Montana Bureau of Mines and Geology

MONTANA GROUND WATER ASSESSMENT ATLAS NO. 4

GROUNDWATER RESOURCES OF THE LOLO-BITTERROOT AREA: MINERAL, MISSOULA, AND RAVALLI COUNTIES, MONTANA

Part A* - Descriptive Overview and Water-Quality Data

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*The atlas is published in two parts: Part A contains a descriptive overview of the study area, water-quality data, and an illustrated glossary to introduce and explain many specialized terms used in the text; Part B contains the ten maps referenced in this document. The maps offer expanded discussions about many aspects of the hydrogeology of the Lolo-Bitterroot area. Parts A and B are published separately and each map in Part B is also available individually.

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PREFACE

The Montana Ground Water Assessment Act

In response to concerns about management of groundwater in Montana, the 1989 Montana State Legislature instructed the Environmental Quality Council (EQC) to evaluate the State's groundwater programs. The EQC task force identified major problems in managing groundwater attributable to insufficient data and lack of systematic data collection. The task force recommended implementing long-term monitoring, systematic characterization of groundwater resources, and a computerized database. Responding to these recommendations, the 1991 Legislature passed the Montana Ground Water Assessment Act (85-2-901 et seq., MCA) so that the quality of decisions related to groundwater management, protection, and development might be improved. The Act established three programs at the Montana Bureau of Mines and Geology to address groundwater information needs in Montana:

- the groundwater monitoring program: to provide long-term records of water quality and water levels for the State's major aquifers;
- the groundwater characterization program: to map the distribution of and document the water quality and water-yielding properties of individual aquifers in specific areas of the State, and
- the groundwater information center (GWIC): to provide readily accessible information about groundwater to land users, well drillers, and local, State, and Federal agencies.

The Groundwater Assessment Steering Committee oversees program implementation. The Steering Committee includes representatives from water agencies in State and Federal government, and representatives from local governments and water user groups. The committee also provides a forum through which units of State, Federal, and local government can coordinate groundwater research.

Montana Ground Water Assessment Atlas Series

This atlas is the fourth of a series systematically describing Montana's hydrogeologic framework. Figure 1 shows the characterization-area boundaries as defined by the Steering Committee and the active study areas at the time of this report; an atlas is planned for each area. Each atlas is published in two parts: Part A contains a descriptive overview of the study area along with water-quality data and an illustrated glossary to introduce and explain some of the specialized terms used; Part B contains maps that offer expanded discussions of the hydrogeology. Parts A and B are published separately, and each map in Part B is available individually. The overview and maps are intended for interested citizens and others who may make decisions about groundwater use but who are not necessarily hydrogeologists.

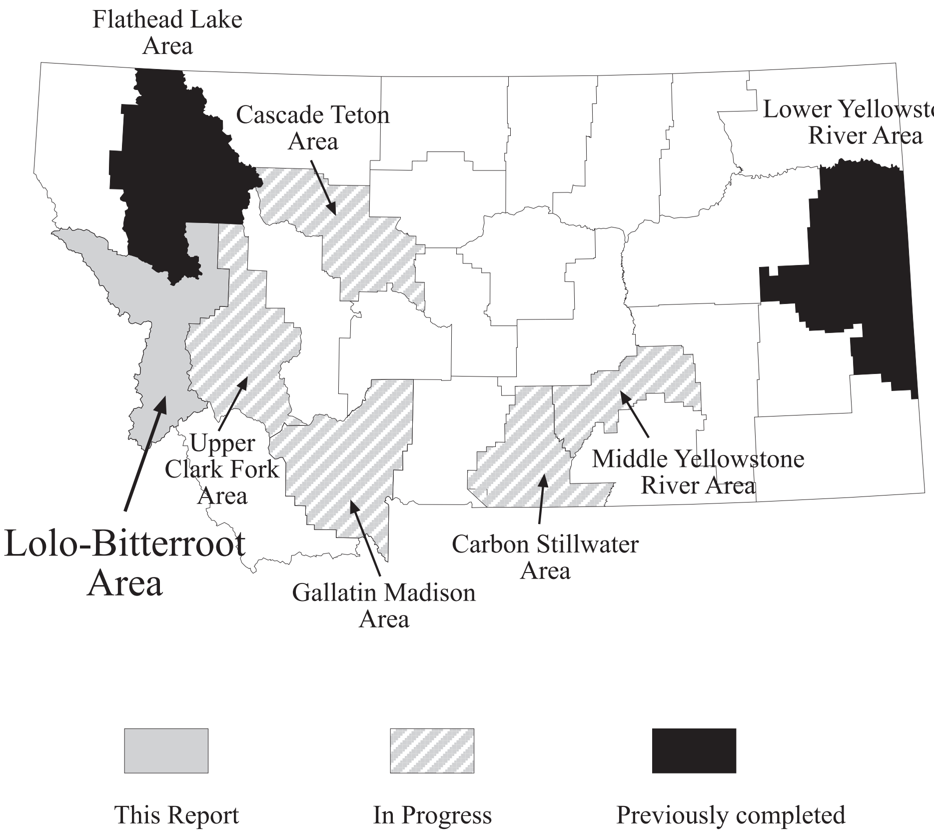


Figure 1. The Lolo-Bitterroot Area Ground Water Assessment Atlas is the fourth atlas prepared by the Ground Water Characterization Program. Other areas selected by the Ground Water Assessment Program Steering Committee where work was in progress at the time of this report are marked with stripes.

This atlas focuses on water-quality and development attributes of the Lolo-Bitterroot Groundwater Characterization area, starting from a discussion of the area's climate, hydrologic budget, underlying geology, and hydrogeologic framework. The 10 Lolo-Bitterroot area Part B maps that accompany this document offer more detailed descriptions of the hydrogeology. Readers are encouraged to use the Part B maps in conjunction with this document to best understand the area's hydrogeology.

INTRODUCTION

The Montana Bureau of Mines and Geology (MBMG) conducted the Lolo-Bitterroot area groundwater characterization study as part of the Montana Ground Water Assessment Program. The objectives were to: (1) describe the extent, thickness, and water-bearing properties of the area's aquifers, and (2) describe the chemical characteristics of the groundwater. In the Lolo-Bitterroot, groundwater supplies 97 percent of the drinking water and provides about 86 percent of water used by industry (Cannon and Johnson, 2004). The basic information presented here in conjunction with the 10 part B maps will help landowners and public officials make decisions regarding groundwater development, protection, and management.

Because of differences in the geology and groundwater flow within the study area, discussion of the hydrogeology has been divided into subareas. Place names and the subarea locations are shown in figure 2 and generally conform to geographic areas defined by the major valleys:

- Bitterroot Valley subarea (from the headwaters of the Bitterroot River to the canyon between Lolo and Missoula),
- Missoula Valley subarea (including the Missoula Valley from Huson to Hellgate Canyon and the Ninemile Valley),
- Canyons subarea (main stem of Clark Fork River and tributaries upstream and downstream of the Missoula Valley),
- Seeley–Swan subarea (including Placid Lake),
- Potomac subarea,
- St. Regis subarea, and
- Mountains subarea.

Purpose and Scope

The primary purpose of the Lolo-Bitterroot groundwater assessment was to develop a better understanding of the area's groundwater resources. The data used to compile the aquifer descriptions presented in this atlas and the Part B maps are stored in the MBMG's Ground Water Information Center (GWIC) database, which is continually updated with new information. Because the GWIC database allows automated storage and retrieval of groundwater data, up-to-date information can be retrieved and used to enhance the interpretations presented here. Paper copies of the individual maps in Part B are available through the MBMG Publication Sales office, or electronic versions may be downloaded from the GWIC website (http://mbmggwic.mtech.edu) and the MBMG publications catalog (http://www.mbmg.mtech.edu).

Description of Study Area

The Lolo-Bitterroot area includes Mineral and Ravalli Counties, and that part of Missoula County outside the Flathead Indian Reservation. The area covers about 6,000 square miles; about 68 percent is managed by either Federal or State government, while about 32 percent is privately owned (fig. 2). The estimated 2005 population was about 144,000 people. The five principal population centers—Missoula, Hamilton, East Missoula, Stevensville, and Seeley Lake—account for 47 percent of all residents. Between 1990 and 2005, Missoula and Ravalli Counties experienced growth rates of 21 and 37 percent, respectively, some of the highest in Montana (http://factfinder.census.gov/). The rest of the population resides outside of the major population centers in small communities or is spread across rural acreage at an average of 15 people per square mile (outside federally managed land). Most people work in management, professional, sales, office work, and services fields (U.S. Census data).

