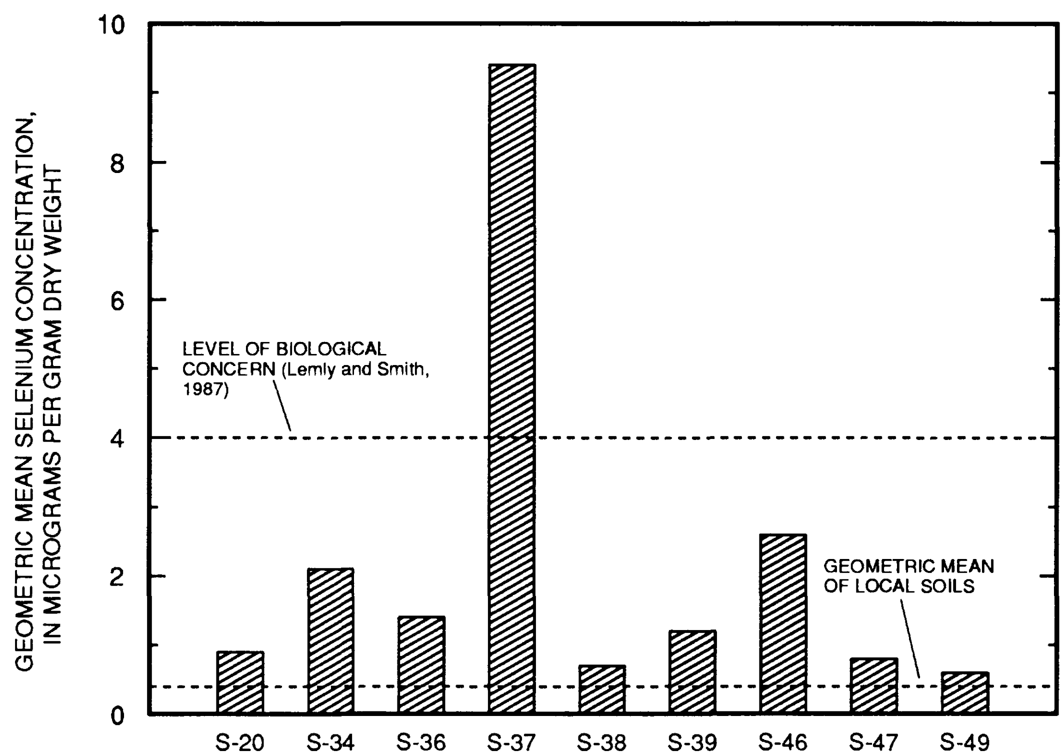
[1]Base period for average annual flow estimates is 1970-91 (Steve Martin, U.S. Fish and Wildlife Service, written commun., 1992).

[2]Average selenium concentrations were estimated from discharge-weighted concentrations for samples of natural runoff collected during 1990-92 (Lambing and others, 1994).

Chemical Characteristics of Bottom Sediment

Selenium concentrations in bottom-sediment samples in wetlands of Freezout Lake WMA and Benton Lake NWR ranged from 0.6 to 11 µg/g. Geometric mean selenium concentrations in bottom-sediment samples collected during both the reconnaissance study (Knapton and others, 1988, table 16) and this detailed study (Lambing and others, 1994, table 20) are shown in figure 37. All samples had selenium concentrations slightly to substantially higher than the geometric mean concentration (0.4 µg/g) for soils in and near Freezout Lake WMA. Two samples from the same site had selenium concentrations that exceeded 4 µg/g. Lemly and Smith (1987) suggested that concentrations of 4 µg/g or higher pose a concern for fish and wildlife because of possible food-chain bioaccumulation.

The enrichment of selenium in bottom sediment relative to source sediments of the basin presumably is caused by transfer of selenium from water to bottom sediment by biogeochemical processes. Bottom-sediment samples from most wetland sites were black, organic-rich, and presumably anaerobic, with the possible exception of a thin, surficial oxidized layer. Selenium species that tend to occur in anaerobic, reducing environments are virtually insoluble and likely to remain bound to the bottom sediment. Although each bottom-sediment sample was a composite mixture of



EXPLANATION
SITE NUMBER AND NAME

S-20 Muddy Creek near Power
S-34 Priest Butte Lakes
S-36 Freezout Lake WMA (Pond 1)
S-37 Freezout Lake WMA (Pond 5)
S-38 Freezeout Lake (north end)
S-39 Freezeout Lake (south end)
S-46 Benton Lake (Pool 1)
S-47 Benton Lake (Pool 2)
S-49 Benton Lake (Pool 5)

Figure 37. Geometric mean selenium concentration in bottom sediment collected during 1986-92 from Muddy Creek and wetlands in the Sun River area, Montana.

5-10 samples collected in the vicinity of the surface-water sampling site, the samples may not adequately represent the spatial variability of selenium concentrations in bottom sediment if distinct concentration gradients exist outward from the mouths of drains or other surface inflows.

The selenium concentration in bottom sediment probably is a function of both the amount of selenium entering the wetland and the surface area available for dispersal and deposition of selenium that has been converted to solid-phase forms. Although spatial variability may be poorly defined by the relatively few bottom-sediment samples that were collected, a pattern of higher selenium concentrations in the bottom sediment of wetlands that receive larger selenium loads relative to their surface area is apparent. The wetland area at the south end of Freezeout Lake receives an estimated 0.7 lb/acre and Pond 1 receives an estimated 0.9 lb/acre of selenium annually. The similar loads per surface area of wetland results in similar selenium concentrations in the bottom sediment (geometric mean selenium concentration of 1.2 µg/g in the south end of Freezeout Lake and 1.4 µg/g in Pond 1). The highest selenium concentration (geometric mean of 9.4 µg/g) in bottom sediment occurred in Pond 5 (site S-37), which receives the highest estimated annual selenium load relative to wetland surface area (3.2 lbs/acre) of the Freezout Lake WMA wetlands. This was the only site having selenium concentrations that exceeded the 4 µg/g concentration representing possible biological risk (Lemly and Smith, 1987). The wetland with the lowest selenium concentration (0.7 µg/g) in bottom sediment was the north end of Freezeout Lake (S-38), which is a large distance from irrigation-return-flow inputs. This low selenium concentration is consistent with the hypothesis of a decreasing concentration of selenium in bottom sediment with distance from the mouths of surface inflows.

Priest Butte Lakes (S-34), which receive no direct irrigation return flow but do receive an estimated 172 lbs of selenium annually from a single seep, had the second highest selenium concentration (geometric mean of 2.1 µg/g) in bottom sediment of Freezout Lake WMA. The estimated annual selenium load per surface area of the south part of Priest Butte Lakes (0.5 lb/acre) is smaller than that for wetlands in the central and southern part of Freezout Lake WMA; consequently, a lower concentration in the bottom sediment of Priest Butte Lakes might be expected. The higher selenium concentration indicates an inconsistency in the relation between selenium load and selenium concentration in bottom sediment compared to the other wetlands. This anomaly may result from either a significant underestimation of selenium load contributed to Priest Butte Lakes from non-irrigated land, sampling variability if spatial concentration gradients exist, or a higher initial selenium concentration in bottom sediment prior to the beginning of agricultural activities in the area.

Proximity of bottom sediment to localized inputs also seems to be important in Benton Lake. Selenium concentrations in bottom sediment decrease in a downstream direction, from Pool 1 to Pool 2 to Pools 3-6. (Pools 3-6 are considered equivalent because each of these pools receives water from Pool 2 and because water transfers between Pools 3-6 are rare.) The decrease in concentration could result from a large portion of the selenium load from Lake Creek being incorporated into the bottom sediment of Pool 1 (site S-46, geometric mean concentration of 2.6 µg/g) near the mouth of Lake Creek. A strong spatial gradient of selenium concentration is evident in Pool 1 along transects starting at the mouth of Lake Creek (Johnnie Moore, University of Montana, written commun., 1994). Although most dissolved selenium discharged by Lake Creek is removed from solution to the bottom sediment in Pool 1, some is flushed to Pool 2 (S-47), where moderate enrichment of selenium (geometric mean concentration of 0.8 µg/g) in bottom sediment has occurred. Water leaving Pool 2 generally has very little dissolved selenium and therefore bottom sediments in Pools 3-6 were less enriched in selenium (geometric mean concentration of 0.5 µg/g) than sediment in the upgradient pools.

Processes Affecting Selenium Concentrations in Wetlands

The two most notable features of selenium concentrations in the wetlands of the study area are (1) lower selenium concentrations in the water of most wetlands relative to concentrations in water that drains to the wetlands and (2) the elevated concentrations of selenium in Priest Butte Lakes relative to the other wetlands. Factors potentially affecting constituent concentrations in wetlands include physical or biogeochemical processes, evaporative concentration, and constituent loading from various source areas.

The lower dissolved-selenium concentrations in most wetlands compared to water that drains to the wetlands is consistent with selenium enrichment in bottom sediment as observed in this and other studies where loss of dissolved selenium from lakes through biogeochemical mechanisms is common (Lemly and Smith, 1987). 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, 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).

In arid and semiarid climates, evaporative concentration is a major control on water composition (Drever, 1988). Ratios of stable isotopes of hydrogen and oxygen (figs. 12 and 23) show that evaporative concentration occurs in wetlands of the Sun River area. The increase in dissolved-solids concentrations that occurs as water moves downstream through wetlands (figs. 30 and 32) presumably is caused by evaporation.

The effect of evaporation on selenium concentrations in wetlands can be evaluated by relations between selenium and chloride concentrations. Chloride is a relatively conservative element and, therefore, chloride concentrations tend to increase at a constant rate during evaporative loss of water. If selenium were equally conservative, chloride and selenium concentrations would increase at a similar rate during evaporation. Theoretical evaporative-concentration lines can be derived by calculating the median concentration of selenium and chloride in the predominant water supply for the wetlands and projecting a line of unit slope to indicate expected concentration increases resulting from equal rates of evaporative water loss. Paired values of selenium and chloride concentrations that fall on or near the line indicate that the observed concentrations could result simply from evaporation of the initial supply water. Deviations from the evaporative-concentration line may indicate that processes other than evaporation have caused either gains or losses of selenium. Values that plot above the line indicate dissolved-selenium enrichment in water that is most likely caused by additional inputs. Values that plot below the line indicate a loss of dissolved selenium from the water.

Because irrigation return flow supplies the bulk of water to Freezout Lake WMA, an evaporative-concentration line (fig. 38) was derived from the median concentration of chloride (13 mg/L) and selenium (8 µg/L) for mixed irrigation return flow from gravel and glacial deposits. These water-quality characteristics are intermediate to those of either individual source and probably best represent the average quality of water entering Freezout Lake WMA. Samples from most sites in Freezout Lake WMA plot well below the evaporation line, indicating a loss of selenium from the water rather than an increase in concentration that would be expected to result from evaporation.

A separate evaporative-concentration line for Priest Butte Lakes (fig. 39) was derived to specifically evaluate selenium concentrations measured in this wetland relative to theoretical effects of evaporation because Priest Butte Lakes primarily receive water from the north end of Freezeout Lake rather than from direct inputs of irrigation drains. This evaporation line is based on initial concentrations of 150 µg/L of chloride and 1 µg/L of selenium measured in Freezeout Lake. All of the paired selenium-chloride concentrations for Priest Butte Lakes plot well above the evaporative-concentration line. This relation indicates that processes other than evaporation, such as local inputs, are causing an increase in selenium concentrations in Priest Butte Lakes. The potential for local inputs are evidenced by salt crusts along the shoreline, indicating seepage from adjacent land. One seep in particular (site S-35) that drains into Priest Butte Lakes from non-irrigated land has a small, but generally sustained, flow and extremely high concentrations of selenium. The unique quality of inflow from this seep warranted examination of its potential individual impact on the selenium concentration in Priest Butte Lakes.

The potential for the selenium load contributed by the seep east of Priest Butte Lakes to cause the elevated selenium concentrations in the water of Priest Butte Lakes was evaluated using several simplifying assumptions. Based on a surface area of 480 acres and an estimated average depth of 7 ft (Mark Schlepp, Montana Department of Fish, Wildlife and Parks, written commun., 1993), the volume of Priest Butte Lakes was estimated to be 3,360 acre-ft. If the lake volume is assumed to be constant and the lake water is assumed to have an initial selenium concentration equivalent to that of the inflow from the north end of Freezeout Lake (1 µg/L), then 172 lbs of selenium from the seep added to a volume of 3,360 acre-ft of water containing 1 µg/L would result in a selenium concentration of about 20 µg/L. Measured selenium concentrations in Priest Butte Lakes (site S-34) ranged from 9-15 µg/L during 1991-92. The estimated selenium concentration in the lakes resulting from the seep's selenium load is slightly larger than measured concentrations, but it clearly indicates that a small, but concentrated, source of selenium could be the primary cause for elevated concentrations in Priest Butte Lakes. Considering that the selenium load contributed by the seep in a single year can produce the observed concentrations in the lakes, multiple years of loading would greatly elevate selenium concentrations in the water if most of the load were not removed either through flushing or incorporation into bottom sediment or biota.

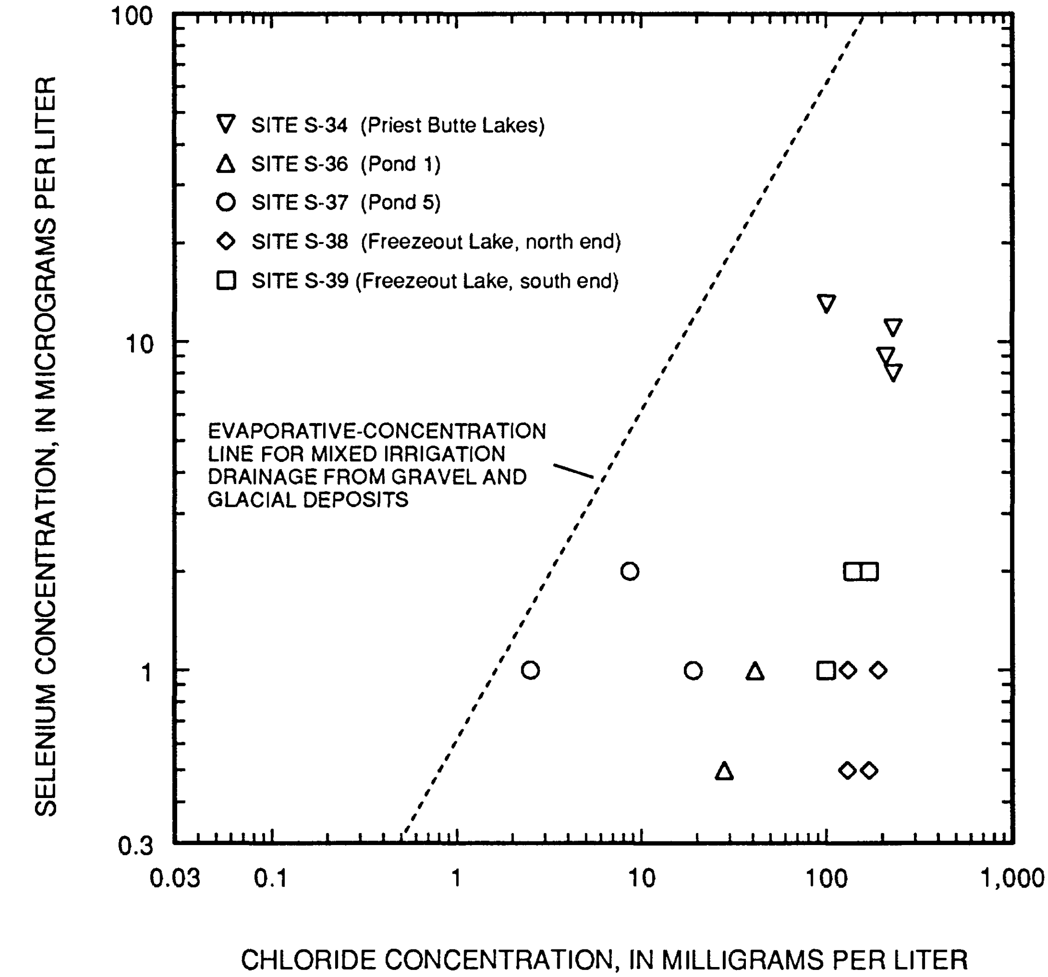


Figure 38. Selenium and chloride concentrations in water of wetlands of Freezout Lake Wildlife Management Area and theoretical evaporative concentration of irrigation return flow from the Sun River area, Montana. Concentrations less than the minimum reporting level (1 microgram per liter) are plotted as 0.5 microgram per liter.

The process causing the conversion of dissolved selenium to immobile forms in Priest Butte Lakes appears to be inconsistent with other wetlands in Freezout Lake WMA. Because water in this wetland has higher selenium concentrations even though it receives a smaller annual selenium load than other wetlands, different conversion processes or rates of conversion presumably are occurring. The reasons for these differences are uncertain.

An evaporative-concentration line for Benton Lake NWR (fig. 40) was derived based on the primary water supply during 1990-92, which was water pumped from Muddy Creek that consisted mostly of irrigation return flow. The evaporative-concentration line is based on median concentrations of 8 mg/L of chloride and 3 µg/L of selenium measured in Muddy Creek during times of pumping. All samples from Benton Lake plot below the line, indicating that selenium is being removed from the water. Even though intermittent natural runoff to the lake contains high selenium concentrations, the water in Pool 1 of Benton Lake had consistently low selenium concentrations at site S-46, which was only a short distance from the mouth of Lake Creek. The lack of an outlet that could provide flushing from Benton Lake presumably would contribute to substantial evaporative concentration and accumulation of selenium in the water. Ground-water information from two boreholes at Benton Lake indicates that no significant discharge of water occurs through the lake beds, thus precluding the possibility that selenium is lost by seepage into the ground-water system. Consequently, the selenium loss from the

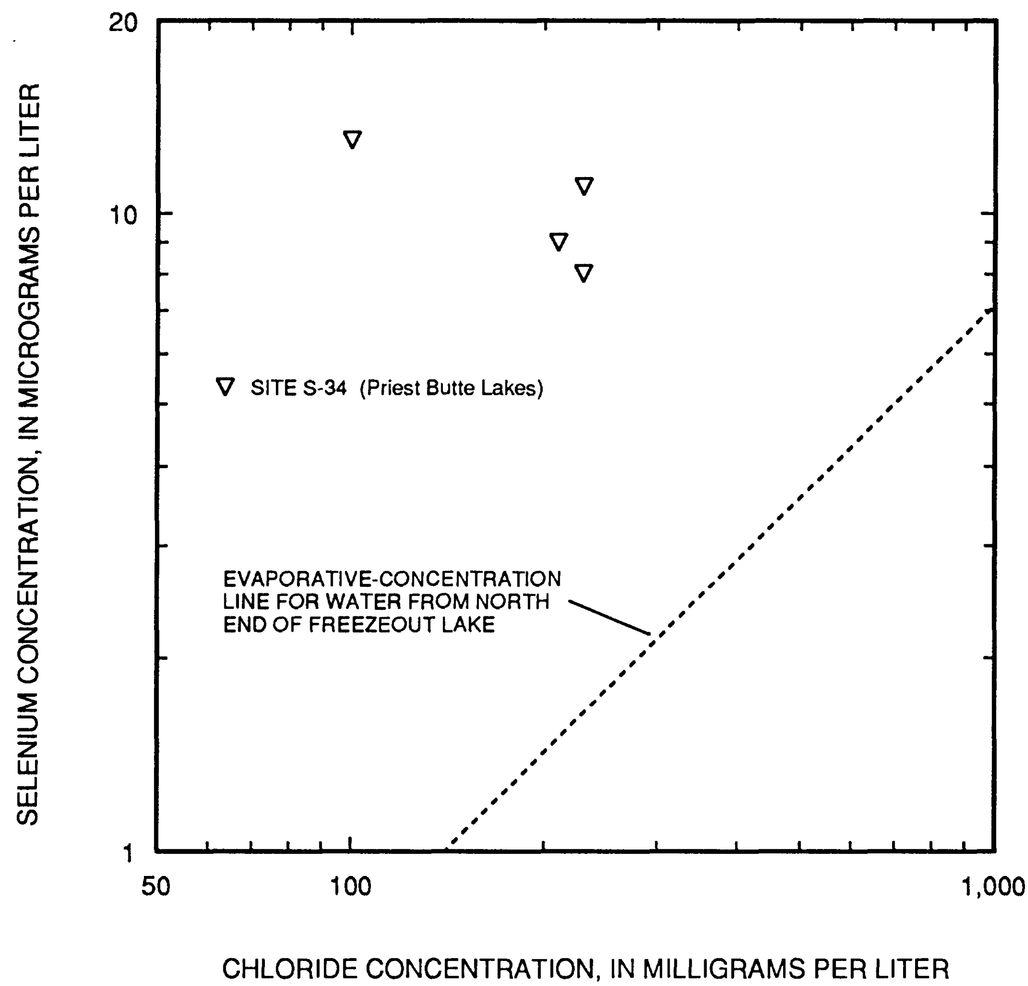


Figure 39. Selenium and chloride concentrations in water of Priest Butte Lakes and theoretical evaporative concentration for water from the north end of Freezeout Lake, Montana.

water of Benton Lake indicates that similar processes of selenium immobilization probably are occurring in both Freezout Lake WMA and Benton Lake NWR.

