Tuck--Reconnaissance of Arsenic in Surface and Ground Water along the Madison and Upper Missouri Rivers, Southwestern and West-Central Montana--USGS/WRIR 00-4028

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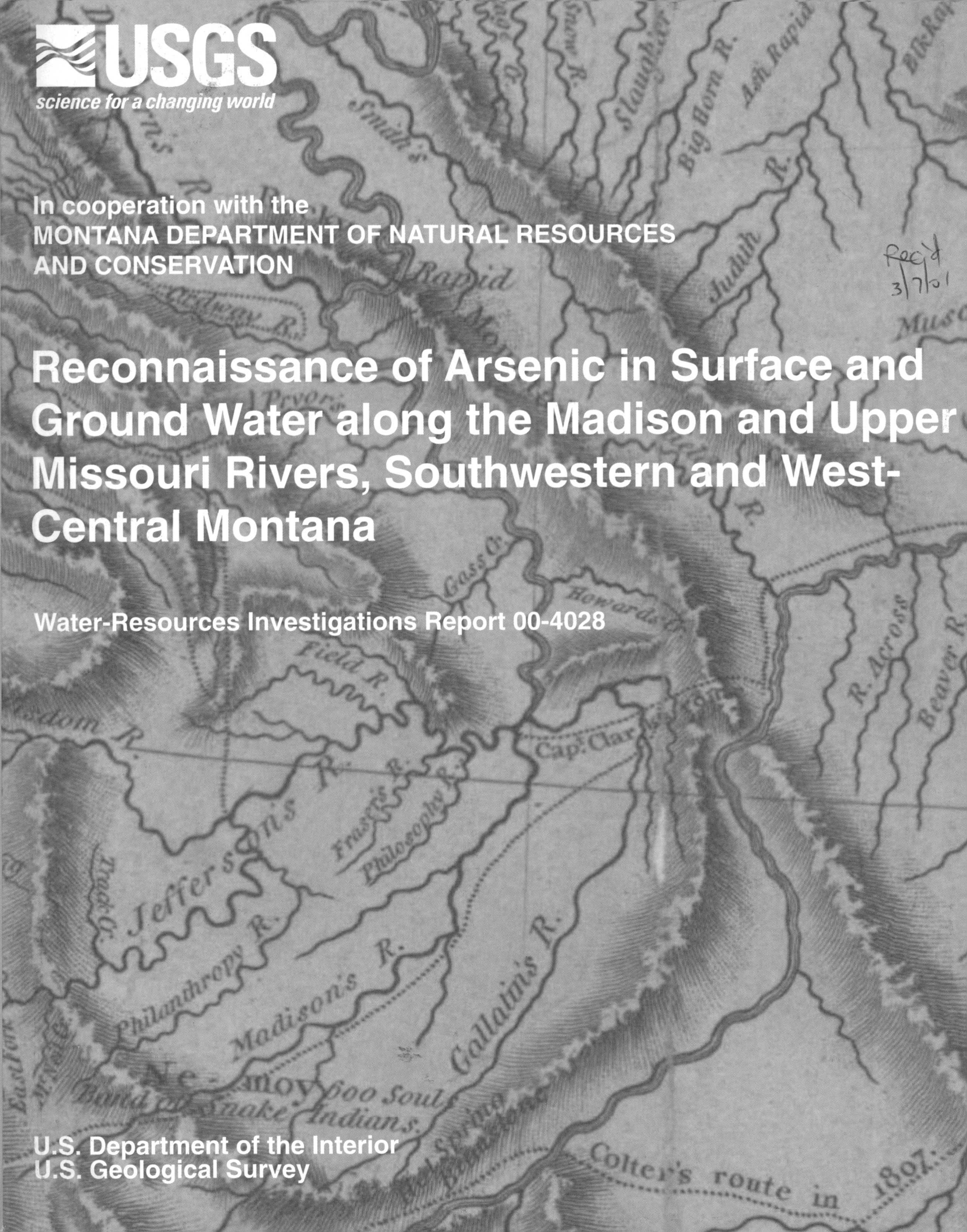

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In cooperation with the
MONTANA DEPARTMENT OF NATURAL RESOURCES
AND CONSERVATION

Reconnaissance of Arsenic in Surface and Ground Water along the Madison and Upper Missouri Rivers, Southwestern and West-Central Montana

Water-Resources Investigations Report 00-4028

U.S. Department of the Interior
U.S. Geological Survey

COVER: Shows part of a map of the Lewis and Clark expedition across the western part of present day Montana. The Jefferson, Madison, and Gallatin Rivers meet to form the Missouri River in Montana.

FROM: Paul Allen, 1814, A History of the Expedition Under the Command of Lewis and Clark to the Source of the Missouri, Thence Across the Rocky Mountains, and Down the Columbia River to the Pacific Ocean (Philadelphia: Bradford and Inskeep, 1914), 2 volumes.

SOURCE: Looking for Lewis and Clark: On-Line images of the voyage of discovery, compiled by Daniel Slosberg, accessed 03-03-00 at URL: http://people.we.mediaone.net/danslos/map.html

U.S. Department of the Interior
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Reconnaissance of Arsenic in Surface and Ground Water along the Madison and Upper Missouri Rivers, Southwestern and West-Central Montana

By L.K. Tuck

Water-Resources Investigations Report 00-4028

In cooperation with the
MONTANA DEPARTMENT OF NATURAL RESOURCES
AND CONSERVATION

U.S. Department of the Interior

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CONVERSION FACTORS, VERTICAL DATUM, ABBREVIATED WATER-QUALITY UNITS, AND ACRONYMS

Multiply	By	To obtain
acre	4,047	square meter
cubic foot per second (ft^3/s)	0.028317	cubic meter per second
foot (ft)	0.3048	meter
gallon per minute (gal/min)	0.06309	liter per second
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter
inch	25,400	micrometer (µm)
mile (mi)	1.609	kilometer
million gallons per day (Mgal/d)	0.04381	cubic meter per second
pound per day (lb/d)	453.6	gram per day
square mile (mi^2)	2.59	square kilometer

Degree Celsius (°C) may be converted to degree Fahrenheit (°F) by using the following equation:

$$°F = 9/5(°C)+32$$

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.

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

Chemical concentration in water is reported in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the solute mass (milligrams) 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.

Abbreviated water-quality units and symbols used in this report:

µg/g	microgram per gram
µg/L	microgram per liter
µS/cm	microsiemens per centimeter at 25 degrees Celsius
mg/L	milligram per liter
<	less than minumum reporting level

Acronyms used in this report:

BOR	Bureau of Reclamation, Department of the Interior
EPA	U.S. Environmental Protection Agency
GIS	Geographic Information System
MBMG	Montana Bureau of Mines and Geology
MDEQ	Montana Department of Environmental Quality
MDNRC	Montana Department of Natural Resources and Conservation
MCL	Maximum Contaminant Level
NWIS	National Water Information System
RASA	Regional Aquifer-System Analysis
USGS	U.S. Geological Survey

Reconnaissance of Arsenic in Surface and Ground Water along the Madison and Upper Missouri Rivers, Southwestern and West-Central Montana

By L.K. Tuck

Abstract

Geothermal waters in Yellowstone National Park contribute large quantities of arsenic to the headwaters of the Madison River. The Madison River flows for about 150 miles to the confluence of the Jefferson and Gallatin Rivers near Three Forks where the Missouri River begins. Arsenic concentrations in the Madison and upper Missouri Rivers and some ground water commonly exceed the State of Montana water-quality human-health standard of 18 micrograms per liter (µg/L) as well as the U.S. Environmental Protection Agency Maximum Contaminant Level for drinking water of 50 µg/L. This report describes the magnitude, extent, and possible sources of arsenic in surface and ground water, describes the processes controlling arsenic in ground water, and assesses the effect of irrigation on ground-water quality.

The median dissolved-arsenic concentration of the Madison River near West Yellowstone is 270 µg/L, whereas the median dissolved-arsenic concentration of the Missouri River at Toston is 30 µg/L. Arsenic concentrations decrease from the Madison River near West Yellowstone to the Missouri River at Toston because tributaries having much smaller arsenic concentrations dilute water in the Madison and upper Missouri Rivers. Downstream trends in arsenic loads and boron and lithium concentrations indicate that arsenic in the main-stem Madison and upper Missouri Rivers is largely chemically conservative.

In the upper Madison River Valley, arsenic concentrations in irrigation-supply water range from <1 to 88.5 µg/L, whereas arsenic concentrations in water in drains and springs and seeps range from <0.7 to 25.8 µg/L. Arsenic loads in water at selected surface-water sites increase during the irrigation season, which likely indicates that some arsenic originates from irrigation. Most arsenic concentrations in water at these sites are less than about 20 µg/L, and some arsenic from applied irrigation water is removed by sorption onto soils. Arsenic concentrations in ground water of the upper Madison River Valley range from 0.5 to 40 µg/L, with a median of 2.0 µg/L.

In the lower Madison River Valley, arsenic concentrations in irrigation-supply water range from 27.0 to 113 µg/L. Arsenic concentrations in water in drains and Rey and Spring Creeks range from 42.2 to 321 µg/L. The predominant effect on arsenic concentrations in water in drains and Rey and Spring Creeks probably is inflow from deeper ground water that discharges to these sites. Arsenic concentrations in ground water of the lower Madison River Valley and areas along the lower Jefferson and Gallatin Rivers range from 0.4 to 176 µg/L, with a median concentration of 54 µg/L.

In the Townsend Valley, arsenic concentrations in irrigation-supply water range from 4.0 to 38.4 µg/L. Arsenic concentrations in water in drains and seeps range from <1 to 12.8 µg/L. Arsenic loads in water at some surface-water sites increased during the irrigation season, which likely indicates that some arsenic originates from irrigation. Most arsenic concentrations in water in drains and seeps are less than about 8 µg/L; thus, most arsenic from applied irrigation water is removed by sorption onto soil. Arsenic concentrations in ground water of the Townsend Valley range from <1 to 18 µg/L, with a median of 2.2 µg/L.

In the Helena Valley, arsenic concentrations in irrigation-supply water range from 1.1 to 31 µg/L. Arsenic concentrations in water in drains range from <0.8 to 25 µg/L. Most arsenic concentrations in water from drains are less than about 5 µg/L; thus, either arsenic is diluted by other water sources, or much is removed from applied irrigation water by sorption onto soils. Arsenic concentrations in ground water of the Helena Valley range from 0.9 to 22 µg/L, with a median of 2.0 µg/L.

The behavior and fate of arsenic in the study area are complex and dependent on many chemical and physical processes. Sorption/desorption reactions probably are the primary chemical processes controlling arsenic concentrations in ground water of the study area. In the upper Madison River, Townsend, and Helena Valleys, arsenic concentrations in irrigation-supply water generally are higher than arsenic concentrations in water from drains and springs and seeps. Arsenic concentrations in very shallow ground water generally are higher than arsenic concentrations in deeper ground water. The most likely explanation for these decreases in arsenic concentrations is sorption of arsenic onto soils from applied irrigation water. Desorption appears to be an important chemical process causing some high arsenic concentrations in ground water primarily in the lower Madison River Valley. Evapoconcentration might be a significant factor in causing high arsenic concentrations in soil moisture and some very shallow ground water. Dilution also appears to physically control arsenic concentrations where large quantities of tributary inflow recharge basin-fill deposits or where regional ground water has an upward component of flow.

In the upper Madison River, Townsend, and Helena Valleys, the areas where ground water is affected by canal leakage or applied irrigation water are variable and are not apparent in many instances. In all three valleys, local conditions near or at the well--such as distance from irrigation recharge sources, sorption/desorption reactions, aquifer permeability, well depth and construction, dilution by tributaries or regional ground water, and horizontal and vertical gradients--affect the ground-water quality and control the arsenic concentrations in water at the well. The net result of these conditions is that most arsenic concentrations in ground water of the upper Madison River, Townsend, and Helena Valleys that is recharged or might be partly recharged by irrigation are much lower than the State of Montana water-quality human-health standard of 18 μg/L, as well as the U.S. Environmental Protection Agency Maximum Contaminant Level of 50 μg/L.

The effects of irrigation on ground-water quality of the lower Madison River Valley cannot be determined in a large part of the valley. Most arsenic concentrations in ground water are higher than the State of Montana human-health standard of 18 μg/L and are caused by unique hydrogeologic and chemical conditions. Ground-water quality and arsenic concentrations are affected predominantly by direct recharge from the Madison River and ground water inflows from upgradient areas. The effects of irrigation on ground-water quality are not apparent but might only occur in the near-surface part of the aquifer. Horizontal and vertical flow gradients might prevent deep percolation of irrigation water. Along the eastern valley margin, recharge from irrigation and leaching of arsenic from Tertiary sediment affect ground-water quality and arsenic concentrations.

INTRODUCTION

Geothermal waters in Yellowstone National Park contribute large quantities of arsenic to the headwaters of the Madison River (fig. 1). The median total-recoverable arsenic concentration in water from the Madison River near West Yellowstone is 280 μg/L. The Madison River joins the Jefferson and Gallatin Rivers near Three Forks to form the upper Missouri River, where the median total-recoverable arsenic concentration in water is 74 μg/L. Farther downstream below Canyon Ferry Lake near Helena, the median total-recoverable arsenic concentration in water is 27 μg/L (Knapton and Horpestad, 1987; Knapton and Brosten, 1987, 1989; U.S. Geological Survey, published annually). Ground water in some Quaternary and Tertiary deposits along the Madison and upper Missouri Rivers is locally enriched in arsenic. Arsenic concentrations in ground water are highest in the lower Madison River Valley near Three Forks, where a dissolved-arsenic concentration of 176 μg/L has been reported (Sonderegger and Sholes, 1989).

Arsenic in surface and ground water in the Madison and upper Missouri River Valleys is a public-health concern. Arsenic concentrations in the Madison and upper Missouri Rivers and some ground water commonly exceed the State of Montana water-quality human-health standard of 18 μg/L (Montana Department of Environmental Quality (MDEQ), 1995) as well as the U.S. Environmental Protection Agency (EPA) Maximum Contaminant Level (MCL) for drinking water of 50 μg/L (U.S. Environmental Protection Agency, 1996). In addition, the EPA is proposing to change the MCL for arsenic in drinking water from 50 to 5 μg/L. The extent of affected areas and the mechanisms that control arsenic concentrations in surface and ground water in the Madison and upper Missouri River Valleys are relatively unknown.

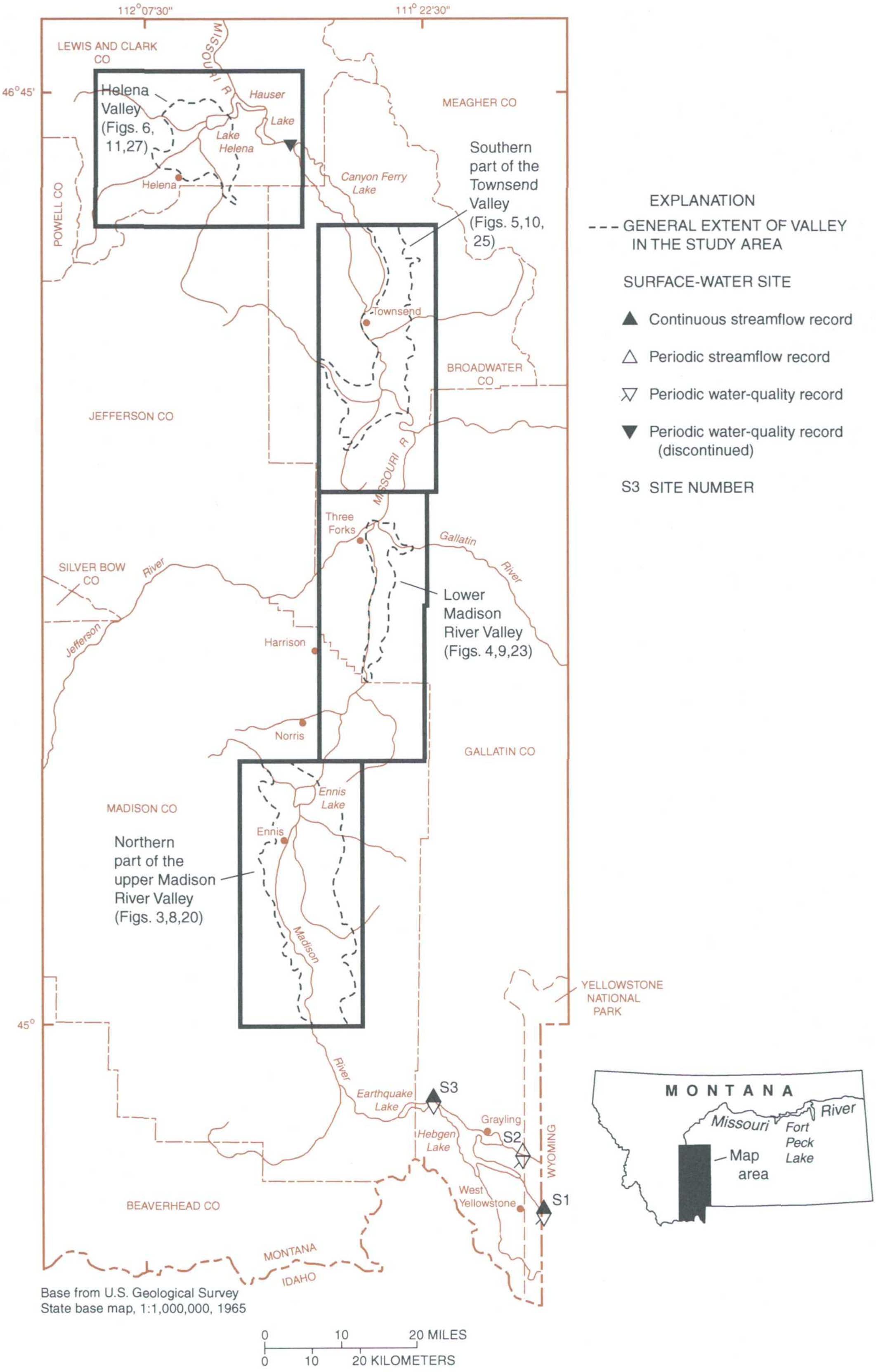

Figure 1. Location of the study area in Montana.

The Montana Department of Natural Resources and Conservation (MDNRC) adopted a water allocation policy in 1992 that prevents new irrigation projects if water diverted for irrigation increases arsenic concentrations in surface or ground water. A better understanding of the historic effects of irrigation on arsenic in surface and ground water was needed to enable managers to predict the effect that proposed new irrigation projects will have on arsenic concentrations. Consequently, the U.S. Geological Survey (USGS), in cooperation with MDNRC, conducted a study to obtain additional information to meet this need.

Purpose and Scope

This report documents the results of a reconnaissance evaluation of arsenic in the Madison and upper Missouri Rivers and the irrigation canals, ditches, drains, springs and seeps, and ground water along these rivers. Specifically, the report describes the magnitude, extent, and possible sources of arsenic in surface and ground water, describes the processes controlling arsenic in ground water, and assesses the effect of irrigation on ground-water quality. The emphasis of the report is on four valleys where water from the Madison and Missouri Rivers has been diverted for irrigation: the northern part of the upper Madison River Valley, the lower Madison River Valley, the southern part of the Townsend Valley, and the Helena Valley (fig.1).

Water-quality data used in this report and information about sampling locations, types of data, methods of data collection and compilation, sample processing and analysis, and quality assurance for those data are presented in a companion data report by Tuck and others (1997). The hydrologic and water-quality data were collected and compiled during 1988-95.

Previous Investigations

General hydrogeologic investigations have been conducted in all four valleys. The most recent study that included all four valleys was part of the Regional Aquifer-System Analysis (RASA) program, which was a nationwide series of studies by the USGS. Reports from that study include hydrogeologic data from wells in western Montana (Dutton and others, 1995), geologic and hydrologic summaries of valleys in western Montana (Kendy and Tresch, 1996), geologic history and hydrogeologic units (Tuck and others, 1996), ground-water levels (Briar and others, 1996), and quality of ground and surface water (Clark and Dutton, 1996). In addition, Nimick and others (1998) investigated the transport and fate of arsenic in the Madison and Missouri Rivers from Yellowstone National Park to Fort Peck Lake. Mangelson and Brummer (1994) also investigated the occurrence of arsenic along the Madison and upper Missouri Rivers. Site-specific hydrogeologic investigations have been conducted in the lower Madison River Valley (Nimick, 1998; Sonderegger and Sholes, 1989; and Sonderegger and Ohguchi, 1988), the Townsend Valley (Pardee, 1925; Lorenz and McMurtrey, 1956; Wyatt, 1984) and the Helena Valley (Lorenz and Swenson, 1951; Wilke and Coffin, 1973; Moreland and others, 1979; Moreland and Leonard, 1980; Briar and Madison, 1992; and Kendy and others, 1998).

Site-Numbering Systems

Surface-water sites are assigned a site number from S1 through S103 (table 1 at back of report). Eight-digit station-identification numbers for routine surface-water sites represent the standard USGS numbering system for streamflow-gaging stations. Fifteen-digit station-identification numbers are used for miscellaneous or temporary surface-water stations; these numbers represent the approximate latitude and longitude of the site (first 13 digits), plus the sequence number (last 2 digits).

Ground-water sites are assigned a site number that refers to the valley in which the well is located (table 2 at back of report). For example, well H21 is located in the Helena Valley.

Ground-water sites also are assigned location numbers according to their geographic position within the rectangular grid system used for the subdivision of public lands (fig. 2). The location number consists of as many as 14 characters. The first three characters specify the township and its position north or south (N or S) of the Montana Base Line. The next three characters specify the range and its position east or west (E or W) of the Montana Principal Meridian. The next two characters are the section number. The next one to four characters designate the quarter section (160-acre tract), the quarter-quarter section (40-acre tract), the quarter-quarter-quarter section (10-acre tract), and the quarter-quarter-quarter-quarter section (2.5-acre tract), respectively, in which the well is located. These four subdivisions of the section are designated A,B,C, and D in a counter-clockwise direction, beginning in the northeastern quadrant. The last two numeric characters specify a sequence number to distinguish between multiple wells at a single location. For example, as shown in figure 2, well 11N03W33BBAA02 is the second well inventoried in the NE 1/4 (A) of the NE 1/4 (A) of the NW1/4 (B) of the NW1/4 (B) of sec. 33, T. 11 N., R. 3 W.

Methods of Investigation and Analysis of Data

Generalized land use was mapped in the northern part of the upper Madison River Valley, the lower Madison Valley, and the southern part of the Townsend Valley during the 1993-94 irrigation seasons. Land use was delineated on USGS 7.5-minute topographic quadrangles, digitized, and included in a Geographic Information System (GIS). Generalized land-use information for the Helena Valley was available in a GIS from a previous study (Briar and Madison, 1992).

The potentiometric surfaces in basin-fill deposits in the northern part of the upper Madison River Valley, southern part of the Townsend Valley, and Helena Valley are based primarily on measured water levels and surface-water altitudes from 7.5-minute topographic quadrangles. Reported water levels from drillers' logs were used where measured water levels were sparse. In the southern two-thirds of the lower Madison River Valley, the potentiometric surface of the basin-fill deposits is based primarily on reported water levels from drillers' logs and surface-water altitudes from 7.5-minute topographic quadrangles. In the northern part of the lower Madison River Valley, many water-

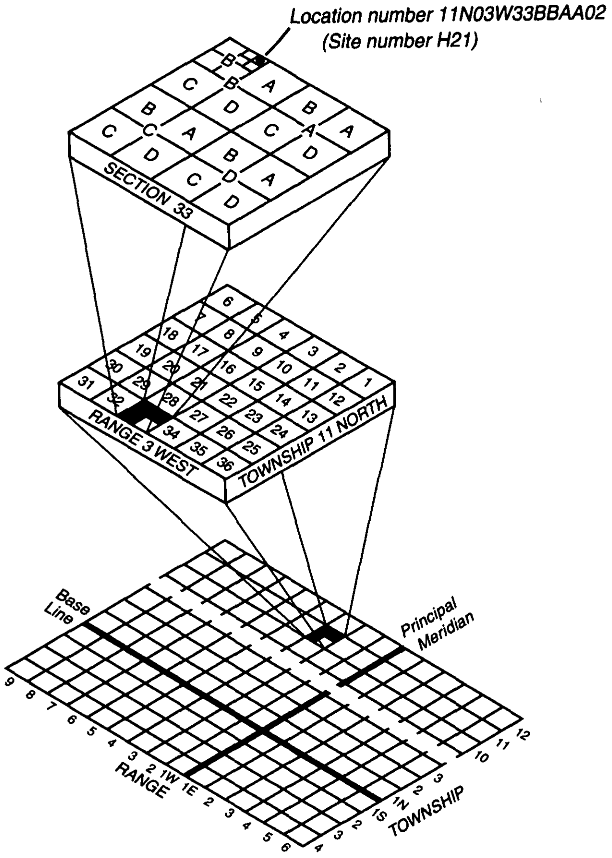

Figure 2. Numbering system for ground-water sites along the Madison and upper Missouri Rivers, Montana.

level data from drillers' logs are inconsistent with nearby surface-water altitudes; thus, surface-water altitudes also were used to construct the potentiometric surface.

For data analysis and incorporation into a GIS, arsenic concentrations that were less than the minimum reporting level were assumed to be one-half the minimum reporting level rounded to the nearest 0.1 µg/L. For example, the minimum reporting levels for arsenic concentrations for surface-water site S16 (table 3 at back of report), for the non-irrigation (October 15 through April 14) and irrigation seasons (April 15 through October 14) were 0.7 µg/L and 1 µg/L, respectively. The mean and median arsenic concentrations for water samples from this site were calculated by using 0.4 µg/L and 0.5 µg/L, respectively, as if these values were the minimum arsenic concentrations determined for this site. The convention of using one-half the minimum reporting level also was used for comparing arsenic, boron, and lithium concentrations in graphs in the section "Arsenic in Ground Water." For ground-water sites where more than one sample was analyzed for arsenic, the mean concentration was used in figures in the section "Arsenic in Ground Water."

Water samples were analyzed by one of three laboratories: USGS National Water Quality Laboratory, Denver, Colo.; Montana Bureau of Mines and Geology (MBMG) Analytical Division, Butte, Mont.; and Bureau of Reclamation (BOR), Bismarck, N.D. Significant figures for arsenic concentrations are those reported by the respective laboratories; other concentrations are rounded according to standard USGS procedures (Tuck and others, 1997). Significant figures for maximum and minimum arsenic concentrations and for summaries (tables 3-10 at back of report) are as reported by the analyzing laboratory. Significant figures for mean and median arsenic concentrations are rounded to standard USGS reporting levels.

Arsenic can exist in organic and inorganic species in natural waters. Water samples sent to the USGS laboratory were analyzed after a sulfuric-acid potassium-persulfate digestion, and water samples sent to the BOR laboratory were analyzed after a nitric acid digestion. Both digestion procedures are designed to liberate organic arsenic-containing compounds prior to analysis. Water samples sent to the MBMG laboratory were analyzed with no digestion before analysis. Thus, arsenic concentrations reported by the USGS and the BOR laboratories include both organic and inorganic species of arsenic, whereas arsenic concentrations reported by the MBMG laboratory include only inorganic arsenic. The different digestion procedure of the MBMG laboratory could result in lower arsenic concentrations if organic arsenic exists in large concentrations. However, on the basis of qualitative data from only four samples, Nimick and others (1998) determined that organic arsenic probably composes less than 20 percent of the dissolved arsenic in water from the Madison River. Therefore, arsenic concentrations reported by the MBMG laboratory were treated as comparable to those of the USGS and BOR laboratories. Distinctions between organic and inorganic arsenic are not made in subsequent discussions and figures.

Total-recoverable arsenic was determined on unfiltered samples, whereas dissolved arsenic was determined on samples filtered through a 0.45-µm pore-size filter. Data for both total-recoverable and dissolved arsenic concentrations are not available for many surface-water sites. In particular, only total-recoverable arsenic concentrations are available for many of the samples collected from most irrigation canals, ditches, drains, and springs or seeps. Discharge in irrigation canals and ditches generally was less than 150 ft^3/s (Tuck and others, 1997), and suspended-sediment concentrations were assumed to be low on the basis of suspended-sediment concentrations determined in the mainstem Madison and Missouri Rivers (table 4) for much higher discharges. Likewise, discharge in drains or flow from springs and seeps also was low and was assumed to have little or negligible quantities of suspended sediment. Suspended-sediment concentrations in the Madison and upper Missouri Rivers typically are low (median concentrations range from 2 to 21 mg/L) and most of the arsenic is dissolved during most of the year (Nimick and others, 1998). Thus, arsenic concentrations in water from irrigation canals, ditches, drains, and springs and seeps were assumed to be primarily dissolved. For comparison and data analysis, total-recoverable and dissolved-arsenic concentrations were considered essentially equivalent at all sites except on the mainstem Madison and Missouri Rivers (sites S1-3, S8, S24, S26, S58, and S63) at high flows. Distinctions between total-recoverable and dissolved arsenic are not made in subsequent discussions and figures (except for the initial discussion of the mainstem sites in the section "Arsenic in Surface Water"). For clarity, concentrations or statistics about concentrations will be referred to only as "arsenic concentrations" even though data for both total-recoverable and dissolved arsenic are presented in some figures.

Dissolved arsenic in ground water is presented in Tuck and others (1997) as As^{+3} and As^{+5}. Distinctions between arsenic species generally are not made in subsequent discussions and figures. For clarity, concentrations or statistics about concentrations of As^{+3} and As^{+5} in ground water will be referred to only as "arsenic concentrations" even though data for both arsenic species are presented in figures.

The magnitude and extent of arsenic in ground water were delineated using multiple lines of evidence including arsenic concentration determined from sample analysis, land use, geology, and known or probable hydraulic connection between basin-fill deposits and the Madison or upper Missouri Rivers, or the irrigation canals or ditches in each of the four valleys. Information about vertical hydraulic gradients also was used to delineate the magnitude and extent of arsenic in ground water in the Helena Valley. Each valley was delineated to represent regions where arsenic in ground water was or probably was within the following general concentration ranges: less than 4.0 µg/L (Region 1), 4.0 to 17.9 µg/L (Region 2), 18.0 to 49.9 µg/L (Region 3), and 50.0 µg/L or greater (Region 4). The range of less than 4 µg/L shows where arsenic concentrations were less than the minimum reporting level to slightly elevated[1]. The range of 4.0 to 17.9 µg/L shows where arsenic concentrations were slightly elevated to elevated, but still below the State of Montana water-quality standard of 18 µg/L. The range of 18.0 to 49.9 shows where arsenic concentrations were equal to or higher than the State standard, but lower than the EPA MCL of 50 µg/L. The range of 50 µg/L or greater shows where the arsenic concentrations were equal to or greater than the EPA MCL. In addition, Region A was delineated to represent areas where arsenic concentrations are estimated to be about 4 µg/L or higher, but where arsenic was not necessarily determined from sample analysis. Information about land use, geology, and known or probable hydraulic connections between the aquifers and the Madison or upper Missouri Rivers, or the irrigation canals, was used to infer that arsenic might exist in ground water at concentrations of about 4 µg/L.

Each of the four valleys contains anomalies where at least one value for arsenic was greater than or less than the general range of arsenic concentration for a specific region. For example, in the lower Madison River Valley (see fig. 23), Region 2 along the western part of the valley has three arsenic concentrations within the range of 4.0 to 17.9 µg/L and one arsenic concentration (29 µg/L) that is greater than 17.9 µg/L. These anomalies presumably exist because of localized factors such as land use, geology, topography, and hydraulic connection to arsenic sources. In addition, the location of some ground-water sites from the MBMG were not field checked, which might affect interpretation of the areal extent of certain concentration ranges.

Acknowledgments

The author acknowledges with appreciation the many individuals who assisted in the study. Particular thanks are given to the many landowners in the study area for allowing access to their wells and property. Appreciation also is extended to Charles E. Dalby, MDNRC, and DeAnn M. Dutton and David A. Nimick, USGS, for assisting in the collection, compilation, discussion, review of data, and the interpretation of arsenic occurrence in surface and ground water along the Madison and upper Missouri Rivers.

DESCRIPTION OF STUDY AREA

The study area consists of about 2,320 mi^2 located within Madison, Gallatin, Jefferson, Broadwater, and Lewis and Clark Counties in southwestern and west-central Montana (fig. 1). The study area extends from West Yellowstone downstream to the Helena Valley and is divided into four areas where stream water is diverted for irrigation: the northern part of the upper Madison River Valley, the lower Madison River Valley, the southern part of the Townsend Valley, and the Helena Valley. Additionally, three surface-water sites (S1-3) are located southeast of the upper Madison River Valley from West Yellowstone to Earthquake Lake (also known as Quake Lake) (fig. 1).

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[1] In this report, the terms "slightly elevated" and "elevated" are used simply to identify concentration ranges above the minimum reporting level. The terms do not imply that concentrations are attributable to recharge from the Madison or upper Missouri Rivers or irrigation.

General Features

The northern part of the upper Madison River Valley (hereinafter called upper Madison River Valley) extends from south of Cameron north to Ennis Lake (fig. 3). About 10,000 acres of land located primarily on the Cameron Bench and along the West Madison Canal are irrigated (see fig. 8). Water is diverted for irrigation from the Madison River and some of its major tributaries, which include Indian, O'Dell, Bear, and Blaine Spring Creeks. Therefore, many areas are irrigated with a mixture of water from the Madison River and its tributaries. The main supply canals include Granger and Shewmaker Ditches, an unnamed canal that diverts water from O'Dell Creek to the Jeffers area, and the West Madison Canal. Water has been diverted for irrigation to some areas in the upper Madison River Valley for more than 80 years (Keith, 1995). Irrigated crops consist of alfalfa and native grass. Some irrigated land is used for pasture.

The lower Madison River Valley, which also includes areas along the lower Jefferson and Gallatin Rivers, extends from near Elk Creek to Trident (fig. 4). About 5,900 acres of land, located mostly between the river and prominent cliffs of the Madison Plateau to the east, are irrigated (see fig. 9). Water is diverted for irrigation from the Madison River near Elk Creek to near the Missouri River north of Three Forks, as well as from Spring and Rey Creeks that originate as springs on the valley floor. Some areas are sub-irrigated by shallow ground water. The main supply canals include Sloan, Hutchison, Dell, Crowley, and Darlington Ditches and Spring and Rey Creeks on the east side of the valley, and the Francis Walbert Ditch on the northwest side of the valley. Water has been diverted for irrigation to some areas in the lower Madison River Valley for more than 90 years (Keith, 1995). Irrigated crops consist of cereal grains, alfalfa, and native grass. Some irrigated land is used for pasture.

The southern part of the Townsend Valley (hereinafter called Townsend Valley) extends from about Plunket Lake to Canyon Ferry Lake (fig. 5). About 31,700 acres of land are irrigated (see fig. 10). Water is diverted from the Missouri River from near Toston to as far north as Duck Creek. Many areas are irrigated with a mixture of water from the Missouri River and its tributaries. The main supply canals include Toston Canal, Warm Springs Creek, Broadwater-Missouri Westside Canal, Broadwater Missouri Canal, and Montana Ditch. Water has been diverted for irrigation to some areas in the Townsend Valley for more than 100 years (Lorenz and McMurtrey, 1956). Irrigated crops consist of cereal grains, seed potatoes, alfalfa, and native grass. Some irrigated land is used for pasture.

The Helena Valley extends from Helena and the Scratchgravel Hills northeast to Lake Helena (fig. 6). About 21,200 acres of land are within the irrigation district (see fig. 11). Water is diverted from the Missouri River below Canyon Ferry Dam and is pumped to the Helena Valley Regulating Reservoir. Water is then released to the Helena Valley Canal and its extensive network of distributary canals and ditches. Water is also diverted from Prickly Pear, Tenmile, and Sevenmile Creeks. Therefore, some areas are irrigated with a mixture of water from these sources. Some areas are sub-irrigated by shallow ground water. Water has been diverted for irrigation to some areas in the Helena Valley for more than 100 years (Lorenz and Swenson, 1951). Irrigated crops consist of cereal grains, alfalfa, and native grass. Some irrigated land is used for pasture.

General Geology

The four valleys in the study area are north-trending structural basins that formed as a result of intermittent crustal movements throughout Tertiary time. Except for the lower Madison River Valley, faults or fault systems extend along the valleys, which have dropped relative to adjacent mountains (fig. 7). The lower Madison River Valley is part of a larger structural basin that includes areas east of the Madison Plateau and west of the Jefferson River. Movement along these faults generally followed existing zones of structural weakness and has occurred since about middle Eocene time (Fields and others, 1985). The fault-controlled structural basins (or valleys) became depositional centers for locally derived sediment during the middle Eocene to early Oligocene. Lower Tertiary sediments primarily are fine-grained tuffaceous sandstone, siltstone, claystone, limestone, and volcanic ash that were deposited in shallow subsiding basins that extended across present valleys and mountain ranges. During middle Miocene time extensional, basin-and-range type faulting caused erosion and folding of lower Tertiary rocks. This episode of faulting probably established the general outline of valleys in the study area (Reynolds, 1979). Present valley floors began to form about 5 million years ago during the Pliocene Epoch as renewed faulting uplifted mountain blocks, as rivers and streams began to form their present drainage patterns, and as the basins continued to fill with sediment (Fields and others, 1985). Upper Tertiary sediments primarily are coarse-grained conglomerate, sandstone, siltstone, claystone, and volcanic ash that were deposited along high-energy streams. Pleistocene and Holocene streams continued to deposit gravel, sand, silt, and clay across channels, flood plains, terraces, and alluvial-fans on valley floors and valley margins.

The Tertiary to Quaternary basin-fill deposits, which contain modern stream channels, flood plains, terraces, and alluvial fans, form a complexly stratified sequence of gravel, sand, silt, and clay. That sequence generally can be from about 2,000 to 15,000 ft thick (Robinson, 1967; Schofield, 1981).

Bedrock of Late Archean to Quaternary age surrounds and underlies most valleys and is composed of many rock types (fig. 7) that can be more than 15,000 ft thick (Kinoshita and others, 1965). Most bedrock crops out in uplifted, fault-bounded blocks that form mountains or crops out as erosional remnants within the valleys.

Hydrologic Framework

The Madison River originates in Yellowstone National Park, in northwest Wyoming, and flows for about 150 mi to the confluence of the Jefferson and Gallatin Rivers near Three Forks, where the Missouri River begins (fig. 1). About 110 mi downstream, the Missouri River flows into Canyon Ferry Lake. Three hydroelectric dams and one natural dam impound waters of the Madison and Missouri Rivers. Hebgen and Canyon Ferry Lakes are sufficiently large to have average water residence times of about 200 days. Earthquake Lake and Ennis Lake are small and shallow with short (less than 12 days) water residence times (Nimick and others, 1998). The Missouri River also is impounded at Hauser Dam, forming Hauser Lake. Lake Helena is a small and shallow lake that is actually an arm of Hauser Lake.

Periodic streamflow measurements of the Madison River near West Yellowstone (site S1) ranged from about 350 to 1,700 ft^3/s and below Ennis Lake (site S24) ranged from about 1,100 to 6,300 ft^3/s in 1989-95 (Tuck and others, 1997). Annual mean streamflows ranged from 442 to 2,050 ft^3/s at these two sites (water years 1989-95; U.S. Geological Survey, published annually). Streamflows probably are larger downstream at the Madison River near Norris (site S26, fig. 4) and at Three Forks (site S58, fig. 4), owing to tributary inflows and ground-water discharge. However, periodic streamflow information is insufficient to adequately describe the range of streamflows at sites S26 and S58. Periodic streamflow measurements of the Missouri River at Toston (site S63, fig. 5) ranged from 1,080 to 25,400 ft^3/s in 1988-95 (Tuck and others, 1997), with annual mean streamflows that ranged from about 3,170 to 6,040 ft^3/s (water years 1989-95; U.S. Geological Survey, published annually).