Much of the Federal and State-managed land is mountainous, undeveloped, and essentially uninhabited (fig. 2). The Lolo-Bitterroot area is part of the Northern Rocky Mountains physiographic province, where north- to northwest-trending mountain ranges separate intermontane valleys drained by the Clark Fork River and its tributaries. The entire Bitterroot

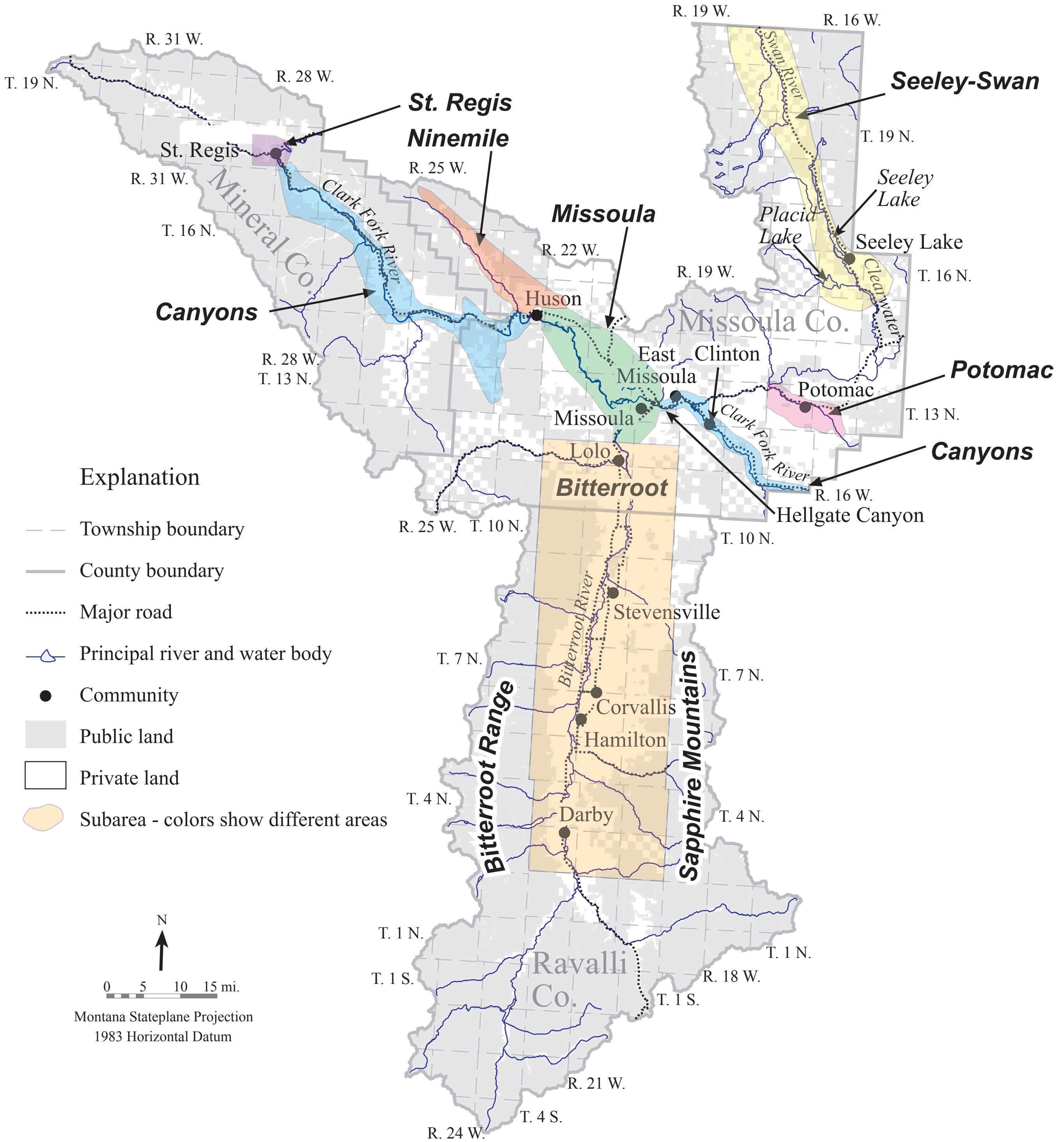


Figure 2. The Lolo-Bitterroot Area groundwater characterization study covers all of Ravalli, Mineral and Missoula Counties, and the parts of Missoula County outside of the Flathead Indian Reservation. The hydrogeologic subareas described in the atlas are shown, as are geographic names used in the text.

River watershed—a major tributary to the Clark Fork River—is included in the study area, as are parts of the St. Regis, Swan, and Clearwater river drainages.

The Bitterroot and Missoula Valleys typically contain large areas of low-relief grassy and wooded terrain into which modern streams have cut relatively narrow channels 50 to 100 ft below the valley floors; downstream of Missoula, the Clark Fork River is entrenched as much as 200 ft below the valley floor. Areas of greatest relief are along the fronts of the Bitterroot, Swan, and Mission Ranges. About 30 mountaintops exceed altitudes of 9,000 ft above mean sea level, mostly in the Bitterroot Range, but some high peaks also are in the Mission and Swan

Ranges. The study area's lowest point, at 2,580 ft above mean sea level, is where the Clark Fork River exits Mineral County.

The principal aquifers that store and yield most of the groundwater used in the Lolo-Bitterroot area occur in the unconsolidated to semi-consolidated basin-fill sediments found within the intermontane valleys. Fractured consolidated sedimentary, metasedimentary, and intrusive igneous bedrock around the valley margins are secondary aquifers.

Methods of Investigation

Well-log data were used to prepare maps and cross sections showing location, depth, and thickness of the principal hydrogeologic units. Hydrogeologists reviewed lithologic descriptions for about 16,000 of the area's 28,500 wells and assigned geologic unit codes to these water-well records in the GWIC database. Field staff mapped, measured, and described geologic exposures in selected areas. Most of the hydrologic field work and field visits were conducted during 1998 and 1999; 885 wells were visited to measure water levels and collect basic water-quality parameters (temperature, pH, and specific conductance). Wells were field-located to the nearest 2.5 acres using navigational grade Geographical Positioning Systems (GPS) or U.S. Geological Survey 7.5-minute topographic maps (appendix A).

Seasonal water-level data were obtained from several sources to assess the magnitude and timing of water-level fluctuations. Between 1999 and 2002, the Characterization Program measured water levels daily or monthly in about 120 wells. Historical water-level data from the GWIC database helped staff assess long-term water-level trends and evaluate effects of climate variability, development, and water use on groundwater supplies. Much of the water-level information is summarized in Part B, Map 10. The Ground Water Assessment program continues to monitor 79 wells in the three counties as part of the statewide groundwater monitoring network.

Water-quality sampling

Characterization Program field staff collected water samples from 261 wells between 1997 and 2000 to generate baseline water-quality data. In addition, analytical results from 9 wells sampled prior to 1997 and 15 wells sampled after 2000 were evaluated. Samples came from domestic, stock, public supply, and dedicated groundwater monitoring wells and were submitted to the MBMG analytical lab to determine concentrations of major cations and anions, nitrate, and trace elements (for explanations of these water-quality parameters see the glossary). Nitrate-only samples were collected from an additional 52 wells. A subset of 144 samples was analyzed for tritium (^3H) to identify water recharged within the past 50 years. Analytical laboratory results are available at the GWIC website (http://mbmggwic.mtech.edu/). Isotopic results are in appendix B.

The Characterization Program repeatedly sampled some sites to generate time-series on nitrate (as nitrogen) concentrations in water; for the purpose of the statistical summaries later portrayed for each subarea, the most recent analysis was used. The total water-quality data set (new and historical data) contains representative samples from all the major aquifers in the Lolo-Bitterroot area. Where applicable, the water-quality data were compared with U.S. Environmental Protection Agency (EPA) primary, secondary, and proposed maximum contaminant levels (MCL, SMCL, and PMCL) for drinking water (see glossary for further explanation).

Trace-element analysis of rocks and sediments

Elevated arsenic concentrations near Hamilton and Corvallis in the Bitterroot Valley may be derived from nearby hydrothermally altered and mineralized Tertiary-age granitic rocks in the Sapphire Mountains. To assess the distribution of arsenic in aquifer materials for comparison to groundwater arsenic concentrations, bulk samples of bedrock and aquifer materials were submitted to ALS Chemex for trace-element analysis using a strong-acid extraction solution. This study analyzed 10 samples of granitic rocks from the Willow Creek and Skalkaho plutons (Presley, 1971; La Tour, 1974) and other intrusive igneous rocks, and 7 samples of sediments and sedimentary rocks derived from the igneous rocks. Three of the samples were also treated with weak-acid solution, using a standard U.S. Environmental Protection Agency (EPA) method, to model leaching by mildly acidic rainwater. The MBMG analytical laboratory analyzed the leachate for arsenic.