BIOTA

Water-bird use of Freezout Lake WMA and Benton Lake NWR was estimated during the migration and breeding season of 1991 to assess the importance of these areas to U.S. Department of the Interior trust resources. Concentrations of selenium in aquatic plants, aquatic invertebrates, fish, amphibians, and water birds were investigated at sites in Freezout Lake WMA and Benton Lake NWR (Lambing and others, 1994, table 4) to determine concentrations in the food chain; assess the major pathways for selenium to be accumulated by higher trophic-level organisms, such as fish and birds; and evaluate the potential for selenium to impact fish and water-bird reproduction in the area.

Toxicity tests were conducted to determine if water-dependent biota were adversely affected by exposure to or ingestion of surface water from the study area. Aquatic organisms and ducklings were exposed, under controlled conditions, to surface water having a range of water-quality characteristics observed in the study area. Aquatic organisms representing lower and higher trophic levels of the local food chain were tested to identify any surface water that induced acute toxicological responses in food-

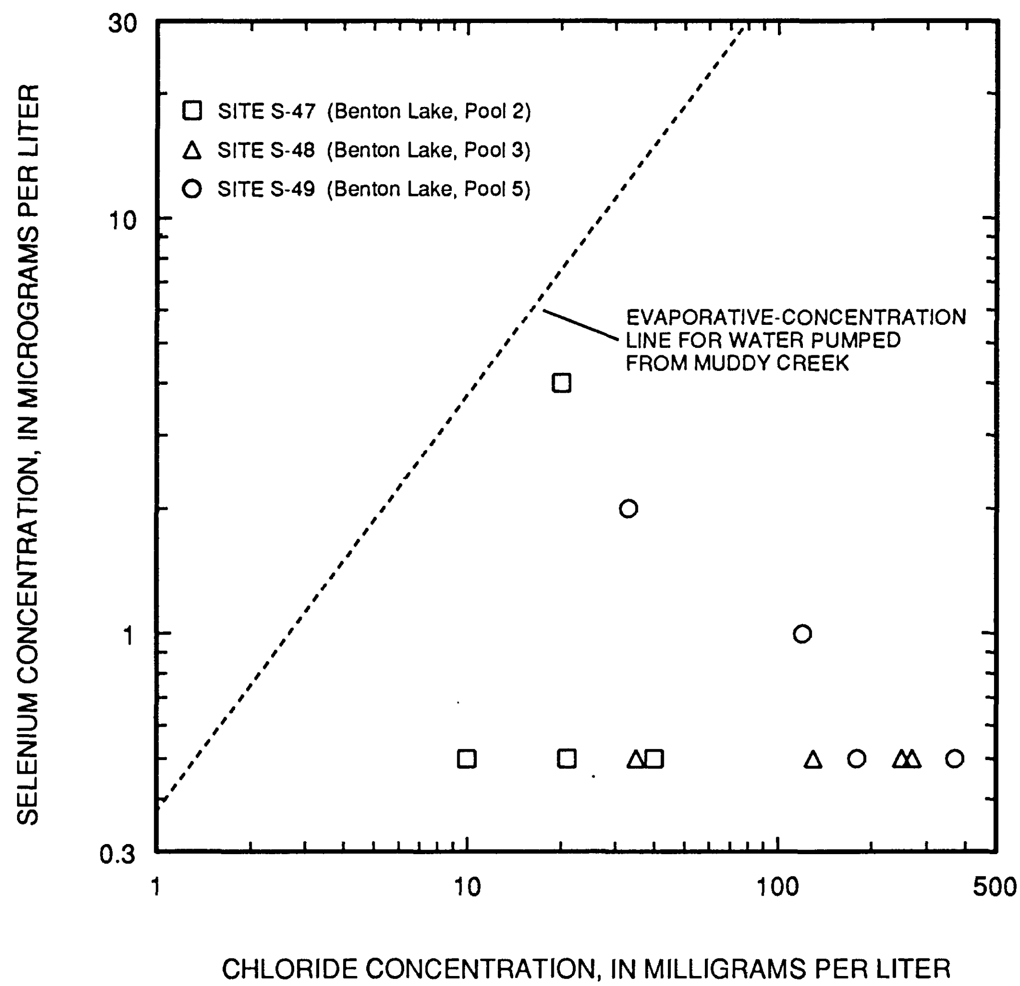


Figure 40. Selenium and chloride concentrations in water of wetlands of Benton Lake National Wildlife Refuge and theoretical evaporative concentration for water pumped from Muddy Creek, Montana. Concentrations less than the minimum reporting level (1 microgram per liter) are plotted as 0.5 microgram per liter.

chain organisms. Duckling exposures were designed to detect both acute and chronic surface-water toxicity to waterfowl.

Biological data collected during 1990-92 as part of this study plus additional data collected during 1987-89 as part of U.S. Fish and Wildlife Service investigations are presented in Lambing and others (1994, tables 21-37). Biological data collected during 1986 as part of the reconnaissance study are presented in Knapton and others (1988, tables 17-21).

Water-Bird Migration

Water birds utilizing Freezout Lake WMA and Benton Lake NWR were counted during the spring and fall migration of 1991. The highest waterfowl count during the spring migration of 1991 at Freezout Lake WMA occurred on March 29, 1991 (table 12), when more than 13,000 ducks, primarily northern pintail, were counted. Also on March 29, the number of snow geese reached a peak value of more than 13,000. An estimated 101,000 lesser snow geese and 14,000 Ross geese passed through Freezout Lake WMA during spring migration. Eared grebes, American coots, and shorebirds were not included in the waterfowl counts discussed above. However, observations at Freezout Lake WMA in the spring of 1991 indicated that numbers of migratory eared grebes and American coots were very high, perhaps exceeding those of ducks present. Thirteen species of shorebirds were identified during this period. The highest water-bird count during fall migration occurred on September 19, 1991 at Freezout Lake WMA and on October 17, 1991 at Ben-

Table 12. Number of waterfowl representing the highest cumulative daily total of ducks, geese, and swans counted on observation dates during the 1991 spring and fall migration period at Freezout Lake Wildlife Management Area and Benton Lake National Wildlife Refuge, Montana

Common name (scientific name)	Number of waterfowl counted		
	Freezout Lake Wildlife Management Area		Benton Lake National Wildlife Refuge
	March 29, 1991	September 19, 1991	October 17, 1991
Tundra swan (*Cygnus columbianus*)	1,540	0	30
Canada goose (*Branta canadensis*)	214	467	2,000
Snow goose (*Chen caerulescens*)	13,505	0	300
Ross' goose (*Chen rossii*)	0	0	200
Mallard (*Anas platyrhynchos*)	480	475	18,110
Northern pintail (*Anas acuta*)	10,300	500	6,265
Gadwall (*Anas strepera*)	5	205	5,710
American wigeon (*Anas americana*)	970	5,145	5,675
Northern shoveler (*Anas clypeata*)	16	175	3,931
Blue-winged teal (*Anas discors*)	0	0	1,566
Cinnamon teal (*Anas cyanoptera*)	0	0	0
Green-winged teal (*Anas crecca*)	5	660	3,840
Redhead (*Aythya americana*)	52	56	130
Canvasback (*Aythya valisineria*)	62	33	750
Ring-neck duck (*Aythya collaris*)	20	0	10
Lesser scaup (*Aythya affinis*)	56	70	123
Common goldeneye (*Bucephala clangula*)	1,759	4	0
Barrow's goldeneye (*Bucephala islandica*)	3	0	0
Bufflehead (*Bucephala albeola*)	9	12	53
Ruddy duck (*Oxyura jamaicensis*)	0	1,716	276
Unidentified duck	0	12,980	0
TOTAL	28,996	22,498	48,969

ton Lake NWR (table 12). American wigeon (*Anas americana*) accounted for the largest number (5,145) of identified ducks at Freezout Lake WMA, whereas mallards were the most abundant fall migrant (18,110) at Benton Lake NWR.

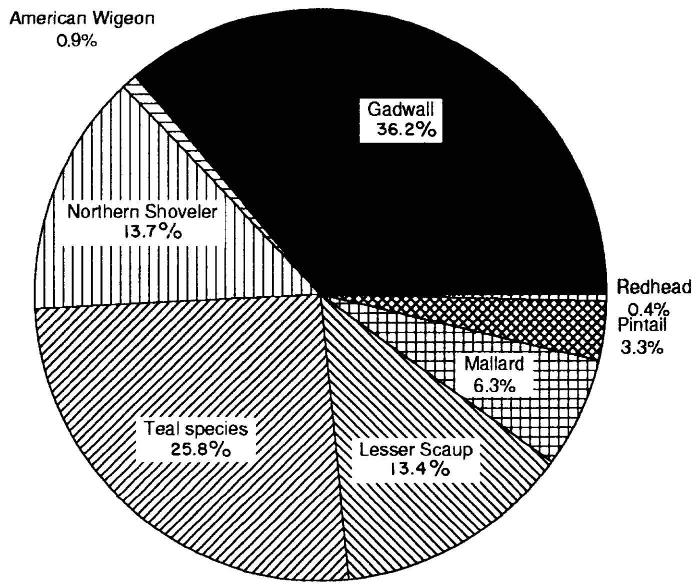
Water-Bird Reproduction

Reproductive toxicity to waterbirds is one of the most sensitive endpoints in assessing the ecological impacts of selenium contamination. Reproduction of eared grebes, ducks, and American avocets within the study area was evaluated by (1) conducting a waterfowl breeding-pair census, (2) determining nest success, (3) estimating embryo viability, and (4) qualitatively examining juvenile survival and growth.

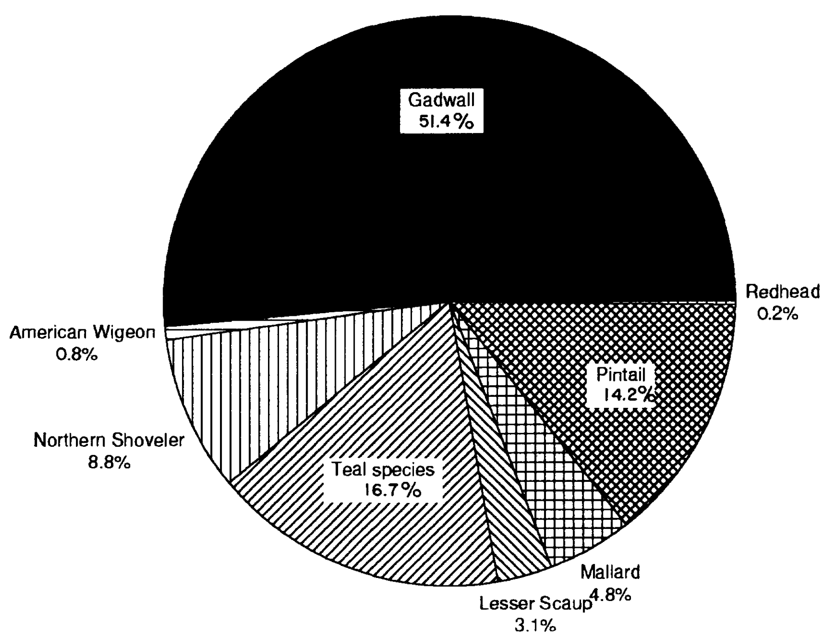
Breeding-Pair Estimates

Estimates of the number of waterfowl breeding pairs were obtained from roadside surveys at Freezout Lake WMA in 1991 and 1992. Pair densities at Freezeout Lake averaged 300 pairs/mi^2 in 1991 and 269 pairs/mi^2 in 1992. In comparison to the number of nests located during nesting surveys (assuming one nest per breeding pair), the estimated potential number of breeding duck pairs was 352 pairs/mi^2 (6,066 total) in 1991 and 464 pairs/mi^2 (7,964 total) in 1992. Although no breeding-pair surveys were conducted at Benton Lake NWR, breeding-pair estimates based on the number of nests were 409 pairs/mi^2 (7,442 total) in 1991 and 228 pairs/mi^2 (4,139 total) in 1992. These pair densities compare favorably to those reported for major breeding areas in the prairies (Pospahala and others, 1974).

Species composition of breeding waterfowl differed somewhat between the two wildlife areas (fig. 41). Based on the number of nests located, Benton Lake NWR supported a higher proportion of breeding northern pintail and gadwall than Freezout Lake WMA. However, blue-winged and cinnamon teal,



Freezout Lake Wildlife Management Area



Benton Lake National Wildlife Refuge

Figure 41. Species composition of breeding ducks observed in 1991-92 at Freezout Lake Wildlife Management Area and Benton Lake National Wildlife Refuge, Montana.

northern shoveler, and mallard were more prevalent breeders at Freezout Lake WMA than at Benton Lake NWR.

American avocets were the most numerous shorebird species in the area. It was estimated that 500 to 1,000 pairs of American avocets bred at Freezout Lake WMA in 1990 (M.T. Schwitters, U.S. Fish and Wildlife Service, written commun., 1991), and 1,560 individuals were counted at Benton Lake NWR in May 1991. Dole (1986) estimated that approximately 2,000 avocets bred at Benton Lake NWR in 1983 and 1984.

Nest Success

The number of eared grebe nests monitored at Freezout Lake WMA and Benton Lake NWR was 57 and 28, respectively. Mean clutch size was 2.82 at Freezout Lake WMA and 2.93 at Benton Lake NWR. Clutch sizes at the two refuges were not significantly different (t-test, $p > 0.90$). Nest success was determined by both the apparent and Mayfield methods (Johnson, 1979). Mayfield estimates of nest success for eared grebes at Freezout Lake WMA and Benton Lake NWR were not significantly different (z-test, $p = 0.246$). Mayfield and apparent nest success estimates for both areas ranged from 46 to 85 percent (fig. 42), and were within the range of apparent nest success values (29 to 88 percent) for eared grebes reported by Forbes (1985) and Palmer (1962).

For upland-nesting ducks, 0.45 nests/acre were located in 1991 and 0.73 nests/acre in 1992. Nest density varied among sampling locations from 0.008 to 3.61 nests/acre. Based on these nest-density values, the estimated total number of nests at Freezout Lake WMA was 6,066 in 1991 and 7,964 in 1992.

In both years of study at Freezout Lake WMA, nest success for upland-nesting ducks exceeded the 15-20 percent thought necessary to maintain viable populations of waterfowl in the prairies (Cowardin and others, 1985). Nest success calculated by the Mayfield method (Johnson, 1979) was 41 percent in 1991 and 43 percent in 1992 (fig. 42). Apparent nest success was 60 percent in 1991 and 66 percent in 1992. Maximum clutch size for all successful nests was nine in both years; however, only eight eggs per nest hatched. Most nest failures, which accounted for 1 percent of the egg losses in 1991 and 8 percent in 1992, resulted from predation. The calculated total number of ducklings produced at Freezout Lake WMA was 24,281 in 1991 and 31,882 in 1992.

Duck nest density at Benton Lake NWR was similar to Freezout Lake WMA with 0.36 nests/acre in 1991 and 0.28 nests/acre in 1992. Based on these nest densities, the estimated total number of nests at the refuge was 7,442 in 1991 and 4,139 in 1992.

The Mayfield nest success for all duck species combined at Benton Lake NWR was 39 percent in 1991 and 51 percent in 1992, which is above the 15-20 percent nest success thought necessary to maintain stable populations. Apparent nest success was 63 percent in 1991 and 72 percent in 1992. Both measures of nest success are similar to those determined at Freezout Lake WMA in 1991 and 1992. Mean clutch size of successful nests was nine in both years, similar to Freezeout Lake. Egg mortality was not measured at Benton Lake NWR. The estimated number of ducklings produced at Benton Lake was 29,800 in 1991 and 16,600 in 1992.

At Freezout Lake WMA, 185 avocet nests were located in 1990 and 35 in 1991. At Benton Lake NWR, 104 avocet nests were located in 1990 and 20 in 1991. Mean clutch sizes were 3.59 in 1990 and 3.61 in 1991 at Freezout Lake WMA and were 3.64 in 1990 and 3.76 in 1991 at Benton Lake NWR. Clutch sizes were not significantly different for either site within years or either year within sites (t-test, $p > 0.40$ in all cases).

Mayfield nest success estimates for avocets nesting at Freezout Lake WMA did not differ significantly between years (fig. 42), but the difference between avocet nesting success in 1990 and 1991 at Benton Lake NWR was highly significant (z-test, $p = 0.004$). Different colonies were monitored at Benton Lake NWR in 1990 and 1991, which may account for the very different estimates. Also, management of water levels resulted in flooding of many nests monitored at Benton Lake NWR in 1991. However, apparent nest success estimates in both years at both sites (fig. 42) were similar to percentages reported earlier for Benton Lake NWR (58 percent in 1983, 79 percent in 1984; Dole, 1986). Ohlendorf and others (1989) reported Mayfield nest success estimates of 16.1 percent to 87.2 percent for American avocets breeding in California. They attributed differences in nest success between years to varying predation pressure. Most nest failures at Freezout Lake WMA or Benton Lake NWR for which causes of failure could be determined resulted from flooding or mammalian predation.

Embryo Viability

All of the eared grebe eggs randomly collected from Freezout Lake WMA and Benton Lake NWR in 1991 contained viable embryos (table 13). The geometric mean selenium concentration in eared grebe embryos collected at Freezout Lake WMA was 14 µg/g dry weight and 12 µg/g dry weight for embryos collected at Benton Lake NWR. The geomet-

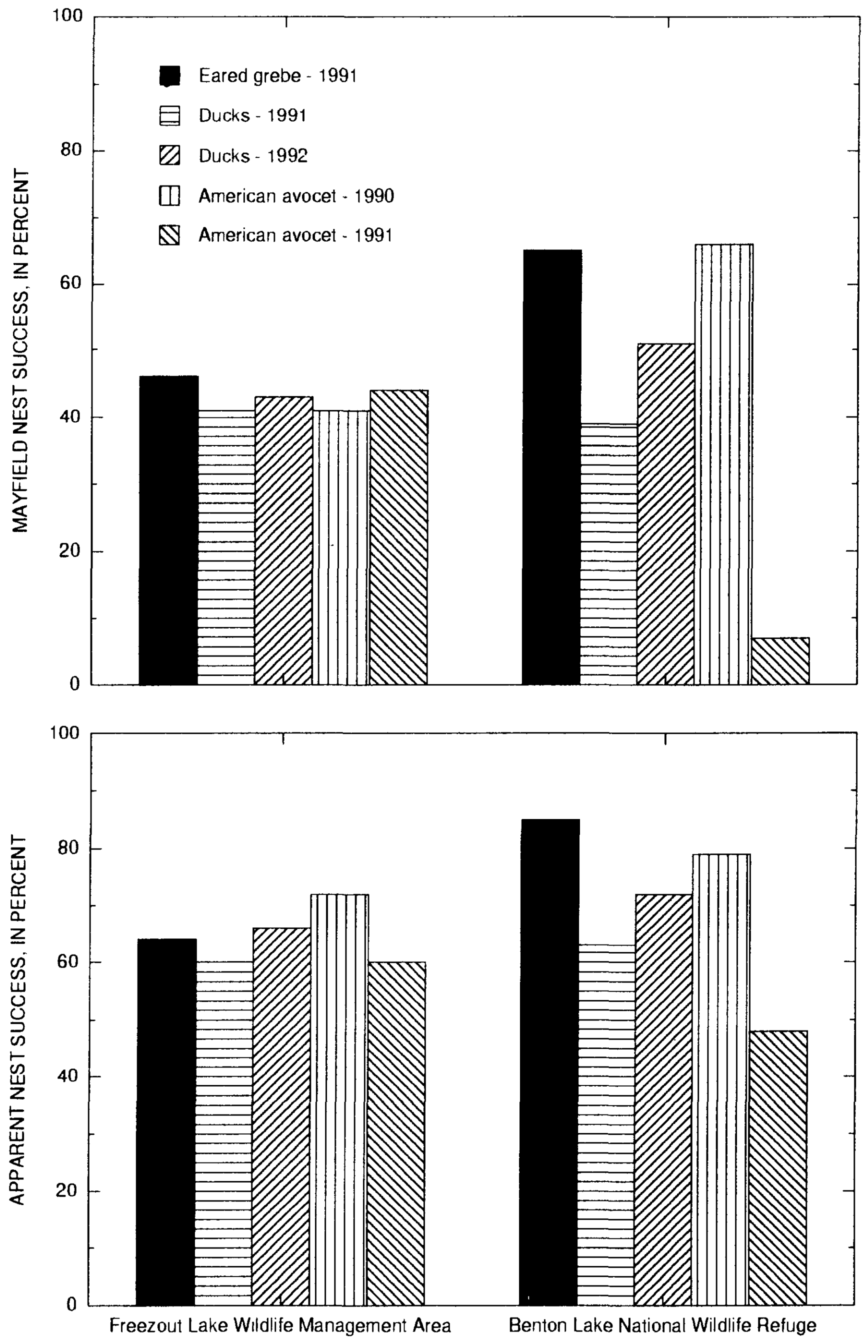


Figure 42. Mayfield and apparent nest success by year for eared grebes, ducks, and American avocets at Freezout Lake Wildlife Management Area and Benton Lake National Wildlife Refuge, Montana.

ric mean selenium concentrations in embryos from these populations exceeded the 8 µg/g concentration associated with low hatchability of eggs from shorebird populations in the Tulare Basin, Calif. (Skorupa and Ohlendorf, 1991).