The basin-fill deposits (hydrogeologic units Qal, QTd, and Ts, fig. 7) are composed principally of unconsolidated to consolidated gravel, sand, silt, clay, and volcanic ash that typically form a thick sequence of complexly stratified deposits. In most of the valleys, these hydrogeologic units probably respond as a complex aquifer system. Basin-fill deposits can be unconfined, leaky confined, or confined. Most basin-fill deposits are unconfined and yields from some wells can be as large as 3,400 gal/min (Dutton and others, 1995). Quaternary and Tertiary undifferentiated deposits (QTd) and Tertiary sediment (Ts) typically have fine-grained layers that can be laterally discontinuous and are considered to be leaky-confining units. The lateral discontinuity generally allows interconnection between the coarse-grained sediments of the different basin-fill deposits. With depth, fine-grained layers within Tertiary sediment are more consolidated, thicker, and less permeable, resulting in confined conditions (Tuck and others, 1996; Briar and others, 1996).

In general, recharge to basin-fill deposits is by direct infiltration of precipitation, leakage from streams or rivers, subsurface inflow from surrounding bedrock, and infiltration of water from irrigation canals or water applied to fields. In some areas, the largest component of recharge to basin-fill deposits is infiltration from irrigation canals or water applied to fields. Discharge from basin-fill deposits is by seepage to rivers and streams, evapotranspiration, withdrawals from wells, and flow to springs. The largest component of ground-water discharge from most basin-fill deposits is seepage to rivers and streams (Tuck and others, 1996; Briar and others, 1996).

Ground-water flow in all four valleys is dominated by recharge to the adjacent uplands and valley sediments and discharge to the major streams and

EXPLANATION FOR FIGURE 3

- - - - - - GENERAL EXTENT OF VALLEY IN THE STUDY AREA

SURFACE-WATER SITE

▲ Continuous streamflow record

△ Periodic streamflow record

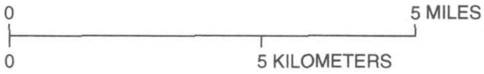
⊽ Periodic water-quality record

S4 Site number

GROUND-WATER SITE

● Hydrologic data. For some sites, data include onsite measurements of water temperature, specific conductance, pH, and nitrate concentration

⦶ Hydrologic and water-quality data



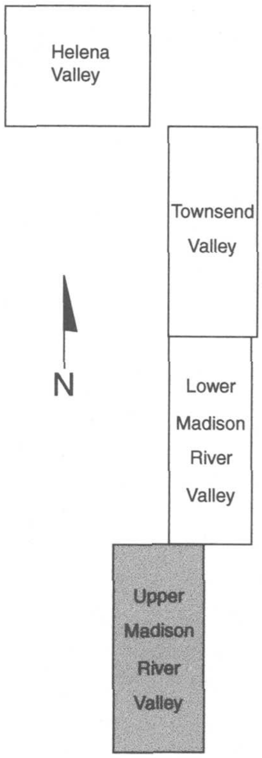
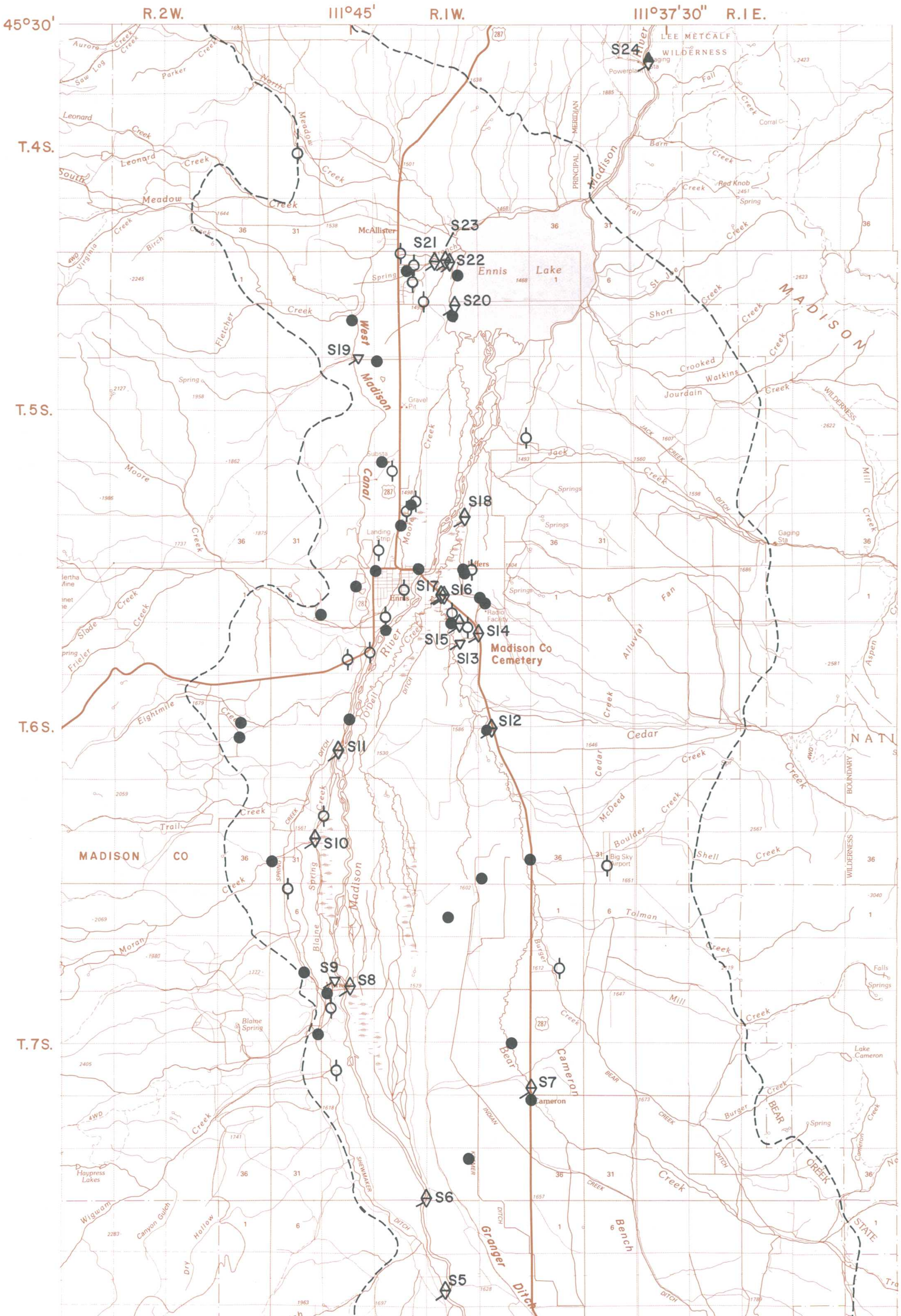


DIAGRAM SHOWING LOCATION OF VALLEYS



Base modified from U.S. Geological Survey
Ennis, 1989; 1:100,000

Figure 3. General extent and location of surface- and ground-water sites of the upper Madison River Valley, Montana.

FIGURE 3 10

EXPLANATION FOR FIGURE 4

- - - - - - GENERAL EXTENT OF VALLEY IN THE STUDY AREA

SURFACE-WATER SITE

△ Periodic streamflow record

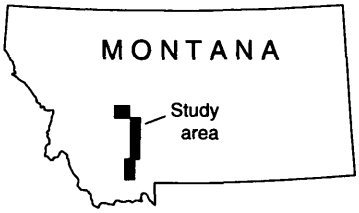
⊽ Periodic water-quality record

S25 Site number

GROUND-WATER SITE

● Hydrologic data. For some sites, data include onsite measurements of water temperature, specific conductance, pH, and nitrate concentration

2 ϕ Hydrologic and water-quality data. Numeral indicates the number of wells at the same general location



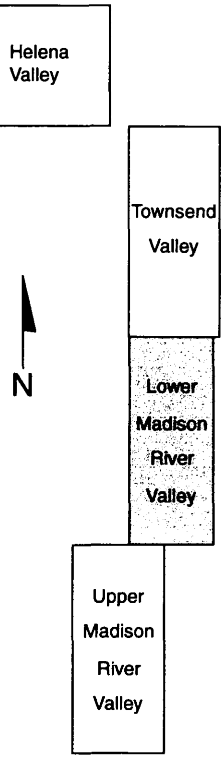
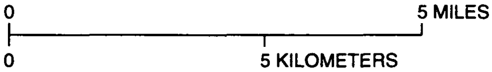
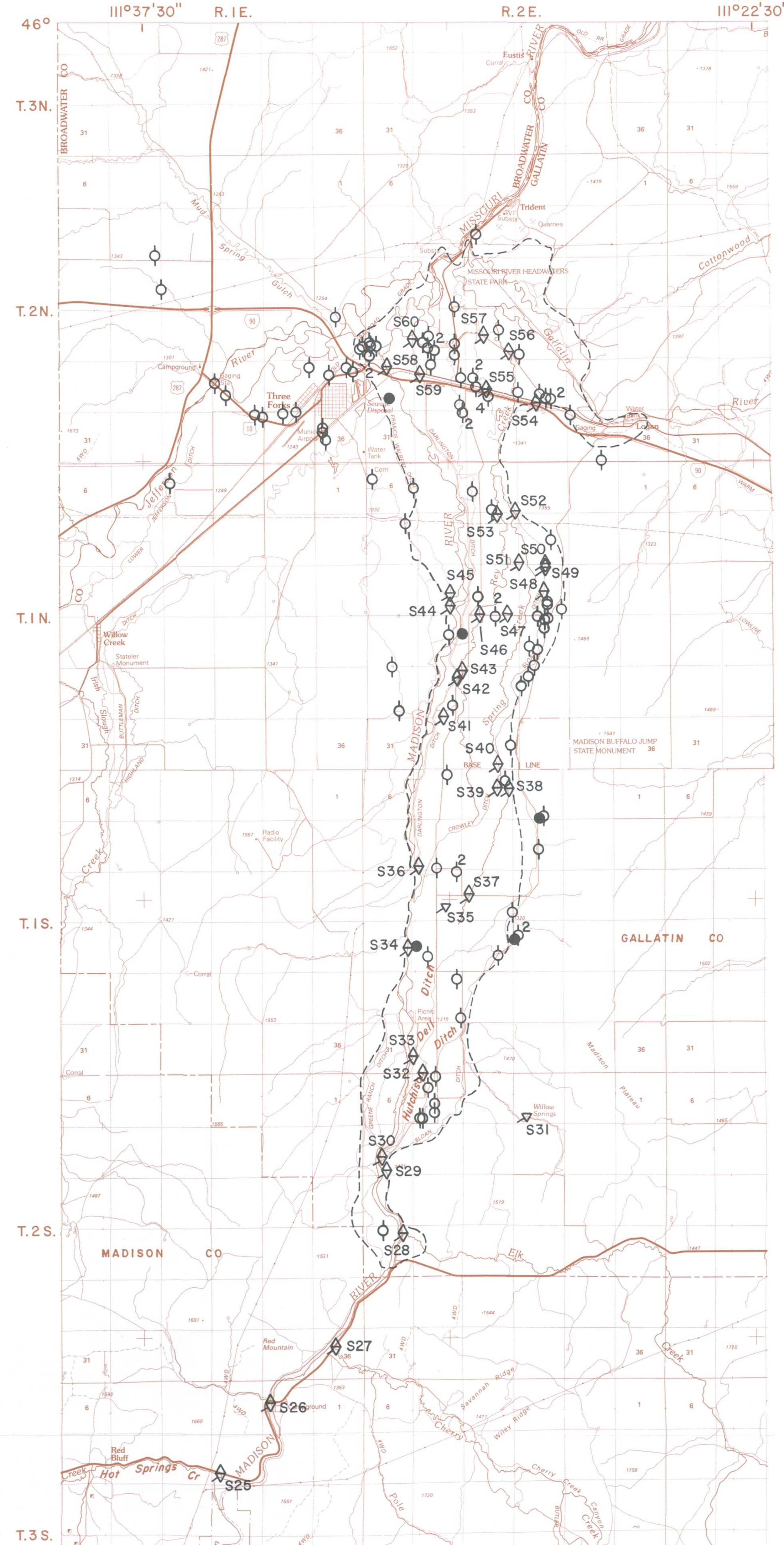


DIAGRAM SHOWING LOCATION OF VALLEYS





Base modified from U.S. Geological Survey Bozeman, 1992; 1:100,000

Figure 4. General extent and location of surface- and ground-water sites of the lower Madison River Valley, Montana.

EXPLANATION FOR FIGURE 5

\- - - - - - GENERAL EXTENT OF VALLEY IN THE STUDY AREA

SURFACE-WATER SITE

▲ Continuous streamflow record

△ Periodic streamflow record

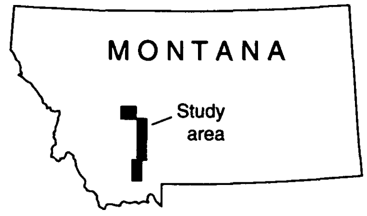
▽ Periodic water-quality record

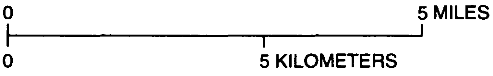
S61 Site number

GROUND-WATER SITE

● Hydrologic data. For some sites, data include onsite measurements of water temperature, specific conductance, pH, and nitrate concentration

ϕ Hydrologic and water-quality data





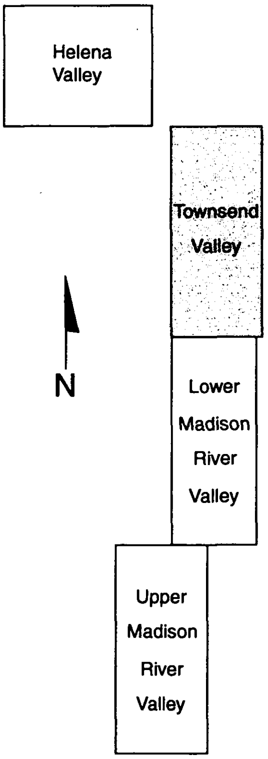
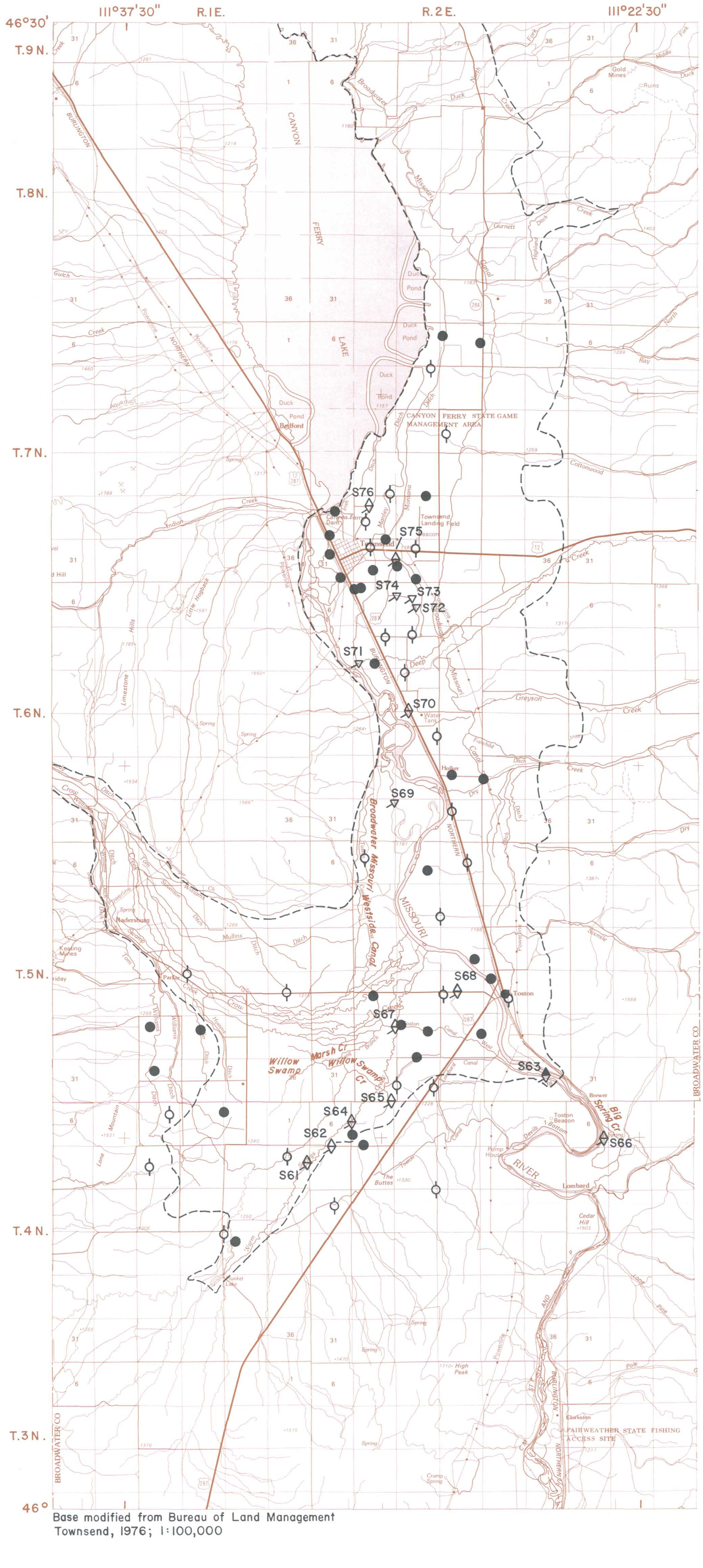


DIAGRAM SHOWING LOCATION OF VALLEYS



Base modified from Bureau of Land Management
Townsend, 1976; 1:100,000

Figure 5. General extent and location of surface- and ground-water sites of the Townsend Valley, Montana.

EXPLANATION FOR FIGURE 6

- - - - - - GENERAL EXTENT OF VALLEY IN THE STUDY AREA

SURFACE-WATER SITE

△ Periodic streamflow record

▽ Periodic water-quality record

▼ Periodic water-quality record (discontinued)

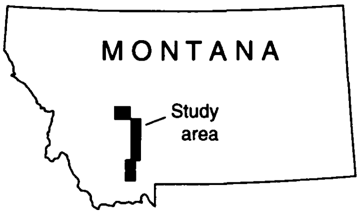
□ Periodic Lake Helena water-quality record

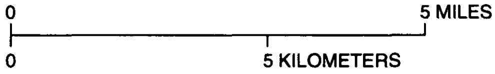
S77 Site number

GROUND-WATER SITE

● Hydrologic data. For some sites, data include onsite measurements of water temperature, specific conductance, pH, and nitrate concentration

2 ϕ Hydrologic and water-quality data. Numeral indicates the number of wells at the same general location





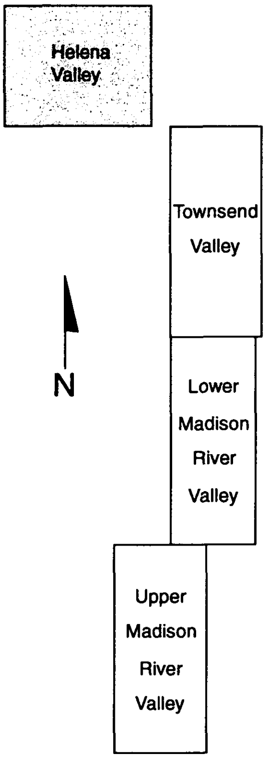
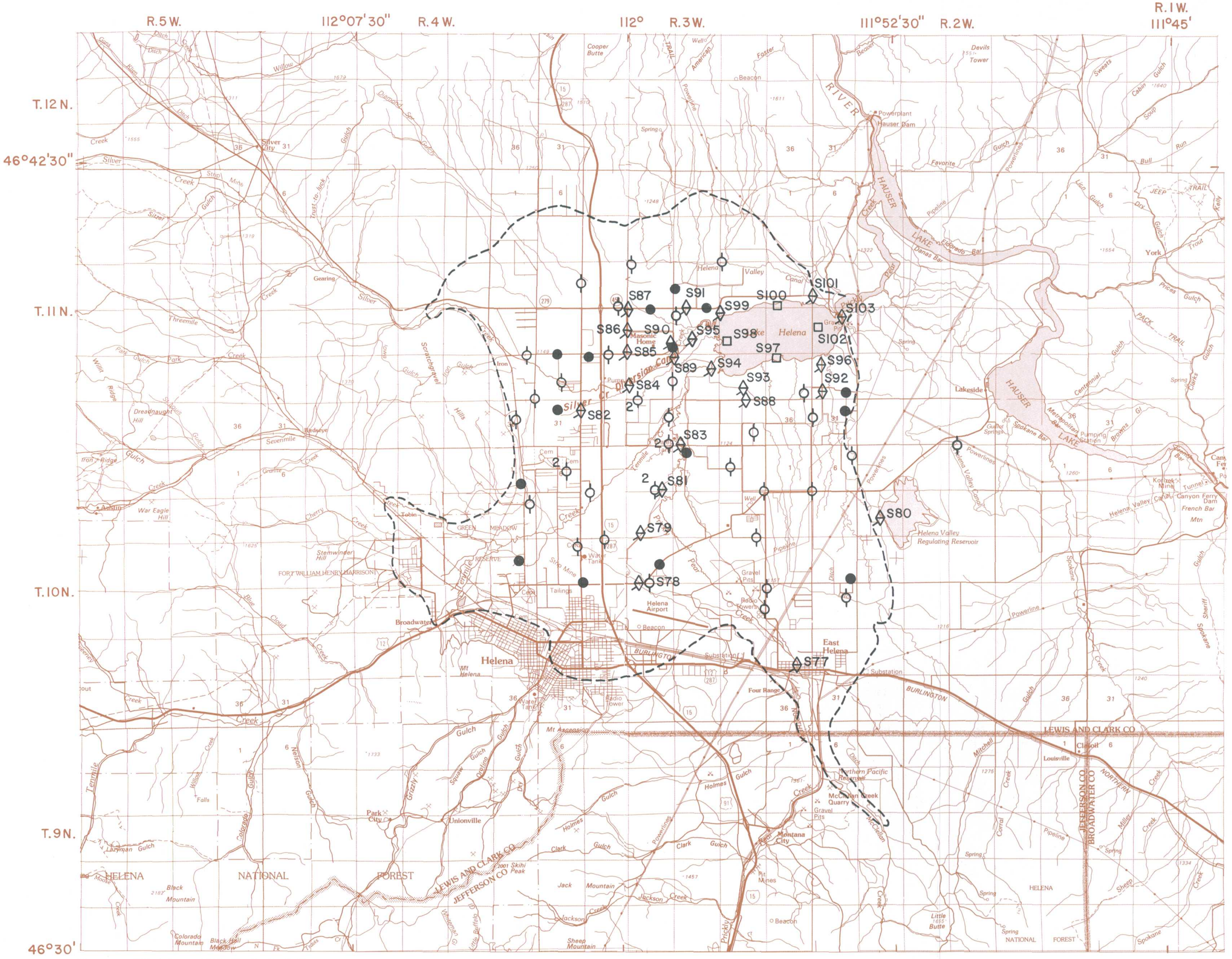


DIAGRAM SHOWING LOCATION OF VALLEYS

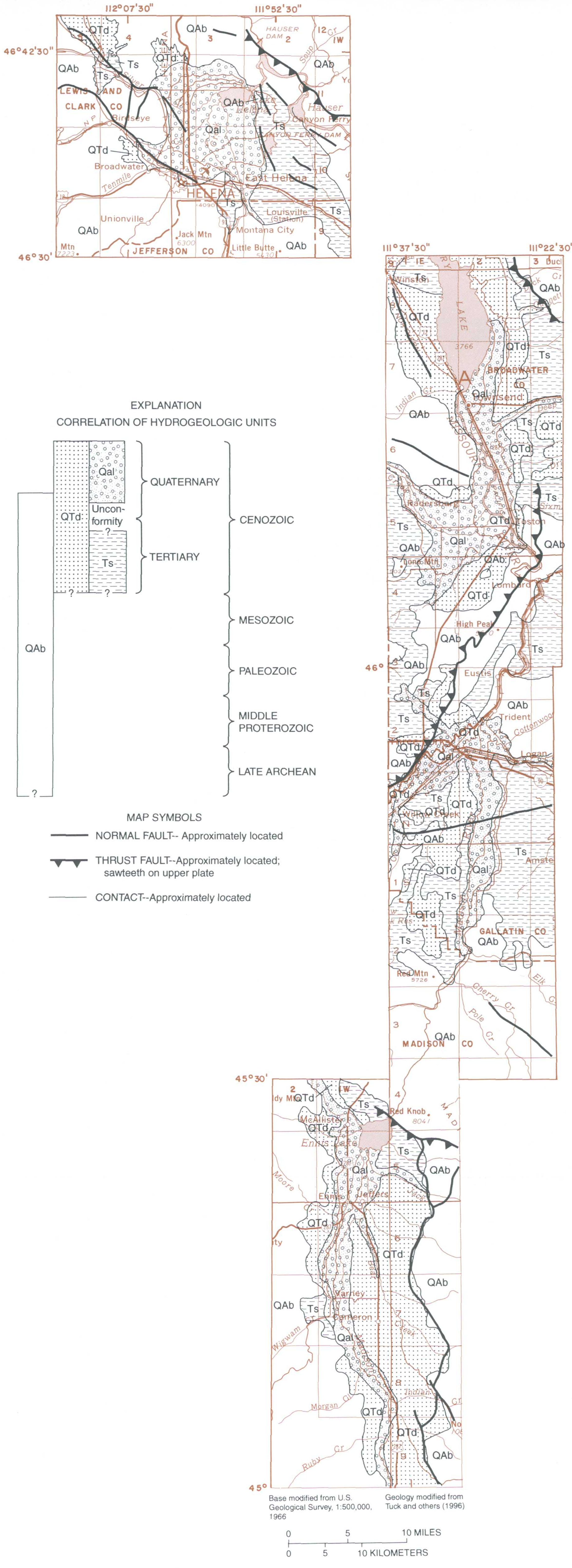


Base modified from U.S. Geological Survey
Elliston, 1990 and Bureau of Land Manage-
ment Canyon Ferry Dam, 1975; 1:100,000

Figure 6. General extent and location of surface- and ground-water sites of the Helena Valley, Montana.

DESCRIPTION OF HYDROGEOLOGIC UNITS

	MAJOR LITHOLOGY	EXTENT OF OUTCROPS	WATER-BEARING PROPERTIES
Qal	ALLUVIAL DEPOSITS (Quaternary)-- Unconsolidated stream-laid gravel, sand, silt, and clay that are poorly to moderately well sorted. Includes some talus, colluvium, landslide, and placer deposits and mine tailings	Mainly present along present-day stream channels, flood plains and low-level terraces near rivers and as smaller deposits near perennial and ephemeral streams. In mountainous areas, Qal is found as narrow deposits that are not laterally or vertically extensive. In most mountainous regions these deposits are not shown on figure 7	Deposits generally yield abundant water to wells throughout the study area. Yields range from about 1 to 650 gallons per minute (gal/min). Specific capacity ranges from 0.2 to 130 gallons per minute per foot [(gal/min)/ft] (Dutton and others, 1995)
QTd	UNDIFFERENTIATED DEPOSITS (Quaternary and Tertiary)--Unconsolidated to semiconsolidated gravel, sand, silt, clay, volcanic ash and locally contains limestone. Includes colluvium and landslide deposits, extensive alluviual-fan deposits within and outside of basins, alluvium on some alluvial fans, Tertiary sediments with a veneer of Quaternary deposits. Includes areas where Quaternary and Tertiary deposits are indistinct	Mainly present along valley margins or as erosional remnants near present-day stream channels, flood plains, and low-level terraces where streams and rivers dissect these deposits	Yields are variable and might be dependent on hydraulic interconnection with more permeable units and extent of interbedded gravel
Ts	SEDIMENT (Tertiary)--Lower part generally contains fine-grained tuffaceous sandstone, siltstone, claystone, limestone, and volcanic ash. Upper part generally contains coarse-grained conglomerate, sandstone, siltstone, claystone, and volcanic ash	Mainly present near valley margins as erosional remnants and as isolated outcrops in uplifted fault-bounded blocks which form mountains	Yields are variable and might be dependent on hydraulic interconnection with more permeable units and extent of interbedded gravel. Yields range from about 3 to 3,400 gal/min. Specific capacity ranges from 0.1 to 100 (gal/min)/ft
QAb	BEDROCK (Quaternary to Late Archean)--Many rock types, including volcanic, and volcaniclastic rocks that range in composition from rhyolite to basalt. Granite and rocks of granitic composition related to the Boulder Batholith, smaller plutons, stocks, dikes, and sills. Marine shale with interbedded nonmarine sandstone, siltstone, mudstone, and marine limestone. Massive and thick- to thin-bedded limestone with dolomite, interbedded phosphatic sandstone, quartzite, siltstone, mudstone, and shale. Argillaceous limestone, dolomite, ubiquitous thin-to-medium interbedded siltite and argillite, arkosic conglomerate and sandstone, massive feldspathic quartzite with interbedded limestone, siltite, and conglomerate which have been subjected to low-grade metamorphism. Metamorphosed granitic plutons, dikes and sills, quartzo-feldspatic gneiss, amphibolite, anorthosite, schist, dolomitic marble, quartzite, and iron formation	Most rocks crop out in uplifted, fault-bounded blocks which form mountains in southwestern and west-central Montana. In the upper Madison River and the Helena Valleys, these rocks surround deposits of Qal, QTd, and Ts. In the lower Madison River and Townsend Valley, structural deformation is more extensive; thus, rocks crop out as remnants within those deposits	Yields are variable and are dependent on the occurrence and extent of fractures, faults, joints, breccia, and caverns in volcanic and volcaniclastic rocks, granite, limestone, and argillaceous limestone and dolomite. One spring located in the Townsend Valley issues from limestone and discharges in excess of 5 million gallons per day (Mgal/d) (Lorenz and McMurtrey, 1956). Bedrock surrounding the Helena Valley supplies large volumes of subsurface recharge (about 35.5 Mgal/d) to Qal, QTd, and Ts deposits. Water-yielding zones in the generally low permeability marine shale with interbedded nonmarine sandstone, siltstone, mudstone, and marine limestone are dependent on occurrence and extent of more permeable conglomerate and sandstone. These rocks can yield water locally, but generally water-yielding properties are unknown. Metamorphic rocks generally are a barrier to ground-water flow. Might yield water locally, but generally water-yielding characteristics are unknown



Base modified from U.S. Geological Survey, 1:500,000, 1966

Geology modified from Tuck and others (1996)

Figure 7. Generalized hydrogeology.

rivers within each valley. Bedrock (hydrogeologic unit QAb, fig. 7) or relatively impermeable Tertiary sediment surrounding the valleys restricts ground-water flow between adjacent valleys. Throughflowing streams such as the Madison and Missouri Rivers probably provide the predominant hydraulic connection between these valleys.

Potentiometric-surface maps were constructed for basin-fill deposits of the four valleys (figs. 8-11). The potentiometric surface in the upper Madison River Valley (fig. 8) indicates that ground water generally flows from recharge areas near the valley margins toward the Madison River and northward to Ennis Lake, which are local discharge areas. Bear Creek (from about 5 mi southeast of Ennis to its confluence with O'Dell Creek) also is a local discharge area for ground water, as evidenced by many springs and one flowing well. Hydraulic gradients are steep (about 0.03) along the western side of the valley south of Ennis. Hydraulic gradients in other parts of the valley range from about 0.005 from Ennis to Ennis Lake to about 0.01 northwest of McAllister.

Ground water in the lower Madison River Valley generally flows parallel to the valley margins and northward. The potentiometric surface in the lower Madison River Valley (fig. 9) indicates that streamflow is lost as the river enters the valley west of Willow Springs and, thus, recharges ground water. The potentiometric surface also indicates that ground water discharges to the river as it flows north through the valley. Ground-water flow is subparallel to the valley margins in response to recharge from irrigation and, possibly, from adjacent Tertiary sediments. The confluence of the Jefferson, Madison, and Gallatin Rivers forms the Missouri River near Three Forks, which is a local discharge area for the lower Madison River Valley. Most of the valley is drained by two small perennial creeks—Rey and Spring Creeks. These streams gain flow in the central third of the valley and function as local discharge areas. Irrigation return flow (water from drains or springs and seeps) also supplements streamflow to these creeks (David A. Nimick, U.S. Geological Survey, written commun., 1997). Hydraulic gradients are relatively flat (0.006 to 0.004) throughout the valley.

The potentiometric surface in the Townsend Valley (fig. 10) between Radersburg and Toston indicates that ground water generally flows southeast and then northeast from recharge areas near the valley margins and Crow Creek toward the Missouri River, which is a local discharge area. In the rest of the Townsend Valley, the potentiometric surface indicates that flow is from the valley margins to the Missouri River and then northward to Canyon Ferry Lake, which also are local discharge areas in the Townsend Valley. Ground water also flows from the valley margins northeast of Townsend to Canyon Ferry Lake. Hydraulic gradients along the west side of the valley between Radersburg and Toston range from about 0.007 to 0.012. Hydraulic gradients are relatively flat in other parts of the valley and are about 0.002 from Toston to Townsend.

The potentiometric surface in the Helena Valley (fig. 11) indicates that ground water generally flows from recharge areas near the northern, western, and southern valley margins to Lake Helena. Prickly Pear, Tenmile, Sevenmile, and Silver Creeks lose water as they enter the Helena Valley, recharging basin-fill deposits (Briar and Madison, 1992). Recharge from surrounding bedrock accounts for about 46 percent of total recharge to basin-fill deposits (Briar and Madison, 1992). Hydraulic gradients are relatively flat throughout the valley and range from about 0.003 just south of Lake Helena to about 0.012 north of Helena. Briar and Madison (1992) approximated vertical hydraulic gradients and divided the Helena Valley into two areas. First, the area within about 4 mi of Lake Helena has an upward gradient that ranges from 0.002 to 0.221; the rest of the Helena Valley has a downward gradient that ranges from 0.002 to 0.319.

ARSENIC IN SURFACE WATER

Mainstem Madison and upper Missouri Rivers

Concentrations of total-recoverable and dissolved arsenic were determined (table 4) for surface-water sites along the mainstem Madison and upper Missouri Rivers (sites S1-3, S8, S24, S26, S58, and S63; figs. 1, and 3-5). Total-recoverable arsenic concentrations represent the concentration of dissolved and particulate arsenic associated with suspended sediment. Suspended-sediment concentrations in the Madison and upper Missouri Rivers typically are low (median concentrations range from 2 to 21 mg/L) and most arsenic is dissolved (table 4). During spring runoff, when streamflow and suspended-sediment concentrations are higher than at other times of the year, the

EXPLANATION

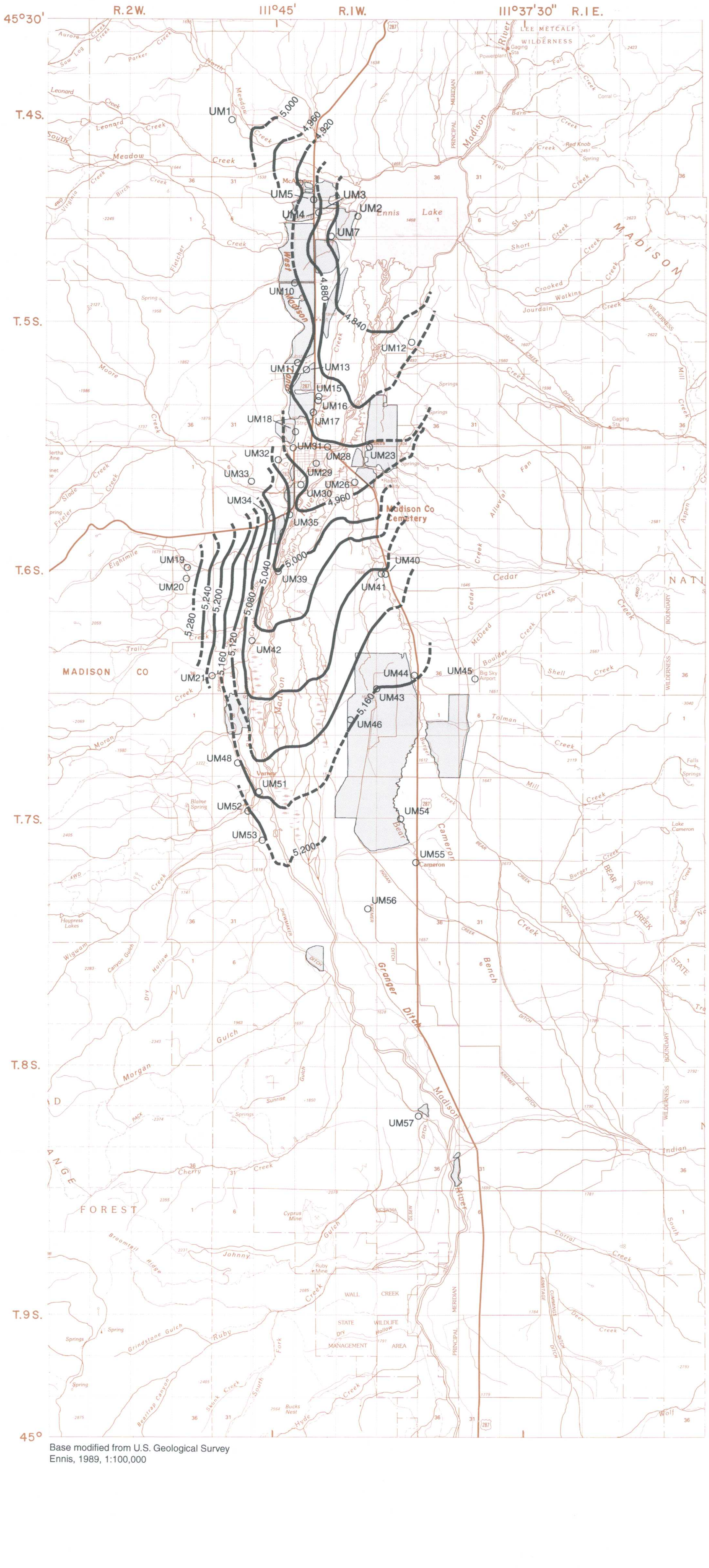
▨ IRRIGATED LAND

—— 5,200 — — POTENTIOMETRIC CONTOUR--Shows altitude at which water would have stood in tightly cased wells, 1960-93. Dashed where approximately located. Contour interval is 40 feet. Datum is sea level

UM48 ○ GROUND-WATER SITE AND NUMBER

0 5 MILES

0 5 KILOMETERS



Base modified from U.S. Geological Survey
Ennis, 1989, 1:100,000

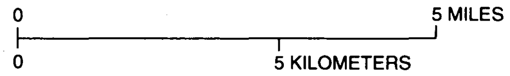
Figure 8. Location of irrigated land and altitude and configuration of the potentiometric surface in basin-fill deposits of the upper Madison River Valley, Montana.