Previous Investigations

Previous groundwater resource studies in the Lolo-Bitterroot area have included regional investigations (e.g., Kendy and Tresch, 1996), topical studies concentrated in parts of the area, and descriptions of pollution of shallow, unconfined aquifers. Groundwater resource investigations of the Clark Fork basin (Rorabaugh and Simons, 1966; Boettcher and Gosling, 1977), of the Bitterroot Valley (McMurtrey and others, 1959, 1972; Briar and Dutton, 2000), and of the Missoula Valley (McMurtrey and others, 1965; Woessner, 1988) mostly discussed shallow, unconfined aquifers and surface water. Uthman (1988), Stewart (1998), Finstick (1986), and Norbeck and McDonald (2001) have also discussed hydrogeology in portions of the Bitterroot Valley. Numerous studies in the Missoula Valley have concentrated on the hydrogeology and water quality of the sole source Missoula aquifer (Morgan, 1986; Woessner, 1988; Wogsland, 1988; Miller, 1991; Smith, 1992; Woessner and others, 1995; King, 1996; Antonelli, 2001; LaFave, 2002; Morrow, 2002; Joy, 2005; Tallman, 2005; Cook, 2005). Groundwater investigations in the northeastern part of Missoula County have been limited to the Seeley–Swan area (Norbeck and McDonald, 1999).

Norbeck (1980) reported on the only deep-drilling program that investigated the basin-fill deposits within the study area at depths greater than a few hundred feet. Geographic, geologic, and hydrologic summaries of several basins included in the study area are presented in Caldwell and others (2004), Kendy and Tresch (1996), Briar and others (1996), Clark and Dutton (1996), and Tuck and others (1996).

Climate

Measured mean annual precipitation at valley-bottom meteorological stations ranges from 12.2 inches per year (in/yr) at Hamilton to 29.8 in/yr at Haugen in the northwest part of the study area near St. Regis (Western Regional Climate Center: Montana Climate Summaries, 2005). Much greater annual precipitation occurs in the mountainous areas surrounding the valleys, but aside from measurements at a few high-altitude snow survey sites, no measurements are available. Based on the 1971–2000 period, modeled precipitation by the PRISM group at Oregon State University shows that annual precipitation varies from 11 in/yr across most valley bottoms to as much as 85 in/yr in the mountains (fig. 3a). Area-wide, the modeled mean annual precipitation is about 34 in/yr. Precipitation measured at valley stations (fig. 3b) shows that at Haugen and St. Regis in the mountainous northwestern part of the study area, the wettest part of each year is November through February. Wintertime precipitation in the mountains falls mostly as snow. Stations in valley areas in the southern part of the study area receive most of their precipitation from rainfall in May and June.

Valley-bottom monthly-minimum temperatures (1893–2005 period of record) measured in Missoula and typical for the study area average about 15°F in January and 50°F in July. Monthly maximum temperatures range from 30°F in January to about 85°F in July and August. Extreme temperatures can be as low as -35° to -45°F in the winter, but can be greater than 100°F in the summer.

Water Balance

In the Lolo-Bitterroot, the annual water balance accounts for the distribution of water and defines pathways by which water enters and leaves the area. The boundary of the Lolo-Bitterroot study is largely coincident with the Clark Fork River drainage below Rock Creek and the Blackfoot River below Ovando; a small area in the northeast is drained by the northward-flowing Swan River (fig. 4) and not considered in this budget. The Clark Fork River drainage extends east and outside of the Lolo-Bitterroot area, but gauges on Rock Creek, the main stem of the Clark Fork River, and the Blackfoot River provide annual measurements of surface water entering the area. A gauge on the Clark Fork River near St. Regis measures surface-water discharge. For watersheds like the Lolo-Bitterroot where the surface water and groundwater divides more or less coincide and for which there are no external inflows or outflows of groundwater, the annual water balance equation is:

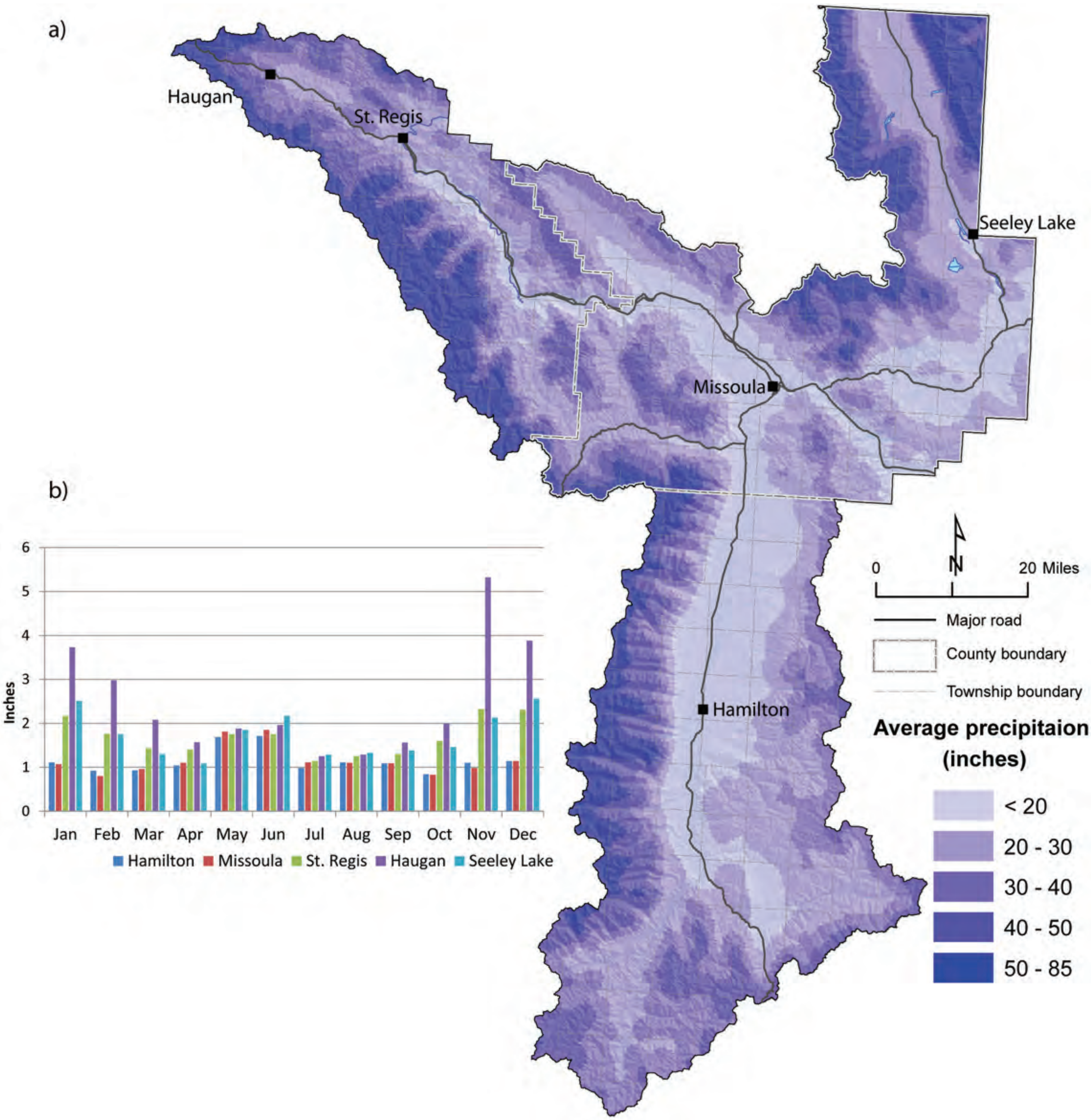


Figure 3. (a) Modeled precipitation data show that it is generally dryer in the valleys and wetter in the mountains, especially in the western and northeastern parts of the area. Modeled average precipitation for the years 1971–2000 is from the PRISM Group, Oregon State University, http://www.prismclimate.org. (b) Precipitation data for selected stations are from the Western Regional Climate Center, http://www.wrcc.dri.edu/.