For upland-nesting ducks at Freezout Lake WMA, egg failure resulting from embryo death was 5 percent in 1991 and 13 percent in 1992. Infertility caused 0 percent (1991) and 4 percent (1992) of the egg failure, and predation accounted for 1 percent (1991) and 8 percent (1992). These rates are not abnormally high (Ohlendorf and others, 1989). Snart (1970) attributed increased embryo death to extreme summer heat and dry conditions. These conditions may have been a factor in the embryo death rate observed at Freezout Lake WMA in 1992.

Of the 43 duck eggs collected from Freezout Lake WMA in 1990 and 1991 that met the require-

Table 13. Embryo viability and selenium concentrations in water-bird eggs randomly collected from Freezout Lake Wildlife Management Area and Benton Lake National Wildlife Refuge, Montana

[Abbreviation: µg/g, micrograms per gram dry weight.]

Species	Year	Number of samples for embryo viability	Embryo viability		Number of samples for selenium concentration	Selenium concentration in eggs (µg/g)	
			Viability of samples (percent)	95 percent binomial confidence interval for mean viability (percent)		Geometric mean	Range
			Freezout Lake Wildlife Management Area				
Eared grebe	1991	20	100	83-100	20	14	10-18
Duck	1991	[1]16	100	79-100	16	5.6	2.3-8.8
Duck	1992	[2]27	96	80-100	26	5.7	2.3-9.3
American avocet	1990	84	96	90-100	73	6.0	2.9-33
American avocet	1991	17	100	81-100	17	17	2.6-39
			Benton Lake National Wildlife Refuge				
Eared grebe	1991	13	100	75-100	13	12	6.3-20
American avocet	1990	36	100	90-100	36	3.7	2.2-11
American avocet	1991	11	73	39-94	10	3.4	2.7-5.0

[1]Sample size represents 7 mallards and 9 northern shovelers.

[2]Sample size represents 13 northern shovelers, 10 lesser scaup, 3 ruddy ducks, and 1 gadwall.

ments of randomness, 98 percent had viable embryos (table 13). The geometric mean selenium concentration in 42 of these embryos was 5.6 µg/g dry weight in 1990 and 5.7 µg/g dry weight in 1991. Eggs randomly collected from uncontaminated populations are expected to have viability rates of approximately 95 percent (J.P. Skorupa, U.S. Fish and Wildlife Service, written commun., 1993).

None of the duck eggs collected at Benton Lake NWR satisfied the criterion of randomness necessary to calculate an embryo-viability rate. However, an additional 536 eggs collected non-randomly from 179 nests located at Benton Lake NWR in 1988 were examined for embryo deformities (Palawski and others, 1991). Only three of those eggs contained embryos with observable malformations (D.J. Hoffman, U.S. Fish and Wildlife Service, written commun., 1989), and only one of those three was found to have a selenium concentration greater than 3.0 µg/g dry weight.

Overall viability of American avocet embryos from eggs randomly collected at Freezout Lake WMA and Benton Lake NWR was 96 percent (table 13) which is similar to the expected 95-percent embryo viability rate for uncontaminated eggs (J.P. Skorupa, U.S. Fish and Wildlife Service, written commun., 1993). Geometric mean selenium concentrations in the American avocet embryos examined from each area ranged from 3.4 to 17 µg/g dry weight (table 13). The highest selenium concentrations in avocet embryos occurred in samples collected in 1991 from Priest Butte Lakes within the Freezout Lake WMA. No overt malformations were observed in avocet embryos.

Juvenile Survival and Growth

Post-hatching mortality in eared grebes, waterfowl, and American avocets was not quantified. Qualitative observation of juvenile eared grebes and waterfowl did not indicate that juvenile survival in the study area differed from the norm. However, qualitative observation of juveniles at Priest Butte Lakes, where nest success was apparently normal, indicated possible poor survival. In many hours of observation, few juvenile avocets were observed at Priest Butte Lakes, even though many juveniles were observed at other colonies in the study area with similar densities of nesting avocets. Priest Butte Lakes are isolated by considerable distance from other wetland units, so the absence of juvenile avocets likely would not be caused by their leaving the area prior to fledging.

Ten young avocets of approximately fledging age (28 to 42 days) were collected from Freezout Lake WMA, including Priest Butte Lakes, and ten more from Benton Lake NWR in 1990. Age was estimated based on plumage characteristics. The body mass, liver mass, tarsus length, wing length, tail length, and bill length of each juvenile was measured. The birds from Benton Lake NWR were significantly smaller (t-test, $p < 0.05$, in all cases) than those from Freezout Lake WMA for measures of body mass, liver mass, wing length, and tarsus length. There appeared to be a difference in juvenile growth rates, with Benton Lake NWR avocets attaining flight plumage at lower mass and smaller size than Freezout Lake WMA avocets.

To examine the possible influence of egg size on juvenile size, Hoyt's (1979) equation with an appropriate constant (0.50) for ovate pyriform eggs was used to calculate avocet egg volume from length and breadth dimensions. There was no significant difference between the volumes of randomly collected avocet eggs from Freezout Lake WMA and Benton Lake NWR (t-test, $p = 0.216$). Swanson and others (1984) suggested that growth and plumage development of ducklings on saline lakes may be so retarded that size- and plumage-based age-classification systems become unreliable. That also may be the case for young American avocets, but would not account for the apparently different avocet growth rates observed at similarly saline habitats within Freezout Lake WMA and Benton Lake NWR. Therefore, the causes for the smaller mass and size of juvenile avocets at Benton Lake NWR compared to Freezout Lake WMA are unknown, but may be related to post-hatching growth rates rather than egg-volume deficiency.

Selenium Residue in Biota

Bioaccumulation of selenium in tissues of different species, representing several trophic levels of the wetland community at the wildlife areas, was examined to identify variability between species and between sites. Sampling sites are shown in figures 43 and 44. Selenium data for individual samples of the various biological matrices were reported by Lambing and others (1994, tables 21-31). Differences in selenium concentrations in biota were statistically analyzed with the nonparametric Mann-Whitney two-sample test or the Kruskal-Wallis test for three or more samples using data-analysis procedures employed by Saiki and others (1993). The statistical computer program SYSTAT (Wilkinson, 1987) was used to conduct the tests. If the Kruskal-Wallis test indicated significant ($p < 0.05$) differences, the multiple-comparisons procedure described by Conover (1980, p. 231) was employed to test for within-species differences between sample sites. A value of one-half the lowest minimum reporting level was substituted for any concentration that was less than the minimum reporting level in calculations of geometric means and test statistics. Geometric means and test statistics were calculated only if half or more of the values in the group of interest were above the minimum reporting level.

Aquatic Plants

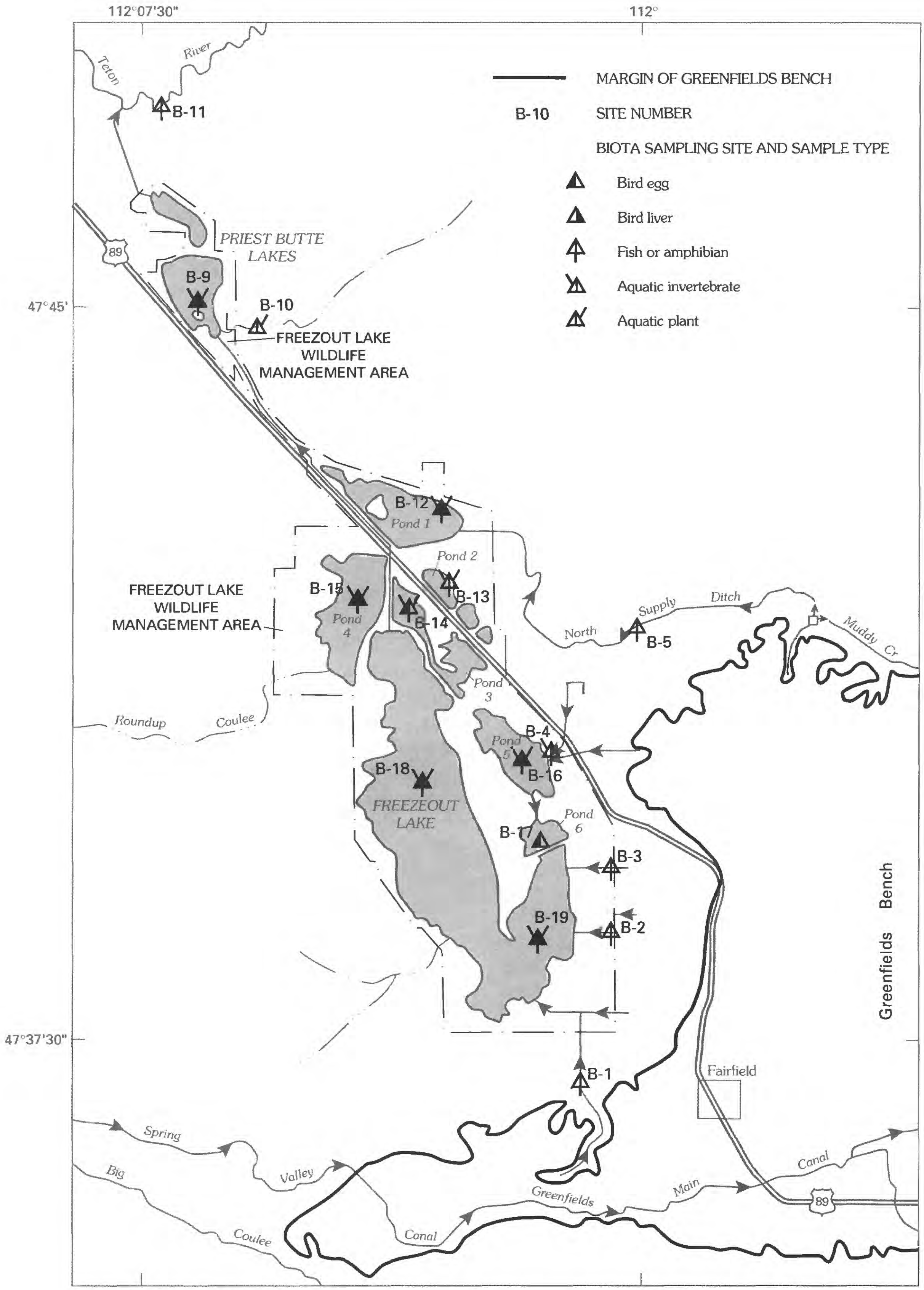
Plants were collected from wetlands and analyzed for selenium to assess selenium uptake from water and sediment. Submergent aquatic plants of three taxa were collected: algae (nonfilamentous, and filamentous, Phylum Chlorophyta), sago pondweed (*Potamogeton pectinatus*), and water milfoil (*Myriophyllum* sp.).

Algae are not highly preferred food plants, but they are consumed in at least small quantities by water birds feeding on the diverse invertebrate community living within the mats (Krull, 1970). A nonfilamentous algae sample from the seep east of Priest Butte Lakes (site B-10) was collected because it was the only aquatic plant present in the very saline water. Sago pondweed was collected whenever possible because it is a highly preferred waterfowl food plant (Martin and Uhler, 1939) and is associated with the invertebrate prey of ducks (Berg, 1949). Although not a preferred plant, water milfoil is widely distributed and present in some locations where sago pondweed does not occur.

A reference selenium concentration of 5 µg/g dry weight representing a critical threshold for dietary consumption by birds was extrapolated from the lowest mean selenium concentration in bird eggs showing teratogenic effects at Kesterson NWR (Skorupa and Ohlendorf, 1991, p. 353). Selenium concentrations in 4 of 26 aquatic-plant samples (table 14) collected from the study area exceeded this critical threshold for dietary consumption by birds. Two of the four samples exceeding the threshold were filamentous algae from Pool 2 (site B-22) and Pool 4C (site B-26) of Benton Lake, one was a sample of nonfilamentous algae from the seep east of Priest Butte Lakes (site B-10), and one was a sago pondweed sample from Priest Butte Lakes (site B-9). Because of small sample sizes, no distinct spatial patterns in selenium concentrations could be determined.

Aquatic Invertebrates

Aquatic invertebrates are represented by the benthic organisms (Chironomidae larvae) and water-column organisms (Cladocera, Amphipoda, Odonata,



Base modified from U.S. Geological Survey Choteau, 1987 (prov. ed.); Choteau SE, 1987 (prov. ed.); Cleiv, 1983; Fairfield, 1983; Freezeout Lake, 1987 (prov. ed.); Golden Ridge, 1987 (prov. ed.); Lowry, 1987 (prov. ed.); and Sevenmile Hill 1987 (prov. ed.) 1:24,000 quadrangles

Figure 43. Location of biological sampling sites within and near Freezout Lake Wildlife Management Area, Montana.

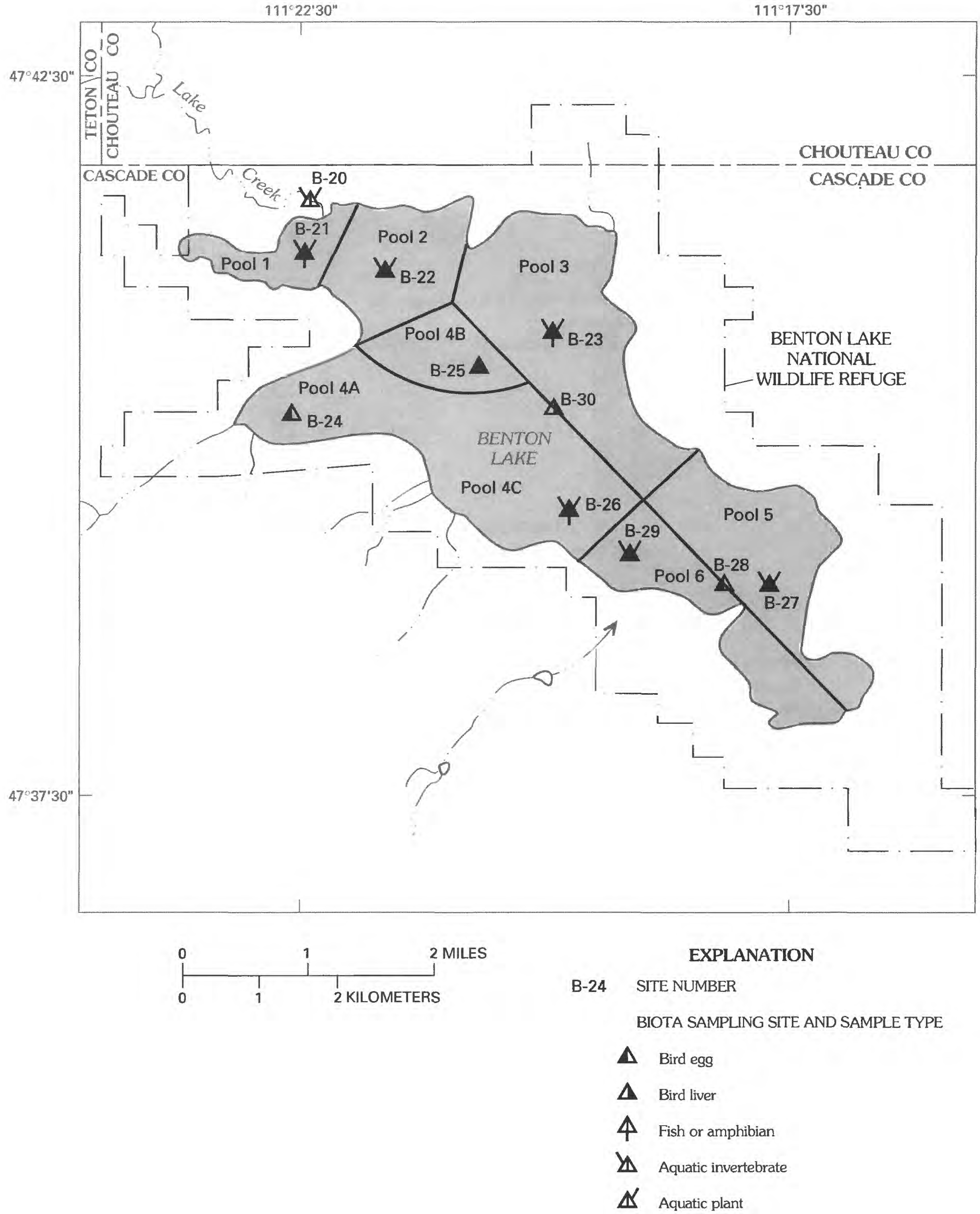


Figure 44. Location of biological sampling sites within Benton Lake National Wildlife Refuge, Montana.

Table 14. Selenium concentrations in aquatic plants collected from Freezout Lake Wildlife Management Area and Benton Lake National Wildlife Refuge, Montana

[Samples composed of whole plants. Abbreviation: µg/g, micrograms per gram dry weight; WMA, Wildlife Management Area. Symbols: <, less than; --, no data]

Site number (fig. 43, 44)	Site name	Number of samples	Selenium concentration (µg/g)	
			Geometric mean	Range
	ALGAE			
	Freezout Lake Wildlife Management Area			
B-10	Seep east of Priest Butte Lakes	1	10	--
	Benton Lake National Wildlife Refuge			
B-21	Benton Lake (Pool 1)	2	2.2	2.1-2.4
B-22	Benton Lake (Pool 2)	1	5.6	--
B-23	Benton Lake (Pool 3)	1	1.8	--
B-26	Benton Lake (Pool 4C)	1	8.9	--
B-27	Benton Lake (Pool 5)	1	1.8	--
B-29	Benton Lake (Pool 6)	1	1.2	--
	SAGO PONDWEED			
	Freezout Lake Wildlife Management Area			
B-9	Priest Butte Lakes	1	5.5	--
B-12 to B-16	Freezout Lake WMA Ponds	5	1.2	<1.2-2.9
B-18, 19	Freezeout Lake	2	1.6	<1.2-4.3
	Benton Lake National Wildlife Refuge			
B-21	Benton Lake (Pool 1)	3	1.5	1.3-1.9
B-22	Benton Lake (Pool 2)	1	.8	--
B-26	Benton Lake (Pool 4C)	2	1.3	1.1-1.5
	WATER MILFOIL			
	Benton Lake National Wildlife Refuge			
B-21	Benton Lake (Pool 1)	2	1.7	1.3-2.2
B-26	Benton Lake (Pool 4C)	2	.9	.7-1.1

Hemiptera) collected at Freezout Lake WMA and Benton Lake NWR. These taxa were the most abundant invertebrates collected at the sample sites and are important dietary items of water birds. Invertebrates constitute about 45 percent of the diet of some dabbling ducks (ducks in the genus *Anas*) during the breeding season, and approximately 70 percent during egg laying (Serie and Swanson, 1976). The diets of young ducklings are composed of the most available invertebrates, consistent with the feeding adaptations of each species of duckling (Sugden, 1973).

