In cooperation with the
GALLATIN LOCAL WATER QUALITY DISTRICT

Magnitude, Extent, and Potential Sources of Nitrate in Ground Water in the Gallatin Local Water Quality District, Southwestern Montana, 1997-98

Water-Resources Investigations Report 01-4037

U.S. Department of the Interior
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By Eloise Kendy

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U.S. Department of the Interior

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March 2001

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Multiply	By	To obtain
acre	0.4047	hectare
cubic foot per second (ft^3/s)	0.028317	cubic meter per second
foot (ft)	0.3048	meter
foot per foot (ft/ft)	1.0	meter per meter
foot per mile (ft/mi)	0.1894	meter per kilometer
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter
inch (in.)	25,400	micrometer (µm)
mile (mi)	1.609	kilometer
ounce	28.35	gram (g)
pound (lb)	453.6	gram
pound per acre (lb/acre)	1.121	kilograms per hectare
square mile (mi^2)	2.59	square kilometer

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

$$^{o}C = 5/9\ (^{o}F - 32)$$

$$^{o}F = 9/5\ (^{o}C) + 32$$

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

Chemical concentration in water is reported in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the solute mass (milligram) per unit volume (liter) of water and is about the same as parts per million unless concentrations are more than 7,000 milligrams per liter (Hem, 1985, p. 55). One thousand micrograms per liter is equivalent to 1 milligram per liter. Specific conductance of water is a measure of the ability of water and dissolved constituents to conduct an electrical current and is an indication of the ionic strength of the solution. Specific conductance is expressed in microsiemens per centimeter at 25°C (µS/cm) and increases with the concentration of dissolved constituents.

Abbreviated water-quality units used in this report:

µS/cm	microsiemens per centimeter at 25 degrees Celsius
mg/L	milligrams per liter
mL	milliliter
mm	millimeter
µm	micrometer
‰	permil (or parts per thousand)
pg/kg	picogram per kilogram

Abbreviated hydrogeologic units used in this report:

Cenozoic basin-fill deposits:

Qal	Quaternary alluvium
QTd	Quaternary and Tertiary deposits, undifferentiated
Tb	Tertiary Bozeman Group

Bedrock

Tv	Volcanic rocks (Eocene)
TYsaq	Sedimentary bedrock--potential aquifers (Paleocene through Middle Proterozoic)
KЄscu	Sedimentary bedrock--typically confining units (Cretaceous through Cambrian)
Am	Metamorphic rocks (Archean)

Acronyms used in this report:

CFCs	chlorofluorocarbons
CFC-11	trichlorofluoromethane
CFC-12	dichlorodifluoromethane
CFC-113	trichlorotrifluoroethane
GIRAS	Geographic Information Retrieval and Analysis System
GIS	Geographic Information System
GLWQD	Gallatin Local Water Quality District
MCL	Maximum Contaminant Level
NWQL	National Water Quality Laboratory, Denver, Colo.
SLAP	Standard Light Antarctic Precipitation
SMCL	Secondary Maximum Contaminant Level
TIGER	Topologically Integrated Geographic Encoding and Referencing
USGS	U.S. Geological Survey
VSMOW	Vienna Standard Mean Ocean Water

Magnitude, Extent, and Potential Sources of Nitrate in Ground Water in the Gallatin Local Water Quality District, Southwestern Montana, 1997-98

By Eloise Kendy

Abstract

The population of Gallatin County, Montana, has increased rapidly in recent years, and much of the associated new development has been concentrated in the northern part of the county. In response to increasing public concerns about the sustainability of the local water resources, the Gallatin Local Water Quality District (GLWQD) was established in 1995 to preserve, protect, and improve the quality of surface and ground water in the District. This report, prepared in cooperation with the GLWQD, describes the magnitude, extent, and potential sources of nitrate in ground water in the GLWQD.

The GLWQD encompasses most of the Gallatin Valley, which is an approximately north-south-trending intermontane basin about 520 square miles in area, consisting of a broad alluvial plain flanked on the west by the Madison Plateau and on the east and south by smaller benches. Mountainous areas compose almost one-half of the GLWQD. Land use in the GLWQD is predominantly agricultural.

Water-level, oxygen-isotope, and chlorofluorocarbon (CFC) data indicate that Cenozoic basin-fill aquifers beneath the irrigated and subirrigated parts of the GLWQD are recharged primarily by the Gallatin River and its irrigation diversions. Recharge to basin-fill deposits beneath the benches originates more locally as low-altitude snowmelt, seepage from ephemeral streams, and summer rainfall. On the basis of CFC data, estimated recharge dates for 27 ground-water samples collected in 1998 from the Gallatin Valley range from the 1960s to the 1990s.

Nitrate concentrations generally were low in ground water of the GLWQD and in 1998 ranged from <0.05 to 13 milligrams per liter (mg/L). Nitrate concentrations (10 and 13 mg/L) equaled or exceeded the U.S. Environmental Protection Agency drinking-water standard of 10 mg/L in water from 2 of the 96 sites sampled. Median nitrate concentrations in water from basin-fill deposits where many residents obtain their water were less than about 3 mg/L. Median nitrate concentrations in water from wells located within all land-use categories were less than 3 mg/L. Seasonal variations in nitrate concentrations were determined in water from some wells.

Potential sources of nitrate to ground water include runoff or infiltration from areas of timber harvests, atmospheric deposition, livestock waste, fertilizer, soil organic nitrogen, and domestic septic-system effluent. However, fertilizers and soil organic nitrogen probably contribute most of the nitrate to ground water in the GLWQD. Irrigation can facilitate the movement of nitrogen from fertilizers through permeable soils and into underlying aquifers, although nitrate concentrations in ground water in the GLWQD are not as high as in similar agricultural areas of the United States, where nitrate concentrations frequently exceed 10 mg/L. Some higher nitrate concentrations in water beneath the eastern benches probably are related more to the quantity of ground-water recharge than to the source of the nitrate. With limited recharge and flow, nitrate in water beneath the benches is not diluted to the same extent as the irrigated and subirrigated areas. On the basis of water-quality data from three subdivisions, domestic septic-system effluent does not appear at present to be a major source of nitrate to ground water in the GLWQD.

INTRODUCTION

The population of Gallatin County has increased from about 21,900 in 1950 to 60,170 in 1996 (Montana Department of Commerce, 2000). Much of the associated new residential and commercial development has been concentrated in the northern part of the county. This development has resulted in concerns regarding the sustainability of local water resources. Of particular concern are the potential effects of development on the quality of water in the underlying aquifers because much of the population increase has been outside of established cities and towns, in housing areas where each dwelling or commercial development has its own well and septic system. Septic systems and application of pesticides and fertilizers to lawns and gardens could increase the potential for ground-water contamination. The occurrence of higher nitrate concentrations in ground water beneath more densely developed areas can indicate a probable influence of increased development on ground-water quality (Slagle, 1995a).

Nutrients, including nitrate, are associated with certain land uses. Nationally, nitrate concentrations in natural waters typically are less than 2 mg/L (Mueller and others, 1995), although background concentrations vary locally. Nitrate concentrations that exceed background levels commonly are due to human activities such as sewage disposal and fertilizer application, and the occurrence of elevated nitrate concentrations might indicate a potential for the presence of pesticides, pathogenic bacteria, and viruses. The U.S. Environmental Protection Agency (1991) has established a Maximum Contaminant Level (MCL) of 10 mg/L for nitrate (as nitrogen) for public drinking-water supplies in the United States. Infants can be seriously and occasionally fatally poisoned by ingestion of water containing more than 10 mg/L of nitrate, which inhibits the ability of hemoglobin to release oxygen to cells, resulting in cell asphyxiation, or methemoglobinemia ("blue baby syndrome").

In response to increasing public concerns about the sustainability of the local water resources, the Gallatin Local Water Quality District (GLWQD) was established in 1995 to preserve, protect, and improve the quality of surface and ground water in an 816 mi^2 area of the District (fig. 1). In 1997, the U.S. Geological Survey (USGS) began a study, in cooperation with the GLWQD, to provide the GLWQD with hydrogeologic information needed to make sound decisions regarding the local water resources. A primary objective of the study was to determine the magnitude, extent, and sources of nitrate in ground water in the GLWQD.

Purpose and Scope

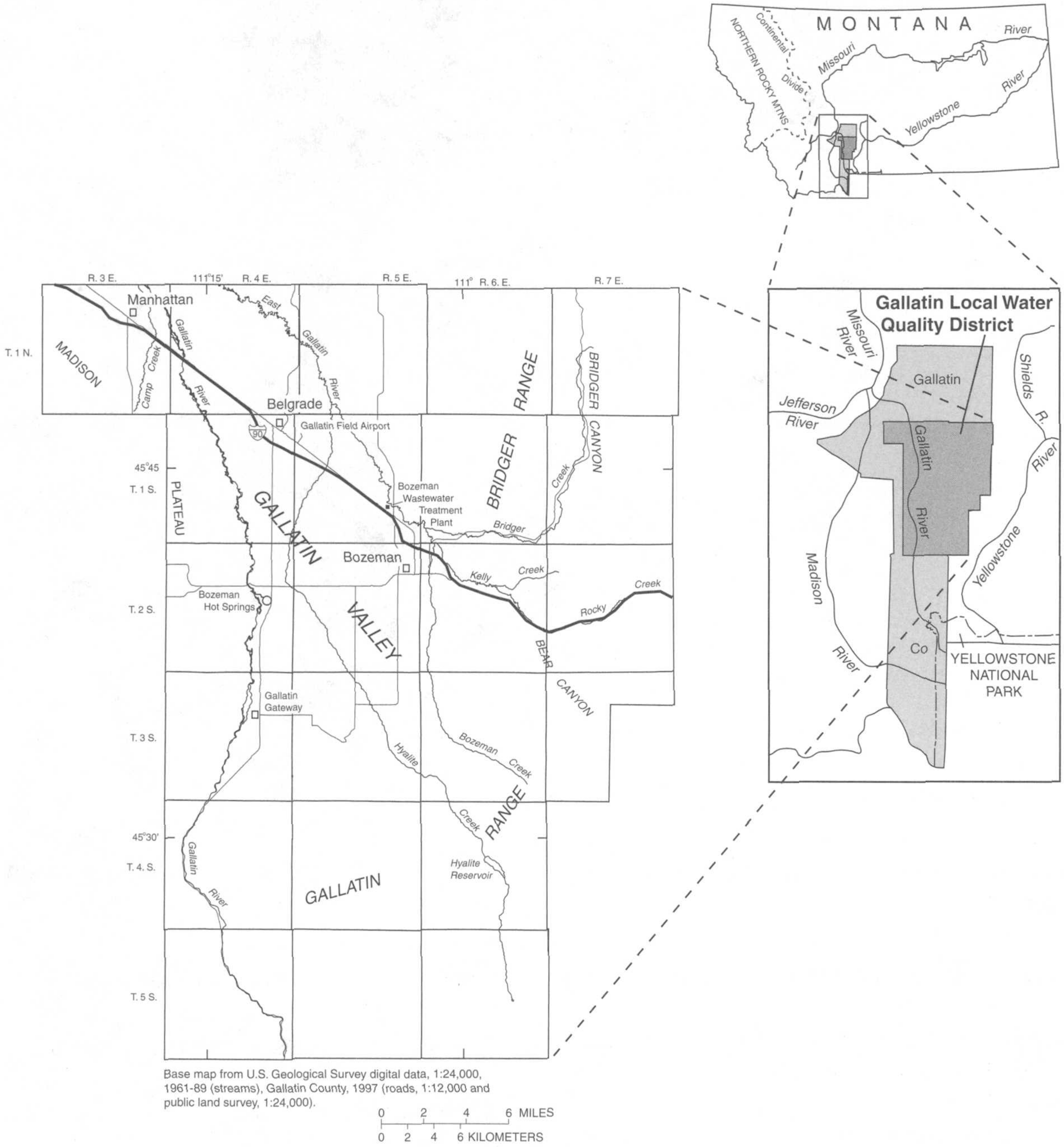
This report describes the magnitude, extent, and potential sources of nitrate in ground water in the GLWQD. The magnitude and extent of nitrate in ground water were determined by sampling 96 sites, including one hot spring, and the Gallatin River in 1998. Potential sources of nitrate were determined by analyzing the spatial patterns of various water-quality constituents (major ions, nutrients, and stable isotopes), comparing land uses to ground-water quality, and age-dating ground water using chlorofluorocarbons (CFCs). Interpretations presented herein are based on previously published data; well-inventory, water-level, and water-quality data collected from July 1997 through November 1998; and unpublished data obtained from the GLWQD in 1997-98.

Site-Numbering System

Sites are assigned location numbers according to geographic position within the rectangular grid system used for the subdivision of public lands (fig. 2). The location consists of as many as 14 characters. The first three characters specify the township and its position north (N) or south (S) of the Montana Base Line. The next three characters specify the range and its position east (E) of the Montana Principal Meridian. The next two characters are the section number. The next three to four characters designate the quarter section (160-acre tract), quarter-quarter section (40-acre tract) quarter-quarter-quarter section (10-acre tract), and quarter-quarter-quarter-quarter section (2 1/2-acre tract), respectively, in which the site is located. These four subdivisions of a section are designated A, B, C, and D in a counter-clockwise direction, beginning in the northeast quadrant. The last two characters are a sequence number assigned to distinguish multiple wells in a single 2 1/2-acre tract. For example, well 01S04E04ACDC01 (fig. 2) is the first well inventoried in the SW1/4SE1/4SW1/4NE1/4 of sec. 4, T. 1 S., R. 4 E.

Acknowledgments

The author acknowledges with appreciation David N. Whitson, Kerri Fleming, and Cynthia Crayton of the Gallatin Local Water Quality District for technical guidance, water-level measurement, and assistance with sample collection. Stewart A. Dixon and Stephan G. Custer of Montana State University are gratefully acknowledged for their hydrogeologic map compilation. Appreciation also is extended to Johnkarl F. Bohlke of the U.S. Geological Survey for suggesting the use of oxygen isotopes to distinguish sources of ground-water recharge and to Lee M. Shanklin of the U.S. Environmental Protection Agency for explaining Geographic Information System (GIS) applications. Finally, many thanks to the citizens of the Gallatin Local Water Quality District who generously allowed access to their wells for water-level measurement and sample collection.



Base map from U.S. Geological Survey digital data, 1:24,000, 1961-89 (streams), Gallatin County, 1997 (roads, 1:12,000 and public land survey, 1:24,000).

Figure 1. Location of the Gallatin Local Water Quality District, Montana.

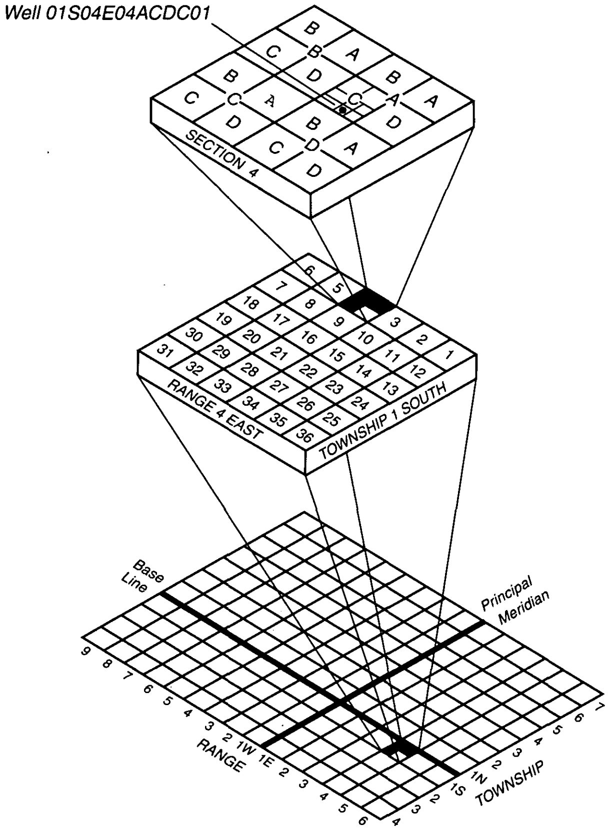


Figure 2. Site-numbering system.

METHODS OF DATA COLLECTION AND ANALYSIS

Well Inventory and Water-Level Measurement

In June 1997 through July 1998, private wells throughout the study area were inventoried or revisited to augment the existing database of wells (table 1--all tables are at the back of this report) that were inventoried for previous studies (Hackett and others, 1960; Slagle, 1995a,b). Well-construction information (Lapham and others, 1997) and information about land use were obtained during the inventory because of the potential effect of these aspects on nitrate in ground water.

In 1997, a long-term water-level monitoring network of 101 wells was established. Many of the wells in the network had been previously monitored; other wells were included to expand the network spatially to represent most of the aquifers in the GLWQD. Water levels generally were measured eight times a year by GLWQD staff. Table 2 summarizes water-level data for wells in the network.

Water-Quality Sampling and Analysis

Ground-water samples were collected from 96 sites using the existing submersible pumps. Thirty-eight of the sites were sampled only once for field parameters and nitrate during the well inventory (table 1). Nitrate concentrations were determined either using an onsite spectrophotometer or by chemical analysis by the USGS National Water Quality Laboratory, Denver, Colo., using methods described by Fishman (1993). Fifty-eight sites, including Bozeman Hot Springs, were resampled for additional constituents (table 3) (fig. 1). All wells were pumped until at least three well volumes of water were removed and field parameters (specific conductance, pH, water temperature, and dissolved oxygen) had stabilized. Specific conductance, dissolved oxygen, and alkalinity were measured onsite according to standard methods described by Knapton (1985). Water samples were collected from a flow-through chamber using a peristaltic pump. Bottles and equipment were prepared in the laboratory, and samples were processed, filtered, and preserved in the field as described by Knapton (1985) and Horowitz and others (1994). An individual, disposable 0.45-µm capsule filter was used for each site. Water sampled for stable isotopes of oxygen, hydrogen, and nitrogen was not filtered.

Most ground-water samples were collected from domestic wells that were completed well below the water table to obtain drinking water. However, most potential sources of nitrate originate at or near the land surface and effects of various land uses on ground-water quality presumably would be more pronounced near the water table than at the depths from which domestic supplies generally are obtained. Thus, the ground-water quality data presented in this report represent water that is being used by residents, rather than shallower water that might be more affected by land use. Over time, effects near the water table could migrate deeper into the aquifer if inputs to the ground-water system continued or increased.

Two surface-water samples were collected from the Gallatin River (table 3) from a bridge by depth and width integration at multiple stream verticals according to methods described by Knapton (1985) and Horowitz and others (1994). These samples were collected in a glass bottle using a D-74 sampler with a 0.25-in. nylon nozzle, and composited in a polyethylene churn splitter. A sample also was collected from unchlorinated effluent from the Bozeman Wastewater Treatment Plant (fig. 1, table 3). Field processing, including sample filtration and preservation, was performed in the same manner for surface-water samples as for ground-water samples.

Data-collection and analytical procedures used in this study incorporated practices designed to assure, control, verify, and assess the quality of sample data. Analyses for major ions and nutrients were performed by the USGS National Water Quality Laboratory (NWQL), Denver, Colo., using methods described by Fishman and Friedman (1989) and Fishman (1993). Methods and associated quality control for collection and processing of water samples are described by Knapton (1985), Knapton and Nimick (1991), and Horowitz and others (1994). Quality-assurance and quality-control procedures used by the NWQL are described by Pirkey and Glodt (1998), Friedman and Erdmann (1982), and Jones (1987). All sample bottles, standard solutions, and preservatives for water samples analyzed by the NWQL were provided by the NWQL and were systematically tested by internal quality control for conformance with criteria described in Bench-Level Protocols on file in the Quality Control Office of the laboratory.

Quality-control data to document sample contamination and reproducibility of analytical results were provided by test samples that consisted of either a field-blank sample of deionized water or a replicate environmental sample. Quality-control samples comprised 11 percent of the total number of samples submitted for analysis. A field-blank sample is a volume of deionized water that is treated as an environmental sample in all aspects, including contact with sampling equipment, sample containers, filtration apparatus, and chemical preservatives in the field, and to holding times and laboratory processing. Five field-blank samples were collected and concentrations of nitrate (nitrite plus nitrate, dissolved) were determined to be less than the minimum reporting level of 0.05 mg/L in all five. Results of chemical analyses of field blanks are presented at the end of table 3. A replicate environmental sample is a volume of sampled water split into subsamples in such a manner that the physical and chemical characteristics of each subsample are considered to be essentially identical in composition. To assess the degree to which sample collection and laboratory analytical methods affected nitrate concentration data, 10 replicate samples were collected and submitted for laboratory analysis. The differences in the concentration of nitrate between the replicates ranged from 0.0 mg/L to 0.1 mg/L. Results of chemical analyses of replicate samples are presented in tables 1 and 3.

Stable Isotopes of Water

Ratios of the stable isotopes of oxygen (oxygen-18/oxygen-16, or $^{18}O/^{16}O$) and hydrogen (deuterium/hydrogen, or D/H) can be used as natural tracers of ground-water recharge if the different recharge sources are isotopically distinct. Isotopically distinct recharge sources are common in mountainous areas, where recharge originates as precipitation over a large range of altitudes (Clark and Fritz, 1997). Precipitation becomes progressively depleted in ^{18}O and D (the ratios become more negative) as an air mass is transported to lower temperature and higher altitude on the windward side of a mountain (Coplen, 1993). Therefore, ratios of $^{18}O/^{16}O$ and D/H in ground water can reflect the values in the local precipitation that recharged the aquifer. Alternatively, ground water or surface water originating at high altitude may transport ^{18}O-depleted water to aquifers at lower altitudes (Deak and others, 1995). Thus, spatial variations in isotopic content of ground water can be used to distinguish local from regional sources of recharge to aquifers in the Gallatin Valley.

$^{18}O/^{16}O$ and D/H were analyzed by the USGS at laboratories in Reston, Va. Oxygen-isotope ratios were determined using the carbon-dioxide equilibration technique at 25°C (Epstein and Mayeda, 1953). Hydrogen-isotope ratios were determined by equilibration with hydrogen gas at 30°C (Coplen and others, 1991).

Isotopic data are reported as ratios, which are more precisely determined than abundances, and are expressed as delta (δ) values in units of parts per thousand, or permil (‰), relative to a standard. This ratio is calculated as follows:

$$\delta\chi\ (‰) = \left(\frac{R_\chi}{R_{\mathrm{standard}}} - 1\right) \times 1000 \qquad (1)$$

where R_χ and R_{standard} are the atomic ratios of the sample and standard, respectively. For example, a sample with a $\delta^{18}O$ value of -10‰ is depleted in ^{18}O by 1 percent, or 10‰, relative to the standard.

The standard for $\delta^{18}O$ and δD is Vienna Standard Mean Ocean Water (VSMOW). Oxygen and hydrogen isotopic results are normalized (Gonfiantini, 1984; Hut, 1987; Coplen, 1988, 1994) on scales such that the oxygen and hydrogen isotopic values of SLAP (Standard Light Antarctic Precipitation) are -55.5‰ and -428‰, respectively.

Nitrogen Isotopes of Nitrate

Ratios of the stable isotopes of nitrogen ($^{15}N/^{14}N$) in nitrate can, in many circumstances, be used to determine the source of nitrate in ground water or pore water (for example, Kreitler, 1975; Gormly and Spalding, 1979; Flipse and Bonner, 1985; Böttcher and others, 1990; and Wassenaar, 1995, among many others). Comparison of $\delta^{15}N_{NO3}$ ($\delta^{15}N$ of the nitrogen in nitrate) values in nitrate sources to $\delta^{15}N_{NO3}$ values in ground water can be made only if the isotopic composition of the nitrate has remained unchanged along the ground-water flow path. Denitrification (the conversion of reduced or organic nitrogen into gaseous nitrogen) is the most likely process that might change $\delta^{15}N_{NO3}$ values. If denitrification occurs, then $\delta^{15}N_{NO3}$ values in the residual nitrate increase (Böttcher and others, 1990; Nimick and Thamke, 1998). Typically, denitrification is not significant in shallow, transmissive aquifers with oxic water (Gillham and Cherry, 1978; Gormly and Spalding, 1979; Starr and Gillham, 1993), like most aquifers in the Gallatin Valley.

Interpretation of nitrate sources requires caution because the ranges of isotope ratios from different sources may overlap. $\delta^{15}N_{NO3}$ values for precipitation range from about -7 to +2.5‰ and are typically lower than values for other sources (Hubner, 1986; LeTolle, 1980; Heaton, 1986). $\delta^{15}N_{NO3}$ values for inorganic fertilizers depend on the form of nitrogen in the fertilizer (Shearer and others, 1974; Spalding and others, 1982; Heaton, 1986; Hubner, 1986). Urea and ammonium-based fertilizers have values that typically range from -4 to +2‰; nitrate fertilizers have slightly higher values, typically ranging from 0 to +6‰ (Spalding and others, 1982). Nitrate derived from ammonium fertilizer may retain the original $\delta^{15}N_{NO3}$ value if little or no volatilization of ammonia occurs. Alkaline conditions promote volatilization and can result in $\delta^{15}N_{NO3}$ enrichment of 2 to 5‰ (Fenn and Kissel, 1973; Feigin and others, 1974; Kreitler, 1975). $\delta^{15}N_{NO3}$ values for nitrate derived from mineralization or oxidation of organic nitrogen in soil typically are between +4 and +9‰ (Boyce and others, 1976; Gormly and Spalding, 1979; Wolterink and others, 1979; Heaton, 1986), and the range in a given area typically is small, often within ±1‰, when derived from soil of uniform type (Heaton, 1986). Nitrate derived from livestock waste and domestic septic-system effluent generally has $\delta^{15}N_{NO3}$ values between +9 and +22‰ (Kreitler, 1975; Gormly and Spalding, 1979; Heaton, 1986).

$^{15}N/^{14}N$ in nitrate was analyzed by Global Geochemistry, Canoga Park, Calif., by distillation with NaOH and Dvarda's alloy to reduce the nitrate to ammonium, then NaOBr oxidation to convert ammonium to nitrogen gas. The nitrogen was then purified in a Cu-CuO furnace at 700°C (Miyake and Wada, 1967) and analyzed by mass spectrometry.

The isotopic ratio of nitrogen is calculated using equation 1. The standard for $\delta^{15}N$ is atmospheric nitrogen.

Chlorofluorocarbons

Nitrate concentrations in shallow ground water commonly can be associated with land use. Because land uses change in response to economics and other factors, understanding the relation between specific land uses and ground-water recharge dates can provide useful information for analyzing current water-quality conditions. The recent development of a technique using chlorofluorocarbons (CFCs, or Freons) to estimate the recharge date of ground water less than about 50 years old (Plummer and others, 1993) allows comparison of recharge dates, land use, and nitrate concentrations for water from shallow aquifers (Bohlke and Denver, 1995).

The stability of CFCs in water has led to their effective use as conservative tracers to estimate the date that ground water was recharged during the past 50 years (Plummer and others, 1993). CFCs are synthetic compounds whose atmospheric concentrations have steadily increased since they were first manufactured in the 1930s and are stable in aerobic conditions, but subject to degradation processes in anaerobic conditions. Detectable concentrations are present in post-1950 ground water or mixtures of older ground water and post-1950 water. CFC concentrations in recharge water depend on the atmospheric concentration of CFCs and the temperature at the bottom of the unsaturated zone during recharge. Recharge temperature can be estimated from mean annual air temperature and concentrations of argon and nitrogen gas dissolved in ground water. The estimated age of ground water is the difference between the time when the water became isolated from the unsaturated zone (and recharged the aquifer) and the time when the water sample was collected.

Ground-water ages were estimated for 27 samples collected in May-June 1998. Samples were collected for CFC analysis using equipment and methods described in Busenberg and Plummer (1992). A copper-tube discharge line was connected directly to a spigot as close to the well as possible to ensure samples were not contaminated with atmospheric CFCs. Five glass ampules were filled and sealed at each site. While the samples were being collected, field parameters were monitored in a flow-through chamber.

Concentrations of CFCs and associated dissolved gases used to estimate ground-water recharge dates were analyzed by the USGS CFC Laboratory, Reston, Va. The analytical methods are described in Busenberg and Plummer (1992). CFC concentrations are reported in table 4.

DESCRIPTION OF THE STUDY AREA

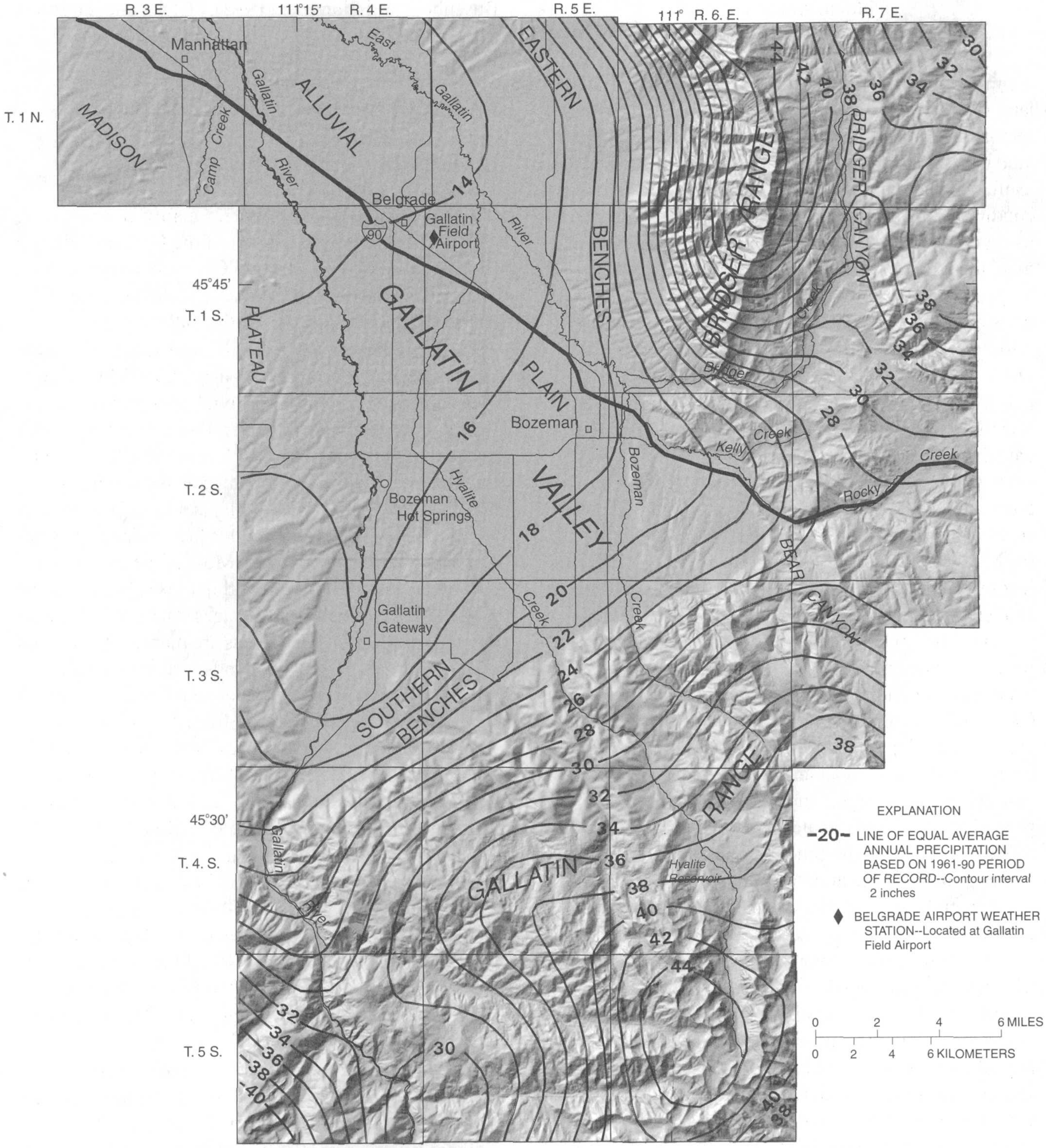
Physiography, Drainage, and Climate

The Gallatin Local Water Quality District (GLWQD) encompasses most of the Gallatin Valley (fig. 1). In addition, the GLWQD includes undeveloped mountains that are probable recharge zones for aquifers near and in the Gallatin Valley.