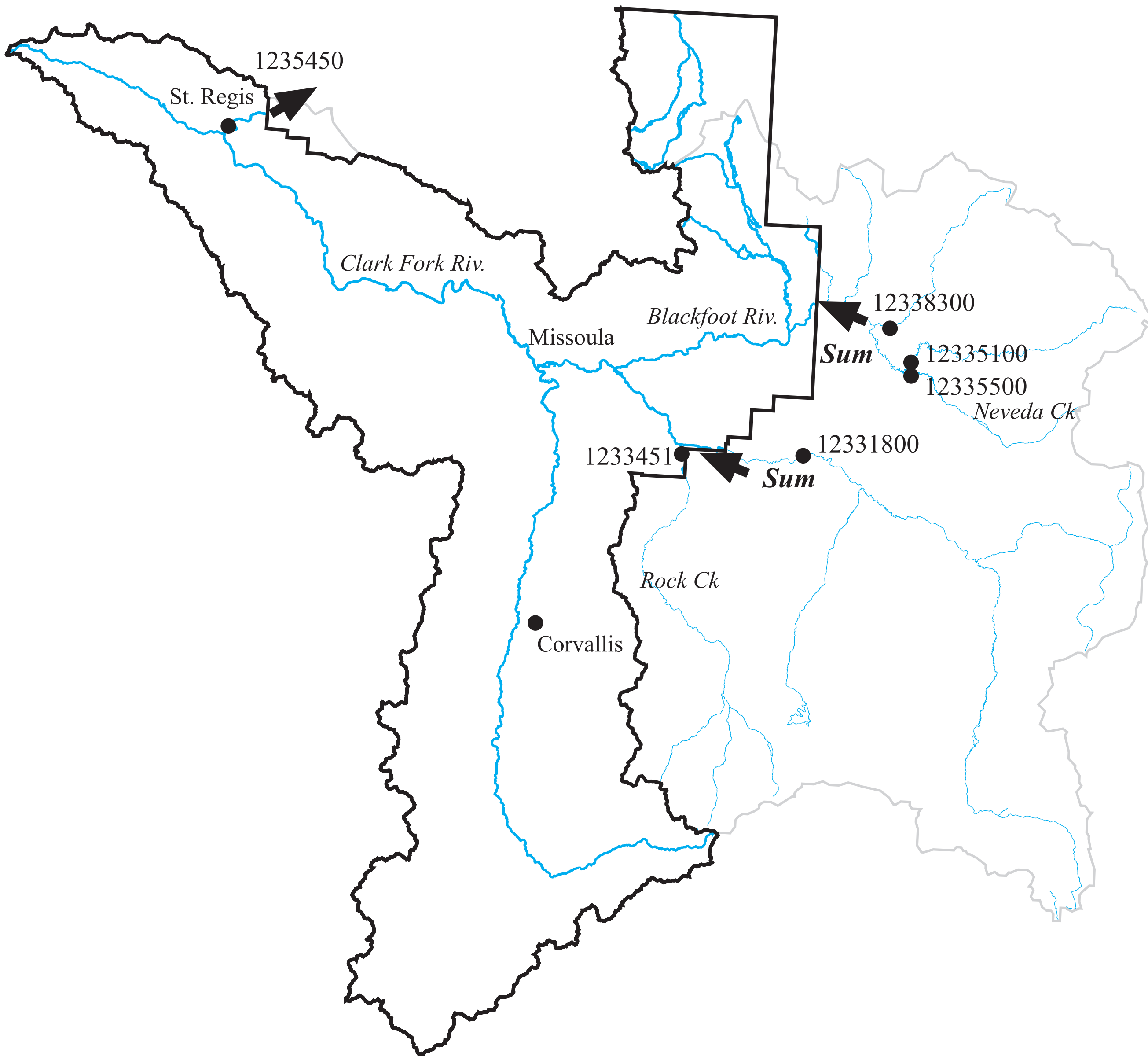


Figure 4. The Clark Fork drainage basin upstream of its confluence with the Flathead River roughly coincides with the study-area boundary. U.S. Geological Survey stream gauges on Rock Creek, the Blackfoot River and its tributaries, and the Clark Fork main stem provide surface-water inflow. The U.S. Geological Survey gauge on the Clark Fork River mainstem at St. Regis provides surface-water discharge.

Inflow = Outflow ± ΔSS ± ΔSG,

where:

- 'Inflow' is water flowing into the study area,
- 'Outflow' is water flowing out of the study area,
- SS is the change in storage of the surface-water reservoir, and
- SG is the change in storage of the groundwater reservoir.

When long time periods are considered, natural variations in groundwater and surface-water storage caused by wet or dry climatic conditions are generally balanced, resulting in no long-term change in groundwater or surface-water storage (ΔSS = ΔSG = 0). If so, the water balance equation simplifies to:

Inflow = Outflow

'Inflow' to the Lolo-Bitterroot area consists of precipitation that falls within its boundaries and water entering from Rock Creek, the Clark Fork River basin east of the study area, and the Blackfoot River at the area's eastern border. 'Outflow' consists of evapotranspiration (includes evaporated soil and surface water, and water transpired by plants and animals) and flow in the Clark Fork River near St. Regis. Using these components, the Lolo-Bitterroot water balance equation becomes:

CFRin + BFRin +PPTin = CFRout +ETout,

where:

- CFRin is Clark Fork River flow in (2002–2006 sum of average annual discharge at Rock Creek and Clark Fork gauges),
- BFRin is Black Foot River in (2002–2006 sum of average annual discharge at Blackfoot River gauges),
- PPTin is precipitation in (1971–2000 PRISM modeled precipitation; fig.3; Daly and others, 1994; Daly and others, 1997),
- CFRout is Clark Fork River out (2002–2006 sum of average annual discharge at St. Regis), and
- ETout is evapotranspiration out (residual after other factors are balanced).

Based on mean annual precipitation of 34 in. (1971–2000 PRISM modeled average, WRCC, 2005), the amount of water entering the 5,700 sq mi Lolo-Bitterroot area from the atmosphere (PPTin) is about 10,336,000 acre-ft/yr (90% of the inflow). Average annual streamflow entering from the Clark Fork River (CFRin) is about 702,200 acre-ft/yr (6% of the total inflow). This value is the sum of Clark Fork River streamflows at Drummond (USGS gauge 12331800) and Rock Creek flows near Clinton (USGS gauge 12334510). The Blackfoot River (BFRin) contributes about 504,800 acre-ft/yr (4% of the total inflow); this value is the sum of average annual Blackfoot River mainstem discharge measured above Nevada Creek (USGS gauge 12335100), Nevada Creek above Nevada Reservoir (USGS gauge 12335500), and the North Fork Blackfoot River near Ovando (USGS gauge 12338300). Total average annual inflow (streamflow and precipitation) into the Lolo-Bitterroot area is about 11,543,000 acre-ft/yr (table 1).

At St. Regis, average annual streamflow leaving the area (CFRout; USGS gauge 12354500) is about 4,360,900 acre-ft/yr (38% of total inflow). Subtraction of CFRout from the total inflow results in a 7,182100 acre-ft/yr (62% of total inflow) residual, which is the estimated average annual evapotranspiration (ETout). Included in the estimate is 131,300 acre-ft/yr consumed by irrigated crops and 16,900 acre-ft/yr consumed by public, industrial, and domestic uses.

Evapotranspiration (ETout) is crop-water use, riparian and forest vegetation uptake, and evaporation from rivers and other surface-water bodies. Annual average reference evapotranspiration for Corvallis, Montana, located in the Bitterroot Valley, is 31.5 in. per year and includes growing season vegetation-based estimates as well as evaporation from bare soil during the winter season (USBR, 2005). Comparison of the reference evapotranspiration rates at Corvallis to average annual precipitation (fig. 5) shows that annual evapotranspiration exceeds precipitation by about three times. Even though the estimated average annual evapotranspiration is greater than average annual precipitation in the Lolo-Bitterroot and in all of Montana, individual or sustained precipitation events often overwhelm evapotranspiration processes, causing the earth's surface to

Table 1. Water balance summary. Precipitation data from the Western Regional Climatic Center (2005); discharge data from the U.S. Geological Survey (2005).

	Drainage area (square miles)	Average annual precipitation (inches)	Average annual discharge from the basin (acre-feet) (inches)	Average annual calculated evapotranspiration (inches) (% of precipitation)
Clark Fork River basin in the Lolo-Bitterroot Area	5,700	34 in	3,160,000 af 10.4 in	23.6 in 69%