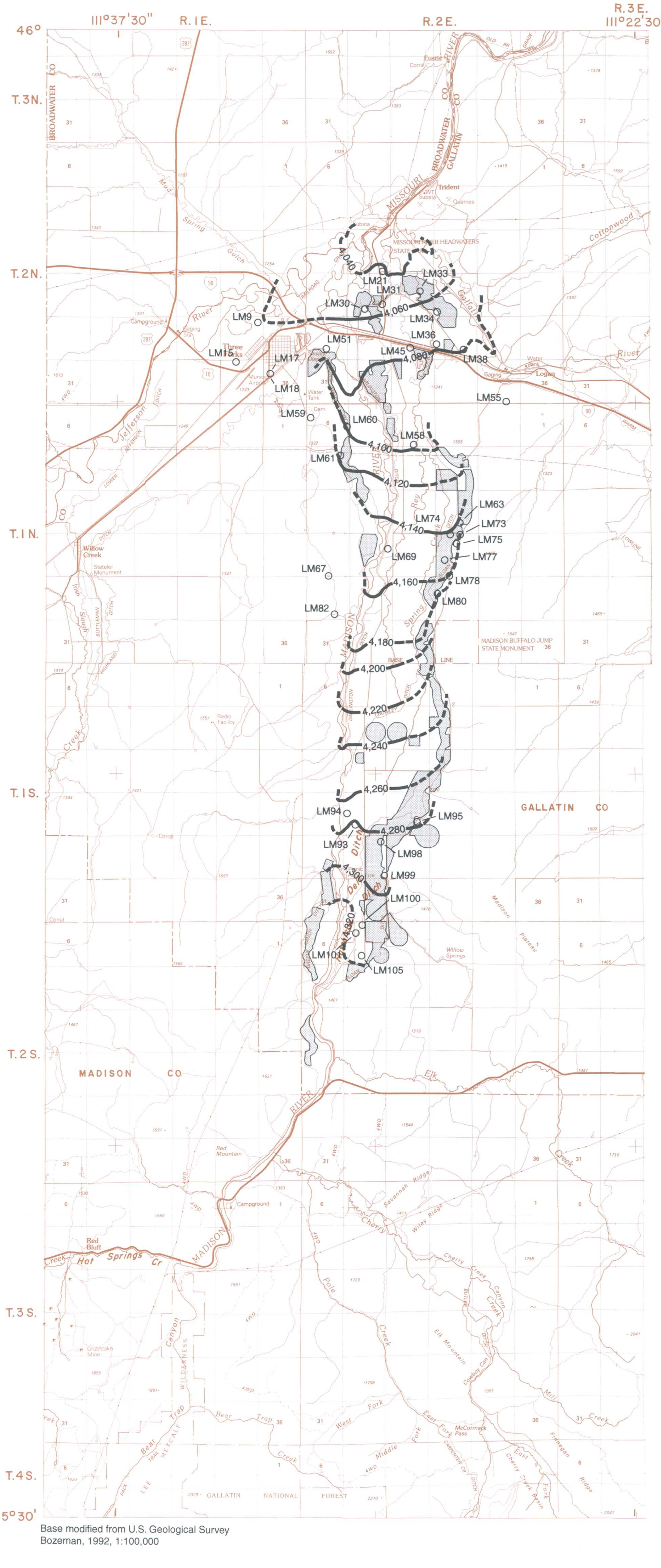
EXPLANATION

▨ IRRIGATED LAND

— 4,300 – – POTENTIOMETRIC CONTOUR--Shows altitude at which water would have stood in tightly cased wells, 1952-93. Dashed where approximately located. Contour interval is 20 feet. Datum is sea level

LM15 ○ GROUND-WATER SITE AND NUMBER





Base modified from U.S. Geological Survey
Bozeman, 1992, 1:100,000

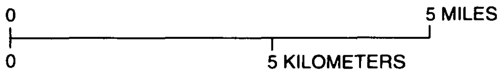
Figure 9. Location of irrigated land and altitude and configuration of the potentiometric surface in basin-fill deposits of the lower Madison River Valley, Montana.

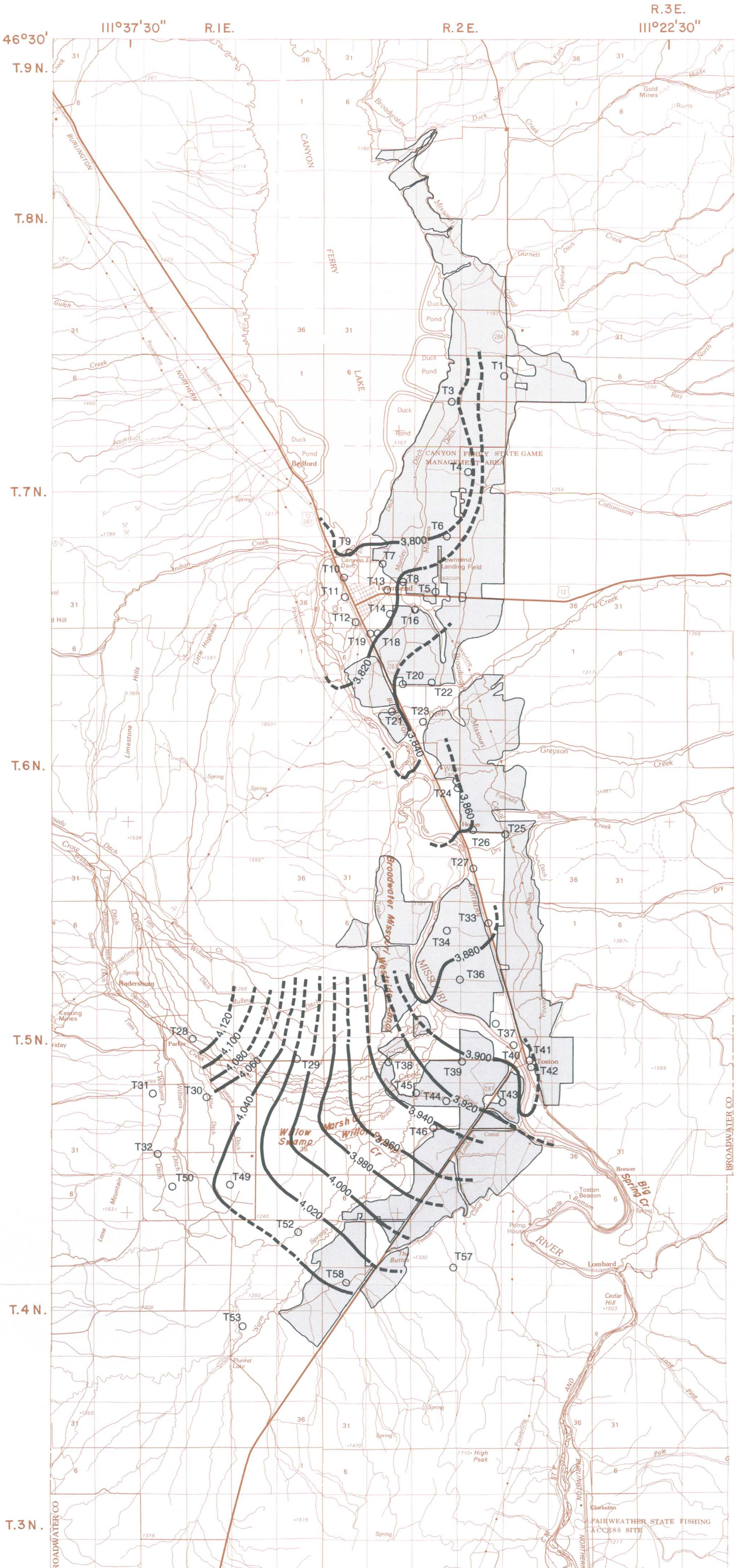
EXPLANATION

▨ IRRIGATED LAND

— 4,120 – – POTENTIOMETRIC CONTOUR--Shows altitude at which water would have stood in tightly cased wells, 1968-93. Dashed where approximately located. Contour interval is 20 feet. Datum is sea level

T3 ○ GROUND-WATER SITE AND NUMBER





Base modified from Bureau of Land Management
Townsend, 1976, 1:100,000

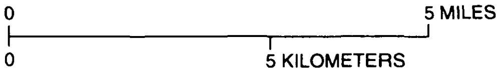
Figure 10. Location of irrigated land and altitude and configuration of the potentiometric surface in basin-fill deposits of the Townsend Valley, Montana.

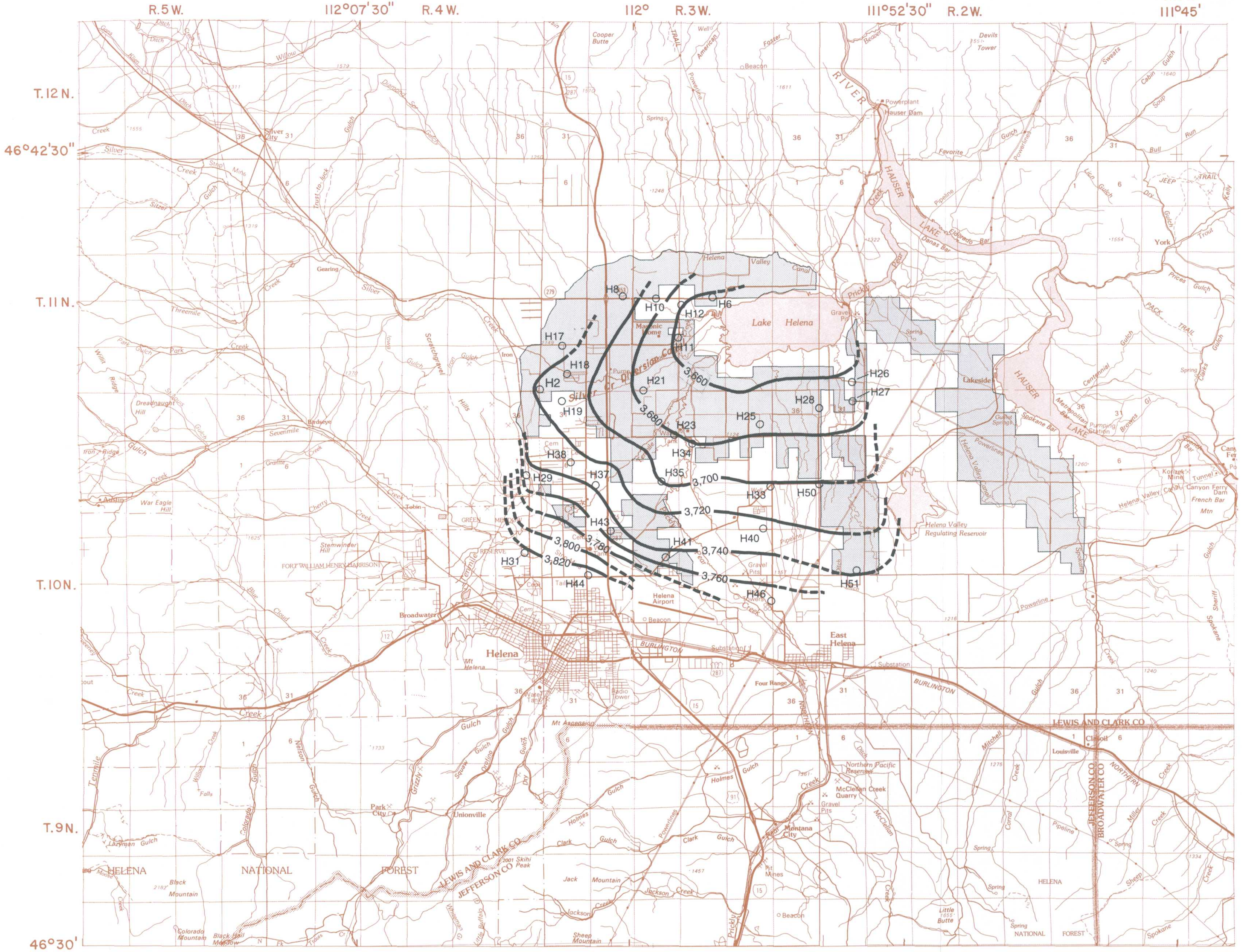
EXPLANATION

▨ IRRIGATED LAND

—— 3,820 – – POTENTIOMETRIC CONTOUR--Shows altitude at which water would have stood in tightly cased wells, 1989-95. Dashed where approximately located. Contour interval is 20 feet. Datum is sea level

H25 ○ GROUND-WATER SITE AND NUMBER





Base modified from U.S. Geological Survey
Elliston, 1990 and Bureau of Land Management
Canyon Ferry Dam, 1975, 1:100,000

Figure 11. Location of irrigated land and altitude and configuration of the potentiometric surface in basin-fill deposits of the Helena Valley, Montana.

proportion of particulate arsenic increases. For the Missouri River at Toston (site S63), particulate arsenic can compose as much as 50 percent of total-recoverable arsenic when streamflow is greater than about 5,600 ft^3/s. When streamflow is less than about 2,800 ft^3/s, particulate arsenic composes less than 10 percent of the total-recoverable arsenic (Nimick and others, 1998).

The median total-recoverable arsenic concentration at site S1 is 280 µg/L, and 50 percent of the total-recoverable arsenic concentrations are between 200 µg/L (25th percentile) and 310 µg/L (75th percentile). Downstream about 130 mi, the median total-recoverable arsenic concentration at site S63 is 33 µg/L and 50 percent of the total-recoverable arsenic concentrations are between 23 µg/L and 38 µg/L (table 4).

The median dissolved-arsenic concentration at site S1 is 270 µg/L (table 4) and 50 percent of the dissolved-arsenic concentrations are between 200 µg/L and 310 µg/L. Downstream at site S63, the median dissolved-arsenic concentration is 30 µg/L, and 50 percent of the arsenic concentrations are between 22 µg/L and 39 µg/L. Overall, between sites S1 and S63, arsenic concentrations decrease by about an order of magnitude. Arsenic concentrations decrease downstream because tributaries having much smaller arsenic concentrations dilute water in the Madison and upper Missouri Rivers. Knapton and Horpestad (1987) and Knapton and Brosten (1987) previously determined that arsenic concentrations in some tributaries were, in general, less than 4 µg/L, but at times as high as 22 µg/L. The Jefferson River at Three Forks contributes more arsenic than any other tributary to the Missouri River, with the exception of the Madison River. The quantity of arsenic in the Jefferson River typically is less than 6 percent of the quantity of arsenic in water from the Madison River at Three Forks at site S58 (Nimick and others, 1998).

Arsenic generally is chemically reactive and its concentration can be controlled by sorption in oxic (dissolved-oxygen concentrations generally larger than 1 mg/L) aqueous environments (Goldberg, 1986; Xu and others, 1988, 1991; Belzile and Tessier, 1990). Suspended sediment can affect particulate arsenic transport if the sediments have high concentrations of sorbed arsenic. Downstream trends in total-recoverable and dissolved-arsenic concentrations and streamflow were used to evaluate whether arsenic transport is mostly chemically conservative (non-reactive). Arsenic loads in water from site S1 are fairly constant over the range of sampled streamflows, except for slightly increased arsenic loads at the highest streamflows (Nimick and others, 1998). Arsenic loads are not as constant downstream from site S1, probably because of water storage and management effects in large reservoirs such as Hebgen Lake. Hebgen Lake partly controls suspended arsenic concentrations by allowing particulate arsenic to settle from suspension. In addition, arsenic concentrations in Hebgen Lake outflow during the summer and fall can be less than during the rest of the year owing to relatively dilute tributary inflow that enters and is stored in the lake during spring runoff. Arsenic concentrations in lake outflow during spring runoff periods can be higher because of relatively high concentrations in water stored during base-flow conditions (Nimick and others, 1998).

Downstream trends in dissolved boron and lithium concentrations also were used to evaluate whether arsenic is mostly chemically conservative (Nimick and others, 1998). These elements are chemically conservative and the concentration ratios of boron to lithium (range of 1.0 to 1.5) remain relatively constant between the Madison River near West Yellowstone (site S1) and at Three Forks (site S58). Comparison of arsenic, boron, and lithium concentrations indicates that arsenic transport is largely conservative along the Madison River between these two sites. Boron to lithium ratios in water from the Missouri River at Toston (S63) are not as constant (1.1 to 2.4) and indicate that boron probably is added from tributary inflow. Insufficient data are available for the Jefferson and Gallatin Rivers to verify that dissolved arsenic transport is conservative at site S63. Consequently, non-conservative reactions might affect some arsenic in streamflow between sites S58 and S63. However, Nimick and others (1998) concluded that arsenic transport was largely conservative in the Madison and upper Missouri River downstream to Canyon Ferry Lake.

Irrigation Supply and Drainage, Tributaries, and Lake Helena

During the irrigation season, irrigation-supply water in canals and ditches is primarily from either the Madison or upper Missouri Rivers. Water in canals and ditches also can consist of inflow from shallow ground water and surface runoff (irrigation return flow), tailwater from lateral canals, as well as inflow from deeper ground water. During the non-irrigation season, water in canals and ditches can consist of irrigation return flow and inflow from deeper ground water where canals and ditches drain irrigated fields and the ground-water table is high. Thus, water at some canals and ditches is a mixture from these sources and arsenic concentrations determined at these sites represent the contribution from more than one source.

Similarly, during the irrigation season, water in drains also can consist of tailwater from canals and ditches and inflow from deeper ground water, as well as irrigation return flow. Thus, water at some ditches and drains, springs and seeps, and some tributaries is a mixture from these sources and arsenic concentrations determined at some of these sites represent the contribution from more than one source.

Upper Madison River Valley

In the upper Madison River Valley (fig. 3), arsenic concentrations in surface water range widely from <1 to 150 µg/L, depending on the source of water. Arsenic concentrations in irrigation-supply water in the upper Madison River Valley at sites S4-5, S11, and S19 range from 31.9 to 88.5 µg/L and generally are lower than arsenic concentrations in the Madison River (sites S8 and S24), which range from 42 to 150 µg/L (tables 3, 4; fig. 12). Arsenic concentrations in irrigation-supply water at site S14, which range from <1 to 6.9 µg/L (table 3), are much lower than those at sites S8 and S24, which might indicate that supply is a mixture of water and diluted by ground-water discharge to the canal. Site S14 also might function as a drain during the non-irrigation season.

Arsenic concentrations in water from drains at sites S15-16 (Bear Creek) and springs and seeps at sites S10 and S20-23 range from <0.7 to 25.8 µg/L (table 3) and generally are lower than arsenic concentrations in irrigation-supply water (fig. 12). The decrease in arsenic concentrations in water at these sites relative to

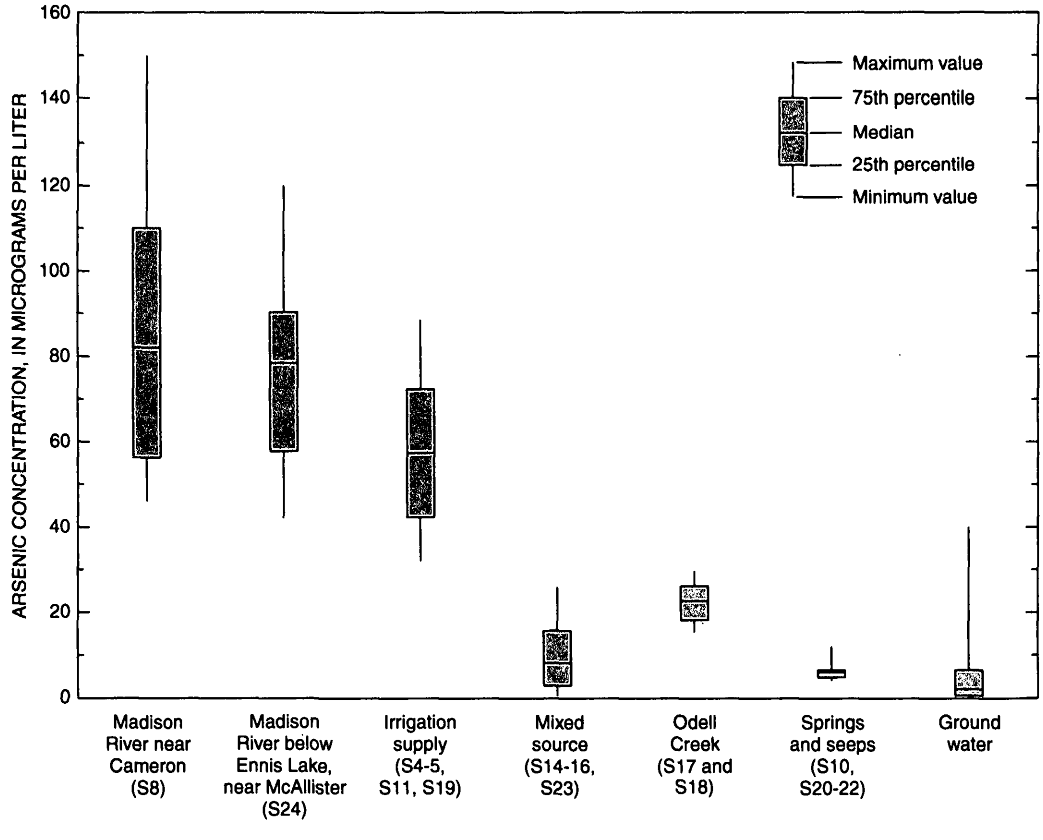


Figure 12. Range of arsenic concentrations in surface and ground water of the upper Madison River Valley, Montana. Arsenic concentrations for sites S8 and S24 are dissolved. Arsenic concentrations for other surface-water sites are a combination of total-recoverable and dissolved. Arsenic concentrations (As^{+3} and As^{+5}) for ground water are dissolved. Arsenic concentrations reported as less than the minimum reporting level are plotted as one-half the minimum reporting level.

irrigation-supply water indicates that some arsenic is removed from applied irrigation water. Keith (1995) and Mangelson and Brummer (1994) demonstrated the sorption capacity of soils in the study area and concluded that arsenic sorbs to irrigated soils, thus reducing arsenic concentrations in drainage originating from applied irrigation water. In addition, inflow from deeper ground water might dilute arsenic concentrations in water from drains and springs and seeps. Most arsenic concentrations in water at these sites are less than about 20 µg/L; therefore, arsenic either is diluted by other water sources (tributaries or regional ground water), or some is removed from applied irrigation water (range from <1 to 88.5 µg/L) by sorption onto soils and aquifer materials.

Arsenic concentrations and loads (table 5) are plotted for the non-irrigation and irrigation seasons for selected sites in the upper Madison River Valley (fig. 13). Dashed lines connecting measured concentrations and loads are drawn to infer a hypothetical temporal

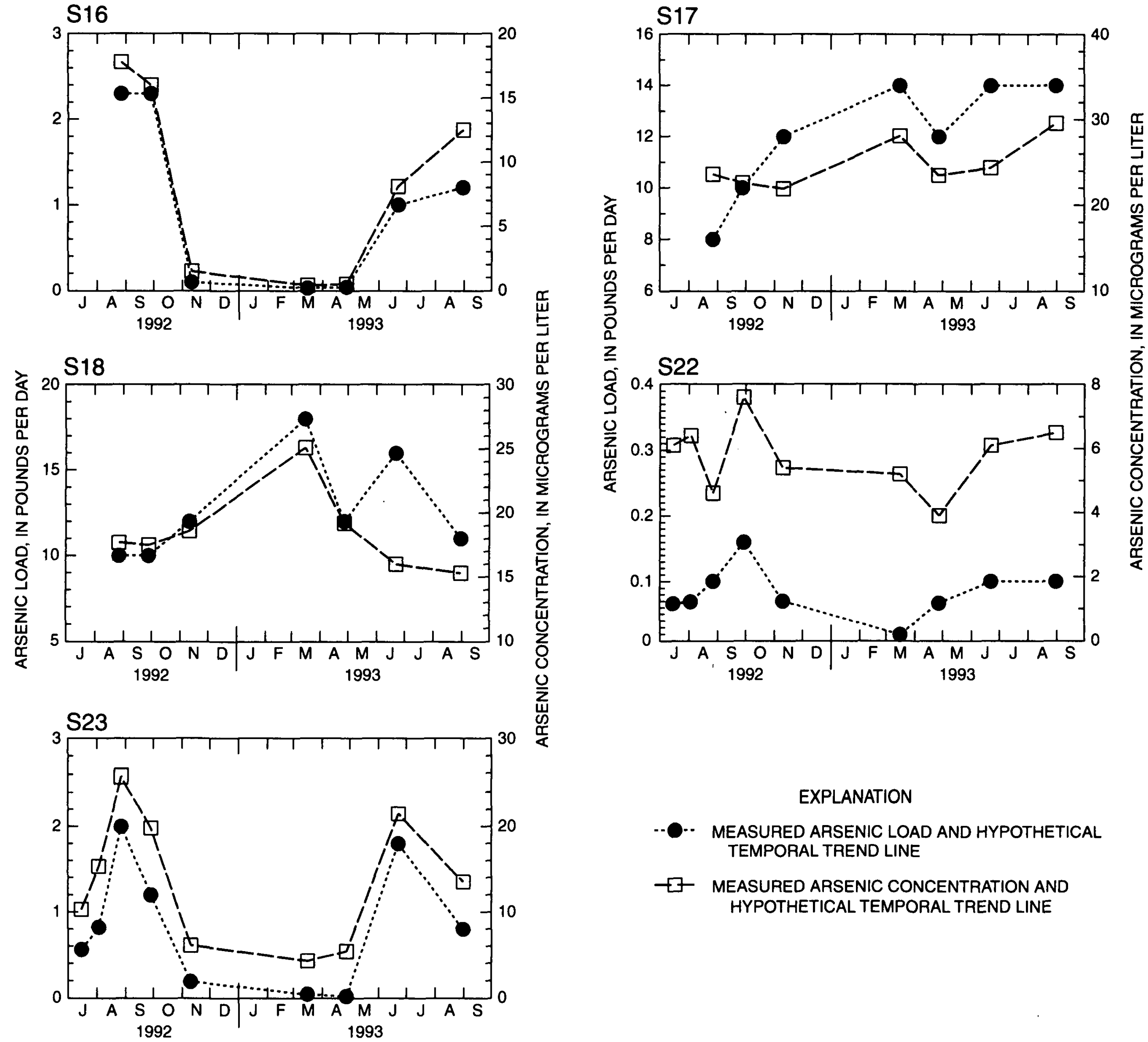


Figure 13. Hypothetical temporal trend of arsenic in water at selected surface-water sites of the upper Madison River Valley, Montana (see figure 3 for site locations). Arsenic concentrations are a combination of total-recoverable and dissolved. Arsenic concentrations reported as less than the minimum reporting level are plotted as one-half the minimum reporting level.

trend based on arsenic concentrations and streamflow. These lines do not imply actual temporal patterns, but rather are used to illustrate relative differences between seasons and to infer possible sources of arsenic in water from selected surface-water sites. Although concentrations differ between the sites and arsenic loads can be low, increasing concentration and load during months of irrigation are evident for some sites.

Water from Bear Creek (sites S12-13 and S15-16) has arsenic concentrations that range from <0.7 to 20.6 µg/L (table 3). In the area along Bear Creek south to near the center of sec. 26, T. 6 S., R. 1 W., water from basin-fill deposits discharges to Bear Creek (fig. 3). Thus, Bear Creek below site S13 functions as a drain for irrigation return flow and as a discharge area for deeper ground water. Arsenic concentrations and loads in water at site S16 vary seasonally and increase during the irrigation season (table 5, fig. 13). The increase in arsenic loads during the irrigation season likely indicates that some arsenic originates from irrigation-supply water and that not all arsenic is removed by sorption onto soils and aquifer materials.

Arsenic concentrations in water from sites S10 and S20-23 (fig. 3) range from 3.9 to 25.8 µg/L (table 3). Some of the larger values at site S23 probably are from West Madison Canal tailwater that is directed into Spring Branch (Mangelson and Brummer, 1994). Median arsenic concentrations are about the same during the non-irrigation as the irrigation season (5.4 and 6.1 µg/L, respectively) for water at site S22, but increase during the irrigation season for water at site S23 (4.3 to 15 µg/L, respectively). However, arsenic loads generally increase during the irrigation season in water at both sites (table 5, fig. 13). The increase in loads during the irrigation season also likely indicates that some arsenic originates from irrigation and that not all arsenic is removed by sorption onto soils and aquifer materials.

Water from O'Dell Creek, a distributary channel of the Madison River (fig. 12) has arsenic concentrations at sites S17-18 that range from 15.3 to 29.6 µg/L. Arsenic concentrations in water at these sites are relatively constant, which might reflect the hydrologic connection with the Madison River. However, these concentrations are much lower than arsenic concentrations in the Madison River (tables 3, 4, and 5; fig. 12) and might reflect dilution by regional ground water. Because of upstream regulation of the Madison River, generally higher streamflow in the fall and winter can result in larger arsenic loads in the non-irrigation season even though arsenic concentrations can be relatively low (Nimick and others, 1998).

Lower Madison River Valley

In the lower Madison River Valley (fig. 4), arsenic concentrations in surface water range widely from <1 to 321 µg/L, depending on the source of water. Arsenic concentrations in irrigation-supply water (sites S29-30, S32-34, S36, S39, S42, S44-45, S47-48, S54, and S59-60) range from 27.0 to 113 µg/L (table 3), and generally are similar to arsenic concentrations in the Madison River (sites S26 and S58), which range from 41 to 100 µg/L (table 4; fig. 14). Several canals and ditches also function as drains (sites S42, S47-48, S54, and S60). For example, the highest arsenic concentration of 113 µg/L was determined at site S48 during the non-irrigation season when this site probably was functioning as a drain for irrigation return flow.

Arsenic concentrations in water in drains and Rey and Spring Creeks (sites S37-38, S42-43, S46, S51, S56-57, and S60) range from 42.2 to 321 µg/L (tables 3 and 5). Arsenic concentrations in water in some drains and sites along Rey and Spring Creeks are similar to arsenic concentrations in local ground water. For example, arsenic concentrations in water in drains and Rey and Spring Creeks (sites S37-38, and S41-43, and S46-47), which are in the south and central parts of the valley, range from about 42 to 63 µg/L, and generally are similar to concentrations in ground water in this part of the valley. Arsenic concentrations in water at sites S48-S50 close to the irrigated east-central part of the valley range from about 96 to 114 µg/L. These values are similar to arsenic concentrations in ground water that is recharged by irrigation water that has percolated through Tertiary sediment (David A. Nimick, written commun., 1997). In addition, arsenic concentrations in water at most of these sites are comparable to those of the Madison River (sites S26 and S58, table 4); therefore, the surface-water component of irrigation return flow does not substantially affect arsenic concentrations in the Madison River (David A. Nimick, written commun., 1997).

Arsenic concentrations in drains and Rey and Spring Creeks in the lower Madison River Valley are high compared with arsenic concentrations in water from drains elsewhere in the study area (figs. 12, 14, 15, and 17), which seems to indicate that arsenic is not removed as effectively by sorption onto soils in this valley. Although some arsenic is removed from

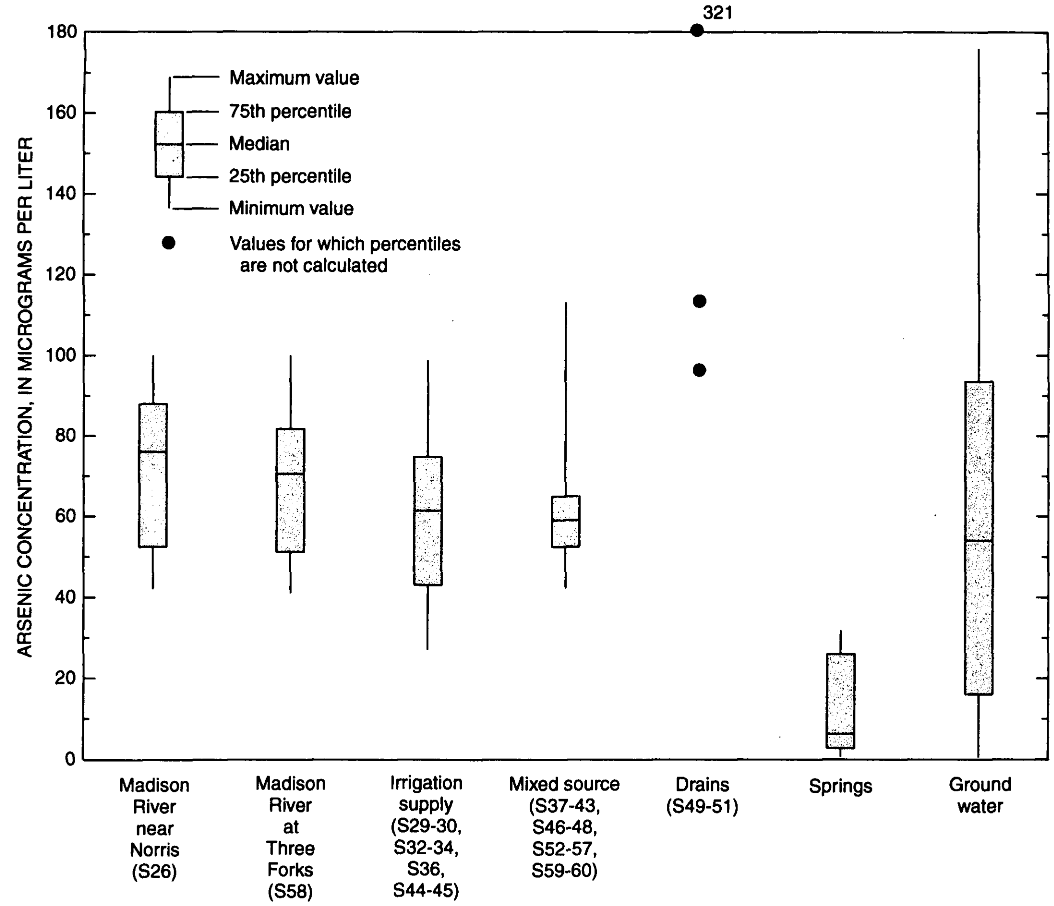


Figure 14. Range of arsenic concentrations in surface and ground water of the lower Madison River Valley, Montana. Arsenic concentrations for sites S26 and S58 are dissolved. Arsenic concentrations for other surface-water sites are a combination of total-recoverable and dissolved. Arsenic concentrations (As^{+3} and As^{+5}) for ground water are dissolved. Arsenic concentrations reported as less than the minimum reporting level are plotted as one-half the minimum reporting level.

irrigation water by sorption onto soils or aquifer materials (Keith, 1995), the predominant effect on arsenic concentrations in water in drains and Rey and Spring Creeks probably is inflow from ground water that discharges to these sites in the south- and east-central parts of the valley (fig. 9). Water from the Madison River recharges alluvium of the lower Madison River Valley, and a significant amount of the arsenic in the ground water originates from this recharge (Nimick, 1998). The ground water then discharges to drains and Rey and Spring Creeks.

Water from two geothermal springs (sites S31 and S35, fig. 4), near or within the lower Madison River Valley, has arsenic concentrations that range from <1 to 31.8 µg/L (table 3). Geothermal water probably is not a major source of arsenic to ground water in the lower Madison River Valley (Nimick, 1998). Both springs probably issue from metamorphic bedrock of Late Archean age associated with deep ground-water flows along concealed faults or fractures. In addition, water from site S35 has different major-ion concentrations, higher boron (2,200 µg/L) and lithium (350 µg/L) concentrations, and higher water temperature (32.0 °C) than either surface or ground water.

Townsend Valley

In the Townsend Valley (fig. 5), arsenic concentrations in surface water range from <1 to 67 µg/L (tables 3 and 4; fig. 15). Arsenic concentrations in irrigation-supply water at sites S62 and S71 range from

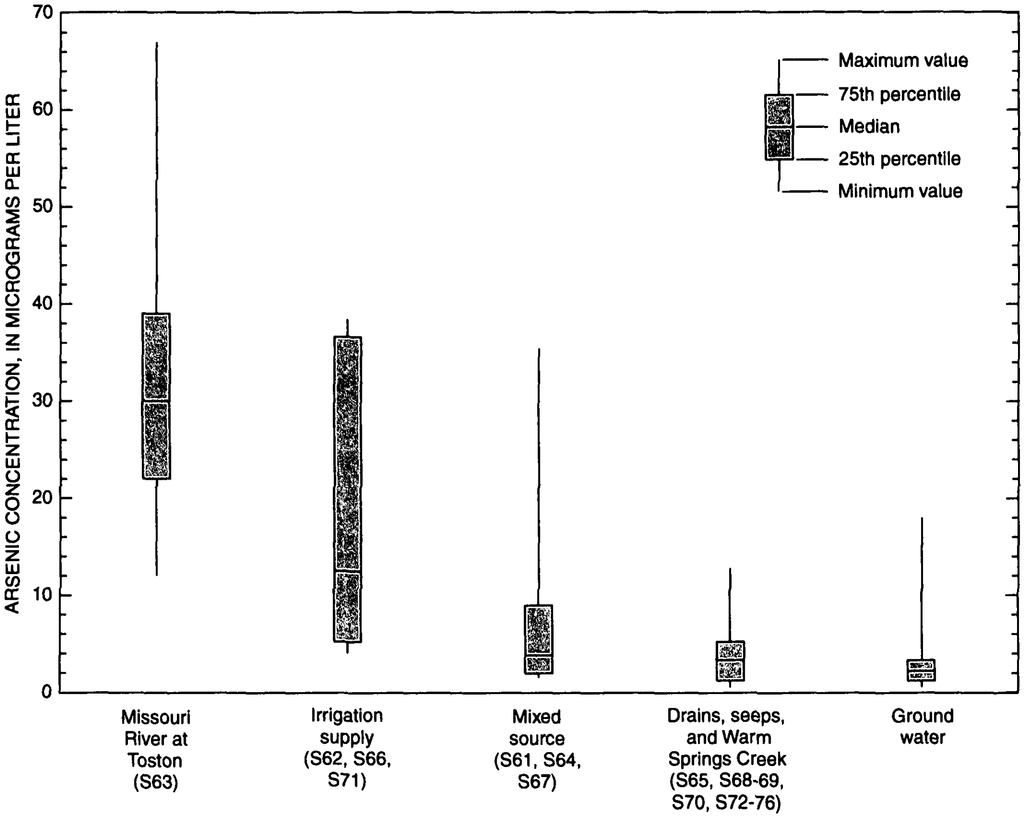


Figure 15. Range of arsenic concentrations in surface and ground water of the Townsend Valley, Montana. Arsenic concentrations for site S63 are dissolved. Arsenic concentrations for other surface-water sites are a combination of total-recoverable and dissolved. Arsenic concentrations (As^{+3} and As^{+5}) for ground water are dissolved. Arsenic concentrations reported as less than the minimum reporting level are plotted as one-half the minimum reporting level.

12.5 to 38.4 µg/L. Arsenic concentrations at site S66 (Big Spring Creek) are 4.0 and 6.4 µg/L. Water from this irrigation source issues from bedrock along the Missouri River. Arsenic concentrations in water in drains, seeps, and Warm Springs Creek (sites S61, S64-65, S67-69, S70, S72-76) range from <1 to 35.4 µg/L. Depending on the site, water in Warm Springs Creek probably is a combination of natural streamflow, irrigation return flow, tailwater from the Toston Canal, and ground water. Inflow from deeper ground water might dilute arsenic concentrations in water from drains, seeps, and Warm Springs Creek.