The Gallatin Valley is an approximately north-south-trending intermontane basin about 520 mi^2 in area consisting of a broad alluvial plain flanked on the west by the Madison Plateau and on the east and south by smaller benches (fig. 3). West of the alluvial plain, the Madison Plateau (also known as the Madison Bluffs or the Camp Creek Hills) is a broad bench with an altitude of more than 5,000 ft that drains northeastward into the Gallatin River. Most of the eastern edge of the Madison Plateau lies within the GLWQD. Some of the smaller benches, or terraces, that flank the eastern and southern basin margins are mantled by alluvial fans, the largest of which extends well into the alluvial plain between Hyalite and Bozeman Creeks. The Gallatin Valley ranges in altitude from about 4,100 ft where the Gallatin River leaves the basin, to about 6,300 ft at the southeastern mountain front. In the rest of this report, "Gallatin Valley" refers to that part of the intermontane basin that is located within the GLWQD.

Mountainous areas compose almost one-half of the GLWQD. East and south of the Gallatin Valley, the sparsely populated Bridger and Gallatin Ranges rise from the valley floor. The crest of the Gallatin Range, with an altitude of more than 10,000 ft, is the highest part of the GLWQD. East of the Bridger Range, Bridger Creek drains the mountainous Bridger Canyon area.

The Gallatin River and its tributaries drain the GLWQD, except for about 20 mi^2 in the northeastern part, which drain to the Shields River (fig. 1). The Gallatin River originates in Yellowstone National Park and flows northward about 80 mi through a bedrock canyon before entering the Gallatin Valley near Gallatin Gateway. From there, the river flows northward to the northern valley margin, then westward out of the valley. After leaving the Gallatin Valley, the Gallatin River joins the Madison and Jefferson Rivers to form



Base map from U.S. Geological Survey digital data, 1:24,000, 1961-89 (streams), Gallatin County, 1997 (roads, 1:12,000 and public land survey, 1:24,000). Hillshade base from U.S. Geological *Survey digital data, 1:24,000, 1979. Universal* Transverse Mercator Projection Standard, zone 12.

Figure 3. Topographic features and average annual precipitation in the Gallatin Local Water Quality District, Montana. Digital precipitation data *compiled by the Oregon Climate Service (George Taylor, unpub. data, 1995).*

the Missouri River. The East Gallatin River, which is the principal tributary to the Gallatin River, meanders northwesterly near the northern edge of the Gallatin Valley and joins the mainstem about two miles north of Manhattan. Mean annual flow of the Gallatin River near Gallatin Gateway (USGS streamflow-gaging station 06043500, drainage area 825 mi^2) is 818 ft^3/s for water years 1894-1997 (during periods of operation; U.S. Geological Survey, 1998). About 1 mi downstream from the GLWQD, mean annual flow of the Gallatin River at Logan (USGS station 06052500; drainage area 1,795 mi^2) is 1,077 ft^3/s for water years 1893-1997 (during periods of operation; U.S. Geological Survey, 1998). Inflow from tributaries and discharge from ground water contribute to the downstream increase in flow.

The climate of the Gallatin Valley is typical of mid-altitude intermontane basins of the Northern Rocky Mountains east of the Continental Divide, with cold winters and mild summers. On the basis of the 1961-90 period of record, the average annual temperature is 41.9 °F at the Belgrade Airport Weather Station located at Gallatin Field Airport (altitude 4,450 ft) and 44.2 °F at Bozeman (altitude 4,860 ft) (National Oceanic and Atmospheric Administration, 1992). The average last occurrence of frost (32 °F) is June 3 in Belgrade and May 27 in Bozeman, and the average first occurrence is September 13 in Belgrade and September 18 in Bozeman (Natural Resources Conservation Service, U.S. Department of Agriculture, unpub. data., 1994). Mean monthly climatic data for the Belgrade Airport Weather Station are shown in figure 4. Average annual precipitation in the GLWQD ranges from less than 14 in. near Manhattan to more than 44 in. on mountaintops in the Gallatin and Bridger Ranges (fig. 3). The average annual precipitation in the valley area ranges from less than 14 in. to more than 20 in. (George Taylor, unpub. data, National Oceanic and Atmospheric Administration, 1992).

Land and Water Use

Land use in the Gallatin Valley is predominantly agricultural (fig. 5). In 1996, Gallatin County farmers harvested crops from 170,230 acres, 89,630 acres of which were irrigated (Montana Agricultural Statistics Service, 1997). On the Madison Plateau, the principal crop is irrigated potatoes; hay and grains also are important crops, as well as native grasses used for cattle grazing. On the intensively irrigated and subirrigated alluvial plain, hay and grains are the principal crops; on the eastern benches, dryland grains are the principal crops. Most of the dryland farmers use crop-fallow rotations to increase moisture storage on the relatively dry benches. For the period 1964-92, farmland acreages have declined by more than 300,000 acres (fig. 6) in all of Gallatin County (U.S. Department of Commerce, issued periodically). Residential and commercial development in the GLWQD have accounted for some of this decline, particularly on the alluvial plain and the eastern benches. Most new residential developments contain lots ranging in size from about 0.25 to 10 acres. The mountainous parts of the GLWQD are mostly forested and the primary land uses

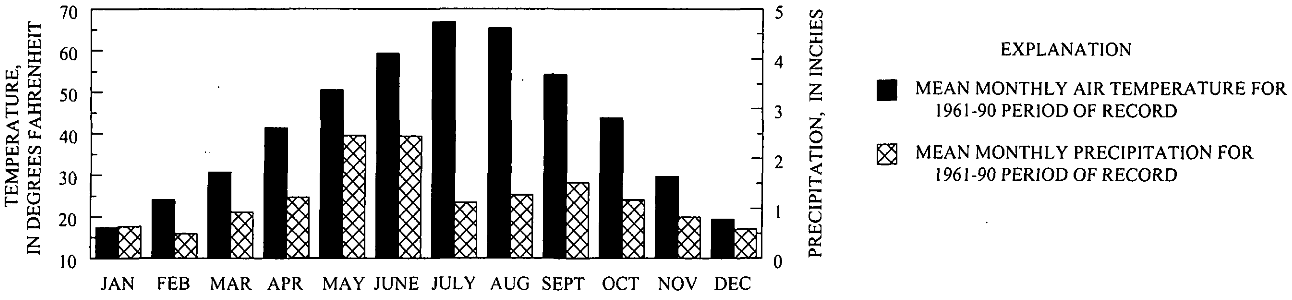
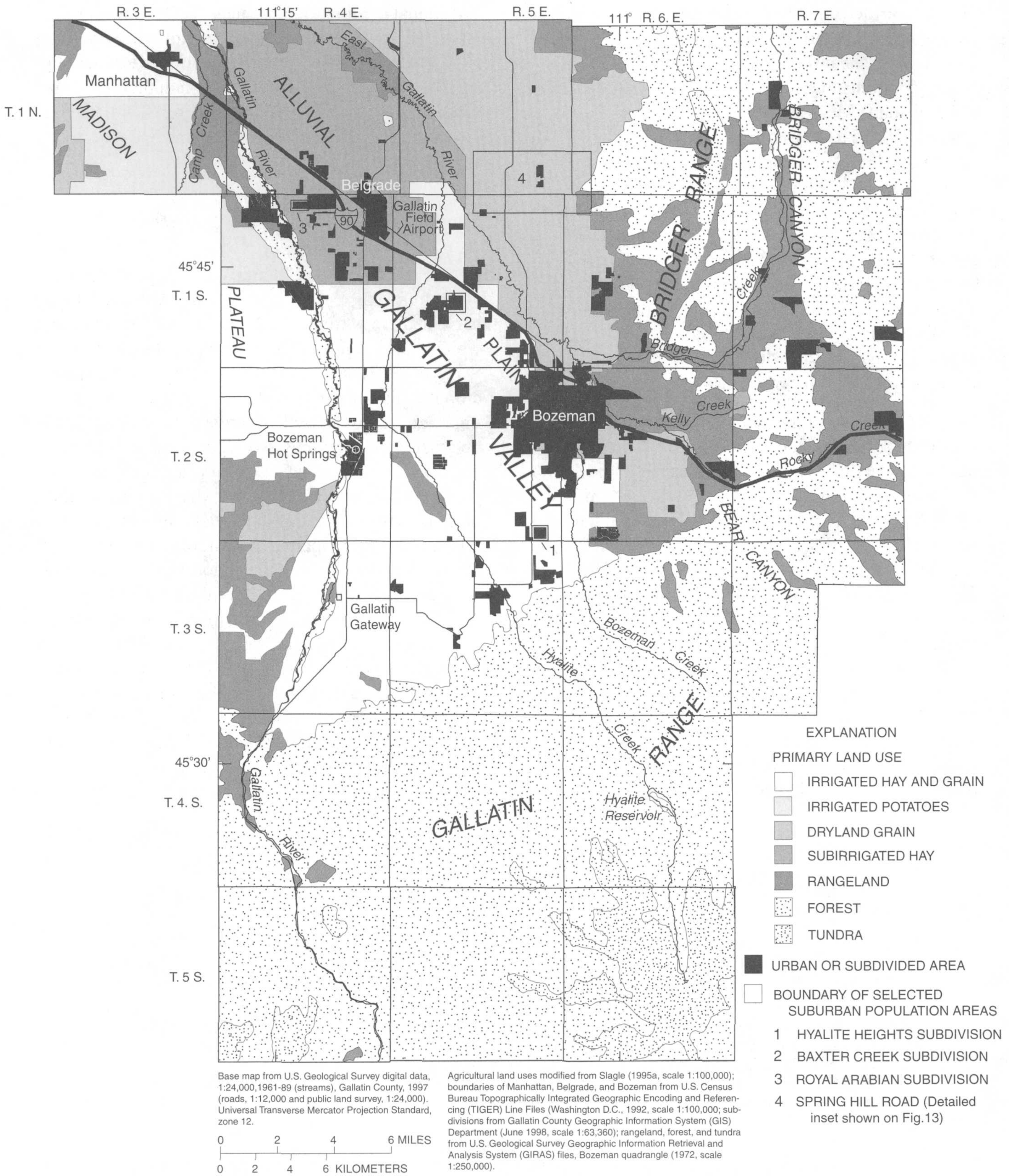


Figure 4. Mean monthly air temperature and precipitation at the Belgrade Airport Weather Station, Montana. Data from National Oceanic and Atmospheric Administration (1992).



Base map from U.S. Geological Survey digital data, 1:24,000,1961-89 (streams), Gallatin County, 1997 (roads, 1:12,000 and public land survey, 1:24,000). Universal Transverse Mercator Projection Standard, zone 12.

Agricultural land uses modified from Slagle (1995a, scale 1:100,000); boundaries of Manhattan, Belgrade, and Bozeman from U.S. Census Bureau Topographically Integrated Geographic Encoding and Referencing (TIGER) Line Files (Washington D.C., 1992, scale 1:100,000; subdivisions from Gallatin County Geographic Information System (GIS) Department (June 1998, scale 1:63,360); rangeland, forest, and tundra from U.S. Geological Survey Geographic Information Retrieval and Analysis System (GIRAS) files, Bozeman quadrangle (1972, scale 1:250,000).

Figure 5. Generalized land uses in the Gallatin Local Water Quality District, Montana.

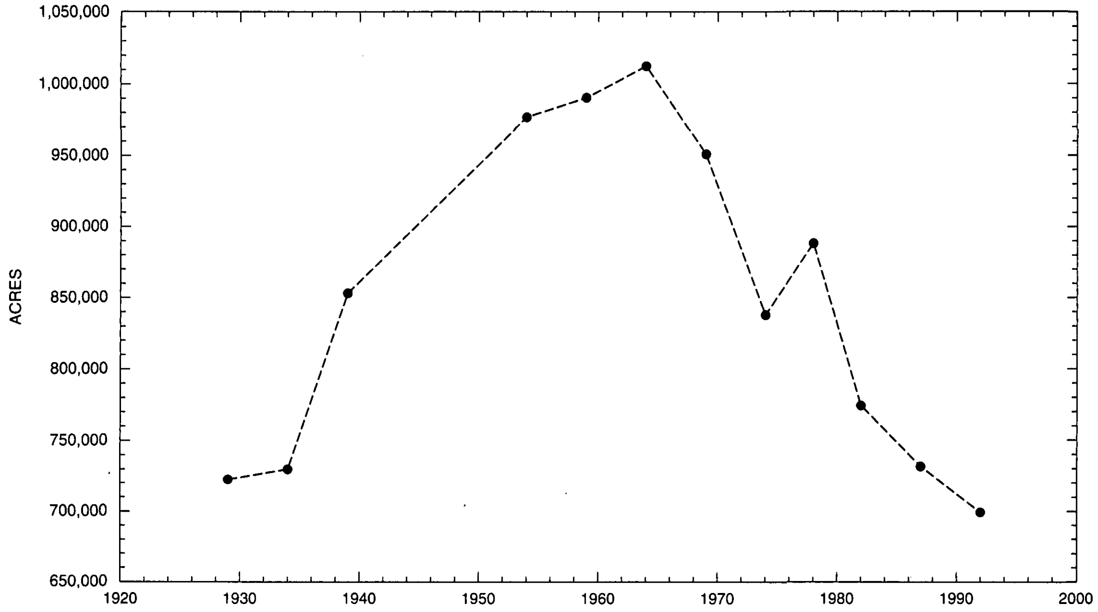


Figure 6. Acres of farmland in Gallatin County, Montana, 1929-92. Data from U.S. Department of Commerce (issued periodically).

are timber harvesting, cattle grazing, and recreation. Residential development has recently spread into these mountainous areas, especially in Bridger and Bear Canyons.

Water use in the GLWQD is primarily for municipal and domestic supply, irrigation, and livestock. Municipal-supply water for the City of Bozeman is obtained from Hyalite Reservoir and diversions from Bozeman Creek. Ground water provides domestic supplies for about 17,000 residents of the GLWQD and also provides irrigation water for about 2,800 acres (Parrett and Johnson, 1988). The Gallatin River is the major source of irrigation water in the GLWQD (Parrett and Johnson, 1988; [Montana] State Engineer's Office, 1953a,b).

HYDROGEOLOGY

Several investigators have described the general hydrogeology of the Gallatin Valley or detailed hydrogeology of small areas (Donohue, 1984; Kendy and Tresch, 1996). Murdock (1926) investigated ground water, focusing on irrigation and drainage problems in the Gallatin Valley. Hackett and others (1960) measured water levels and streamflow, mapped basin fill, and sampled wells to provide the first comprehensive hydrogeological assessment of the Gallatin Valley. Earth Science Services, Inc. (1978) sampled ground water and measured water levels in wells throughout the Gallatin Valley. Custer (1991) reexamined the water-yielding potential of the unconsolidated deposits west of Bozeman. Slagle (1995b) appraised the 1992-93 hydrologic conditions throughout the Gallatin Valley, focusing on hydrologic changes resulting from changes in land use. Erickson (1995) and Hay (1997) estimated water budgets for unconsolidated aquifers underlying the benches north of Bozeman. Moore (1984) examined ground-water quality and availability in bedrock aquifers of the Bridger Canyon area.

Structurally, the Gallatin Valley intermontane basin composes the eastern two-thirds of an eastward-tilted graben (Robinson, 1961). The southwestern basin boundary is not flanked by obvious faults and might be a depositional contact between Cenozoic basin fill and pre-Cenozoic bedrock. The eastern boundary of the Gallatin Valley is a series of steep normal faults along the fronts of the Bridger and Gallatin Ranges (Robinson, 1961). Gravity data indicate that more than 6,000 ft of Cenozoic sediments fill the basin at its deepest point, east of Bozeman Hot Springs (Noble and others, 1982). Tertiary deformation is evidenced by several broad folds (Custer, 1991) and by possible faulting along the western margin of the Madison Plateau (Schneider, 1970).

Hydrogeologic Units

In general, geologic units of the GLWQD consist of poorly consolidated Cenozoic basin-fill deposits in the Gallatin Valley and complexly folded and faulted Tertiary through Archean bedrock in the mountains. These geologic units can be grouped into seven hydrogeologic units on the basis of major lithology, water-bearing characteristics, and geomorphologic relations. Figure 7 is a generalized map of these hydrogeologic units.

Basin-Fill Deposits

Cenozoic basin-fill deposits are subdivided into three hydrogeologic units: Quaternary alluvium (Qal), Quaternary and Tertiary undifferentiated deposits (QTd), and Tertiary Bozeman Group (Tb).

Basin-fill deposits can contain aquifers that are unconfined, leaky confined, or confined. Aquifers in basin-fill deposits that consist of Quaternary alluvium commonly are unconfined and highly productive (Briar and others, 1996). Fine-grained layers within Tertiary deposits (QTd or Tb) can restrict flow into or out of more permeable layers, which result in leaky-confined or confined aquifers. With depth, these fine-grained layers become more consolidated and, therefore, less permeable. However, some Tertiary basin-fill deposits contain productive aquifers (Briar and others, 1996).

Quaternary alluvium (Qal) was deposited by the Gallatin River and its tributaries and extends across the northern part of the alluvial plain between the Gallatin and East Gallatin Rivers. This unit is mostly composed of moderately sorted cobbles and pebbles, but sand, silt, and clay also are present. The proportion of fine-grained material generally increases to the north. Estimates of the thickness of the alluvium range from 70 ft near Bozeman Hot Springs to more than 800 ft near Belgrade (Hackett and others, 1960). Quaternary alluvium generally is the most permeable hydrogeologic unit and the most reliable source of ground water in the GLWQD. Typical wells completed in alluvium are less than 100 ft deep and provide sufficient supplies for most uses, including irrigation (Dutton and others, 1995). Based on 24 aquifer tests, transmissivity ranges from 5,100 to 90,000 ft^2/d and averages 27,000 ft^2/d for alluvium of the Gallatin and East Gallatin Rivers; based on four multiple-well aquifer tests, storage coefficients range from 0.01 to 0.06 (Hackett and others, 1960).

Quaternary and Tertiary undifferentiated deposits (QTd) consist of unconsolidated Quaternary alluvial-fan deposits overlying Tertiary sedimentary pediments that form benches and underlie the south-central part of the alluvial plain and the eastern benches (fig. 7). Alluvial-fan deposits, probably of late Pleistocene age, extend into the Gallatin Valley from the Bridger and Gallatin Range fronts and consist of a heterogenous mixture of unconsolidated to consolidated, poorly sorted rock fragments in a sand, silt, and clay matrix with some carbonate cement (Hay, 1997; Erickson, 1995; Custer, 1991; Hackett and others, 1960). Typically, grain sizes decrease toward the toes of the fans. Likewise, fan thicknesses decrease from more than 150 ft at the heads to zero thickness at the toes of the fans (Custer, 1991; Hackett and others, 1960). Tertiary sediments in the Gallatin Valley belong to the nonmarine Bozeman Group described by Fields and others (1985). In general, Tertiary sediments that underlie the Quaternary alluvial fans grade from moderately well-cemented conglomerate along the Bridger and Gallatin Range fronts to finer-grained, tuffaceous siltstone and sandstone to the northwest. However, within this general framework, the Tertiary sediments are extremely heterogeneous and include laterally discontinuous beds of volcanic ash; tuffaceous marl, siltstone, and sandstone; limestone; cemented and uncemented conglomerate; and cross-bedded sandstone (Hackett and others, 1960; Custer, 1991; Hanneman and Wideman, 1991). Owing to their similar compositions, Quaternary alluvial-fan deposits cannot easily be distinguished from the underlying Tertiary sediments. Therefore, the thickness of these deposits at any location is uncertain. The depths of wells completed in QTd range from 40 to 375 ft, with the deeper wells located on topographically higher benches. In some areas with low aquifer permeability, landowners have reported difficulties in obtaining ground water. The hydraulic characteristics of QTd vary widely, reflecting the heterogeneity of the deposits. Based on aquifer tests of six wells completed on alluvial fans, the transmissivity of QTd ranges from 3,500 to 8,700 ft^2/d and averages 6,400 ft^2/d (Hackett and others, 1960).

The Tertiary Bozeman Group (Tb) consists of the Tertiary Sixmile Creek and Renova Formations (Fields and others, 1985) where they crop out as pediments on the Madison Plateau, east of Bozeman, and 5 mi north of Belgrade (fig. 7). The Miocene Sixmile Creek Formation consists of three unconformable cyclic units. The basal part of each unit is a fluviatile, cross-bedded, andesitic conglomerate with coarse-grained sandstone. Each unit grades upward into sediments that vary laterally from lacustrine beach sands to laminated clays with tuffaceous claystone. The entire formation is rich in tuffaceous siltstone and sandstone and contains numerous ash beds ranging in thickness from 0.5 to 12 ft (Schneider, 1970). The Eocene to Oligocene Renova Formation (Fields and others, 1985) is not well-exposed in the Gallatin Valley. However, the formation crops out extensively to the west of the GLWQD. These fine-grained, dominantly lacustrine, tuffaceous sediments underlie the Sixmile Creek Formation in most, if not all, of the Gallatin Valley (Hackett and others, 1960; Robinson, 1961). North of Belgrade and east of Bozeman, wells completed in Tb typically have low well yields. Specific-capacity values for 16 wells completed in Tb north of Belgrade and east of Bozeman range from 0.2 to 47.6 (gal/min)/ft with a median value of 0.78 (gal/min)/ft (Slagle, 1995a). Transmissivity values determined from four aquifer tests range from 40 to 2,300 ft^2/d (Hackett and others, 1960). In contrast, wells completed in Tb on the Madison Plateau tap a permeable zone capable of yielding as much as 2,800 gal/min to irrigation wells. These wells are about 200 to more than 500 ft deep, with well depths increasing to the south. Specific-capacity values estimated from data from drillers' logs can be as high as 59 (gal/min)/ft (Dutton and others, 1995). Hackett and others (1960) calculated a transmissivity of 3,500 ft^2/d for a 225-ft well on the Madison Plateau (01N03E33DD).

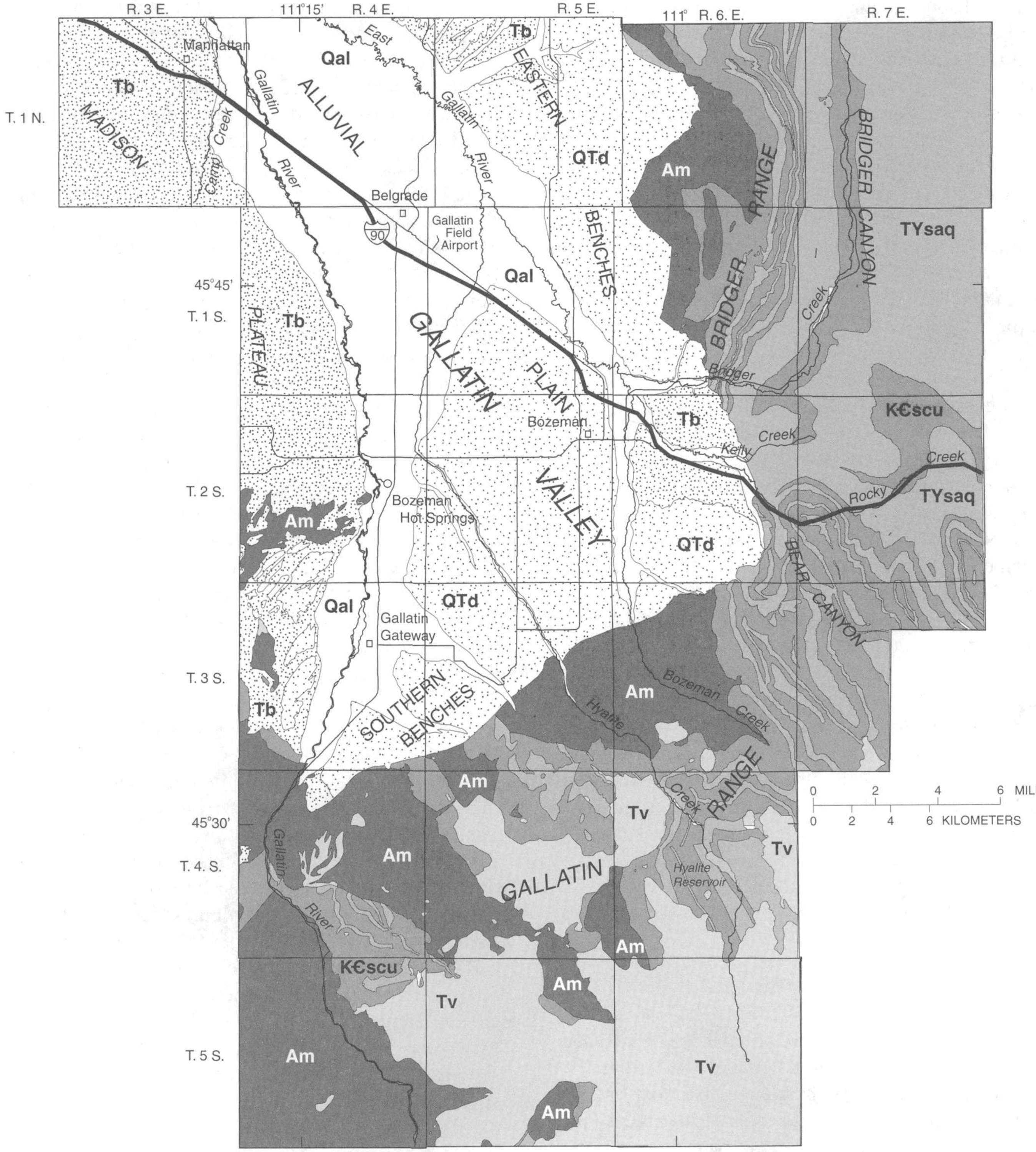
Bedrock

Mountains within the Gallatin Local Water Quality District are composed of complexly folded and faulted bedrock that can be grouped into four hydrogeologic units: Tertiary (Eocene) volcanic rocks (Tv), Tertiary through Middle Proterozoic sedimentary bedrock that contains potential aquifers (TYsaq), Cretaceous through Cambrian sedimentary bedrock that contains confining units (KꞒscu), and Archean metamorphic rocks (Am).

Tertiary volcanic rocks (Tv) mostly are present in the topographically highest parts of the GLWQD. These rocks include andesite and basalt flows, breccia, agglomerate, and tuff of the Gallatin-Absaroka Volcanics. Owing to their poorly accessible locations and dense, crystalline nature, the volcanic rocks have not been developed as a ground-water source.

Tertiary through Proterozoic sedimentary bedrock units that contain potential aquifers (TYsaq) include the Paleocene to Upper Cretaceous Fort Union Formation; Upper Cretaceous Hoppers Formation, Miner Creek Formation, Cokedale Formation, Eagle Sandstone, Telegraph Creek Formation, and Frontier Formation; the lower part of the Lower Cretaceous Kootenai Formation; Permian Phosphoria Formation; Pennsylvanian Quadrant Formation; Mississippian Mission Canyon Limestone; Cambrian Flathead Sandstone; and the Middle Proterozoic Belt Supergroup (S.G. Custer, Montana State University, written commun., 1998). Sandstone, conglomerate, and limestone predominate the lithologies of TYsaq. Because these units have not been extensively developed, they are considered only potential aquifers. Permeability of these formations depends on grain size and sorting, degree of cementation, and fracturing, which are not uniform throughout a formation. Rugged terrain and deep water tables may restrict development of these potential aquifers.

Cretaceous through Cambrian sedimentary bedrock units that contain confining units (KꞒscu) include the Upper Cretaceous Billman Creek Formation, Miner Creek Formation, Cokedale Formation, and Cody Shale; Lower Cretaceous Mowry and Thermopolis Shales; the upper part of the Lower Cretaceous Kootenai Formation; Upper Jurassic Morrison Formation; Upper to Middle Jurassic Ellis Group; Pennsylvanian to Mississippian Amsden Formation; Mississippian Big Snowy Group, Charles Formation, and Lodgepole Limestone; Devonian Three Forks Shale, Jefferson Dolomite, and Maywood Formation; and the Cambrian Snowy Range Formation, Pilgrim Limestone, Park Shale, Meagher Limestone, and Wolsey Shale. Fine-grained sandstone, shale, mudstone, siltstone, and chert predominate the lithologies of KꞒscu. Structural relations might prevent these rocks from actually confining underlying aquifers in some areas, but they are termed "typically confining units" to distinguish them from the potential aquifers included in TYsaq. Even with its poor water-yielding characteristics, more ground-water development has occurred in KꞒscu than in TYsaq. However, ground water generally is not readily available in many areas where this

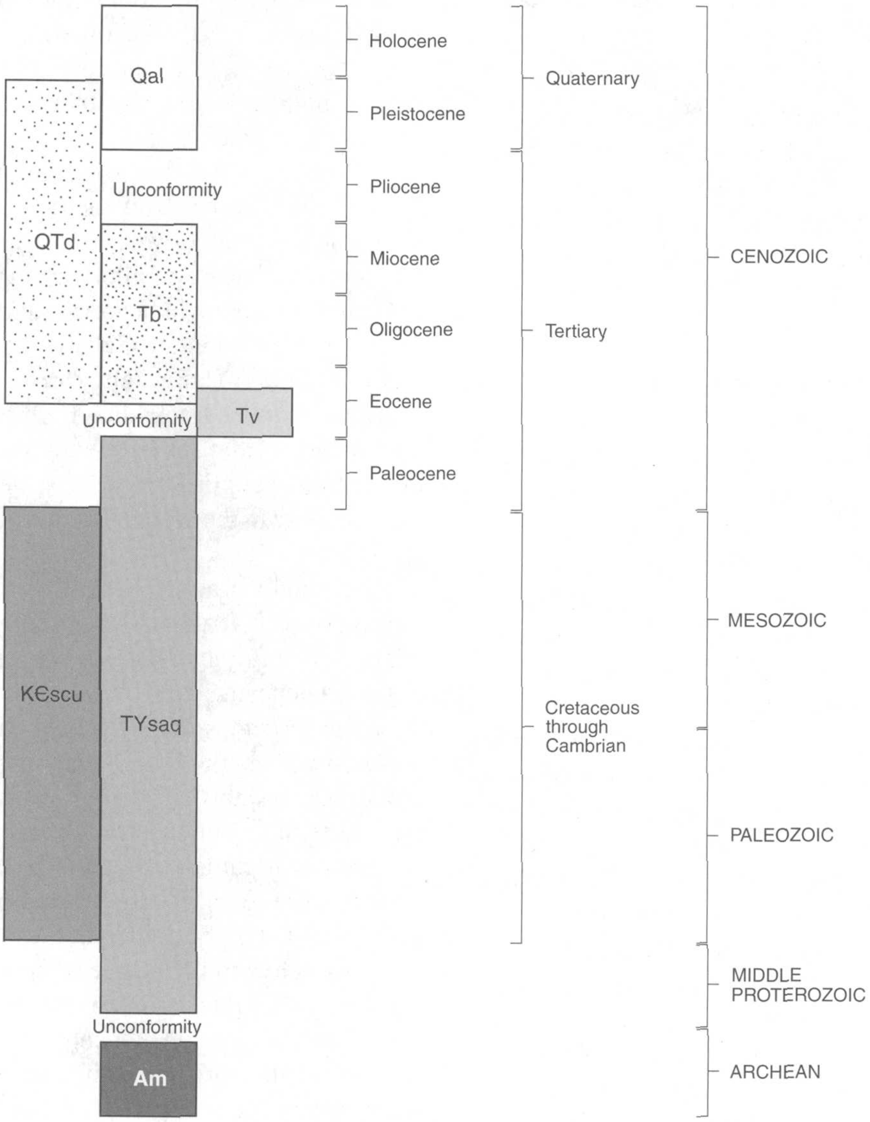


Base map from *U.S. Geological Survey digital data, 1:24,000,* 1961-89 (streams), Gallatin County, 1997 (roads, 1:12,000 and public land survey, 1:24,000). Universal Transverse Mercator Projection Standard, zone 12.