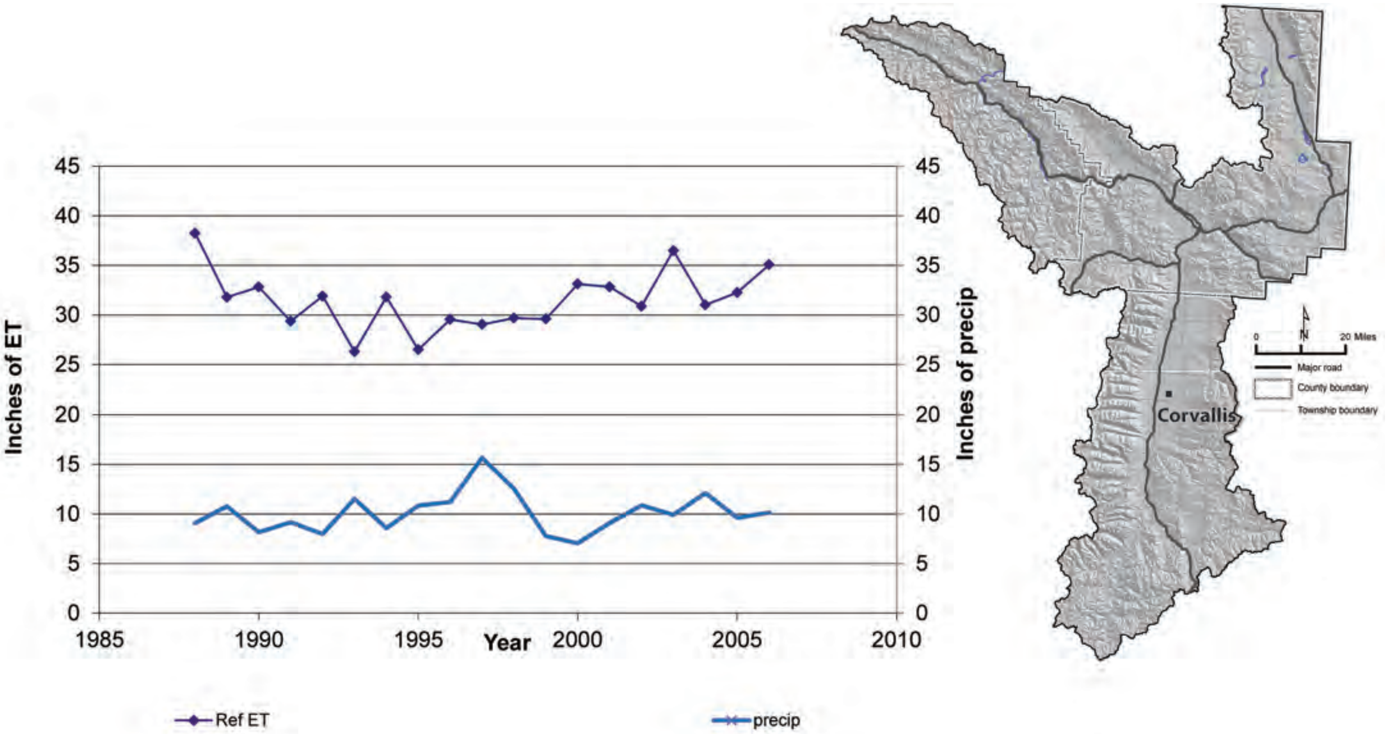


Figure 5. Evapotranspiration (ET) demand exceeds average annual precipitation in most of the valleys. Data are from Corvallis Montana Agrimet Station (U.S. Bureau of Reclamation).

capture and store water in soils and aquifers.

Basin-wide water balances provide information about the relative amounts of water coming into and leaving an area. However, the assumptions necessary to complete the balance at the Lolo-Bitterroot groundwater assessment scale generates a simplified, broad-scale view of the hydrologic system. At more detailed scales within the Lolo-Bitterroot there may be local variability in precipitation, runoff, water use, and evapotranspiration that may cause important transient or long-term water imbalances.

Water Use

Estimated water-use data for 2000 (Cannon and Johnson, 2004) show that Lolo-Bitterroot residents withdrew 463 million gallons per day (Mgal/d) from streams and aquifers. Surface-water sources provided about 399 Mgal/d (86 percent), and groundwater sources provided about 64 Mgal/d (14 percent). The combined withdrawals are about 16 percent of the 1971–2000 average annual Clark Fork water discharge measured at St. Regis.

Cannon and Johnson (2004) compiled water-use data for five categories: irrigation, public supply, self-supplied domestic, industrial, and stock. In the Lolo-Bitterroot, irrigation withdrawals of 404 Mgal/d, or 87 percent of all the water withdrawn (table 2), overwhelm other demands. Irrigation withdrawals vary across the study area: Ravalli County (mostly the Bitterroot Valley) used the most irrigation water, 322 Mgal/d, followed by Missoula County (78 Mgal/d), and Mineral County (5

Table 2. Estimated water withdrawals (in Mgal/d) for 2000 and consumptive use of groundwater in Mineral, Missoula, and Ravalli counties (Cannon and Johnson, 2004).

Use	Total	Ground water	Surface water	Ground water consumed
Irrigation	404	10	394	3
PWS	27	27	1	10
Domestic	4	4	0	4
Industrial	26	22	4	3.2
Stock	0.4	0.1	0.4	0.1

Mgal/d). Other water uses in order of volume are public water supply (6 percent), industrial water (5 percent), self-supplied domestic (1 percent), and stock water (less than 1 percent; fig. 6).

There is an important difference between the amount of water withdrawn from streams and aquifers and the amount of water that is actually consumed. Consumed water is "evaporated, transpired, incorporated into products or crops, consumed by humans and livestock, or otherwise removed from the immediate water environment" (Cannon and Johnson, 2004). Water withdrawn from streams and aquifers, but not consumed, may be returned to the "immediate water environment"; this is especially true for irrigation withdrawals. Consumptive-use estimates for irrigation withdrawals show that, on average, 29 percent of the irrigation water withdrawn in the study area is consumed; statewide, 15 percent of industrial water withdrawals and 37 percent of public water withdrawals are consumed (Cannon and Johnson, 2004).

Of the 64 Mgal/d of groundwater withdrawn, the largest use is public water supply (43 percent), followed by industrial water (34 percent), irrigation (16 percent), self-supplied domestic (7 percent), and stock (less than 1 percent; fig. 6). The estimated consumptive use of groundwater in the study area is 21 Mgal/d (Cannon and Johnson, 2004).

GEOLOGIC HISTORY/SETTING

Within the Lolo-Bitterroot area, a variety of Precambrian through Tertiary rock units are exposed in mountains, foothills, and along valley margins (figs. 7, 8). Heat, pressure, and/or cementation during long geologic time periods lithified these rocks, making them relatively resistant to erosion and prone to fracturing when acted upon by geologic forces.

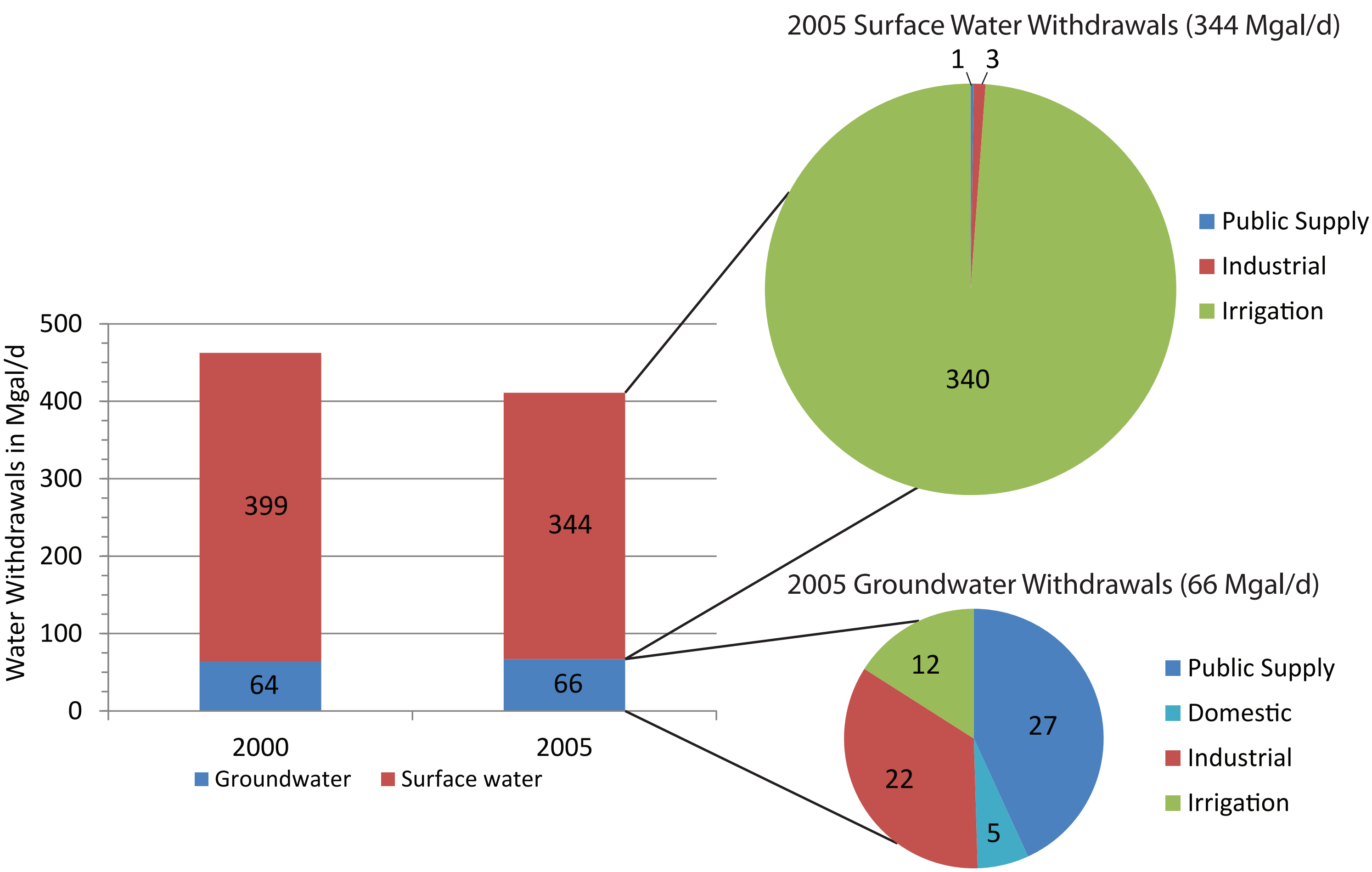


Figure 6. Estimated fresh-water withdrawals for Mineral, Missoula, and Ravalli counties show that surface water dominates; in 2000 an estimated 399 Mgal/d of surface water was withdrawn compared to 64 Mgal/d of groundwater. Most groundwater withdrawals are for public supply and industrial uses. Domestic use accounts for 8 percent of groundwater withdrawals. Data are from the U.S. Geological Survey, http://water.usgs.gov/watuse/.