Arsenic concentrations and loads in water in drains, seeps, and Warm Springs Creek in the Townsend Valley vary seasonally (table 5, fig. 16). Arsenic concentrations generally decreased through the fall and winter, then increased at the beginning of the irrigation season. Arsenic loads in water at sites S64, S67-S68, and S75 generally increased during the irrigation season. The increase in arsenic loads during the irrigation season likely indicates that some arsenic originates from irrigation-supply water and that not all arsenic is removed by sorption onto soils and aquifer materials. However, most arsenic concentrations in water at these sites are less than about 8 µg/L; thus, either arsenic is diluted by other water sources (tributaries or regional ground water), or much is removed from applied irrigation water (range from 4.0 to 38.4 µg/L) by sorption onto soils.

Helena Valley

In the Helena Valley (fig. 6), arsenic concentrations in surface water range from <0.8 to 31 µg/L depending on the source of water (tables 3 and 4; fig. 17). Arsenic concentrations in irrigation-supply water from canals (sites S78, S80, S84, S95, and S101) in the Helena Valley and from the Missouri River below Canyon Ferry Dam (discontinued periodic water-quality

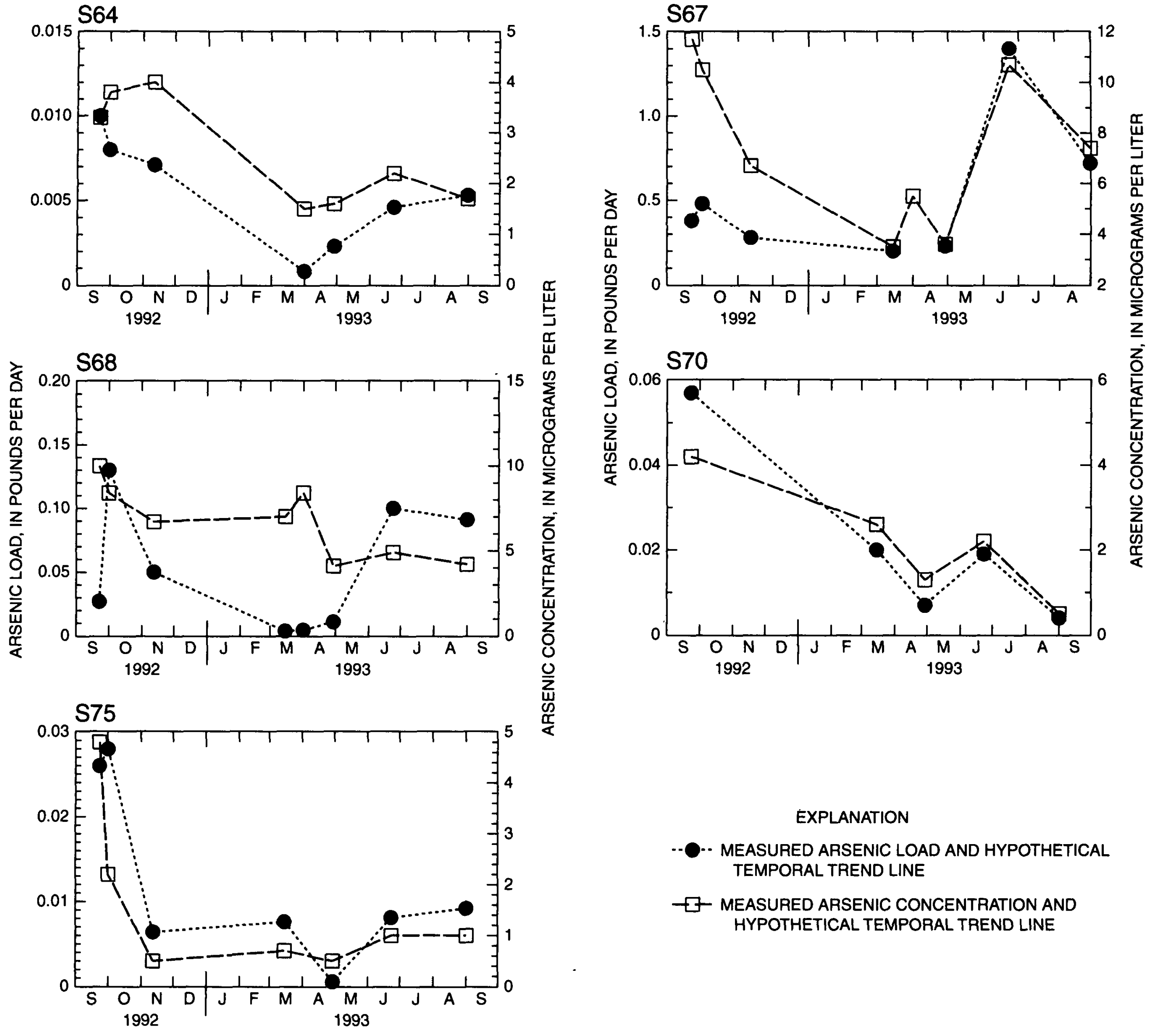


Figure 16. Hypothetical temporal trend of arsenic in water at selected surface-water sites of the Townsend Valley, Montana (see figure 5 for site locations). Arsenic concentrations are a combination of total-recoverable and dissolved. Arsenic concentrations reported as less than the minimum reporting level are plotted as one-half the minimum reporting level.

site, fig. 6) indicate that arsenic concentrations in irrigation-supply water might be slightly lower than arsenic concentrations in water from the Missouri River at Toston (site S63, fig. 17). Water is pumped from Canyon Ferry Lake to the Helena Valley Regulating Reservoir, then discharged to the Helena Valley Canal. Some arsenic might be sorbed to suspended sediment as water resides in Canyon Ferry Lake (Nimick and others, 1998) and subsequently removed from the water by settling. Arsenic concentrations in water from irrigation-supply canals range from 1.1 to 31 µg/L. Arsenic concentrations can be lower in the canals where canals also function as drains (sites S84 and S95) because water probably is a mixture of water from the river, irrigation return flow, tailwater, and deeper ground water.

Arsenic concentrations in water from drains (sites S79, S81-82, S85-93, S96, and S99) in the Hel-

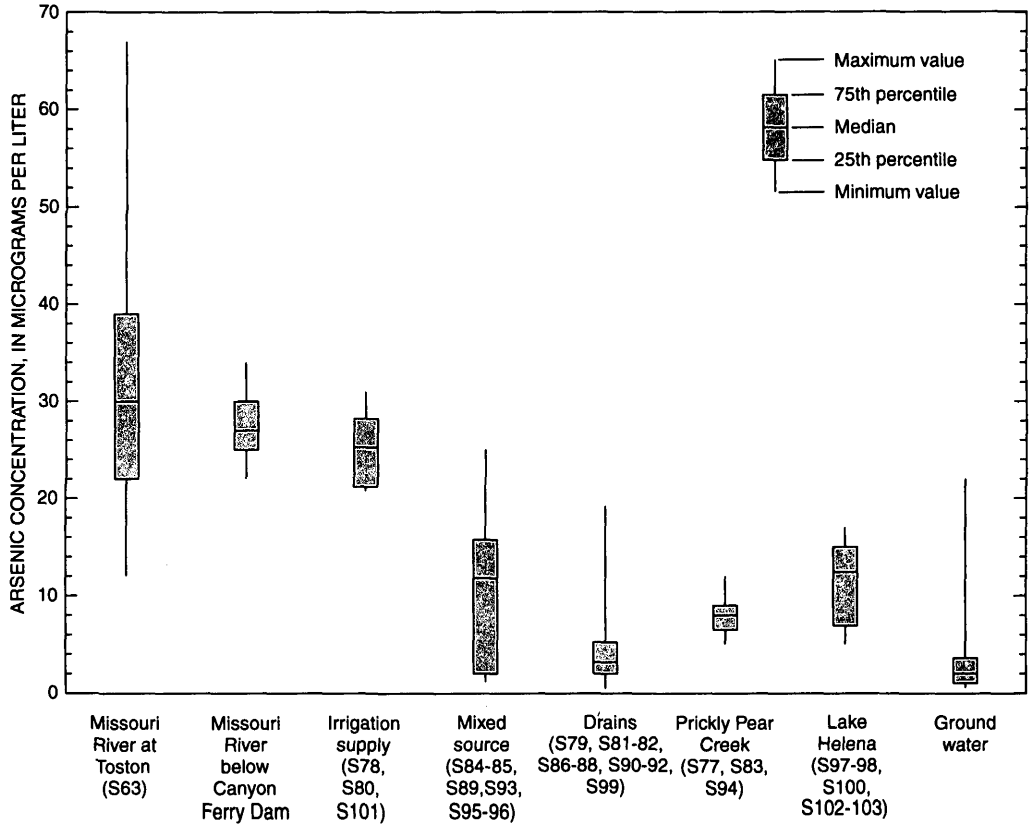


Figure 17. Range of arsenic concentrations in surface and ground water of the Helena Valley and comparison with concentrations of the Missouri River at Toston (site S63) of the Townsend Valley and the Missouri River below Canyon Ferry Dam, Montana. Arsenic concentrations for site S63 are dissolved. Arsenic concentrations for the Missouri River below Canyon Ferry Dam are total recoverable. Arsenic concentrations for other surface-water sites are a combination of total-recoverable and dissolved. Arsenic concentrations (As^{+3} and As^{+5}) for ground water are dissolved. Arsenic concentrations reported as less than the minimum reporting level are plotted as one-half the minimum reporting level.

ena Valley vary seasonally and range from <0.8 to 25 µg/L. Large discharges during the irrigation season at sites S85, S89, S93, and S96 probably represent tailwater from a lateral supply canals. Water in drains probably is a mixture of water from irrigation return flow, tailwater, and deeper ground water. Temporal trends of arsenic loads at most sites in the Helena Valley are not apparent owing to limited data and low arsenic concentrations. Most arsenic concentrations in water in drains are less than about 5 µg/L; thus, either arsenic is diluted by other water sources (tributaries or regional ground water), or much is removed from applied irrigation water (range from 1.1 to 31 µg/L) by sorption onto soils.

Prickly Pear, Tenmile, Sevenmile, and Silver Creeks have losing reaches as they enter the Helena Valley and streamflow from these creeks recharges ground water (Briar and Madison, 1992). Arsenic from historical mining in the drainages of these creeks might be a source of arsenic to surface and ground water in the Helena Valley (Kendy and others, 1998). Hot springs that discharge into Tenmile Creek contain arsenic (Leonard and others, 1978) and could be a source of some arsenic to ground water where Tenmile Creek recharges the aquifer. Arsenic concentrations in water from Prickly Pear Creek (sites S77, S83, and S94) range from 5 to 12 µg/L, with a median of 8.0 µg/L (tables 3 and 5). Limited data (two values) indicate that arsenic loads increase downstream during the non-irrigation season from site S77 to site S94. Arsenic loads also increase from the non-irrigation to the irrigation season and increase downstream during the irrigation season (fig. 18). Increasing arsenic loads with decreasing streamflow during the irrigation season indicates an intervening source of arsenic between the sites. Possible sources include irrigation return flow and unused irrigation water that spills directly into Prickly Pear Creek (Kendy and others, 1998).

Arsenic concentrations in water from Lake Helena (sites S97-98, S100, and S102) range from 5 to 17 µg/L, with a median of 14 µg/L (table 3). Lake Helena receives inflow from Prickly Pear and Tenmile Creeks, irrigation tailwater from canals and drains, and backwater from Hauser Lake. Arsenic concentrations increase from west to east in Lake Helena. This trend has been attributed to the mixing of water in the eastern part of Lake Helena with the water of Hauser Lake which contains arsenic derived from the Missouri River (Kendy and others, 1998).

ARSENIC IN GROUND WATER

Arsenic in ground water is primarily from one or more of the following sources: recharge from the Madison or Missouri River, either by hydraulic connection or infiltration and percolation of irrigation water; Quaternary alluvium with arsenic-rich coatings in floodplain and low terrace deposits along the Madison and Missouri Rivers; Tertiary sediment, which contains arsenic-rich volcanic ash; and hydrothermal water outside of Yellowstone National Park (Leonard and others, 1978). Other potential sources of arsenic in ground water of the Helena Valley include tailings from mining-related activities, aerially deposited emissions from smelter operations, bedrock containing naturally occurring arsenic minerals, and hot springs (Kendy and others, 1998).

Water from the Madison and upper Missouri Rivers has unusually high concentrations of arsenic, boron, and lithium, which are derived from the geothermal sources in Yellowstone National Park. These elements generally are chemically conservative (or nonreactive) in water of the Madison and upper Missouri Rivers. Where boron and lithium are chemically conservative, their concentration ratios should remain relatively constant. Tributary inflow and ground-water discharge that have low concentrations of these elements would dilute concentrations in the rivers, but would not change the concentration ratios (David A. Nimick, written commun., 1997). Ratios of boron to lithium range from 1.0 to 2.4 and remain relatively constant in water at all mainstem sites on the Madison and Missouri Rivers. However, arsenic concentrations in ground water generally are low, except for the lower Madison River Valley. Most ground water is depleted in arsenic relative to water from the Madison and upper Missouri Rivers most likely because arsenic is removed from these sources by sorption onto soils and aquifer materials. Arsenic from applied-irrigation water (water from the Madison and upper Missouri Rivers) apparently is chemically reactive and generally is removed as irrigation water infiltrates and percolates to the water table. Thus, boron and lithium concentrations and their ratios are used to trace recharge from the rivers and irrigation to determine the source of arsenic

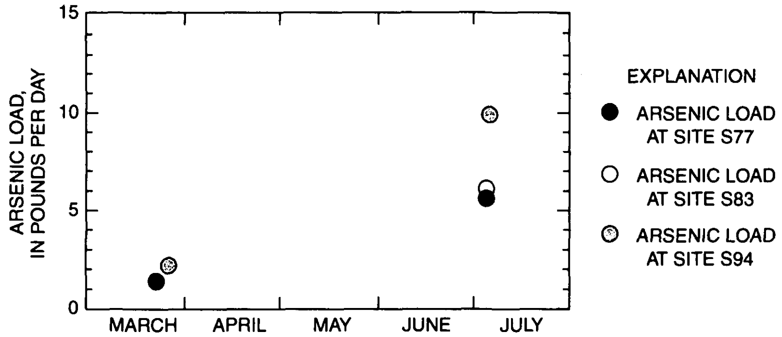


Figure 18. Seasonal and downstream variation of arsenic loads in Prickly Pear Creek, Helena Valley, Montana. Arsenic concentrations are dissolved.

in ground water and to assess the effects of irrigation on ground-water quality.

Upper Madison River Valley

Ground water of the upper Madison River Valley can be divided into three groups defined primarily by chemical characteristics: (1) ground water that is recharged primarily by the Madison River or irrigation, (2) ground water that is not recharged primarily by the river or irrigation, and (3) ground water that does not have clear chemical characteristics that indicate the primary source of recharge. Arsenic concentrations in ground water of this valley range from 0.5 to 40 µg/L, with a median of 2.0 µg/L. All arsenic concentrations in ground water are less than those (fig. 12) determined for the Madison River at sites S8 and S24 (fig. 3). Because arsenic concentrations in ground water generally are low, arsenic concentrations alone are not an indicator of whether or not ground water has been recharged by the Madison River or irrigation. However, geothermal tracers such as boron and lithium concentrations and ratios of boron to lithium concentrations are useful indicators of recharge from these sources. In addition, the hydrologic setting helps define these three groups (table 6 at back of the report).

Water from wells UM3, UM6, UM13, UM30, UM35, and UM57 (group 1, table 6) is thought to be recharged primarily by the Madison River or irrigation. Figure 19A,B shows comparisons of arsenic to boron and lithium concentrations, respectively, in water from the Madison River streamflow at sites S8 and S24, and ground water of the upper Madison River Valley; the graphs indicate that arsenic in ground water generally is less than about 10 µg/L. Concentrations for surface and ground water are not similar. Therefore, ground water generally is depleted in arsenic relative to surface water from sites S8 and S24 (fig. 12). However, arsenic concentrations in water from four of these wells are higher than most ground-water concentrations, and concentrations in water from two wells are near the range of arsenic concentrations for the Madison River. Figure 19C shows comparisons of boron to lithium concentrations in surface and ground water and indicates that samples from four wells have concentrations similar to those in surface water at sites S8 and S24, thereby indicating likely recharge from the Madison River or irrigation water. In addition, samples from two wells have boron and lithium concentrations that are within or near the range of water from the Madison River, but are depleted in arsenic. All six wells are either downgradient from canals, near lateral canals or located near the Madison River (table 6).

Ratios of boron to lithium in water from these same six wells (UM3, UM6, UM13, UM30, UM35, and UM57) are similar to ratios determined for the water from sites S8 and S24 (table 6). The similarity of ratios between surface and ground water demonstrates that ground water at these six wells probably is recharged primarily by the Madison River or irrigation and that most arsenic (which ranges in concentration from 2.1 to 40 µg/L) probably originates either from the river or from irrigation. Water in well UM 57 is slightly depleted in boron, having a ratio of 0.46. The low boron concentration in water from this well (60 µg/L) is not well understood, but the high lithium concentration of 130 µg/L (when most other ground water is depleted in lithium) indicates a hydraulic connection to the river.

Water from wells UM1, UM12, UM18, UM34, UM40, UM45, UM49, and UM53 (group 2, table 6) is not recharged primarily by the Madison River or irrigation. Arsenic concentrations (0.5 to 4.2 µg/L), are low, whereas ratios of boron to lithium[2] in ground water generally are high when compared to water from the Madison River (table 6). Wells UM1, UM12, UM34, and UM45, are upgradient from irrigation; wells UM18, UM40, UM49, and UM53 either are located downgradient from irrigation or are within irrigated areas. However, low boron and lithium concentrations in water indicate that ground water near these wells is not recharged primarily by irrigation.

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[2] Some boron and lithium concentrations in surface and ground water of the upper Madison River Valley are reported as less than the minimum reporting levels of <20 µg/L and <6 µg/L, respectively. For these analyses, ratios of boron to lithium are calculated using one-half the minimum reporting level. Actual ratios are unknown, but are limited by the minimum reporting level for each constituent.

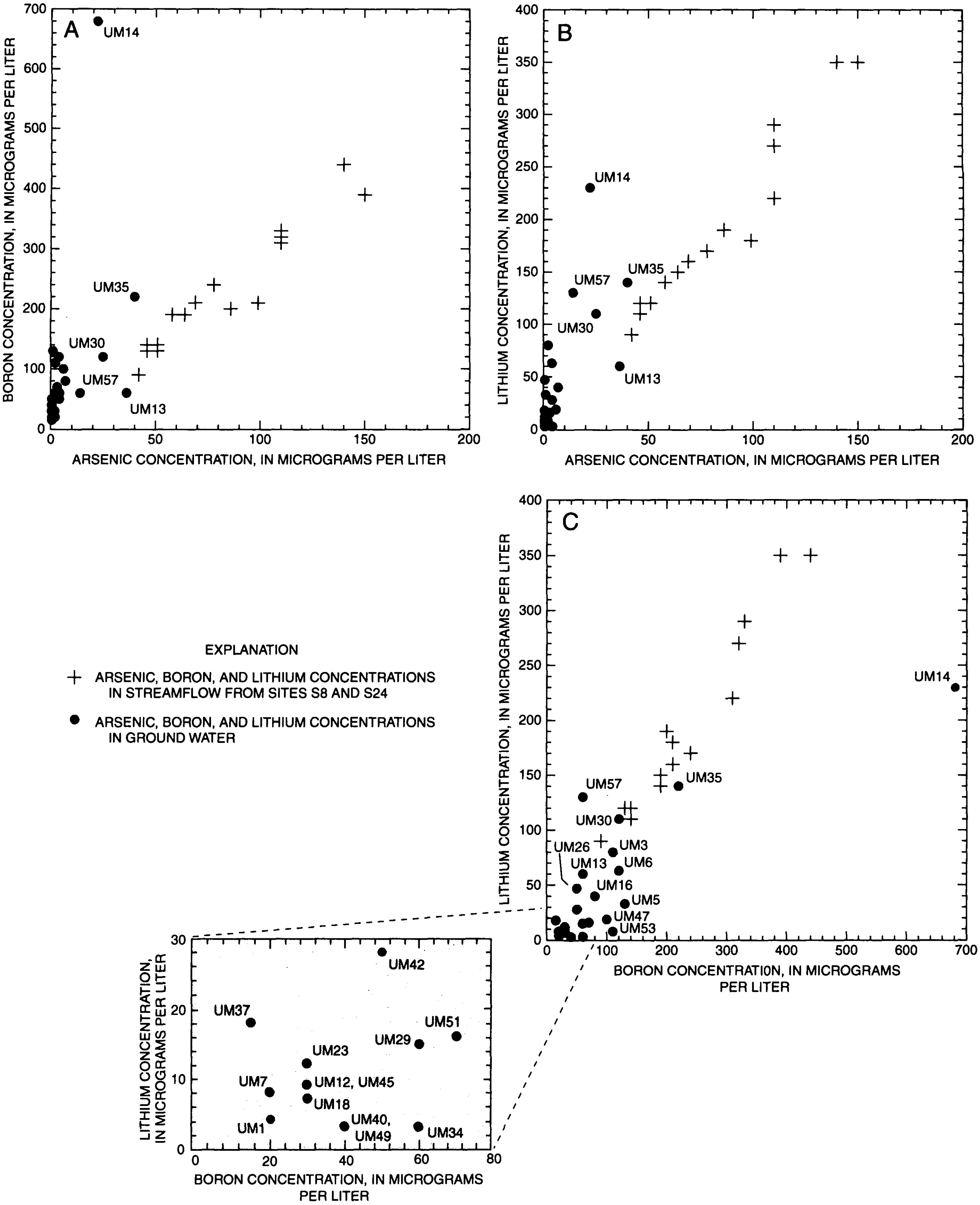


Figure 19. Comparison of arsenic to boron and lithium concentrations in surface water from the Madison River near Cameron (site S8) and the Madison River below Ennis Lake, near McAllister (site S24) and ground water of the upper Madison River Valley, Montana. Arsenic concentration for sites S8 and S24 are dissolved. Arsenic concentrations (As^{+3} and As^{+5}) for ground water also are dissolved. Arsenic and lithium concentrations reported as less than the minimum reporting level are plotted as one-half the minimum reporting level.

Ground water at well UM14 (group 2, table 6) also is not recharged primarily by the Madison River or irrigation. This well produces geothermal water from metamorphic bedrock of Late Archean age. Large boron and lithium concentrations (680 and 230 µg/L) and a temperature of about 90 °C indicate that arsenic in water from this well (22 µg/L) is not from irrigation.

Water from wells UM5, UM7, UM16, UM23, UM26, UM29, UM37, UM42, UM47, and UM51 (group 3, table 6) does not have clear chemical characteristics that indicate the primary source of recharge. Arsenic concentrations range from <1 to 6.9 µg/L. Figure 19C shows that water from these wells generally is depleted in boron and lithium relative to water from the Madison River at sites S8 and S24. Ratios of boron to lithium range from 0.83 to 5.3, which are within or near the range of ratios in water from drains. Water from drains and springs and seeps within the valley that has ratios that are higher than irrigation-supply water (water from the Madison River) (table 6) implies an additional source of boron or that lithium is diluted in water from these sites. Boron might be leached from soils or aquifer materials derived from clay-rich Tertiary sediment (Nimick, 1998), because boron typically is associated with these deposits (Welch and others, 1988). Lithium could be diluted with regional ground water having low lithium concentrations. The slightly higher ratios determined for water from some of these wells might indicate that lithium is diluted. All wells are located downgradient from irrigation and well UM29 is located about 1,100 ft from the river. As a result, the potential is large for ground water to receive some recharge from the river or irrigation. However, relations between boron and lithium concentrations in water from these wells are ambiguous.

Dissolved oxygen was measured in water from selected wells in the upper Madison River Valley. Dissolved-oxygen concentrations range from 0.0 to 9.5 mg/L, and most ground water is oxic. Ground water with higher arsenic concentrations generally has higher dissolved-oxygen concentrations, because aquifers near these wells probably are hydraulically connected to the Madison River.

Water samples were analyzed to determine the oxidation state of arsenic that generally exists in ground water of the upper Madison River Valley. Of eight samples analyzed for arsenite (As^{+3}), all concentrations are below the minimum reporting level of 1 µg/L. Concentrations of combined arsenite (As^{+3}) and arsenate (As^{+5}) in those same eight samples range from <1 to 25 µg/L. Therefore, arsenate probably is the predominant species of arsenic in ground water of the upper Madison River Valley.

The magnitude and extent of arsenic in ground water of the upper Madison River Valley are shown in figure 20. Several areas of Region 1 (with arsenic concentrations of generally less than 4.0 µg/L) occur within the valley; arsenic concentrations generally are 3 µg/L or less, with one value of 6.9 µg/L. Springs and seeps (sites S21-23) located in parts of Region 1 have arsenic concentrations that range from 3.9 to 25.8 µg/L.

Two areas of Region 2 (with arsenic concentrations of 4.0 to 17.9 µg/L) in the upper Madison River Valley extend along a low terrace just north of the confluence of Indian Creek and the Madison River and along the upper Madison River Valley from Varney to just north of Trail Creek (fig. 20). Arsenic concentrations in water range from 4.1 and 14 µg/L. Arsenic concentrations in water from site S10 (4.0 and 5.4 µg/L) are similar to concentrations in water from some wells in Region 2.

One area of Region 3 (with arsenic concentrations of 18.0 to 49.9 µg/L) located north of Ennis (fig. 20) is recharged by upward moving geothermal water associated with the Ennis hydrothermal anomaly located primarily in sec. 28, T. 5 S., R. 1 W. (Leonard and Wood, 1988). Arsenic concentrations in water from two wells are 36 and 22 µg/L. Well UM13 is downgradient from the West Madison Canal and ground water near the well probably is recharged primarily by water from the canal. However, a slightly elevated water temperature of 14.0 °C and the absence of dissolved oxygen imply that water from this well also might have a geothermal, or deep, source. Well UM14 is completed in metamorphic bedrock of Late Archean age with no hydraulic connection to surface water.

A second area within Region 3 extends along the upper Madison River Valley just south of Ennis (fig. 20). Arsenic concentrations in water from two wells are 25 and 40 µg/L. These wells are thought to be hydraulically connected to either the Madison River (UM30) or the West Madison Canal (UM35).

Areas that compose Region A in the upper Madison River Valley extend from the southern study-area boundary to Ennis Lake along the Madison River, or occur on the Cameron Bench (fig. 20). Region A, where arsenic concentrations might be about 4 µg/L or higher, was delineated to represent areas where arsenic

EXPLANATION

GENERAL EXTENT OF ARSENIC CONCENTRATION IN GROUND WATER, IN MICROGRAMS PER LITER (µg/L)

░ REGION 1--Less than 4.0

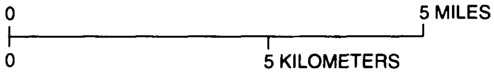
▒ REGION 2--4.0-17.9

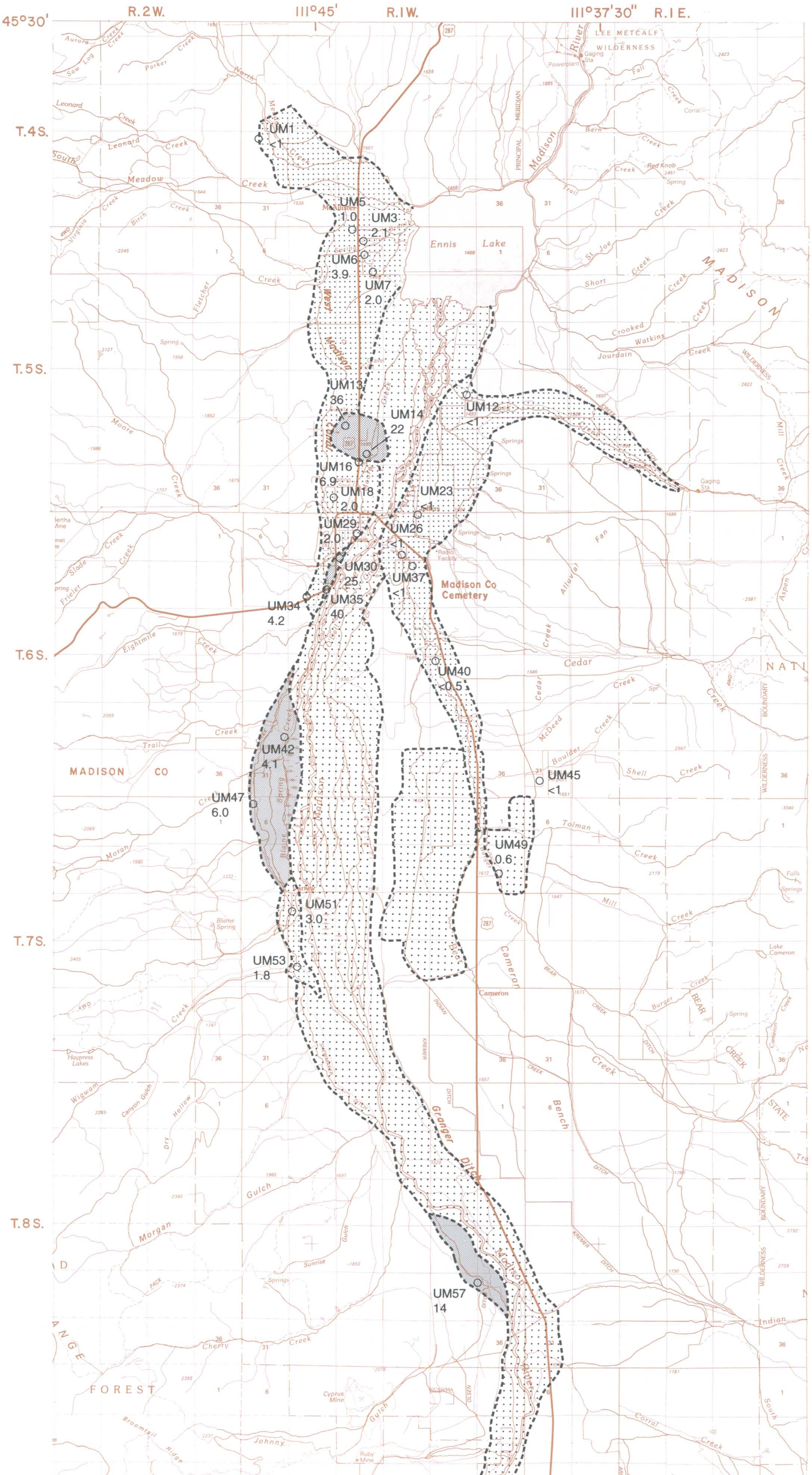
▓ REGION 3--18.0-49.9

░ REGION A--Shows general extent where arsenic concentrations in ground water might be slightly elevated (about 4µg/L or higher). Possible arsenic concentrations not determined by sample analysis but are inferred from land use, geology, and known or probable hydraulic connections between the aquifers and the Madison River and irrigation canals

-------- CONTACT--Approximately located. Shows general boundary of each region

UM7 ○ 2.0 WATER-QUALITY SITE--Number is arsenic concentration, in µg/L. <, less than minimum reporting level





Base modified from U.S. Geological Survey
Ennis, 1989, 1:100,000

Figure 20. Magnitude and extent of arsenic in ground water of the upper Madison River Valley, Montana.

concentrations can be indirectly inferred from land use, geology, and known or probable hydraulic connections between the aquifers and the Madison River or the irrigation canals. Along the Madison River, the aquifer probably is hydraulically connected to the river and pumping might induce flow from surface-water to the wells. Arsenic concentrations in surface water from sites S8 and S24 range from 42 to 150 µg/L, with a median of about 80 µg/L (table 4). Thus, ground water in this part of Region A might have arsenic in concentrations greater than about 4 µg/L.

On the Cameron bench, land use and geology indicate that ground water might have arsenic concentrations of about 4 µg/L. In this area, land is irrigated with a mixture of water from the Madison River and Indian Creek. Therefore, arsenic in water from the Granger Ditch probably is diluted. Additionally, Keith (1995) and Mangelson and Brummer (1994) concluded that arsenic in irrigation water applied to fields sorbs to soil, thereby further decreasing arsenic concentrations in irrigation drainage. Tertiary sediment that composes the aquifer beneath the Cameron Bench might be enriched in arsenic. Background arsenic concentrations in water from this aquifer can range from about <1 to 15 µg/L (Sonderegger and others, 1989; Slagle, 1995). If arsenic exists in ground water in this area, concentrations might represent background concentrations from Tertiary sediment.

Lower Madison River Valley

The hydrogeology and geochemistry of the lower Madison River Valley has been described in previous studies (Sonderegger and Sholes, 1989; Sonderegger and Ohguchi, 1988). Nimick (1998) conducted a detailed study in conjunction with this investigation. The hydrogeochemistry in the lower Madison River Valley is unique in the study area, because most ground water has high arsenic concentrations and, in some wells, arsenic concentrations are higher (as much as 176 µg/L) than those for the Madison River (41 to 100 µg/L at sites S26 and S58; figs. 4 and 14). In addition, ground water in most of the northern part of the valley generally is anoxic (contains little or no dissolved oxygen). Ground water in the lower Madison River Valley can be divided into three areas (Nimick, 1998) defined primarily by hydrogeologic and chemical characteristics: (1) ground water is oxic (contains dissolved-oxygen concentrations generally larger than 1 mg/L) and recharged directly by the Madison River, (2) ground water is oxic, recharged by irrigation, and affected by Tertiary sediment, and (3) ground water is primarily anoxic and recharged by upgradient ground water (fig. 21).

Arsenic concentrations in ground water in the lower Madison River Valley and in areas along the lower Jefferson and Gallatin Rivers range from 0.4 to 176 µg/L, with a median of 54 µg/L. In addition, the highest 25 percent of arsenic concentrations in ground water is between 93 and 176 µg/L (fig. 14), whereas the highest 25 percent of arsenic concentrations from the Madison River (sites S26 and S58) is between about 85 and 100 µg/L. Arsenic concentrations can be an indicator of recharge by the Madison River or irrigation. Geothermal tracers such as boron and lithium concentrations and ratios of boron to lithium also are useful indicators of recharge from the river or irrigation. In addition, hydrologic setting helps define these three areas (table 8 at back of report).

Ground water that is oxic and recharged directly by the Madison River (Area 1) occurs in the south and central parts of the valley (Nimick, 1998). Sampled wells are completed in alluvium (wells LM68, LM70-71, LM81, LM87-88, LM91-93, LM95, LM98-106). Arsenic concentrations in ground water of Area 1 range from about 25 to 124 µg/L, with a median of 44 µg/L. Figure 22A,B shows comparisons of arsenic to boron, and to lithium concentrations, respectively, in surface water from sites S26 and S58, and ground water of the lower Madison River Valley. Most arsenic concentrations in ground water in Area 1 are near, but slightly depleted, relative to the range for water from sites S26 and S58 (table 8, fig. 22). Boron and lithium concentrations generally are within the range of boron and lithium concentrations for surface-water sites S26 and S58. Most ratios of boron to lithium concentrations in ground water of Area 1 are within the range of ratios in water from sites S26 and S58 (table 8). The similarity of ratios between surface and ground water indicates that ground water of Area 1 is recharged primarily by the Madison River.

Ground water in Area 1 is oxic based on limited data for dissolved oxygen (2.2 to 8.2 mg/L), arsenite (less than 1 µg/L), and nitrate (0.32 to 5.0 mg/L) concentrations, and the near absence of iron (<2 to 12 µg/L) and manganese (less than 2 µg/L). Ground-water quality characteristics of this region are similar to

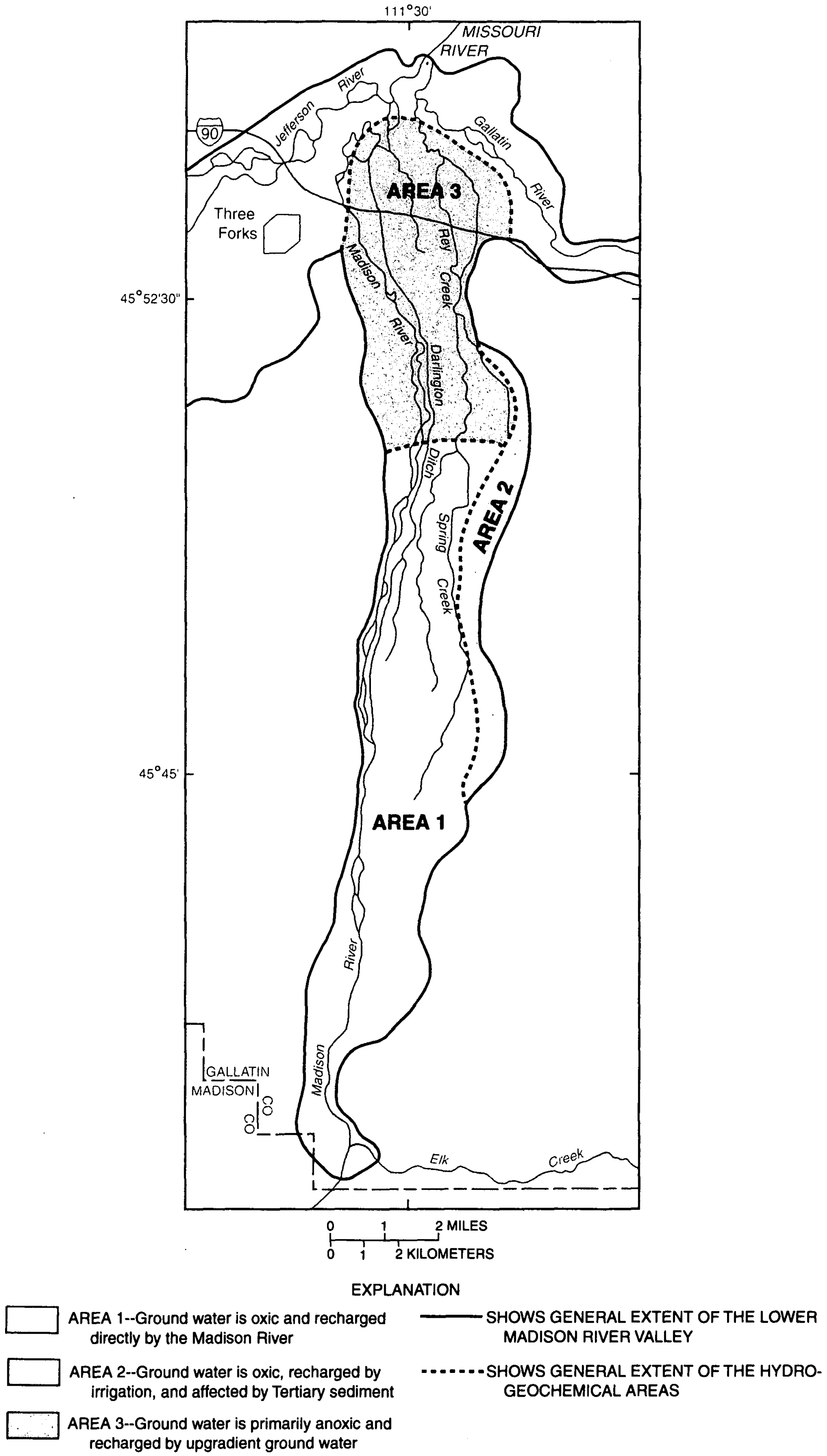


Figure 21. Hydrogeochemical areas of the lower Madison River Valley, Montana (modified from Nimick, 1998).

water-quality characteristics of the Madison River (Nimick, 1998). Thus, water from the Madison River recharges alluvium, and arsenic in ground water of Area 1 originates from this recharge. Arsenic concentrations in ground water are slightly depleted relative to streamflow, probably because some arsenic is adsorbed to soils or aquifer materials (Nimick, 1998; Keith, 1995).