Hydrogeologic units modified from S.G. Custer, Montana State University (unpublished digital data, 1998) and Hackett and others (1960).

Figure 7. Generalized hydrogeologic units in the Gallatin Local Water Quality District, Montana.

CORRELATION OF HYDROGEOLOGIC UNITS



EXPLANATION

Qal	ALLUVIUM (Quaternary)
QTd	UNDIFFERENTIATED DEPOSITS (Quaternary and Tertiary)
Tb	BOZEMAN GROUP (Eocene through Miocene)
Tv	VOLCANIC ROCKS (Eocene)
TYsaq	SEDIMENTARY BEDROCK--Potential aquifers (Paleocene through Middle Proterozoic)
KЄscu	SEDIMENTARY BEDROCK--Typically confining units (Cretaceous through Cambrian)
Am	METAMORPHIC ROCKS (Archean)
—	CONTACT--Approximately located

unit is found. Most drillers' logs indicate that wells completed in KꞒscu provide inadequate supplies for sustained pumping that is required for domestic supplies.

Archean metamorphic rocks (Am) are present in undeveloped areas of the Gallatin and Bridger Ranges, and probably underlie Cenozoic basin-fill deposits in much of the Gallatin Valley. These rocks are mainly biotite gneiss, with some schist, quartzite, and marble. If the rocks were fractured and the fractures interconnected, this unit could potentially yield water to wells.

Ground-Water Occurrence, Movement, and Recharge

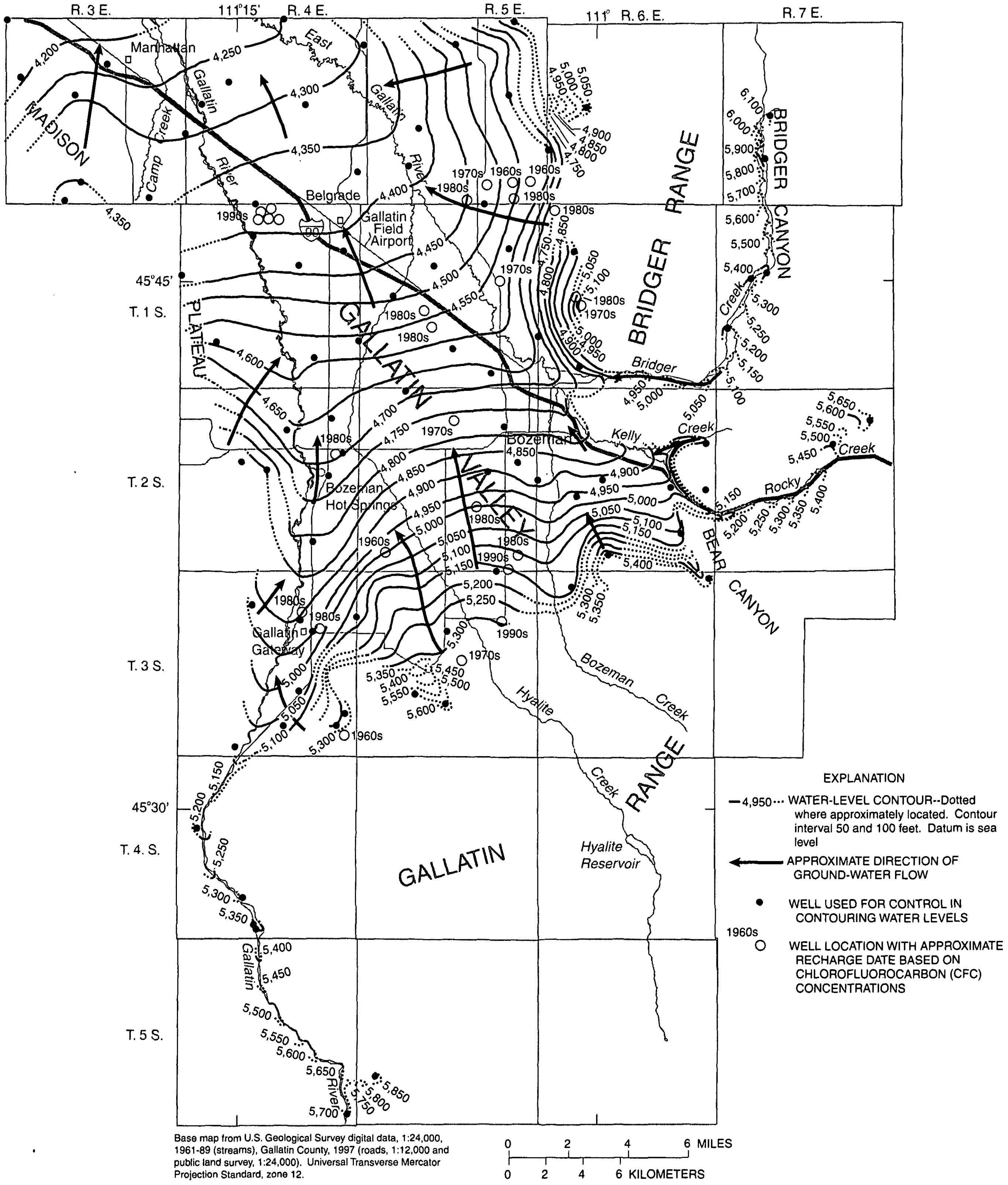
Comprehensive records of water levels in wells in the Gallatin Valley begin in 1947. Periodic water-level measurements in more than 100 wells from 1947 to 1954 were used to draw the first map of the water table (Hackett and others, 1960). In 1978, water levels were remeasured in 76 of those wells and no long-term trends were observed (Earth Science Services, Inc., 1978). Likewise, Slagle (1995a) determined no substantial long-term water-level changes for the period 1947 to 1993. Contours of water levels measured in April 1998 (fig. 8) are similar to previous maps (Murdock, 1926; Hackett and others, 1960; Earth Science Services, Inc., 1978; Slagle, 1995a), and indicate that the direction of regional ground-water flow in the basin-fill deposits generally is from the south, west, and east margins of the Gallatin Valley toward the Gallatin or East Gallatin Rivers (fig. 9). However, heterogeneities caused by discontinuous beds and lenses in the basin-fill deposits can result in complex local ground-water flow patterns. Therefore, local flow directions may be somewhat different from those shown in figure 8. In most parts of the GLWQD, water levels fluctuate seasonally. Water levels generally rise from spring through mid-summer, peak in June or July, and gradually recede until about April or May, when snowmelt, seepage from streams, and summer rainfall begin to recharge aquifers. The greatest fluctuations in developed aquifers occur in Quaternary and Tertiary undifferentiated deposits along the western flank of the Bridger Range front (Hay, 1997), where seasonal fluctuations of more than 40 ft occur. In contrast, wells completed in Quaternary alluvium near the Gallatin and East Gallatin Rivers typically fluctuate less than 10 ft seasonally (fig. 10).

Depths to ground water vary considerably within the GLWQD. In subirrigated areas (fig. 5), the water table is usually less than about 5 ft below land surface. Also, much of the area southwest of Bozeman and east of Hyalite Creek has a shallow water table within about 8 ft of land surface. In contrast, ground water in some mountainous areas outside of the GLWQD is hundreds of feet below land surface.

Generalized recharge sources may be determined on the basis of water-level contours, which are perpendicular to the ground-water flow direction. For example, contours that are parallel to mountain fronts (fig. 8) indicate that mountain bedrock aquifers recharge basin-fill deposits in the Gallatin Valley. Basin-fill deposits in the Gallatin Valley are recharged by subsurface flow from bedrock, direct infiltration of precipitation, seepage from some streams and canals, and infiltration of applied irrigation water. In general, bedrock aquifers in the mountains are recharged by precipitation.

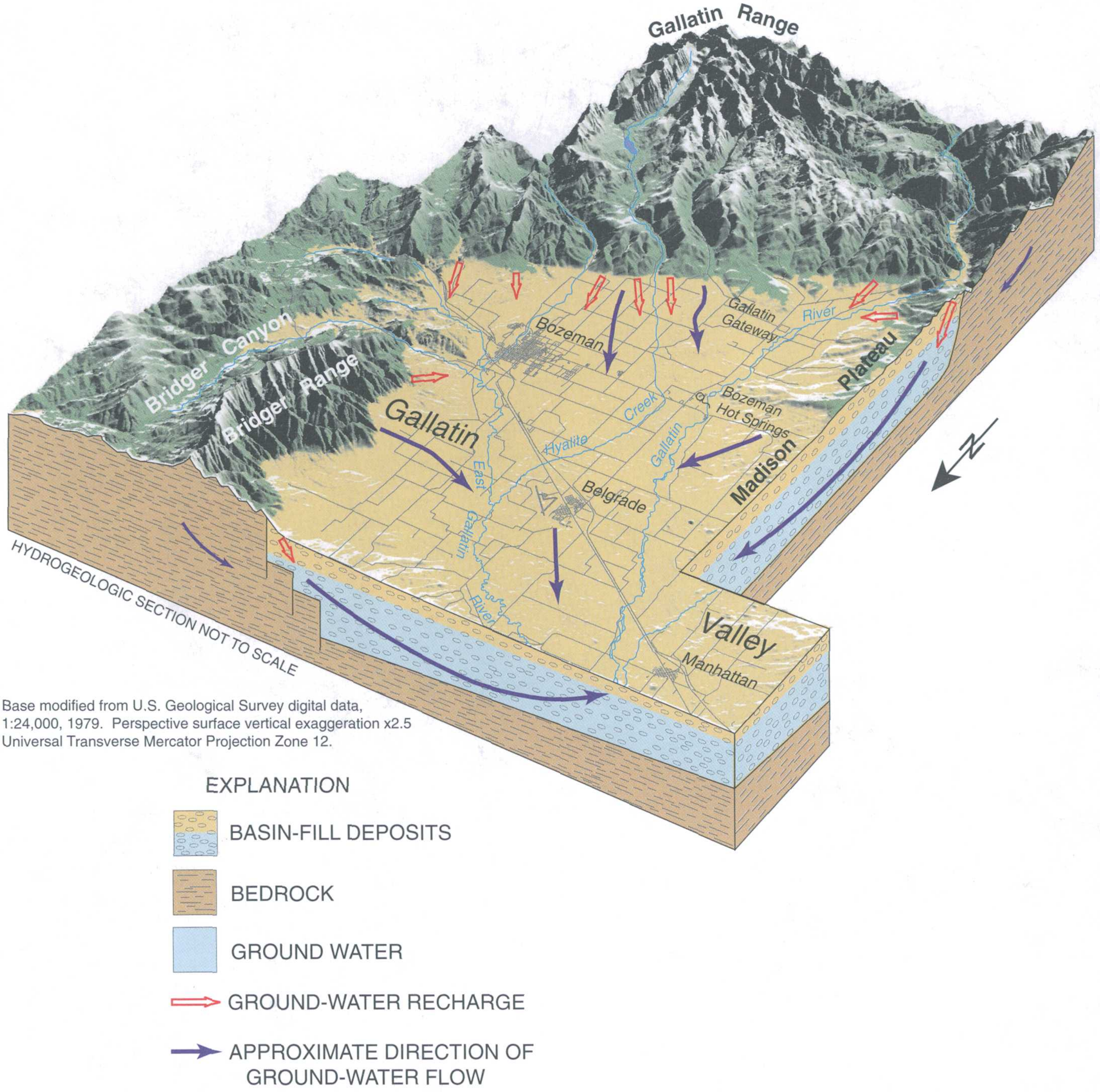
Spatial variations in the ratios of stable isotopes of oxygen ($\delta^{18}O$) and hydrogen (δD) in ground water were used to further delineate sources of recharge to basin-fill deposits in the Gallatin Valley. $\delta^{18}O$ and δD values in ground water reflect the values in the precipitation that recharged the ground water, unless some process or reaction caused the isotopes to be fractionated. One such process is evaporation, which results in deuterium enrichment relative to hydrogen (reflected in a higher δD value), because water lost to the atmosphere has a slightly greater proportion of the hydrogen isotope relative to the heavier deuterium isotope (that is, a lower δD value) (Coplen, 1993). Most of the $\delta^{18}O$ and δD values (fig. 11) plot between the meteoric water line for North American continental precipitation described by the equation $\delta D = 8(\delta^{18}O) + 6‰$ (Gat, 1980) and the global meteoric water line described by the equation $\delta D = 8(\delta^{18}O) + 10‰$ (Craig, 1961), indicating that most of the isotopic compositions have not been affected by evaporation. Data for 5 of the 8 wells completed beneath unirrigated benches plot below both lines, indicating some isotopic fractionation caused by evaporation, as might be expected for dryland farming areas.

In this study, the stable-isotope data (fig. 11) were used primarily to distinguish recharge sources for ground water in different areas. The sample collected from the Gallatin River in 1998 had a $\delta^{18}O$ value of -18.74‰. The other value ($\delta^{18}O$ value of -18.45‰ and δD value of -137) from the Gallatin River plotted in figure 11 represents a sample collected in June 1993



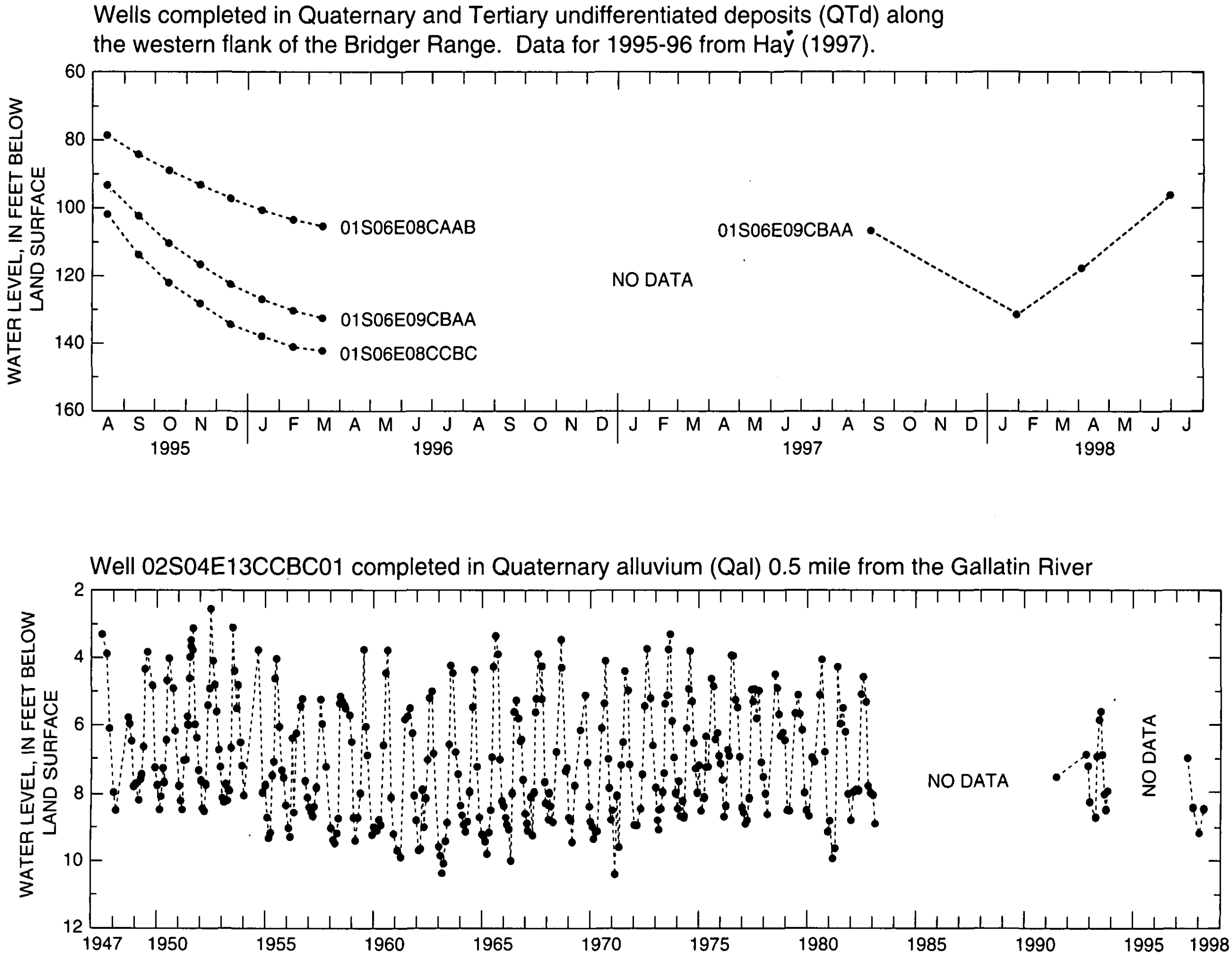
Base map from U.S. Geological Survey digital data, 1:24,000, 1961-89 (streams), Gallatin County, 1997 (roads, 1:12,000 and public land survey, 1:24,000). Universal Transverse Mercator Projection Standard, zone 12.

Figure 8. Water-level contours and approximate direction of ground-water flow in the basin-fill deposits in April 1998, and approximate ground-water recharge dates, Gallatin Local Water Quality District, Montana.



Base modified from U.S. Geological Survey digital data, 1:24,000, 1979. Perspective surface vertical exaggeration x2.5 Universal Transverse Mercator Projection Zone 12.

Figure 9. Perspective view and diagrammatic hydrogeologic section showing ground-water recharge and flow in the basin-fill deposits in the Gallatin Local Water Quality District, Montana.



Wells completed in Quaternary and Tertiary undifferentiated deposits (QTd) along the western flank of the Bridger Range. Data for 1995-96 from Hay (1997).

Well 02S04E13CCBC01 completed in Quaternary alluvium (Qal) 0.5 mile from the Gallatin River

Figure 10. Hydrographs of selected wells in the Gallatin Local Water Quality District, Montana.

from an overflow channel about 6 mi downstream from the GLWQD (location number 02N02E17DDCC01; U.S. Geological Survey, unpub. data). $\delta^{18}O$ values for ground water collected from 12 wells completed beneath the irrigated or subirrigated parts of the Gallatin Valley (fig. 5) range from -18.07‰ to -18.69‰ and are similar to the values for the Gallatin River (fig. 11). Thus, the Gallatin River and water diverted from the river for irrigation probably are the primary sources of ground-water recharge in the irrigated and subirrigated areas. The importance of irrigation water in recharging basin-fill deposits and sustaining aquifer storage is supported by the water table rising to maximum altitudes during periods of intense irrigation rather than during periods of intense precipitation (Brustkern, 1977; Slagle, 1995a).

Conversely, water levels beneath the unirrigated benches rise in response to intense precipitation (Slagle, 1995a). $\delta^{18}O$ values from eight samples collected from these areas spanned a much larger range (-16.21‰ to -18.93‰) than samples collected from irrigated and subirrigated areas. Higher (less negative) $\delta^{18}O$ values indicate enrichment in ^{18}O, which results from fractionation at a lower altitude or a higher temperature. The larger range of $\delta^{18}O$ values suggests that some combination of factors, including evaporation and the altitude and season of the precipitation that recharged the aquifer, varies throughout the unirrigated bench areas. In contrast to the irrigated and subirrigated areas, which apparently have a common recharge source, the unirrigated benches probably are recharged from a variety of sources, including low-altitude snow melt, seepage from ephemeral streams, and summer rainfall. The recharge area and resultant quantity of

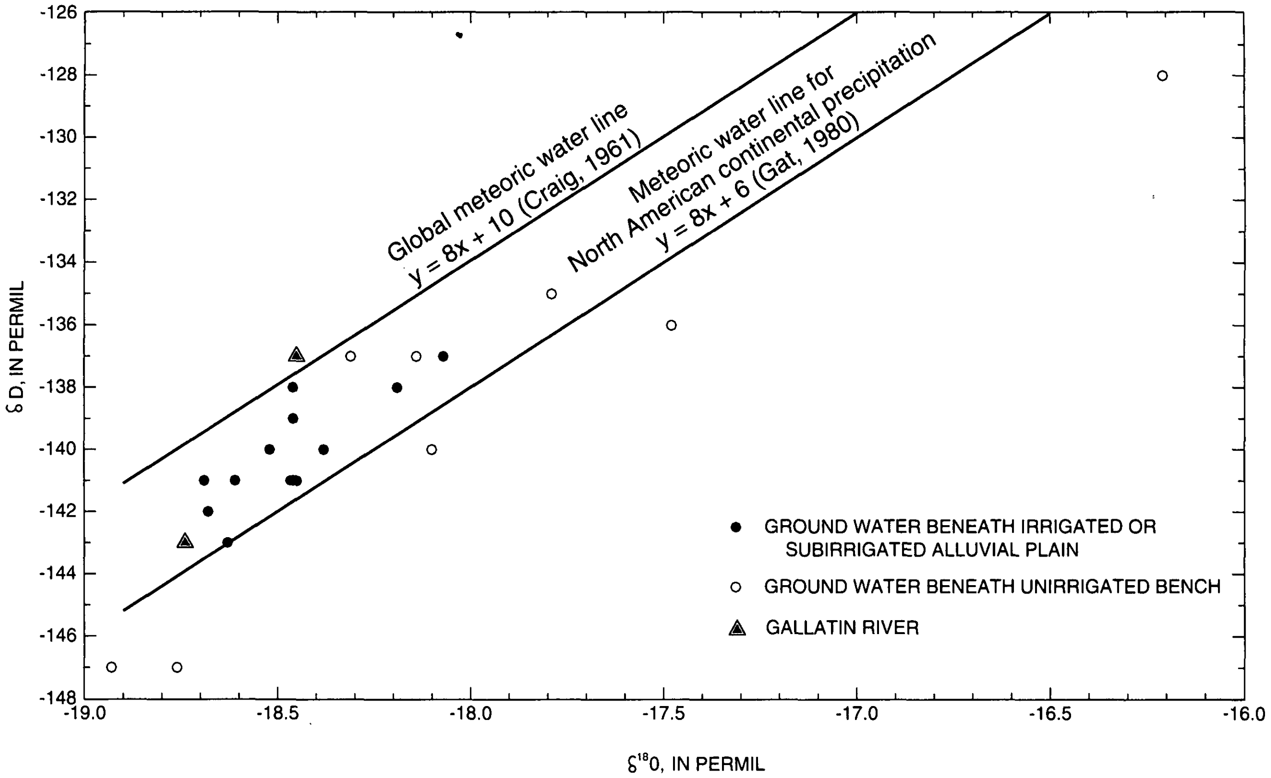


Figure 11. Relation between $\delta^{18}O$ and δD in ground water and the Gallatin River, Gallatin Local Water Quality District, Montana, 1998.

recharge for aquifers beneath these unirrigated benches are small compared to the recharge area for aquifers beneath the subirrigated and irrigated areas. Only limited ground-water supplies are reported by drillers and residents of the unirrigated benches, despite the relatively high transmissivities of potential aquifers (Custer, 1991). Furthermore, the large seasonal water-level fluctuations probably result from seasonal infiltration of precipitation rather than recharge from a major perennial surface-water source, which could sustain more consistent water levels throughout the year.

Water from the Tertiary Bozeman Group (Tb) beneath the Madison Plateau has an isotopic composition distinct from the other unconsolidated deposits. Water from samples collected in 1991 from depths of 710, 289, and 245 ft, had $\delta^{18}O$ values of -21.0‰, -19.2‰, and -18.5‰, respectively (U.S. Geological Survey, unpub. data). This apparent trend of ^{18}O depletion with well depth might indicate that deeper wells are recharged at higher altitudes and have longer, more regional recharge flowpaths than shallower wells. Similarity between isotopic composition of water from the two shallower wells with that of the Gallatin River could indicate recharge from the Gallatin River. But hydraulic gradients (K.B. Waren, Montana Department of Natural Resources and Conservation, written commun., 1991; Slagle, 1995a) indicate that direct recharge from the river is unlikely. However, recharge from irrigation water diverted from the Gallatin River is likely, based on water-level mounds beneath canals (Slagle, 1995a). In contrast, $\delta^{18}O$ values for ground water from Tb beneath the Madison Plateau are different from the Madison River (5 spring and summer samples with values ranging from -16.8‰ to -17.9‰) and shallow alluvial ground water west of the Madison Plateau (11 samples with values ranging from -17.2‰ to -17.9‰; Tuck and others, 1997). Therefore, based on hydraulic gradients and the isotopic composition of water, Tb beneath the Madison Plateau probably is recharged by irrigation water diverted from the Gallatin River, and not by the Madison River. Precipitation, seepage from streams, and subsurface flow from bedrock to the south probably also provide recharge (K.B. Waren, written commun., 1991).

To understand the timing of ground-water recharge, ground-water ages were estimated using CFC data for water collected from 27 sites in May-June 1998 (fig. 8, table 4). All samples had detectable concentrations of CFCs, indicating recharge dates ranging from the 1960s to the 1990s. In general, ground water near the Gallatin River was recharged during the 1980s and 1990s. In places along the western flank of the Bridger Range, ground water also was recharged during the 1980s. These recent ground-water ages support the interpretations that the Gallatin River recharges nearby Quaternary alluvium (Qal) and that local infiltration recharges aquifers beneath the eastern benches on the western flank of the Bridger Range.

CFC data also demonstrate that local ground-water flow patterns can be different from the regional flow pattern. If local flow paths corresponded exactly to the regional flow paths depicted in figure 8, then the approximate recharge dates based on CFC data would become older downgradient. For example, south of Bozeman between Hyalite and Bozeman Creeks, recharge dates progress downgradient from the 1990s to the 1980s. In contrast, along the western flank of the Bridger Range (T.1 N., R. 5 E.), coalescing alluvial fans consisting of heterogeneous, laterally discontinuous sediments locally control ground-water flow such that younger water (1970s) was sampled down hill from older water (1960s). The 1970s water was sampled from a 47-ft well, and the 1960s water was sampled from 80- and 120-ft wells. These age and depth relations suggest that either the shallower deposits were recharged closer to the wells or that the shallower deposits are more permeable than the deeper deposits, allowing ground water to flow faster from the same recharge source. Similar $\delta^{18}O$ values (-18.31‰ and -18.76‰) for the 47-ft and 120-ft wells indicate that water from both wells has a common recharge source. Conversely, 1980s ground water sampled from the center of the Gallatin Valley (T. 1 S., R. 5 E.) had different $\delta^{18}O$ values (-18.19‰ and -18.46‰) from regional ground water sampled upgradient, along the basin margin (T. 3 S., R. 5 E; -17.48‰ and -17.79‰). The younger water probably represents infiltrated irrigation water rather than precipitation and stream seepage that infiltrated along the valley margin and flowed down-valley. Therefore, in this case, the $\delta^{18}O$ values indicate that the age relations probably result from distinct recharge sources.

Water from basin-fill deposits discharges to streams, irrigation drains, wells, and evapotranspiration, particularly in the northern part of the valley where the water table is very shallow. Pumpage from wells is a small component of ground-water discharge. Water that does not evapotranspire eventually flows out of the GLWQD along the Gallatin River, either as surface water or as ground water. Discharge from the Gallatin Valley exceeds recharge throughout the fall, winter, and early spring (Hackett and others, 1960). Water from bedrock aquifers discharges to streams and as subsurface flow to basin-fill deposits.

Ground-Water Quality

The major-ion chemistry of ground and surface water sampled in the GLWQD (table 3) is shown in figure 12. Wells completed in Quaternary alluvium (Qal) and Quaternary and Tertiary undifferentiated deposits (QTd) beneath the alluvial plain of the Gallatin Valley produce calcium bicarbonate or calcium-magnesium bicarbonate water. Water from Quaternary and Tertiary undifferentiated deposits (QTd) and the Tertiary Bozeman Group (Tb) beneath the eastern benches (fig. 7) has major-ion chemistry similar to that of the alluvial plain. Concentrations of dissolved solids from these hydrogeologic units ranged from 149 to 405 mg/L. Generally, water from Tb beneath the Madison Plateau has similar anion chemistry, but with a larger percentage of sodium than ground water from basin-fill deposits to the east (table 3; Slagle, 1995a). Water from two samples from the Gallatin River also are a calcium bicarbonate type.

Wells completed in sedimentary bedrock (TYsaq and K€scu, fig. 7) east of the Gallatin Valley have a wide variety of water types (fig. 12) owing to the different rock types that compose these units. Dissolved-solids concentrations for seven wells sampled in 1998 ranged from 127 to 438 mg/L. Some Cretaceous rocks in Bridger Canyon contain thin beds of sulfur-rich lignite and coal which, under reducing conditions, impart an unpleasant "rotten egg" odor to ground water (Moore, 1984).