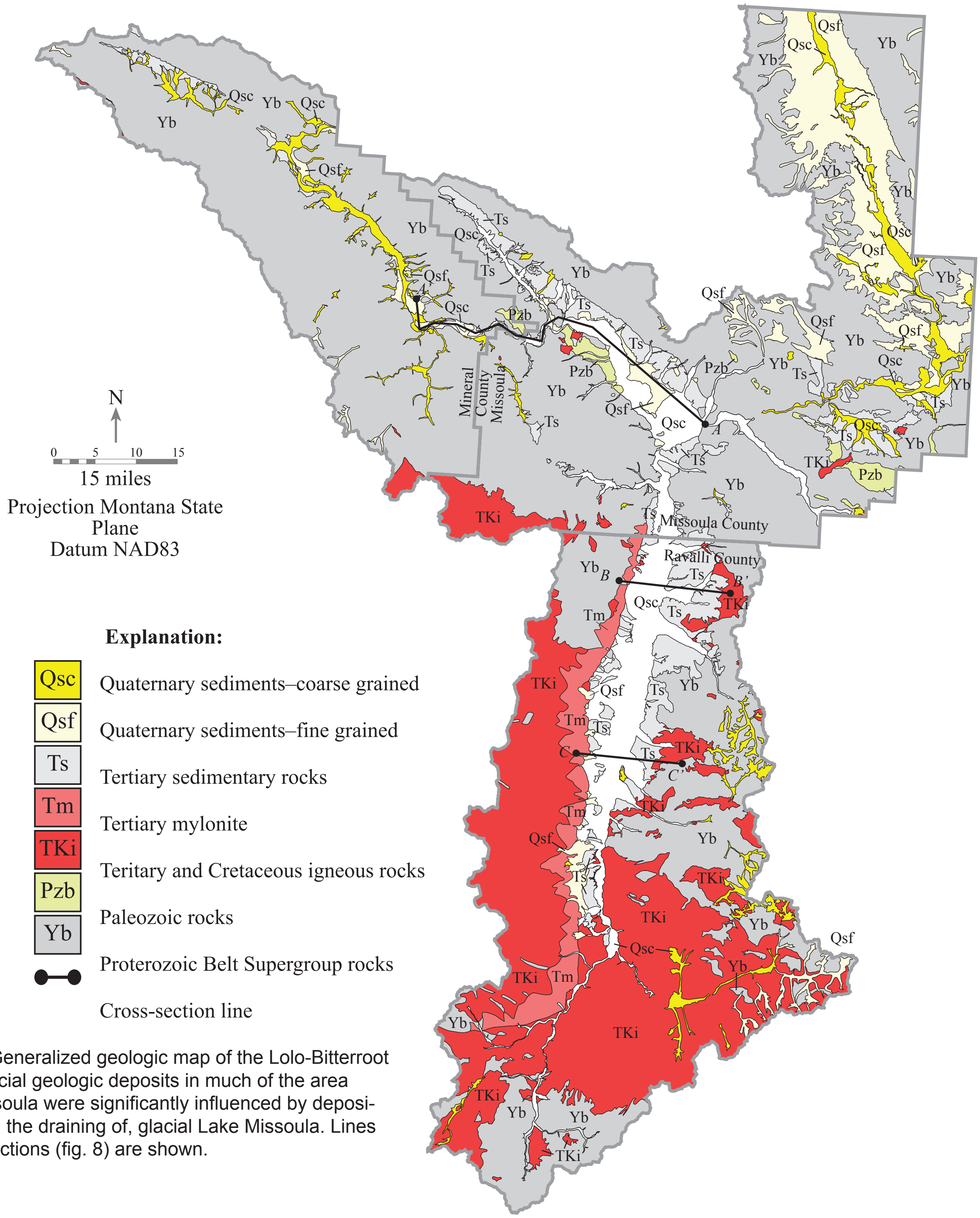


Figure 7. Generalized geologic map of the Lolo-Bitterroot Area. Surficial geologic deposits in much of the area below Missoula were significantly influenced by deposition in, and the draining of, glacial Lake Missoula. Lines of cross sections (fig. 8) are shown.

These lithified and fractured rocks are collectively referred to as 'bedrock' in this report (figs. 7, 8, 9).

Within the Bitterroot, Missoula, Potomac, Seeley–Swan, and similar valleys, unconsolidated to weakly lithified materials, ranging from less than 100 ft to as much as several thousand feet thick, fill areas that have been down-dropped by faults relative to the surrounding mountains. These deposits are collectively labeled as 'basin-fill' in this report and are generally surrounded and underlain by 'bedrock.'

The oldest rock unit, the Precambrian Belt Supergroup (1.4 to 1.5 billion years old), is a thick sequence of low-grade metamorphosed sedimentary rocks that form the mountains and also underlie the valleys (Yb in fig. 7). Units within the 'Belt' include fine-grained clastic rocks (sandstone, siltstone, and