Ground water that is oxic, recharged by irrigation, and affected by Tertiary sediment (Area 2) in the lower Madison River Valley (fig. 21) occurs beneath the side slopes in the east-central part of the valley. Sampled wells (LM63-66, LM72-80, LM83-84, LM86, LM89-90) are completed in Tertiary sediment (Nimick, 1998). Arsenic concentrations in ground water of Area 2 range from 38 to 138 µg/L, with a median of 79 µg/L. Most arsenic concentrations in ground water are within or near the arsenic range for surface-water sites S26 and S58 (table 8, fig. 22). However, some ground water has arsenic concentrations that are higher than those for water from sites S26 and S58 (fig. 22). Arsenic concentrations from soil and rock samples collected from non-irrigated areas (about 4 to 18 µg/g) indicate that Tertiary sediment could be an additional source of arsenic to ground water (Nimick, 1998). Boron concentrations in ground water generally are higher than those in water from sites S26 and S58, whereas lithium concentrations are within or near the range of those for water from sites S26 and S28. Ratios of boron to lithium concentrations in ground water generally are higher than ratios in water from sites S26 and S58 (table 8). Higher boron concentrations and ratios of boron to lithium imply an additional source of boron to ground water. Arsenic and boron might be leached from clay-rich Tertiary sediment in the aquifer of Area 2.

Limited data (fig. 22) show that arsenic, boron, and lithium concentrations in water from five wells completed in Tertiary sediment east of the lower Madison River Valley in Gallatin County (Slagle, 1995) are much lower than those from wells in Area 2. Arsenic concentrations range from <1 to 11 µg/L, boron concentrations range from 20 to 130 µg/L, and lithium concentrations are less than 6 µg/L in water from all five wells. Comparison of the low arsenic, boron, and lithium concentrations in water from these five wells with concentrations in water from wells in Area 2 also demonstrates that ground water in the east-central part of the valley is probably recharged from irrigation. Thus, most arsenic in ground water of Area 2 probably originates from irrigation.

Ground water in Area 2 is oxic based on limited data for dissolved oxygen (1.7 to 5.7 mg/L), nitrate (0.42 to 7.2 mg/L), iron (1 to 15 µg/L), and manganese (<1 to 26 µg/L) concentrations. Concentrations of arsenite are generally low (<1 to 5.5 µg/L) and indicate that arsenate probably is the dominant arsenic species in this part of the lower Madison Valley (Nimick, 1998).

Ground water that is anoxic in the lower Madison River Valley (Area 3) occurs beneath the northern quarter of the valley, where wells (LM21, LM27-36, LM40-50, LM52-53, LM 57-58, LM60, LM62) are completed in Quaternary alluvium and Tertiary sediment. Arsenic concentrations in ground water of Area 3 range from about 16 to 176 µg/L, with a median of 89 µg/L. Some of the arsenic concentrations determined for ground water in this part of the valley are higher (118 to 176 µg/L) than arsenic concentrations in surface water at sites S26 and S58 (table 8, fig. 22). Therefore, some ground water is enriched in arsenic relative to water from sites S26 and S58. One source of arsenic in ground water of Area 3 includes recharge by arsenic-rich ground water that flows in from Areas 1 and 2. A second source of arsenic includes sediment of the alluvial aquifer that is naturally enriched in arsenic because of sorption from the high dissolved-arsenic concentrations in the Madison River. When redox conditions change from oxic to anoxic in Area 3, sorbed arsenic likely is released to ground water (Nimick, 1998). Boron concentrations in ground water also show enrichment relative to surface water from sites S26 and S58, whereas lithium concentrations generally are within the range of lithium concentrations in water from sites S26 and S58. Generally, ratios of boron and lithium concentrations are slightly higher than the range of ratios in water from sites S26 and S58 (table 8, fig. 22).

The water-quality characteristic that distinguishes the northern part of the lower Madison River Valley from the rest of the valley is that ground water is anoxic. Very low dissolved-oxygen (less than 0.3 mg/L) and nitrate (less than 2.2 mg/L) concentrations, and high iron (2 to 1,300 µg/L) and manganese (2 to 3,000 µg/L) concentrations also indicate that ground water is reduced. In addition, samples from seven wells had a high proportion of arsenite (As^{+3}), indicating that ground water is reduced (Nimick, 1998).

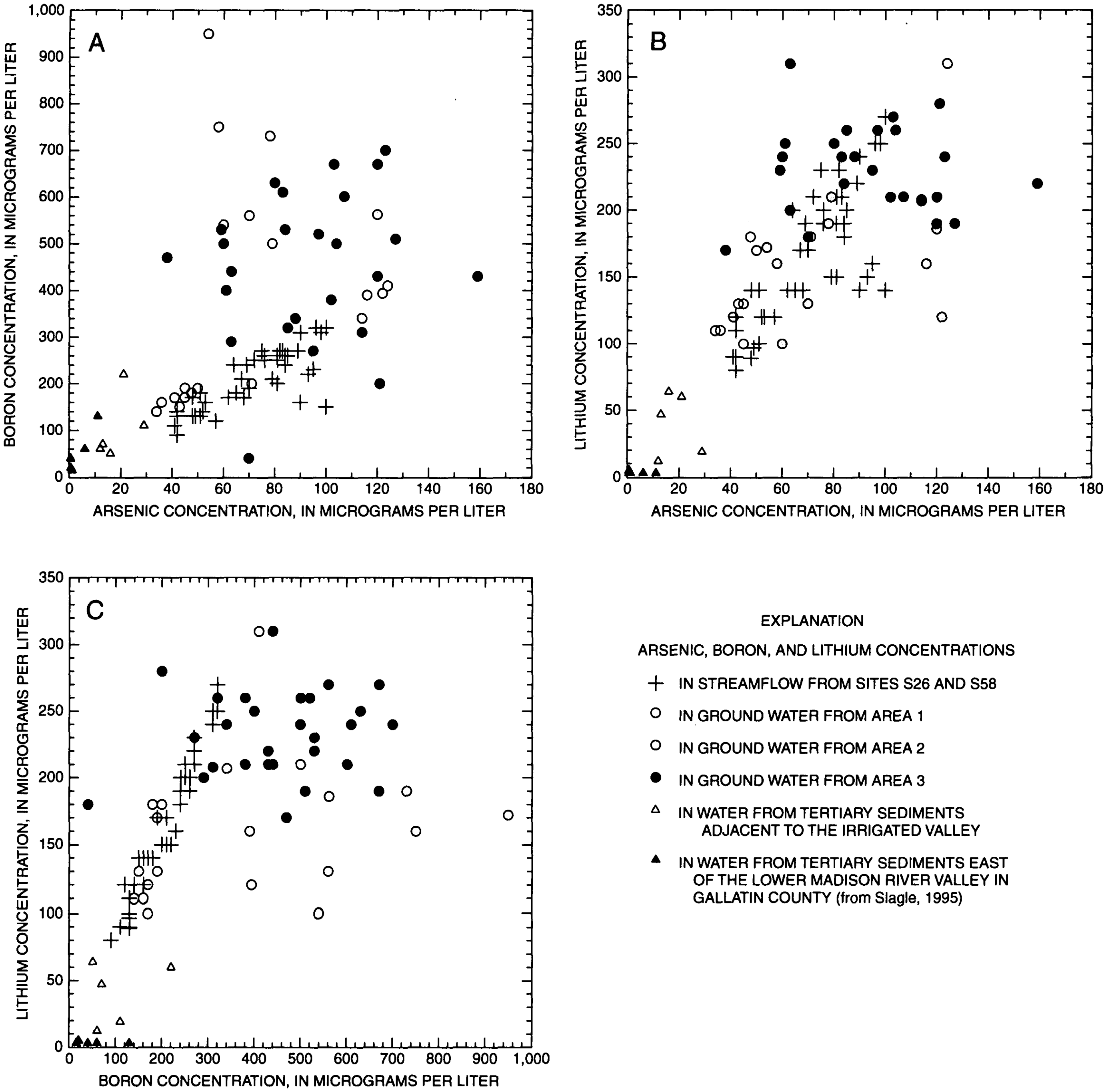


Figure 22. Comparison of arsenic to boron and lithium concentrations in surface water from the Madison River near Norris (site S26) and the Madison River at Three Forks (site S58) and ground water of the lower Madison River Valley, Montana (modified from Nimick, 1998). Arsenic concentrations for surface water from sites S26 and S58 are dissolved. Arsenic concentrations (As^{+3} and As^{+5}) for ground water are dissolved. Arsenic and lithium concentrations reported as less than the minimum reporting level are plotted as one-half the minimum reporting level.

Ground water in Area 3 is within a few feet of land surface, and most of Area 3 is a discharge area for the lower Madison River Valley. Thus, ground water has an upward component of flow, and recharge from irrigation probably affects arsenic concentrations only in water from very shallow wells (Nimick, 1998).

In addition to the hydrogeochemical areas defined by Nimick (1998), regions in the lower Madison River Valley are described in this report by magnitude and extent of arsenic in ground water (fig. 23). Region 1 (with arsenic concentrations of generally less than 4.0 µg/L) includes areas along the Jefferson and Gallatin Rivers where ground water is not recharged by the Madison River or irrigation. Arsenic concentrations range from 0.4 to 7.2 µg/L, with a median of 2.3 µg/L. The two highest values (4.8 and 7.2 µg/L) for Region 1 (fig. 23) are near the boundary between Region 1 and Region 4, and mixing of ground water between the two regions might account for the slightly higher values. Ground water in Region 1 presumably is affected by hydraulic connection with the Jefferson and Gallatin Rivers and by regional ground-water flow from underlying basin-fill deposits. Therefore, most arsenic in Region 1 probably does not originate from recharge from the Madison River or irrigation.

Areas of Region 2 (with arsenic concentrations that generally range from 4.0 to 17.9 µg/L) occur west of the valley (fig. 23). Arsenic concentrations determined west of the valley range from 12 to 29 µg/L. This part of Region 2 might receive some recharge from the Madison River, and arsenic in ground water in Region 2 might originate from this recharge. However, some arsenic also might originate from Tertiary sediment. This area has been irrigated in the past, but was not irrigated in 1992-95.

Areas of Region 3 (with arsenic concentrations that generally range from 18.0 to 49.9 µg/L) generally occur in the southern part of the lower Madison River Valley, and between Logan and Three Forks (fig. 23). Arsenic concentrations range from 16 to 124 µg/L, with a median of 38 µg/L. In the southern part, water from the Madison River recharges the aquifer and arsenic in ground water originates from this recharge. Irrigation does not appear to be an important source of recharge (Nimick, 1998).

Between Logan and Three Forks, two wells have arsenic concentrations of 16 and 18 µg/L (fig. 23). Both wells are within about 1,000 ft of land irrigated with water from the Madison River (site S54 with arsenic concentrations of 62.6 and 52.9 µg/L). The source of arsenic in ground water in this part of Region 3 might include irrigation and the release of arsenic that was sorbed to aquifer sediment.

An area of Region 4 (with arsenic concentrations that generally are 50 µg/L or greater) in the lower Madison River Valley occurs along the east-central and northern parts of the valley. Arsenic concentrations from this area range from 22 to 176 µg/L. The source of arsenic in ground water of Region 4 probably includes some recharge from upgradient ground water and the release of arsenic that was sorbed to the aquifer sediment. Irrigation does not appear to be an important source of recharge (Nimick, 1998).

Areas that compose Region A in the lower Madison River Valley occur northwest of the Jefferson and Missouri Rivers, between the Jefferson and Madison Rivers, and east of the lower Madison River Valley (fig. 23). Region A (where arsenic concentrations might be about 4 µg/L or higher) was delineated to represent areas where arsenic concentrations can be indirectly inferred from land use, geology, and known or possible hydraulic connections between the aquifers and the Madison or Missouri River, or irrigation canals. Arsenic concentrations in a limited number of samples for ground water of Region A range from 4.7 and 47 µg/L. The high arsenic concentrations at wells LM1 (35 µg/L) and LM5 (47 µg/L) are not well understood. Tertiary sediment that composes the aquifer near these wells might be enriched in arsenic and could be the principal source of arsenic in ground water. However, arsenic concentrations in water from other wells completed in Tertiary sediment that are not recharged by the Madison or Missouri Rivers or irrigation indicate that arsenic is generally 11 µg/L or less (Slagle, 1995). Sonderegger and others (1989) estimated background concentrations of arsenic in Tertiary sediment along the lower Madison River Valley to be less than 15 µg/L. Ground water near well LM97 (21 µg/L) could receive recharge from irrigation by lateral flow induced by pumping this well.

Townsend Valley

Ground water of the Townsend Valley can be divided into three groups primarily defined by chemical characteristics: (1) ground water that is recharged primarily by the Missouri River or irrigation, (2) ground water that is not recharged primarily by the river or irrigation, and (3) ground water that does not

EXPLANATION

GENERAL EXTENT OF ARSENIC CONCENTRATION IN GROUND WATER, IN MICROGRAMS PER LITER (µg/L)

░ REGION 1--Less than 4.0

▒ REGION 2--4.0-17.9

▒ REGION 3--18.0-49.9

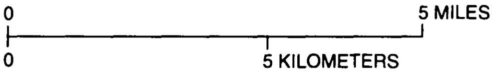
▓ REGION 4--50.0 or greater

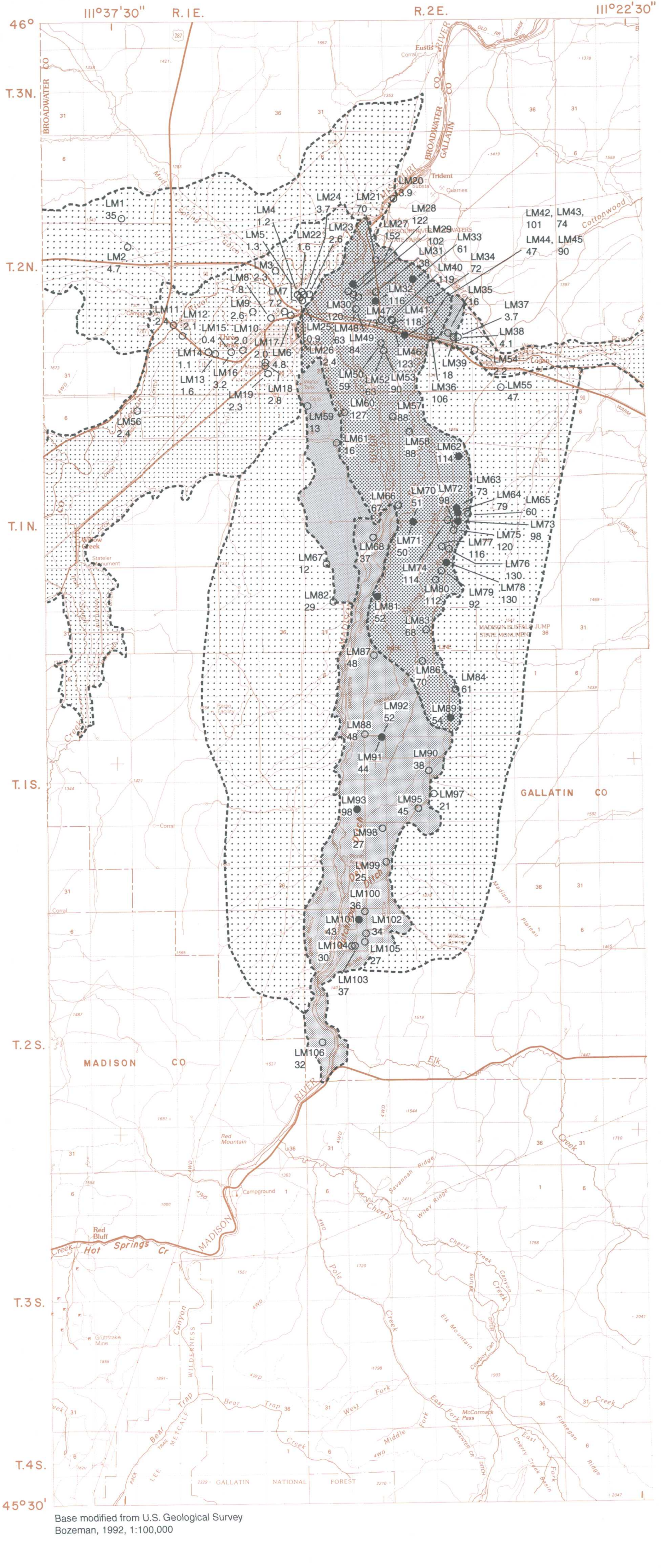
░ REGION A--Shows general extent where arsenic concentrations in ground water might be slightly elevated (about 4µg/L or higher). Possible arsenic concentrations not determined by sample analysis but are inferred from land use, geology, and known or probable hydraulic connections between the aquifers and the Madison River and irrigation canals

-------- CONTACT--Approximately located. Shows general boundary of each region

LM56
2.4 ○ WATER-QUALITY SITE--Number is arsenic concentration, in µg/L

LM81
52 ● WATER-QUALITY SITE--Number is mean arsenic concentration, in µg/L





Base modified from U.S. Geological Survey
Bozeman, 1992, 1:100,000

Figure 23. Magnitude and extent of arsenic in ground water of the lower Madison River Valley, Montana.

have clear chemical characteristics that indicate the primary source of recharge. Arsenic concentrations in ground water of this valley range from <1 to 18 µg/L, with a median of 2.2 µg/L. Arsenic concentrations in ground water can be an indicator of whether ground water has been recharged by the river or irrigation, because concentrations are high only at wells where the aquifer probably is hydraulically connected to the Missouri River or irrigation canals. Geothermal tracers such as boron and lithium concentrations and ratios of boron to lithium, which vary from place to place, can be useful as indicators of recharge from the river or irrigation. Hydrologic setting also is an important factor in determining if the aquifer might be recharged by the Missouri River or irrigation (table 9 at back of report).

Water from wells T5, T27, T33, T36, and T42 (group 1, table 9) is thought to be recharged primarily by the Missouri River or irrigation canals. Figure 24A,B shows a comparison of arsenic to boron and lithium concentrations, respectively, in water from the Missouri River at Toston (site S63) and ground water in the Townsend Valley; the graphs indicate that arsenic in ground water generally has a concentration of 6 µg/L or less. Concentrations for surface water and ground water are not similar; therefore, ground water generally is depleted in arsenic relative to water from site S63. However, arsenic concentrations in water from wells T33, T36, and T42 are within the range of arsenic concentrations in water from site S63 (fig. 24). The data indicate that the aquifer probably is hydraulically connected to the Missouri River (wells T27, T36, and T42) or the irrigation canal (well T33).

Ratios of boron to lithium at these same five wells (T5, T27, T33, T36, and T42) are similar to ratios determined for surface water from site S63 (table 9, fig. 24C). The similarity of ratios between surface and ground water demonstrates that ground water at these five wells probably is recharged by the Missouri River or irrigation and that arsenic in water from these wells (2.4 to 18 µg/L) probably originates from these sources.

Water from wells T4, T22, T28-29, T50-51, T54, and T57 (group 2, table 9) is not recharged primarily by the Missouri River or irrigation. Arsenic concentrations (range of <1 to 1.3 µg/L) are low, whereas ratios of boron to lithium concentrations[3] generally are high (table 9). Wells T28-29, T50-51, T54, and T57 are either upgradient from or not affected by the river or irrigation, whereas wells T4 and T22 are within irrigated areas and downgradient from canals. Wells T50, T51, T54, and T57 are deep (253 to 400 ft) and are completed in Tertiary sediment and ground water in this part of the Townsend Valley probably is recharged from underlying bedrock (Lorenz and McMurtrey, 1956). Ground water near wells T28 and T29 probably is recharged, in part, from Crow Creek (fig. 10). The complex flow system between the different hydrogeologic units between Radersburg and Toston probably accounts for the variable concentrations of boron and lithium in water from these wells.

Water from wells T4 and T22 has ratios of boron to lithium of 17 and 30, respectively. Both boron concentrations are within the range of boron concentrations in water from site S63, but the low lithium concentrations indicate that water probably is not recharged primarily by irrigation or that water from these wells is diluted with regional ground water having low lithium concentrations.

Water from wells T3, T7, T13, T15, T20, T23-24, T35, T39, T47-48, T52, and T58 (group 3, table 9) does not have clear chemical characteristics that indicate the primary source of recharge. Arsenic concentrations range from 0.9 to 3.3 µg/L, which is lower than arsenic concentrations in water from site S63 (table 9). Figure 24C shows that water from these wells has boron concentrations within the range or higher than concentrations in water from S63, but lithium concentrations are depleted when compared to water from site S63. Ratios of boron to lithium range from 3.3 to 12, which generally is higher than the range of boron and lithium ratios in water from drains and seeps. Boron concentrations higher than the range in water from drains and seeps might be caused by leaching from the aquifer, whereas lithium concentrations lower than this range might be caused by dilution from regional ground water. All thirteen wells are downgradient from irrigation canals or irrigated land, and most are shallow

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[3] Some boron and lithium concentrations in ground water of the Townsend Valley are reported as less than the minimum reporting levels of <20 µg/L and <6 µg/L, respectively. For these analyses, ratios of boron to lithium are calculated using one-half the minimum reporting level. Actual ratios are unknown, but are limited by the minimum reporting level for each constituent.

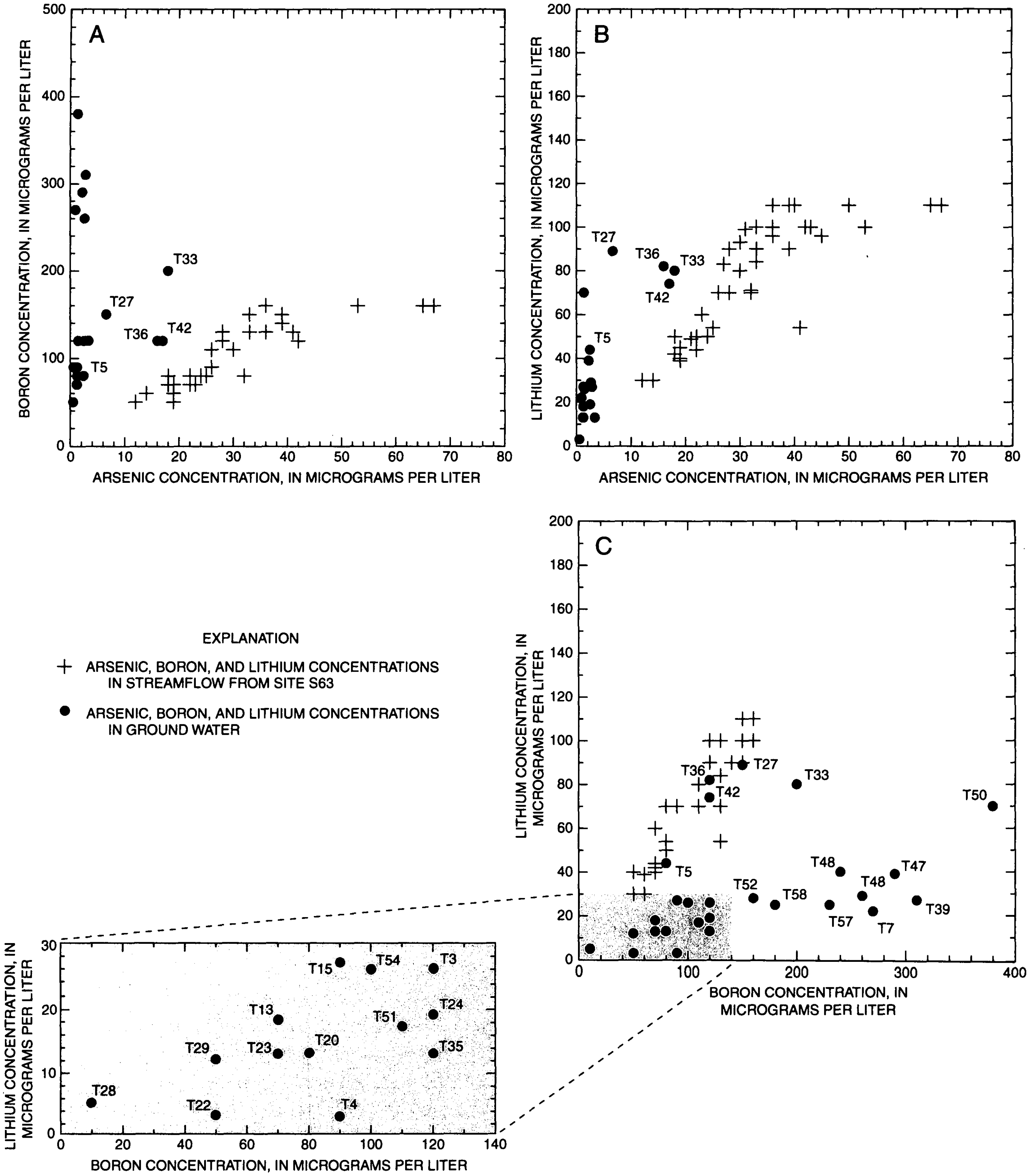


Figure 24. Comparison of arsenic to boron and lithium concentrations in surface water from the Missouri River at Toston (site S63) and ground water of the Townsend Valley, Montana. Arsenic concentrations for surface water from site S63 are dissolved. Arsenic concentrations (As^{+3} and As^{+5}) for ground water are dissolved. Arsenic, boron, and lithium concentrations reported as less than the minimum reporting level are plotted as one-half the minimum reporting level.

(42 or less ft deep). As a result, the potential is large for ground water near these wells to receive some recharge from irrigation.

Dissolved oxygen was measured in water from selected wells in the Townsend Valley. Dissolved-oxygen concentrations range from 2.9 to 12.8 mg/L, and ground water is oxic. Ground water having high arsenic concentrations generally has high dissolved-oxygen concentrations, perhaps because these wells probably are hydraulically connected to the Missouri River. However, some ground water with low arsenic concentrations also has high dissolved-oxygen concentrations.

Water samples were analyzed to determine the oxidation state of arsenic that generally exists in ground water of the Townsend Valley. Of seven samples analyzed for arsenite (As^{+3}), all concentrations are below the minimum reporting level of 1 μg/L. Concentrations of combined arsenite (As^{+3}) and arsenate (As^{+5}) in those same seven samples range from 1.2 to 16 μg/L. Therefore, arsenate probably is the predominant species in ground water in the Townsend Valley.

The magnitude and extent of arsenic in ground water of the Townsend Valley are shown in figure 25. Areas of Region 1 (with arsenic concentrations of less than 4.0 μg/L) extend from about Plunket Lake along the west side of the Townsend Valley to the confluence of the Missouri River and the Broadwater-Missouri Westside Canal and from Toston to about Gurnette Creek in the central part of the valley. Arsenic concentrations in these parts of the valley generally are less than about 3 μg/L. From near well T24 to Canyon Ferry Lake, ground-water levels are near land surface and most of this part of Region 1 is a discharge area for the Townsend Valley. Because ground water has an upward component of flow, recharge from underlying hydrogeologic units might dilute arsenic and some boron and lithium concentrations, or the upward component of flow prevents irrigation water from recharging to deeper ground water in this part of Region 1.

Region 2 (with arsenic concentrations that generally range from 4.0 to 17.9 μg/L) extends along the Missouri River from Toston to just south of Holker (fig. 25). Arsenic concentrations in Region 2 range from 6.6 to 18 μg/L. The aquifer near four of these wells is thought to be hydraulically connected with the Missouri River or irrigation canals, and arsenic in water from these wells probably originates from these sources.

Areas that compose Region A in the Townsend Valley generally extend along the Missouri River from near Holker to Canyon Ferry Lake and along the east side of the valley (fig. 25). Region A, where arsenic concentrations might be about 4 μg/L or higher, was delineated to represent areas where arsenic concentrations can be indirectly inferred from information about land use, geology, and known or probable hydraulic connections between the aquifers and the Missouri River, or irrigation canals. Arsenic concentrations in water from wells T27, T36, and T42 are greater than 4 μg/L, and the aquifer near these wells probably is hydraulically connected to the Missouri River. Along the Missouri River in this part of Region A, the aquifer probably is hydraulically connected to the river and pumping might induce surface-water flow to wells.

Along the east side of the valley, land use and geology indicate that ground water might have arsenic concentrations about 4 μg/L. In this area, land is either irrigated or downgradient from canals. Keith (1995) and Mangelson and Brummer (1994) concluded that arsenic sorbed to soil, which reduced arsenic concentrations in percolating irrigation water. Tertiary sediment that composes the aquifer along the east side of the valley might be enriched in arsenic. Background arsenic concentrations in water from this aquifer can range from about <1 to 15 μg/L (Sonderegger and others, 1989; Slagle, 1995). If arsenic exists in ground water in this area, concentrations might represent background concentrations in Tertiary sediment.

Helena Valley

Briar and Madison (1992) studied the ground water of the Helena Valley and determined that about 39 percent of all recharge to the Helena valley-fill aquifer (Qal and QTd hydrogeologic units; fig. 7) is from canal leakage or from excess irrigation water applied to fields. About 46 percent of all recharge to the Helena valley-fill aquifer is from bedrock adjacent to and underlying this aquifer and about 15 percent of all recharge is from infiltration of streamflow. Kendy and others (1998) investigated water quality, bottom sediment, and biota associated with irrigation drainage in the Helena Valley and determined that potential sources of arsenic to ground water include irrigation water from the Missouri River; tailings from mining-related activities in and near the Helena Valley; aerially deposited emissions from smelter operations; Tertiary

EXPLANATION

GENERAL EXTENT OF ARSENIC CONCENTRATION IN GROUND WATER, IN MICROGRAMS PER LITER (µg/L)

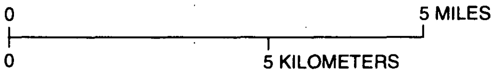
⠿ REGION 1--Less than 4.0

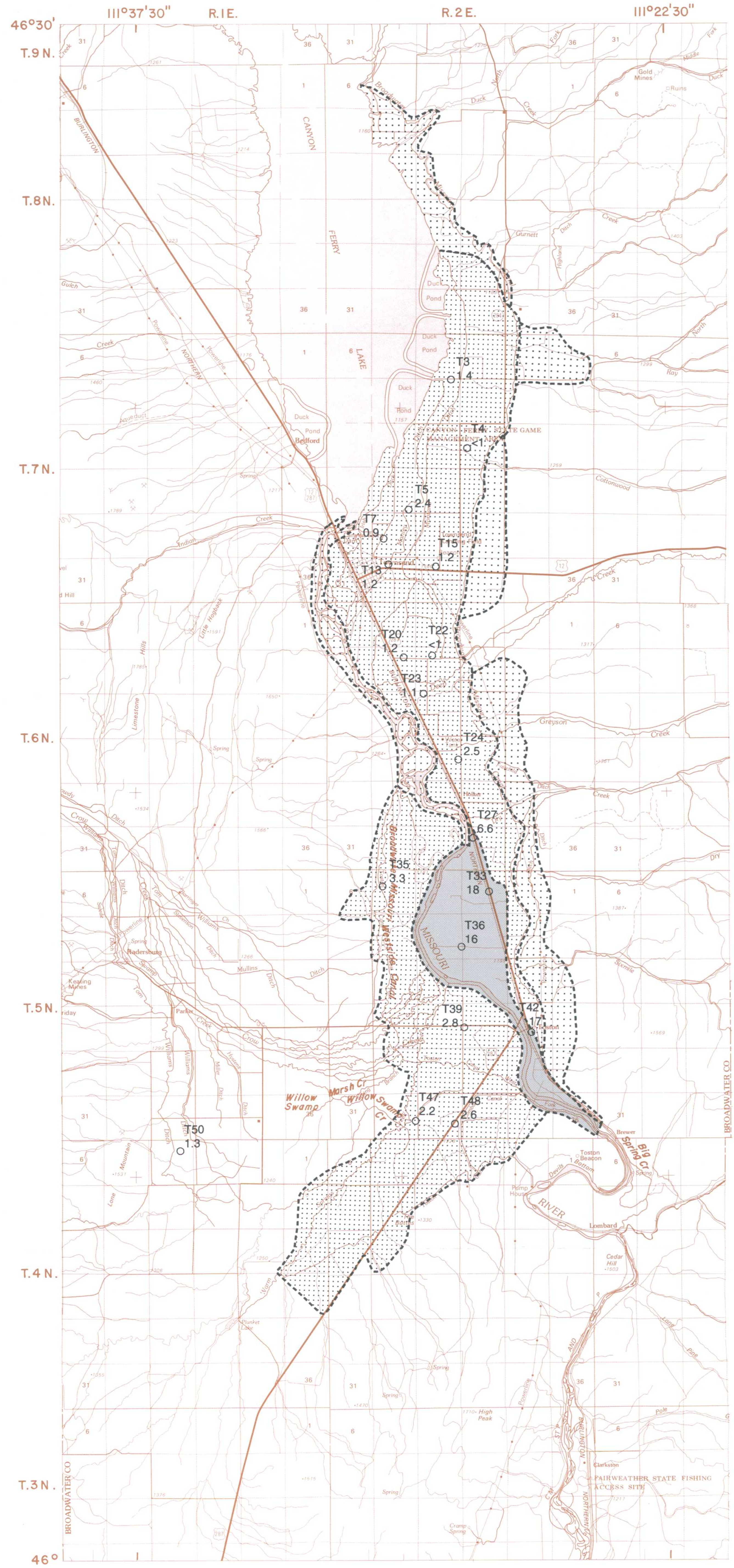
▒ REGION 2--4.0-17.9

⁘ REGION A--Shows general extent where arsenic concentrations in ground water might be slightly elevated (about 4µg/L or higher). Possible arsenic concentrations not determined by sample analysis but are inferred from land use, geology, and known or probable hydraulic connections between the aquifers and the Missouri River and irrigation canals

-------- CONTACT--Approximately located. Shows general boundary of each region

T35 3.3 ○ WATER-QUALITY SITE--Number is arsenic concentration, in µg/L. <, less than minimum reporting level





Base modified from Bureau of Land Management
Townsend, 1976, 1:100,000

Figure 25. Magnitude and extent of arsenic in ground water of the Townsend Valley, Montana.

sediment, or bedrock, with naturally occurring arsenic minerals; and hot springs.

Water used for irrigation that is pumped from Canyon Ferry Lake to the Helena Valley Regulating Reservoir and the Helena Valley Canal might have arsenic, boron, and lithium concentrations that are different from those of the Missouri River at Toston (site S63, fig. 17). Some arsenic might be sorbed to suspended sediment as water resides in Canyon Ferry Lake (Nimick and others, 1998). Because chemical data for irrigation-supply water are limited, comparison of geothermal indicators (boron and lithium concentrations and ratios of boron to lithium concentrations) in water from site S63 in the Townsend Valley and ground water of the Helena Valley might not show the actual relation between the chemical characteristics of irrigation water that potentially recharges ground water.

Ground water of the Helena Valley can be divided into three groups defined primarily by chemical characteristics: (1) ground water that is recharged primarily from irrigation, (2) ground water of intermediate composition that might be recharged, in part, from irrigation, and (3) ground water that does not have clear chemical characteristics that indicate the primary source recharge. Arsenic concentrations in ground water in the Helena Valley range from 0.9 to 22 µg/L, with a median of 2.0 µg/L (fig. 17). Arsenic concentrations in ground water might not be an indicator of whether or not ground water has been recharged by irrigation because concentrations generally are very low. Geothermal tracers such as boron and lithium concentrations and ratios of boron to lithium concentrations vary, but generally are useful indicators of recharge from irrigation. However, many boron and lithium concentrations in water from the Helena Valley typically are low and relations between these constituents are ambiguous (table 10 at back of report).

Water from wells H14, H20, and H50 (group 1, table 10) is recharged primarily from irrigation. Figure 26A,B shows comparisons of arsenic to boron and lithium concentrations, respectively, in water from site S63 and ground water from the Helena Valley. Arsenic concentrations in ground water generally are less than about 4 µg/L. Therefore, ground water is depleted in arsenic relative to water from site S63. Wells H14 and H20 are completed in the shallow alluvial aquifer (table 7) and arsenic concentrations in water (16 and 6.0 µg/L) from these two wells along with arsenic concentrations in water from four auger holes (Mangelson and Brummer, 1994) range from 1.0 to 23.7 µg/L, with a median of 10.7 µg/L. Ground water from the wells and auger holes probably was derived from irrigation water that percolated through irrigated soils to the top of the water table (Kendy and others, 1998). Figure 26C, which shows boron and lithium concentrations from ground water of the Helena Valley, indicates that water from well H50 has boron and lithium concentrations within the range of those in water from site S63 and presumably in water from irrigation canals. Well H50, which is located downgradient from irrigation, has water levels that respond seasonally, in part, to recharge from irrigation (Briar and Madison, 1992) and a boron to lithium ratio of 2.0 (table 10). The similarity of ratios between surface and ground water indicates that ground water near well H50 is recharged from irrigation, and arsenic in water from this well (2.0 µg/L) probably originates from irrigation.

Water from well H12 (group 2, table 10) might be recharged, in part, from irrigation. Figure 26C shows that water from this well has boron concentrations within the range of those for water from site S63, whereas lithium concentrations can be lower than lithium concentrations for water in site S63. Ratios of these constituents generally are higher than those ratios in water from site S63, but within the range of ratios of these constituents in water from drains in the Helena Valley (table 10). This well is located downgradient from irrigation and has water levels that respond seasonally, in part, to recharge from irrigation (Briar and Madison, 1992). Therefore, ground water at well H12 might be recharged, in part, from irrigation, and some arsenic might originate from irrigation.

Water from wells H1-4, H7-9, H13, H15, H18, H21-25, H28, H30, H32-33, H35-40, H42-43, H45-49, and H52 (group 3, table 10) in the Helena Valley does not have clear chemical characteristics that indicate the primary source of recharge. Figure 26C shows that water from most of these wells has boron and lithium concentrations that generally are lower than most concentrations in water from site S63. Ratios of boron to lithium concentrations[4] in water from some of these

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[4] Some boron concentrations in ground water of the Helena Valley are reported as less than the minimum reporting level of <20 µg/L or <40 µg/L. Ratios of boron to lithium are calculated using one-half the minimum reporting level. Actual ratios are unknown, but range between 0.0 and the upper limit defined by the minimum reporting level for boron.