Geometric mean selenium concentrations of all taxa exceeded the critical dietary threshold of 5.0 µg/g dry weight for water birds at one or more collection sites (table 15). All invertebrate samples from Priest Butte Lakes and the south end of Freezeout Lake (site B-19) exceeded the threshold.

Significant differences in selenium concentrations in aquatic invertebrates collected among various sample sites were detected in amphipods (Kruskal-Wallis test, $p = 0.007$) and waterboatmen ($p = 0.008$), but not in daphnia ($p = 0.452$), damselflies ($p = 0.320$), or chironomid larvae ($p = 0.331$). The highest selenium concentrations in most invertebrate taxa were from samples collected from Priest Butte Lakes. The second highest selenium concentrations in daphnia, damselflies, and waterboatmen were collected from the south end of Freezeout Lake in the near shore area close to the mouths of irrigation drains. Selenium concentrations in water-column taxa collected at Benton Lake NWR were highest in Pool 1 near the mouth of Lake Creek and decreased in downstream ponds. Geometric mean selenium concentrations in a bottom-dwelling taxon (chironomid larvae) displayed a similar spatial pattern, declining from a maximum at Pool 2 to a minimum at Pool 6 of Benton Lake. Geometric mean concentrations for chironomid larvae generally were higher at Benton Lake NWR than at Freezout Lake WMA, exclusive of Priest Butte Lakes.

Almost all geometric mean selenium concentrations in chironomid larvae exceeded geometric mean concentrations in other invertebrate taxa collected from the same sites, presumably because of their benthic habitat and consumption of selenium-enriched

Table 15. Selenium concentrations in invertebrates collected from Freezout Lake Wildlife Management Area and Benton Lake National Wildlife Refuge, Montana

[Abbreviations: µg/g, micrograms per gram dry weight; WMA, Wildlife Management Area. Symbol: --, no data. Within a taxon, concentrations preceding the same capital letter are not significantly different ($p < 0.05$). Data from several sites are combined to describe broad areas]

Site number (fig. 43, 44)	Site name	Number of samples	Selenium concentration, (µg/g)	
			Geometric mean	Range
	CLADOCERA (DAPHNIA)			
	Freezout Lake Wildlife Management Area			
B-14, 16	Freezout Lake WMA Ponds	2	3.8	2.8-5.3
B-18, 19	Freezeout Lake	2	8.2	5.1-13
	Benton Lake National Wildlife Refuge			
B-21	Benton Lake (Pool 1)	5	5.8	3.7-8.8
B-22	Benton Lake (Pool 2)	2	5.0	4.9-5.1
B-23	Benton Lake (Pool 3)	2	4.3	2.7-6.8
B-26	Benton Lake (Pool 4C)	2	5.4	3.9-7.5
B-27	Benton Lake (Pool 5)	2	2.1	1.0-4.4
B-29	Benton Lake (Pool 6)	2	2.7	1.7-4.3
	AMPHIPODA (AMPHIPODS)			
	Freezout Lake Wildlife Management Area			
B-4	Drain to Pond 5	2	14A	9.0-20
B-9	Priest Butte Lakes	1	11AB	--
B-12 to B-16	Freezout Lake WMA Ponds	5	5.2ABC	3.4-7.4
	Benton Lake National Wildlife Refuge			
B-21	Benton Lake (Pool 1)	8	4.2BCD	3.2-9.0
B-22	Benton Lake (Pool 2)	3	2.6DE	1.4-3.7
B-23	Benton Lake (Pool 3)	3	3.1DE	2.1-5.2
B-26	Benton Lake (Pool 4C)	7	2.6E	1.8-3.9
B-27	Benton Lake (Pool 5)	2	3.0CDE	2.6-3.4
B-29	Benton Lake (Pool 6)	4	2.2E	1.6-3.1
	ODONATA (DAMSELFLY NYMPHS)			
	Freezout Lake Wildlife Management Area			
B-9	Priest Butte Lakes	1	13	--
B-13, 15	Freezout Lake WMA Ponds	2	4.9	4.6-5.3
B-18, 19	Freezeout Lake	1	7.1	--
	Benton Lake National Wildlife Refuge			
B-21	Benton Lake (Pool 1)	1	5.5	--
B-23	Benton Lake (Pool 3)	1	2.5	--
	HEMIPTERA (WATERBOATMEN)			
	Freezout Lake Wildlife Management Area			
B-9	Priest Butte Lakes	2	15A	15-15
B-12 to B-16	Freezout Lake WMA Ponds	6	5.5AB	4.6-8.4
B-18,19	Freezeout Lake	4	5.9AB	2.8-16
	Benton Lake National Wildlife Refuge			
B-21	Benton Lake (Pool 1)	8	4.6AB	2.8-8.4
B-22	Benton Lake (Pool 2)	3	2.7BC	1.0-6.8
B-23	Benton Lake (Pool 3)	3	2.7C	2.0-3.3
B-26	Benton Lake (Pool 4C)	7	2.9C	1.5-5.5
B-27	Benton Lake (Pool 5)	4	2.6C	1.6-4.3
B-29	Benton Lake (Pool 6)	4	2.2C	1.3-4.2
	CHIRONOMIDAE (CHIRONOMID LARVAE)			
	Freezout Lake Wildlife Management Area			
B-9	Priest Butte Lakes	1	36	--
B-12 to B-16	Freezout Lake WMA Ponds	6	9.9	3.3-26
B-18, 19	Freezeout Lake	5	7.8	3.4-14
	Benton Lake National Wildlife Refuge			
B-21	Benton Lake (Pool 1)	6	13	9.7-23
B-22	Benton Lake (Pool 2)	3	16	12-23
B-23	Benton Lake (Pool 3)	2	10	8.3-12
B-26	Benton Lake (Pool 4C)	6	10	5.5-14
B-27	Benton Lake (Pool 5)	4	8.9	6.5-14
B-29	Benton Lake (Pool 6)	4	7.1	2.8-15

sediment and detritus. However, maximum selenium concentrations in chironomid larvae did not occur at sites having maximum selenium concentrations in bottom sediment. Daphnia generally had the highest geometric mean selenium concentrations among water-column invertebrate taxa collected from the same locations.

Crayfish (Decapoda) were opportunistically collected from the Sun River. Selenium concentrations (1.5 and 2.4 µg/g dry weight) in the two crayfish samples from the Sun River were well below the critical dietary threshold of 5 µg/g for water birds (Skorupa and Ohlendorf, 1991) and concentrations of concern for aquatic life identified by Lemly and Smith (1987).

Fish and Amphibians

Fish distribution and species composition in the study area are much modified from pre-settlement patterns. Sections of the Sun River upstream from Muddy Creek support a fair to good fishery, whereas downstream from Muddy Creek the fishery is considered poor due to high sediment loading from Muddy Creek (Ingman and others, 1984). Coldwater fish populations in the Sun and Teton Rivers are adversely affected by water diversions during the irrigation season, with sections of the Teton River being totally dewatered during this period. The supply canals and drains of the irrigation district and the Benton Lake NWR water-supply system permit forage fish to move into shallow wetland units at Freezout Lake WMA and Benton Lake NWR during spring, summer, and fall. However, these wetlands do not have sufficient depth to sustain fish populations through the winter. Freezeout Lake and Priest Butte Lakes are deep enough to sustain fish populations throughout the year. The Montana Department of Fish, Wildlife and Parks stocked Priest Butte Lakes with black crappie (*Pomoxis nigromaculatus*) in 1981 and 1984; and yellow perch (*Perca flavescens*) in 1981, 1983, and 1985 (William Hill, Montana Department of Fish, Wildlife and Parks, oral commun., 1992).

Northern redbelly dace (*Phoxinus eos*), brassy minnows (*Hybognathus hankinsoni*), fathead minnows (*Pimephales promelas*), and brook sticklebacks (*Culaea inconstans*) were collected from drains and wetland units at Freezout Lake WMA and Benton Lake NWR. Mountain whitefish (*Prosopium williamsoni*), brown trout (*Salmo trutta*), common carp (*Cyprinus carpio*), longnose dace (*Rhinichthys cataractae*), white suckers (*Catostomus commersoni*), brook sticklebacks, black crappie, yellow perch, and mottled sculpins (*Cottus bairdi*) were collected from rivers and lakes within the study area. Tiger salamander larvae (*Ambystoma tigrinum*) were opportunistically collected at two sites at Freezout Lake WMA.

Selenium concentrations in all fish samples collected in the study area (tables 16-18) exceeded the 2 µg/g dry weight concentration found by Ohlendorf (1989) to be the average concentration in whole-body freshwater fish collected nationwide during the U.S. Fish and Wildlife Service National Contaminant Biomonitoring Program (May and McKinney, 1981; Lowe and others, 1985). All but a few of the fish samples collected in the study area exceeded the 5 µg/g dry weight concentration suggested by Skorupa and Ohlendorf (1991) as a critical dietary threshold for birds. Selenium concentrations were not significantly different among fathead minnows (Kruskal-Wallis test, $p = 0.185$) or brook sticklebacks ($p = 0.065$) collected from the various sample sites.

Fish samples from Priest Butte Lakes contained particularly high selenium concentrations relative to the other wetlands and nearby rivers (table 18). Black crappie samples, both whole body and fillets, and whole-body yellow perch samples contained selenium concentrations of 39 to 67 µg/g dry weight. Selenium concentrations in fish samples from the drain entering Freezout Lake WMA at Pond 5, the drains on the east side of the south end of Freezeout Lake, and from the south end of the lake itself, also were elevated.

The capture of only adult-age classes of gamefish and the very low catch per unit of effort at Priest Butte Lakes indicate that only individuals surviving from the original stockings occur there. No evidence of successful reproduction by the introduced species was observed. Lemly and Smith (1987) stated that whole-body selenium concentrations greater than 12 µg/g dry weight in sensitive warmwater fish species were associated with reproductive failure. Gillespie and Baumann (1986) found that female bluegills (*Lepomis macrochirus*) with high whole-body selenium concentrations (approximately 24 µg/g dry weight) produced larvae which did not survive to the swim-up stage. Only one of the fourteen whole-body fish samples collected at Priest Butte Lakes had a selenium concentration lower than 24 µg/g dry weight. Native forage fish collected at Priest Butte Lakes probably continue to move into the lake periodically by way of the water delivery canal from the north end of Freezeout Lake.

Lemly (1986) identified crappie as being susceptible to extensive mortality from waterborne selenium at concentrations in the low parts per billion (µg/L) range. The median selenium concentration in water from Priest Butte Lakes was 10 µg/L. The absence of observable reproduction in the species introduced to

Table 16. Selenium concentrations in forage fish and salamanders collected at Freezout Lake Wildlife Management Area and Benton Lake National Wildlife Refuge, Montana

[Abbreviations: µg/g, micrograms per gram dry weight; WMA, Wildlife Management Area. Symbol: --, no data]

Site number (fig. 43, 44)	Site name	Number of samples	Selenium concentration, (µg/g) Geometric mean	Selenium concentration, (µg/g) Range	Number of samples	Selenium concentration (µg/g) Geometric mean	Selenium concentration (µg/g) Range
		NORTHERN REDBELLY DACE			BRASSY MINNOW		
		Freezout Lake Wildlife Management Area					
B-4	Drain to Pond 5	1	16	--	--	--	--
B-9	Priest Butte Lakes	--	--	--	1	29	--
B-13	Freezout Lake WMA (Pond 2)	--	--	--	1	4.2	--
		FATHEAD MINNOW			BROOK STICKLEBACK		
		Freezout Lake Wildlife Management Area					
B-1 to B-5	Drains to Freezout Lake WMA	2	19	11-33	4	19	7.6-26
B-9	Priest Butte Lakes	2	25	25-25	1	35	--
B-12,14,15,16	Freezout Lake WMA Ponds	[1]1	4.8	--	4	5.2	3.3-7.0
B-18,19	Freezeout Lake	2	13	7.9-21	1	17	--
		Benton Lake National Wildlife Refuge					
B-21	Benton Lake (Pool 1)	1	5.1	--	--	--	--
B-23	Benton Lake (Pool 3)	1	2.5	--	--	--	--
B-26	Benton Lake (Pool 4C)	1	2.8	--	--	--	--
		TIGER SALAMANDER					
		Freezout Lake Wildlife Management Area					
B-9	Priest Butte Lakes	5	42	30-52			
B-15	Freezout Lake WMA (Pond 4)	1	4.9	--			

[1]Sample collected from site B-13

Priest Butte Lakes could be caused by either early mortality of young fish or necrosis and rupture of ovarian follicles induced by selenium exposure (Lemly, 1986).

Selenium concentrations in five salamander samples from Priest Butte Lakes ranged from 30 to 52 µg/g dry weight (table 16). The single sample from Freezout Lake WMA Pond 4 contained substantially less selenium (4.9 µg/g dry weight) than samples from Priest Butte Lakes. Selenium concentrations in salamander samples from both sites were very similar to concentrations in fish collected from the same sites indicating similar bioaccumulation rates for the two taxa.

Water-Bird Eggs

All eared grebe eggs from Freezout Lake WMA exceeded the 8 µg/g dry weight selenium concentration associated with low hatchability of populations of black-necked stilts (*Himantopus mexicanus*) and American avocets (Skorupa and Ohlendorf, 1991). The mean selenium concentration in eared grebe eggs collected from Benton Lake Pool 1 also exceeded 8 µg/g dry weight (table 19).

No significant differences in selenium concentrations were detected (Kruskal-Wallis test, $p = 0.120$) among eared grebe eggs collected from the various sample sites in the study area; however, samples from Freezout Lake WMA collected from Pond 5 and the south end of Freezeout Lake had selenium concentrations more than twice as high as concentrations associated with reduced duckling survival (5.2 µg/g dry weight, Heinz and Gold, 1987; Heinz and others, 1987, 1988). Selenium accumulation in eggs from both of these colonies at Freezout Lake WMA probably was influenced by selenium inputs associated with nearby drains from irrigated glacial deposits and subsequent selenium cycling through the local aquatic food chain. No samples of eared grebe eggs were available from Priest Butte Lakes. Selenium concentrations in grebe eggs at Benton Lake NWR were highest in samples from Pool 1, which receives direct inflow from Lake Creek.

Table 17. Selenium concentrations in fish collected from rivers within the Sun River area, Montana

[Abbreviation: µg/g, micrograms per gram dry weight. Symbol: --, no data]

Site number (Lambing and others, 1994, fig. 5)	Site name	Number of samples	Selenium concentration (µg/g)		Number of samples	Selenium concentration (µg/g)	
			Geometric mean	Range		Geometric mean	Range
		MOUNTAIN WHITEFISH			BROWN TROUT		
B-7	Sun River	1	7.7	--	1	3.9	--
B-11	Teton River	1	5.4	--	6	5.5	3.7-12
		LONGNOSE DACE			WHITE SUCKER		
B-6	Muddy Creek at pump station	1	6.6	--	--	--	--
B-7, B-8	Sun River	2	5.4	5.3-5.5	2	3.0	2.5-3.5
B-11	Teton River	2	7.4	7.1-7.7	2	4.2	4.0-4.5
		BROOK STICKLEBACK			MOTTLED SCULPIN		
B-6	Muddy Creek at pump station	--	--	--	1	5.9	--
B-7, B-8	Sun River	--	--	--	2	5.5	3.7-8.3
B-11	Teton River	2	6.5	2.9-15	--	--	--

Table 18. Selenium concentrations in common carp, white suckers, black crappie, and yellow perch collected at Priest Butte Lakes, Montana

[Concentrations are for whole body, unless otherwise indicated. Abbreviation: µg/g, micrograms per gram dry weight. Symbol: --, no data]

Site number (fig. 43)	Site name	Number of samples	Selenium concentration (µg/g)		Number of samples	Selenium concentration (µg/g)	
			Geometric mean	Range		Geometric mean	Range
		COMMON CARP			WHITE SUCKERS		
B-9	Priest Butte Lakes	3	27	19-32	3	27	25-29
		BLACK CRAPPIE (WHOLE BODY)			YELLOW PERCH		
B-9	Priest Butte Lakes	3	42	39-47	1	67	--
		BLACK CRAPPIE (FILLETS)					
B-9	Priest Butte Lakes	3	52	40-63			

Table 19. Selenium concentrations in eared grebe and American avocet eggs collected at Freezout Lake Wildlife Management Area and Benton Lake National Wildlife Refuge, Montana

[Abbreviations: µg/g, micrograms per gram dry weight; WMA, Wildlife Management Area. Symbol: --, no data. Within a taxon, concentrations sharing the same capital letter are not significantly different ($p < 0.05$)]

Site number (fig. 43, 44)	Site name	Number of samples	Selenium concentration (µg/g)		Number of samples	Selenium concentration (µg/g)	
			Geometric mean	Range		Geometric mean	Range
		EARED GREBE EGGS			AMERICAN AVOCET EGGS		
		Freezout Lake Wildlife Management Area					
B-9	Priest Butte Lakes	--	--	--	24 (23)[1]	24A	16-39
B-12,14,15	Freezout Lake WMA Ponds 1,3,4	--	--	--	22 (22)	4.5BC	2.6-7.8
B-16	Freezout Lake WMA (Pond 5)	5	13	10-18	--	--	--
B-19	Freezeout Lake	21	14	10-18	49 (45)	5.0C	2.9-10
		Benton Lake National Wildlife Refuge					
B-21	Benton Lake Pool 1	27	11	5.9-20	--	--	--
B-23	Benton Lake Pool 3	10	5.7	4.2-8.2	14 (11)	3.8BD	3.2-4.9
B-24,25,26	Benton Lake Pool 4	17	7.3	5.5-11	22 (20)	3.9D	2.8-11
B-27	Benton Lake Pool 5	--	--	--	14 (10)	3.2DE	2.6-5.0
B-29	Benton Lake Pool 6	--	--	--	10 (5)	2.9E	1.6-4.0

[1]Sample sizes in parentheses pertain to the randomly collected eggs used in statistical comparisons.

Table 20. Selenium concentrations in duck and American coot eggs collected at Freezout Lake Wildlife Management Area and Benton Lake National Wildlife Refuge, Montana

[Abbreviations: µg/g, micrograms per gram dry weight. Symbol: --, no data]

Water bird	Number of samples	Selenium concentration (µg/g)		Number of samples	Selenium concentration (µg/g)	
		Geometric mean	Range		Geometric mean	Range
	Freezout Lake Wildlife Management Area			**Benton Lake National Wildlife Refuge**		
Mallard	10	3.8	0.9-8.8	50	3.4	0.7-14
Northern pintail	2	1.1	.9-1.3	35	3.3	1.2-11
Gadwall	6	3.8	2.9-4.6	68	3.9	1.6-14
American wigeon	1	1.4	--	--	--	--
Northern shoveler	24	4.9	1.5-8.9	29	3.1	1.7-7.9
Teal spp.	5	1.9	1.5-2.4	24	2.2	1.2-9.0
Redhead	2	11	9.4-12	3	2.7	1.9-4.4
Lesser scaup	21	3.7	1.3-10	28	3.5	1.3-8.4
Ruddy duck	10	7.6	2.5-13	--	--	--
American coot	8	6.8	4.7-9.3	36	3.1	1.5-5.9

Elevated concentrations of selenium in water and biota of Benton Lake Pool 1 probably are caused by selenium inputs from Lake Creek.

Geometric mean selenium concentrations in the eggs of redhead ducks collected from Freezout Lake WMA (table 20) exceeded the 8 µg/g dry weight concentration associated with low hatchability in water-bird populations (Skorupa and Ohlendorf, 1991). The geometric mean selenium concentrations in the eggs of other duck species did not exceed 8 µg/g dry weight, although at least one mallard, northern shoveler, lesser scaup, and ruddy duck egg collected at Freezout Lake WMA did exceed that level.