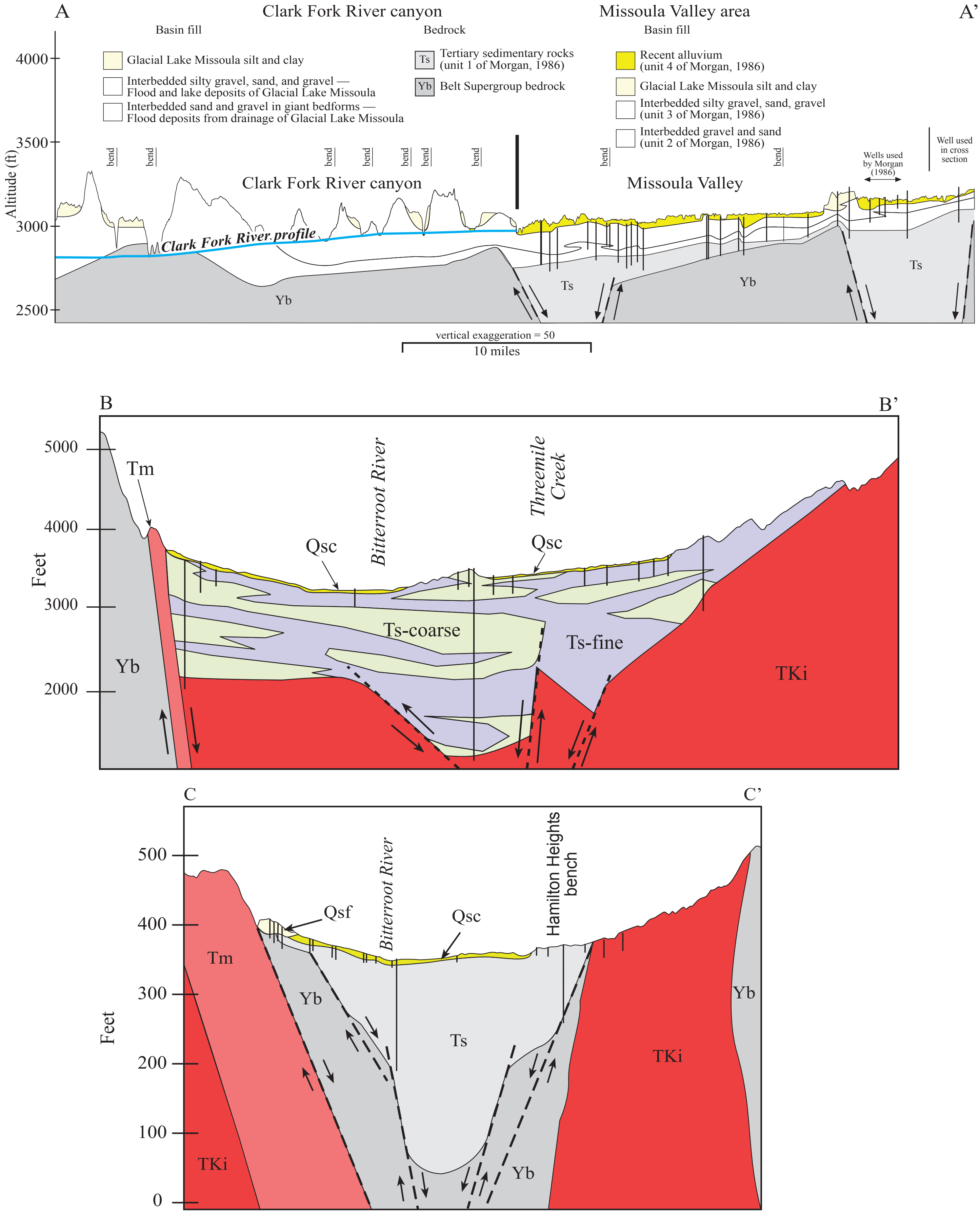


Figure 8. Generalized cross sections of geologic units in the Missoula and Bitterroot subareas based on interpretations of water-well logs. Current development exploits only the upper-most segments of deep basin-fill aquifers.

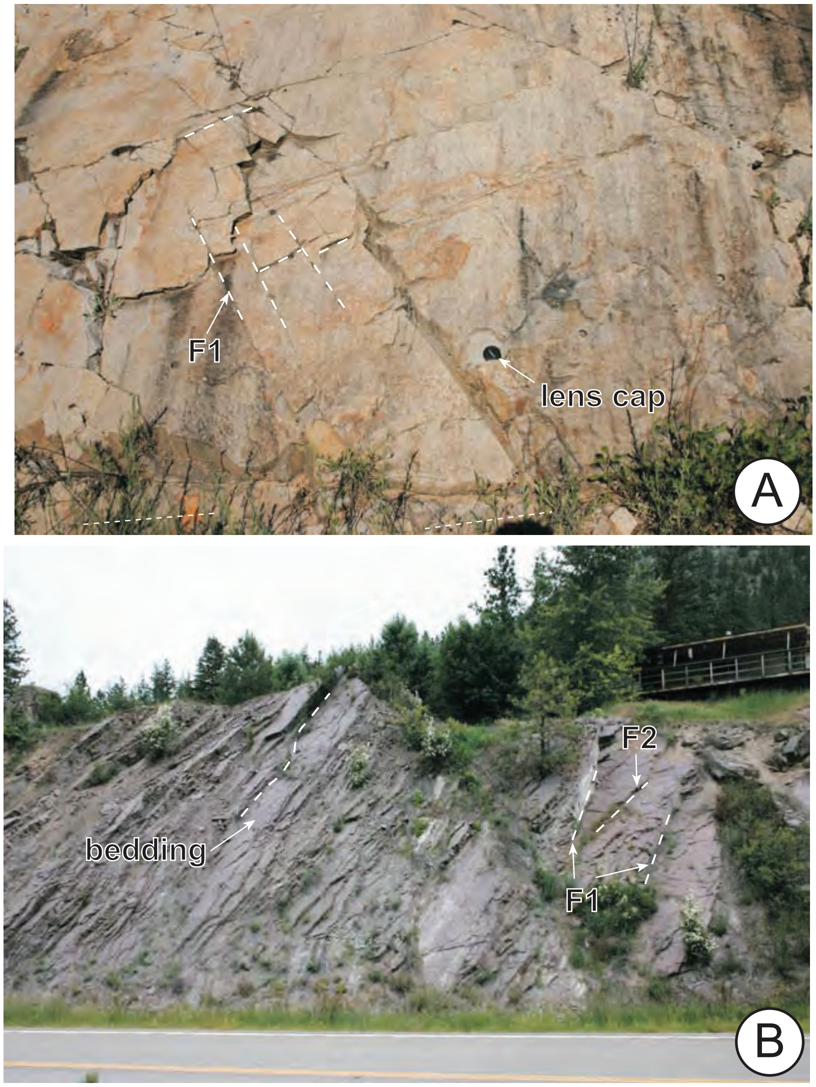


Figure 9. Bedrock underlies mountains and foothills along the perimeters of valleys and yields water to wells mostly through fractures (F1) and bedding planes (F2). (A) Granitic intrusive igneous rocks occur locally in the Sapphire and Bitterroot Mountains (location Township 11 North, Range 16 West Section 11, near Beavertail State Park). (B) Belt Supergroup rocks are very thick units of bedded siltstone, quartzite, and carbonate rocks (location near Alberton, MT).

mudstone) and carbonate rocks (limestone and dolomite). Very hard, high-grade metamorphic rock (mylonite; Tm in fig. 7) of Tertiary age defines the east-facing Bitterroot Range front. In the southern part of the Bitterroot valley, Cretaceous and Tertiary granitic plutons (TKi in fig. 7) intruded older bedrock units during tens of millions of years. A few Tertiary volcanic rocks, included with TKi in figure 7, are exposed in the southern Bitterroot Valley between Charlo Heights and Darby.

Beginning about 110 million years ago, compressive tectonic forces thrust the bedrock eastward, uplifting, folding, and fracturing the rocks. As the compressive forces relaxed 40 to 50 million years ago, normal faults developed. The faulting controlled the locations of down-dropped intermontane valleys where, between 2 and 50 million years ago (during the Tertiary), up to 3,000 ft of basin-fill deposits accumulated (fig. 8, cross sections; McMurtrey and others, 1965; Crosby, 1984; Wells, 1989). Large depth-to-bedrock differences in individual valleys show that structural subsidence and subsequent in-valley deposition varied greatly; in particular, thickness of basin-fill in the Seeley–Swan subarea is poorly known (Smith, 2006a, b). Tertiary basin-fill sedimentary rocks are mostly claystone, sandstone, and conglomerate (fig. 10).

Thick basin-fill deposits are common in the Bitterroot, Missoula, Potomac, and Seeley–Swan valleys, and occur along the Clark Fork River canyon near St. Regis (fig. 7). As much as 2,400 ft of partially consolidated Tertiary-age sediment have been penetrated in a few drill holes in the Missoula and Bitterroot Valleys (Norbeck, 1980). Moderately consolidated rocks with similar lithologies have been encountered at depth in a few drill holes in the Seeley–Swan Valley.

The most important recent geologic events were

Figure 10. The Tertiary sedimentary rocks include sandstones, claystones, conglomerates, and some coals. Outcrops along the Bitterroot River near the Missoula/Ravalli County boundary contain sandstone, mudstone, and siltstone typical of deep-basin fill aquifers. (Location along the Bitterroot River in Township 11 North, Range 19 West, Section 31).

multiple glacial advances and retreats that occurred between about 2 million and 15,000 years ago. Valley glaciers filled side drainages in the Bitterroot, Swan, and Mission mountains, creating sculpted valleys. Ice also occupied the entire Seeley–Swan Valley and flowed southward into the Clearwater and Blackfoot River drainages. In these areas, the glacial ice deposited till, a compacted and poorly sorted mixture of silt, clay, sand, and gravel.

A glacier near the current Montana–Idaho border blocked the Clark Fork River and impounded Glacial Lake Missoula (Pardee, 1910; Webber, 1972; Levish, 1997; Alt, 2001). Thinly bedded silt and clay, diagnostic of glacial-lake deposition, occur in the Missoula Valley, along the Clark Fork River canyon (fig. 11), and in small areas of the Bitterroot Valley. In many valley locations downstream from Missoula, glaciation (or floods from catastrophic draining of glacial lakes) deposited tens to hundreds of feet of gravelly sediment, some of which is capped by fine-grained glacial-lake sediments (fig. 12). Where these sand and gravel deposits are water-saturated, they can be prolific aquifers.

Dissection of till and glacial-lake sediments by the Clark Fork River and its tributaries occurred after deglaciation. As water levels in the Glacial Lake Missoula basin dropped rapidly during the last drainage event, the Clark Fork River cut an inner canyon, currently between 60 and 310 ft deep, into bedrock and basin-fill.

Gravelly alluvial deposits along stream valleys throughout the study area are important aquifers (fig. 13). In some places, such as the Missoula and Bitterroot Valleys, shallow alluvium is interlayered with silty deposits, making separation of the shallow alluvium from the deep alluvium arbitrary.