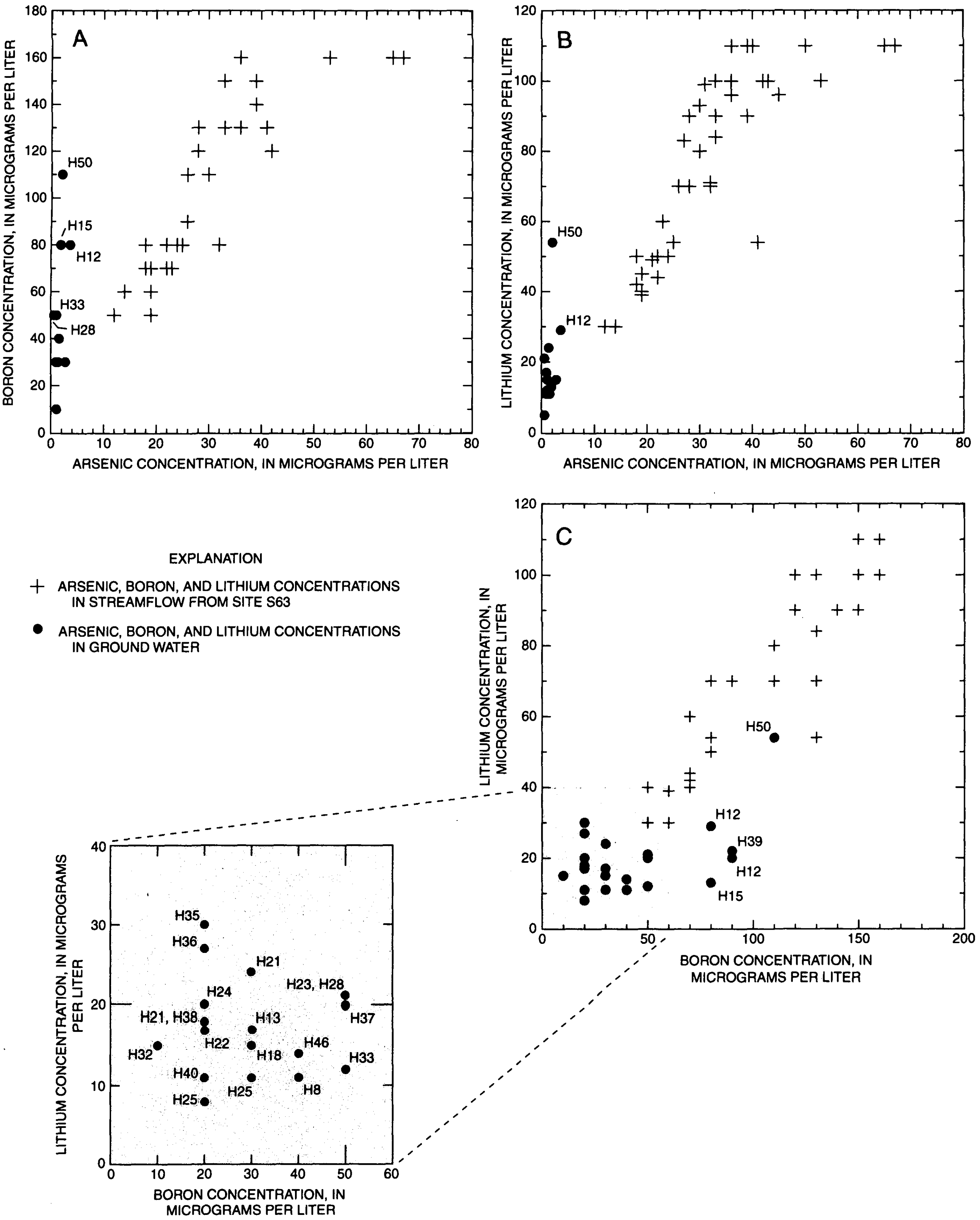


Figure 26. Comparison of arsenic to boron and lithium concentrations in ground water of the Helena Valley and comparison with concentrations of the Missouri River at Toston (site S63) of the Townsend Valley, Montana. Arsenic concentrations for site S63 are dissolved. Arsenic concentrations (As^{+3} and As^{+5}) for ground water are dissolved. Arsenic and boron concentrations reported as less than the minimum reporting level are plotted as one-half the minimum reporting level.

wells are within or near the range of ratios for water from site S63 and water from drains (table 10). However, most boron and lithium concentrations in water from these wells are relatively low. Therefore, relations between boron and lithium concentrations are ambiguous. Most wells are downgradient from irrigation (table 10) and water levels in some wells respond seasonally, in part, to recharge from irrigation (Briar and Madison, 1992; Kendy and others, 1998). As a result, the potential is large for ground water near these wells to receive some recharge from irrigation.

Dissolved oxygen was measured in water from selected wells in the Helena Valley. Dissolved-oxygen concentrations range from 0.9 to 8.6 mg/L and ground water is oxic. Some wells producing water with high dissolved-oxygen concentrations (such as wells H48 and H49) have high arsenic concentrations, because the aquifer near these wells might be recharged from water in canals (Kendy and others, 1998). However, some ground water with low arsenic concentrations also has high dissolved-oxygen concentrations.

Water samples were analyzed to determine the oxidation state of arsenic that generally existed in ground water of the Helena Valley. Of six samples analyzed for arsenite (As^{+3}), all concentrations are below the minimum reporting level of 1 µg/L. Concentrations of combined arsenite (As^{+3}) and arsenate (As^{+5}) in those same six samples range from 0.9 to 3.6 µg/L. Therefore, arsenate probably is the predominant species of arsenic in ground water in the Helena Valley.

The magnitude and extent of arsenic in ground water of the Helena Valley are shown in figure 27. Region 1 (with arsenic concentrations generally less than 4.0 µg/L) extends throughout most of the Helena Valley below the Helena Valley Canal. Arsenic concentrations generally are less than about 3 µg/L, except at wells H14 and H20, which are very shallow (6.5 and 8.3 ft deep, respectively, with arsenic that probably was derived from percolating irrigation water). Most water from wells does not have clear chemical characteristics that indicate the primary source of recharge. However, canal leakage and excess irrigation water supply about 39 percent of all recharge to the Helena valley-fill aquifer. A large quantity of water moves from recharge areas around the margins of the Helena Valley to Lake Helena (Briar and Madison, 1992). This regional ground water might locally dilute water recharged from irrigation and would dilute arsenic, boron, and lithium concentrations (fig. 26). Ground water in Region 1 might be a mixture of regional ground water (having low arsenic concentrations), local irrigation water from upgradient areas, and surface water that has infiltrated to the valley-fill aquifer. In addition, horizontal and vertical flow gradients might prevent irrigation water from percolating deeper into the aquifer (Kendy and others, 1998).

Another area of Region 1 occurs between Spokane Creek and the eastern valley margin. Some land is irrigated from the Helena Valley Canal and lateral canals, and most wells probably are completed in Tertiary sediment. Water from eight wells has arsenic concentrations that range from about 3 to 5 µg/L (Ken Mangelson, Bureau of Reclamation, written commun., 1998). Sources of arsenic in this part of Region 1 include irrigation water and Tertiary sediment.

Small areas of Region 2 (with arsenic concentrations of 4.0 to 17.9 µg/L) occur near the eastern, southwestern, and western parts of the Helena Valley downgradient from the Helena Valley Regulating Reservoir and the Helena Valley Canal (fig. 27). Water from three wells (within Region 2) has arsenic concentrations of 6.0, 5.0, and 17 µg/L, respectively. Sources of arsenic in this part of Region 2 include irrigation and Tertiary sediment.

Another area of Region 2 occurs between Hauser Lake and the eastern valley margin. Land is irrigated from the Helena Valley Canal and lateral canals, and most wells probably are completed in Tertiary sediment. Water from four wells and one spring has arsenic concentrations that range from about 5 to 15 µg/L (Ken Mangelson, written commun., 1998). Sources of arsenic in ground in this part of Region 2 include irrigation water and Tertiary sediment.

One area of Region 3 (with arsenic concentrations of 18.0 to 49.9 µg/L) occurs in the Helena Valley between Hauser Lake and the eastern valley margin (fig. 27). The arsenic concentration in water in well H48 is 22 µg/L. Water from one well and one spring has arsenic concentrations of 24 and 21 µg/L, respectively (Ken Mangelson, written commun., 1998). The aquifer near these sites might be hydraulically connected to the Helena Valley Canal and some arsenic might, in part, originate from irrigation water. However, some arsenic also might be leached from Tertiary sediment (Kendy and others, 1998).

Areas that compose Region A occur east of Lake Helena (fig. 27). Region A, where arsenic concentrations might be about 4 µg/L or higher, was delineated to represent areas where arsenic concentrations can be

EXPLANATION

GENERAL EXTENT OF ARSENIC CONCENTRATION IN GROUND WATER, IN MICROGRAMS PER LITER (µg/L)

░ REGION 1--Less than 4.0

▒ REGION 2--4.0-17.9

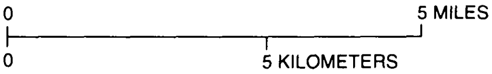
▓ REGION 3--18.0-49.9

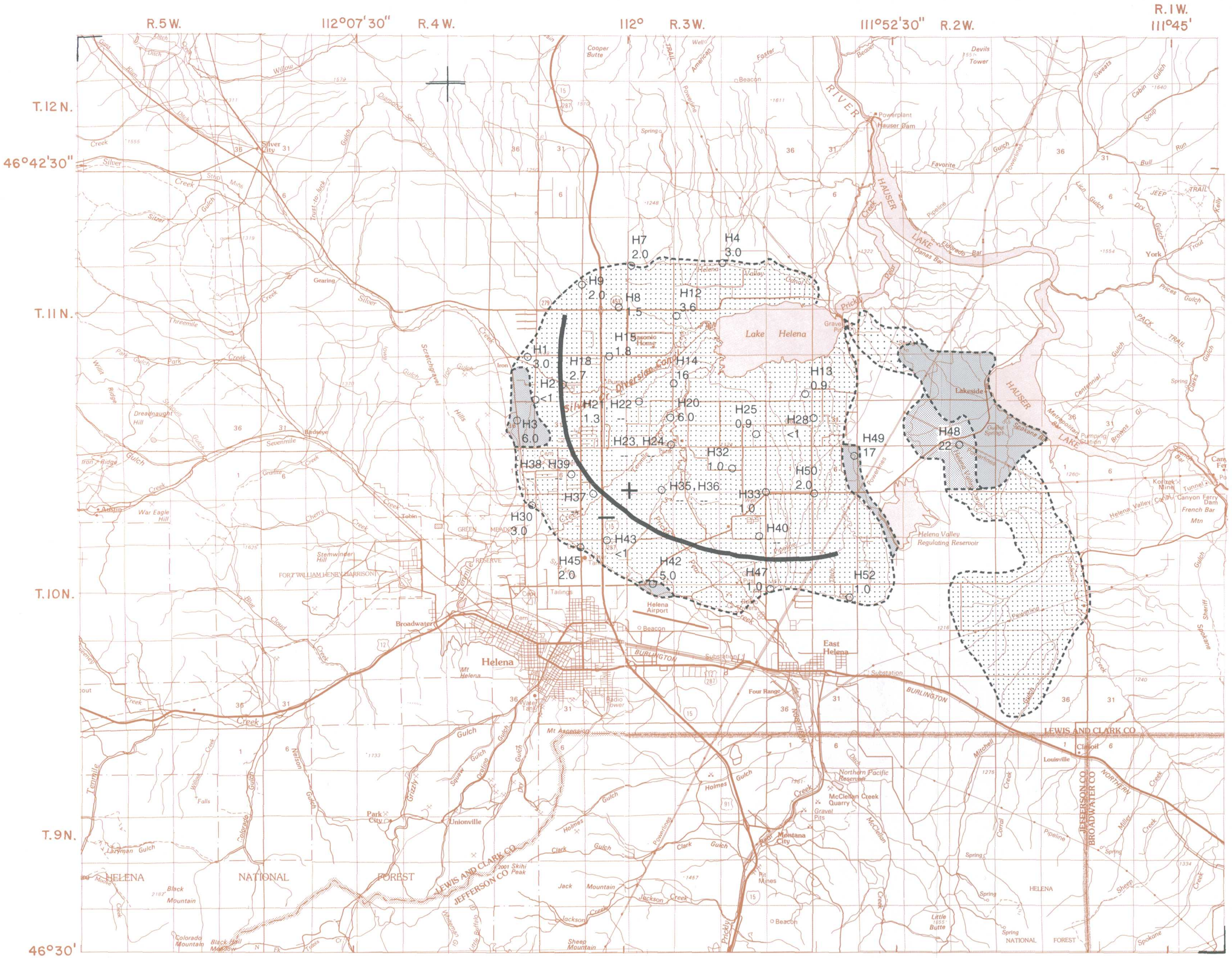
░ REGION A--Shows general extent where arsenic concentrations in ground water might be slightly elevated (about 4µg/L or higher). Possible arsenic concentrations not determined by sample analysis but are inferred from land use, geology, and known or probable hydraulic connections between the aquifers and the irrigation canals

-------- CONTACT--Approximately located. Shows general boundary of each region

+ ━━ − APPROXIMATE BOUNDARY BETWEEN AREAS WITH UPWARD (+) AND DOWNWARD (-) GRADIENT

H21 ○ 1.3 WATER-QUALITY SITE--Number is arsenic concentration, in µg/L. <, less than minimum reporting level. --, arsenic concentration not available





Base modified from U.S. Geological Survey Elliston, 1990 and Bureau of Land Management Canyon Ferry Dam, 1975, 1:100,000

Figure 27. Magnitude and extent of arsenic in ground water of the Helena Valley, Montana.

indirectly inferred from information about land use, geology, and known or probable hydraulic connections between the aquifers and irrigation. East of Lake Helena, land is irrigated and most wells probably are completed in Tertiary sediment. On the basis of nearby ground water, with arsenic concentrations as much as about 24 µg/L, and land use, ground water in this part of Region A might have arsenic concentrations about 4 µg/L or higher.

PROCESSES CONTROLLING ARSENIC IN GROUND WATER

The behavior and fate of arsenic in the study area are complex and dependent on many chemical and physical processes, including sorption/desorption and dissolution/precipitation reactions. Redox conditions and pH significantly affect these reactions. Evapoconcentration and dilution also can control arsenic concentrations. In all likelihood, these chemical and physical processes, to some degree, concurrently control arsenic concentrations. In addition, geologic and hydrologic conditions affect the magnitude and extent of arsenic in ground water.

Sorption/desorption reactions probably are the primary chemical processes controlling arsenic concentrations in ground water of the study area. In oxic environments, arsenic occurs in the oxidized form of arsenate (As^{+5}) and can be readily adsorbed by clay minerals and iron- and manganese-oxide minerals in soils or aquifer materials (Welch and others, 1988). On the basis of high dissolved-oxygen concentrations and the slightly alkaline pH values, arsenic is assumed to occur in the oxidized form of arsenate (As^{+5}) throughout the mainstem Madison and upper Missouri Rivers (Nimick and others, 1998). Therefore, arsenic in water in the Madison or upper Missouri Rivers and irrigation water would be expected to sorb strongly to soils. Keith (1995) and Mangelson and Brummer (1994) demonstrated the sorption capacity of soils in the study area and concluded that arsenic sorbed to irrigated soils, thereby reducing arsenic concentrations in applied irrigation water. Comparison of arsenic concentrations in irrigation-supply water, water from drains and springs and seeps, and ground water demonstrates that sorption probably is an important chemical process controlling arsenic concentrations in the study area. Generally, arsenic concentrations in water from drains and springs and seeps are substantially less than those in irrigation-supply water (figs. 12, 15, and 17). In the upper Madison River Valley, most arsenic concentrations in water from drains and springs and seeps are less than about 20 µg/L, whereas concentrations in irrigation-supply water can be as high as about 88 µg/L. In the Townsend Valley, arsenic concentrations in water from drains and seeps are less than about 13 µg/L, whereas concentrations in irrigation-supply water can be as high as about 38 µg/L. In the Helena Valley, arsenic concentrations in water from drains are less than about 25 µg/L, whereas those in irrigation-supply water can be as high as 31 µg/L.

In the upper Madison River Valley, arsenic concentrations in very shallow ground water (less than about 9 ft below land surface) range from 3.1 to 31.2 µg/L (table 7), with a median of 6.1 µg/L. Some of these concentrations are higher than those determined in deeper ground water (median of 2.0 µg/L). In the Townsend Valley, arsenic in very shallow ground water ranges between 1.5 and 198 µg/L, with a median of 3.8 µg/L. Many of these concentrations are higher than those determined in deeper ground water (median of 2.2 µg/L). In the Helena Valley, arsenic concentrations in very shallow ground water range from 1.0 to 23.7, with a median of 10.7 µg/L. Most of these concentrations are higher than those determined from deeper ground water (median of 2.0 µg/L). Thus, in the upper Madison River, Townsend, and Helena Valleys, arsenic concentrations in irrigation-supply water generally are higher than arsenic concentrations in water from drains and springs and seeps. Arsenic concentrations in very shallow ground water generally are higher than arsenic concentrations in deeper ground water (generally deeper than about 40 ft) where most domestic and stock water supplies are obtained. The most likely explanation for these decreases in arsenic concentrations is sorption of arsenic onto soils from applied irrigation water (Kendy and others, 1998; Keith, 1995; and Mangelson and Brummer, 1994).

Desorption appears to be an important chemical process causing some high arsenic concentrations in ground water primarily in the lower Madison River Valley. Ground water in the northern part of the valley is recharged from upgradient flow and this recharge is one source of arsenic to ground water. However, some arsenic concentrations in ground water (118 to 176 µg/L) in the northern part of the valley are higher than arsenic concentrations (25 to 138 µg/L) in this upgradient flow. Thus, an additional source of arsenic is needed to explain the higher arsenic concentrations. Arsenic from sediment of the alluvial aquifer might be desorbed and be an additional source of arsenic to ground water in the northern part of the lower Madison River Valley (Nimick, 1998).

Desorption also appears to control arsenic concentrations in local areas. The highest arsenic concentrations in very shallow ground water of 153 μg/L in the lower Madison River Valley and 198 μg/L in the Townsend Valley were determined from depths less than about 8 ft (table 6). Both arsenic concentrations are higher than in the local irrigation-supply water. In a related study of soils, Jones and others (1996) determined that a seasonal or permanently high water table can create temporary reducing conditions that can release sorbed arsenic, resulting in arsenic concentrations higher than those in irrigation-supply water.

Dissolution of solid phase materials, such as naturally occurring arsenic minerals within Tertiary sediment or bedrock, potentially could release arsenic (Kendy and others, 1998). Tertiary sediment is considered a likely source of arsenic to ground water in many parts of the western United States (Welch and others, 1988). Nimick (1998) and Sonderegger and others (1989) consider Tertiary sediment to be one source of arsenic to ground water in some parts of the lower Madison River Valley. Precipitation of arsenic minerals can decrease arsenic concentrations in ground water. However, many of these minerals are not likely to occur in most geochemical environments (Welch and others, 1988). Precipitation of arsenic minerals such as calcium arsenate can occur but is unlikely at the relatively low arsenic concentrations in the study area (Kendy and others, 1998; David A. Nimick, oral commun., 1999).

Redox conditions and pH significantly affect arsenic concentrations in ground water throughout the study area. Ground water generally has dissolved-oxygen concentrations higher than 2.0 mg/L and is oxic. Thus, arsenate is the predominant species of arsenic in ground water in most of the study area. Ground water also is slightly alkaline, with pH values generally between 7.0 and 8.0. Arsenic has a strong affinity for sorption sites in oxic environments with slightly alkaline pH values, and arsenic that infiltrates to basin-fill aquifers might further be removed by sorption to aquifer materials. In the northern part of the lower Madison River Valley, ground water generally has low dissolved-oxygen concentrations (less than 0.3 mg/L) and is anoxic. Arsenite can compose a large proportion of the arsenic concentration in samples from some wells in this area. Nimick (1998) attributed high arsenic concentrations in ground water to sediment-bound arsenic that is likely released where ground water conditions change from oxic to anoxic. The large extent of anoxic ground water in the lower Madison River Valley is unique in the study area.

Physical processes such as evapoconcentration and dilution also control arsenic concentrations in the study area. Evapoconcentration might be significant in causing high arsenic concentrations in soil moisture and very shallow ground water (Kendy and others, 1998; Keith, 1995; and Mangelson and Brummer, 1994). High concentrations of arsenic in soil moisture were determined in irrigated and non-irrigated soils. In the upper Madison River Valley, arsenic concentrations in soil moisture determined from non-irrigated soil range from 209 to 663 μg/L (Mangelson and Brummer, 1994), which is about four times the highest arsenic concentration (150 μg/L) in water from the Madison River near Cameron (site S8). In the lower Madison River Valley, arsenic concentrations in soil moisture determined from non-irrigated soil range from 1 to 14,590 μg/L, which is more than 140 times the highest arsenic concentration (100 μg/L) in water from the Madison River near Norris (site S26). In the Townsend Valley, arsenic concentrations in soil moisture determined from non-irrigated soil range from 4 to 477 μg/L (Keith, 1995; Mangelson and Brummer, 1994), which is about seven times the highest arsenic concentration (67 μg/L) in water from the Missouri River at Toston (site S63). In the Helena Valley, arsenic concentrations in soil moisture determined from non-irrigated soil range from 10 to 125 μg/L (Mangelson and Brummer, 1994), which is about two times the highest arsenic concentration in water from the Missouri River at Toston (site S63). In all four valleys, the areas near these sites have a high water table which would allow arsenic to be evapoconcentrated by plant transpiration in the root zone.

Dilution also appears to physically control arsenic concentrations where large quantities of tributary inflow recharge basin-fill deposits or where regional ground water has an upward component of flow. In the upper Madison River Valley along Bear Creek, ground water discharges from basin-fill deposits and arsenic concentrations in ground water are less than 1 μg/L. Bear Creek appears to function as a drain for irrigation return flow, and the water has arsenic concentrations as high as about 20 μg/L. In the Townsend Valley between Radersburg and Toston, basin-fill deposits probably are recharged from Crow Creek and underlying bedrock. Arsenic concentrations in ground water are less than about 3 µg/L, whereas arsenic from drains and seeps can be as high as about 13 µg/L. In the area from about Deep Creek north to Canyon Ferry Lake, basin-fill deposits probably are recharged from underlying Tertiary sediment and bedrock and arsenic concentrations are less than about 2 µg/L. In the Helena Valley, a previous study (Briar and Madison, 1992) has determined that about 46 percent of recharge to the Helena valley-fill aquifer is from bedrock adjacent to and underlying this aquifer. Arsenic concentrations in water from deeper alluvium within the valley-fill aquifer generally are 3 µg/L or less, whereas arsenic concentrations in water from drains can be as high as 25 µg/L. Kendy and others (1998) concluded that, in the Helena Valley, the net effect of dilution and upward flow is that elevated arsenic concentrations generally are not found in basin-fill deposits at depths greater than about 10 ft below land surface. On the basis of limited data and similar hydrogeologic conditions, a similar conclusion can be made in parts of upper Madison River and Townsend Valleys. Dilution from tributaries or regional ground water might decrease arsenic concentrations where ground water is recharged by the Madison and Missouri Rivers or irrigation. Upward flow might prevent irrigation water from percolating deeper into the aquifer where domestic and stock wells are completed.

EFFECTS OF IRRIGATION ON GROUND-WATER QUALITY

The upper Madison River Valley, Townsend Valley, and Helena Valley have some similar hydrogeologic conditions. Therefore, the general effects of irrigation on ground-water quality are similar in these three valleys. The lower Madison River Valley has unique hydrogeologic and chemical conditions in the study area. Results of this study provide some insight into the possible effects of irrigation on ground-water quality.

Comparison of arsenic concentrations in irrigation-supply water and water from drains and springs and seeps indicates that some of the arsenic in irrigation water sorbs to soil or aquifer materials. However, some arsenic, as well as boron and lithium, remains in solution and percolates through soil to ground water. Boron and lithium concentrations and the ratios of these constituents were used to trace this recharge from irrigation. Comparison of these ratios from water of the Madison and upper Missouri Rivers (water used for irrigation) and ground water indicates that in the upper Madison River, Townsend, and Helena Valleys, the areas where ground water is affected by canal leakage or applied irrigation water are variable and are not apparent in many instances. In all three valleys, wells in close proximity have water that is recharged primarily by irrigation, have water that is not recharged by irrigation, and have water that does not have clear chemical characteristics that indicate the primary source of recharge. The occurrence of these groups of water downgradient from canals and irrigated areas and in close proximity seems to imply that local conditions near or at the well--such as distance from irrigation recharge source, sorption/desorption reactions, aquifer permeability, well depth and construction, dilution by tributaries or regional ground water, and horizontal and vertical gradients--affect the ground-water quality and control the arsenic concentrations in water at the well. The net result of these conditions is that arsenic concentrations in most ground water of the study area that is primarily recharged or might be partly recharged by irrigation are much lower than the State of Montana water-quality human health standard of 18 µg/L, as well as the EPA MCL of 50 µg/L. However, the EPA is proposing to change the MCL for arsenic in drinking water from 50 to 5 µg/L.

The effects of irrigation on ground-water quality of the lower Madison River Valley cannot be determined in a large part of the valley. Most arsenic concentrations in ground water are higher than the State of Montana human-health standard of 18 µg/L and are caused by unique hydrogeologic and chemical conditions. In the south-central and northern parts of the valley, the predominant effect on ground-water quality and arsenic concentrations is direct recharge from the Madison River and ground water inflows from upgradient areas. The effects of irrigation on ground-water quality are not apparent but might only occur in the near-surface part of the aquifer. Horizontal and vertical flow gradients might prevent deep percolation of irrigation water. Along the eastern valley margin, recharge from irrigation and leaching of arsenic from Tertiary sediment affect ground-water quality and arsenic concentrations (Nimick, 1998).

SUMMARY AND CONCLUSIONS

Geothermal waters in Yellowstone National Park contribute large quantities of arsenic to the headwaters of the Madison River. The Madison River flows for about 150 mi to the confluence of the Jefferson and Gallatin Rivers near Three Forks where the Missouri River begins. Arsenic concentrations in the Madison and upper Missouri Rivers and in some ground water commonly exceed the State of Montana water-quality human health standard of 18 μg/L as well as the EPA MCL for drinking water of 50 μg/L. This report describes the magnitude, extent, and possible sources of arsenic in surface and ground water, describes the processes controlling arsenic in ground water, and assesses the effect of irrigation on ground-water quality.

The median dissolved-arsenic concentration of the Madison River near West Yellowstone is 270 μg/L and 50 percent of the arsenic concentrations are between 200 μg/L and 310 μg/L. Downstream, the median dissolved-arsenic concentration of the Missouri River at Toston is 30 μg/L and 50 percent of the arsenic concentrations were between 22 and 39 μg/L. Arsenic concentrations decrease from the Madison River near West Yellowstone to the Missouri River at Toston because tributaries having much smaller arsenic concentrations dilute water in the Madison and upper Missouri Rivers. Downstream trends in arsenic loads and boron and lithium concentrations indicate that arsenic in the mainstem Madison and upper Missouri Rivers is largely chemically conservative.

In the upper Madison River Valley, arsenic concentrations in irrigation-supply water range from <1 to 88.5 μg/L. Arsenic concentrations in water in drains and springs and seeps range from <0.7 to 25.8 μg/L. The decrease in arsenic concentrations in water in drains and springs and seeps relative to irrigation-supply water indicates that some arsenic is removed from applied irrigation water. Arsenic loads in water at selected surface-water sites increase during the irrigation season, which likely indicates that some arsenic originates from irrigation-supply water and that not all arsenic is adsorbed to soils and aquifer materials. Most arsenic concentrations in water at these sites are less than about 20 μg/L, and some arsenic from applied irrigation water is removed by sorption onto soils.

Arsenic concentrations in ground water of the upper Madison River Valley range from 0.5 to 40 μg/L, with a median of 2.0 μg/L. Water from six wells, with arsenic concentrations that range from 2.1 to 40 μg/L, is recharged primarily by the Madison River or irrigation; thus, arsenic probably originates from this recharge.

In the lower Madison River Valley, arsenic concentrations in irrigation-supply water range from 27.0 to 113 μg/L. Arsenic concentrations in water in drains and Rey and Spring Creeks range from 42.2 to 321 μg/L. Arsenic concentrations in water at most of these sites are comparable to those of the Madison River; therefore, the surface-water component of irrigation return flow does not significantly affect arsenic concentrations in the Madison River. Arsenic concentrations in water in some drains and sites along Rey and Spring Creeks are similar to arsenic concentrations in local ground water. The predominant effect on arsenic concentrations in water in drains and Rey and Spring Creeks probably is inflow from ground water that discharges to these sites in the south- and east-central parts of the valley.

Arsenic concentrations in ground water of the lower Madison River Valley and in areas along the lower Jefferson and Gallatin Rivers range from 0.4 to 176 μg/L, with a median of 54 μg/L. The highest 25 percent of arsenic concentrations in ground water is between 93 and 176 μg/L, whereas the highest 25 percent of arsenic concentrations from the Madison River is between about 85 and 100 μg/L.

Three hydrogeochemical areas have been defined in the lower Madison River Valley. In the south and central parts of the lower Madison River Valley, arsenic concentrations in ground water range from about 25 to 124 μg/L, with a median concentration of 44 μg/L. Water from the Madison River recharges alluvium, and arsenic in ground water originates from this recharge. In the east-central part of the valley where most wells are completed in Tertiary sediment, ground water is oxic, recharged by irrigation, and affected by Tertiary sediment. Arsenic concentrations range from 38 to 138 μg/L with a median of 79 μg/L. Most arsenic in ground water probably originates from irrigation, but Tertiary sediment might be an additional source of arsenic. In the northern quarter of the valley, ground water is primarily anoxic and recharged by upgradient ground water. Arsenic concentrations in the northern quarter of the valley range from about 16 to 176 μg/L, with a median concentration of 89 μg/L. Two sources of arsenic to ground water in the northern part of the lower Madison River Valley include arsenic-rich ground water that flows in from upgradient areas and sediment of the alluvial aquifer.

In the Townsend Valley, arsenic concentrations in irrigation-supply water range from 4.0 to 38.4 µg/L. Arsenic concentrations in water in drains and seeps range from <1 to 12.8 µg/L. Arsenic loads in water at some surface-water sites increased during the irrigation season, which likely indicates that some arsenic originates from irrigation. Most arsenic concentrations in water in drains and seeps are less than about 8 µg/L; thus, most arsenic from applied irrigation water is removed by sorption onto soils.

Arsenic concentrations in ground water of the Townsend Valley range from <1 to 18 µg/L, with a median of 2.2 µg/L. Water from five wells, with arsenic concentrations that range from 2.4 to 18 µg/L, is recharged primarily by the Missouri River or irrigation; thus, arsenic probably originates from these sources.

In the Helena Valley, arsenic concentrations in irrigation-supply water range from 1.1 to 31 µg/L. Arsenic concentrations in water in drains range from <0.8 to 25 µg/L. Most arsenic concentrations in water from drains are less than about 5 µg/L; thus, either arsenic is diluted by other water sources, or much is removed from applied irrigation water by sorption onto soils.

Arsenic concentrations in ground water of the Helena Valley range from 0.9 to 22 µg/L, with a median of 2.0 µg/L. Water from three wells, with arsenic concentrations that range from 2.0 to 16 µg/L, is recharged primarily by irrigation and arsenic probably originates from this recharge.

The behavior and fate of arsenic in the study area are complex and dependent on many chemical and physical processes, including sorption/desorption and dissolution/precipitation reactions. Redox and pH significantly affect these reactions. Evapoconcentration and dilution also can control arsenic concentrations. In all likelihood, these chemical and physical processes, to some degree, concurrently control arsenic concentrations.

Sorption/desorption reactions probably are the primary chemical processes controlling arsenic concentrations in ground water of the study area. Arsenic is assumed to occur in the oxidized form of arsenate throughout the Madison and upper Missouri Rivers and arsenic in any applied irrigation water would be expected to sorb strongly to soils. Researchers have demonstrated that arsenic sorbs to irrigated soils in the study area. Arsenic concentrations in water from drains and springs and seeps are less than about 25 µg/L, whereas irrigation-supply water can be as high as 88 µg/L. Thus, in the upper Madison River, Townsend, and Helena Valleys, arsenic concentrations in irrigation-supply water generally are higher than arsenic concentrations in water from drains and seeps and springs. In the upper Madison River, Townsend, and Helena Valleys, median arsenic concentrations (about 2 µg/L) in deeper ground water (generally deeper than about 40 ft) are less than median arsenic concentrations (3.8 to 10.7 µg/L) in very shallow ground water (less than about 9 ft). The most likely explanation for these decreases in arsenic concentrations is sorption of arsenic onto soils from applied irrigation water. Desorption appears to be an important chemical process causing some high arsenic concentrations in ground water primarily in the lower Madison River Valley. Arsenic from sediment of the alluvial aquifer might be desorbed and an additional source of arsenic to ground water. Desorption also appears to locally control arsenic concentrations in very shallow ground water. A seasonal or permanently high water table can create temporary reducing conditions that could release sorbed arsenic, resulting in arsenic concentrations higher than in irrigation-supply water.

Dissolution of solid phase materials, such as naturally occurring arsenic minerals within Tertiary sediment or bedrock, potentially could release arsenic. Tertiary sediment is considered to be a source of arsenic to ground water in some parts of the lower Madison River Valley. Precipitation of arsenic minerals can decrease arsenic concentrations in ground water, but is unlikely at the relatively low arsenic concentrations in the study area.

Redox conditions and pH significantly affect arsenic concentrations in ground water throughout the study area. Ground water generally is oxic and slightly alkaline. Arsenic that infiltrates to basin-fill deposits might further be removed by sorption to aquifer materials. In the northern part of the lower Madison River Valley, ground water is anoxic. The large extent of anoxic ground water in the northern part of the lower Madison River Valley is unique in the study area.

Physical processes such as evapoconcentration and dilution also control arsenic concentrations in the study area. Evapoconcentration might be significant in causing high arsenic concentrations in soil moisture and very shallow ground water. In all four valleys, some areas have high water tables which would allow arsenic to be evapoconcentrated by plant transpiration in the root zone. Dilution might reduce arsenic concentrations where large quantities of tributary inflow recharge basin-fill deposits or regional ground water has an upward component of flow. The net effect of dilution and upward flow is that elevated arsenic concentrations generally are not found in basin-fill deposits at depths greater than about 10 ft below land surface.

In the upper Madison River, Townsend, and Helena Valleys, the areas where ground water is affected by canal leakage or applied irrigation water are variable and are not apparent in many instances. In all three valleys, local conditions near or at the well--such as distance from irrigation recharge sources, sorption/desorption reactions, aquifer permeability, well depth and construction, dilution by tributaries or regional ground water, and horizontal and vertical gradients--affect the ground-water quality and control the arsenic concentrations in water at the well. The net result of these conditions is that most arsenic concentrations in ground water of the study area that is primarily recharged or might be partly recharged by irrigation are much lower than the State of Montana water-quality human health standard of 18 µg/L, as well as the EPA MCL of 50 µg/L.

The effects of irrigation on ground-water quality of the lower Madison River Valley cannot be determined in a large part of the valley. Most arsenic concentrations in ground water are higher than the State of Montana human-health standard of 18 µg/L and are caused by unique hydrogeologic and chemical conditions. Ground-water quality and arsenic concentrations are affected predominantly by direct recharge from the Madison River and ground water inflows from upgradient areas. The effects of irrigation on ground-water quality are not apparent but might only occur in the near-surface part of the aquifer. Horizontal and vertical flow gradients might prevent deep percolation of irrigation water. Along the eastern valley margin, recharge from irrigation and leaching of arsenic from Tertiary sediment affect ground-water quality and arsenic concentrations.

REFERENCES CITED

Belzile, Nelson, and Tessier, Andre, 1990, Interactions between arsenic and iron oxides in lacustrine sediments: Geochimica Cosmochimica Acta, v. 54, p. 103-109.

Briar, D.W., Lawlor, S.M., Stone, M.A.J., Parliman, D.J., Schaefer, J.L., and Kendy, Eloise, 1996, Ground-water levels in intermontane basins of the Northern Rocky Mountains, Montana and Idaho: U.S. Geological Survey Hydrologic Investigations Atlas HA-738B, scale 1:750,000.

Briar, D.W., and Madison, J.P., 1992, Hydrogeology of the Helena valley-fill aquifer system, west-central Montana: U.S. Geological Survey Water-Resources Investigations Report 92-4023, 92 p.

Clark, D.W., and Dutton, D.M., 1996, Quality of ground water and surface water in intermontane basins of the Northern Rocky Mountains, Montana and Idaho: U.S. Geological Survey Hydrologic Investigations Atlas HA-738C, scale 1:750,000.

Dutton, D.M., Lawlor, S.M., Briar, D.W., and Tresch, R.E., 1995, Hydrologic data for the Northern Rocky Mountains intermontane basins, Montana: U.S. Geological Survey Open-File Report 95-143, 94 p.

Fields, R.W., Tabrum, A.R., Rasmussen, D.L., and Nichols, Ralph, 1985, Cenozoic rocks of the intermontane basins of western Montana and eastern Idaho--A summary, *in* Flores, R.M., and Kaplan, S.S., eds., Cenozoic paleogeography of the West Central United States: Rocky Mountain Paleogeography Symposium 3, Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, Denver, Colo., p. 9-36.

Goldberg, Sabine, 1986, Chemical modeling of arsenate adsorption on aluminum and iron oxide minerals: Soil Science Society of America Journal, v. 50, p. 1154-1157.

Hem, J.D., 1985, Study and interpretation of chemical characteristics of natural water (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Jones, C.A., Inskeep, W.P., and Bauder, J.W., 1996, Arsenic solubility in soils of the lower Madison River Valley--the role of redox potential [abs.], *in* American Water Resources Association, Montana Section, 1996 Annual Meeting, Abstracts: Dillon, Mont., unpaged.

Keith, K.E., 1995, Arsenic in soils of the Madison and upper Missouri River Valleys: Bozeman, Montana State University, M.S. thesis, 119 p.

Kendy, Eloise, Olsen, Bill, and Malloy, J.C., 1998, Water quality, bottom sediment, and biota associated with irrigation drainage in the Helena Valley, west-central Montana, 1995: U.S. Geological Survey Water-Resources Investigations Report 97-4214, 62 p.

Kendy, Eloise, and Tresch, R.E. 1996, Geographic, geologic, and hydrologic summaries of the intermontane basins of the Northern Rocky Mountains, Montana: U.S. Geological Survey Water-Resources Investigations Report 96-4025, 233 p.

Kinoshita, W.T., Davis, W.E., Smedes, H.W., and Nelson, W.H., 1965, Bouguer gravity, aeromagnetic and generalized geologic map of Townsend and Duck Creek Pass quadrangles, Broadwater County, Montana: U.S. Geological Survey Geophysical Investigations Map GP-439, 2 sheets, scale 1:62,500.

Knapton, J.R., and Brosten, T.M., 1987, Supplemental data for selected streams in the Missouri River basin, Montana, 1987: U.S. Geological Survey Open-File Report 87-697, 14 p.

Knapton, J.R., and Brosten, T.M., 1989, Arsenic and chloride data for five stream sites in the Madison River drainage, Montana, 1988: U.S.Geological Survey Open-File Report 88-722, 12 p.

Knapton, J.R., and Horpestad, A.A., 1987, Arsenic data for streams in the upper Missouri River basin, Montana and Wyoming: U.S. Geological Survey Open-File Report 87-124, 25 p.

Leonard, R.B., Brosten, T.M., and Midtlyng, N.A., 1978, Selected data from thermal-spring areas, southwestern Montana: U.S. Geological Survey Open-File Report 78-438, 71 p.

Leonard, R.B., and Wood, W.A., 1988, Evaluation of a hydrothermal anomaly near Ennis, Montana: U.S. Geological Survey Professional Paper 1044-K, 53 p.

Lorenz, H.W., and McMurtrey, R.G., 1956, Geology and occurrence of ground water in the Townsend Valley, Montana, *with a section on* the Chemical quality of the ground water, by H.A. Swenson: U.S. Geological Supply Paper 1360-C, p.171-290.

Lorenz, H.W., and Swenson, F.A., 1951, Geology and ground water resources of the Helena Valley, Montana, *with a section on* Chemical quality of the water, by H.A. Swenson: U.S. Geological Survey Circular 83, 68 p.

Mangelson, K.A., and Brummer, Joseph, Jr., 1994, Upper Missouri basin arsenic study, 1991-1993: Denver, Colo., Bureau of Reclamation, 50 p.