At Freezout Lake WMA, selenium concentrations in duck eggs tended to be higher in samples collected from Ponds 1 and 5 and the south end of Freezeout Lake than in duck eggs collected elsewhere. This result may be associated with higher selenium concentrations in irrigation drainage entering those units or periodic runoff to Pond 1 from non-irrigated glacial deposits.

Because no duck eggs were randomly collected at Benton Lake NWR, statistical comparison between the two refuges could not be performed. Selenium concentrations generally were higher in duck egg samples collected from Pools 1, 2, and 3 at Benton Lake NWR than in those from Pools 4, 5, and 6. A similar trend in selenium concentration was observed for aquatic invertebrate, eared grebe, and American avocet samples collected at Benton Lake NWR.

Selenium concentrations in American avocet eggs from the various sample sites (table 19) differed significantly (Kruskal-Wallis test, $p < 0.001$). Although the high selenium concentrations in avocet eggs collected at Priest Butte Lakes did not result in a decreased embryo-viability rate, the geometric mean selenium concentration in avocet eggs from Priest Butte Lakes (table 19) greatly exceeded the 8 µg/g dry weight concentration associated with reduced embryo viability of black-necked stilt and American avocet eggs (Skorupa and Ohlendorf, 1991). Concentrations in avocet eggs from Priest Butte Lakes also were significantly higher than concentrations in avocet eggs from all other sites (Conover's multiple comparisons procedure, $p < 0.05$). The geometric mean selenium concentrations in avocet eggs collected from other locations in the study area did not exceed the 8 µg/g concentration threshold.

Water-Bird Livers

Selenium concentrations in the livers of young-of-the-year eared grebes (table 21) from Freezout Lake WMA were significantly different (Mann-Whitney U-test, $p = 0.043$) from the livers from Benton Lake NWR. The highest selenium concentrations were found in the livers of eared grebes collected from Benton Lake Pool 1 (range 11 - 74 µg/g dry weight), which was a pattern similar to eared grebe eggs. Selenium concentrations in all grebe livers from Pool 1 exceeded the approximately 10.4 µg/g dry weight concentration found to cause reproductive problems in female mallards (Heinz and others, 1987). The median selenium concentration in the livers of water-bird populations collected from uncontaminated non-marine environments is 6 µg/g dry weight and selenium residues typically range between 4 and 9 µg/g dry weight (J.P. Skorupa, U.S. Fish and Wildlife Service, written commun., 1993; Ohlendorf and Skorupa, 1989). The mean selenium concentration in eared grebe livers collected from Benton Lake NWR and Freezout Lake WMA exceeded the median selenium concentration associated with uncontaminated environments.

Liver samples from mallards, northern shoveler, and lesser scaup were collected at both Freezout Lake WMA and Benton Lake NWR, but sample sizes were too small to make statistical comparisons between the two areas. No obvious differences were detected in duck liver selenium concentrations between areas within species. Geometric mean selenium concentrations in the livers of all duck species (table 21) exceeded the 9 µg/g dry weight concentration suggested by Ohlendorf and Skorupa (1989) as the upper end of the range of normal selenium concentrations in water bird livers, and all but American coots and northern shovelers exceeded the approximately 10.4 µg/g dry weight concentration associated with reproductive inhibition in female mallards (Heinz and others, 1987). Selenium concentrations in four of the five mallard livers collected also exceeded 10.4 µg/g dry weight. In general, selenium concentrations in the livers of ducks and coots were lower than in eared grebes and American avocets, but exceeded expected background levels.

Selenium concentrations in avocet livers from Freezout Lake WMA and Benton Lake NWR (table 21) were not significantly different (Mann-Whitney U-test, $p = 0.53$). Selenium concentrations in all American avocet livers analyzed from birds collected at Freezout Lake WMA and Benton Lake NWR exceeded 9 µg/g dry weight (table 21). Geometric mean selenium concentrations in avocet livers from both areas exceeded the approximately 10.4 µg/g dry weight associated with reproductive problems in female mallards (Heinz and others, 1987).

Table 21. Selenium concentrations in water-bird livers collected at Freezout Lake Wildlife Management Area and Benton Lake National Wildlife Refuge, Montana

[Abbreviations: µg/g, micrograms per gram dry weight. Symbol: --, no data]

Water bird	Number of samples	Selenium concentration (µg/g) Geo-metric mean	Range	Number of samples	Selenium concentration (µg/g) Geo-metric mean	Range
	Freezout Lake Wildlife Management Area			Benton Lake National Wildlife Refuge		
Eared grebe	10	[1]14	8.3-27	31	[1]22	3.6-74
Canada goose	1	14	--	--	--	--
Mallard	3	19	12-24	2	12	10-16
Northern pintail	--	--	--	2	16	15-17
Gadwall	--	--	--	5	13	8.5-16
American wigeon	--	--	--	1	21	--
Northern shoveler	4	11	4.6-17	5	9.8	4.0-21
Anas spp.	--	--	--	[2]2	16	11-22
Lesser scaup	2	12	11-14	17	14	11-31
Ruddy duck	--	--	--	2	19	19-20
American coot	--	--	--	17	6.9	3.4-23
American avocet	16	22	13-43	28	20	9.3-45

[1]Significantly different, $p = 0.043$.
[2]Liver salvaged from unidentified dabbling duck species that died of avian botulism.

Bioassays

Bioassay testing was performed using photoluminescent marine bacteria as an initial toxicity screening tool to identify surface water within the study area that caused a toxic response in an aquatic organism. Follow-up bioassay testing using aquatic invertebrates, fish, and ducklings was conducted to determine the salinity threshold of freshwater organisms in relation to the salinity of various surface water within the Sun River study area and to identify sites where surface water was overtly toxic to representative food-chain organisms and ducklings. Aquatic invertebrate, fish, and duckling bioassay tests were considered valid if mortality in control tests did not exceed 10 percent. The methods used to conduct bioassays are described in Lambing and others (1994, p. 17-18).

Photoluminescent Bacteria

The Microtox[R] bioassay system (Ribo and Kaiser, 1987) was used to test toxic responses to 49 water samples collected in 1991 and 28 samples collected in 1992 from the Sun River study area. The Microtox[R] bioassay system utilizes a photoluminescent bacterium, *Photobacterium phosphoreum*. Light output of the test organisms was measured under control and experimental conditions. Reduced light output by the bacterium under experimental conditions is indicative of a toxic response. The response cannot be attributed to a particular water-quality property or constituent concentration, but can provide a relative indication of the toxicity of the tested water to aquatic organisms.

Surface-water samples assayed using this technique were split from samples collected for chemical analysis from surface-water sites within the study area. Water-quality characteristics and trace-element concentrations for the samples are in Lambing and others (1994, tables 14 and 15). Phenol, which elicits a known toxic response to the bacteria, was used as a reference toxicant after performance of 24 assays to verify the precision of the assay technique.

In 1991, surface-water samples from the seep east of Priest Butte Lakes (site S-35), the north end of Freezeout Lake (site S-38), the south end of Freezeout Lake (site S-39), the tributary to Lake Creek (site S-43), Benton Lake Pool 2 (site S-47), and Benton Lake

Pool 5 (site S-49) were toxic to the bacteria. Surface-water samples from the tributary to Lake Creek (site S-43) and Benton Lake Pool 5 (site S-49) were toxic to the bacteria in 1992.

Aquatic Invertebrates and Fish

Static acute bioassay tests were conducted in 1992 on *Hyalella azteca*, *Daphnia magna*, and fathead minnows using 33 surface-water samples and a reference toxicant of saltwater formulated at a concentration known to be toxic to the test organisms. The results are reported in Lambing and others (1994, tables 32-34).

Aquatic invertebrate and fish acute bioassay tests were used to evaluate the toxicity of samples from 18 surface-water locations associated with irrigated land, non-irrigated farm and range land, saline seeps, streams, and lakes. The organisms selected for testing represent important wildlife food-chain organisms of Freezout Lake WMA and Benton Lake NWR. Aquatic invertebrate and fish bioassays were conducted with water from eight surface-water sampling sites within the Greenfields Irrigation Division, five sites within Freezout Lake WMA, and five sites within Benton Lake NWR. Tests were performed with water samples collected in the spring and summer to determine the effects on aquatic organisms from seasonal variation of surface-water quality associated with irrigation drainage. However, from the chemical analyses of constituents alone, it was not possible to identify the specific causative element or combination of elements that killed test organisms in some of the bioassays. To assess the potential adverse effects of exposure to saline water, aquatic invertebrate and fish acute-toxicity tests were performed using a saltwater reference toxicant to determine the salinity threshold of freshwater organisms common to the wetlands at Freezout Lake WMA and Benton Lake NWR; and to assist in the evaluation of whether particular major-ion compositions of surface water correlate to observed toxic responses in test organisms.

Salinity-Toxicity Threshold

In acute-toxicity testing using a saltwater reference toxicant, the calculated salinity toxicity threshold of reconstituted saltwater (48-hour median lethal concentration expressed as specific conductance) for *H. azteca* was 22,300 μS/cm. *D. magna* were approximately twice as sensitive (48-hour median lethal concentration = 11,900 μS/cm) to the saltwater reference toxicant as *H. azteca*. The acute toxicity of reconstituted saltwater to *H. azteca* and *D. magna* in this study was similar to that reported by Ingersoll and others (1992). The calculated salinity toxicity threshold for fathead minnows exposed to the saltwater reference toxicant was 19,600 μS/cm. Fathead minnows used in this study had a greater salinity tolerance compared to data reported by Adelman and Smith (1976).

Based on these salinity toxicity thresholds for *H. azteca* and fathead minnows, the only site where specific-conductance values of surface-water samples exceeded the salinity toxicity threshold was the seep east of Priest Butte Lakes (site S-35, Lambing and others, 1994, table 14). The median specific-conductance value of samples from this site was 32,700 μS/cm. The specific-conductance value associated with the salinity toxicity threshold level for *D. magna* was exceeded in one or more surface-water samples collected at the northwest tributary to Muddy Creek (site S-18), the seep east of Priest Butte Lakes (site S-35), the tributary to Lake Creek (site S-43), Lake Creek near Power (site S-44), and the tributary to Benton Lake Pool 4 (site S-45). All samples exceeding thresholds for salinity tolerance of freshwater organisms were collected from sites that drain non-irrigated land.

Greenfields Irrigation Division and Adjacent Land

Samples from six drains in the Greenfields Irrigation Division collected in the spring prior to the irrigation season did not cause more than 50 percent mortality to *H. azteca* (table 22). *H. azteca* experienced 30 percent mortality during exposure to surface water from the drain south of Freezeout Lake (site S-5). The only sample collected during the spring from the Greenfields Irrigation Division that caused mortality of *D. magna* (40 percent) was collected from Blackfoot Coulee (site S-30). Greenfields Irrigation Division pre-irrigation (spring season) surface-water samples eliciting a toxic response to fathead minnows included samples from the drain south of Freezeout Lake (site S-5), south and middle drains at old Highway 89 (sites S-6 and S-7), drain to Freezout Lake WMA Pond 5 (site S-11), and Blackfoot Coulee (site S-30).

Irrigation (summer) season surface-water samples from the Greenfields Irrigation Division that induced toxic responses in *H. azteca* or *D. magna* (table 22) included the Greenfields Main Canal (site S-1), drain to Pond 5 (site S-11), and Muddy Creek at the pump station (site S-21). The observed mortality of the Greenfields Main Canal surface-water sample to *H. azteca* may have been induced by the low ionic strength of the undiluted sample compared to the Giant Springs (fig. 1) culture water (Lambing and others, 1994, tables 15 and 37). The addition of culture water having higher ionic strength to the low ionic sample

Table 22. Cumulative percent mortality at the conclusion of acute bioassays using dilution water (control), saline solution (reference toxicant), and undiluted surface water from 18 sites in the Sun River area, Montana, for *Hyalella azteca, Daphnia magna,* and fathead minnows

[Bioassays for *Hyalella azteca* and *Daphnia magna* were 48-hour duration; bioassays for fathead minnow were 96-hour duration. Abbreviations: *H. azteca*, *Hyalella azteca*; *D. magna*, *Daphnia magna*; FHM, fathead minnow; g, gram; µS/cm, microsiemens per centimeter at 25 degrees Celsius. Symbol: --, no data]

Site number (fig. 25)	Site name	Percent mortality					
		Spring season			Summer season		
		H. azteca	*D. magna*	FHM	*H. azteca*	*D. magna*	FHM
	Control and Reference Toxicant Treatments						
--	Giant Springs	0	0	0	10	0	0
--	Reconstituted saltwater[1]	80	100	100	100	100	100
	Greenfields Irrigation Division and Adjacent Land						
S-1	Greenfields Main Canal	--	--	--	80	10	0
S-5	Drain (south of Freezeout Lake)	30	0	20	10	0	0
S-6	Drain at old Highway 89 (south)	10	0	40	--	--	--
S-7	Drain at old Highway 89 (middle)	0	0	20	10	0	0
S-11	Drain to Pond 5	0	0	40	30	20	0
S-12	North Supply Ditch	0	0	0	0	0	0
S-21	Muddy Creek at pump station	--	--	--	0	20	10
S-30	Blackfoot Coulee	0	40	100	10	0	0
	Freezout Lake Wildlife Management Area and Adjacent Land						
S-34	Priest Butte Lakes	50	0	20	0	0	0
S-35	Seep east of Priest Butte Lakes	100	100	100	100	100	100
S-37	Freezout Lake WMA (Pond 5)	--	--	--	0	0	0
S-38	Freezeout Lake (north end)	0	10	10	80	0	20
S-39	Freezeout Lake (south end)	10	0	0	50	0	10
	Benton Lake National Wildlife Refuge and Adjacent Land						
S-43	Tributary to Lake Creek	50	100	100	100	100	100
S-44	Lake Creek at mouth	10	0	80	50	10	0
S-47	Benton Lake (Pool 2)	0	0	0	10	0	10
S-48	Benton Lake (Pool 3)	--	--	--	0	0	0
S-49	Benton Lake (Pool 5)	20	0	60	--	--	--

[1]Reconstituted saltwater: Spring season undiluted reconstituted saltwater control treatment equals 30,700 µS/cm; (20.8 g of Instant Ocean[R] per liter of Giant Springs water); Summer season undiluted reconstituted saltwater control treatment equals 29,700 µS/cm (21.7 g Instant Ocean[R] per liter of Giant Springs water).

water eliminated the toxic response. The sample from the drain to Freezout Lake WMA Pond 5 caused partial mortality to *H. azteca* and *D. magna*. Partial mortality of the *D. magna* test population was also observed in the sample from Muddy Creek at the pump station (site S-21). In contrast to the toxicity caused by some samples collected in the spring, surface water collected from the Greenfields Irrigation Division during the summer was not acutely toxic to fathead minnows.

The drain to Freezeout Lake WMA Pond 5 was the only sampling location within the Greenfields Irrigation Division that caused mortality to at least one of the bioassay organisms during both the spring and summer sampling periods. In general, toxic responses in *H. azteca* and *D. magna* occurred more often in samples collected during the summer, whereas fathead minnows were more sensitive to samples collected during the spring.

Freezout Lake Wildlife Management Area and Adjacent Land

Surface water from Priest Butte Lakes (site S-34) and the seep east of Priest Butte Lakes (site S-35) collected during the spring and samples from the seep east of Priest Butte Lakes, the north end of Freezeout Lake (site S-38), and the south end of Freezeout Lake (site S-39) collected during the summer caused acutely toxic responses in bioassay organisms (table 22). The water from Priest Butte Lakes collected during the spring caused 20-percent mortality of fathead minnows and 50-percent mortality of *H. azteca* compared to no observed mortality in the corresponding control-treatment water from Giant Springs. Priest Butte Lakes water collected during the summer did not elicit any toxic responses among the three bioassay species. However, samples from the seep east of Priest Butte Lakes (site S-35), which drains to Priest Butte Lakes, were acutely toxic to all three test species during both the spring and summer (table 22).

Given the salinity tolerance (22,300 µS/cm) of *H. azteca* to reconstituted saltwater, the 80 percent mortality observed in samples from the seep east of Priest Butte Lakes (S-35) that had been diluted by 75 percent (Lambing and others, 1994, table 33) cannot be attributed solely to the salinity of the water. Atypical ion ratios and interactive effects of contaminant mixtures in combination with elevated salinity has been implicated in increasing the toxic response of aquatic organisms compared to single chemical exposures (Ingersoll and others, 1992). Water-quality characteristics did not vary substantially among sampling events at the seep east of Priest Butte Lakes, but did indicate very high concentrations of selenium and a major-ion composition dominated by magnesium and sulfate.

Surface-water samples collected from both the north and south ends of Freezeout Lake during the summer were acutely toxic (50 to 80 percent mortality) to *H. azteca* (table 22). The summer sample from north end of Freezeout Lake also induced 20-percent mortality of fathead minnows compared to no mortality in the control treatment. Mortalities did not exceed 10 percent in the aquatic invertebrate or fish test species exposed to Freezeout Lake surface water collected during the spring (pre-irrigation) season.

The similarity of water-quality characteristics and trace-element concentrations for Freezeout Lake during the spring and summer sampling periods indicate that other chemical constituents or interactions may account for the observed seasonal differences in toxicity to *H. azteca* organisms. In all cases, toxicity induced by Freezeout Lake water was eliminated by 50-percent dilution with Giant Springs control water.

Benton Lake National Wildlife Refuge and Adjacent Land

All surface-water samples from the tributary to Lake Creek (site S-43) were acutely toxic to all three test species (table 22). Water-quality characteristics and trace-element concentrations were similar for all sampling events at this site (Lambing and others, 1994, tables 14 and 15). Two major water-quality factors influencing the consistent toxicity of water samples from this site probably are the acidic conditions (pH range of 4.4-4.6) and high values of specific conductance (range of 12,300-15,000 µS/cm). *H. azteca* was the least sensitive of the three test species, with mortality ranging from 50 to 100 percent. Exposure of *D. magna* and fathead minnows to this water caused 100-percent mortality in all cases. Because acidic water increases the solubility of many trace elements, it is possible that synergistic effects between metals and acidic water, in addition to high salinity, could influence the magnitude of the toxic response.

The spring sample from Lake Creek consisted of natural flow and was acutely toxic (80-percent mortality) to fathead minnows. Relatively high specific conductance, acidic pH (5.3), and high concentrations of cadmium, nickel, and zinc probably contributed collectively to the toxic response of fathead minnows exposed to natural flow. The summer sample from Lake Creek consisted primarily of irrigation return flow pumped from Muddy Creek and was acutely toxic (50-percent mortality) to *H. azteca* (table 22). It is uncertain why the higher pH and the lower specific conductance and trace-element concentrations in the water pumped from Muddy Creek induced a toxic response in *H. azteca*, especially when no mortality occurred in water from Muddy Creek at the pump station (S-21).

Acute toxicity to fathead minnows (60-percent mortality) occurred from exposure to water from Benton Lake Pool 5 collected during the spring. The cause of toxicity is uncertain because concentrations of trace elements in Pool 5 were lower than aquatic-life criteria designed to protect aquatic organisms (U.S. Environmental Protection Agency, 1986); however, the dissolved-solids concentration of 9,150 mg/L was substantially higher than in the other sampled pools of Benton Lake.

Salt-Toxicity Relation

The toxicity of irrigation drainage to fish can be caused by atypical major-ion ratios, high salinities, and elevated concentrations of trace elements (Ingersoll and others, 1992). A salt-toxicity-relation (STR) model using multivariate regression equations was developed by Gulley and others (1992) to predict the acute toxicity of reconstituted highly saline water, composed of various mixtures of major ions, to *Ceriodaphnia dubia*, *Daphnia magna*, and fathead minnows. Mortality of *D. magna* at 48-hour exposure and fathead minnows at 96-hour exposure to undiluted surface water collected from sites in the Sun River area was compared to mortality predicted by the STR model (table 23). If observed mortality in test organisms is substantially greater or less than predicted mortality, factors other than the ratio of dissolved salts in the surface water are assumed to be responsible for the alteration in toxicity. Factors causing observed mortality rates greater than predicted may be associated with elevated concentrations of other contaminants. Factors causing observed mortality rates less than predicted could be related to less sensitivity of the organism to contaminants.