The presence of Bozeman Hot Springs (02S04E14DADC01 and 02; fig. 1) indicates subsurface flow of geothermal water from Archean metamorphic bedrock (Am) (Chadwick and Leonard, 1979). Water discharges with a temperature of 53.0°C and a dissolved-solids concentration of 456 mg/L at a rate of 74 gal/min. A 685-ft flowing well at the same location produces 1,000 gal/min of 55°C water (Sonderegger

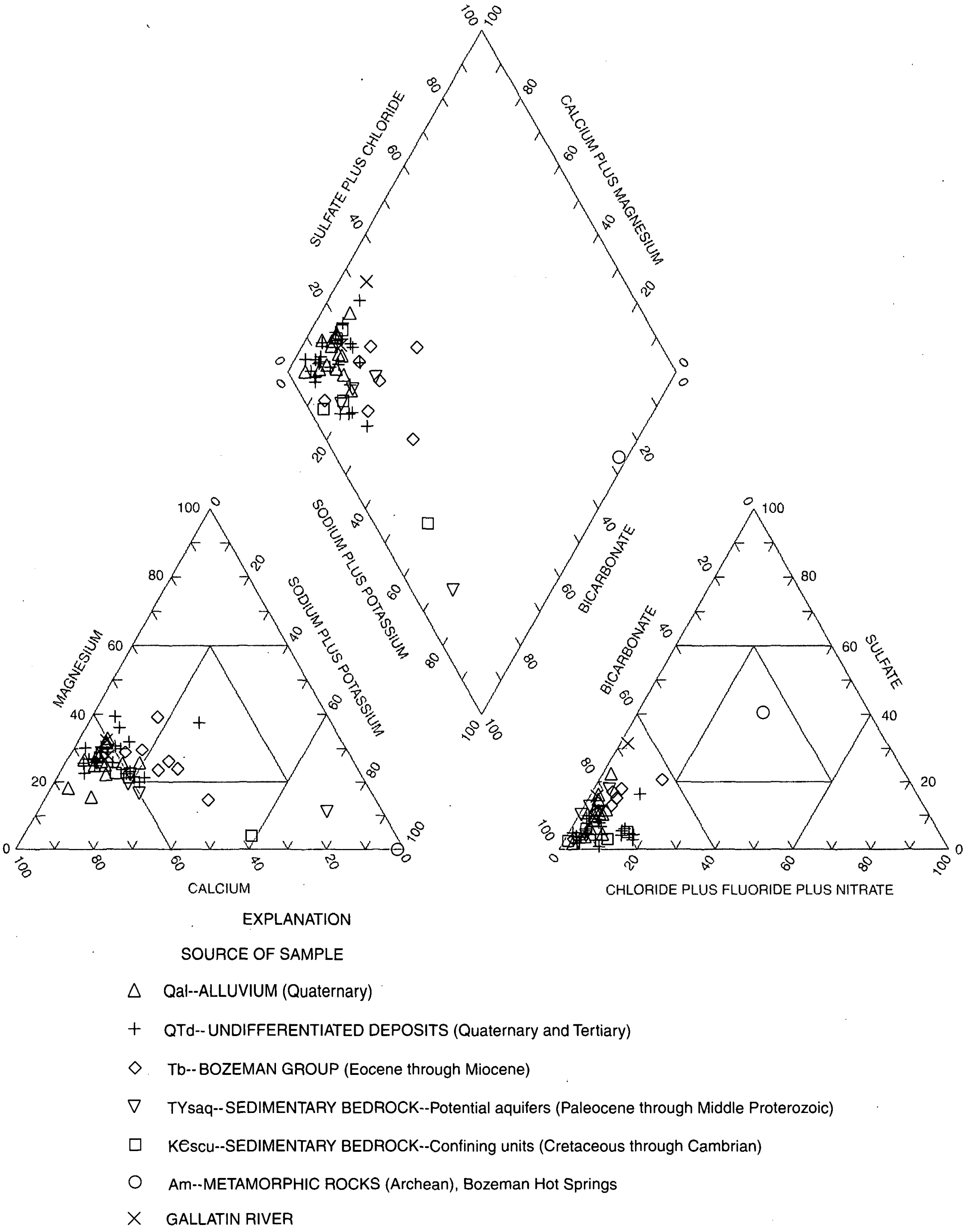


Figure 12. Modified trilinear diagram showing percentages of major ions in ground water, Bozeman Hot Springs, and the Gallatin River in the Gallatin Local Water Quality District, Montana. Data were converted from milligrams per liter to milliequivalents per liter before computing percentages.

and Bergantino, 1981). However, subsurface flow from metamorphic bedrock probably does not substantially recharge basin-fill deposits, based on the dissimilarity between the chemistry of the thermal water and that of ground water from Qal and QTd (fig. 12).

Concentrations of constituents in water samples (tables 1 and 3) were compared to standards and guidelines established by the Montana Department of Environmental Quality (1995) and the U.S. Environmental Protection Agency (1996) for the protection of human health (table 5). Constituents in most samples were present at concentrations considered safe for human consumption. The standards and guidelines for fluoride were exceeded in water from Bozeman Hot Springs (11 mg/L as F), which is not used for drinking.

Fluoride is present naturally in most ground water and can reduce the incidence of tooth decay in children when the water is consumed during the period of enamel calcification. Fluoride concentrations in ground water of the GLWQD ranged from <0.1 to 11 mg/L and commonly were less than the 0.8 to 1.2 mg/L fluoride that is considered optimum for dental health (Centers for Disease Control and Prevention, 1985).

Much of the ground water in the GLWQD is considered hard because it has a relatively high proportion of calcium and magnesium. Hard water consumes soap before a lather will form, leaves soap deposits, and forms scale in boilers, water heaters, and pipes. The hardness of water is expressed in terms of an equivalent amount of calcium carbonate--the principal constituent of limestone. Water is considered soft if it contains 0 to 60 mg/L of hardness, moderately hard if it contains 61 to 120 mg/L of hardness, hard if it contains 121 to 180 mg/L of hardness, and very hard if it contains more than 180 mg/L of hardness (Hem, 1985). Hardness of ground water of the GLWQD ranged from 6 to 340 mg/L. Many GLWQD residents use water softeners to reduce the hardness of their well water.

MAGNITUDE AND EXTENT OF NITRATE IN GROUND WATER

In 1998, samples collected from 96 sites in the GLWQD were analyzed in the laboratory for nitrate concentrations (tables 1 and 3; figure 13). Most samples were collected from domestic wells; therefore, the water-quality data represent the water that residents drink, rather than the shallower water that might be more affected by land use. Concentrations of nitrite plus nitrate were determined and reported in units of mg/L as nitrogen (N). All nitrite concentrations in this study were at or less than the minimum reporting level of 0.01 mg/L (table 3). The concentration of nitrate is equal to the difference between the concentration of nitrite plus nitrate and the concentration of nitrite. Because nitrite concentrations were negligible, nitrite plus nitrate concentrations are considered essentially equivalent to nitrate concentrations in this report.

Nitrate concentrations for ground-water samples collected from the GLWQD in 1998 ranged from less than the minimum reporting level of 0.05 to 13 mg/L (tables 1 and 3). Nitrate concentrations (10 and 13 mg/L) equaled or exceeded the U.S. Environmental Protection Agency drinking-water standard (10 mg/L) in water from 2 of the 96 sites sampled. Figure 14 illustrates the range of nitrate concentrations (data from table 3 only) and the relations between nitrate concentrations, hydrogeologic unit, and land use[1]. However, some nitrate concentrations (table 3) are from water near suburban population areas adjacent to irrigated and subirrigated areas and dryland grain. For these data sites, nitrate concentrations were plotted in figure 14 as "Suburban population areas."

Figure 14 shows that nitrate concentrations generally are low in water from the most of the hydrogeologic units of the GLWQD. Nitrate concentrations in water from basin-fill deposits where many residents obtain their water (hydrogeologic units Qal, QTd, and Tb) ranged from 0.18 to 8.1 mg/L (table 3). Median nitrate concentrations for these three units were less than about 3 mg/L. Nitrate concentrations in water from Quaternary and Tertiary undifferentiated deposits (QTd) have a wider range of values and a slightly higher median value than nitrate concentrations in water from Quaternary alluvium (Qal) and the Tertiary Bozeman Group (Tb). Nitrate concentrations in water from sedimentary bedrock (hydrogeologic units TYsaq and KЄscu) ranged from <0.05 to 10 mg/L (fig. 14, table 3), with three of the highest nitrate concentrations (8.0, 8.8, and 10 mg/L) detected in samples from one well (well 02S06E36BDBB01).

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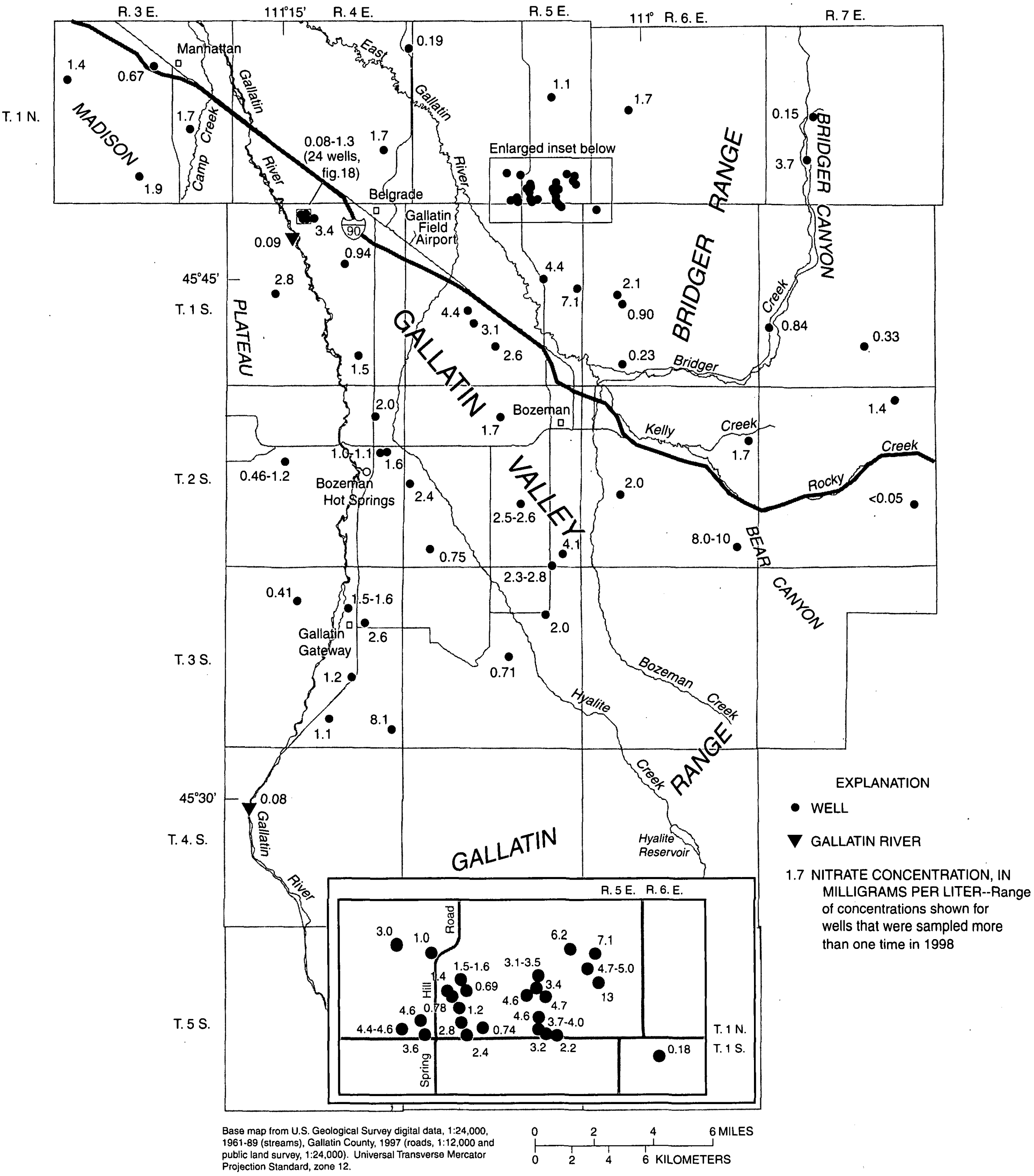
[1] Land-use information is not available for most sites from table 1.



Base map from U.S. Geological Survey digital data, 1:24,000, 1961-89 (streams), Gallatin County, 1997 (roads, 1:12,000 and public land survey, 1:24,000). Universal Transverse Mercator Projection Standard, zone 12.

Figure 13. Nitrate concentrations in ground water and the Gallatin River, Gallatin Local Water Quality District, Montana, 1998. Samples collected and analyzed by U.S. Geological Survey.

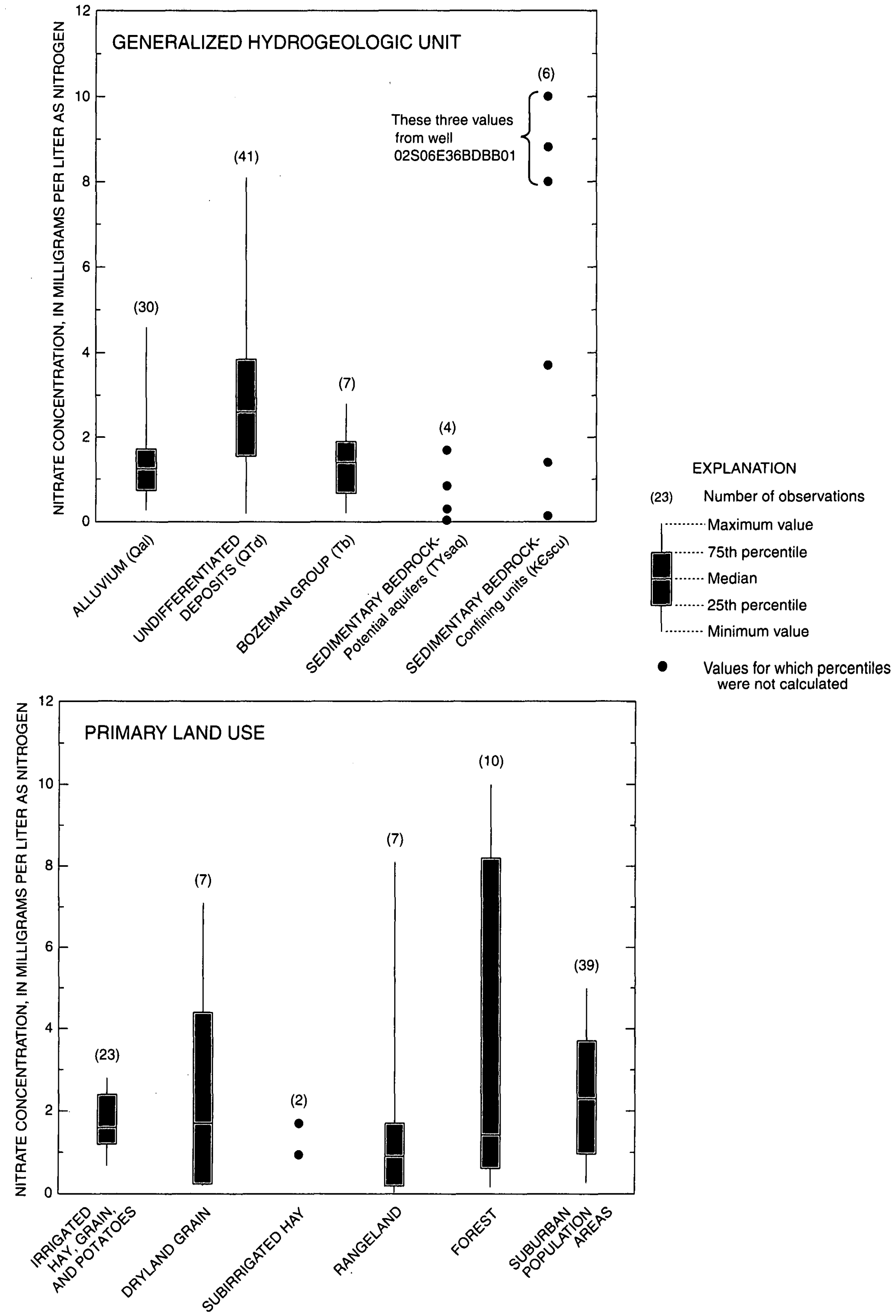


Figure 14. Range of nitrate concentrations in ground water in relation to hydrogeologic unit and land use, Gallatin Local Water Quality District, Montana, 1998. Nitrate concentrations reported as less than the minimum reporting level (0.05 mg/L) are plotted as one-half the minimum reporting level. Several sites include multiple analyses. Samples collected and analyzed by the U.S. Geological Survey (table 3).

Figure 14 also shows that nitrate concentrations generally are low in water from wells in all land-use categories. Median nitrate concentrations for all land-use categories were less than 3 mg/L. Nitrate concentrations in water from wells in irrigated and subirrigated parts of the GLWQD ranged from 0.67 and 2.8 mg/L. Nitrate concentrations in water from wells in areas where dryland grain production, rangeland, and forests were the dominant land-use categories varied widely and ranged from <0.05 to 10 mg/L. However, for these three land-use categories, the median nitrate concentration was about 1.2 mg/L (the combined concentrations). Three of the four highest nitrate concentrations (8.0, 8.8, 10 mg/L) in these three categories were determined from one well (well 02S06E36BDBB01). Nitrate concentrations in water from suburban population areas ranged from 0.26 to 5.0 mg/L, with a median concentration of about 2.3 mg/L (fig. 14, table 3).

Nitrate concentrations in ground water can fluctuate seasonally owing to changing environmental conditions such as fertilizer application, quality of recharge water, and water-table levels (Hallberg and Keeney, 1993). Examples of seasonal changes in nitrate concentrations in water from four wells located in the Gallatin Valley during 1998 are shown in figure 15. The cause of the minor degree of seasonal variability in nitrate concentration (generally less than 1.5 mg/L) cannot be determined from the available data.

POTENTIAL SOURCES OF NITRATE IN GROUND WATER

Potential sources of nitrate to ground water in the GLWQD include runoff from areas of timber harvests, atmospheric deposition, livestock waste, fertilizer, soil organic nitrogen, and domestic septic-system effluent. Generally, the more permeable the soil and the shallower the water table, the greater the likelihood that nitrate from these sources will percolate to ground water. However, additional factors specific to each potential source also control the movement of nitrate. The sources discussed below have not been quantified

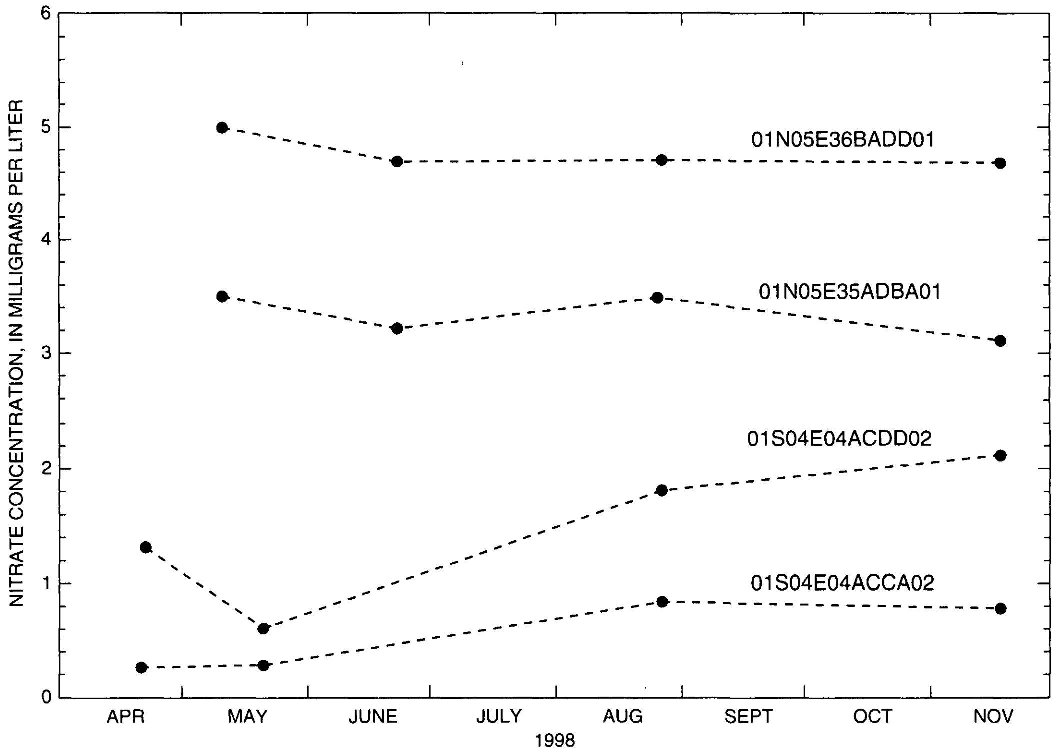


Figure 15. Seasonal changes in nitrate concentrations in water from selected wells in the Gallatin Local Water Quality District, Montana.

in terms of their relative contribution to nitrate in ground water but are presented in a general manner to conceptually support the potential relation between nitrate concentrations and spatial variations in land use.

Timber Harvests

Timber has been harvested from forests in Gallatin County for more than 100 years ([Montana] State Engineer's Office, 1953a). Timber harvests can accelerate soil erosion which might generate nitrogen-rich runoff (Likens and others, 1970). Harvests also reduce the amount of nitrogen uptake from soils by trees, thereby increasing the amount of nitrogen available for infiltration to aquifers (Hallberg and Keeney, 1993). Data are insufficient to describe nitrogen-rich runoff resulting from timber harvests as a potential source of nitrate in ground water. However, nitrogen-rich runoff from logged areas might be a source of nitrate in ground water in permeable basin-fill deposits downslope from areas where timber has been harvested in the GLWQD.

Atmospheric Deposition

Nitrogen oxides in the atmosphere are present naturally and from the combustion of fossil fuels. These oxides undergo various chemical alterations that produce nitrate (Hem, 1985). In 1995, precipitation in the GLWQD had an average nitrate concentration of about 0.1 mg/L, or a total annual wet deposition of 200,000 lb of nitrogen (900,000 lb of nitrate) over the 816-mi^2 area of the GLWQD. An additional 0.1 mg/L, or 200,000 lb, of nitrogen was deposited in the form of wet ammonium (NH_4^+) (National Atmospheric Deposition Program/National Trends Network, 1996). Measurements of nitrogen in dry deposition are not available for Montana but may be as much as 1.5 times the amount contained in wet deposition (D.L. Sisterson, Argonne National Laboratory, oral commun., 1998). Using this ratio and assuming that all the nitrogen in atmospheric precipitation--both wet and dry--directly recharged ground water, then about 0.5 mg/L nitrate in ground water could be derived from atmospheric deposition. Lower nitrate concentrations in ground water could result if this nutrient is used by vegetation; higher concentrations could result from evapoconcentration if nitrate concentrations increase as water evaporates from the land surface, especially in fallow parts of fields used for dryland grain production.

$\delta^{15}N_{NO3}$ values for precipitation range from about -7 to +2.5‰ and are typically lower than values for other sources (Hubner, 1986; LeTolle, 1980; Heaton, 1986). Well 01S06E06ABCB01 is completed in alluvial-fan deposits upgradient from any human activity and produced water with a nitrate concentration of 0.18 mg/L and a $\delta^{15}N_{NO3}$ value of +1.6‰ (fig. 16, table 3). These data indicate that water from this well probably was recharged by precipitation and not subsequently influenced by human activity. Water from two shallow wells (01S04E04ACAC01 and 01S04E04ACCA02) that were recharged in the 1990s (fig. 8) by the Gallatin River also had low nitrate concentrations (range of 0.26 to 0.84 mg/L) and $\delta^{15}N$ values (+1.1 and +2.4‰). Although $\delta^{15}N_{NO3}$ was not determined for water from the Gallatin River, atmospheric precipitation in the Gallatin River watershed (970 mi^2 above Manhattan; 825 mi^2 above the Gallatin Valley) probably is the major source of nitrate to the river and would impart a low $\delta^{15}N_{NO3}$ value to Gallatin River water, similar to values in these wells. Water from nearby wells (SW1/4 NE1/4 sec. 4, T. 1 S., R. 4 E.) had nitrate concentrations ranging from 0.08 to 1.3 mg/L (table 1 and Montana Microbiological Services, Bozeman, Mont., written commun., 1998). In addition, water from bedrock wells that were sampled east of the Gallatin Valley had a nitrate concentration of less than 0.5 mg/L, indicating a nitrate source attributable primarily, if not completely, to atmospheric deposition.

Although the several wells described above had $\delta^{15}N_{NO3}$ values indicative of recharge from precipitation, most ground water sampled during this study had nitrate concentrations that exceeded what could be expected from atmospheric deposition or precipitation (fig. 16). Therefore, an additional source or sources can be inferred to have contributed nitrate to ground water. These other potential sources include livestock waste, fertilizer, soil organic nitrogen, and domestic septic-system effluent.

Livestock Waste

Livestock produce nitrogen-rich organic waste that can oxidize to form nitrate. Cattle have been the primary stock raised in Gallatin County since about 1944 (Montana Agricultural Statistics, issued annually). In 1992, farm operators in Gallatin County raised 61,960 cattle and calves, 1,980 horses and ponies, and

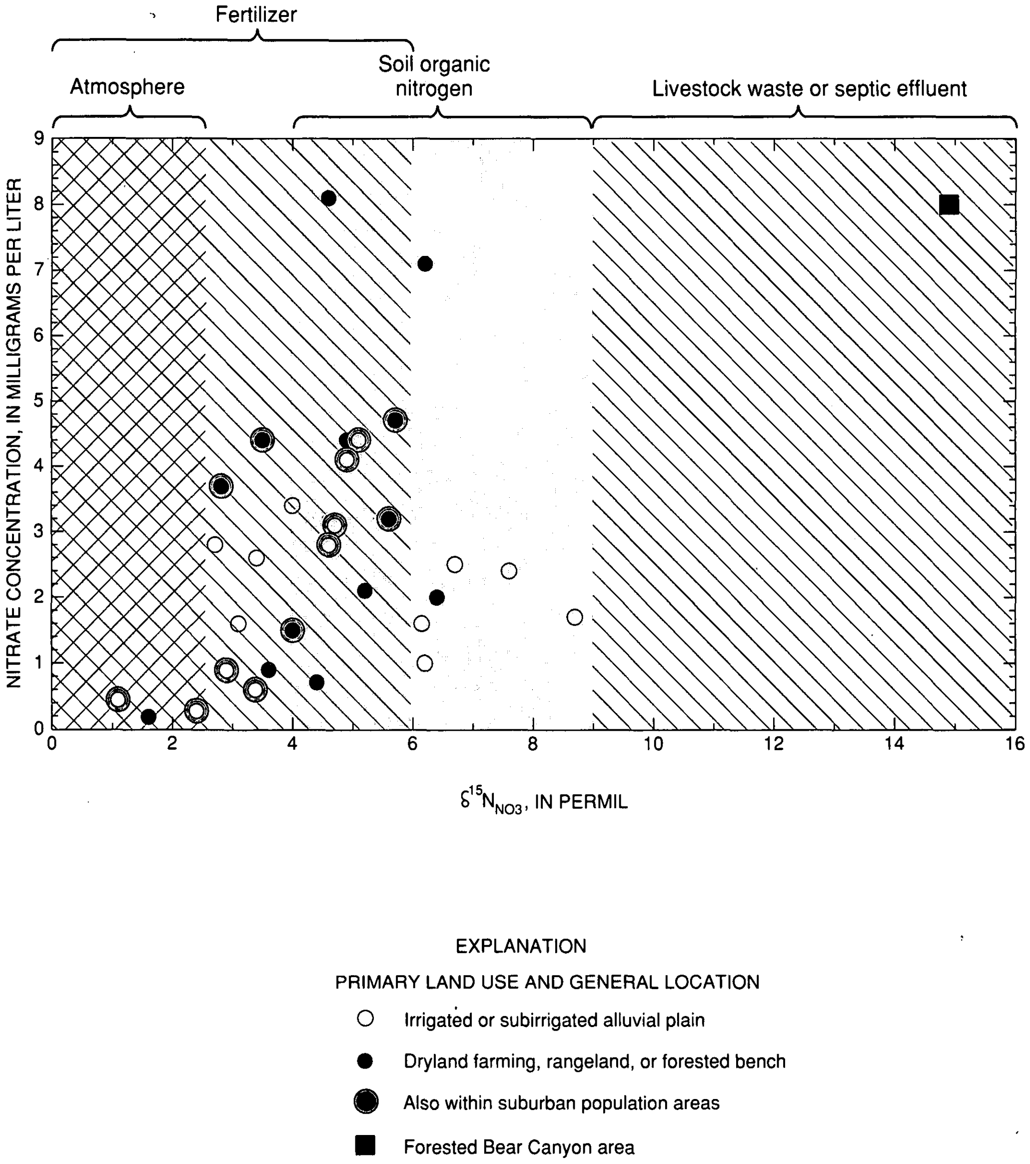


Figure 16. Relation between nitrate concentrations and $\delta^{15}N_{NO3}$ values for ground water in the Gallatin Local Water Quality District, Montana. All wells were completed in Cenozoic basin-fill deposits (Qal, QTd, and Tb) except for one well in forested Bear Canyon area, which was completed in Cretaceous shale (K€scu). Patterns indicate typical ranges of $\delta^{15}N_{NO3}$ values for various nitrate sources (Kreitler, 1975; Boyce and others, 1976; Gormly and Spalding, 1979; Wolterink and others, 1979; LeTolle, 1980; Spalding and others, 1982; Heaton, 1986; Hubner, 1986).

3,650 hogs and pigs (U.S. Department of Commerce, 1994). If the average cow, horse, and pig excrete 156, 128, and 150 lb of nitrogen per year, respectively (Van Vuren, 1949, p. 158), then waste from these animals produced about 10.5 million lb of nitrogen in Gallatin County in 1992. Livestock waste from concentrated feeding operations is applied to farmland, whereas waste from range livestock is not managed. The quantity of nitrate leached from livestock waste to ground water depends on the quantity of nitrate in the waste, the infiltration rate, the soil texture, and the ambient air temperature (National Academy of Sciences, 1978).

$\delta^{15}N_{NO3}$ values of nitrate from livestock waste typically range from +9 to +22‰ (fig. 16; Kreitler, 1975; Gormly and Spalding, 1979; Lindau and Spalding, 1984; Heaton, 1986). Water from one well completed in alluvium and 1,500 ft downgradient from a livestock waste land-application area (well 01S04E04ADDD01) had a nitrate concentration of 3.4 mg/L and a $\delta^{15}N_{NO3}$ value of +4.0‰ (fig. 16). However, the $\delta^{15}N_{NO3}$ value for this well is within the reported range for fertilizer and soil organic nitrogen (fig. 16).

Conceivably, the observed $\delta^{15}N_{NO3}$ value of +4.0‰ might have resulted from the mixing of atmospheric nitrate with livestock waste-derived nitrate. To assess this possibility, hypothetical mixing curves were calculated. The $\delta^{15}N_{NO3}$ value of a water sample that is a mixture of water from two sources is:

$$\delta^{15}N_m = \frac{(\delta^{15}N_a)(C_a)(P_a) + (\delta^{15}N_b)(C_b)(P_b)}{(C_a)(P_a) + (C_b)(P_b)} \qquad (2)$$

and the concentration of nitrate in the mixture is:

$$C_m = (C_a)(P_a) + (C_b)(P_b) \qquad (3)$$

where $\delta^{15}N$ is the $\delta^{15}N_{NO3}$ value, C is the nitrate concentration, and P is the percent by volume, and the subscripts *m*, *a*, and *b* represent mixed, source a, and source b water, respectively (Davidson and Bassett, 1993).

The curves shown in figure 17A represent the mixing of two waters, as calculated using these equations. The first water is atmospheric water (source a, equations 2 and 3) with a nitrate concentration of 0.28 mg/L and a $\delta^{15}N_{NO3}$ value of +2.4‰ (as sampled from well 01S04E04ACCA02, which is located about 2,000 ft (0.4 mi) west of well 01S04E04ADDD01). The second water is wastewater from livestock (source b, equations 2 and 3). Because the wastewater is hypothetical, its nitrate concentration and $\delta^{15}N_{NO3}$ values are unknown. Therefore, two plausible wastewaters were used to generate separate mixing curves that bracket possible mixtures of atmospheric water with livestock wastewater. The two plausible livestock wastewaters have nitrate concentrations of 5 and 50 mg/L and $\delta^{15}N_{NO3}$ values of +9 and +15‰, respectively. The point having a nitrate concentration of 3.4 mg/L and a $\delta^{15}N_{NO3}$ value of +4.0‰, representing the sample from well 01S04E04ADDD01, does not plot between the two mixing curves shown in figure 17A. Therefore, based on the nitrogen isotopic values, fertilizer or soil-organic nitrogen--not livestock waste--are more likely sources of nitrate in the sample from this well.

Fertilizer and Soil Organic Nitrogen

Fertilizers contain nitrogen as nitrate or in other forms which, if not used by plants, contribute nitrate to the soil. Nitrate is soluble in water and can easily leach to the water table. Over-application of fertilizers to cropland has resulted in extensive nitrate contamination of aquifers in many agricultural areas of the United States (Bohlke and Denver, 1995; Nolan and others, 1997). Dissolved constituents in fertilizers, including nitrate, can percolate and infiltrate through the permeable, gravelly loam soils into the basin-fill deposits.