Montana Department of Environmental Quality, 1995, Montana numeric water quality standards: Montana Department of Environmental Quality Division Circular WQB-7, 39 p.

Moreland, J.A., and Leonard, R.B., 1980, Evaluation of shallow aquifers in the Helena Valley, Lewis and Clark County, Montana: U.S. Geological Survey Open-File Report 80-1102, 24 p.

Moreland, J.A., Leonard, R.B., Reed, T.E., Clausen, R.O., and Wood, W.A., 1979, Hydrologic data from selected wells in the Helena Valley, Lewis and Clark County, Montana: U.S. Geological Survey Open-File Report 79-1676, 54 p.

Nimick, D.A., 1998, Arsenic hydrogeochemistry in an irrigated river valley—a reevaluation: Ground Water, v. 36, no. 5, p. 743-753.

Nimick, D.A., Moore, J.N., Dalby, C.E., and Savka, M.W., 1998, The fate of geothermal arsenic in the Madison and Missouri Rivers, Montana and Wyoming: Water Resources Research, v. 34, no. 11, p. 3051-3067.

Pardee, J.T., 1925, Geology and ground-water resources of Townsend Valley, Montana: U.S. Geological Survey Water-Supply Paper 539, 61 p.

Reynolds, M.W., 1979, Character and extent of basin-range faulting, western Montana and east-central Idaho: Rocky Mountain Association of Geologists and Utah Geological Association, Basin and Range Symposium, p. 185-193.

Robinson, G.D., 1967, Geologic map of the Toston quadrangle, southwestern Montana: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-486, 2 sheets, scale 1:24,000.

Schofield, J.D., 1981, Structure of the Centennial and Madison Valleys based upon gravitational interpretation, *in* Montana Geological Society Field Conference and Symposium Guidebook to Southwest Montana: [Billings, Mont.], Montana Geological Society, p. 275-284.

Slagle, S.E., 1995, Geohydrologic conditions and land use in the Gallatin Valley, southwestern Montana, 1992-93: U.S. Geological Survey Water-Resources Investigations Report 95-4034, 2 sheets, scale 1:100,000.

Sonderegger, J.L., and Ohguchi, Takeshi, 1988, Irrigation related arsenic contamination of a thin, alluvial aquifer, Madison River Valley, Montana, USA: Environmental Geology and Water Sciences, v. 11, no. 2, p. 153-161.

Sonderegger, J.L., and Sholes, B.R., 1989, Complete data compilation, the lower Madison Valley, *accompanying a reprint of* Arsenic contamination of aquifers caused by irrigation with diluted geothermal water, by J.L. Sonderegger, B.R. Sholes, and Takeshi Ohguchi, 1989: Montana Bureau of Mines and Geology Open-File Report 210, 23 p.

Sonderegger, J.L., Sholes, B.R., and Ohguchi, Takeshi, 1989, Arsenic contamination of aquifers caused by irrigation with diluted geothermal water, *in* Woessner, W.W., and Potts, D.F., eds., Proceedings of the Symposium on Headwaters Hydrology: American Water Resources Association Technical Publication Series TPS-89-1, p. 685-694.

Tuck, L.K., Briar, D.W., and Clark, D.W., 1996, Geologic history and hydrogeologic units of intermontane basins of the Northern Rocky Mountains, Montana and Idaho: U.S. Geological Survey Hydrologic Investigations Atlas HA-738A, 2 sheets, scale 1:750,000.

Tuck, L.K., Dutton, D.M., and Nimick, D.A., 1997, Hydrologic and water-quality data related to the occurrence of arsenic for areas along the Madison and upper Missouri Rivers, southwestern and west-central Montana: U.S. Geological Survey Open-File Report 97-203, 124 p.

U.S. Environmental Protection Agency, 1996, Drinking water regulations and health advisories, Office of Water: EPA 822-B-002, October 1996 [variously paged].

U.S. Geological Survey, published annually, Water resources data, Montana: U.S. Geological Survey Water Data Report.

Welch, A.H., Lico, M.S., and Hughes, J.L., 1988, Arsenic in ground water of the western United States: Ground Water, v. 26, no. 3, p. 333-347.

Wilke, K.R., and Coffin, D.L., 1973, Appraisal of the quality of ground water in the Helena Valley, Montana: U.S. Geological Survey Water-Resources Investigations Report 32-73, 31 p.

Wyatt, G.M., 1984, Hydrogeology and geothermal potential of the Radersburg Valley, Broadwater County, Montana: Bozeman, Montana State University, M.S. thesis, 160 p.

Xu, H., Allard, B., and Grimvall, A., 1988, Influence of pH and organic substance on the adsorption of As(V) on geologic materials: Water, Air, and Soil Pollution, v. 40, p. 293-305.

Xu, H., Allard, B., and Grimvall, A., 1991, Effects of acidification and natural organic materials on the mobility of arsenic in the environment: Water, Air, and Soil Pollution, v. 57-58, p. 269-278.

DATA

Table 1. Site and station-identification numbers for surface-water sites along the Madison and upper Missouri Rivers, Montana

[Site and station-identification numbers described in text. Abbreviations: Site type: C, irrigation-supply canal or ditch; D, drain; L, lake; M, mainstem; S, spring or seep, T, tributary]

Site number	Station-identification number	Station name	Site type
		MADISON RIVER ABOVE UPPER MADISON RIVER VALLEY	
S1	06037500	Madison River near West Yellowstone	M
S2	06037600	Madison River above Hebgen Lake, near West Yellowstone	M
S3	06038500	Madison River below Hebgen Lake, near Grayling	M
		UPPER MADISON RIVER VALLEY	
S4	450734111402901	Granger Ditch at diversion with the Madison River	C
S5	450857111424301	Shewmaker Ditch at diversion with the Madison River	C
S6	451029111430901	O'Dell Creek at diversion with the Madison River	T
S7	451218111404201	Bear Creek at bridge north of Cameron	T
S8	06040000	Madison River near Cameron	M
S9	451403111452301	Blaine Spring Creek near Varney	T
S10	451628111455001	Seeps east of Thexton house	S
S11	451756111451801	West Madison Canal near Ennis	C
S12	451818111414201	Bear Creek about 2.5 miles south of O'Dell Creek	T
S13	451942111422701	Bear Creek above O'Dell Creek Ditch Crossing	T
S14	451953111415801	O'Dell Creek Ditch at Highway 287 south of Ennis	C,D[1]
S15	452005111422901	Bear Creek at road near Madison County Cemetery	T,D[1]
S16	452031111425101	Bear Creek at mouth, at Ennis	T,D[1]
S17	452032111425201	O'Dell Creek at Ennis	T
S18	452149111421901	O'Dell Creek near mouth, near Ennis	T
S19	452426111445401	West Madison Canal 2 miles west of Ennis Lake	C
S20	452520111423501	Ennis Lake seep 1 near McAllister	S
S21	452603111430301	Seeps at bridge over Spring Branch	S
S22	452604111424501	Ennis Lake seep 3 near McAllister	S
S23	452606111424701	Ennis Lake seep 2 near McAllister	S
S24	06041000	Madison River below Ennis Lake, near McAllister	M
		LOWER MADISON RIVER VALLEY	
S25	06041300	Hot Springs Creek near Norris	T
S26	06041500	Madison River near Norris	M
S27	06041700	Cherry Creek near Norris	T
S28	453916111311001	Elk Creek at mouth, near Norris	T
S29	454019111313501	Sloan Ditch near Norris	C
S30	454033111314301	Hutchison Ditch near Norris	C
S31	454115111280901	Willow Springs east of Kilgore Ranch	S
S32	454159111303801	Dell Ditch near Harrison	C
S33	454218111305501	Abandoned ditch near Harrison	C
S34	454406111305901	Crowley Ditch near Willow Creek	C

Table 1. Site and station-identification numbers for surface-water sites along the Madison and upper Missouri Rivers, Montana (Continued)

Site number	Station-identification number	Station name	Site type
		LOWER MADISON RIVER VALLEY--Continued	
S35	454450111300501	01S02E17DCAB01	S
S36	454531111304401	Darlington Ditch near Willow Creek	C
S37	454504111293201	Spring Creek near Willow Creek	T,D
S38	454653111283401	Spring Creek above Crowley Ditch, near Logan	T,D
S39	454653111284801	Crowley Ditch above Spring Creek, near Logan	C,D[1]
S40	454718111284701	Spring Creek below Crowley Ditch, near Logan	T,D
S41	454806111300701	Darlington Ditch tributary near Logan	T,D[1]
S42	454847111294601	Darlington Ditch near Logan	C,D[1]
S43	454852111294001	Rey Creek at Madison County road, near Logan	T,D[1]
S44	455000111295901	Frances Walbert Ditch 1 near Three Forks	C
S45	455011111295601	Frances Walbert Ditch 2 near Three Forks	C
S46	454952111291601	Rey Creek at Crowley Lane, near Logan	T,D[1]
S47	454952111283301	Spring Creek diversion near Logan	C,D
S48	455017111273801	Sloan Ditch near Crowley Lane, near Logan	C,D
S49	455054111273801	Sloan Ditch drain 3 near Logan	D
S50	455044111273801	Sloan Ditch drain 2 near Logan	D
S51	455043111281601	Rey Creek drain near Logan	D
S52	455137111282201	Spring Creek at mouth, near Logan	T,D[1]
S53	455134111284801	Rey Creek above Spring Creek, near Logan	T,D[1]
S54	455330111274901	Unnamed ditch from Rey Creek near Logan	C,D[1]
S55	455342111290101	Rey Creek at frontage road, near Logan	T,D
S56	455421111283001	Rey Creek above diversion, near Logan	T,D
S57	455438111290801	Rey Creek tributary near Logan	T,D[1]
S58	06042600	Madison River at Three Forks	M
S59	455359111304201	Unnamed ditch from Darlington Ditch near Three Forks	C,D[1]
S60	455435111305201	Darlington Ditch near Three Forks	C,D[1]
		TOWNSEND VALLEY	
S61	460700111320701	Warm Springs Creek above Willow Swamp Creek, near Toston	T,D[1]
S62	460720111312601	Warm Springs Creek tributary near Toston	C
S63	06054500	Missouri River at Toston	M
S64	460748111305401	Warm Springs Creek tributary above Willow Swamp Creek, near Toston	T,D[1]
S65	460814111294201	Warm Springs Creek tributary above Marsh Creek, near Toston	T,D[1]
S66	460729111233101	Big Spring Creek near Toston	C[1]
S67	460944111293301	Warm Springs Creek above Marsh Creek, near Toston	T,D[1]
S68	461026111274601	Broadwater-Missouri drain near Toston	D
S69	461415111293701	Seep on west side of road on Stanfill property	S,D[1]
S70	461609111291201	Missouri River drain near Townsend	D
S71	461704111303901	Montana Ditch at siphon, at Deep Creek	C
S72	461812111285701	Field drain pipe outlet on same drain	D
S73	461823111290601	Drain on Bruce property near center section 4	D
S74	461827111293301	Drain below UM108-D on same drain	D
S75	461908111293101	Townsend drain east near Townsend	D
S76	462016111302101	Townsend drain north at Townsend	D

Table 1. Site and station-identification numbers for surface-water sites along the Madison and upper Missouri Rivers, Montana (Continued)

Site number	Station-identification number	Station name	Site type
		HELENA VALLEY	
S77	06062000	Prickly Pear Creek at East Helena	T
S78	463701111593401	Helena Valley Canal at Highway 280, near Helena	C
S79	463758111593301	Helena Valley diversion canal site 1 near Helena	D
S80	463816111525601	Helena Valley Regulating Reservoir outlet near East Helena	C
S81	463846111585901	Helena Valley diversion canal site 2 near Helena	D
S82	464018112011301	Drain at Montana Avenue, by radio towers	D
S83	463939111582801	Prickly Pear Creek above Tenmile Creek, near East Helena	T
S84	464047111595501	Helena Valley diversion canal 3 near Helena	C,D
S85	464124111595801	Silver Creek drain at Masonic Home Road, near East Helena	C,D[1]
S86	464150111595601	Drain south of Lincoln Road, near Masonic Home	D
S87	464214111595601	Drain south of Lincoln Road, near Masonic Home north	D
S88	464031111564101	Helena Valley Field Drain site 2 near East Helena	D
S89	464119111583901	Drain 3 near Masonic Home, near Helena	C,D
S90	464137111584201	Helena Valley diversion canal 5 near Helena	D
S91	464217111581901	Helena Valley drain above Lincoln Road, near Helena	D
S92	464042111543401	Helena Valley Field Drain 1 near East Helena	D
S93	464045111564401	Helena Valley Field Drain 2 near East Helena	C,D[1]
S94	464107111573701	Prickly Pear Creek at Lake Helena, near East Helena	T
S95	464140111580901	Silver Creek diversion canal near East Helena	C,D[1]
S96	464122111543501	Helena Valley Field Drain 1 at mouth, near East Helena	C,D
S97	464120111555001	Lake Helena (south) near East Helena	L
S98	464139111571201	Lake Helena (west) near East Helena	L
S99	464210111572401	Helena Valley drain above Lake Helena, near Helena	D
S100	464220111555001	Lake Helena (north) near East Helena	L
S101	464230111545001	End of Helena Valley Canal	C
S102	464155111544101	Lake Helena (east) near East Helena	L
S103	464207111540201	Outlet of Lake Helena (Prickly Pear Creek)	L

[1] Site type has been revised (Tuck and others, 1997).

Table 2. Site and location numbers for ground-water sites along the Madison and upper Missouri Rivers, Montana

Site number	Location number	Site number	Location number	Site number	Location number
		UPPER MADISON RIVER VALLEY			
UM1	04S01W30BA 01	UM21	06S02W36DAAD01	UM41	06S01W23BBBA01
UM2	05S01W03ACCC01	UM22	06S01W02CBCB01	UM42	06S01W30DADD01
UM3	05S01W04ABDD01	UM23	06S01W03AABA01	UM43	06S01W34DDDA01
UM4	05S01W04ACBC01	UM24	06S01W03ABAB01	UM44	06S01W35DAAB01
UM5	05S01W04BAAB01	UM25	06S01W03ABAC01	UM45	06S01E31CAAC01
UM6	05S01W04DBAB01	UM26	06S01W03CDAD01	UM46	07S01W03CAB 01
UM7	05S01W04DDDB01	UM27	06S01W03DAAA01	UM47	07S01W06BBAC01
UM8	05S01W08ACBB01	UM28	06S01W04AABB01	UM48	07S01W07DBCD01
UM9	05S01W10BADC01	UM29	06S01W04ACCB01	UM49	07S01W12DBBC01
UM10	05S01W17AAAA01	UM30	06S01W04CCDB01	UM50	07S01W17BBBB01
UM11	05S01W21CCCC01	UM31	06S01W05AAAA01	UM51	07S01W17BCBD01
UM12	05S01W23DABA01	UM32	06S01W05ACBD01	UM52	07S01W18DDAC01
UM13	05S01W28BACB01	UM33	06S01W06DDA 01	UM53	07S01W20CBAA01
UM14	05S01W28DBDD01	UM34	06S01W08CADD01	UM54	07S01W23ABBA01
UM15	05S01W28DCBA01	UM35	06S01W08DABD01	UM55	07S01W26AAAA01
UM16	05S01W28DCCB01	UM36	06S01W09BBCA01	UM56	07S01W34AAC 01
UM17	05S01W33BADB01	UM37	06S01W10ABAC01	UM57	08S01W25BBC 01
UM18	05S01W33CBCB01	UM38	06S01W10BAAA01		
UM19	06S02W13CDCD01	UM39	06S01W17CDDA01		
UM20	06S02W24BACD01	UM40	06S01W23BBAC01		
		LOWER MADISON RIVER VALLEY			
LM1	02N01E08DDCA01	LM21	02N02E17DDCC01	LM41	02N02E28BCD 01
LM2	02N01E17DAAD01	LM22	02N02E19CBCC01	LM42	02N02E28CADC01
LM3	02N01E24BADA01	LM23	02N02E19CCAB01	LM43	02N02E28CADC02
LM4	02N01E24DDA 01	LM24	02N02E19CCB 01	LM44	02N02E28CADC03
LM5	02N01E24DDAA01	LM25	02N02E19CCCB01	LM45	02N02E28CADC04
LM6	02N01E25AACC01	LM26	02N02E19CCCB02	LM46	02N02E28CBDD01
LM7	02N01E25AB 01	LM27	02N02E20CABC01	LM47	02N02E29AD 01
LM8	02N01E25BDBB01	LM28	02N02E20CBDC01	LM48	02N02E29BABD01
LM9	02N01E26AA 01	LM29	02N02E20CCAA01	LM49	02N02E29BABD02
LM10	02N01E26DCDC01	LM30	02N02E20CDAC01	LM50	02N02E29DD 01
LM11	02N01E27BCCB01	LM31	02N02E20DAC 01	LM51	02N02E30CDAA01
LM12	02N01E27CBD 01	LM32	02N02E20DDCB01	LM52	02N02E32AAAA01
LM13	02N01E34AAAD01	LM33	02N02E21ACDB01	LM53	02N02E32AAAA02
LM14	02N01E34AABA01	LM34	02N02E22CCC 01	LM54	02N02E35BBB 01
LM15	02N01E35BABA01	LM35	02N02E27CADD01	LM55	02N02E35DCD 01
LM16	02N01E35BABA02	LM36	02N02E27CBC 01	LM56	01N01E04BCDC01
LM17	02N01E36BCBD01	LM37	02N02E27DCA 01	LM57	01N02E04CB 01
LM18	02N01E36BCDD01	LM38	02N02E27DCA 02	LM58	01N02E04DCCC01
LM19	02N01E36CBA 01	LM39	02N02E27DCB 01	LM59	01N02E06BCBA01
LM20	02N02E09CBDA01	LM40	02N02E28BC 01	LM60	01N02E06DAA 01

Table 2. Site and location numbers for ground-water sites along the Madison and upper Missouri Rivers, Montana (Continued)

Site number	Location number	Site number	Location number	Site number	Location number
LOWER MADISON RIVER VALLEY--Continued					
LM61	01N02E07AACA01	LM76	01N02E22CA 01	LM91	01S02E17AAAB01
LM62	01N02E10DBAB01	LM77	01N02E22CABD01	LM92	01S02E17AAB 01
LM63	01N02E15DCBB01	LM78	01N02E22CDCC01	LM93	01S02E20CACC01
LM64	01N02E15DCBD01	LM79	01N02E27BBDA01	LM94	01S02E20CBBA01
LM65	01N02E15DD 01	LM80	01N02E27BCCB01	LM95	01S02E21DBDB01
LM66	01N02E16CBD 01	LM81	01N02E29DCA 01	LM96	01S02E22BCBC01
LM67	01N02E19CDDD01	LM82	01N02E30DCAC01	LM97	01S02E22BCCB01
LM68	01N02E20AC 01	LM83	01N02E33DAB 01	LM98	01S02E29AAC 01
LM69	01N02E20ADDB01	LM84	01S02E03DCC 01	LM99	01S02E29DDDB01
LM70	01N02E21ABBA01	LM85	01S02E03DCCC02	LM100	02S02E05BAA 01
LM71	01N02E21ABBB01	LM86	01S02E04AACC01	LM101	02S02E05BDBB01
LM72	01N02E22ABB 01	LM87	01S02E05AB 01	LM102	02S02E05CAAD01
LM73	01N02E22ABBB01	LM88	01S02E08CDDC01	LM103	02S02E05CC 01
LM74	01N02E22BABA01	LM89	01S02E10CAAC01	LM104	02S02E05CCC 01
LM75	01N02E22BADD01	LM90	01S02E16DDA 01	LM105	02S02E05CDA 01
				LM106	02S02E19BA 01
TOWNSEND VALLEY					
T1	07N02E03ADDA01	T21	06N02E08DCBC01	T41	05N02E23DBBB01
T2	07N02E03BCBA01	T22	06N02E09BACD01	T42	05N02E23DBCA01
T3	07N02E09AABB01	T23	06N02E16BBAA01	T43	05N02E27ADDA01
T4	07N02E15CBAB01	T24	06N02E21DAAA01	T44	05N02E28ACDA01
T5	07N02E20DDCD01	T25	06N02E26CBBB01	T45	05N02E28BBCC01
T6	07N02E21DCDD01	T26	06N02E27BDCB01	T46	05N02E28CDDD01
T7	07N02E29CABC01	T27	06N02E34BDBB01	T47	05N02E32DAAD01
T8	07N02E29DDCD01	T28	05N01E22BBAB01	T48	05N02E33DACA01
T9	07N02E30ACBC01	T29	05N01E24BDD 01	T49	04N01E02BBCC01
T10	07N02E30CDDA01	T30	05N01E27BDA 01	T50	04N01E04ADBB01
T11	07N02E31BDAD01	T31	05N01E28BCAA01	T51	04N01E09CAB 01
T12	07N02E31DCDA01	T32	05N01E33BACD01	T52	04N01E12BADD01
T13	07N02E32BADB01	T33	05N02E03ACDC01	T53	04N01E23BAC 01
T14	07N02E32CADA01	T34	05N02E04DBDA01	T54	04N01E23BBB 01
T15	07N02E33ABCD01	T35	05N02E05BDCB01	T55	04N02E05CBCC01
T16	07N02E33CBBC01	T36	05N02E10CBCC01	T56	04N02E05CDDC01
T17	07N02E33CDDA01	T37	05N02E15DACB01	T57	04N02E16AAA 01
T18	06N02E05BBAC01	T38	05N02E20CAAA01	T58	04N02E18ACAC01
T19	06N02E05BBCB01	T39	05N02E22CBBA01		
T20	06N02E08AACC01	T40	05N02E23BBDA01		
HELENA VALLEY					
H1	11N04W25AABA01	H6	11N03W15DCDD01	H11	11N03W21DDAD01
H2	11N04W25DDDD01	H7	11N03W16BBBB01	H12	11N03W22BBCB02
H3	11N04W36ACCA01	H8	11N03W17DDCC01	H13	11N03W25DDBD01
H4	11N03W14BBBB01	H9	11N03W18ADDD01	H14	11N03W28DAAD01
H5	11N03W15CBCC01	H10	11N03W21BBAA01	H15	11N03W29ABBA01

Table 2. Site and location numbers for ground-water sites along the Madison and upper Missouri Rivers, Montana (Continued)

Site number	Location number	Site number	Location number	Site number	Location number
		HELENA VALLEY--Continued			
H16	11N03W29BBAC01	H31	10N04W13ACCD01	H46	10N03W23DAAD01
H17	11N03W30BAAA01	H32	10N03W02BCDD01	H47	10N03W24BBBC01
H18	11N03W30DBCA01	H33	10N03W02DDDD03	H48	10N02W03BBAB01
H19	11N03W31BADD01	H34	10N03W03BACB02	H49	10N02W06AADC01
H20	11N03W33ADDB01	H35	10N03W04DCCD01	H50	10N02W07BBBB01
H21	11N03W33BBAA02	H36	10N03W04DCCD02	H51	10N02W18DDCD01
H22	11N03W33BBAA03	H37	10N03W05CCDD01	H52	10N02W19ADBB01
H23	11N03W33DDDC01	H38	10N03W06DBAA01		
H24	11N03W33DDDC02	H39	10N03W06DBAA02		
H25	11N03W35DACC01	H40	10N03W11DDCC02		
H26	11N02W30DCAD01	H41	10N03W16DBAD01		
H27	11N02W31ACAA01	H42	10N03W16DCCC02		
H28	11N02W31BCCB01	H43	10N03W17ABBB01		
H29	10N04W01DCAD01	H44	10N03W17CCCC01		
H30	10N04W12AACD01	H45	10N03W18AADA01		

Table 3. Statistical summary of arsenic concentrations at selected surface-water sites along the Madison and upper Missouri Rivers, Montana, 1988-95[1]

[Site number described in text. All concentrations are reported in micrograms per liter (µg/L). Symbols: <, less than minimum reporting level; --, no data or value for indicated statistic is not applicable]

Site number	Value for indicated statistic									
	Non-irrigation season (October 15-April 14)					Irrigation season (April 15-October 14)				
	Number of samples	Maximum	Minimum	Mean	Median	Number of samples	Maximum	Minimum	Mean	Median
MADISON RIVER ABOVE UPPER MADISON RIVER VALLEY										
S1[2]	11	330	250	300	300	20	340	96	230	230
S2[2]	3	290	260	280	290	4	290	100	190	180
S3[2]	11	190	110	160	170	19	140	71	110	110
UPPER MADISON RIVER VALLEY										
S4	--	--	--	--	--	1	58.4	58.4	--	--
S5	--	--	--	--	--	2	75.2	65.6	70	--
S6	--	--	--	--	--	2	85.2	58.0	72	--
S7	--	--	--	--	--	1	<1	<1	--	--
S8	6	150	86	118	110	8	99	46	64	61
S9	--	--	--	--	--	1	3.0	3.0	--	--
S10	--	--	--	--	--	2	5.4	4.0	4.7	--
S11	--	--	--	--	--	7	88.5	31.9	56	54
S12	--	--	--	--	--	1	<1	<1	--	--
S13	--	--	--	--	--	1	2.3	2.3	--	--
S14	1	1.5	1.5	--	--	2	6.9	<1	3.7	--
S15	--	--	--	--	--	2	14.4	7.9	11	--
S16	3	1.5	<.7	1.1	1.4	7	20.6	<1	13	13
S17	3	28.8	21.9	26	28	10	29.6	21.2	25	24
S18	2	25.1	18.6	22	--	5	19.2	15.3	17	18
S19	--	--	--	--	--	2	56.4	43.4	50	--
S20	1	7.1	7.1	--	--	6	11.9	4.4	6.6	6.1
S21	1	4.7	4.7	--	--	2	6.2	5.8	6.0	--
S22	3	6.2	5.2	5.6	5.4	7	7.6	3.9	5.9	6.1
S23	3	6.1	4.2	4.9	4.3	7	25.8	5.4	16	15
S24	12	120	68	100	90	18	99	42	68	69
LOWER MADISON RIVER VALLEY										
S25	1	2.0	2.0	--	--	3	4.0	2.0	3.0	3.0
S26	7	98	76	87	85	13	100	42	65	62
S27	1	2.0	2.0	--	--	2	2.0	1.0	1.5	--
S28	1	3.0	3.0	--	--	2	5.0	4.0	4.5	--
S29	2	82.9	48.5	66	--	6	76.0	31.0	54	52
S30	1	71.9	71.9	--	--	6	81.5	27.0	55	51
S31	1	20.2	20.2	--	--	1	31.8	31.8	--	--
S32	1	86.2	86.2	--	--	5	74.8	27.0	55	61
S33	1	91.9	91.9	--	--	4	86.7	29.6	64	71
S34	2	69.7	61.4	66	--	5	65.8	45.1	52	49
S35	2	4.8	<1	2.7	--	3	6.2	4.0	5.0	4.8
S36	--	--	--	--	--	5	79.4	36.8	62	68

Table 3. Statistical summary of arsenic concentrations at selected surface-water sites along the Madison and upper Missouri Rivers, Montana, 1988-95[1] (Continued)

Site number	Value for indicated statistic									
	Non-irrigation season (October 15-April 14)					Irrigation season (April 15-October 14)				
	Number of samples	Maximum	Minimum	Mean	Median	Number of samples	Maximum	Minimum	Mean	Median
	LOWER MADISON RIVER VALLEY--Continued									
S37	1	46.1	46.1	--	--	1	44.5	44.5	--	--
S38	1	63.4	63.4	--	--	1	51.6	51.6	--	--
S39	1	64.2	64.2	--	--	1	65.9	65.9	--	--
S41	1	52.4	52.4	--	--	2	48.2	42.8	46	--
S42	1	54.5	54.5	--	--	1	54.3	54.3	--	--
S43	1	43.3	43.3	--	--	1	46.0	46.0	--	--
S44	--	--	--	--	--	3	74.6	36.3	51	42
S45	1	85.4	85.4	--	--	5	98.7	35.4	64	67
S46	2	43.7	42.2	43	--	1	51.2	51.2	--	--
S47	1	60.5	60.5	--	--	1	57.3	57.3	--	--
S48	1	113	113	--	--	--	--	--	--	--
S49	1	96.5	96.5	--	--	--	--	--	--	--
S50	1	114	114	--	--	--	--	--	--	--
S51	1	321	321	--	--	--	--	--	--	--
S52	2	106	94.8	100	--	1	61.0	61.0	--	--
S53	3	65.4	60.5	62	61	5	73.6	57.3	65	65
S54	1	52.9	52.9	--	--	1	62.6	62.6	--	--
S55	1	68.1	68.1	--	--	--	--	--	--	--
S56	4	68.2	57.8	64	65	6	72.0	52.0	62	62
S57	1	66.0	66.0	--	--	1	66.7	66.7	--	--
S58	7	100	64	80	81	15	95	41	64	53
S59	--	--	--	--	--	1	48.2	48.2	--	--
S60	4	73.0	45.0	57	56	6	59.4	54.0	57	56
	TOWNSEND VALLEY									
S61	--	--	--	--	--	1	35.4	35.4	--	--
S62	--	--	--	--	--	2	38.4	12.5	26	--
S63	18	43	26	34	35	25	67	12	29	23
S64	3	4.0	1.5	2.4	1.7	5	3.8	1.6	2.5	2.2
S65	3	5.0	2.2	3.5	3.4	5	6.3	2.1	4.1	3.3
S66	--	--	--	--	--	2	6.4	4.0	5.2	--
S67	3	6.7	3.5	5.2	5.5	5	11.7	3.6	8.8	11
S68	3	8.4	6.7	7.4	7.0	5	10.0	4.1	6.3	4.9
S69	--	--	--	--	--	1	12.8	12.8	--	--
S70	2	2.6	1.2	1.9	--	4	4.2	<1	2.1	1.8
S71	--	--	--	--	--	1	34.8	34.8	--	--
S72	--	--	--	--	--	1	3.5	3.5	--	--
S73	--	--	--	--	--	1	1.2	1.2	--	--
S74	--	--	--	--	--	1	2.4	2.4	--	--
S75	3	<1	.7	.6	.5	4	4.8	<1	1.9	1.0
S76	2	7.9	1.0	4.5	--	3	5.2	2.7	3.8	3.4

Table 3. Statistical summary of arsenic concentrations at selected surface-water sites along the Madison and upper Missouri Rivers, Montana, 1988-95[1] (Continued)

Site number	Value for indicated statistic									
	Non-irrigation season (October 15-April 14)					Irrigation season (April 15-October 14)				
	Number of samples	Maximum	Minimum	Mean	Median	Number of samples	Maximum	Minimum	Mean	Median
					HELENA VALLEY					
S77	1	7.0	7.0	--	--	1	5.0	5.0	--	--
S78	1	5.4	5.4	--	--	3	27.3	21.3	25	26
S79	1	5.4	5.4	--	--	3	2.5	2.0	2.3	2.3
S80	--	--	--	--	--	1	31	31	--	--
S81	1	5.4	5.4	--	--	3	4.2	3.5	3.9	3.9
S82	--	--	--	--	--	2	4.8	3.1	4.0	--
S83	1	8.0	8.0	--	--	1	8.0	8.0	--	--
S84	1	1.1	1.1	--	--	3	21.5	13.7	17	14
S85	1	2.0	2.0	--	--	1	25	25	--	--
S86	--	--	--	--	--	1	2.7	2.7	--	--
S87	--	--	--	--	--	1	1.7	1.7	--	--
S88	1	<1	<1	--	--	3	2.1	<.8	1.4	1.6
S89	1	1.8	1.8	--	--	3	16.0	10.9	13	13
S90	1	4.2	4.2	--	--	4	5.3	3.2	3.9	3.6
S91	1	2.4	2.4	--	--	4	3.7	2.0	2.7	2.5
S92	1	1.8	1.8	--	--	4	1.3	<1	.8	.8
S93	1	2.0	2.0	--	--	1	7.0	7.0	--	--
S94	1	8.0	8.0	--	--	1	12	12	--	--
S95	1	3	3	--	--	1	17	17	--	--
S96	1	2.0	2.0	--	--	1	15	15	--	--
S97	--	--	--	--	--	1	15	15	--	--
S98	1	6	6	--	--	1	12	12	--	--
S99	2	19.2	16.2	18	--	4	19.2	5.2	10	7.8
S100	--	--	--	--	--	1	15	15	--	--
S101	--	--	--	--	--	2	24.4	20.7	23	--
S102	1	5	5	--	--	1	17	17	--	--
S103	--	--	--	--	--	2	12.8	9.7	11	--

[1] Data from Tuck and others (1997).

[2] Sites are shown on figure 1.

Table 4. Statistical summary of selected physical and water-quality data for surface water at mainstem sites along the Madison and upper Missouri Rivers, Montana, 1988-95[1]

[Constituents are reported as dissolved except as indicated. Abbreviation: ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligrams per liter; µg/L, micrograms per liter. Symbols: --, no data or value for indicated statistic is not applicable]

Parameter or constituent and unit of measure	Number of samples	Maximum	Minimum	Mean	Value for indicated percentile		
					75	50 (median)	25
MADISON RIVER NEAR WEST YELLOWSTONE 06037500 (S1)							
Discharge, instantaneous (ft^3/s)	52	1,710	352	573	618	425	391
Specific conductance (µS/cm)	52	559	174	429	504	471	362
Chloride (mg/L as Cl)	37	70	19	53	64	60	42
Fluoride (mg/L as F)	10	8.2	2.9	5.9	7.4	6.6	4.3
Dissolved solids (mg/L)	10	366	135	244	329	244	157
Arsenic, total-recoverable (µg/L as As)	50	370	110	260	310	280	200
Arsenic (µg/L as As)	31	340	96	250	310	270	200
Boron (µg/L as B)	38	930	260	670	830	750	540
Lithium (µg/L as Li)	32	710	180	540	670	610	430
Sediment, suspended (mg/L)	38	52	2	14	22	9	4
MADISON RIVER ABOVE HEBGEN LAKE, NEAR WEST YELLOWSTONE 06037600 (S2)							
Discharge, instantaneous (ft^3/s)	7	1,630	418	769	1,380	478	440
Specific conductance (µS/cm)	7	479	176	374	463	430	209
Chloride (mg/L as Cl)	7	68	17	47	62	53	22
Fluoride (mg/L as F)	2	6	3.2	4.6	--	4.6	--
Dissolved solids (mg/L)	2	301	158	230	--	230	--
Arsenic, total-recoverable (µg/L as As)	7	300	110	230	300	290	130
Arsenic (µg/L as As)	7	290	100	230	290	260	140
Boron (µg/L as B)	7	790	260	570	710	630	320
Lithium (µg/L as Li)	7	620	190	460	560	550	230
Sediment, suspended (mg/L)	7	50	2	19	27	12	6
MADISON RIVER BELOW HEBGEN LAKE, NEAR GRAYLING 06038500 (S3)							
Discharge, instantaneous (ft^3/s)	44	3,180	485	1,120	1,310	959	732
Specific conductance (µS/cm)	44	398	192	293	338	281	260
Chloride (mg/L as Cl)	28	45	14	27	32	27	22
Fluoride (mg/L as F)	2	3.7	2.6	3.2	--	3.2	--
Dissolved solids (mg/L)	2	194	148	171	--	171	--
Arsenic, total-recoverable (µg/L as As)	44	230	78	130	160	120	110
Arsenic (µg/L as As)	30	190	71	130	150	120	108
Boron (µg/L as B)	30	560	190	350	430	340	290
Lithium (µg/L as Li)	30	450	170	290	370	280	240
Sediment, suspended (mg/L)	30	12	1	2	2	2	1
MADISON RIVER NEAR CAMERON 06040000 (S8)							
Discharge, instantaneous (ft^3/s)	14	5,320	970	2,040	2,160	1,530	1,120
Specific conductance (µS/cm)	14	354	195	261	309	254	224
Chloride (mg/L as Cl)	13	32	9.6	18	24	17	13
Fluoride (mg/L as F)	2	2.0	1.7	1.9	--	1.9	--
Dissolved solids (mg/L)	2	154	141	148	--	148	--
Arsenic, total-recoverable (µg/L as As)	14	160	48	91	130	81	57
Arsenic (µg/L as As)	14	150	46	87	110	82	56
Boron (µg/L as B)	14	440	130	250	320	210	180
Lithium (µg/L as Li)	14	350	110	200	280	180	140
Sediment, suspended (mg/L)	14	322	2	44	16	4	3

Table 4. Statistical summary of selected physical and water-quality data for surface water at mainstem sites along the Madison and upper Missouri Rivers, Montana, 1988-95[1] (Continued)

Parameter or constituent and unit of measure	Number of samples	Maximum	Minimum	Mean	Value for indicated percentile		
					75	50 (median)	25
MADISON RIVER BELOW ENNIS LAKE, NEAR MCALLISTER 06041000 (S24)							
Discharge, instantaneous (ft^3/s)	44	6,290	1,060	1,990	2,110	1,530	1,220
Specific conductance (μS/cm)	44	365	207	289	319	289	258
Chloride (mg/L as Cl)	29	29	7.5	18	22	19	14
Fluoride (mg/L as F)	2	1.7	1.4	1.6	--	1.6	--
Dissolved solids (mg/L)	1	155	--	--	--	--	--
Arsenic, total-recoverable (μg/L as As)	44	120	35	76	88	75	60
Arsenic (μg/L as As)	30	120	42	77	90	79	58
Boron (μg/L as B)	30	340	90	220	270	240	160
Lithium (μg/L as Li)	30	270	90	180	220	190	140
Sediment, suspended (mg/L)	30	53	2	11	13	9	5
MADISON RIVER NEAR NORRIS 06041500 (S26)							
Discharge, instantaneous (ft^3/s)	20	6,300	1,100	2,340	2,290	1,780	1,300
Specific conductance (μS/cm)	20	369	206	276	308	276	236
Chloride (mg/L as Cl)	20	26	7.3	16	21	16	12
Fluoride (mg/L as F)	4	3.2	1.4	2.2	--	2.2	--
Dissolved solids (mg/L)	4	224	148	175	--	175	--
Arsenic, total-recoverable (μg/L as As)	20	120	46	75	89	75	58
Arsenic (μg/L as As)	20	100	42	73	88	76	53
Boron (μg/L as B)	20	320	90	210	270	210	140
Lithium (μg/L as Li)	20	250	80	170	210	160	130
Sediment, suspended (mg/L)	20	45	3	13	16	11	6
MADISON RIVER AT THREE FORKS 06042600 (S58)							
Discharge, instantaneous (ft^3/s)	22	5,650	960	2,140	2,210	1,670	1,220
Specific conductance (μS/cm)	22	363	207	279	305	285	238
Chloride (mg/L as Cl)	21	25	7.7	16	20	15	13
Fluoride (mg/L as F)	5	2.5	1.5	2.1	2.5	2.3	1.6
Dissolved solids (mg/L)	5	184	148	168	182	174	151
Arsenic, total-recoverable (μg/L as As)	20	110	44	72	84	74	55
Arsenic (μg/L as As)	22	100	41	69	82	71	52
Boron (μg/L as B)	22	320	110	210	250	210	160
Lithium (μg/L as Li)	22	270	90	160	200	160	120
Sediment, suspended (mg/L)	22	129	5	31	46	21	11
MISSOURI RIVER AT TOSTON 06054500 (S63)							
Discharge, instantaneous (ft^3/s)	60	25,400	1,080	5,060	5,560	3,630	2,900
Specific conductance (μS/cm)	59	483	213	345	392	350	312
Chloride (mg/L as Cl)	46	38	5.9	12	14	13	7.9
Fluoride (mg/L as F)	25	1.6	.6	1.1	1.4	1.3	.8
Dissolved solids (mg/L)	25	274	136	216	241	219	189
Arsenic, total-recoverable (μg/L as As)	52	69	14	33	38	33	23
Arsenic (μg/L as As)	43	67	12	32	39	30	22
Boron (μg/L as B)	31	160	50	110	150	110	70
Lithium (μg/L as Li)	46	110	30	80	100	82	50
Suspended sediment (mg/L)	45	378	4	34	25	12	8

[1] Data from Tuck and others (1997).