D. magna and fathead minnows had acutely toxic responses from exposure to surface water from four sites within the Greenfields Irrigation Division [Drain south of Freezeout Lake (site S-5), drain to Pond 5 (site S-11), Muddy Creek at the pump station (site S-21), and Blackfoot Coulee (site S-30)], two sites in Freezout Lake WMA [Priest Butte Lakes (site S-34) and the seep east of Priest Butte Lakes (site S-35)], and three sites in the Benton Lake basin [tributary to Lake Creek (site S-43), Lake Creek near Power (site S-44), and Benton Lake Pool 5 (site S-49)]. The STR model predicted that 30 of the 52 bioassays performed would cause greater than 20 percent mortality to test organisms due to salt toxicosis (table 23). However, observed mortality of test organisms in only 7 of 30 bioassays corresponded to the STR model predictions. Surface-water samples from the drain south of Freezeout Lake (site S-5), Muddy Creek at the pump station (site S-21), the tributary to Lake Creek (site S-43), and Benton Lake Pool 5 (site S-49) were more toxic than STR model predictions, indicating the presence of other contaminants or synergistic contaminant interactions. Observed toxicity was less than predicted in 20 other tests. The strains of *D. magna* and fathead minnow used in this study were more salt-tolerant to the reference toxicant and may have been more salt-tolerant than the test organisms used to develop the STR model. Also, variable storage times of surface-water samples prior to initiation of bioassay experiments or antagonistic contaminant interactions may have reduced the potency of individual chemical constituents in the samples.

Ducklings

Two control groups of six ducklings each were exposed for 28 days to drinking water obtained from Giant Springs near Great Falls, Mont. (fig. 1). Twelve other groups of ducklings were divided into six replicate groups of six ducklings each. Each of the paired groups was provided with drinking water obtained from one of six surface-water sampling sites in either Freezout Lake WMA or Benton Lake NWR. The samples used for drinking water represented a range from low to high salinity and selenium concentrations. Water samples used for treatments were split and analyzed for major ions and selenium. Water was obtained for the experimental groups from the seep east of Priest Butte Lakes (site B-10), south end of Freezeout Lake (site B-19), Freezout Lake WMA Pond 5 (site B-16), tributary to Benton Lake Pool 4 (site S-45), Benton Lake Pool 2 (site B-22), and Benton Lake Pool 6 (site B-29). All duckling groups were fed unrestricted quantities of commercial duckling food during the 28-day drinking-water exposure. Surface-water samples from lakes that were used for the duckling bioassay were collected from near-shore areas and did not directly correspond to routine surface-water sampling sites. Analytical results for these near-shore water samples are presented in Lambing and others (1994, table 37). Total-recoverable selenium concentrations ranged from 0.7 to 530 μg/L among treatment groups (table 24). Mean selenium concentration in the two feed samples was 0.75 μg/g dry weight (Lambing and others, 1994, table 36).

Measurements of mass, tarsus length, and culmen length for surviving ducklings in each treatment

Table 23. Observed and predicted percent mortality of *Daphnia magna* and fathead minnows in acute-toxicity tests using dilution water (control), saline solution (reference toxicant), and undiluted surface water from 18 sites in the Sun River area, Montana. Predicted mortality is based on the salt toxicity model of Gulley and others (1992)

[Abbreviation: µS/cm, microsiemens per centimeter at 25 degrees Celsius; WMA, Wildlife Management Area. Symbol: --, no data]

Site number (fig. 25)	Site name	Specific conductance (µS/cm)	Date	Percent mortality			
				Daphnia magna 48 hour		Fathead minnow 96 hour	
				Observed	Predicted	Observed	Predicted
--	Giant Springs	638	04-02-92	0	1	0	3
--	Reconstituted saltwater[1]	30,900	05-27-92	100	100	--	--
--	Reconstituted saltwater[1]	29,700	09-22-92	--	--	100	100
S-1	Greenfields Main Canal	236	05-27-92	10	1	0	2
S-5	Drain (south of Freezeout Lake)	640	04-02-92	0	2	20	5
S-6	Drain at old Highway 89 (south)	3,170	04-02-92	0	9	0	26
S-7	Drain at old Highway 89 (middle)	4,770	04-02-92	0	17	10	58
S-7	Drain at old Highway 89 (middle)	3,570	06-02-92	0	12	0	36
S-11	Drain to Pond 5 at Highway 89	6,450	04-02-92	0	69	40	97
S-12	North Supply Ditch	1,820	04-03-92	0	14	0	15
S-12	North Supply Ditch	820	05-28-92	0	2	0	3
S-21	Muddy Creek pump station	635	05-28-92	22	2	10	4
S-30	Blackfoot Coulee	8,420	04-02-92	40	85	100	100
S-34	Priest Butte Lakes	8,890	04-06-92	0	81	20	99
S-34	Priest Butte Lakes	9,350	06-24-92	0	85	0	100
S-35	Seep east of Priest Butte Lakes	34,400	04-03-92	100	100	100	100
S-35	Seep east of Priest Butte Lakes	32,700	05-28-92	100	100	100	100
S-37	Freezout Lake WMA (Pond 5)	477	06-24-92	0	1	0	2
S-38	Freezeout Lake (north end)	5,360	04-07-92	9	47	0	87
S-38	Freezeout Lake (north end)	6,010	06-24-92	0	54	10	91
S-39	Freezeout Lake (south end)	5,160	04-07-92	0	37	0	82
S-39	Freezeout Lake (south end)	4,510	06-24-92	0	24	10	38
S-43	Tributary to Lake Creek	12,300	04-03-92	100	64	100	99
S-43	Tributary to Lake Creek	14,000	06-02-92	100	74	100	100
S-44	Lake Creek near Power	11,600	04-04-92	0	54	80	99
S-47	Benton Lake (Pool 2)	1,370	04-08-92	0	6	0	10
S-47	Benton Lake (Pool 2)	758	06-23-92	0	3	10	6
S-48	Benton Lake (Pool 3)	1,730	06-23-92	0	12	0	21
S-49	Benton Lake (Pool 5)	9,150	04-08-92	0	6	60	10

[1]Reconstituted saltwater formulated by adding 20.8 grams of Instant Ocean[R] to 1 liter of Giant Springs water.

Table 24. Chemical and physical measurements of water and ducklings during a 28-day exposure using surface water from the Sun River area, Montana

[Measurements of ducklings are arithmetic averages for surviving individuals. Abbreviations: g, gram; µg/g, micrograms per gram dry weight; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; mm, millimeter. Symbol: --, no data]

	Freezout Lake Wildlife Management Area			Benton Lake National Wildlife Refuge			Control
Analyte or measurement	Seep east of Priest Butte Lakes	Freeze-out Lake (south end)	Pond 5	Tributary to Benton Lake (Pool 4)	Pool 6	Pool 2	Giant Springs
Water - Day 0							
Specific conductance, in µS/cm	43,000	2,760	294	16,400	7,260	770	631
Chloride, in mg/L	282	70	3.3	734	141	9.8	6.3
Sodium, in mg/L	2,020	290	6.6	2,080	865	59	9.6
Sulfate, in mg/L	56,200	1,300	36	11,500	3,720	191	152
Magnesium, in mg/L	12,300	141	18	1,470	477	54	28
Selenium, in µg/L	530	5.5	.7	11	.9	.8	.8
Water - Day 13							
Specific conductance, in µS/cm	--	2,610	327	13,100	6,290	695	--
Chloride, in mg/L	--	60	2.5	826	161	8.8	--
Sodium, in mg/L	--	275	6.5	1,550	791	57	--
Sulfate, in mg/L	--	1,300	44	8,900	3,180	181	--
Magnesium, in mg/L	--	154	20	1,140	412	41	--
Selenium, in µg/L	--	21	1.0	2.2	1.0	.7	--
Water - Day 28							
Specific conductance, in µS/cm	43,000	2,630	365	15,500	5,920	693	630
Duckling - Day 1							
Body mass, in g	--	45	45	40	46	44	43
Culmen length, in mm	--	14	13	13	13	13	12
Tarsus length, in mm	--	28	27	28	29	28	27
Duckling - Day 7							
Body mass, in g	--	[1]172	164	[1]116	137	158	147
Culmen length, in mm	--	[1]23	22	[1]17	20	21	21
Tarsus length, in mm	--	40	39	[1]32	39	39	38
Duckling - Day 14							
Body mass, in g	--	[1]349	300	[1]207	323	[1]236	316
Culmen length, in mm	--	31	30	[1]26	29	28	29
Tarsus length, in mm	--	51	50	[1]44	50	[1]46	50
Duckling - Day 21							
Body mass, in g	--	461	435	[1]266	441	[1]369	482
Culmen length, in mm	--	35	34	30	34	33	33
Tarsus length, in mm	--	57	56	[1]50	57	[1]53	56
Duckling - Day 28 - Necropsy at conclusion of experimental exposure							
Survival, in percent	[2]0	92	100	100	100	100	92
Liver selenium, in µg/g	[2]2.5	4.5	4.3	4.1	3.8	4.0	3.8
Brain sodium, in µg/g	[2]9,730	6,380	6,170	6,340	6,370	6,450	6,570
Body mass, in g	--	607	533	[1]327	550	485	556
Liver mass, in g	--	24	22	[1]17	29	21	27
Culmen length, in mm	--	33	32	[1]28	32	31	33
Tarsus length, in mm	--	58	58	[1]50	58	55	59

[1]Significantly different from control (ANOVA, unplanned comparisons, $p < 0.05$).

[2]Due to 100-percent mortality in this treatment, data correspond to 72 hours of exposure.

group (table 24) for each measurement day (days 1, 7, 14, 21, and 28) of the exposure period were compared using the analysis of variance (ANOVA) procedure for nested unbalanced designs provided by SYSTAT (Wilkinson, 1987). The within-treatment mean square error was used as the error term in all ANOVA procedures. When the ANOVA among groups was found to be significant ($p < 0.05$), tests to identify significant differences between each treatment group and the control were performed.

All ducklings in the group drinking water from the seep east of Priest Butte Lakes died within 72 hours. Two ducklings from the other treatment groups died during the 28-day exposure period, but it is inconclusive as to whether they died from the drinking-water exposure. A duckling from the control group was found dead from an undetermined cause on the morning of day 6. A duckling from the group drinking water from the south end of Freezeout Lake was found dead on the morning of day 1. When necropsied, this individual was found to have sustained a head injury. However, it is not known whether the observed injury occurred before or after the death of this duckling.

None of the five surviving replicate treatment groups differed significantly (ANOVA, $p > 0.05$) from the control group for measures of body mass, tarsus length, or culmen length on day 1 of the exposure period (table 24). However, significant differences (ANOVA, $p < 0.05$) were found among the groups on days 7, 14, 21, and 28 for all measures (table 24). Ducklings from the group drinking water from the tributary to Benton Lake Pool 4 were significantly smaller than the control group for all measures on day 28. Ducklings from the groups drinking water from the south of Freezeout Lake, Freezout Lake WMA Pond 5, Benton Lake Pool 2, and Benton Lake Pool 6 did not differ significantly from the controls in any measure after 28 days of exposure.

Liver mass was measured at necropsy on day 28, and only a marginally significant difference was found among groups (ANOVA, $p = 0.053$). Only the liver masses of ducklings drinking water from the tributary to Benton Lake Pool 4 were significantly smaller than the control group ($p < 0.025$).

Liver selenium concentrations among the surviving groups of ducklings were not significantly different (ANOVA, $p = 0.318$). Mean selenium concentrations for each group (table 24) were substantially less than the 8.0 μg/g dry weight concentration calculated by J.P. Skorupa and others (U.S. Fish and Wildlife Service, written commun., 1993) as the mean background concentration of selenium in the livers of ducks collected from relatively uncontaminated wetlands. The low selenium concentrations in livers of captive mallard ducklings drinking from the study area but eating commercial food indicate that the higher selenium concentrations measured in ducks captured in the study area may result primarily from dietary intake of selenium-laden food-chain organisms rather than by ingestion of waterborne selenium.

Dissolved-sodium concentrations ranged from 6.5 to 2,080 mg/L among the six drinking-water treatments (table 24). Mean sodium concentrations in water from the seep east of Priest Butte Lakes and the tributary to Benton Lake Pool 4 exceeded the 1,500 mg/L concentration at which decreased feather growth occurred in mallard ducklings (Mitcham and Wobeser, 1988a). No significant difference was found among the surviving groups for brain sodium concentration (ANOVA, $p = 0.358$). However, brain sodium concentrations in the ducklings that drank water from the seep east of Priest Butte Lakes and died within 72 hours of exposure were significantly higher than brain sodium concentrations in pre-exposure controls sacrificed on day 1 (t-test, $p < 0.001$) and substantially higher than sodium concentrations in ducklings exposed for 28 days at all of the other sites, including the tributary to Benton Lake Pool 4 which had a similar sodium concentration in the water. The order in which those ducklings died was significantly correlated with their brain sodium concentrations (Spearman's $r = 0.672$, $p < 0.02$). Therefore, duckling brain sodium concentrations can be used to diagnose the occurrence of salt toxicosis in ducklings.

Although the specific element causing death or growth inhibition for affected ducklings is unknown, salinity, as indicated by specific-conductance values of sample water (table 24), appears to correlate with observed toxic effects. The water from the seep east of Priest Butte Lakes had a specific conductance of 43,000 μS/cm, and was fatal to the ducklings within 72 hours. Water from the tributary to Benton Lake Pool 4, with a mean specific conductance of 15,500 μS/cm, did not cause duckling mortality but was associated with reduced duckling growth. Both of these sites are in non-irrigated basins. Water from Benton Lake Pool 6, with a mean specific conductance of 5,920 μS/cm, showed no overt toxic effects.

The correlation of salinity to mortality is consistent with the findings of Mitcham and Wobeser (1988b), who reported that 1-day-old mallard ducklings exposed to natural saline water with a specific conductance of 35,000 μS/cm died within 60 hours, and that those exposed to water with a specific conductance of 67,000 μS/cm died within 30 hours. Ducklings in the test that were exposed to water having a specific conductance of 20,000 μS/cm experienced a 60-percent mortality rate after 14 days of exposure.

Mitcham and Wobeser (1988a) found that 14-day-old mallard ducklings exposed to water with a specific conductance of 15,250 µS/cm stopped eating, became inactive, and sometimes died.

Swanson and others (1984) found that mallard ducklings exposed to lake water with a specific conductance of 17,000 µS/cm had significantly lower growth rates than did control ducklings. The mean mass in their treated group was 42-percent less than the mean mass in their control group after 9 days. This study found similar 35-percent and 41-percent reductions in body mass of captive ducklings drinking water from the tributary to Benton Lake Pool 4 group (specific conductance of 15,500 µS/cm) compared to ducklings of the control groups after 14 and 28 days of exposure, respectively.

Most duckling mortality documented in this study and others occurred within the first few days of exposure to highly saline water. Riggert (1977) suggested that the salt gland of a duckling does not become capable of excreting salt until it is 6 days old, although Mitcham and Wobeser (1988a) reported that mallard ducklings as young as 4 days old may develop functional salt glands when exposed to highly saline water. However, exposure to moderately saline water in this study adversely affected duckling growth during the entire 28-day exposure. These results represent the effects of saline water on ducks at what may be their most susceptible time of life.

FATE AND BIOACCUMULATION OF SELENIUM IN WETLANDS

Selenium transported to wetlands by surface inflows is affected by geochemical and biological processes that determine its fate in water and bottom sediment and, ultimately, in organisms utilizing the wetlands. Organisms assimilate selenium from water, sediment, and dietary items and accumulate it within tissues where it can cause possible adverse physiological effects. Examination of selenium concentration patterns in water, sediment, and biota can give insight to the complex biochemical transfer of selenium between physical and biological matrices and, therefore, lead to identification of the potential linkages between environmental exposure to selenium and bioaccumulation in aquatic organisms.

Fate of Selenium in Water and Bottom Sediment

Selenium concentrations in water of wetlands in Freezout Lake WMA and Benton Lake NWR generally are low compared to the biological risk level (fig. 45), with the exception of Priest Butte Lakes. The areas most distant from selenium inflows in each wildlife area (north end of Freezeout Lake and Benton Lake Pools 3-6, figs. 43 and 44) are shown by the left-most bar in each cluster of figure 45. Selenium concentrations commonly were lower in these two areas compared to wetland sites closer to selenium inputs. The bar(s) on the right in each cluster of fig. 45 represent sites that receive direct inputs of selenium from either irrigation return flow, natural runoff, or saline seeps caused by farming with alternate crop-fallow rotation. Most of the wetland sites close to inputs of selenium had higher selenium concentrations in water and bottom sediment than did sites farther from selenium inputs. High selenium concentrations in wetlands generally correlate with high selenium concentrations in supply water. The highest geometric mean selenium concentrations in water and biota occurred in Priest Butte Lakes, where virtually all of the inflowing selenium is derived from seeps draining non-irrigated land.

The lower dissolved-selenium concentrations in most wetlands compared to concentrations in supply water is consistent with removal processes such as selenium enrichment of bottom sediment or assimilation into biological tissue. The rate of selenium immobilization in wetlands is uncertain, but the low concentrations measured in the smaller wetlands, where the distance from irrigation drain to sampling location is small, may indicate that conversion of dissolved selenium to insoluble forms occurs rapidly over a short distance. Therefore, most selenium accumulation in bottom sediment or biota may occur in near-shore areas. Near-shore removal of selenium could cause a decreasing concentration gradient in water with distance from the mouths of inflows, and could explain why water-sampling sites that are generally centrally located in wetlands have uniformly low concentrations, with the exception of sites in Priest Butte Lakes. Limited water-quality data from samples collected near shore in Freezeout Lake (south end) as part of the duckling-bioassay tests in this study (Lambing and others, 1994, table 37) are consistent with this hypothesis. These near-shore samples identified concentrations greater than those reported for routine sampling sites. Similarly, if near-shore selenium immobilization occurs in wetlands, then selenium concentrations in bottom sediment near the mouths of inflows that carry substantial selenium loads may be higher than the selenium concentrations reported for centrally located sampling sites. Consequently, the concentrations of selenium in water and bottom sediment and potential biological impacts may be greatest in near-shore areas of some wetlands.

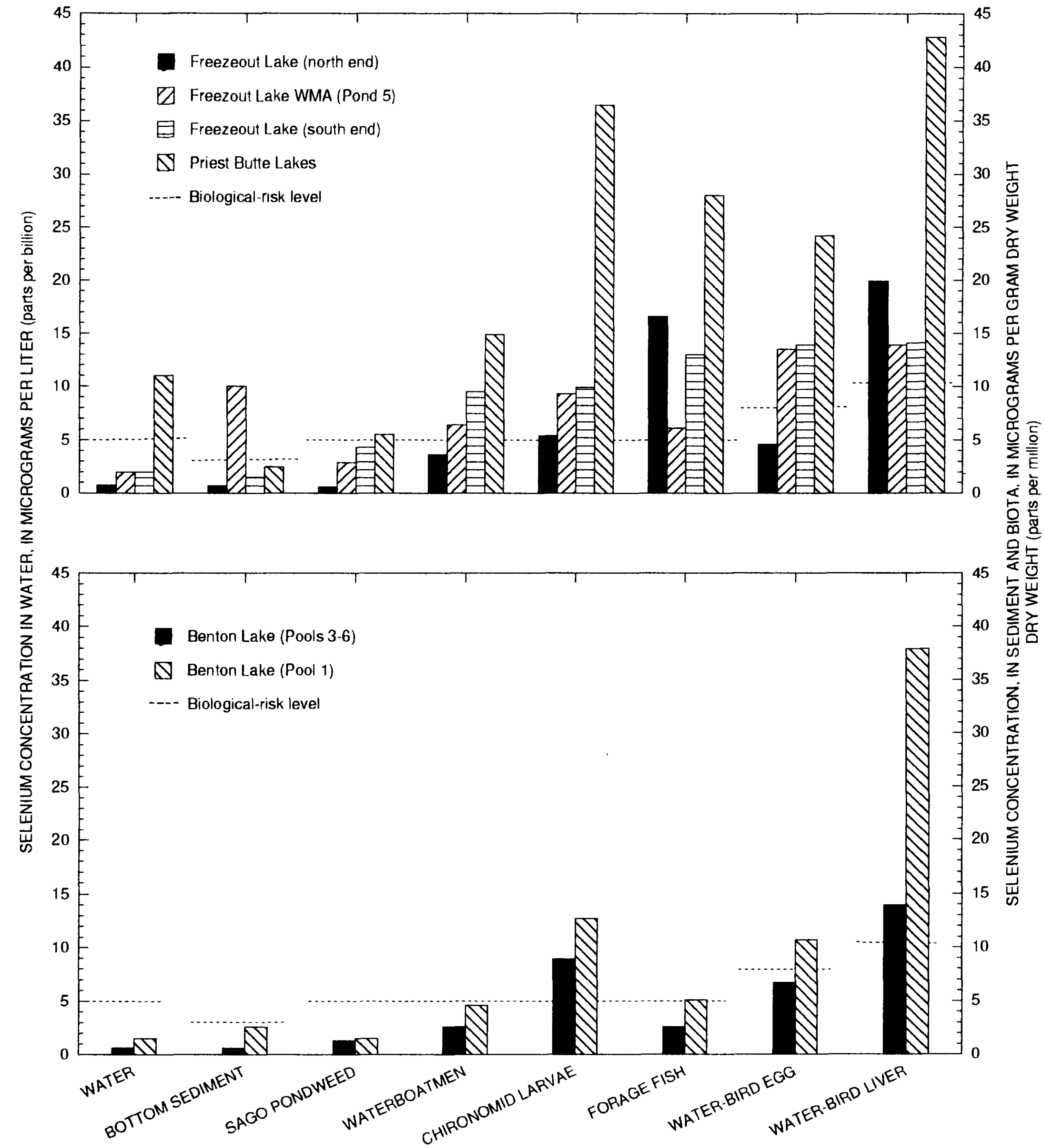


Figure 45. Geometric mean selenium concentration in water, bottom sediment; and biota from sites in Freezout Lake Wildlife Management Area (top) and Benton Lake National Wildlife Refuge (bottom), Montana. Data for samples of bird eggs and livers from Freezeout Lake (north end) and Priest Butte Lakes are for American avocets. All other water-bird data are for samples of eared grebes. Biological-risk levels are impairment thresholds from tables 1 and 3.