The acreage of fertilized farmland in Gallatin County has increased more than 5-fold since 1954 (U.S Department of Commerce, issued periodically), even as the total acreage of farmland has decreased (fig. 6). In 1992, a wide variety of commercial fertilizers was applied to about 127,650 acres of cropland in Gallatin County (U.S. Department of Commerce, 1994). Irrigated wheat typically receives 80-100 lb of nitrogen per acre in the form of ammonium nitrate or urea, irrigated barley requires somewhat less nitrogen, and alfalfa fertilizers contain no nitrogen. Seed potatoes, which are cultivated on the northern part of the Madison Plateau, are the most heavily fertilized crop in the GLWQD. Most potato farmers apply about 150 to 200 lb of nitrogen per acre in the form of ammonium-nitrate fertilizer every fall. Dryland wheat and barley fields are fertilized with 60-70 lb of nitrogen per acre in the form of urea (D.E. Heck, CCA, Crop Production Specialist, Gallatin Farmers Cooperative, Belgrade, Mont., oral commun., 1998). Assuming a uniform nitrogen application rate of 60 lb per acre to all fertilized cropland in the county, roughly 7.7 million lb of nitrogen may be applied annually to cropland in the form of fertilizer.

Fertilizers also are applied to lawns, gardens, and golf courses, primarily in the form of urea. Hantzche and Finnemore (1992) estimated that lawn fertilization in residential subdivisions and rural communities contributes about 1 to 3 lb of nitrogen to ground water per year from each developed acre. The acreage of developed land in the GLWQD has not been determined. However, if one-fifth of the 33 mi^2 (21,000 acres) of urban and subdivided land (fig. 5) is developed, then as much as 12,600 lb of nitrogen might be applied to lawns annually. The amount of nitrogen contributed to

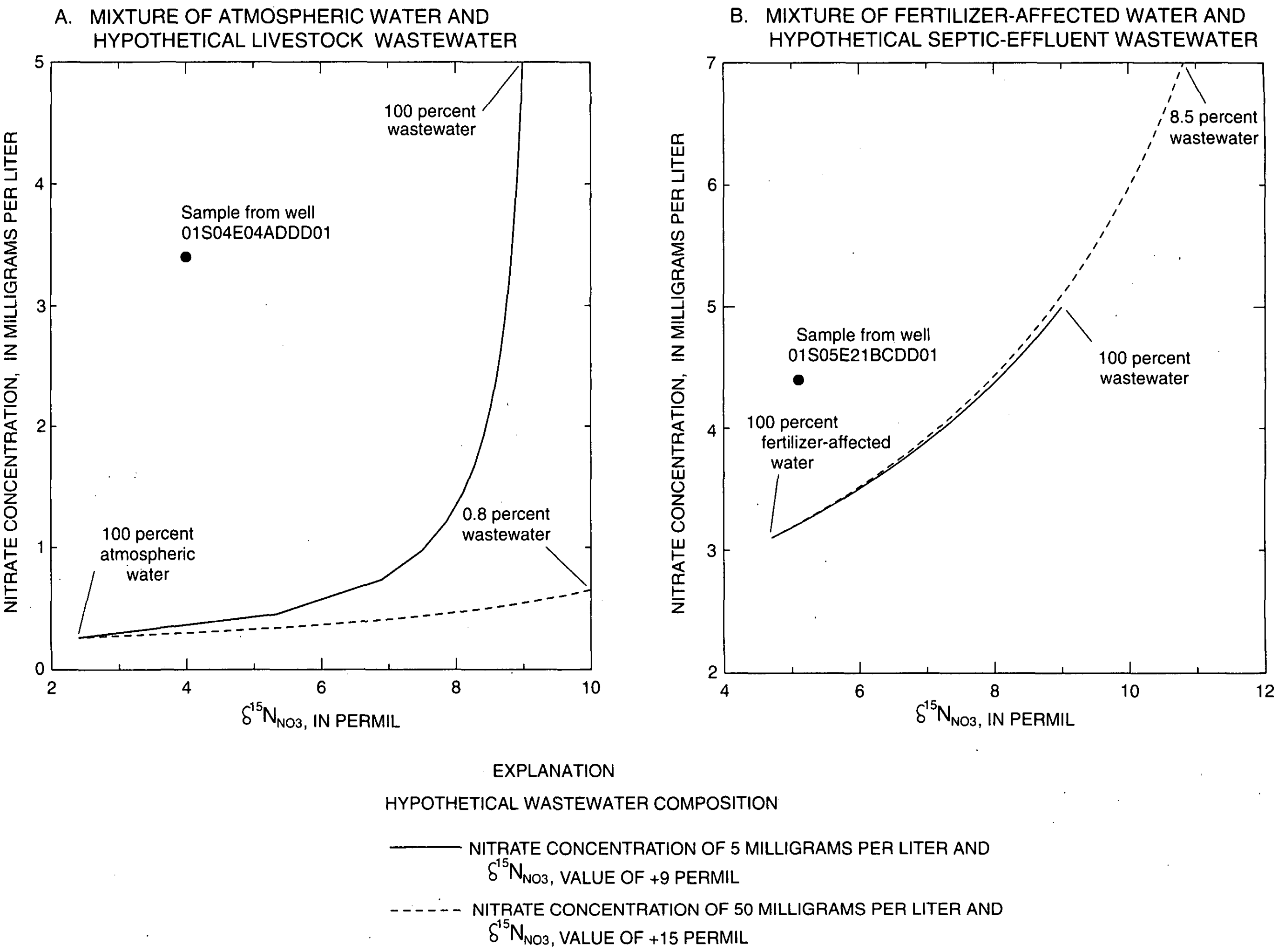


Figure 17. Nitrate concentrations of hypothetical mixed waters as a function of $\delta^{15}N_{NO3}$. In example A, atmospheric water has a nitrate concentration of 0.28 mg/L and a $\delta^{15}N_{NO3}$ value of +2.4 permil (as sampled from well 01S04E04ACCA02). In example B, fertilizer-affected water has a nitrate concentration of 3.1 mg/L and a $\delta^{15}N_{NO3}$ value of +4.7 permil (as sampled from well 01S05E21CDDB01). Several hypothetical wastewater compositions are plotted to show plausible ranges. These mixing curves assume that nitrate is conservative (non-reactive) in ground water.

ground water by fertilizers depends on the type and amount of fertilizer applied, the pH and texture of the soil, the air temperature at the time of application, the amount of water applied after fertilization, and the acreage of fertilized land (Seiler, 1996; Nolan and others, 1997).

Decay of natural organic matter in soil can contribute nitrate to ground water (Nimick and Thamke, 1998). Most of the cropland on the eastern benches of the Gallatin Valley (fig. 5) has been used for growing wheat and barley using crop-fallow rotation. Typically, one-half the farmland in a rotation is left uncropped and weed-free for one growing season. This rotation allows moisture to be stored in the soil below the surficial evaporation zone during the fallow period to complement the cropping-season rainfall. During the fallow period, nitrogen from decaying organic matter is mineralized, resulting in nitrate accumulation in the soil, which provides valuable crop nutrients. However, the added soil moisture can increase the percolation of nitrate into ground water (Power, 1970; Cassel and others, 1971). The quantity of nitrate loading from crop-fallow farming depends on the timing and magnitude of precipitation and the quantity of organic matter and crop residue remaining on the ground after harvest (Nimick and Thamke, 1998).

Nitrogen also is released from natural organic matter when soil is plowed, vegetation is removed, or deep-rooted plants are replaced by shallow-rooted plants, especially if the soil has a large organic component (Lamb and others, 1985). For example, alfalfa is extensively grown in the Gallatin Valley. As a natural nitrogen fixer, alfalfa stores a large quantity of nitrogen in its rhizomes, which may extend as deep as 15 ft below the land surface. When alfalfa fields are converted to other land uses such as residential development, the stored nitrogen in the remnant roots oxidizes to nitrate and can leach into soils and aquifers if not used by other vegetation (Spalding and others, 1982; Hallberg and Keeney, 1993).

Most of the ground-water samples collected in the GLWQD had $\delta^{15}N_{NO3}$ values within the +2.5 to +9‰ range, which coincides with the range expected for nitrate derived from fertilizer or soil organic nitrogen (fig. 16). Eight samples had values indicating fertilizer (+2.7 to +3.6‰), seven samples had values indicating soil organic nitrogen (+6.2 to +8.7‰), and 12 samples had values that could indicate either source (+4.0 to +5.7‰). Owing to the possibility of mixed sources, nitrate from soil organic nitrogen cannot be distinguished from fertilizer nitrate in these samples on the basis of $\delta^{15}N_{NO3}$.

CFC data (table 4, fig. 8) indicate that water from wells completed in basin-fill deposits in unirrigated areas along the eastern benches was recharged prior to the 1990s, when the quantity of nitrogen in fertilizers increased to allow for continuous cropping. Also in the 1990s, subdivision development increased on the benches. Where continuous-cropped agricultural land is converted to subdivisions, increased loading of nitrate from the unconsumed soil organic nitrogen could result in increased concentrations of nitrate in ground water. However, if crop-fallow farming is the main source of soil organic nitrate, then concentrations might decrease following the decline in crop-fallow practices and the associated decrease in deep percolation of water in fallow fields.

Irrigation can facilitate the movement of nitrogen from fertilizers through the permeable Gallatin Valley soils and into underlying aquifers. However, nitrate concentrations in ground water in the Gallatin Valley are not as high as in other agricultural areas of the United States, where nitrate concentrations frequently exceed 10 mg/L (Hem, 1985; Hallberg and Keeney, 1993). Relatively low fertilizer application rates and dilution from snowmelt-derived irrigation water could result in the relatively low nitrate concentrations in ground water of the Gallatin Valley.

In contrast to the irrigated and subirrigated alluvial plain, the eastern benches are not irrigated. Although most of the wells on these unirrigated benches yielded water with relatively low nitrate concentrations, some samples with higher nitrate concentrations (from about 4 to 13 mg/L; fig. 13) were obtained from wells completed beneath these benches. The wells with higher nitrate concentrations were located downgradient from dryland farming areas and, in some cases, in subdivisions where land use changed from rangeland or dryland farms to residential development. Many of these wells are completed beneath thick (40 to 150 ft), fine-grained, unsaturated zones that might have been expected to decrease nitrate concentrations by denitrification of recharge water from the land surface.

The higher nitrate concentrations in some water beneath the eastern benches relative to the alluvial plain (fig. 13) probably are related more to the quantity of ground-water recharge than to the source of the nitrate. As stable-isotope data indicate (fig. 11), ground water beneath the irrigated and subirrigated alluvial plain is recharged by the Gallatin River or irrigation water. In contrast, ground water beneath the eastern benches is recharged locally by snowmelt, seepage from ephemeral streams, and summer rainfall. Low well yields in the eastern bench areas (Custer, 1991) indicate that ground-water flow is limited. With limited recharge and flow, nitrate in water beneath these benches is not diluted to the same extent as the irrigated and subirrigated areas. Moreover, limited stable-isotope data (fig. 11; water from three wells) indicate that some of the recharge to the aquifer is affected by evaporation. Transpiration by plants likely concentrates some dissolved constituents in water. Although nitrate was the focus of this investigation, evapoconcentration and limited recharge also could result in higher concentrations of any conservative (non-reactive) constituent that infiltrates to ground water beneath the unirrigated benches compared to the irrigated alluvial plain.

Based on the interpretations presented in this section, fertilizers and soil organic nitrogen probably contribute most of the nitrate found in ground water beneath the Gallatin Valley. However, if $\delta^{15}N_{NO3}$ values exceeded 9‰, then livestock waste or domestic septic-system effluent would be inferred as the major source of nitrate to ground water. $\delta^{15}N_{NO3}$ values in the range of +2.5 to 9‰ can result from a mixture of sources. For example, using equations 2 and 3, water with a nitrate concentration of 3.1 mg/L and a $\delta^{15}N_{NO3}$ value of +4.7‰ (well 01S05E21CDDB01) might have originated as fertilizer, soil organic nitrogen (fig. 16), or a mixture of 95 percent fertilizer nitrogen (hypothetical nitrate concentration of 2.8 mg/L and +3‰ $\delta^{15}N_{NO3}$) and 5 percent domestic septic-system effluent (hypothetical nitrate concentration of 9 mg/L and +15‰ $\delta^{15}N_{NO3}$).

Domestic Septic-System Effluent

Domestic septic systems are designed to reduce the amount of nitrogen in human waste by ammonia volatilization, denitrification, sorption onto sediments, and retention in organic matter. In recent years, Gallatin County has issued more than 500 septic permits per year. Approximately 7,000 septic systems served residences in the GLWQD in 1998 (S.G. Custer, oral commun., 1998) The average home in rural Gallatin County houses 2.7 people, and the average per capita discharge is about 45 gallons of wastewater per day (Hay, 1997). Average total-nitrogen concentrations in septic-tank effluent range from about 35 to 90 mg/L (Walker and others, 1973; U.S. Environmental Protection Agency, 1980; Alhajjar and others, 1989). On the basis of these estimates, septic systems in the GLWQD discharge about 91,000 to 230,000 lb of nitrogen per year. The quantity of nitrate contributed to ground water depends on the actual quantity of wastewater, the depth to ground water, soil characteristics, and the design and upkeep of septic tanks and drainfields.

Soil properties are critical to septic system function. Clayey soils that shrink and swell, such as those derived from weathered Cretaceous shales in the Bridger and Bear Canyon areas, can impede septic system performance by clogging drainfields and possibly cracking septic tanks and associated plumbing. Sodium chloride from water softeners can make this problem worse by causing clayey soils to expand irreversibly (Gretchen Rupp, Montana State University Extension Service, oral and written commun., 1998).

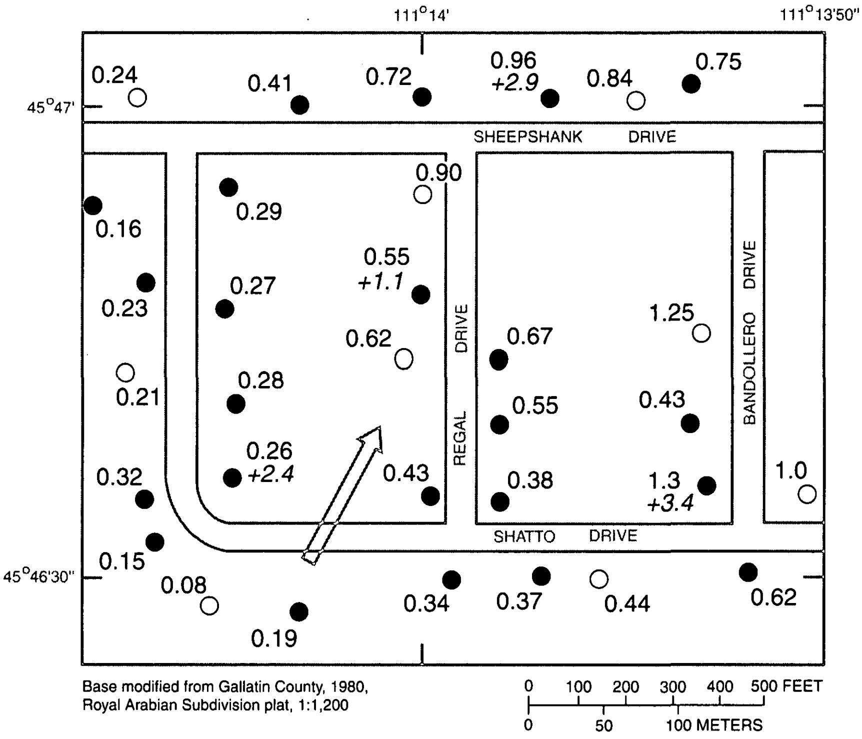
In the absence of other nitrate sources, $\delta^{15}N_{NO3}$ values for ground water affected by domestic septic-system effluent fall in the same +9 to +22‰ range (fig. 16) as water affected by livestock waste (Kreitler, 1975; Gormly and Spalding, 1979; Lindau and Spalding, 1984; Heaton, 1986). The only water sample from the GLWQD that fell within that range was collected from the 75-ft domestic well in Bear Canyon (02S06E36BDBB01) with a $\delta^{15}N_{NO3}$ value of +14.9‰ and a history of elevated nitrate concentrations (8 to 50 mg/L; D.N. Whitson, oral commun., 1998; and Cynthia Crayton, oral commun., 1998, 1999). Based on the nitrate concentrations and $\delta^{15}N_{NO3}$ value, and in consideration of the local soil properties and possible sources of nitrate, this sample is probably affected by livestock waste or domestic septic-system effluent.

To evaluate the effects of domestic septic-system effluent on ground-water quality in other areas, water-quality data were collected from domestic wells on both the upgradient and downgradient edges of three subdivisions with lot sizes of 1 acre or less: Hyalite Heights, Baxter Creek, and Royal Arabian subdivisions (fig. 5).

In the Hyalite Heights subdivision (SW1/4, sec. 36, T. 2 S., R. 5 E.), the two sampled wells are located about 0.5 mi apart with six rows of intervening houses, each with an individual well and septic system. In May 1998, nitrate concentrations measured in upgradient (well 02S05E36CCCD01) and downgradient (well 02S05E36CAAB01) ground water were 2.3 and 4.1 mg/L, respectively. In May and August the corresponding $\delta^{15}N_{NO3}$ values in water from these two wells were +4.6 (May) and +4.9‰ (August). According to drillers' logs, the wells were constructed with open-ended steel casing instead of screens, and completed in sand and gravel at depths of 51.5 and 45 ft, respectively. Interpretations of CFC data indicate that the ground water was recharged in the 1980s and 1990s (fig. 8), more than a decade after most of the homes in the subdivision were constructed.

In the Baxter Creek subdivision (SW1/4, sec. 21, T. 1 S., R. 5 E.), the two sampled wells also are located about 0.5 mi from one another. In May 1998, nitrate concentrations in upgradient (well 01S05E21CDDB01) and downgradient (well 01S05E21BCDD01) ground water were 3.1 and 4.4 mg/L, respectively. The corresponding $\delta^{15}N_{NO3}$ values were +4.7 and +5.1‰. The wells were constructed with open-ended steel casing and completed in a sand and gravel lens of a gravelly, clayey sand sequence that extends upward to the topsoil. Both wells are 83 ft deep. Interpretation of CFC data indicate ground water was recharged in the 1980s (fig. 8). Homes in the upgradient part of the subdivision were constructed in the 1970s and 1980s, and homes in the downgradient part were constructed in the 1990s.

Water in Quaternary alluvium (Qal) beneath the western part of the Royal Arabian subdivision (SW1/4NE1/4 sec. 4, T. 1 S., R. 4 E.) was sampled to describe the magnitude and extent of nitrate in water of a densely developed subdivision. The approximately 50-acre focus area is located on mostly level ground about 0.5 mi east of the Gallatin River. Prior to residential development in 1992-94, the area was used as farmland and irrigated with water diverted from the Gallatin River ([Montana] State Engineer's Office, 1953b). In 1992-94, the land was subdivided into 1-acre residential lots. Each residence has a well, septic system, and drainfield. These wells were constructed with open-ended steel casing at depths ranging from 57 to 80 ft (median depth of 60 ft) in gravel and sand. Water levels in the Royal Arabian subdivision range from about 20 to 40 ft below land surface (table 1). Locally, ground water flows to the northeast (fig. 18).



Base modified from Gallatin County, 1980,
Royal Arabian Subdivision plat, 1:1,200

EXPLANATION

0.15 NITRATE CONCENTRATION, IN MILLIGRAMS PER LITER

● Sample collected April 20-21, 1998 by U.S. Geological Survey

○ Sample collected February 22, 1998 by Gallatin Local Water Quality District and analyzed by Montana Microbial Services (written commun., 1998)

+2.4 $\delta^{15}N_{NO3}$, IN PERMIL--Sample collected May 20-21, 1998

⇨ APPROXIMATE DIRECTION OF GROUND-WATER FLOW--Water-level data determined April 20-21, 1998, from sites with surveyed land-surface altitudes

Figure 18. Nitrate concentrations and $\delta^{15}N_{NO3}$ values in ground water in the western half of the Royal Arabian subdivision, Gallatin Local Water Quality District, Montana, 1998. Location of Royal Arabian subdivision is shown in figure 5.

Based on water-level, CFC, and oxygen-isotope data, alluvium (Qal) underlying the western part of the Royal Arabian subdivision probably was recharged by seepage from the Gallatin River in the early 1990s. Although nitrate concentrations in ground-water samples from the western part of the subdivision are not high, they generally increase in a downgradient direction from about 0.2 to as much as 1.3 mg/L (fig. 18), suggesting that infiltration from the subdivision might contribute some nitrate to the underlying aquifer. Potential sources of nitrate include lawn fertilizers, organic soil nitrogen that has oxidized after the land use changed from agriculture to residential development, and domestic septic-system effluent. $\delta^{15}N_{NO3}$ values (range of +1.1 to 3.4‰) for samples collected from the western part of the Royal Arabian subdivision (fig. 18) indicate atmospheric deposition (or the Gallatin River) and fertilizer as sources of nitrate in ground water (fig. 16).

The $\delta^{15}N_{NO3}$ values for ground-water samples from the three subdivisions ranged from +1.1 to +5.1‰, which is well below the +9‰ minimum associated with domestic septic-system effluent, but within the reported range for atmospheric deposition, fertilizers, and soil organic nitrogen. If the background isotopic composition is caused either by atmospheric deposition or by fertilizers, and domestic septic-system effluent contributes additional nitrate to ground water beneath the subdivisions, then $\delta^{15}N_{NO3}$ values would be expected to increase downgradient. However, mixtures of background water and septic wastewater cannot explain the downgradient increases. To illustrate, figure 17B shows mixing curves for upgradient ground water beneath Baxter Creek subdivision ("fertilizer-affected water" sample from well 01S05E21CDDB01, 3.1 mg/L nitrate and +4.7‰ $\delta^{15}N_{NO3}$) mixed with two plausible septic-effluent wastewaters. The downgradient sample from beneath Baxter Creek subdivision (well 01S05E21BCDD01, 4.4 mg/L nitrate and +5.1‰ $\delta^{15}N_{NO3}$) does not plot on or near these curves, indicating that the hypothetical mixtures could not produce the sample.

In contrast, nitrogen from fertilizers or soil organic nitrogen can explain the downgradient increase in nitrate concentrations. From equations 2 and 3, a mixture of 50 percent water from upgradient well 01S05E21CDDB01and 50 percent fertilizer-affected water from a hypothetical source (5.7 mg/L nitrate and +5.3‰ $\delta^{15}N_{NO3}$) produces the water from downgradient well 01S05E21BCDD01. Based on analogous calculations, ground-water samples collected from the Royal Arabian and Hyalite Heights subdivisions also were not affected by domestic septic-system effluent.

The ratio of chloride to bromide concentrations in ground water can be used to help identify water that has been affected by domestic septic-system effluent. Because humans consume and dispose of salt, or sodium chloride, effluent from septic systems commonly has elevated concentrations of chloride. Both chloride and bromide tend to be conservative (or nonreactive) and can originate from atmospheric deposition or mineral dissolution, but only chloride is usually associated with domestic septic-system effluent. A high ratio of chloride to bromide compared to other waters from an area may indicate the presence of domestic septic-system effluent (Davis and others, 1998; Vengosh and Pankratov, 1998) and, therefore, can be used to trace discharge from septic systems.

The ratios of chloride to bromide concentrations[2] in most of the samples collected from the GLWQD in 1998 average about 90:1 (fig. 19). This ratio is typical for atmospheric deposition in inland areas such as the GLWQD (Davis and others, 1998). Therefore, the chloride and bromide in most of these samples probably originate from this source. Evapoconcentration is the likely principal reason for the order-of-magnitude range in concentrations. Hence, the chloride and bromide data provide additional evidence that domestic septic-system effluent has not affected most ground water of the GLWQD.

Chloride to bromide ratios higher than the average (90:1) indicate that ground water might be affected by domestic septic-system effluent. For four wells, the chloride to bromide ratio in water ranged from 147 to

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[2] Some bromide concentrations in ground water were reported as less than the minimum reporting level of 0.01 mg/L. For these analyses, the ratios of chloride to bromide were not used to calculate the average ratio of 90:1. In addition, the chloride and bromide concentrations in water from wells 01S05E21BCDD01, 02S04E16BCCA01, 02S06E36BDBB01, and 02S05E36CAAB01 were not used to calculate the average ratio of 90:1 because the water from these wells might be affected by domestic septic-system effluent.

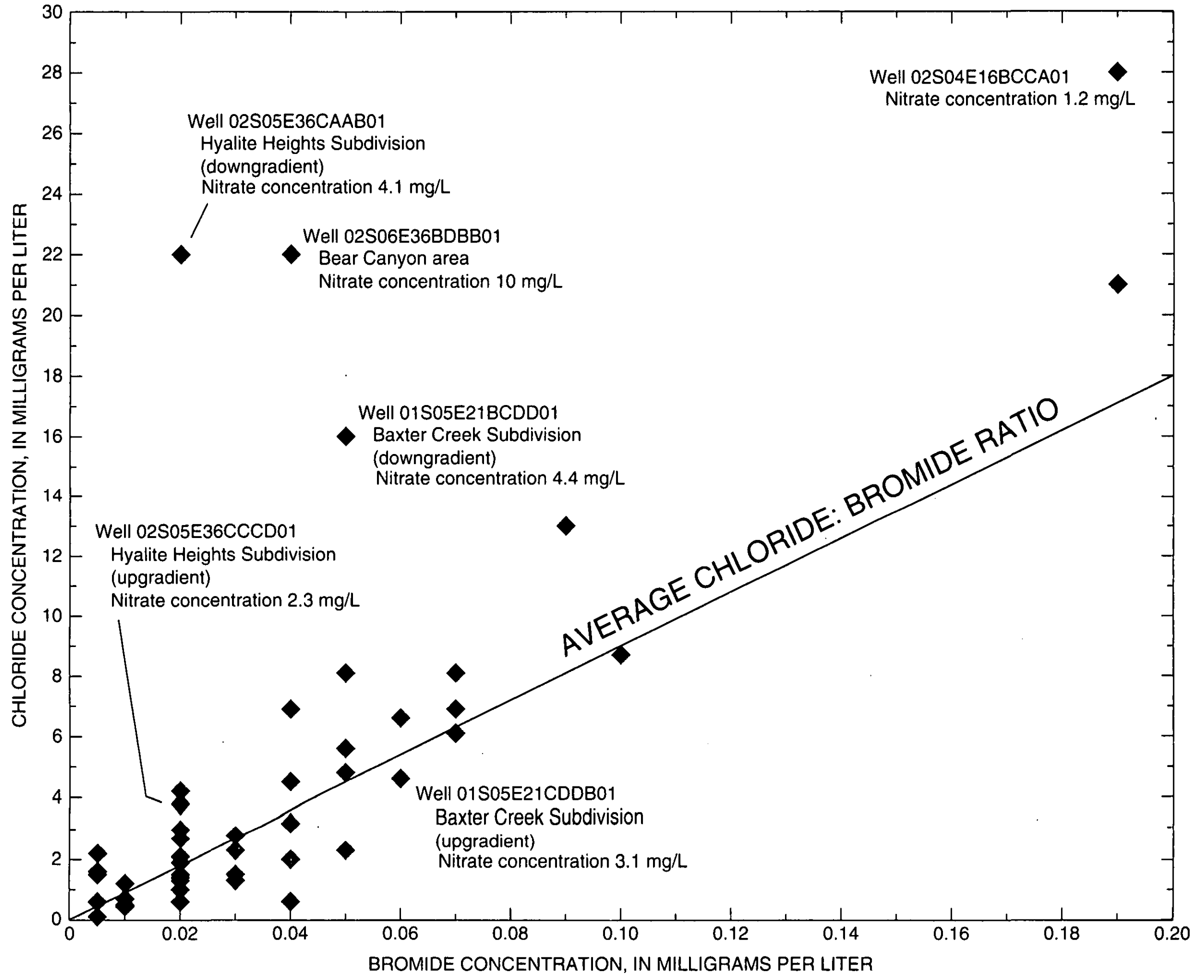

Figure 19. Relation between chloride and bromide concentrations in ground water, Gallatin Local Water Quality District, Montana, 1998. Diagonal line through data represents the average ratio of chloride to bromide in all samples except those with bromide concentration less than the minimum reporting level and the four outliers noted in the text. Bromide concentrations below the minimum reporting level of 0.01 mg/L are plotted as 0.005 mg/L.

1,100. A chloride to bromide ratio of 550, elevated nitrate concentrations, and the $\delta^{15}N_{NO_3}$ value indicate that water from well 02S06E36BDBB01, located in Bear Canyon, is affected by livestock waste or domestic septic-system effluent. Well 02S04E16BCCA01 is completed in the Tertiary Bozeman Group, in a subdivision consisting of 20-acre lots located on the eastern edge of the Madison Plateau. The $\delta^{15}N_{NO_3}$ value for this water is unknown, but specific conductance and concentrations of chloride and nitrate were greater in 1998 than in 1992 (table 1).

Two wells (02S05E36CAAB01 and 01S05E21BCDD01) are located on the downgradient edges of the Hyalite Heights and Baxter Creek subdivisions. The ratios of chloride to bromide concentrations were 1,100 and 320, respectively, which seems to indicate that water from these two wells is affected by domestic septic-system effluent. However, low $\delta^{15}N_{NO_3}$ values (+5.1 and +4.9 ‰) for these wells indicate that nitrate from domestic septic-system effluent has not affected these samples. Possible sources of chloride to ground water beneath these subdivisions include water softeners (which discharge sodium chloride as domestic septic-system effluent) and fertilizers, which contain varying amounts of chloride.

Although high chloride concentrations relative to bromide concentrations can indicate possible effects of domestic septic-system effluent on ground-water quality, $\delta^{15}N_{NO3}$ values are a better indicator of the nitrate source in ground water. Analysis of nitrate, chloride, and bromide concentrations in ground water can provide reconnaissance data to identify potential areas of septic contamination, which can then be used to reduce the number of samples subsequently collected for more definitive identification by $\delta^{15}N_{NO3}$ analysis.

SUMMARY

The population of Gallatin County has increased rapidly in recent years, and much of the associated new development has been concentrated in the northern part of the county. In response to increasing public concerns about the sustainability of the local water resources, the Gallatin Local Water Quality District (GLWQD) was established in 1995 to preserve, protect, and improve the quality of surface and ground water of the District. This report, prepared in cooperation with the GLWQD, describes the magnitude, extent, and sources of nitrate in ground water in the GLWQD. The magnitude and extent of nitrate in ground water were determined by sampling 96 sites and the Gallatin River in 1998. Sources of nitrate were determined by analyzing the spatial patterns of various water-quality constituents (major ions, nutrients, and stable isotopes); comparing land uses to ground-water quality; and age-dating ground water using chlorofluorocarbons (CFCs).

The GLWQD encompasses most of the Gallatin Valley, which is an approximately north-south-trending intermontane basin about 520 mi^2 in area consisting of a broad alluvial plain flanked on the west by the Madison Plateau and on the east and south by smaller benches. West of the alluvial plain, the Madison Plateau is a broad bench at an altitude of more than 5,000 ft that drains northeastward into the Gallatin River. Some smaller benches, or terraces, that flank the eastern and southern parts of the valley are mantled by alluvial fans, the largest of which extends well into the alluvial plain between Hyalite and Bozeman Creeks. The Gallatin River and its tributaries drain most of the GLWQD. Mountainous areas compose almost one-half of the GLWQD. East and south of the Gallatin Valley, the sparsely populated Bridger and Gallatin Ranges rise from the valley floor. The crest of the Gallatin Range, with an altitude of more than 10,000 ft, is the highest part of the GLWQD. East of the Bridger Range, Bridger Creek drains the mountainous Bridger Canyon area.