Table 5. Arsenic loads from selected surface-water sites along the Madison and upper Missouri Rivers, Montana, 1992-95

[Site number described in text. Sample date, discharge, and arsenic-concentration data from Tuck and others (1997). Abbreviations: ft^3/s, cubic feet per second; µg/L, micrograms per liter; lb/d, pounds per day; e, estimated. Symbols: --, no data; <, less than minimum reporting level]

Non-irrigation season (October 15 through April 14)					Irrigation season (April 15 through October 14)				
Site number	Sample date	Discharge (ft^3/s)	Arsenic concentration (µg/L)	Arsenic load (lb/d)[1]	Site number	Sample date	Discharge (ft^3/s)	Arsenic concentration (µg/L)	Arsenic load (lb/d)[1]
				UPPER MADISON RIVER VALLEY					
--	--	--	--	--	S4	07-16-92	--	58.4	--
--	--	--	--	--	S5	07-16-92	69	65.6	24
--	--	--	--	--	S5	08-04-92	--	75.2	--
--	--	--	--	--	S6	07-17-92	e7.5	58.0	2.4
--	--	--	--	--	S6	08-04-92	e50	85.2	23
--	--	--	--	--	S7	08-27-92	e2.0	<1	.0054
--	--	--	--	--	S9	09-22-92	--	3.0	--
--	--	--	--	--	S10	08-27-92	e1.0	4.0	.02
--	--	--	--	--	S10	09-22-92	e.2	5.4	.0058
--	--	--	--	--	S11	07-15-92	--	42.0	--
--	--	--	--	--	S11	08-04-92	--	64.6	--
--	--	--	--	--	S11	08-27-92	52	74.6	20
--	--	--	--	--	S11	09-28-92	e45	53.6	13
--	--	--	--	--	S11	04-27-93	25	88.5	12
--	--	--	--	--	S11	06-22-93	59	31.9	10
--	--	--	--	--	S11	08-31-93	60	34.8	11
--	--	--	--	--	S12	08-27-92	e3.0	<1	.0081
--	--	--	--	--	S13	08-26-92	--	2.3	--
S14	03-30-93	e1.5	1.5	.012	--	--	--	--	--
--	--	--	--	--	S14	07-09-93	--	<1	--
--	--	--	--	--	S14	08-31-93	14	6.9	.52
--	--	--	--	--	S15	07-09-93	--	7.9	--
--	--	--	--	--	S15	08-31-93	16	14.4	1.2
--	--	--	--	--	S16	07-16-92	--	12.8	--
--	--	--	--	--	S16	08-04-92	--	20.6	--
--	--	--	--	--	S16	08-27-92	24	17.8	2.3
--	--	--	--	--	S16	09-28-92	27	16.0	2.3
S16	11-11-92	12	1.5	.097	--	--	--	--	--
S16	03-16-93	13	<.7	.028	--	--	--	--	--
S16	03-30-93	--	1.3	--	--	--	--	--	--
--	--	--	--	--	S16	04-27-93	14	<1	.038
--	--	--	--	--	S16	06-22-93	23	8.1	1.0
--	--	--	--	--	S16	08-31-93	19	12.5	1.2
--	--	--	--	--	S17	07-16-92	--	21.2	--
--	--	--	--	--	S17	08-04-92	--	27.1	--
--	--	--	--	--	S17	08-27-92	63	23.6	8.0
--	--	--	--	--	S17	09-28-92	88	22.6	10
S17	11-11-92	103	21.9	12	--	--	--	--	--
S17	03-16-93	96	28.1	14	--	--	--	--	--

Table 5. Arsenic loads from selected surface-water sites along the Madison and upper Missouri Rivers, Montana, 1992-95--Continued

Non-irrigation season (October 15 through April 14)					Irrigation season (April 15 through October 14)				
Site number	Sample date	Discharge (ft^3/s)	Arsenic concentration (µg/L)	Arsenic load (lb/d)[1]	Site number	Sample date	Discharge (ft^3/s)	Arsenic concentration (µg/L)	Arsenic load (lb/d)[1]
UPPER MADISON RIVER VALLEY--Continued									
S17	03-30-93	--	28.8	--	--	--	--	--	--
--	--	--	--	--	S17	04-27-93	100	23.5	12
--	--	--	--	--	S17	06-22-93	111	24.4	14
--	--	--	--	--	S17	08-31-93	86	29.6	14
--	--	--	--	--	S18	08-27-92	108	17.7	10
--	--	--	--	--	S18	09-28-92	108	17.5	10
S18	11-11-92	e120	18.6	12	--	--	--	--	--
S18	03-16-93	135	25.1	18	--	--	--	--	--
--	--	--	--	--	S18	04-27-93	113	19.2	12
--	--	--	--	--	S18	06-22-93	188	16.0	16
--	--	--	--	--	S18	08-31-93	133	15.3	11
--	--	--	--	--	S19	07-15-92	--	43.4	--
--	--	--	--	--	S19	08-03-92	--	56.4	--
--	--	--	--	--	S20	07-15-92	--	5.8	--
--	--	--	--	--	S20	08-27-92	e.33	4.4	.0078
--	--	--	--	--	S20	09-28-92	e.5	6.5	.017
S20	11-10-92	--	7.1	--	--	--	--	--	--
--	--	--	--	--	S20	04-27-93	.17	11.9	.011
--	--	--	--	--	S20	06-22-93	.40	6.3	.014
--	--	--	--	--	S20	08-31-93	.58	4.8	.015
--	--	--	--	--	S21	08-03-92	e.1	5.8	.0031
--	--	--	--	--	S21	03-30-93	--	4.7	--
--	--	--	--	--	S21	07-08-93	--	6.2	--
--	--	--	--	--	S22	07-15-92	e2	6.1	.066
--	--	--	--	--	S22	08-03-92	e2	6.4	.069
--	--	--	--	--	S22	08-27-92	4.3	4.6	.10
--	--	--	--	--	S22	09-28-92	4.1	7.6	.16
S22	11-10-92	2.4	5.4	.070	--	--	--	--	--
S22	03-16-93	.68	5.2	.019	--	--	--	--	--
S22	03-30-93	--	6.2	--	--	--	--	--	--
--	--	--	--	--	S22	04-27-93	3.2	3.9	.067
--	--	--	--	--	S22	06-22-93	3.2	6.1	.10
--	--	--	--	--	S22	08-31-93	3.0	6.5	.10
--	--	--	--	--	S23	07-15-92	e10	10.3	.56
--	--	--	--	--	S23	08-03-92	e10	15.3	.82
--	--	--	--	--	S23	08-27-92	14	25.8	2.0
--	--	--	--	--	S23	09-28-92	11	19.8	1.2
S23	11-10-92	5.8	6.1	.19	--	--	--	--	--
S23	03-16-93	1.8	4.3	.042	--	--	--	--	--
S23	03-30-93	--	4.2	--	--	--	--	--	--
--	--	--	--	--	S23	04-27-93	.65	5.4	.018
--	--	--	--	--	S23	06-22-93	16	21.5	1.8
--	--	--	--	--	S23	08-31-93	11	13.5	.80

Table 5. Arsenic loads from selected surface-water sites along the Madison and upper Missouri Rivers, Montana, 1992-95--Continued

Non-irrigation season (October 15 through April 14)					Irrigation season (April 15 through October 14)				
Site number	Sample date	Discharge (ft^3/s)	Arsenic concentration (µg/L)	Arsenic load (lb/d)[1]	Site number	Sample date	Discharge (ft^3/s)	Arsenic concentration (µg/L)	Arsenic load (lb/d)[1]
LOWER MADISON RIVER VALLEY									
--	--	--	--	--	S25	06-09-93	5.1	4	.11
--	--	--	--	--	S25	08-18-93	6.1	3	.10
S25	02-17-94	6.9	2	.074	--	--	--	--	--
--	--	--	--	--	S25	05-17-94	14	2	.15
--	--	--	--	--	S27	05-28-93	170	1	.92
--	--	--	--	--	S27	08-19-93	45	2	.48
S27	02-17-94	26	2	.28	--	--	--	--	--
--	--	--	--	--	S28	05-28-93	7.6	4	.16
--	--	--	--	--	S28	08-19-93	5.0	5	.14
S28	02-17-94	1.2	3	.019	--	--	--	--	--
--	--	--	--	--	S29	07-17-92	e50	45.2	12
--	--	--	--	--	S29	08-28-92	19	57.8	5.9
--	--	--	--	--	S29	09-28-92	7.1	76.0	2.9
S29	11-11-92	e9.5	82.9	4.2	--	--	--	--	--
S29	04-02-93	--	48.5	--	--	--	--	--	--
--	--	--	--	--	S29	04-28-93	e1.5	73.6	.60
--	--	--	--	--	S29	06-22-93	9.6	31	1.6
--	--	--	--	--	S29	08-31-93	14	39.7	3.0
--	--	--	--	--	S30	07-17-92	e50	44.2	12
--	--	--	--	--	S30	08-28-92	11	56.8	3.4
--	--	--	--	--	S30	09-28-92	5.3	74.8	2.1
S30	11-11-92	e.5	71.9	.19	--	--	--	--	--
--	--	--	--	--	S30	04-28-93	e9	81.5	4.0
--	--	--	--	--	S30	06-22-93	19	27.0	2.8
--	--	--	--	--	S30	08-31-93	27	42.5	6.2
--	--	--	--	--	S31	08-28-92	--	31.8	--
S31	10-27-92	--	20.2	--	--	--	--	--	--
--	--	--	--	--	S32	08-28-92	21	60.8	6.8
--	--	--	--	--	S32	09-29-92	5.8	70.6	2.2
S32	11-11-92	.5	86.2	.23	--	--	--	--	--
--	--	--	--	--	S32	04-28-93	e1.5	74.8	.60
--	--	--	--	--	S32	06-22-93	7.6	27.0	1.1
--	--	--	--	--	S32	08-31-93	18	42.0	4.0
--	--	--	--	--	S33	08-28-92	12	72.4	4.6
--	--	--	--	--	S33	09-29-92	e.25	69.0	.093
S33	11-11-92	e.3	91.9	.14	--	--	--	--	--
--	--	--	--	--	S33	04-28-93	e.5	86.7	.23
--	--	--	--	--	S33	06-22-93	e1	29.6	.16
--	--	--	--	--	S34	08-28-92	2.7	65.8	.96
--	--	--	--	--	S34	09-29-92	2.3	47.4	.58
S34	11-11-92	e2.1	69.7	.79	--	--	--	--	--
S34	03-16-93	e1.5	61.4	.50	--	--	--	--	--

Table 5. Arsenic loads from selected surface-water sites along the Madison and upper Missouri Rivers, Montana, 1992-95--Continued

Non-irrigation season (October 15 through April 14)					Irrigation season (April 15 through October 14)				
Site number	Sample date	Discharge (ft^3/s)	Arsenic concentration (µg/L)	Arsenic load (lb/d)[1]	Site number	Sample date	Discharge (ft^3/s)	Arsenic concentration (µg/L)	Arsenic load (lb/d)[1]
LOWER MADISON RIVER VALLEY--Continued									
--	--	--	--	--	S34	04-28-93	e.5	49.4	.13
--	--	--	--	--	S34	06-22-93	e4	53.1	1.1
--	--	--	--	--	S34	08-31-93	2.2	45.1	.54
--	--	--	--	--	S35	08-28-92	--	6.2	--
S35	10-27-92	--	4.8	--	--	--	--	--	--
S35	04-02-93	--	<1	--	--	--	--	--	--
--	--	--	--	--	S36	08-26-92	--	67.8	--
--	--	--	--	--	S36	08-28-92	33	79.4	14
--	--	--	--	--	S36	09-29-92	e30	76.0	12
--	--	--	--	--	S36	06-23-93	32	36.8	6.4
--	--	--	--	--	S36	09-09-93	19	47.6	4.8
--	--	--	--	--	S37	09-10-93	10	44.5	2.4
S37	03-30-94	1.3	46.1	.32	--	--	--	--	--
--	--	--	--	--	S38	09-10-93	12	51.6	3.3
S38	03-30-94	2.8	63.4	.96	--	--	--	--	--
--	--	--	--	--	S39	09-10-93	4.8	65.9	1.7
S39	03-30-94	3.0	64.2	1.0	--	--	--	--	--
--	--	--	--	--	S41	08-26-92	--	42.8	--
--	--	--	--	--	S41	09-10-93	4.3	48.2	1.1
S41	03-30-94	3.7	52.4	1.0	--	--	--	--	--
--	--	--	--	--	S42	09-10-93	27	54.3	7.9
S42	03-30-94	11	54.5	3.2	--	--	--	--	--
--	--	--	--	--	S43	09-10-93	3.9	46.0	.96
S43	03-30-94	3.4	43.3	.80	--	--	--	--	--
--	--	--	--	--	S44	08-28-92	15	74.6	6.0
--	--	--	--	--	S44	06-23-93	17	36.3	3.3
--	--	--	--	--	S44	09-01-93	.77	42.4	.18
--	--	--	--	--	S45	08-28-92	14	77.2	5.8
--	--	--	--	--	S45	09-29-92	14	67.0	5.0
S45	11-11-92	28	85.4	12	--	--	--	--	--
--	--	--	--	--	S45	04-28-93	8.9	98.7	4.7
--	--	--	--	--	S45	06-23-93	41	35.4	7.8
--	--	--	--	--	S45	09-01-93	7.0	43.0	1.6
--	--	--	--	--	S46	08-28-92	--	51.2	--
S46	04-02-93	--	43.7	--	--	--	--	--	--
S46	03-30-94	6.0	42.2	1.4	--	--	--	--	--
--	--	--	--	--	S47	09-10-93	6.0	57.3	1.8
S47	03-30-94	6.6	60.5	2.2	--	--	--	--	--
S48	03-13-95	.90	113	.54	--	--	--	--	--
S49	03-13-95	.07	96.5	.036	--	--	--	--	--
S50	03-13-95	.09	114	.055	--	--	--	--	--
S51	03-13-95	.05	321	.086	--	--	--	--	--

Table 5. Arsenic loads from selected surface-water sites along the Madison and upper Missouri Rivers, Montana, 1992-95--Continued

Non-irrigation season (October 15 through April 14)					Irrigation season (April 15 through October 14)				
Site number	**Sample date**	**Discharge (ft^3/s)**	**Arsenic concentration (µg/L)**	**Arsenic load (lb/d)[1]**	**Site number**	**Sample date**	**Discharge (ft^3/s)**	**Arsenic concentration (µg/L)**	**Arsenic load (lb/d)[1]**
LOWER MADISON RIVER VALLEY--Continued									
--	--	--	--	--	S52	09-10-93	9.9	61.0	3.2
S52	03-30-94	1.4	94.8	.72	--	--	--	--	--
S52	03-13-95	1.8	106	1.0	--	--	--	--	--
--	--	--	--	--	S53	08-28-92	16	73.6	6.4
--	--	--	--	--	S53	09-29-92	18	57.3	5.6
S53	11-11-92	e20	61.0	6.6	--	--	--	--	--
S53	03-16-93	19	60.5	6.2	--	--	--	--	--
--	--	--	--	--	S53	04-28-93	22	64.7	7.6
--	--	--	--	--	S53	06-23-93	20	63	6.8
--	--	--	--	--	S53	09-10-93	18	64.8	6.2
S53	03-30-94	18	65.4	6.4	--	--	--	--	--
--	--	--	--	--	S54	09-10-93	3.0	62.6	1.0
S54	03-30-94	4.6	52.9	1.3	--	--	--	--	--
S55	03-31-94	18	68.1	6.6	--	--	--	--	--
--	--	--	--	--	S56	07-17-92	e30	55.6	9.0
--	--	--	--	--	S56	08-29-92	30	72.0	12
--	--	--	--	--	S56	09-29-92	23	64.4	8.0
S56	11-11-92	e21	57.8	6.6	--	--	--	--	--
S56	03-16-93	20	65.0	7.0	--	--	--	--	--
S56	04-01-93	--	66.7	--	--	--	--	--	--
--	--	--	--	--	S56	04-28-93	20	62.4	6.7
--	--	--	--	--	S56	06-23-93	24	52	6.7
--	--	--	--	--	S56	09-09-93	28	62.4	9.4
S56	03-31-94	15	68.2	5.5	--	--	--	--	--
--	--	--	--	--	S57	09-10-93	3.0	66.7	1.0
S57	03-31-94	1.1	66.0	.39	--	--	--	--	--
--	--	--	--	--	S59	09-09-93	.29	48.2	.075
--	--	--	--	--	S60	07-17-92	e25	56.6	7.6
--	--	--	--	--	S60	08-29-92	25	56.4	7.6
--	--	--	--	--	S60	09-29-92	40	59.4	12
S60	11-11-92	19	52.7	5.4	--	--	--	--	--
S60	03-16-93	36	45.0	8.7	--	--	--	--	--
S60	04-01-93	--	73.0	--	--	--	--	--	--
--	--	--	--	--	S60	04-28-93	20	56.8	6.1
--	--	--	--	--	S60	06-23-93	54	54	16
--	--	--	--	--	S60	09-09-93	35	57.9	10
S60	03-31-94	14	58.6	4.4	--	--	--	--	--
TOWNSEND VALLEY									
--	--	--	--	--	S61	10-01-92	1.1	35.4	.21
--	--	--	--	--	S62	09-22-92	e2	38.4	.41
--	--	--	--	--	S62	06-24-93	e6.0	12.5	.40
--	--	--	--	--	S64	09-22-92	e.56	3.3	.010
--	--	--	--	--	S64	10-01-92	.39	3.8	.0080

Table 5. Arsenic loads from selected surface-water sites along the Madison and upper Missouri Rivers, Montana, 1992-95--Continued

Non-irrigation season (October 15 through April 14)					Irrigation season (April 15 through October 14)				
Site number	Sample date	Discharge (ft^3/s)	Arsenic concentration (µg/L)	Arsenic load (lb/d)[1]	Site number	Sample date	Discharge (ft^3/s)	Arsenic concentration (µg/L)	Arsenic load (lb/d)[1]
TOWNSEND VALLEY--Continued									
S64	11-12-92	.33	4.0	.0071	--	--	--	--	--
S64	03-15-93	--	1.7	--	--	--	--	--	--
S64	04-01-93	e.1	1.5	.00081	--	--	--	--	--
--	--	--	--	--	S64	04-29-93	.27	1.6	.0023
--	--	--	--	--	S64	06-24-93	.39	2.2	.0046
--	--	--	--	--	S64	09-01-93	.58	1.7	.0053
--	--	--	--	--	S65	09-22-92	e1.8	5.8	.056
--	--	--	--	--	S65	10-01-92	.84	6.3	.028
S65	11-12-92	.86	3.4	.016	--	--	--	--	--
S65	03-15-93	1.5	2.2	.018	--	--	--	--	--
S65	04-01-93	e1.5	5.0	.040	--	--	--	--	--
--	--	--	--	--	S65	04-29-93	1.8	3.3	.032
--	--	--	--	--	S65	06-23-93	2.0	2.8	.030
--	--	--	--	--	S65	09-01-93	e1.5	2.1	.017
--	--	--	--	--	S66	07-06-93	--	6.4	--
--	--	--	--	--	S66	06-10-94	7.0	4.0	.15
--	--	--	--	--	S67	09-22-92	e6	11.7	.38
--	--	--	--	--	S67	10-01-92	8.4	10.5	.48
S67	11-12-92	8.0	6.7	.28	--	--	--	--	--
S67	03-15-93	11	3.5	.20	--	--	--	--	--
S67	04-01-93	--	5.5	--	--	--	--	--	--
--	--	--	--	--	S67	04-29-93	12	3.6	.23
--	--	--	--	--	S67	06-23-93	25	10.7	1.4
--	--	--	--	--	S67	09-01-93	18	7.4	.72
--	--	--	--	--	S68	09-22-92	e.5	10.0	.027
--	--	--	--	--	S68	10-01-92	2.9	8.4	.13
S68	11-12-92	1.4	6.7	.050	--	--	--	--	--
S68	03-15-93	e.1	7.0	.0038	--	--	--	--	--
S68	04-01-93	e.1	8.4	.0045	--	--	--	--	--
--	--	--	--	--	S68	04-29-93	.5	4.1	.011
--	--	--	--	--	S68	06-24-93	4.0	4.9	.10
--	--	--	--	--	S68	09-01-93	4.0	4.2	.091
--	--	--	--	--	S69	09-24-92	--	12.8	--
--	--	--	--	--	S70	09-23-92	e2.5	4.2	.057
S70	03-15-93	1.4	2.6	.020	--	--	--	--	--
S70	04-01-93	--	1.2	--	--	--	--	--	--
--	--	--	--	--	S70	04-29-93	1.0	1.3	.0070
--	--	--	--	--	S70	06-23-93	e1.5	2.2	.019
--	--	--	--	--	S70	09-01-93	e1.5	<1	.0040
--	--	--	--	--	S71	09-23-92	--	34.8	--
--	--	--	--	--	S72	09-24-92	--	3.5	--
--	--	--	--	--	S73	09-28-92	--	1.2	--

Table 5. Arsenic loads from selected surface-water sites along the Madison and upper Missouri Rivers, Montana, 1992-95--Continued

Non-irrigation season (October 15 through April 14)					Irrigation season (April 15 through October 14)				
Site number	Sample date	Discharge (ft³/s)	Arsenic concentration (µg/L)	Arsenic load (lb/d)[1]	Site number	Sample date	Discharge (ft³/s)	Arsenic concentration (µg/L)	Arsenic load (lb/d)[1]
				TOWNSEND VALLEY--Continued					
--	--	--	--	--	S74	09-28-92	--	2.4	--
--	--	--	--	--	S75	09-23-92	e1	4.8	.026
--	--	--	--	--	S75	10-01-92	2.4	2.2	.028
S75	11-12-92	e2.4	<1	.0064	--	--	--	--	--
S75	03-15-93	e2.0	.7	.0076	--	--	--	--	--
S75	04-01-93	--	<1	--	--	--	--	--	--
--	--	--	--	--	S75	04-29-93	e.2	<1	.0054
--	--	--	--	--	S75	06-23-93	e1.5	1.0	.0081
--	--	--	--	--	S75	09-01-93	e1.7	1.0	.0092
--	--	--	--	--	S76	09-23-92	e5.5	5.2	.15
--	--	--	--	--	S76	10-01-92	5.2	3.4	.095
S76	11-12-92	e5.9	7.9	.25	--	--	--	--	--
S76	04-01-93	--	1.0	--	--	--	--	--	--
--	--	--	--	--	S76	09-01-93	e4.0	2.7	.058
				HELENA VALLEY					
S77	03-23-95	39	7	1.4	--	--	--	--	--
--	--	--	--	--	S77	07-05-95	207	5	5.6
--	--	--	--	--	S78	05-10-93	49	27.3	7.2
--	--	--	--	--	S78	06-30-93	121	26.3	17.2
--	--	--	--	--	S78	08-27-93	135	21.3	15.5
S79	04-01-93	e2	5.4	.058	--	--	--	--	--
--	--	--	--	--	S79	05-10-93	.78	2.5	.010
--	--	--	--	--	S79	06-30-93	e.08	2.3	.00099
--	--	--	--	--	S79	08-27-93	e.08	2.0	.0086
--	--	--	--	--	S80	07-05-95	105	31	18
S81	04-01-93	e5	5.4	.14	--	--	--	--	--
--	--	--	--	--	S81	05-10-93	3.1	4.2	.070
--	--	--	--	--	S81	06-30-93	3.7	3.9	.078
--	--	--	--	--	S81	08-27-93	3.4	3.5	.064
--	--	--	--	--	S82	07-07-93	e.1	4.8	.0026
--	--	--	--	--	S82	08-26-93	e.25	3.1	.0042
S83	03-23-95	--	8.0	--	--	--	--	--	--
--	--	--	--	--	S83	07-05-95	142	8.0	6.1
S84	04-01-93	--	1.1	--	--	--	--	--	--
--	--	--	--	--	S84	05-10-93	24	21.5	2.8
--	--	--	--	--	S84	06-29-93	e20	13.7	1.4
--	--	--	--	--	S84	08-26-93	e52	14.4	4.0
S85	03-23-95	.31	2.0	.0033	--	--	--	--	--
--	--	--	--	--	S85	07-05-95	12	25	1.6
--	--	--	--	--	S86	08-27-93	e1.3	2.7	.018
--	--	--	--	--	S87	08-27-93	e1.3	1.7	.012

Table 5. Arsenic loads from selected surface-water sites along the Madison and upper Missouri Rivers, Montana, 1992-95--Continued

Non-irrigation season (October 15 through April 14)					Irrigation season (April 15 through October 14)				
Site number	Sample date	Discharge (ft^3/s)	Arsenic concentration (μg/L)	Arsenic load (lb/d)[1]	Site number	Sample date	Discharge (ft^3/s)	Arsenic concentration (μg/L)	Arsenic load (lb/d)[1]
HELENA VALLEY--Continued									
S88	04-01-93	e1.0	<1	.0027	--	--	--	--	
--	--	--	--	--	S88	05-05-93	1.3	<.8	.0028
--	--	--	--	--	S88	06-29-93	e2.2	2.1	.024
--	--	--	--	--	S88	08-27-93	e2.2	1.6	.019
S89	04-01-93	--	1.8	--	--	--	--	--	--
--	--	--	--	--	S89	05-10-93	30	16.0	2.56
--	--	--	--	--	S89	06-29-93	35	10.9	2.0
--	--	--	--	--	S89	08-26-93	e150	12.7	10
S90	04-01-93	e.45	4.2	.010	--	--	--	--	--
--	--	--	--	--	S90	05-05-93	e.20	3.7	.0040
--	--	--	--	--	S90	06-29-93	e1.2	3.4	.022
--	--	--	--	--	S90	07-07-93	e.4	5.3	.011
--	--	--	--	--	S90	08-26-93	e1.2	3.2	.020
S91	04-01-93	e.06	2.4	.0078	--	--	--	--	
--	--	--	--	--	S91	05-05-93	.37	2.6	.0052
--	--	--	--	--	S91	06-29-93	e.25	2.4	.0032
--	--	--	--	--	S91	07-07-93	e.6	3.7	.012
--	--	--	--	--	S91	08-26-93	e.25	2.0	.0027
S92	04-01-93	e.4	1.8	.0038	--	--	--	--	--
--	--	--	--	--	S92	05-05-93	.43	1.3	.0030
--	--	--	--	--	S92	06-29-93	.8	<1	.0022
--	--	--	--	--	S92	07-06-93	--	1.0	--
--	--	--	--	--	S92	08-26-93	.8	<1	.0022
S93	03-27-95	9.7	2.0	.10	--	--	--	--	--
--	--	--	--	--	S93	07-06-95	22	7.0	.83
S94	03-27-95	52	8.0	2.2	--	--	--	--	--
--	--	--	--	--	S94	07-06-95	153	12	9.9
S95	03-27-95	13	3	.21	--	--	--	--	--
--	--	--	--	--	S95	07-06-95	48	17	4.4
S96	03-27-95	6.3	2.0	.068	--	--	--	--	--
--	--	--	--	--	S96	07-06-95	24	15	1.9
S99	04-01-93	e.2	16.2	.014	--	--	--	--	--
--	--	--	--	--	S99	05-05-93	e.08	9.8	.0042
--	--	--	--	--	S99	06-29-93	e.03	5.8	.00094
--	--	--	--	--	S99	--	e.1	19.2	.010
--	--	--	--	--	S99	08-26-93	e.20	5.2	.0056
--	03-27-95	.07	17	.0064	--	--	--	--	--
--	--	--	--	--	S99	07-05-95	e.30	11	.018
--	--	--	--	--	S101	07-07-93	--	24.4	--
--	--	--	--	--	S101	08-26-93	24	20.7	2.6

[1] Loads for arsenic concentrations that are less than the minimum reporting level are calculated using one-half the minimum reporting level.

Table 6. Summary of chemical characteristics of surface and ground water, hydrologic setting of wells, and recharge information for aquifers of the upper Madison River Valley, Montana[1]

[See text for explanation of Group 1 through Group 3 ground water. Abbreviations: µg/L, micrograms per liter. Symbols: --, not applicable or no data; <, less than minimum reporting level]

Source of water-quality data	Surface- or ground-water site	Range of arsenic concentrations (µg/L as As)	Range or value of boron concentrations (µg/L as B)	Range or value of lithium concentrations (µg/L as Li)	Range of ratios or value of boron to lithium concentrations (dimensionless)	Hydrologic setting for wells	Source of recharge
Madison River	S8, S24	42-150	90-440	90-350	1.0-1.4	--	--
Irrigation supply (canals and ditches)	S4-5, S11, S19	31.9-88.5	--	--	--	--	--
Irrigation return flow, tailwater, ground water (canals, ditches, and drains[2])	S14-16, S23	<0.7-25.8	20-110	<6-66	1.7-6.7	--	--
Irrigation return flow (springs and seeps)	S10, S20-22	3.9-11.9	110	43	2.6	--	--
Group 1 ground water	UM3, UM6, UM13, UM30, UM35, UM57	2.1-40	60-220	60-140	0.46-1.9	Near the Madison River (UM30, UM57). Downgradient from irrigation (UM3, UM6, UM13, UM35)	Madison River or irrigation the primary source of recharge
Group 2 ground water	UM1, UM12, UM14, UM18, UM34, UM40, UM45, UM49, UM53	0.5-22	20-680	<6-230	3.3-20	Upgradient from irrigation (UM1, UM12, UM34, UM45). Downgradient from irrigation (UM18, UM40, UM49, UM53). Geothermal area (UM14)	Madison River or irrigation not the primary source of recharge; geothermal or deep source the primary source of recharge (UM14)
Group 3 ground water	UM5, UM7, UM16, UM23, UM26, UM29, UM37, UM42, UM47, UM51	<1-6.9	20-130	8-47	0.83-5.3	Near the Madison River (UM29). Downgradient from irrigation (UM5, UM7, UM16, UM23, UM26, UM37, UM42, UM47, UM51)	Primary source of recharge unclear

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[1] Concentration data from Tuck and others (1997).

[2] Water at some sites is a mixture from these sources.

Table 7. Arsenic concentrations in very shallow ground water along the Madison and upper Missouri Rivers, Montana, 1992-95

[Location number described in text. Abbreviations: BOR, Bureau of Reclamation; USGS, U.S. Geological Survey. Symbol: --, no data or not applicable]

General location[1], location number, or site number	Depth to water sampled[2] (in feet below land surface)	Arsenic[3,4] (µg/L as As)	BOR sample designation[5]	Source of data
UPPER MADISON RIVER VALLEY				
05S01W05	1.8	5.0	UM-70	BOR
05S01W33, 05S01W34	5.0	6.1	UM-132	BOR
	5.5	3.1	UM-131	BOR
--[6]	5.5	13.4	--	BOR
--[6]	1.8	5.0	UM-71	BOR
07S01W29	2.1	6.4	UM-13	BOR
--[6]	2.8	31.2	UM-155	BOR
LOWER MADISON RIVER VALLEY				
01N02E15	2.8	153	UM-60	BOR
01S02E21	6.2	84.0	UM-50	BOR
01S02E21	6.8	73.6	UM-53	BOR
--[6]	4.5	41.8	--	BOR
TOWNSEND VALLEY				
06N02E04	2.8	2.6	UM-104	BOR
	3.3	4.1	UM-105	BOR
	3.5	2.5	UM-106	BOR
	5.0	1.5	UM-108	BOR
06N02E04	4.0	2.2	UM-115	BOR
	4.0	4.7	UM-116	BOR
06N02E09	6.6	6.6	UM-102	BOR
	6.8	3.3	UM-103	BOR
	5.2	3.6	UM-107	BOR
05N02E05	7.3	198	UM-80	BOR
	7.3	78.9	UM-82	BOR
05N02E28	--	4.0	UM-126	BOR
HELENA VALLEY				
11N03W15	8.5	15.7	UM-146	BOR
	5.5	7.7	UM-149	BOR
	--	12.2	UM-151	BOR
11N03W21	3.3	23.7	UM-143	BOR
	3.5	13.9	UM-144	BOR
11N03W28DAAD01 (H14)[7]	6.5	16	--	USGS
11N03W33ADDB01 (H20)[7]	2.5	14	--	USGS
	4.4-8.3	[8]7.5	--	USGS
11N03W35	2.0	1.0	UM-139	BOR
	1.5	1.1	UM-140	BOR
11N02W06	--	9.2	UM-152	BOR

[1] General location from Mangelson and Brummer (1994).

[2] Depth to water rounded to 0.1 foot.

[3] Bureau of Reclamation samples were filtered with a 50 micrometer filter.

[4] Bureau of Reclamation values are unrounded as reported in Mangelson and Brummer (1994).

[5] Mangelson and Brummer (1994).

[6] General location from Mangelson and Brummer (1994) not given.

[7] Kendy and others (1998).

[8] Average value.

Table 8. Summary of chemical characteristics of surface and ground water, hydrologic setting of wells, and recharge information for aquifers of the lower Madison River Valley, Montana[1]

[See text for explanation of Area 1 through 3 ground water. Abbreviations: µg/L, micrograms per liter. Symbols: --, not applicable or no data; <, less than minimum reporting level]

Source of water-quality data	Surface- or ground-water site	Range of arsenic concentrations (µg/L as As)	Range or value of boron concentrations (µg/L as B)	Range or value of lithium concentrations (µg/L as Li)	Range of ratios of boron to lithium concentrations (dimensionless)	Hydrologic setting for wells	Source of recharge
Madison River	S26, S58	41-100	90-320	80-270	1.0-1.5	--	--
Irrigation supply (canals and ditches)	S29-30, S32-34, S36, S44-45,	27.0-98.7	140-200	70-110	1.0-1.4	--	--
Irrigation return flow, tailwater, ground water (canals, ditches, drains, and Rey and Spring Creeks[2])	S37-43 S46-48, S52-57, S59-60	42.2-113	150-680	130-240	0.94-2.8	--	--
Irrigation return flow (drains only)	S49-51	96.5-321	750-1,400	270-560	2.5-2.8	--	--
Area 1 ground water	LM68, LM70-71, LM81, LM87-88, LM91-93, LM95, LM98-106	25-124	140-410	100-300	1.0-1.7	Most wells downgradient from where the Madison River loses water to basin-fill deposits	Madison River the primary source of recharge
Area 2 ground water	LM63-66, LM72-80, LM83-84, LM86, LM89-90	38-138	340-950	100-210	1.6-5.6	Most wells downgradient from irrigation	Irrigation the primary source of recharge
Area 3 ground water	LM21, LM27-36, LM40-50, LM52-53, LM57-58, LM60, LM62	16-176	40-700	170-310	0.22-3.5	Downgradient from irrigation and ground-water flow from Areas 1 and 2	Upgradient ground-water flow from Areas 1 and 2 the primary source of recharge

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[1] Modified from Nimick (1998). Concentration data from Tuck and others (1997).

[2] Water at some sites is a mixture from these sources.

Table 9. Summary of chemical characteristics of surface and ground water, hydrologic setting of wells, and recharge information for aquifers of the Townsend Valley, Montana[1]

[See text for explanation of Group 1 through Group 3 ground water. Abbreviations: µg/L, micrograms per liter. Symbols: --, not applicable or no data; <, less than minimum reporting level]

Source of water	Surface- or ground-water site	Range of arsenic concentrations (µg/L as As)	Range or value of boron concentrations (µg/L as B)	Range or value of lithium concentrations (µg/L as Li)	Range of ratios or value of boron to lithium concentrations (dimensionless)	Hydrologic setting for wells	Source of recharge
Missouri River	S63	12-67	50-160	30-110	1.1-2.4	--	--
Irrigation supply (canals and ditches)	S62, S66, S71	4.0-38.4	100	50	2.0	--	--
Natural streamflow, irrigation return flow, tailwater, ground water (canals, ditches, and drains[2])	S61, S64, S67	1.5-35.4	130-200	23-46	4.3-5.6	--	--
Irrigation return flow (drains, seeps, and Warm Springs Creek)	S65, S68-69, S70, S72-76	<1-12.8	66-230	19-55	2.7-4.7	--	--
Group 1 ground water	T5, T27, T33, T36, T42	2.4-18	80-200	44-89	1.5-2.5	Near the Missouri River (T27, T36, T42). Downgradient from irrigation (T5, T33)	Missouri River or irrigation the primary source of recharge
Group 2 ground water	T4, T22, T28-29, T50-51, T54, T57	<1-1.3	<20-380	<6-70	1.5-30	Upgradient from irrigation (T28-29, T50-51, T54, T57). Downgradient from irrigation (T4, T22)	Missouri River or irrigation not the primary source of recharge
Group 3 ground water	T3, T7, T13, T15, T20, T23-24, T35, T39, T47-48, T52, T58	0.9-3.3	70-310	13-40	3.3-12	All wells downgradient from irrigation	Primary source of recharge unclear

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[1] Concentration data from Tuck and others (1997).

[2] Depending on the site, water at some sites is a mixture from these sources.

Table 10. Summary of chemical characteristics of surface and ground water, hydrologic setting of wells, and recharge information for aquifers of the Helena Valley, Montana[1]

[Missouri River at Toston (S63) is located in the Townsend Valley. See text for explanation of Group 1 through Group 3 ground water. Abbreviations: ft, feet, µg/L, micrograms per liter. Symbols: --, not applicable or no data; <, less than minimum reporting level]

Source of water-quality data	Surface- or ground-water site	Range or value of arsenic concentrations (µg/L as As)	Range or value of boron concentrations (µg/L as B)	Range or value of lithium concentrations (µg/L as Li)	Range of ratios or value of boron to lithium concentrations (dimensionless)	Hydrologic setting for wells	Source of recharge
Missouri River	S63	12-67	50-160	30-110	1.1-2.4	--	--
Irrigation supply (canals only)	S78, S80, S101	20.7-31	113	91	1.2	--	--
Irrigation return flow, tailwater, ground water (sites that function as canals or drains[2])	S84-85, S89, S93, S95-96	1.1-21.5	90-110	59-68	1.5	--	--
Irrigation return flow (drains only)	S79, S81-82, S86-88, S90-92, S99	<0.8-19.2	42-150	18-35	2.3-4.9	--	--
Group 1 ground water	H14, H20, H50	2.0-16	110	54	2.0	All wells downgradient from irrigation. Wells H14 and H20 are shallow (less than 10 ft)	Irrigation the primary source of recharge
Group 2 ground water	H12	3.6	80-90	20-29	2.8-4.5	Well is downgradient from irrigation	Irrigation partly a source of recharge
Group 3 ground water	H1-4, H7-9, H13, H15, H18, H21-25, H28, H30, H32-33, H35-40, H42-43, H45-49, H52	0.9-22	<20-90	8-30	0.67-6.2	Most wells downgradient from or near irrigation. Upgradient from irrigation (H46)	Primary source of recharge unclear; recharge to most of the valley-fill aquifer can be a mixture of regional ground water, irrigation, and surface water (Briar and Madison (1992)

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[1] Concentration data from Tuck and others (1997).

[2] Water at some sites is a mixture from these sources.

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