Selenium Bioaccumulation and Ecological Risks

Geometric mean selenium concentrations in various biological matrices from wetlands in Freezout Lake WMA and Benton Lake NWR (fig. 45) indicate that selenium residue in at least some biological tissue from most wetland units has attained concentrations that exceed biological risk levels. Similar to water and bottom sediment, selenium concentrations in biota of the wetland units most distant from selenium inflows are commonly lower than those receiving direct inputs of selenium. Although drainage from irrigated land contributes most of the selenium to wetlands, the wetland with the highest selenium concentrations in most matrices and that has potentially the highest ecological risk receives most of its selenium from non-irrigated land.

Selenium concentrations in organisms of various trophic levels follow broadly similar patterns, but exhibit several inconsistencies which indicate that selenium transfer through trophic levels is variable among sites. Inconsistent patterns of bioaccumulation may result from selenium concentrations that are inadequately defined due to small sample sizes at several sites, the grouping of several species that may have different response characteristics into single trophic-level categories, or the existence of spatial concentration gradients in water and bottom sediment within a wetland unit that are not well-represented by samples collected at a single, centrally located sampling site. Because of the potential limitations in correlations between matrices, only general observations are possible rather than firm conclusions.

Selenium concentrations in biota are one or more orders of magnitude higher than concentrations in water. Also, selenium concentrations in biota generally correlate better with selenium concentrations in water than in bottom sediment at most sites in Freezout Lake WMA. The correlation between selenium concentrations in bottom sediment and that of both rooted aquatic plants (sago pondweed) and bottom-dwelling invertebrates (chironomid larvae) is poor at Freezout Lake WMA Pond 5, which had the highest selenium concentration in bottom sediment. However, a consistent pattern that is evident for all sites is an increase of selenium concentration from aquatic plants (sago pondweed) to aquatic invertebrates (waterboatmen and chironomid larvae). This pattern indicates a greater capacity for selenium assimilation by insects relative to plants and implies that ingestion of aquatic invertebrates probably is a more significant pathway than ingestion of plants for the transfer of selenium to water birds. The pattern of selenium concentrations among the different sites for aquatic plants and insects is similar to that for water, possibly indicating that organisms in lower trophic levels derive their selenium primarily from dissolved selenium. Selenium concentrations in bottom-dwelling insects (chironomid larvae) were higher at all sites than concentrations in water-column insects (waterboatmen), which implies that some selenium in chironomid larvae may be derived from bottom sediment even though direct correlation with bottom-sediment selenium concentrations is poor.

In forage fish, selenium concentrations generally were lower than those in chironomid larvae, but were higher than those of waterboatmen. Assuming that forage fish eat more water-column insects than bottom-dwelling insects, then accumulation of selenium through these trophic levels is supported. The only sites where selenium concentrations in fish were higher than in chironomid larvae were the two Freezeout Lake sites (north end and south end). The significance of this observation is uncertain because of the small sample size for fish.

Invertebrates are an important dietary item for water birds and, therefore, comparisons of selenium concentrations between these biota groups may indicate the effectiveness of trophic-level transfer of selenium. All selenium concentrations were higher in juvenile water-bird livers than in invertebrates. Consequently, dietary selenium apparently is concentrated relatively effectively in the livers of water birds. Selenium concentrations in water-bird eggs also were higher than concentrations in waterboatmen, indicating indirect transfer from dietary items to adult water birds to eggs. In contrast, selenium concentrations were lower in all samples of water-bird eggs compared to chironomid larvae, with the exception of two Freezout Lake WMA sites (south end of Freezeout Lake and Pond 5). The proportion of these two types of invertebrates in water-bird diets is uncertain, but the inconsistent pattern of bioaccumulation for invertebrates and eggs indicates that the transfer of selenium from dietary items to water-bird organs is more efficient than the transfer from adult organs to embryonic tissue.

The similarity between selenium concentrations in biological matrices and water is greatest for sago pondweed, waterboatmen, forage fish, and water-bird eggs. Selenium concentrations in forage fish from the north end of Freezeout Lake appear to be an exception to this trend, but the data for this site represent only one sample and may not be sufficiently representative of typical concentrations. The incremental increase in selenium accumulation from sago pondweed to waterboatmen to water-bird eggs represents an approximate doubling of concentration in each trophic level. Accumulation rates from waterboatmen to forage fish generally are smaller and less consistent.

Water-bird livers had somewhat different trends in selenium concentration than sago pondweed, waterboatmen, forage fish, and water-bird eggs. The nesting and feeding habits of the particular species of water birds sampled may be responsible for this difference. Bird species, such as eared grebes and American avocets, that have limited territories and that selectively feed on aquatic invertebrates, have the greatest potential to accumulate high selenium residues compared to other water-bird species that utilize larger feeding territories and have more omnivorous feeding habits. The highest concentrations of selenium in water-bird livers occurred in the two wetland units (Priest Butte Lakes and Benton Lake Pool 1) that receive substantial quantities of poor-quality runoff from non-irrigated land. Selenium accumulation in resultant young-of-the-year livers generally was substantially greater than in eggs, indicating that feeding in these two areas during the fledging period results in more selenium accumulation than the transfer of selenium from female adults to eggs during the egg-formation period.

Priest Butte Lakes, Freezout Lake WMA Pond 5, the south end of Freezeout Lake, and Benton Lake (Pool 1) most commonly exhibited characteristics indicative of excessive selenium bioaccumulation. Aquatic invertebrates, forage fish, water-bird eggs, and water-bird livers had selenium concentrations that were elevated relative to other parts of the study area and environmental reference concentrations for biological risk. Geometric mean selenium concentrations in aquatic invertebrates, forage fish, water-bird eggs, and water-bird livers from these sites exceeded, in all but one case, an applicable biological risk level (table 3).

The highest selenium concentrations for all trophic levels commonly occurred in organisms collected from Priest Butte Lakes, which also had the highest selenium concentrations in water. Almost all selenium in Priest Butte Lakes water and bottom sediment is thought to come from drainage from adjacent non-irrigated farm land. High selenium residues in fish, fish-age characteristics, and the population structure provide circumstantial evidence that fish reproduction has been impaired. The type of breeding-bird habitat on islands and adjacent land surrounding Priest Butte Lakes favors preferential use by nesting American avocets, Canada geese, and their young. Consequently, these species probably are more susceptible to exposure and bioaccumulation of selenium at Priest Butte Lakes than other water-bird species. American avocets nesting at Priest Butte Lakes accumulated the highest concentrations of selenium in their eggs.

Although selenium bioaccumulation at some other wetland sites in both refuges has caused selenium residues to exceed concern levels, direct effects on water-bird reproduction were not detected based on the observations made during this study. Similarly, indications from bioassays of potential toxicity at some wetland sites do not correlate with observed overt effects in water birds. The reason that the relatively high selenium residues and potential toxicity of water from some sites are not producing observable effects at many sites is unknown.

POTENTIAL IMPACTS OF ALTERNATE IRRIGATION-MANAGEMENT PRACTICES ON WETLANDS

The potential impact of irrigation management on wetlands is dependent on the sources, mobilization processes, and solubility controls that affect constituents of concern. The conditions that affect the transport of constituents vary in different irrigated areas because of geologic differences or, possibly, methods of irrigation. Results from this study provide some preliminary insights into possible effects of various irrigation practices on the mobilization and transport of constituents by irrigation drainage.

Irrigated Gravel

Under current (1994) irrigation conditions, water quality in the gravel aquifer of the Greenfields Bench is not expected to change over the next several decades. The current conditions of high recharge rates from irrigation and rapid flow rates through the gravel presumably have existed since irrigation began in 1920. Ample time probably has elapsed for flushing of most soluble salts that had accumulated in the soil prior to irrigation. Current ground-water chemistry probably reflects a near-steady-state condition where ongoing ion exchange and weathering or dissolution of minerals contribute to the chemical evolution of water that flows from canals and fields to aquifers, wells, and groundwater discharge areas.

Possible changes to irrigation management that could reduce selenium loading from irrigated parts of the Greenfields Bench to wetlands include improving irrigation efficiency and reducing the amount of irrigated land. However, the net reduction in selenium loading to Freezout Lake WMA would be minimal because the Greenfields Bench contributes only a small part of the total selenium discharged to the WMA.

Changes in irrigation management may affect not only constituent loads discharged from the Greenfields Bench, but also the availability of water for domestic supplies because of reduced recharge to the gravel aquifer. Currently, some shallow domestic wells on the Greenfields Bench go dry in late winter or early spring as water levels in the aquifer decline. Reducing the amount of irrigation-induced recharge could result in shortages of domestic ground-water supplies in some areas, especially in dry years.

Irrigated Glacial-Lake Deposits

The source of dissolved solids and selenium in water from glacial-lake deposits probably is dissolution of pre-irrigation evaporative salts. Under current conditions, concentrations of these constituents in irrigation drainage may decrease slowly with time as irrigation water continues to flush the salts out of the system and into the wetlands of Freezout Lake WMA. Ongoing weathering of shale detritus and the relatively long ground-water residence times probably will keep concentrations of dissolved solids and selenium from decreasing, at least in the near future, to the lower levels that occur in the gravel under the Greenfields Bench.

The potential to reduce selenium and dissolved-solids loading to Freezout Lake WMA probably is much greater for the irrigated glacial-lake deposits than the irrigated gravel of the Greenfields Bench because most of the selenium discharged to the WMA comes from the glacial-lake deposits (fig. 35). Several potential alternatives to existing irrigation management exist that potentially could reduce loading to the WMA.

Improvements in irrigation efficiency potentially could reduce constituent loads in irrigation drainage because the volume of irrigation-induced recharge, and consequently, irrigation drainage, would be reduced. However, in the case of selenium and dissolved solids, the load discharged to wetlands may or may not change. The load of any constituent discharged in subsurface drainage is a function of both the volume of the drainage and the constituent concentration in the drainage and, therefore, a reduction in drainage volume may not necessarily lead to a commensurate reduction in constituent load if the concentration of the constituent increases. The concentration of a constituent in subsurface drainage depends not only on the amount of water available for dilution but also on the predominant release mechanism for the constituent and whether a solubility control, such as mineral precipitation or adsorption, exists that would limit increases in the constituent concentration. If no solubility control exists for a constituent and the rate at which the constituent is released to pore water or ground water remains unchanged, then no net reduction in constituent loading would occur when irrigation-induced recharge is decreased. For example, under conditions of less recharge, precipitation of carbonate minerals likely would keep concentrations of calcium and bicarbonate from increasing and, thereby, loads of these constituents discharged to drains would decrease. Conversely, constituents such as sodium, sulfate, and selenium, which have no likely solubility controls in the ground-water systems of the study area, would tend to increase in concentration because of less dilution. In this circumstance, decreased water volume possibly would be offset by increased constituent concentrations, and the resulting constituent loads of sodium, sulfate, and selenium in subsurface drainage might remain near current levels.

Water in glacial-lake deposits in irrigated areas, such as near sites W-2 and W-23, has high concentrations of magnesium, sodium, and sulfate and is undersaturated (table 25) with respect to the sulfate minerals that might precipitate to keep concentrations of these constituents at current levels if recharge were reduced. Selenium concentrations also might increase if recharge were decreased because selenium is not limited by solubility controls in the oxidizing conditions that are prevalent in the glacial-lake deposits. In this circumstance, decreased water volume might be offset by increased selenium and dissolved-solids concentrations, and the total load of these constituents discharged to drains might remain near current levels. Therefore, improving irrigation efficiency may not reduce the selenium and dissolved-solids load discharged to drains from irrigated glacial-lake deposits.

Another possible scenario of irrigation management is reduction of the amount of irrigated land. Again, assuming that constituents are released in the unsaturated zone, reductions in irrigated acreage may decrease the amount of soluble constituents leached to ground water and may decrease constituent loads discharged from ground water to drains and wetlands. Ground-water recharge would be almost eliminated in areas where irrigation is discontinued, and the delivery of soluble constituents from the unsaturated zone to ground water may be greatly decreased in these areas. Total constituent loads in irrigation drainage would be decreased because of the decreased size of the irrigated area. Therefore, discontinuing irrigation in selected areas possibly could reduce constituent loads discharged to Freezout Lake WMA. If irrigation is discontinued in small parts of this area, water quality in the glacial-lake deposits probably would not change substantially because of the concurrent decrease in both ground-water recharge volumes and amount of soluble minerals delivered to the aquifer. The chemical

Table 25. Results of thermodynamic calculations for selected water samples associated with irrigated land near Freezeout Lake, Montana

[Saturation indices were calculated using the computer program WATEQ4F (Ball and Nordstrom, 1987). The degree of saturation is expressed by the saturation index; undersaturation is expressed as a negative saturation index, saturation is expressed as a value near zero, and supersaturation is expressed as a positive value]

Site number (figs. 6, 25)	Date	Saturation index						
		Calcite [$CaCO_3$]	Dolomite [$CaMg(CO_3)_2$]	Quartz [SiO_2]	Halite [NaCl]	Gypsum [$CaSO_4 \cdot 2H_2O$]	Mirabilite [$Na_2SO_4 \cdot 10H_2O$]	Thenardite [Na_2SO_4]
				Irrigation water				
S-1	07-23-91	0.55	0.62	-0.01	-11.38	-2.82	-11.07	-12.53
			Water from the Quaternary and Tertiary(?) gravel aquifer of the Greenfields Bench					
W-4A	03-10-92	.26	1.17	.46	-8.40	-2.66	-8.46	-10.15
W-5A	03-10-92	.17	.76	.41	-8.69	-2.64	-8.40	-10.28
				Water from Quaternary glacial-lake deposits				
W-1A	04-16-92	.37	.98	.48	-9.60	-2.10	-7.97	-9.77
W-2A	04-16-92	.41	1.03	.51	-5.99	-.25	-3.72	-5.49
W-23	02-26-91	-.11	.19	.47	-7.39	-1.38	-5.38	-7.17
W-23	08-07-91	.45	1.19	.49	-7.03	-.93	-4.93	-6.67

characteristics of ground water in glacial-lake deposits would continue to be determined by recharge and mineral leaching from the remaining irrigated areas.

If selenium in ground water and irrigation drainage is derived from the cyclic movement of water across the interface between glacial-lake deposits and the underlying shale, any management action that would lower the peak elevation of the water table in the glacial-lake deposits or reduce the amount of time each year when hydraulic gradients are downward might be effective to some extent in reducing the amount of selenium derived by this mechanism. Either improvements in irrigation efficiency or reductions in irrigated acreage would affect these water-level changes in the glacial-lake deposits.

Selenium and Salt Accumulation in Wetlands

Water quality in shallow wetlands of semi-arid regions typically can be improved by increasing water supplies to flush the system of soluble constituents that occur in high concentrations. Dissolved solids, which occur in high concentrations in some wetland units due to evapoconcentration, were demonstrated to cause toxic responses in biota. Unlike selenium, data from this study indicate that dissolved solids remain in solution, rather than being removed by biogeochemical processes. Consequently, dissolved solids probably could be removed effectively from wetlands if additional direct spills were supplied to increase flushing rates. The additional water also would dilute the dissolved-solids concentration, thus reducing the potential for salt toxicosis. Flushing with increased water supplies from the irrigation project could be accomplished at Freezout Lake WMA through the drainage channel constructed between Priest Butte Lakes and the Teton River. Because Benton Lake NWR has no outlet, increased supplies of irrigation drainage would not provide any flushing, but probably would result in lower ambient concentrations of dissolved solids through dilution. However, because the salts delivered to Benton Lake NWR cannot be flushed, salinity levels may increase over time, even with supplemental supplies of low-salinity water.

In contrast to dissolved solids, flushing may not be a feasible option for controlling selenium accumulation in wetlands. Data from this study indicate that the selenium discharged to most of the wetlands in Freezout Lake WMA and Benton Lake NWR could not be flushed from the wetlands, even if water deliveries were increased. Because dissolved selenium is rapidly converted to an immobile form in the wetlands, most selenium delivered to wetlands will continue to accumulate in bottom sediment. Increasing water supplies for greater flushing probably would not inhibit selenium accumulation in wetlands and, instead, may cause increased selenium accumulation in wetlands if the additional water contains any selenium. The most effective strategy to minimize or eliminate future selenium accumulation in wetlands probably is to decrease or eliminate selenium discharge to the wetlands.

Although water-column concentrations of selenium at most of the wetlands probably will continue to remain below biological-risk levels, selenium bioaccumulation in bottom sediment and the subsequent risk to bottom-dwelling invertebrates and water birds could either remain similar to current conditions or increase with time.

In contrast to the other wetlands, flushing may be somewhat effective in reducing selenium accumulation in Priest Butte Lakes because the rate of selenium immobilization apparently is slower than in the other wetlands. As a result, a substantial amount of selenium is retained in solution in the water of Priest Butte Lakes and might reasonably be expected to be removed if flushed to the Teton River. However, increased releases of both selenium and dissolved solids from Priest Butte Lakes potentially could have a deleterious effect on the Teton River. These potential impacts have not been examined.

SUMMARY AND CONCLUSIONS

The Sun River Irrigation Project in west-central Montana has been studied as part of the U.S. Department of the Interior National Irrigation Water Quality Program to address water-quality problems related to irrigation drainage. This report presents the interpretive results of a detailed process-oriented study conducted during 1990-92 to determine the extent, magnitude, sources, pathways and potential fate of selenium and other potential contaminants associated with drainage from irrigated and non-irrigated land in and near the Greenfields Irrigation Division of the Sun River Irrigation Project, Freezout Lake WMA, and Benton Lake NWR. Water-quality data from a 1986-87 reconnaissance study indicated that selenium was the primary trace element that posed potential risks to human health, fish, and wildlife. Selenium was the focus of this 1990-92 detailed study, but dissolved solids and other trace elements also were examined.

Most of the irrigated land in the study area is on the Greenfields Bench, which is capped by Tertiary(?) or Quaternary gravel. However, much of the non-irrigated area draining to the wetlands of the wildlife areas is underlain by seleniferous marine shale of the Cretaceous Colorado Group or by Quaternary glacial deposits derived from the Colorado Group. Irrigation water is diverted from the Sun River and delivered to farms within the Greenfields Irrigation Division. Irrigation return flow from the Greenfields Bench flows primarily to Muddy Creek and the Sun River. However, surface and subsurface drainage from irrigated gravel in the southwest and northwest corners of the Greenfields Bench flows to Freezout Lake WMA. Water from irrigated glacial deposits in the area between Freezeout Lake and the Greenfields Bench also drains to Freezout Lake WMA. Supplemental water supplied to Benton Lake NWR by trans-basin diversion from Muddy Creek is composed primarily of irrigation return flow from the Greenfields Bench. Non-irrigated areas underlain by shale and glacial deposits also provide natural runoff to the wetlands and Muddy Creek. In many areas, the natural runoff is augmented by drainage from saline seeps caused by alternate crop-fallow (dryland) farming.