Land use in the GLWQD is predominantly agricultural. Irrigated and dryland farm crops include hay, grain, potatoes, and native grass. Residential and commercial developments have replaced farmland on both the alluvial plain and the benches. The mountainous parts of the GLWQD are forested and are used for timber harvesting, cattle grazing, and recreation.

In general, geologic units of the GLWQD consist of poorly consolidated Cenozoic basin-fill deposits and complexly folded and faulted Tertiary through Archean bedrock in the mountains. These geologic units can be grouped into seven hydrogeologic units. Basin-fill deposits can contain aquifers which are unconfined, leaky confined, or confined. Aquifers in basin-fill deposits that consist of Quaternary alluvium commonly are unconfined and highly productive. Fine-grained layers within Tertiary deposits can restrict flow into or out of more permeable layers, which result in leaky-confined or confined aquifers. With depth, these fine-grained layers become more consolidated and, therefore, less permeable. However, some Tertiary basin-fill deposits contain productive aquifers.

Some bedrock units also are aquifers but have not been extensively developed in the GLWQD. Many of these bedrock units contain fine-grained sandstone, shale, mudstone, siltstone, or chert that generally are confining units. Ground water generally is not readily available in many areas where some bedrock units are found.

Water-level, oxygen-isotope, and CFC data indicate that Cenozoic basin-fill aquifers beneath the irrigated and subirrigated parts of the GLWQD are recharged primarily by the Gallatin River and its irrigation diversions. Recharge to basin-fill deposits beneath the benches originates more locally as low-altitude snowmelt, seepage from ephemeral streams, and summer rainfall. On the basis of CFC data, estimated recharge dates for 27 ground-water samples collected in 1998 from the Gallatin Valley range from the 1960s to the 1990s.

Nitrate concentrations generally were low in ground water of the GLWQD and in 1998 ranged from <0.05 to 13 mg/L. Nitrate concentrations (10 and 13 mg/L) equaled or exceeded the U.S. Environmental Protection Agency drinking-water standard of 10 mg/L in water from 2 of the 96 sites sampled. Median nitrate concentrations in water from basin-fill deposits where many residents obtain their water were less than about

3 mg/L. Median nitrate concentrations in water from wells located within all land-use categories were less than 3 mg/L. Seasonal variations in nitrate concentrations were determined in water from some wells.

Potential sources of nitrate to ground water include runoff or infiltration from areas of timber harvests, atmospheric deposition, livestock waste, fertilizer, soil organic nitrogen, and domestic septic-system effluent. However, fertilizers and soil organic nitrogen probably contribute most of the nitrate to ground water in the GLWQD, based on nitrogen isotopic ratios in nitrate. Irrigation can facilitate the movement of nitrogen from fertilizers through permeable soils and into underlying aquifers, although nitrate concentrations in ground water in the GLWQD are not as high as in other agricultural areas of the United States, where nitrate concentrations frequently exceed 10 mg/L. Relatively low fertilizer application rates and dilution from irrigation water could be the reasons for the relatively low nitrate concentrations in ground water. Some samples with higher nitrate concentrations were obtained from wells completed beneath the unirrigated eastern benches. The higher nitrate concentrations in water beneath the eastern benches probably are related more to the quantity of ground-water recharge than to the source of the nitrate. With limited recharge and flow, nitrate in water beneath these benches is not diluted to the same extent as the irrigated and subirrigated areas. On the basis of water-quality data from three subdivisions, domestic septic-system effluent does not appear at present to be a major source of nitrate to ground water in the GLWQD.

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DATA

Table 1. Well data and chloride and nitrate concentrations in ground water in the Gallatin Local Water Quality District, Montana

[Data type: I, inventory only; Q, water quality (1997-98); W, water-level monitoring network. Hydrogeologic unit: Qal, Quaternary alluvium; QTd, Quaternary and Tertiary undifferentiated deposits; Tb, Tertiary Bozeman Group; TYsaq, Tertiary through Proterozoic sedimentary bedrock (potential aquifers); KЄscu, Cretaceous through Cambrian sedimentary bedrock (typically confining units); Am, Archean metamorphic rocks. Abbreviations: ft, feet below or above (+) land surface; µS/cm, microsiemens per centimeter at 25 degrees Celsius; lab, laboratory; mg/L, milligrams per liter; (D), depth to water reported by driller. Symbols: --, no data; <, less than minimum reporting level]

Location number	Data type	Hydrogeologic unit	Depth of well (ft)	Date of measurement	Depth to water (ft)	Specific conductance, field (µS/cm)	pH, field (standard units)	Chloride, dissolved, lab (mg/L as Cl)	Nitrate, field[1] (mg/L as N)	Nitrite plus nitrate, dissolved, lab (mg/L as N)
02N03E33DADD01	W	Tb	61	09-09-1951	34.43	--	--	---	--	---
02N05E34DDDD01	I	Tb	92	07-30-1997	7.24	496	7.4	--	1.5	--
01N03E03CADD01	I	Tb	--	04-07-1998	--	447	7.9	--	1.1	--
01N03E06BBBB01	W	Tb	118	09-09-1997	83.29	484	7.5	--	2.1	--
01N03E07CDDA01	Q,W	Tb	--	11-04-1992	227.89	--	--	--	--	--
				06-03-1998	232.87	399	7.5	5.6	--	1.4
01N03E10ABBA01	I	Tb	327	05-02-1991	23.25	--	--	--	--	--
01N03E10BDCD01	Q,W	Tb	47.5	07-31-1997	10.68	500	7.6	--	1.1	--
				05-27-1998	18.76	475	7.4	6.6	--	.67
01N03E11BAAA01	I	Tb	40	04-13-1998	15.93	734	7.6	--	1.7	--
01N03E16CABB01	W	Tb	400	05-14-1991	84.56	--	--	--	--	--
01N03E19ADBB01	I	Tb	526	10-08-1980	310 (D)	--	--	--	--	--
01N03E19DADC01	I	Tb	581	05-06-1986	350 (D)	--	--	--	--	--
01N03E20CADA01	I	Tb	530	05-02-1991	299.48	--	--	--	--	--
01N03E21AAAB01	I	Tb	240	05-02-1991	66.87	--	--	--	--	--
01N03E21ADDD01	I	Tb	212	05-02-1991	151.20	--	--	--	--	--
01N03E23DBBA01	Q	Tb	50	04-13-1998	17.84	523	7.5	--	1.5	--
				05-27-1998	17.47	503	7.3	8.7	--	1.7
01N03E27AACC01	I	Tb	196	05-15-1991	14.36	--	--	--	--	--
01N03E28DCAA01	I	Tb	289	05-14-1991	77.30	--	--	--	--	--
01N03E28DCBB01	I	Tb	284	06-14-1991	115.39	--	--	--	--	--
01N03E33AAAC01	Q	Tb	114	- -1997	48 (D)	--	--	--	--	--
				06-03-1998	--	428	7.5	1.5	--	1.9
01N03E33ABCC01	W	--	--	11-21-1994	69.22	--	--	--	--	--
01N03E33BADD01	I	Tb	275	05-14-1991	78.92	--	--	--	--	--
01N03E33BDBB01	I	Tb	340	05-14-1991	17.42	--	--	--	--	--
01N03E33BDBB02	I	Tb	230	12-01-1984	70 (D)	--	--	--	--	--
01N03E33CCBC01	W	Tb	378	05-14-1991	145.08	--	--	--	--	--
01N03E33DDAA01	I	Tb	135	09-10-1997	--	512	7.8	--	.9	--
01N03E34ABBA01	I	Tb	174	05-15-1991	18.47	--	--	--	--	--
01N03E35DDBB01	W	Qal	72	05-15-1991	11.45	--	--	--	--	--
01N04E01DBAB01	I	Tb	123	06-20-1991	75.73	309	7.6	--	--	--
01N04E01DDBC01	Q,W	Tb	157	07-08-1993	122.98	--	--	--	--	--
				05-28-1998	124.18	424	7.3	2.3	--	.19
01N04E03BBAA01	W	Qal	48	08-05-1992	14.26	--	--	--	--	--
01N04E05DDDD01	I	Qal	65	06-24-1991	8.21	462	7.5	--	--	--
01N04E06CBBB01	I	Qal	82	06-18-1992	4.99	--	--	--	--	--
01N04E10AADD01	I	Qal	5.8	06-18-1992	2.66	--	--	--	--	--

Table 1. Well data and chloride and nitrate concentrations in ground water in the Gallatin Local Water Quality District, Montana (Continued)

Location number	Data type	Hydro-geologic unit	Depth of well (ft)	Date of measurement	Depth to water (ft)	Specific conductance, field (µS/cm)	pH, field (standard units)	Chloride, dissolved, lab (mg/L as Cl)	Nitrate, field[1] (mg/L as N)	Nitrite plus nitrate, dissolved, lab (mg/L as N)
01N04E12CDCC01	I	Qal	7.0	08-14-1992	5.43	--	--	--	--	--
01N04E15DDAA01	W	Qal	225	07-14-1992	3.35	--	--	--	--	--
01N04E17BAAA01	W	Qal	28	06-11-1992	3.75	411	7.2	--	.6	--
01N04E18DBCC01	W	Qal	33	07-15-1992	5.63	364	7.6	--	.9	--
01N04E19CBCC01	W	Qal	81	09-01-1953	4.00	--	--	--	--	--
01N04E25BBCC01	Q	Qal	45	07-30-1997	5.11	430	7.8	--	1.8	--
				05-27-1998	8.59	406	7.4	2.3	--	1.7
01N04E25DCDD01	W	Qal	101	12-07-1951	10.57	--	--	--	--	--
01N04E26BCCC01	W	Qal	51	07-28-1997	8.02	410	7.7	--	.9	--
01N04E26CCCC01	I	Qal	63	07-14-1992	17.94	--	--	--	--	--
01N04E28ABBB01	I	Qal	44	07-14-1992	3.54	426	7.6	--	1.5	--
01N04E28ABBD01	I	Qal	10	07-14-1992	4.00	608	7.4	--	.9	--
01N04E31CAAA01	I	Qal	--	06-18-1992	2.96	298	7.3	--	<.5	--
01N04E33CDCC01	W	Qal	101	06-19-1991	21.85	--	--	--	--	--
01N05E02AAAC01	W	QTd	78	07-22-1992	6.12	185	7.0	--	.9	--
01N05E02BAAD01	I	QTd	40	06-20-1991	5.91	240	7.0	--	--	--
01N05E04DDAD01	W	Qal	13	07-17-1992	11.37	--	--	--	--	--
01N05E04DDAD02	I	Qal	68	07-17-1992	7.46	650	7.6	--	1.3	--
01N05E14ACDD01	Q,W	QTd	109	07-31-1992	86.32	429	7.6	--	1.0	--
				05-28-1998	94.19	412	7.4	1.0	--	1.1
01N05E16DAAA01	I	QTd	120	06-21-1991	43.30	461	7.1	--	--	--
01N05E20DBAA01	W	Qal	33	07-15-1992	12.86	348	7.8	--	1.6	--
01N05E27CCDD01	I	QTd	--	05-13-1998	--	428	7.5	2.6	--	3.0
			--	05-13-1998[2]	--	--	--	2.6	--	3.0
01N05E28DCAD01	I	Qal	40	07-08-1992	4.45	435	7.7	2.7	--	
01N05E29CDAB01	W	Qal	39	07-08-1993	6.27	--	--	--	--	--
01N05E30DDAA01	I	Qal	10	07-07-1951	3.00	--	--	--	--	--
01N05E34ABAB01	I	QTd	40	05-13-1998	6.17	320	7.7	1.3	--	1.0
01N05E34ADAD01	Q	QTd	47	07-28-1997	2.42	308	7.8	--	1.0	--
				05-12-1998	2.85	304	7.8	.9	--	1.6
				06-23-1998	1.20	285	7.7	.7	--	1.5
				08-26-1998	3.05	290	7.5	--	--	1.6
				11-18-1998	--	291	7.7	--	--	1.5
01N05E34ADDA01	I	QTd	95	07-28-1997	+.69	287	7.8	--	.5	--
				05-12-1998	3.56	278	7.7	.7	--	.69
01N05E34ADDC01	I	QTd	103	07-16-1986	26 (D)	--	--	--	--	--
				05-12-1998	--	315	7.7	.8	--	1.4
01N05E34CDBD01	Q	Qal	90	07-29-1997	18.29	346	7.8	--	2.8	--
				05-13-1998	--	344	7.9	1.1	--	4.6
				06-24-1998	--	331	7.7	1.0	--	4.4
01N05E34DAAB01	I	QTd	120	05-12-1998	36.29	282	8.1	.6	--	.78
01N05E34DAAC01	I	QTd	100	05-12-1998	37.32	297	7.9	.7	--	1.2
01N05E34DCBB01	I	QTd	80	05-13-1998	25.96	349	7.8	1.7	--	4.6

Table 1. Well data and chloride and nitrate concentrations in ground water in the Gallatin Local Water Quality District, Montana (Continued)

Location number	Data type	Hydro-geo-logic unit	Depth of well (ft)	Date of meas-urement	Depth to water (ft)	Specific conduc-tance, field (µS/cm)	pH, field (stan-dard units)	Chlo-ride, dissolved, lab (mg/L as Cl)	Nitrate, field[1] (mg/L as N)	Nitrite plus nitrate, dissolved, lab (mg/L as N)
01N05E34DCCD01	I	QTd	--	05-12-1998	33.10	364	7.7	1.8	--	3.6
01N05E34DDAD01	I	QTd	102	07-29-1997	38.65	328	7.9	--	1.7	--
				05-12-1998	44.03	327	8.0	.8	--	2.8
01N05E34DDDC01	W	Qal	102	06-20-1991	64.35	315	7.7	--	--	--
01N05E35ADBA01	Q,W	QTd	80	07-22-1992	25.59	427	7.9	--	3.1	--
				05-12-1998	18.15	450	7.7	3.0	--	3.5
				05-12-1998[2]	--	--	--	2.9	--	3.5
				06-23-1998	13.92	424	7.7	2.8	--	3.2
				06-23-1998[2]	--	453	7.8	2.8	--	3.3
				08-26-1998	14.29	431	7.5	--	--	3.5
				08-26-1998[2]	--	--	--	--	--	3.5
				11-18-1998	15.05	432	7.6	--	--	3.1
				11-18-1998[2]	--	--	--	--	--	3.1
01N05E35ADDB01	I	QTd	--	05-11-1998	25.04	448	7.6	1.7	--	3.4
01N05E35CCAD01	I	QTd	108	07-29-1997	.35	292	--	--	<.5	--
				05-12-1998	11.01	289	7.7	.5	--	.74
01N05E35CCCC01	I	QTd	--	05-12-1998	57.06	310	7.7	.7	--	2.4
01N05E35DABB01	I	QTd	120	05-11-1998	--	402	7.6	.9	--	4.6
01N05E35DABD01	I	QTd	80	05-12-1998	27.15	358	7.7	.7	--	4.6
01N05E35DDBA01	Q	QTd	78	05-12-1998	44.02	322	7.7	.4	--	3.7
				06-24-1998	42.41	312	7.8	.5	--	3.7
				08-27-1998	41.55	307	7.5	--	--	3.7
				11-18-1998	--	313	7.6	--	--	4.0
01N05E35DDCA01	I	QTd	100	05-12-1998	51.94	329	7.7	.7	--	3.2
01N05E35DDDC01	I	QTd	122	05-12-1998	60.43	307	7.7	.5	--	2.2
01N05E36BAAD01	I	QTd	85	05-11-1998	56.04	418	7.7	4.3	--	7.1
01N05E36BADD01	Q	QTd	120	05-11-1998	57.86	421	7.7	7.9	--	5.0
				06-23-1998	--	392	7.7	8.1	4.0	4.7
				08-27-1998	--	398	7.6	--	--	4.7
				11-18-1998	--	402	7.6	--	--	4.7
01N05E36BBBB01	I	QTd	57	- -1971	27 (D)	--	--	--	--	--
				05-11-1998	--	416	7.7	4.6	--	6.2
01N05E36BCCC01	I	QTd	61	05-11-1998	34.34	406	7.6	.9	--	4.7
01N05E36BDAA01	I	QTd	101	05-11-1998	66.12	511	7.7	4.2	--	13
01N06E17CDCB01	Q,W	QTd	60	06-20-1991	10.77	328	7.4	--	--	--
				05-28-1998	11.10	314	7.6	.6	--	1.7
01N06E30BCBB01	W	QTd	154	07-16-1992	116.72	570	7.6	--	3.5	--
01N07E20ABBA01	Q,W	KЄscu	135	07-09-1997	11.50	226	7.0	--	.6	--
				06-04-1998	8.20	212	6.9	.1	--	.15
01N07E20CDDA01	I	KЄscu	--	07-09-1997	41.78	422	7.4	--	.8	--
01N07E29BDCD01	Q,W	KЄscu	485	07-09-1997	139.49	353	8.0	--	2.9	--
				06-04-1998	113.32	342	7.9	2.2	--	3.7
01S03E36BCCD01	W	Tb	113	10-14-1952	14.20	--	--	--	--	--

Table 1. Well data and chloride and nitrate concentrations in ground water in the Gallatin Local Water Quality District, Montana (Continued)

Location number	Data type	Hydro-geo-logic unit	Depth of well (ft)	Date of meas-urement	Depth to water (ft)	Specific conduc-tance, field (µS/cm)	pH, field (stan-dard units)	Chlo-ride, dissolved, lab (mg/L as Cl)	Nitrate, field[1] (mg/L as N)	Nitrite plus nitrate, dissolved, lab (mg/L as N)
01S04E01ACCA01	I	Qal	85	06-19-1991	47.64	450	7.6	--	--	--
01S04E01DCBD01	I	Qal	185	06-19-1991	54.73	--	--	--	--	--
01S04E01DDCC01	I	Qal	205	05-27-1983	57 (D)	--	--	--	--	--
01S04E04ACAA01	Q	Qal	57	10-27-1992	21 (D)	--	--	--	--	--
				04-21-1998	--	357	7.2	1.6	--	.96
				05-20-1998	--	342	6.9	1.4	1.1	.91
				08-27-1998	--	340	6.9	--	--	1.5
				11-18-1998	--	343	6.9	--	--	1.4
01S04E04ACAA02	I	Qal	--	04-21-1998	34.85	352	7.4	1.8	--	.75
01S04E04ACAB01	I	Qal	63	09-17-1992	30 (D)	--	--	--	--	--
				04-21-1998	--	342	7.2	1.3	--	.72
01S04E04ACAC01	Q	Qal	60	04-21-1998	38.67	333	7.2	1.4	--	.55
				05-21-1998	--	312	7.0	1.3	--	.46
				08-27-1998	--	315	6.9	--	--	.59
01S04E04ACAC02	I	Qal	63	04-21-1998	34.83	342	7.1	1.3	--	.67
				04-21-1998[2]	--	--	--	1.3	--	.62
01S04E04ACBA01	I	Qal	80	04-20-1998	32.70	316	7.2	2.2	--	.41
01S04E04ACBA02	I	Qal	60	04-20-1998	31.46	313	7.3	1.5	--	.29
01S04E04ACBB01	I	Qal	60	04-20-1998	32.07	290	7.3	1.7	--	.16
01S04E04ACBC01	I	Qal	60	04-20-1998	30.84	298	7.2	1.5	--	.23
01S04E04ACBD01	I	Qal	60	04-20-1998	29.59	305	7.3	1.4	--	.27
01S04E04ACCA01	I	Qal	60	04-20-1998	30.23	308	7.2	1.7	--	.28
01S04E04ACCA02	Q	Qal	--	04-21-1998	29.87	308	7.2	1.6	--	.26
				05-21-1998	27.40	298	6.9	1.5	--	.28
				08-27-1998	24.74	298	6.8	--	--	.84
				11-18-1998	--	298	6.8	--	--	.78
01S04E04ACCB01	I	Qal	60	04-20-1998	27.02	290	7.2	1.8	--	.15
01S04E04ACCC01	I	Qal	60	04-20-1998	28.57	304	7.2	1.6	--	.32
01S04E04ACCD01	I	Qal	--	04-21-1998	29.79	301	7.1	1.2	--	.19
01S04E04ACDA01	I	Qal	--	04-21-1998	36.71	332	7.0	1.3	--	.43
01S04E04ACDB01	I	Qal	--	04-21-1998	33.94	319	7.2	1.4	--	.43
01S04E04ACDB02	I	Qal	60	04-21-1998	35.35	333	7.1	1.3	--	.55
01S04E04ACDB03	I	Qal	--	04-21-1998	--	323	7.1	1.1	--	.38
01S04E04ACDC01	I	Qal	--	04-21-1998	37.40	315	7.2	1.2	--	.34
01S04E04ACDD01	I	Qal	--	04-21-1998	35.26	328	7.0	1.3	--	.37
01S04E04ACDD02	Q	Qal	60	04-21-1998	36.29	362	7.0	2.0	--	1.3
				04-21-1998[2]	--	--	--	2.2	--	1.3
				05-21-1998	33.27	286	6.9	1.6	--	.61
				08-27-1998	30.01	339	6.8	--	--	1.8
				11-18-1998	--	350	6.8	--	--	2.1
01S04E04ADCC01	I	Qal	--	04-21-1998	37.20	339	7.2	1.5	--	.62
01S04E04ADDB01	I	Qal	58	07-31-1997	32.36	377	7.1	--	1.6	--
01S04E04ADDD01	Q	Qal	64	05-12-1998	39.56	417	7.0	3.0	2.9	3.4

Table 1. Well data and chloride and nitrate concentrations in ground water in the Gallatin Local Water Quality District, Montana (Continued)

Location number	Data type	Hydro-geo-logic unit	Depth of well (ft)	Date of meas-urement	Depth to water (ft)	Specific conduc-tance, field (µS/cm)	pH, field (stan-dard units)	Chlo-ride, dissolved, lab (mg/L as Cl)	Nitrate, field[1] (mg/L as N)	Nitrite plus nitrate, dissolved, lab (mg/L as N)
01S04E09BAAA01	W	Qal	97	03-27-1953	22.58	--	--	--	--	--
01S04E10DDDD01	Q,W	Qal	107	07-30-1992	12.15	379	7.5	--	.8	--
				06-02-1998	32.35	444	7.2	2.7	--	.94
01S04E12BDDC02	W	Qal	146	09-09-1997	43.44	--	--	--	--	--
01S04E12CAAB01	I	Qal	260	02-04-1988	53.4 (D)	--	--	--	--	--
				06-19-1991	--	432	7.6	--	--	--
01S04E17DCDD01	Q,W	Tb	50	06-18-1992	6.52	553	7.6	--	1.5	--
				01-05-1998	--	643	7.8	9.9	1.4	2.8
01S04E18BCB01	W	Tb	318	01-21-1989	70.64	--	--	--	--	--
01S04E25AAA03	I	Qal	50.5	03-07-1953	15.97	--	--	--	--	--
01S04E25ADDD01	W	Qal	34	07-29-1992	7.76	374	7.3	--	1.0	--
01S04E26CDDD01	Q,W	Qal	37	07-30-1992	4.76	457	7.5	--	.6	--
				05-27-1998	6.96	443	7.3	4.5	--	1.5
				05-27-1998[2]	--	457	7.5	4.8	--	1.5
01S04E26CDDD02	I	Qal	27	07-13-1993	6.62	431	7.7	--	2.4	--
01S04E29BCDD01	W	Tb	--	01-30-1986	.67 (D)	--	--	--	--	--
01S05E05CCBB01[3]	I	Qal	47	07-23-1992	17.86	403	7.6	--	1.4	--
01S05E09ACCC01	I	Qal	28	07-09-1992	19.93	465	7.5	--	1.8	--
01S05E09CCAD01	I	Qal	80	07-28-1997	12.24	551	7.4	--	2.1	--
01S05E09DCCC01	W	Qal	141	07-09-1992	21.89	--	--	--	--	--
01S05E12BCCC01	W	QTd	112	07-09-1992	100.73	--	--	--	--	--
01S05E12BCCC02	I	QTd	120	07-09-1992	--	375	7.6	--	3.9	--
01S05E13DBCB01	I	QTd	275	07-30-1997	159.87	487	7.7	--	4.1	--
01S05E13DDDA01	Q	QTd	260	07-30-1997	111.08	504	7.7	--	4.4	--
				01-06-1998	--	488	7.0	13	3.8	7.1
01S05E13DDCB01	I	QTd	224	09-09-1997	109.56	444	7.4	--	3.8	--
01S05E14ACDD01	Q	QTd	140	09-10-1997	107.46	462	7.6	--	3.1	--
				05-19-1998	106.15	454	7.5	13	--	4.4
01S05E14DDCB01	I	Qal	36	09-09-1997	11.67	650	7.3	--	4.8	--
01S05E15BCBA01	I	Qal	60	07-13-1993	28.87	532	7.3	--	2.9	--
01S05E16DBCC01	I	QTd	58.5	06-18-1991	37.24	575	7.3	--	--	--
				07-29-1997	23.66	614	7.6	--	2.9	--
01S05E16DBCC02	I	Qal	80	07-29-1997	24.45	590	7.5	--	3.3	--
01S05E16DBDD01	I	Qal	60	07-29-1997	25.88	505	7.6	--	1.5	--
01S05E17CCDC01	W	Qal	42	07-31-1992	9.05	347	7.2	--	1.0	--
01S05E21BCDD01	Q	QTd	83	07-31-1997	37.61	598	7.4	--	3.9	--
				05-20-1998	--	533	7.1	16	--	4.4
01S05E21CDDB01	Q	QTd	83	07-31-1997	49.51	548	7.3	--	3.2	--
				05-20-1998	60.82	540	7.1	4.6	--	3.1
01S05E22AADD01	I	Qal	52	07-23-1992	3.86	623	7.6	--	2.8	--
01S05E22ADDD01	I	Qal	33	09-10-1997	2.58	572	7.5	--	1.7	--
01S05E24BACB01	I	QTd	60	08-01-1997	19.49	502	7.9	--	4.1	--
01S05E24CACD01	I	Qal	37	07-29-1992	27.73	553	7.5	--	4.5	--

Table 1. Well data and chloride and nitrate concentrations in ground water in the Gallatin Local Water Quality District, Montana (Continued)

Location number	Data type	Hydro-geo-logic unit	Depth of well (ft)	Date of meas-urement	Depth to water (ft)	Specific conduc-tance, field (µS/cm)	pH, field (stan-dard units)	Chlo-ride, dissolved, lab (mg/L as Cl)	Nitrate, field[1] (mg/L as N)	Nitrite plus nitrate, dissolved, lab (mg/L as N)
01S05E25ADAD01	W	QTd	150	01-27-1998	2.16	--	--	--	--	--
				04-14-1998	--	405	7.6	--	.6	--
				04-20-1998	2.04	--	--	--	--	--
01S05E27CBDC01	Q,W	QTd	115	08-06-1992	46.31	598	7.6	--	1.6	--
				05-27-1998	41.60	593	7.3	21	--	2.6
01S05E35CAAB01	W	QTd	67	08-18-1992	19.08	505	7.5	--	3.3	--
01S06E06ABCB01	Q	QTd	375	07-16-1992	281.45	290	7.8	--	<.5	--
				05-13-1998	283.39	266	7.8	.44	.5	.18
01S06E07CCBA01	W	QTd	100	09-10-1991	62 (D)	--	--	--	--	--
01S06E08CBAA01	W	QTd	200	08-09-1997	106.75	--	--	--	--	--
01S06E17CCDD01	Q	QTd	115	09-09-1997	64.58	375	7.6	--	1.3	--
				05-19-1998	84.51	399	7.6	1.3	2.0	2.1
				05-19-1998[2]	--	407	7.8	1.3	--	2.2
01S06E18BBBB01	I	QTd	285	06-20-1991	213.91	405	7.4	--	--	--
01S06E20BCDB01	I	QTd	173	09-10-1997	74.37	554	7.4	--	9.7	--
01S06E20BDAA01	W	QTd	110	06-20-1991	39.39	--	--	--	--	--
01S06E20BDAA02	Q	QTd	128	11-04-1992	45.62	--	--	--	--	--
				07-21-1993	43.08	285	8.1	--	--	--
				05-19-1998	48.73	296	7.9	1.3	.8	.90
01S06E20BDAB01	I	QTd	166	06-20-1991	38.4	276	7.8	--	--	--
01S06E20CAAD01	I	QTd	307	07-17-1997	65.15	--	--	--	--	--
01S06E20CBDD01	I	QTd	230	06-20-1991	88.4	502	7.4	--	--	--
01S06E20CCDD01	I	QTd	173	07-17-1997	79.92	458	7.4	--	5.1	--
01S06E28DABD01	W	KЄscu	620	03-24-1992	320 (D)	--	--	--	--	--
				07-16-1997	--	415	7.8	--	.8	--
01S06E32BADC01	Q,W	QTd	157	07-17-1997	57.06	365	7.7	--	.6	--
				05-28-1998	57.63	336	7.5	2.1	--	.23
01S06E32DCAB01	I	Qal	102	07-17-1997	17.97	494	7.7	--	.9	--
01S06E33DACD01	I	Qal	97	07-17-1997	11.17	278	7.6	--	2.4	--
01S06E36ADDC01	I	KЄscu	--	07-10-1997	--	671	7.3	--	1.2	--
01S07E09CCCA01	I	KЄscu	17	04-14-1998	5.71	331	7.8	--	.6	--
01S07E16BBBA01	I	KЄscu	220	07-09-1997	5.29	262	8.9	--	.5	--
01S07E16CCDA01	I	TYsaq	320	07-08-1997	93.50	178	9.9	--	<.5	--
01S07E17AACA01	W	KЄscu	50	01-26-1998	43.47	--	--	--	--	--
				04-14-1998	--	393	8.0	--	.9	--
				04-20-1998	34.89	--	--	--	--	--
01S07E17BDCB01	W	TYsaq	107	01-26-1998	29.35	--	--	--	--	--
				04-14-1998	--	433	7.6	--	.7	--
				04-20-1998	43.47	--	--	--	--	--
01S07E21BDAB01	I	TYsaq	340	07-08-1997	231.58	218	9.3	--	.7	--
01S07E21CABA01	I	TYsaq	100	07-08-1997	20.95	582	7.3	--	1.1	--
01S07E27CCAB01	I	TYsaq	165	06-04-1998	21.28	60	9.0	--	.6	--
01S07E27DBDC01	Q	TYsaq	80	07-08-1997	34.30	296	7.4	--	.7	--

Table 1. Well data and chloride and nitrate concentrations in ground water in the Gallatin Local Water Quality District, Montana (Continued)

Location number	Data type	Hydro-geo-logic unit	Depth of well (ft)	Date of meas-urement	Depth to water (ft)	Specific conduc-tance, field (µS/cm)	pH, field (stan-dard units)	Chlo-ride, dissolved, lab (mg/L as Cl)	Nitrate, field[1] (mg/L as N)	Nitrite plus nitrate, dissolved, lab (mg/L as N)
				06-04-1998	36.50	297	7.4	.6	--	.33
01S07E30BAAA01	Q,W	TYsaq	118	07-09-1997	49.89	510	7.1	--	.9	--
				06-05-1998	53.03	463	7.1	4.2	--	.84
01S07E33DABD01	I	KЄscu	180	07-08-1997	174.81	196	9.6	--	1.0	--
02S04E01BABC01	I	Qal	44.5	07-24-1997	11.87	482	7.3	--	.7	--
02S04E01CCCD01	Q,W	Qal	40	07-23-1997	18.57	522	7.1	--	1.6	--
				05-27-1998	14.50	514	7.2	4.8	--	2.0
02S04E05BCBB01	I	Tb	178	06-23-1991	58.00	711	7.5	--	--	--
02S04E10ACCA01	W	Tb	119	01-06-1998	39.82	--	--	--	--	--
				04-14-1998	--	462	7.7	--	1.4	--
				04-24-1998	45.29	--	--	--	--	--
02S04E11ADDD01	I	Qal	26	08-11-1992	12.96	--	--	--	--	--
02S04E12CADA01	I	Qal	42	07-24-1997	15.92	452	7.1	--	1.3	--
02S04E13BADA01	Q,W	Qal	40	07-23-1997	20.29	452	7.1	--	1.3	--
				01-05-1998	--	437	7.1	4.2	1.0	1.6
02S04E13BBAC01	I	Qal	35	07-24-1997	13.15	485	7.2	--	1.6	--
02S04E13BBDA01	Q	Qal	30	07-23-1997	9.66	494	7.2	--	.6	--
				05-11-1998	15.90	491	7.1	5.7	.6	1.1
				06-02-1998	12.04	458	7.2	--	--	1.0
02S04E13CBDC01	I	Qal	38	07-23-1997	10.81	498	7.0	--	1.8	--
02S04E13CCBC01	W	Qal	11	06-21-1947	3.30	--	--	--	--	--
02S04E14DADC01[4]	I	Am	--	03-23-1991	--	681	8.9	--	--	--
02S04E14DADC02[4]	Q	Am	--	06-23-1991	--	704	9.0	--	--	--
				01-05-1998	--	681	9.3	54	<.5	--
02S04E16BCCA01	Q,W	Tb	148	08-11-1992	108.25	440	7.8	--	<.5	--
				09-11-1992	--	446	7.9	9.8	--	.46
				05-26-1998	--	571	7.4	28	--	1.2
02S04E16DADA01	W	Tb	177	01-06-1998	72.46	--	--	--	--	--
				04-13-1998	--	427	7.6	--	1.1	--
				04-24-1998	80.52	--	--	--	--	--
02S04E23ACDC01	I	Qal	50	07-23-1997	10.86	440	7.4	--	1.1	--
02S04E29CDDC01	I	QTd	56	06-22-1991	39.35	199	6.7	--	--	--
02S04E35ABBB01	W	Qal	31	08-17-1992	4.78	419	7.6	--	1.0	--
02S05E05ABBB01	I	QTd	40	06-23-1991	6.25	420	7.2	--	--	--
02S05E05ABBD01	W	QTd	125	06-23-1991	2.79	268	7.7	--	--	--
02S05E10AABB01	Q	QTd	55	08-18-1992	10.41	--	--	--	--	--
				05-20-1998	--	474	7.3	2.7	1.7	1.7
02S05E11ADAB01	W	QTd	75	10-24-1988	12.80	--	--	--	--	--
				07-14-1993	--	520	7.2	--	--	--
02S05E12DACC01	I	QTd	80	06-17-1988	26 (D)	--	--	--	--	--
02S05E13BDCD01	W	QTd	185	06-11-1988	11.10	--	--	--	--	--
02S05E14CDBA01	W	QTd	113	04-07-1989	2.60	--	--	--	--	--
				05-11-1989	3.08	412	8.7	--	--	--

Table 1. Well data and chloride and nitrate concentrations in ground water in the Gallatin Local Water Quality District, Montana (Continued)

Location number	Data type	Hydro-geo-logic unit	Depth of well (ft)	Date of meas-urement	Depth to water (ft)	Specific conduc-tance, field (µS/cm)	pH, field (stan-dard units)	Chlo-ride, dissolved, lab (mg/L as Cl)	Nitrate, field[1] (mg/L as N)	Nitrite plus nitrate, dissolved, lab (mg/L as N)
02S05E17BBAA01	W	QTd	39	08-18-1992	18.65	472	7.6	--	<.5	--
02S05E18BCDD01	I	QTd	55	07-23-1997	27.84	364	6.8	--	.6	--
02S05E19BACC01	Q	QTd	152	04-14-1998	57.95	542	7.3	--	1.7	--
				05-11-1998	59.97	--	--	6.1	1.5	2.4
02S05E20DDCC01	I	QTd	30	06-23-1991	5.22	433	7.3	--	--	--
02S05E22CCDC01	I	QTd	165	03-09-1953	10.78	--	--	--	--	--
				08-13-1992	9.60	455	7.6	--	1.0	--
02S05E23AADD01	I	QTd	49	08-19-1992	5.89	--	--	--	--	--
02S05E23CCCB01	Q,W	QTd	80	01-27-1998	6.96	--	--	--	--	--
				04-14-1998	3.89	487	7.4	--	1.9	--
				05-13-1998	5.48	461	7.5	1.2	2.1	2.6
				06-02-1998	4.24	454	7.3	--	--	2.5
02S05E31ADDA01	Q	QTd	125	08-17-1992	30.58	596	8.0	--	1.5	--
				05-26-1998	--	459	7.8	1.3	--	.75
02S05E35DCDC01	W	QTd	156	05-14-1951	35.68	--	--	--	--	--
02S05E36BACD01	I	QTd	138	10-26-1988	11.31	--	--	--	--	--
02S05E36CAAB01	Q	QTd	45	07-31-1997	9.92	507	7.3	--	--	--
				05-18-1998	11.51	507	7.3	22	--	4.1
02S05E36CCCD01	Q	QTd	51.5	07-31-1997	22.22	346	7.7	--	1.6	--
				05-18-1998	--	334	7.3	3.8	--	2.3
				08-26-1998	--	346	7.1	--	--	2.8
02S06E08ADDA01	I	Tb	550	06-24-1991	223.05	372	7.7	--	--	--
02S06E12DCAA01	Q,W	TYsaq	39	07-10-1997	11.40	456	7.0	--	2.8	--
				06-04-1998	6.42	394	6.8	2.7	--	1.7
				06-04-1998[2]	--	414	7.0	2.9	--	1.7
02S06E19BBBB01	W	QTd	--	10-27-1992	23.59	--	--	--	--	--
02S06E20CABD01	Q,W	QTd	300	06-22-1991	140.90	345	7.8	--	--	--
				06-05-1998	143.87	--	--	6.9	--	2.0
02S06E20CACA01	I	QTd	238	06-22-1991	167	472	7.5	--	--	--
02S06E21BBAA01	W	Tb	145	07-30-1997	86.85	661	7.6	--	4.1	--
02S06E21BCDD01	I	QTd	220	07-30-1997	94.91	346	7.5	--	.8	--
02S06E23ABCC01	W	Qal	42	07-30-1997	4.27	714	6.9	--	.5	--
02S06E23DCAD01	I	Qal	120	07-30-1997	9.36	580	7.9	--	1.1	--
02S06E24ACAB01	W	KЄscu	342	01-26-1998	22.11	--	--	--	--	--
02S06E26ADAD01	I	TYsaq	80	07-30-1997	43.91	523	7.4	--	2.6	--
02S06E26DDBA01	W	QTd	70	06-23-1991	23.26	647	7.0	--	--	--
02S06E33ADAC01	I	QTd	176	06-22-1991	88.37	--	--	--	--	--
02S06E33BABD01	I	QTd	305	06-22-1991	126	364	7.5	--	--	--
02S06E33BDDC01	W	QTd	159	06-22-1991	31.71	--	--	--	--	--
02S06E36BDBB01	Q	KЄscu	75	07-30-1997	39.09	1,080	6.9	--	25	--
				01-06-1998	--	683	6.8	19	5.5	8.0
				10-19-1998	--	692	6.9	--	--	8.8
				10-19-1998	--	741	6.8	22	--	10

Table 1. Well data and chloride and nitrate concentrations in ground water in the Gallatin Local Water Quality District, Montana (Continued)

Location number	Data type	Hydro-geo-logic unit	Depth of well (ft)	Date of meas-urement	Depth to water (ft)	Specific conduc-tance, field (µS/cm)	pH, field (stan-dard units)	Chlo-ride, dissolved, lab (mg/L as Cl)	Nitrate, field[1] (mg/L as N)	Nitrite plus nitrate, dissolved, lab (mg/L as N)
02S07E02ACDC01	Q	KЄscu	111	07-08-1997	15.80	397	7.2	--	2.4	--
				06-03-1998	16.46	366	7.1	1.9	--	1.4
02S07E06ADBD01	I	TYsaq	900	- - 1994	300 (D)	--	--	--	--	--
				07-10-1997	--	273	6.6	--	3.6	--
02S07E10DDAD01	W	KЄscu	65	07-07-1997	3.39	345	7.1	--	2.5	--
02S07E12BBAD01	W	KЄscu	66	07-07-1997	1.42	320	7.5	--	1.6	--
02S07E24CCAC01	W	TYsaq	220	07-07-1997	60.29	612	7.3	--	.9	--
02S07E24CDCB01	Q,W	TYsaq	125	07-07-1997	49.54	693	7.9	--	--	--
				06-03-1998	--	697	8.1	.6	--	<.05
02S07E26CACD01	W	TYsaq	395	07-07-1997	51.38	509	7.3	--	.8	--
03S04E02DCAD01	I	Qal	48	08-04-1992	26.95	360	7.7	--	1.7	--
03S04E03ABAA01	I	Qal	22.8	07-13-1993	8.19	371	7.7	--	1.5	--
03S04E09ABBC01	Q,W	Qal	96	07-29-1992	23.99	387	7.5	--	1.1	--
				05-26-1998	24.87	406	7.1	8.1	--	.41
03S04E11BCAD01	Q	Qal	80	07-22-1997	11.53	471	7.4	--	1.4	--
				05-12-1998	14.55	397	7.3	3.2	1.5	1.5
				06-02-1998	13.84	405	7.3	--	--	1.6
03S04E11BDCD01	I	Qal	45	07-22-1997	9.47	447	7.4	--	3.8	--
03S04E11CAAA01	I	Qal	58.5	07-22-1997	30.97	447	7.6	--	1.8	--
03S04E11CBBA01	W	Qal	40	06-18-1991	5.48	541	7.2	--	--	--
03S04E11DCCB01	W	Qal	50	07-22-1997	27.69	--	--	--	--	--
03S04E11DDBC01	Q	Qal	65	07-22-1997	30.19	440	7.6	--	1.6	--
				05-13-1998	36.17	426	7.5	2.8	2.1	2.6
03S04E21DDBD01	I	Qal	105	03-31-1971	26 (D)	--	--	--	--	--
				06-18-1991	--	310	7.5	--	--	--
03S04E23AADC01	I	QTd	208	07-29-1992	130.02	374	7.8	--	2.1	--
03S04E23CABB01	Q	Qal	100	07-22-1997	56.28	412	7.5	--	1.0	--
				05-26-1998	60.49	434	7.2	1.5	--	1.2
03S04E23CCBD01	W	Qal	80	07-22-1997	43.82	331	7.7	--	.6	--
03S04E25DBBD01	W	Qal	50	06-18-1991	15.81	299	7.2	--	--	--
				09-10-1997	17.85	349	7.4	--	.6	--
03S04E32DADA01	W	KЄscu	71	06-18-1991	53.28	576	7.2	--	--	--
03S04E34ABBB01	Q,W	QTd	92	07-28-1992	46.11	354	7.4	--	2.4	--
				05-26-1998	44.49	369	7.1	1.5	--	1.1
03S04E36ABDD01	I	QTd	150	09-11-1997	59.17	714	7.5	--	4.9	--
03S04E36ACAC01	Q	QTd	197	09-11-1997	136.66	658	7.6	--	4.8	--
				05-19-1998	135.82	643	7.5	2.0	--	8.1
03S04E36BABB01	W	QTd	312	06-18-1991	233.40	340	7.2	--	--	--
				09-10-1997	229.41	318	7.5	--	.5	--
03S05E04AAAD01	I	QTd	54	08-19-1992	4.79	300	7.1	--	3.0	--
03S05E06DAAA01	W	QTd	178	06-03-1998	157.37	496	7.7	--	2.6	--
03S05E07BCCC01	W	Qal	36	06-18-1991	3.87	235	7.5	--	--	--
03S05E10CCCB01	W	QTd	70	06-22-1991	41.66	464	7.5	--	--	--

Table 1. Well data and chloride and nitrate concentrations in ground water in the Gallatin Local Water Quality District, Montana (Continued)

Location number	Data type	Hydro-geo-logic unit	Depth of well (ft)	Date of meas-urement	Depth to water (ft)	Specific conduc-tance, field (µS/cm)	pH, field (stan-dard units)	Chlo-ride, dissolved, lab (mg/L as Cl)	Nitrate, field[1] (mg/L as N)	Nitrite plus nitrate, dissolved, lab (mg/L as N)
03S05E11BCAD01	I	QTd	95	07-31-1997	62.63	308	7.9	--	.9	--
03S05E11DAAC01	I	QTd	74	06-22-1991	60	--	--	--	--	--
03S05E11DAAC02	Q,W	QTd	--	01-17-1998	101.49	--	--	--	--	--
				05-18-1998	--	215	6.5	6.9	1.6	2.0
03S05E15DCCA01	Q,W	QTd	220	06-22-1991	210.13	219	7.3	--	--	--
				05-13-1998	--	222	7.2	1.4	1.1	.71
03S05E21BBBA01	I	Qal	22	08-04-1992	8.27	315	7.7	--	.6	--
03S05E21CCCC01	W	QTd	263	04-15-1998	185.99	813	7.5	--	5.0	--
03S05E27BCBB01	W	KꞒscu	50	01-27-1998	7.03	--	--	--	--	--
03S05E27CBBD01	I	KꞒscu	77	- -1965	29 (D)	--	--	--	--	--
03S06E01AACB01	W	KꞒscu	51	07-30-1997	20.91	610	7.2	--	.9	--
03S06E05CBAA01	W	QTd	128	08-19-1992	82.14	--	--	--	--	--
				07-20-1993	81.95	262	7.4	--	--	--
04S04E18ACAA01	W	Qal	40	06-18-1991	--	135	6.7	--	--	--
				11-02-1992	24.71	--	--	--	--	--
04S04E28CBDA01	W	Qal	104	07-29-1997	23.14	296	7.4	--	<.5	--
04S04E33DBBA01	W	KꞒscu	100	07-23-1997	50.65	285	8.2	--	<.5	--
04S04E33DBDA01	W	Qal	80	07-24-1997	52.75	250	8.0	--	<.5	--
05S04E36DBDB01	W	Qal	38	07-29-1997	9.14	382	7.8	--	.5	--
05S05E30ACCC01	W	Qal	40	07-29-1997	8.00	232	7.6	--	<.5	--

[1] Nitrate concentrations determined on unfiltered samples using a spectrophotometer by USGS personnel.

[2] Replicate sample.

[3] Well destroyed.

[4] Bozeman Hot Springs.

Table 2. Summary of water-level data for wells in the Gallatin Local Water Quality District water-level monitoring network, Montana

[Hydrogeologic unit: Qal, Quaternary alluvium; QTd, Quaternary and Tertiary undifferentiated deposits; Tb, Tertiary Bozeman Group; TYsaq, Tertiary through Proterozoic sedimentary bedrock (potential aquifers); KЄscu, Cretaceous through Cambrian sedimentary bedrock (typically confining units). Abbreviation: ft, feet below land surface. Symbol: --, no data]

Location number	Hydro-geologic unit	Well depth (ft)	Period of record (calendar year)	Number of measure-ments	Water level (ft)			
					Highest	Date of highest	Lowest	Date of lowest
02N03E33DADD01	Tb	61	1951-98	21	34.00	09-09-51	42.37	04-15-93
01N03E06BBBB01	Tb	118	1997-98	8	83.30	09-09-97	85.86	10-08-97
01N03E07CDDA01	Tb	--	1992-98	6	227.89	11-04-92	241.68	10-08-97
01N03E10BDCD01	Tb	47.5	1997-98	10	10.70	07-31-97	20.83	04-22-98
01N03E16CABB01	Tb	400	1989-98	24	73.59	10-04-97	86.05	07-29-91
01N03E33ABCC01	Tb	--	1989-98	32	39.23	10-16-95	78.52	11-06-91
01N03E33CCBC01	Tb	378	1986-98	26	139.80	04-26-86	174.46	10-08-97
01N03E35DDBB01	Qal	72	1986-98	21	6.36	10-14-98	13.92	02-13-92
01N04E01DDBC01	Tb	157	1993-98	21	122.98	07-08-93	125.59	05-19-94
01N04E03BBAA01	Qal	48	1992-98	21	14.26	08-05-92	21.17	02-25-93
01N04E15DDAA01	Qal	225	1992-98	22	3.02	04-15-93	3.93	01-12-98
01N04E17BAAA01	Qal	28	1992-98	11	3.40	08-07-98	6.86	03-06-98
01N04E18DBCC01	Qal	33	1992-98	9	5.27	06-09-98	8.91	10-08-97
01N04E19CBCC01	Qal	81	1953-98	22	3.29	05-04-93	4.82	06-11-92
01N04E25DCDD01	Qal	101	1951-98	203	5.92	08-06-52	16.91	05-04-94
01N04E26BCCC01	Qal	51	1997-98	9	7.95	10-08-97	13.69	04-22-98
01N04E33CDCC01	Qal	101	1991-98	11	21.60	08-03-93	27.64	04-22-98
01N05E02AAAC01	QTd	78	1992-98	11	5.60	08-02-93	7.04	05-03-93
01N05E04DDAD01	Qal	13	1992-98	19	2.24	06-10-93	11.37	07-17-92
01N05E14ACDD01	QTd	109	1992-98	15	77.92	07-02-97	95.10	04-22-98
01N05E20DBAA01	Qal	33	1992-98	14	11.27	04-22-98	13.03	09-03-92
01N05E29CDAB01	Qal	39	1993-98	18	5.74	07-07-98	8.81	02-15-95
01N05E34DDDC01	Qal	102	1991-98	13	47.92	10-06-97	52.21	06-09-98
01N05E35ADBA01	QTd	80	1992-98	13	13.22	11-01-93	26.10	05-04-93
01N06E17CDCB01	QTd	60	1991-98	23	9.36	07-09-93	14.38	02-25-93
01N06E30BCBB01	QTd	154	1992-98	10	102.99	10-06-97	117.14	05-04-93
01N07E20ABBA01	KЄscu	135	1997-98	7	3.12	04-20-98	20.05	03-02-98
01N07E29BDCD01	KЄscu	485	1997-98	6	113.32	06-04-98	139.00	07-09-97
01S03E36BCCD01	Tb	113	1952-98	22	14.20	10-14-52	39.72	06-11-98
01S04E09BAAA01	Qal	97	1953-98	25	17.04	07-09-93	25.50	04-04-98
01S04E10DDDD01	Qal	107	1992-98	13	12.15	07-30-92	53.29	04-24-98
01S04E12BDDC02	Qal	146	1997-98	8	43.44	09-09-97	64.79	04-24-98
01S04E17DCDD01	Tb	50	1992-98	11	5.63	09-09-92	11.71	05-05-93
01S04E18BCB 01	Tb	318	1989-98	21	70.50	11-05-92	89.39	10-14-98
01S04E25ADDD01	Qal	34	1992-98	13	6.35	07-07-98	14.31	03-06-98
01S04E26CDDD01	Qal	37	1992-98	24	2.78	07-07-98	11.55	03-06-98

Table 2. Summary of water-level data for wells in the Gallatin Local Water Quality District water-level monitoring network, Montana (Continued)

Location number	Hydro-geologic unit	Well depth (ft)	Period of record (calendar year)	Number of measure-ments	Water level (ft)			
					Highest	Date of highest	Lowest	Date of lowest
01S04E29BCDD01	Tb	--	1986-98	37	58.22	11-21-89	104.06	07-02-97
01S05E09DCCC01	Qal	141	1992-98	20	15.19	11-01-93	30.33	02-25-93
01S05E12BCCC01	QTd	112	1992-98	21	75.72	10-04-97	103.99	11-03-92
01S05E17CCDC01	Qal	42	1992-98	12	7.55	08-02-93	25.57	03-02-98
01S05E25ADAD01	QTd	150	1998	5	1.00	10-13-98	2.31	06-08-98
01S05E27CBDC01	QTd	115	1992-98	14	30.38	11-01-93	48.50	11-03-92
01S05E35CAAB01	QTd	67	1992-98	11	16.29	04-24-98	21.56	08-02-93
01S06E07CCBA01	QTd	100	1998	1	54.14	07-06-98	54.14	07-06-98
01S06E08CBAA01	QTd	200	1997-98	6	95.12	06-30-98	130.31	01-30-98
01S06E20BDAA01	QTd	110	1991-98	7	36.19	06-10-93	39.39	06-20-91
01S06E28DABD01	KꞒscu	620	1997-98	3	280.69	10-06-97	325.77	10-13-98
01S06E32BADC01	QTd	157	1997-98	8	57.06	07-17-97	60.76	10-06-97
01S07E17AACA01	KꞒscu	50	1998	5	24.54	06-04-98	43.47	01-26-98
01S07E17BDCB01	TYsaq	107	1998	5	28.25	06-04-98	31.33	10-13-98
01S07E30BAAA01	TYsaq	118	1997-98	9	49.89	07-09-97	57.47	10-06-97
02S04E01CCCD01	Qal	40	1997-98	8	8.71	06-11-98	23.35	03-06-98
02S04E10ACCA01	Tb	119	1998	5	28.15	08-11-98	45.29	04-24-98
02S04E13BADA01	Qal	40	1997-98	5	16.75	06-11-98	22.10	02-23-98
02S04E13CCBC01	Qal	11	1947-98	370	2.54	06-27-52	10.40	02-20-71
02S04E16BCCA01	Tb	148	1992-98	13	106.59	06-08-98	124.55	11-02-92
02S04E16DADA01	Tb	177	1998	3	72.50	01-06-98	80.52	04-24-98
02S04E35ABBB01	Qal	31	1992-98	14	3.69	06-10-98	8.72	01-08-98
02S05E05ABBD01	QTd	125	1991-98	14	.72	08-07-98	2.83	03-02-98
02S05E11ADAB01	QTd	75	1988-98	19	10.83	08-02-93	22.85	02-25-93
02S05E13BDCD01	QTd	185	1988-98	10	11.10	06-11-88	14.17	04-11-98
02S05E14CDBA01	QTd	113	1989-98	10	1.90	04-23-98	5.22	03-01-98
02S05E17BBAA01	QTd	39	1992-98	13	15.69	08-03-93	20.32	05-03-93
02S05E23CCCB01	QTd	80	1998	7	3.89	04-15-98	6.96	01-27-98
02S05E35DCDC01	QTd	156	1951-98	18	11.64	10-04-97	43.99	05-03-93
02S06E12DCAA01	TYsaq	39	1997-98	9	6.11	04-15-98	11.40	07-10-97
02S06E19BBBB01	QTd	--	1992-98	22	22.99	06-11-93	25.74	04-15-93
02S06E20CABD01	QTd	300	1991-98	14	121.58	07-20-93	182.58	05-04-93
02S06E21BBAA01	Tb	145	1997-98	6	84.20	06-08-98	87.02	07-31-98
02S06E23ABCC01	Qal	42	1997-98	7	3.88	04-15-98	9.02	03-02-98
02S06E24ACAB01	KꞒscu	342	1998	3	19.32	04-15-98	22.10	01-26-98
02S06E26DDBA01	QTd	70	1991-98	11	18.82	10-06-97	26.98	05-04-93
02S06E33BDDC01	QTd	159	1991-98	23	18.83	07-02-97	35.43	02-25-93
02S07E10DDAD01	KꞒscu	65	1997-98	8	3.29	01-17-98	6.90	01-17-98

Table 2. Summary of water-level data for wells in the Gallatin Local Water Quality District water-level monitoring network, Montana (Continued)

Location number	Hydro-geologic unit	Well depth (ft)	Period of record (calendar year)	Number of measure-ments	Water level (ft)			
					Highest	Date of highest	Lowest	Date of lowest
02S07E12BBAD01	KꞒscu	66	1997-98	9	.50	04-17-98	4.96	12-13-97
02S07E24CCAC01	TYsaq	220	1997-98	5	60.29	07-07-97	74.81	12-13-97
02S07E24CDCB01	TYsaq	125	1997-98	2	49.54	07-07-97	70.49	10-13-98
02S07E26CACD01	TYsaq	395	1997-98	4	51.38	07-07-97	85.71	12-13-97
03S04E09ABBC01	Qal	96	1992-98	24	23.46	06-10-98	29.68	02-23-98
03S04E11CBBA01	Qal	40	1991-98	13	5.45	08-03-93	9.06	10-07-97
03S04E11DCCB01	Qal	50	1997-98	9	27.69	07-22-97	39.03	04-24-98
03S04E23CCBD01	Qal	80	1997-98	9	35.69	10-15-98	59.54	02-23-98
03S04E25DBBD01	Qal	50	1991-98	22	13.80	07-07-98	20.29	11-02-92
03S04E32DADA01	KꞒscu	71	1991-98	8	50.21	05-03-93	55.74	11-02-92
03S04E34ABBB01	QTd	92	1992-98	13	40.75	10-07-97	49.96	08-03-93
03S04E36BABB01	QTd	312	1991-98	11	229.41	10-07-97	253.08	11-02-92
03S05E06DAAA01	QTd	178	1998	1	157.37	06-03-98	157.37	06-03-98
03S05E07BCCC01	Qal	36	1991-98	12	2.02	06-10-98	14.72	02-23-98
03S05E10CCCB01	QTd	70	1991-98	13	27.80	08-12-98	41.66	06-22-91
03S05E11DAAC02	QTd	--	1998	5	78.82	08-12-98	101.49	01-17-98
03S05E15DCCA01	QTd	220	1991-98	2	199.34	05-13-98	210.13	06-22-91
03S05E21CCCC01	QTd	263	1998	3	178.99	10-19-98	185.99	04-15-98
03S05E27BCBB01	KꞒscu	50	1998	5	6.55	06-10-98	7.03	01-27-98
03S06E01AACB01	KꞒscu	51	1997-98	7	19.01	04-15-98	25.85	03-02-98
03S06E05CBAA01	QTd	128	1992-98	12	77.22	10-06-97	92.03	05-09-93
04S04E18ACAA01	Qal	40	1992-98	10	19.97	10-14-98	25.18	04-13-98
04S04E28CBDA01	Qal	104	1997-98	9	22.61	06-08-98	25.30	11-24-98
04S04E33DBBA01	KꞒscu	100	1997-98	9	49.84	06-08-98	58.19	04-26-98
04S04E33DBDA01	Qal	80	1997-98	5	52.63	06-08-98	56.70	02-23-98
05S04E36DBDB01	Qal	38	1997-98	7	8.56	06-08-98	10.46	11-24-97
05S05E30ACCC01	Qal	40	1997-98	8	8.00	07-29-97	9.55	10-07-97

Table 3. Water-quality data for ground and surface water in the Gallatin Local Water-Quality District, Montana, 1998

[All sites are private wells unless otherwise indicated. Primary land use: DG, dryland grain; F, forest; IHG, irrigated hay and grain; IP, irrigated potatoes; R, rangeland; SH, subirrigated hay. Hydrogeologic unit: Qal, Quaternary alluvium; QTd, Quaternary and Tertiary undifferentiated deposits; Tb, Tertiary Bozeman Group; TYsaq, Tertiary through Proterozoic sedimentary bedrock (potential aquifers); K€scu, Cretaceous through Cambrian sedimentary bedrock (typically confining units); Am, Archean metamorphic rocks. Abbreviations: ft, feet below land surface; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; permil, parts per thousand. Symbols: --, no data; <, less than minimum reporting level]

Location number	Primary land use	Hydro-geologic unit	Depth of well (ft)	Date	Depth to water (ft)	Specific conduc-tance (µS/cm)	pH, field (stan-dard units)	Water temperature, field (°C)	Oxygen, dissolved, field (mg/L)	Hardness, dissolved (mg/L as $CaCO_3$)	Cal-cium, dissolved (mg/L as Ca)	Magne-sium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potas-sium, dissolved (mg/L as K)
							WELLS							
01N03E07CDDA01	IHG	Tb	--	06-03-98	232.87	399	7.5	21.0	4.4	120	35	7.1	31	14
01N03E10BDCD01	IHG	Tb	47.5	05-27-98	18.76	475	7.4	10.0	7.0	190	52	14	25	6.5
01N03E23DBBA01	IP	Tb	50	05-27-98	17.47	503	7.3	11.0	5.8	220	56	19	18	6.3
01N03E33AAAC01	IHG	Tb	114	06-03-98	--	428	7.5	10.5	7.9	170	44	14	23	8.9
01N04E01DDBC01	DG	Tb	157	05-28-98	124.18	424	7.3	12.0	5.2	200	53	16	12	4.6
01N04E25BBCC01	SH	Qal	45	05-27-98	8.59	406	7.4	10.0	6.0	200	56	15	5.2	3.2
01N05E14ACDD01	DG	QTd	109	05-28-98	94.19	412	7.4	9.5	9.8	220	61	17	2.1	1.3
01N05E34ADAD01[1]	DG	QTd	47	05-12-98	2.85	304	7.8	9.5	9.5	--	--	--	--	--
				06-23-98	1.20	285	7.7	9.0	9.6	150	42	10	3.5	2.5
				08-26-98	3.05	290	7.5	9.5	10.1	--	--	--	--	--
				11-18-98	--	291	7.7	9.0	10.1	--	--	--	--	--
01N05E34CDBD01[1]	DG	Qal	90	05-13-98	--	344	7.9	9.0	10.5	--	--	--	--	--
				06-24-98	--	331	7.7	9.0	10.0	170	48	11	2.5	1.8
01N05E35ADBA01[1]	DG	QTd	80	05-12-98	18.15	450	7.7	11.0	9.6	--	--	--	--	--
				05-12-98[2]	--	--	--	--	--	--	--	--	--	--
				06-23-98	13.92	424	7.7	11.0	8.7	210	55	17	11	3.3
				06-23-98[2]	--	453	7.8	--	--	--	55	17	11	3.2
				08-26-98	14.29	431	7.5	11.0	9.9	--	--	--	--	--
				08-26-98[2]	--	--	--	--	--	--	--	--	--	--
				11-18-98	15.05	432	7.6	10.5	10.1	--	--	--	--	--
				11-18-98[2]	--	--	--	--	--	--	--	--	--	--
01N05E35DDBA01[1]	DG	QTd	78	05-12-98	44.02	322	7.7	9.0	11.2	--	--	--	--	--
				06-24-98	42.41	312	7.8	8.5	11.0	160	47	10	2.3	2.2
				08-27-98	41.55	307	7.5	9.0	11.2	--	--	--	--	--
				11-18-98	--	313	7.6	8.5	11.8	--	--	--	--	--

Table 3. Water-quality data for ground and surface water in the Gallatin Local Water Quality District, Montana, 1998 (Continued)