Soil

Soil samples from irrigated farmland on the western part of the Greenfields Bench generally had the lowest concentrations of total and water-extractable selenium of all areas sampled. The low concentrations in these soils are attributed to low selenium content in the gravel deposits that underlie the Greenfields Bench. Although the selenium concentrations are low, selenium solubilized from soils may contribute to the selenium occurring in underlying ground water.

The soils derived from glacial deposits between the Greenfields Bench and Freezout Lake WMA had higher concentrations of total selenium as well as greater variability than soils of the Greenfields Bench. In addition, water-extractable selenium constituted a larger percentage of the total selenium. The higher concentrations and the large variability of both total and water-extractable selenium in the soils result from the high selenium content of the glacial deposits. Although spatial and depth distribution of selenium is erratic in this area, chemically mobile forms of selenium are available in many locations to ground water. In areas underlain by the Colorado Group or glacial deposits, selenium concentrations in soils from non-irrigated farmland and rangeland were similar to those from irrigated farmland.

Soils west of Freezout Lake WMA are derived from the Upper Cretaceous Montana Group. Soils in this area had low selenium concentrations and do not appear to be significant sources of selenium to the wetlands.

Alkali-flat and saline-seep soils on the east side of Freezout Lake WMA, where glacial deposits are the primary parent material, had uniformly high total and water-extractable selenium concentrations. Soil from a saline seep associated with non-irrigated farming east of Priest Butte Lakes had the highest total-selenium concentration of all sampling sites.

Ground Water

Water in the gravel aquifer capping the Greenfields Bench is derived primarily from irrigation-induced recharge, flows quickly through the aquifer, and discharges to drains and seeps around the perimeter of the Bench. Most ground water in the gravel aquifer flows towards Muddy Creek and the Sun River, but ground-water discharge from small areas in the northwest and southwest corners of the Greenfields Bench flows to Freezout Lake WMA. In these areas, water quality generally is good, with only minor chemical changes occurring to the irrigation water as it passes through the gravel. Changes in the major-ion composition and increases in dissolved-solids concentration are due primarily to geochemical processes such as ion exchange and dissolution of carbonate minerals that occur in the unsaturated zone. Concentrations of dissolved solids were relatively low and ranged from 194 to 530 mg/L. Mixing with more saline water from the underlying shale may occur locally. Nitrate concentrations generally are elevated (0.54-12 mg/L), likely from leaching of fertilizer. Redox conditions are sufficiently oxidizing in the gravel to keep selenium, if it occurs, in solution. Dissolved-selenium concentrations in the western third of the Bench were low, generally less than 3 μg/L, except in the northwest corner of the Bench where concentrations ranged from 2-18 μg/L.

The occurrence of dissolved selenium in the northwest corner of the Greenfields Bench may be important because ground-water discharge from this area flows to Freezout Lake WMA. The source of selenium in this part of the aquifer probably is either underlying shale, from which selenium is released by cyclic movement of oxidized water between gravel and shale, or by shale detritus being weathered in the unsaturated zone. Pre-irrigation evaporative salts that likely contained selenium probably have been flushed from the gravel soils and aquifer during the decades of irrigation due to rapid flow rates and probably are not a significant source of the selenium. Selenium concentrations in water in the underlying shale are low (<1 μg/L) due to reducing conditions and, therefore, upward flow is not transporting appreciable amounts of selenium to the gravel.

Glacial-lake deposits between the Greenfields Bench and Freezeout Lake are less than 20-ft thick and overlie Colorado Group shale. Irrigation water is the primary source of recharge and the primary flow direction is assumed to be towards Freezeout Lake. Redox conditions are oxidizing in the glacial-lake deposits and dissolved-selenium concentrations in water in the aquifer were as high as 190 μg/L. The possible sources of dissolved selenium are the same as those identified for the gravel aquifer of the Greenfields Bench, although the relative contributions from each source probably are different. Based on the high concentrations of sodium, magnesium, and sulfate, and the correlation between concentrations of selenium and concentrations of these major ions, the most likely source of selenium is dissolution of soluble pre-irrigation evaporative salts. Ground water flows more slowly in the glacial-lake deposits in comparison to the gravel, and irrigation probably has not yet flushed these salts out of the aquifer. More shale detritus and longer ground-water residence times in glacial-lake deposits, as compared to the gravel aquifer, could also contribute to the higher concentrations of dissolved selenium. Concentrations of dissolved solids are high in glacial-lake deposits and are derived from the same sources as the selenium. Based on similarities in water chemistry, the primary source of base flow to the numerous drains in this area is drainage from glacial-lake deposits and not from the underlying shale.

Colorado Group shale and local areas of glacial drift constitute a shallow ground-water system that discharges poor quality water to seeps and channels throughout the non-irrigated Benton Lake basin. Geochemical reactions result in mostly acidic ground water with high concentrations of magnesium, sodium, sulfate, and several trace metals. Selenium concentrations are high due to the high selenium concentrations in the Colorado Group and the oxidizing conditions in shallow ground water. Crop-fallow farming practices increase recharge, thereby increasing the amount of dissolved solids and selenium transported by ground water to discharge areas. Benton Lake probably is not a significant source of recharge to shallow ground water, and contaminants transported by Lake Creek to Benton Lake most likely do not leave the lake by ground-water flow.

Surface Water and Bottom Sediment

Irrigation supply water from the Sun River is of good quality, with dissolved-solids concentrations ranging from 100 to 150 mg/L and selenium concentrations less than the minimum reporting level of 1 μg/L. Irrigation return flow from gravel of the Greenfields Bench had median concentrations of dissolved solids (414 mg/L) and selenium (3 μg/L) that represented about a threefold increase over that of supply water from the Greenfields Main Canal. Overall, selenium concentrations in streams and drains across the Greenfields Irrigation Division ranged from <1 to 27 μg/L, with the higher concentrations occurring in three localized areas—Blackfoot Coulee, Muddy Creek, and the northwest corner of the Greenfields Bench. Water in Blackfoot Coulee and Muddy Creek is derived partly from natural runoff from non-irrigated land. Muddy Creek, whose flow consists mostly of irrigation return flow from gravel, had selenium concentrations in water of 2 to 10 µg/L. Primary drinking-water MCL's were not exceeded in irrigation return flow from gravel. The aquatic-life chronic criterion of 5 µg/L for selenium was exceeded in several samples from Blackfoot Coulee, Muddy Creek, and the northwest corner of the Greenfields Bench. No other aquatic-life criteria were exceeded in irrigation return flow from gravel.

Irrigation return flow from glacial deposits had a median concentration of dissolved solids (2,870 mg/L) that represented a twentyfold increase over that of irrigation supply water. The median selenium concentration of 108 µg/L was about one hundred times greater than that of the supply water. Selenium concentrations during the irrigation season, when drainage volumes are at a maximum, were substantially lower (12 to 21 µg/L) than the median concentration, but still were moderately elevated. Irrigation return flow from glacial deposits is not used as domestic drinking-water supply and probably does not pose a human-health risk. Selenium concentrations, however, exceeded the acute aquatic-life criterion of 20 µg/L in about 90 percent of the samples. No other aquatic-life criteria were exceeded.

Natural runoff flowing to Freezout Lake WMA from non-irrigated land provides small quantities of water relative to irrigation drainage in most years. In natural runoff from the Montana Group west of Freezout Lake WMA, dissolved-solids concentrations ranged from 1,210 to 2,330 mg/L and selenium concentrations ranged from less than 1 to 2 µg/L. In contrast, natural runoff from non-irrigated glacial deposits east of Freezout Lake WMA were more saline and had much higher selenium concentrations. Dissolved-solids concentrations as high as 55,700 mg/L and selenium concentrations as high as 1,000 µg/L were measured in a seep discharging to Priest Butte Lakes. All samples from the seep and one sample from a tributary to Muddy Creek greatly exceeded the acute criterion for selenium; however, no other trace-element concentrations exceeded criteria.

The wetlands of Freezout Lake WMA receive the combined inputs of irrigation return flow, precipitation runoff, direct precipitation on the wetlands, and discharges from saline seeps. Irrigation return flow, including direct spills of irrigation supply water, provides the bulk of water to the wetlands in most years. Dissolved-solids concentrations increased in a downgradient direction within the interconnected wetlands of Freezout Lake WMA due to evapoconcentration of major ions. Unlike dissolved solids, no pattern of increasing selenium concentrations occurred through the wetlands. Although maximum selenium concentrations were measured in Priest Butte Lakes (median of 10 µg/L), other wetlands had consistently low concentrations of 2 µg/L or less. The lack of an increasing concentration gradient for selenium indicates that processes other than evaporation are controlling selenium concentrations in the wetlands. Priest Butte Lakes are the only wetlands in Freezout Lake WMA in which selenium concentrations in water exceeded the aquatic-life chronic criterion.

Benton Lake receives natural runoff from its non-irrigated basin, water pumped to Lake Creek from Muddy Creek, and direct precipitation on the lake. During the below-normal precipitation conditions of 1991-92, 94 percent of the total inflow to Benton Lake was pumped from Muddy Creek, which consists mostly of irrigation return flow from the Greenfields Bench. In comparison, long-term average pumped volumes represent only about 54 percent of the estimated annual inflow.

Water quality in Lake Creek during periods of pumping was very similar to that of irrigation return flow from gravel. The median dissolved-solids concentration of pumped water was 420 mg/L compared to 9,920 mg/L in natural runoff. The median selenium concentration in pumped water (3 µg/L) also was much lower than that of natural runoff (90 µg/L). No aquatic-life criteria were exceeded in Lake Creek during pumping, whereas more than 75 percent of the samples of natural runoff exceeded the acute criterion for selenium.

The wetlands of Benton Lake NWR had a wide range of dissolved-solids concentration (516 to 7,740 mg/L). Concentrations commonly decreased during periods of pumping from Muddy Creek. Salinity generally increased in a downgradient direction among the interconnected pools due to evaporation. The median selenium concentration in water in the wetlands was less than 1 µg/L. No aquatic-life criteria for trace elements were exceeded in the wetlands of Benton Lake NWR.

Selenium loads to Freezout Lake WMA from irrigated and non-irrigated land were estimated in order to identify source areas that contribute significant amounts of selenium to wetlands. The estimated average annual selenium load discharged to Freezout Lake WMA is about 1,470 lbs. Selenium derived from irrigated land accounts for 82 percent of the total load, with most (77 percent) coming from irrigated glacial deposits. Non-irrigated land contributes about 18 percent of the total selenium load to Freezout Lake WMA.

A seep east of Priest Butte Lake, whose non-irrigated basin is underlain by glacial deposits, contributes almost 12 percent of the total selenium load discharge to the WMA. Relatively small selenium loads are discharged from irrigated gravel (5 percent), non-irrigated glacial deposits east of Freezout Lake WMA (6 percent), and from non-irrigated land underlain by the Montana Group west of Freezout Lake WMA (0.1 percent).

In Benton Lake NWR, an average annual selenium load of 170 lbs was estimated for the combined long-term average-annual inflow of natural runoff from the Benton Lake basin and water pumped from Muddy Creek. The average annual selenium load (96 lbs) estimated for the Benton Lake basin during 1991-92 was considerably less than the estimated long-term average due to below-normal precipitation runoff. The long-term average annual volume of natural runoff is estimated to contribute 79 percent of the total average annual selenium load, even though during the study period only 43 percent of the total selenium load was contributed by natural runoff. Therefore, although 1991-92 data indicate that pumped irrigation return flow was the primary source of selenium, runoff estimates provide evidence that natural runoff from the Benton Lake basin is the major source of selenium loading to Benton Lake.

Bottom-sediment samples from nine sites in the study area had selenium concentrations ranging from 0.6 to 11 µg/g. All concentrations were greater than the geometric mean for local soils (0.4 µg/g). Bottom sediment in wetlands is enriched relative to soils because selenium delivered to wetlands presumably is converted by biogeochemical processes from soluble chemical species in the water to insoluble species that accumulate in the reducing environment at the bottom of wetlands. The magnitude of selenium enrichment appears to be related to the selenium load entering the wetland and the surface area available for dispersal.

Selenium concentrations in water in wetlands are lower than concentrations in their supply water. Relations between concentrations of selenium and chloride indicate that concentrations of selenium in most wetlands generally are much lower than those expected from evaporative effects. The transfer of selenium from water to bottom sediment or to biological sinks is thought to be the cause of selenium loss from the water. One exception is Priest Butte Lakes, where additional selenium inputs from non-irrigated local sources are thought to be the cause of concentrations in water that are higher than those predicted from evaporative concentration of the predominant supply water.

Limited data for lake-water samples collected near shore identified higher dissolved-selenium concentrations than those reported for the centrally located routine sampling sites, thereby indicating that selenium is being removed from lake water and immobilized in sediment in the near-shore areas of most wetlands. This process would result in dissolved-selenium concentrations decreasing with distance from the mouths of drains or other surface inflows, and could explain why selenium concentrations at the routine sampling locations in wetlands are consistently low (<1-2 µg/L), with the exception of Priest Butte Lakes. If selenium is accumulating predominantly in sediment of near-shore areas, then potential impacts to water quality, and presumably biota, may be greatest near the mouths of inflows. Also, it is likely that selenium delivered to wetlands will continue to accumulate in the bottom sediment rather than moving out of the wetlands through water releases.

Biota

Impacts of selenium contamination commonly are manifested in the reproduction of water birds. The methods used in this study to examine water-bird reproduction did not detect overt evidence of reproductive toxicity induced by selenium. Eared grebe and duck clutch size, nest success, and embryo viability at Freezout Lake WMA and Benton Lake NWR in 1991 were typical for the species. Clutch size, embryo viability, and nest success of American avocets breeding in the study area were typical of the species throughout its range. American avocet reproduction in the study area, with the possible exception of reduced juvenile survival at Priest Butte Lakes, appeared normal. However, the growth rate of juvenile avocets at Benton Lake NWR was significantly less than their growth rates at Freezout Lake WMA.

Selenium residues were measured in aquatic organisms representing several trophic levels. Geometric mean selenium concentrations in various biological matrices from wetlands in Freezout Lake WMA and Benton Lake NWR indicate that selenium in biological tissue from some wetland units exceeded biological risk levels. The highest selenium concentrations in biota commonly occurred in Priest Butte Lakes, which also had the highest selenium concentration in water. Selenium concentrations in all invertebrate samples from Priest Butte Lakes and the south end of Freezeout Lake exceeded the critical dietary threshold of 5.0 µg/g dry weight for birds.

Selenium concentrations in all fish samples collected in the study area exceeded a nationwide average concentration in whole-body freshwater fish of 2 µg/g dry weight. All but a few of the fish samples collected in the study area exceeded the 5 µg/g dry-weight concentration suggested by Skorupa and Ohlendorf (1991) as a critical dietary threshold for birds. Fish-age characteristics, population structure, and associated high selenium residues provide evidence that fish reproduction has been impaired in Priest Butte Lakes.

American avocets nesting at Priest Butte Lakes accumulated the highest concentrations of selenium in their eggs. Eared grebes nesting in Freezout Lake WMA Pond 5, the south end of Freezeout Lake, and Benton Lake Pool 1 also accumulated elevated concentrations of selenium in their eggs. Geometric mean selenium concentrations in the livers of all water-bird species, except American coots, exceeded the 9 µg/g dry-weight concentration suggested by Ohlendorf and Skorupa (1989) as the upper end of the range of selenium concentrations in water bird livers collected from uncontaminated non-marine environments. Liver samples from all bird species, except coots and northern shovelers, had selenium concentrations that exceeded the approximately 10.4 µg/g dry-weight concentration associated with reproductive inhibition in female mallards (Heinz and others, 1987). In general, selenium concentrations in the livers of ducks and coots were lower than in eared grebes and American avocets, but exceeded typical background levels of 4-9 µg/g dry weight.

The bioassay of aquatic organisms using surface-water samples from several locations in the study area resulted in toxic responses in fathead minnows and two species of invertebrates. With the exception of water from the seep east of Priest Butte Lakes, which caused 100 percent mortality in all tests, toxic responses were variable among sites and between seasons. Notably, however, water from some of the sites producing toxic responses came from wetlands in the wildlife areas.

The bioassay of captive mallard ducklings using surface water from six locations within the study area indicated that the salinity at some sites was sufficiently high to result in mortality. Based on results of this test, salinity levels, in terms of specific conductance, at which no acute toxicity occurred was 15,500 µS/cm. The salinity level at which no overt duckling growth effects were observed was 5,920 µS/cm. Specific-conductance values higher than 15,500 µS/cm only occurred in non-irrigated areas. Values higher than 5,920 µS/cm occurred in irrigated and non-irrigated areas.

Fate and Bioaccumulation of Selenium in Wetlands

Data for Priest Butte Lakes, Freezout Lake WMA Pond 5, the south end of Freezeout Lake, and Benton Lake Pool 1 most commonly indicated excessive selenium bioaccumulation by aquatic invertebrates, fish, and water birds relative to other parts of the study area and to environmental reference concentrations. Selenium in Priest Butte Lakes is derived almost entirely from non-irrigated areas whereas irrigated land contributes almost all the selenium entering Pond 5 and the south end of Freezeout Lake. Benton Lake Pool 1 receives selenium from non-irrigated areas and irrigation return flow pumped from Muddy Creek.

Selenium concentrations in water, bottom sediment, and biota of wetland units most distant from selenium inflows are generally lower than those receiving direct inputs of selenium. Selenium concentrations in biota are one or more orders of magnitude higher than concentrations in water. Selenium concentrations among biota types also appear to correlate better with selenium concentrations in water than in bottom sediment.

Selenium concentrations in organisms of various trophic levels follow broadly similar patterns among sites. Selenium concentrations are lower in aquatic plants (sago pondweed) than in aquatic invertebrates (waterboatmen and chironomid larvae). This consistent difference indicates a greater capacity for selenium assimilation by invertebrates relative to plants and may imply that aquatic invertebrates are a more significant pathway for the transfer of selenium to higher trophic levels. Selenium concentrations generally were higher in forage fish than in water-column insects. All selenium concentrations in juvenile water-bird livers were higher than those for invertebrates. Consequently, dietary selenium apparently is concentrated relatively effectively in the livers of water birds. Selenium concentrations in water-bird eggs also were higher than concentrations in waterboatmen, indicating some indirect transfer from dietary items to eggs. The incremental increase in selenium accumulation from sago pondweed to waterboatmen to water-bird eggs represents an approximate doubling of concentration in each trophic level. Accumulation rates from waterboatmen to forage fish are generally smaller and less consistent.

At Priest Butte Lakes and Benton Lake Pool 1, which receive substantial quantities of poor quality runoff from non-irrigated land, selenium accumulation in young-of-the-year bird livers generally was substantially greater than in eggs. This increase during growth indicates that feeding in these two areas during the fledging period results in more selenium accumulation than the transfer of selenium from female adults to eggs during the egg-formation period.

The highest selenium concentrations for all trophic levels commonly occurred in organisms collected from Priest Butte Lakes, which also had the highest selenium concentrations in water. High selenium residues in fish, fish-age characteristics, and the population structure provide circumstantial evidence that fish reproduction has been impaired. American avocets nesting at Priest Butte Lakes accumulated the highest concentrations of selenium in their eggs. The type of breeding-bird habitat on islands and adjacent land surrounding Priest Butte Lakes favors preferential use by nesting American avocets, Canada geese, and their young. Consequently, these species probably are more susceptible to exposure and bioaccumulation of selenium at Priest Butte Lakes than other water-bird species.

Potential Impacts of Alternate Irrigation-Management Practices on Wetlands

Irrigation management possibly could affect the amount of constituents discharged to wetlands by irrigation drainage. The potential effect of management alternatives will depend largely on the predominant geochemical release mechanism and solubility controls of the constituent of concern. Flushing wetlands with additional water may be effective at removing dissolved solids and diluting concentrations. However, additional flushing might not substantially remove selenium from the wetlands because it rapidly accumulates in bottom sediment through biogeochemical immobilization from the water.

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