Alkalinity, field (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Bromide, dissolved (mg/L as Br)	Silica, dissolved (mg/L as SiO_2)	Solids, sum of constituents, dissolved (mg/L)	Nitrite, dissolved (mg/L as N)	Nitrite plus nitrate, dissolved (mg/L as N)	Ammonia, dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)	Deuterium/hydrogen stable-isotope ratio (permil)	Oxygen-18/oxygen-16 stable-isotope ratio (permil)	Nitrogen-15/nitrogen-14 stable-isotope ratio in NO_3 (permil)	Location number
								WELLS						
162	30	5.6	0.8	0.05	88	316	<0.01	1.4	<0.02	<0.01	--	--	--	01N03E07CDDA01
185	38	6.6	.3	.06	44	302	.01	.67	<.02	.01	--	--	--	01N03E10BDCD01
204	46	8.7	.3	.10	40	324	<.01	1.7	.02	.03	--	--	--	01N03E23DBBA01
202	24	1.5	.4	.03	54	300	<.01	1.9	<.02	<.01	--	--	--	01N03E33AAAC01
222	6.5	2.3	.5	.05	55	284	<.01	.19	<.02	<.01	--	--	--	01N04E01DDBC01
184	24	2.3	.1	.03	22	245	.01	1.7	<.02	.03	--	--	--	01N04E25BBCC01
214	9.2	1.0	<.1	.02	9.9	234	.01	1.1	.03	<.01	--	--	--	01N05E14ACDD01
--	--	.9	--	--	--	--	<.01	1.6	--	--	--	--	--	01N05E34ADAD01[1]
146	7.9	.7	<.1	.01	12	174	<.01	1.5	.06	<.01	-137	-18.31	+4.0	
--	--	--	--	--	--	--	--	1.6	--	--	--	--	--	
--	--	--	--	--	--	--	--	1.5	--	--	--	--	--	
--	--	1.1	--	--	--	--	<.01	4.6	--	--	--	--	--	01N05E34CDBD01[1]
169	8.3	1.0	<.1	.02	11	205	<.01	4.4	.06	.01	--	--	+3.5	
--	--	3.0	--	--	--	--	<.01	3.5	--	--	--	--	--	01N05E35ADBA01[1]
--	--	2.9	--	--	--	--	<.01	3.5	--	--	--	--	--	
211	15	2.8	.1	.03	20	251	<.01	3.2	.05	.03	--	--	+5.6	
[3]211	15	2.8	.1	.03	20	265	<.01	3.3	.04	.03	--	--	+5.3	
--	--	--	--	--	--	--	--	3.5	--	--	--	--	--	
--	--	--	--	--	--	--	--	3.5	--	--	--	--	--	
--	--	--	--	--	--	--	--	3.1	--	--	--	--	--	
--	--	--	--	--	--	--	--	3.1	--	--	--	--	--	
--	--	.4	--	--	--	--	<.01	3.7	--	--	--	--	--	01N05E35DDBA01[1]
144	7.5	.5	<.1	.01	12	184	<.01	3.7	.05	.02	--	--	+2.8	
--	--	--	--	--	--	--	--	3.7	--	--	--	--	--	
--	--	--	--	--	--	--	--	4.0	--	--	--	--	--	

Table 3. Water-quality data for ground and surface water in the Gallatin Local Water Quality District, Montana, 1998 (Continued)

Location number	Primary land use	Hydro-geologic unit	Depth of well (ft)	Date	Depth to water (ft)	Specific conduc-tance (µS/cm)	pH, field (stan-dard units)	Water temperature, field (°C)	Oxygen, dissolved, field (mg/L)	Hardness, dissolved (mg/L as $CaCO_3$)	Cal-cium, dissolved (mg/L as Ca)	Magne-sium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potas-sium, dissolved (mg/L as K)
						WELLS--continued								
01N05E36BADD01[1]	DG	QTd	120	05-11-98	57.86	421	7.7	10.5	9.5	--	--	--	--	--
				06-23-98	--	392	7.7	10.5	9.0	190	53	15	7.2	3.4
				08-27-98	--	398	7.6	11.0	9.4	--	--	--	--	--
				11-18-98	--	402	7.6	10.5	9.8	--	--	--	--	--
01N06E17CDCB01	DG	QTd	60	05-28-98	11.10	314	7.6	7.0	9.2	160	45	11	4.4	1.6
01N07E20ABBA01	F	K€scu	135	06-04-98	8.20	212	6.9	6.0	8.4	97	28	6.3	7.5	.1
01N07E29BDCD01	F	K€scu	485	06-04-98	113.32	342	7.9	8.5	4.4	77	27	2.1	49	<.1
01S04E04ACAA01[1]	SH	Qal	57	04-21-98	--	357	7.2	9.0	7.4	--	--	--	--	--
				05-20-98	--	342	6.9	9.0	6.9	170	44	15	4.9	2.3
				08-27-98	--	340	6.9	8.5	9.1	--	--	--	--	--
				11-18-98	--	343	6.9	8.5	8.7	--	--	--	--	--
01S04E04ACAC01[1]	SH	Qal	60	04-21-98	38.67	333	7.2	9.0	2.8	--	--	--	--	--
				05-21-98	--	312	7.0	8.0	5.3	160	41	13	4.5	2.1
				08-27-98	--	315	6.9	8.5	7.1	--	--	--	--	--
01S04E04ACCA02[1]	SH	Qal	60	04-21-98	29.87	308	7.2	8.0	6.6	--	--	--	--	--
				05-21-98	27.40	298	6.9	7.5	6.3	150	39	12	4.5	1.7
				08-27-98	24.74	298	6.8	8.0	8.5	--	--	--	--	--
				11-18-98	--	298	6.8	8.0	7.6	--	--	--	--	--
01S04E04ACDD02[1]	SH	Qal	60	04-21-98	36.29	362	7.0	9.5	7.6	--	--	--	--	--
				04-21-98[2]	--	--	--	--	--	--	--	--	--	--
				05-21-98	33.27	286	6.9	9.0	8.2	140	38	12	4.3	1.9
				08-27-98	30.01	339	6.8	9.0	8.8	--	--	--	--	--
				11-18-98	--	350	6.8	9.0	8.6	--	--	--	--	--
01S04E04ADDD01	SH	Qal	64	05-12-98	39.56	417	7.0	10.0	7.3	210	56	18	6.4	2.4
01S04E10DDDD01	SH	Qal	107	06-02-98	32.35	444	7.2	10.5	8.5	220	63	16	6.8	3.2
01S04E17DCDD01	IHG	Tb	50	01-05-98	--	643	7.8	8.5	9.9	290	62	33	24	6.6
01S04E26CDDD01	IHG	Qal	37	05-27-98	6.96	443	7.3	9.0	7.6	210	61	14	10	2.8
				05-27-98[2]	--	457	7.5	--	--	210	61	14	10	2.8

Table 3. Water-quality data for ground and surface water in the Gallatin Local Water Quality District, Montana, 1998 (Continued)

Alkalinity, field (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Bromide, dissolved (mg/L as Br)	Silica, dissolved (mg/L as SiO_2)	Solids, sum of constituents, dissolved (mg/L)	Nitrite, dissolved (mg/L as N)	Nitrite plus nitrate, dissolved (mg/L as N)	Ammonia, dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)	Deuterium/ hydrogen stable-isotope ratio (permil)	Oxygen-18/ oxygen-16 stable-isotope ratio (permil)	Nitrogen-15/ nitrogen-14 stable-isotope ratio in NO_3 (permil)	Location number
							WELLS--continued							
--	--	7.9	--	--	--	--	<.01	5.0	--	--	--	--	--	01N05E36BADD01[1]
174	12	8.1	<.1	.07	20	245	<.01	4.7	.05	.05	-147	-18.76	+5.7	
--	--	--	--	--	--	--	--	4.7	--	--	--	--	--	
--	--	--	--	--	--	--	--	4.7	--	--	--	--	--	
155	9.5	.6	<.1	.02	13	186	.01	1.7	<.02	<.01	--	--	--	01N06E17CDCB01
113	3.3	.1	.1	<.01	13	127	<.01	.15	<.02	<.01	--	--	--	01N07E20ABBA01
160	6.2	2.2	1.3	<.01	16	--	<.01	3.7	<.02	<.01	--	--	--	01N07E29BDCD01
--	--	1.6	--	--	--	--	<.01	.96	--	--	--	--	--	01S04E04ACAA01[1]
171	29	1.4	.1	.02	20	223	<.01	.91	.04	<.01	-142	-18.68	+2.9	
--	--	--	--	--	--	--	--	1.5	--	--	--	--	--	
--	--	--	--	--	--	--	--	1.4	--	--	--	--	--	
--	--	1.4	--	--	--	--	<.01	.55	--	--	--	--	--	01S04E04ACAC01[1]
152	29	1.3	.2	.02	19	202	<.01	.46	.05	.01	--	--	+1.1	
--	--	--	--	--	--	--	--	.59	--	--	--	--	--	
--	--	1.6	--	--	--	--	<.01	.26	--	--	--	--	--	01S04E04ACCA02[1]
121	34	1.5	.2	<.01	17	184	<.01	.28	.05	<.01	--	--	+2.4	
--	--	--	--	--	--	--	--	.84	--	--	--	--	--	
--	--	--	--	--	--	--	--	.78	--	--	--	--	--	
--	--	2.0	--	--	--	--	<.01	1.3	--	--	--	--	--	01S04E04ACDD02[1]
--	--	2.2	--	--	--	--	<.01	1.3	--	--	--	--	--	
128	21	1.6	.1	<.01	18	176	<.01	.61	.05	<.01	-141	-18.61	+3.4	
--	--	--	--	--	--	--	--	1.8	--	--	--	--	--	
--	--	--	--	--	--	--	--	2.1	--	--	--	--	--	
218	30	3.0	.1	.02	21	283	<.01	3.4	.03	.02	-140	-18.52	+4.0	01S04E04ADDD01
193	25	2.7	.3	.02	23	259	<.01	.94	<.02	.02	--	--	--	01S04E10DDDD01
[3]289	44	9.9	.4	--	41	405	<.01	2.8	<.02	.03	--	--	+2.7	01S04E17DCDD01
205	25	4.5	.4	.04	22	269	.01	1.5	<.02	.02	--	--	--	01S04E26CDDD01
208	24	4.8	.4	.04	22	271	.01	1.5	<.02	.02	--	--	--	

Table 3. Water-quality data for ground and surface water in the Gallatin Local Water Quality District, Montana, 1998 (Continued)

Location number	Primary land use	Hydro-geologic unit	Depth of well (ft)	Date	Depth to water (ft)	Specific conduc-tance (µS/cm)	pH, field (stan-dard units)	Water temperature, field (°C)	Oxygen, dissolved, field (mg/L)	Hardness, dissolved (mg/L as $CaCO_3$)	Cal-cium, dissolved (mg/L as Ca)	Magne-sium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potas-sium, dissolved (mg/L as K)
						WELLS--continued								
01S05E13DDDA01	DG	QTd	260	01-06-98	--	488	7.0	9.1	10.1	240	65	18	7.0	2.2
01S05E14ACDD01	DG	QTd	140	05-19-98	106.15	454	7.5	9.5	9.4	230	61	18	6.3	1.8
01S05E21BCDD01[1]	IHG	QTd	83	05-20-98	--	533	7.1	10.0	7.8	230	68	15	18	6.4
01S05E21CDDB01[1]	IHG	QTd	83	05-20-98	60.82	540	7.1	10.5	7.9	240	69	16	20	6.8
01S05E27CBDC01	IHG	QTd	115	05-27-98	41.60	593	7.3	10.5	3.8	290	82	19	9.2	4.0
01S06E06ABCB01	R	QTd	375	05-13-98	283.39	266	7.8	8.0	14.0	140	32	14	2.4	2.6
01S06E17CCDD01	DG	QTd	115	05-19-98	84.51	399	7.6	13.0	10.8	210	59	14	4.7	1.2
				05-19-98[2]	--	407	7.8	--	--	210	59	14	4.7	1.2
01S06E20BDAA02	R	QTd	128	05-19-98	48.73	296	7.9	9.5	5.7	150	36	14	5.7	1.1
01S06E32BADC01	DG	QTd	157	05-28-98	57.63	336	7.5	9.0	9.5	160	43	14	7.8	1.1
01S07E27DBDC01	F	TYsaq	80	06-04-98	36.50	297	7.4	7.0	6.5	130	38	7.4	14	.1
01S07E30BAAA01	F	TYsaq	118	06-05-98	53.03	463	7.1	8.0	5.2	190	59	10	27	.5
02S04E01CCCD01	IHG	Qal	40	05-27-98	14.50	514	7.2	9.5	7.0	250	72	17	9.8	3.4
02S04E13BADA01	IHG	Qal	40	01-05-98	--	437	7.1	10.5	8.2	190	52	14	18	4.7
02S04E13BBDA01	IHG	Qal	30	05-11-98	15.90	491	7.1	9.0	5.3	230	64	16	16	4.2
				06-02-98	12.04	458	7.2	8.5	5.5	--	--	--	--	--
02S04E14DADC02	--	Am	--	01-05-98	--	681	9.3	53.0	--	6	2.4	.005	140	2.6
02S04E16BCCA01	IHG	Tb	148	05-26-98	--	571	7.4	10.0	9.0	210	55	17	36	6.8
02S05E10AABB01	IHG	QTd	55	05-20-98	--	474	7.3	8.5	2.3	240	70	16	7.0	4.1
02S05E19BACC01	IHG	QTd	152	05-11-98	59.97	--	--	10.5	4.5	--	--	--	--	--
02S05E23CCCB01	IHG	QTd	80	05-13-98	5.48	461	7.5	7.5	2.8	230	67	16	6.7	3.8
				06-02-98	4.24	454	7.3	7.5	2.2	--	--	--	--	--
02S05E31ADDA01	IHG	QTd	125	05-26-98	--	459	7.8	--	--	180	35	24	32	1.7
02S05E36CAAB01[1]	IHG	QTd	45	05-18-98	11.51	507	7.3	9.0	8.6	240	67	17	13	3.7
				05-18-98[2]	--	--	--	--	--	--	--	--	--	--
02S05E36CCCD01[1]	IHG	QTd	51.5	05-18-98	--	334	7.3	9.0	9.1	170	51	9.9	3.2	3.5
				08-26-98	--	346	7.1	8.5	11.3	--	--	--	--	--
02S06E12DCAA01	R	TYsaq	39	06-04-98	6.42	394	6.8	6.5	7.8	170	50	11	18	.3
				06-04-98[2]	--	414	7.0	--	--	--	50	12	18	.3

Table 3. Water-quality data for ground and surface water in the Gallatin Local Water Quality District, Montana, 1998 (Continued)

Alkalinity, field (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Bromide, dissolved (mg/L as Br)	Silica, dissolved (mg/L as SiO_2)	Solids, sum of constituents, dissolved (mg/L)	Nitrite, dissolved (mg/L as N)	Nitrite plus nitrate, dissolved (mg/L as N)	Ammonia, dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)	Deuterium/hydrogen stable-isotope ratio (permil)	Oxygen-18/oxygen-16 stable-isotope ratio (permil)	Nitrogen-15/nitrogen-14 stable-isotope ratio in NO_3 (permil)	Location number
						WELLS--continued								
[3]207	12	13	<.1	--	11	284	<.01	7.1	<.02	.02	--	--	+6.2	01S05E13DDDA01
203	11	13	.1	.09	14	266	<.01	4.4	.05	<.01	-147	-18.93	+4.9	01S05E14ACDD01
228	18	16	.2	.05	35	334	<.01	4.4	.03	.04	-138	-18.19	+5.1	01S05E21BCDD01[1]
253	23	4.6	.2	.06	41	348	<.01	3.1	.03	.04	-139	-18.46	+4.7	01S05E21CDDB01[1]
222	50	21	.1	.19	31	362	.01	2.6	.02	.02	--	--	--	01S05E27CBDC01
150	8.0	.44	.1	.01	12	163	<.01	.18	<.02	<.01	-137	-18.14	+1.6	01S06E06ABCB01
202	10	1.3	.1	.03	18	240	<.01	2.1	.05	.01	-140	-18.10	+5.2	01S06E17CCDD01
[3]204	10	1.3	.1	.03	18	240	<.01	2.2	.04	.01	--	--	+5.4	
158	3.6	1.3	.3	.02	30	191	<.01	.90	.02	.03	--	--	+3.6	01S06E20BDAA02
160	16	2.1	.2	.02	19	199	<.01	.23	.03	.01	--	--	--	01S06E32BADC01
138	20	.6	.1	.02	12	176	<.01	.33	<.02	<.01	--	--	--	01S07E27DBDC01
202	45	4.2	.5	.02	14	285	<.01	.84	<.02	<.01	--	--	--	01S07E30BAAA01
255	17	4.8	.1	.05	25	311	<.01	2.0	<.02	.03	--	--	--	02S04E01CCCD01
[3]207	19	4.2	.3	--	31	275	<.01	1.6	<.02	.06	--	--	+6.2	02S04E13BADA01
265	29	5.7	.2	--	33	333	<.01	1.1	.04	.06	-141	-18.69	--	02S04E13BBDA01
217	--	--	--	--	--	--	--	1.0	--	--	--	--	+6.2	
[3]88	130	54	11	--	66	456	--	--	--	--	--	--	--	02S04E14DADC02
176	54	28	.6	.19	44	352	.01	1.2	<.02	.06	--	--	--	02S04E16BCCA01
265	8.4	2.7	.1	.02	29	304	<.01	1.7	.04	.05	-141	-18.46	+8.7	02S05E10AABB01
260	37	6.1	<.1	.07	42	--	<.01	2.4	.03	.07	-143	-18.63	+7.6	02S05E19BACC01
252	5.6	1.2	<.1	.01	30	293	<.01	2.6	.03	.04	-138	-18.46	--	02S05E23CCCB01
240	--	--	--	--	--	--	<.01	2.5	<.02	.04	--	--	+6.7	
226	25	1.3	.8	.03	21	280	.01	.75	<.02	.04	--	--	--	02S05E31ADDA01
212	8.0	22	.2	.02	32	308	<.01	4.1	.03	.12	--	--	+4.9	02S05E36CAAB01[1]
--	--	--	--	--	--	--	--	--	--	--	--	--	+4.7	
161	5.2	3.8	.2	.02	34	217	<.01	2.3	.05	.09	-137	-18.07	--	02S05E36CCCD01[1]
--	--	--	--	--	--	--	--	2.8	--	--	--	--	+4.6	
196	9.2	2.7	.1	.02	16	233	<.01	1.7	<.02	<.01	--	--	--	02S06E12DCAA01
[3]204	9.2	2.9	.2	.02	16	238	<.01	1.7	<.02	<.01	--	--	--	

Table 3. Water-quality data for ground and surface water in the Gallatin Local Water Quality District, Montana, 1998 (Continued)

Location number	Primary land use	Hydro-geologic unit	Depth of well (ft)	Date	Depth to water (ft)	Specific conductance (µS/cm)	pH, field (standard units)	Water temperature, field (°C)	Oxygen, dissolved, field (mg/L)	Hardness, dissolved (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)
						WELLS--continued								
02S06E20CABD01	IHG	QTd	300	06-05-98	143.87	--	--	9.5	10.8	--	--	--	--	--
02S06E36BDBB01	F	KЄscu	75	01-06-98	--	683	6.8	6.0	4.8	340	94	26	12	2.6
				10-19-98	--	692	6.9	7.5	2.5	--	--	--	--	--
				10-19-98	--	741	6.8	7.5	2.7	--	--	--	--	--
02S07E02ACDC01	R	KЄscu	111	06-03-98	16.46	366	7.1	6.5	5.7	160	48	11	17	.2
02S07E24CDCB01	R	TYsaq	125	06-03-98	--	697	8.1	7.0	--	100	22	11	130	1.2
03S04E09ABBC01	R	Qal	96	05-26-98	24.87	406	7.1	8.0	5.2	190	62	8.0	8.9	4.6
03S04E11BCAD01	IHG	Qal	80	05-12-98	14.55	397	7.3	10.0	6.1	190	56	11	9.3	4.6
				06-02-98	13.84	405	7.3	9.5	7.1	--	--	--	--	--
03S04E11DDBC01	IHG	Qal	65	05-13-98	36.17	426	7.5	9.0	12	210	63	14	6.8	3.1
03S04E23CABB01	IHG	Qal	100	05-26-98	60.49	434	7.2	8.5	8.5	220	73	10	3.8	1.9
03S04E34ABBB01	IHG	QTd	92	05-26-98	44.49	369	7.1	8.0	8.5	160	47	10	15	4.3
03S04E36ACAC01	R	QTd	197	05-19-98	135.82	643	7.5	7.5	8.0	280	80	19	35	2.9
03S05E11DAAC02	F	QTd	--	05-18-98	--	215	6.5	7.0	8.8	96	24	8.6	5.3	2.4
03S05E15DCCA01	F	QTd	220	05-13-98	--	222	7.2	7.0	10.2	91	27	5.7	11	1.0
				06-02-98	--	218	7.2	7.0	9.3	--	--	--	--	--
						OTHER SITES								
01S04E09BAAB01[4]	--	--	--	05-12-98	--	188	8.4	7.2	--	86	24	6.5	3.5	1.2
01S05E26ACDD01[5]	--	--	--	01-05-98	--	617	7.0	10.5	--	180	47	14	48	9.9
04S04E07DDDA01[6]	--	--	--	01-06-98	--	322	7.4	0.0	11.6	160	41	14	4.6	1.5
						FIELD BLANKS								
	--	--	--	03-31-98	--	1	--	--	--	--	.04	.01	<.1	<.1
	--	--	--	05-12-98	--	2	--	--	--	--	<.02	<.004	<.1	<.1
	--	--	--	05-26-98	--	2	--	--	--	--	<.02	<.004	<.1	<.1
	--	--	--	06-04-98	--	2	5.3	5.5	--	--	<.02	<.004	<.1	<.1
	--	--	--	06-24-98	--	2	5.2	15.0	7.5	--	.08	.01	<.1	<.1

[1] Also within suburban population areas, see figures 5 and 14.

[2] Replicate sample. Specific conductance, pH, and alkalinity (if shown) were measured in the laboratory.

[3] Alkalinity measured in the laboratory.

[4] Gallatin River at Amsterdam Road, near Belgrade.

[5] Bozeman Wastewater Treatment Plant effluent prior to chlorination.

[6] Gallatin River near Gallatin Gateway.

Table 3. Water-quality data for ground and surface water in the Gallatin Local Water Quality District, Montana, 1998 (Continued)

Alkalinity, field (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Bromide, dissolved (mg/L as Br)	Silica, dissolved (mg/L as SiO_2)	Solids, sum of constituents, dissolved (mg/L)	Nitrite, dissolved (mg/L as N)	Nitrite plus nitrate, dissolved (mg/L as N)	Ammonia, dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)	Deuterium/ hydrogen stable-isotope ratio (permil)	Oxygen-18/ oxygen-16 stable-isotope ratio (permil)	Nitrogen-15/ nitrogen-14 stable-isotope ratio in NO_3 (permil)	Location number
							WELLS--continued							
164	10	6.9	.5	.07	46	--	<.01	2.0	<.02	.03	--	--	--	02S06E20CABD01
[2]307	20	19	.3	--	16	409	<.01	8.0	<.02	.02	--	--	+14.9	02S06E36BDBB01
[2]307	--	--	--	--	--	--	--	8.8	--	--	--	--	--	
--	--	22	--	.04	--	--	--	10	--	--	--	--	--	
186	12	1.9	.2	.02	13	221	<.01	1.4	<.02	.01	--	--	--	02S07E02ACDC01
363	41	.6	.4	.04	10	438	<.01	<.05	.26	<.01	--	--	--	02S07E24CDCB01
184	22	8.1	.2	.05	37	263	<.01	.41	.03	.08	--	--	--	03S04E09ABBC01
195	18	3.2	.2	.04	38	264	<.01	1.5	.02	.04	-141	-18.45	--	03S04E11BCAD01
192	--	--	--	--	--	--	--	1.6	--	--	--	--	+3.1	
252	9.6	2.8	.1	.03	27	290	<.01	2.6	.04	.03	-140	-18.38	+3.4	03S04E11DDBC01
236	4.0	1.5	.1	.02	21	263	<.01	1.2	.05	.04	--	--	--	03S04E23CABB01
168	6.7	1.5	.2	.03	44	236	.01	1.1	<.02	.07	--	--	--	03S04E34ABBB01
309	3.7	2.0	.8	.04	38	403	.01	8.1	.03	.04	-128	-16.21	+4.6	03S04E36ACAC01
87	5.3	6.9	.1	.04	34	149	<.01	2.0	.04	.05	-135	-17.79	+6.4	03S05E11DAAC02
107	5.6	1.4	.5	.02	55	176	<.01	.71	.02	.09	-136	-17.48	--	03S05E15DCCA01
88	--	--	--	--	--	--	--	.70	--	--	--	--	+4.4	
							OTHER SITES							
[2]82	15	.6	.1	<.01	13	113	<.01	.09	<.02	.02	-143	-18.74	--	01S04E09BAAB01[4]
[2]149	20	53	1.0	--	26	309	--	--	--	--	--	--	--	01S05E26ACDD01[5]
[2]116	53	1.2	.3	--	14	199	<.01	.08	<.02	<.01	--	--	--	04S04E07DDDA01[6]
							FIELD BLANKS							
1.7	<.1	<.1	<.1	--	<.1	--	<.01	<.05	.03	<.01	--	--	--	
[2]1.9	<.1	<.1	<.1	<.01	<.1	--	<.01	<.05	<.02	<.01	--	--	--	
[2]1.8	<.1	<.1	<.1	<.01	<.1	--	<.01	<.05	<.02	<.01	--	--	--	
[2]<1.0	<.1	<.1	--	<.01	.1	--	<.01	<.05	<.02	<.01	--	--	--	
[2]1.7	<.1	<.1	<.1	<.01	<.1	--	<.01	<.05	.04	<.01	--	--	--	

Table 4. Chlorofluorocarbon (CFC) data and estimated recharge dates for ground water in the Gallatin Local Water Quality District, Montana, 1998

[Estimated recharge dates are based on CFC concentrations and estimated recharge temperatures and altitudes (U.S. Geological Survey, unpublished data). Abbreviation: pg/kg, picograms per kilogram of solution; CFC-11, chlorofluorocarbon-11; CFC-12, chlorofluorocarbon-12; CFC-113, chlorofluorocarbon-113. Symbol: --, not determined]

Location number	Sampling date	Concentration (pg/kg)			Estimated recharge date (year)
		CFC-11	CFC-12	CFC-113	
01N05E34ADAD01	06-23-98	825.1	29,764.5	13.8	1970s
		822.7	1,045.1	13.1	
		828.5	1,371.8	14.4	
01N05E34CDBD01	06-24-98	1,236.8	568.2	33.2	1980s
		1,239.3	565.3	32.6	
		1,253.4	570.3	32.9	
01N05E35ADBA01	06-23-98	119.7	52.9	0.0	1960s
		119.5	52.9	3.4	
		118.1	51.5	4.2	
01N05E35DDBA01	06-24-98	734.2	681.8	59.0	1980s
		737.3	677.3	59.5	
		729.4	651.4	59.1	
01N05E36BADD01	06-23-98	39.0	26.9	0.0	1960s
		39.3	28.3	2.8	
		39.8	26.5	2.6	
01S04E04ACAA01	05-20-98	712.6	390.7	102.6	1990s
		718.0	383.2	110.1	
		716.1	370.4	104.6	
01S04E04ACAC01	05-21-98	666.5	572.1	97.0	1990s
		666.3	571.9	96.6	
		675.6	602.3	96.8	
01S04E04ACCA02	05-21-98	692.2	522.1	109.7	1990s
		694.9	511.7	102.9	
		698.9	498.2	111.1	
01S04E04ACDD02	05-21-98	618.4	334.3	101.9	1990s
		616.6	332.4	106.0	
		614.8	311.9	89.6	
01S04E04ADDD01	05-12-98	629.4	349.0	101.2	1990s
		630.9	354.2	99.5	
		626.2	335.6	95.3	
01S05E14ACDD01	05-19-98	273.2	126.9	21.3	1970s
		274.6	137.3	19.9	
		268.1	127.4	10.7	
01S05E21BCDD01	05-20-98	2,144.1	287.3	--	1980s
		2,208.1	286.5	--	
		2,559.5	276.7	53.5	
01S05E21CDDB01	05-20-98	555.0	260.3	62.0	1980s
		554.5	262.4	56.4	
		559.1	266.0	63.4	

Table 4. Chlorofluorocarbon (CFC) data and estimated recharge dates for ground water in the Gallatin Local Water Quality District, Montana, 1998 (Continued)

Location number	Sampling date	Concentration (pg/kg)			Estimated recharge date (year)
		CFC-11	CFC-12	CFC-113	
01S06E06ABCB01	05-13-98	726.1	317.0	77.9	1980s
		704.8	315.0	69.1	
		717.9	304.5	74.2	
01S06E17CCDD01	05-19-98	599.4	327.1	69.3	1980s
		602.3	337.6	76.0	
		617.8	343.3	79.8	
01S06E20BDAA02	05-19-98	218.4	12.6	0.0	1970s
		170.8	11.4	0.0	
		197.5	12.4	0.0	
02S04E13BBDA01	05-11-98	546.0	4,200.4	62.0	1980s
		546.5	4,189.6	63.8	
		553.5	4,271.4	68.8	
02S05E19BACC01	05-11-98	27.6	41.7	0.0	1960s
		28.5	45.1	0.0	
		27.8	42.9	0.0	
02S05E23CCCB01	05-13-98	445.1	260.1	61.7	1980s
		444.5	255.7	61.4	
		444.3	252.9	61.7	
02S05E36CAAB01	05-18-98	638.8	352.9	95.0	1980s
		639.2	354.2	84.3	
		636.5	354.6	115.5	
02S05E36CCCD01	05-18-98	625.6	354.2	97.0	1990s
		625.1	354.3	100.4	
		617.4	352.7	110.6	
03S04E11BCAD01	05-12-98	560.1	340.6	62.4	1980s
		563.3	340.1	63.2	
		559.9	342.7	60.5	
03S04E11DDBC01	05-13-98	539.8	299.1	74.6	1980s
		548.5	314.0	85.2	
		545.8	312.5	86.1	
03S04E36ACAC01	05-19-98	34.1	28.5	0.0	1960s
		34.4	30.4	0.0	
		34.9	27.4	0.0	
03S05E11DAAC02	05-18-98	875.4	381.1	114.5	1990s
		906.7	399.1	111.3	
		896.8	387.3	113.2	
03S05E15DCCA01	05-13-98	392.9	123.5	26.4	1970s
		260.6	66.5	6.4	
		266.0	55.3	4.3	
		261.7	64.1	5.4	

Table 5. Drinking-water standards and guidelines for public-water supply

[Abbreviations: mg/L, milligrams per liter. Symbol: --, no standard or guideline concentration has been adopted]

Constituent	Montana Human Health Standard[1]	Maximum Contaminant Level (MCL)[2]	Secondary Maximum Contaminant Level (SMCL)[2]
pH (standard pH units)	--	--	[3]6.5-8.5
Sulfate (mg/L as SO_4)	--	[4]500	250
Chloride (mg/L as Cl)	--	--	250
Fluoride (mg/L as F)	4	4	2
Dissolved solids (mg/L)	--	--	500
Nitrite (mg/L as N)	1	1	--
Nitrate (mg/L as N)	10	10	--

[1] Montana Department of Environmental Quality (1995).

[2] National Primary Drinking-Water Regulations are established for contaminants which, if present in drinking water, may cause adverse human health effects. Either a Maximum Contaminant Level (MCL) or an action level with a treatment technique is specified by these regulations for regulated contaminants for public drinking-water supplies. MCLs are health-based and enforceable; proposed MCLs are nonenforceable. Secondary Drinking-Water Standards are established for contaminants that can adversely affect the taste, odor, or appearance of water and result in discontinuation of use of the water. These regulations specify Secondary Maximum Contaminant Levels (SMCL), which are esthetically based and nonenforceable (U.S. Environmental Protection Agency, 1996).

[3] Ideal range; not a maximum level (U.S. Environmental Protection Agency, 1996).

[4] Proposed MCL.

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