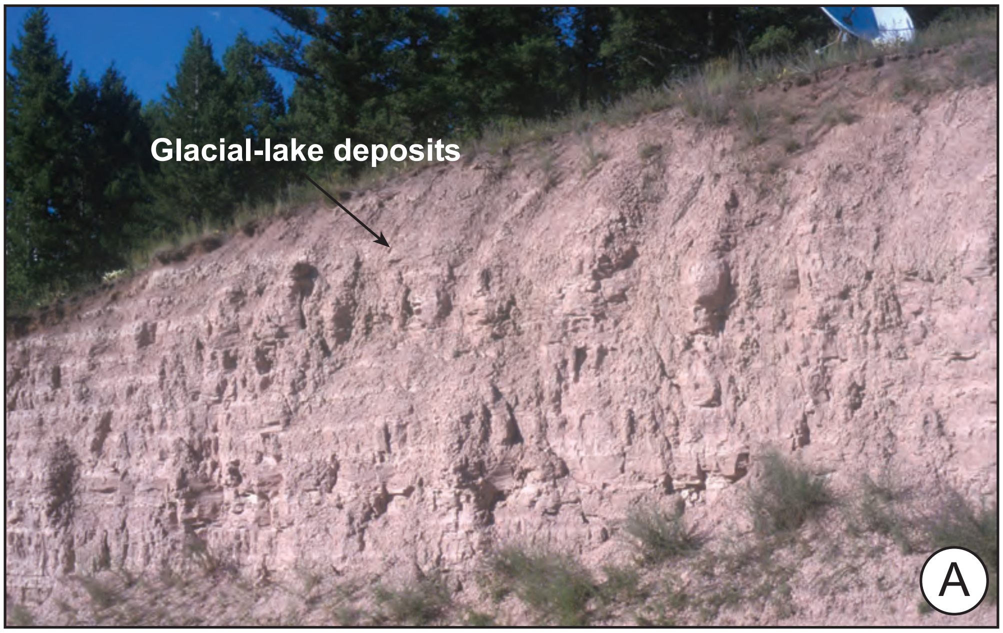
HYDROGEOLOGY

Groundwater is a plentiful and important resource throughout the Lolo-Bitterroot Area. The discussion below describes general relationships among aquifers, non-aquifers, and the geologic framework. Hydrogeologic conditions specific to each subarea (fig. 2) are discussed in the subarea summaries.

Groundwater Flow Systems

A groundwater flow system defines the paths along which water moves from recharge areas to discharge areas. Water may flow through one or more aquifers and confining beds, all functioning regionally as a single entity.

Shallow groundwater flow systems are gener-



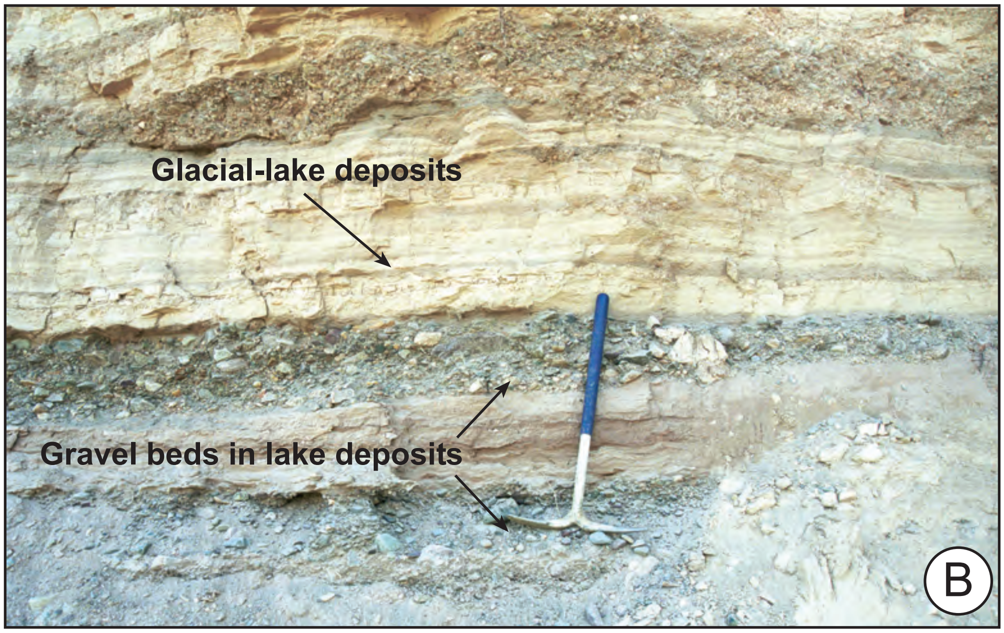


Figure 11. Glacial-lake sediments are well exposed on benches along the Clark Fork River from Missoula to NE of St. Regis. (A) The beds are mostly laminated silt and clay, resulting from deposition of fine sediments dispersed in the lake (Township 15 North, Range 22 West, Section 28); (B) In some areas the silts include beds of silty sand containing gravel (Location: Township 18 North, Range 28 West, Section 25).

ally found within near-surface alluvial deposits, are unconfined, and transport water short distances (generally less than 1–2 miles) from relatively high topographic positions to nearby streams or lakes. Where shallow aquifers are in hydrologic connection with underlying aquifers, they can serve as important recharge sources to deep flow systems.

Deep flow systems provide paths for groundwater flowing from high altitudes in mountainous bedrock aquifers along the valley margins (regional topographic highs—drainage basin divides) to discharge areas in deep sand and gravel aquifers in the valley centers (regional topographic lows). Shallow and deep flow systems are generally separated by confining units, but discontinuity in the confining units may allow shallow and deep systems to have local hydraulic connection.

Hydrologic Framework

Although the Lolo-Bitterroot's geologic framework influences the occurrence and movement of groundwater, relationships among geologic units, hydrogeologic units, and aquifers are not necessarily coincident, as is shown by figures 8, 14, and 15. Figure 15 schematically portrays vertical and horizontal relationships between geologic units and shallow and deep aquifers occurring within typical intermontane basin-fill deposits and bedrock.

Figure 12. Sand and gravel, exposed beneath glacial-lake sediments along the Clark Fork River west of Huson, likely were deposited during the drainage of one or more stands of glacial Lake Missoula prior to deposition of the overlying silt and clay by a subsequent lake. These materials make up much of the alluvial aquifers in Frenchtown and Huson, and along the Clark Fork River canyon through Missoula and Mineral Counties. These deposits may be analogous to the deep alluvium in the Missoula valley subarea; measuring staff (5 ft tall) for scale (Location: Township 15 North, Range 25 West, Section 27).

Figure 13. Shallow alluvium is mostly made up of sand and gravel deposits of glacial meltwater streams (outwash), modern streams, or older gravel near the land surface (Township 16 North, Range 25 West, Section 33).

Shallow basin-fill aquifers

Shallow basin-fill aquifers are coarse-grained recent alluvial deposits or Tertiary-age sand and gravel, generally at depths within 75–80 ft of land surface. The aquifers are often unconfined; the upper surface of the saturated zone (the water table) is at atmospheric pressure and not bounded or confined by low-permeability barriers. Shallow aquifers are important water sources, but are aerially limited to surficial alluvium associated with modern rivers or streams, glacial outwash, or areas where coarse-grained Tertiary sedimentary rocks are near the surface (see Part B, maps 6 and 8).

Recharge to shallow basin-fill aquifers occurs by infiltration of precipitation, stream losses, and leakage from irrigation ditches. Groundwater discharge is through springs and seeps along valley bottoms, gaining reaches of perennial streams, transpiration by plants, and pumpage from wells.

Shallow aquifers are intrinsically susceptible to surficial contamination sources. Distances from the land surface to groundwater are short; the water table is generally within 20 ft of the land surface.

Period	Epoch	Geologic Units	Characteristics	Hydrologic Units
Quaternary	Holocene	Sediments – coarse grained	*Coarse-grained:* Light to medium brown and grayish brown sand and gravel; some silt and clay; along active stream valleys and areas of sheetwash; contains minor amount of colluvium; thicknesses average 50 ft, but reach 250 ft in paleochannels in the Clark Fork River valley; can yield significant quantities of groundwater.	Mostly shallow basin-fill aquifer, deep basin-fill aquifer where thicker than 75 ft
	Pleistocene	Sediments – fine grained	*Fine-grained:* Grayish brown, light to dark yellowish brown gravelly silt, light pink silt and sand, and silty and/or clayey gravel; thicknesses range from 5 to 140 ft; generally does not yield water.	Non-aquifer basin-fill unit
			unconformity	
Tertiary	Oligocene and Miocene	Sedimentary rocks: coarse grained and fine grained	Yellowish brown to light gray pebbly sandstone, pebble and cobble conglomerate; uncemented to moderately cemented; light tan to gray claystone and siltstone; rare carbonaceous shale and lignite; sandstone and conglomerate yield adequate supplies of water to wells for household use.	Mostly deep basin-fill aquifer, shallow basin-fill aquifer where within 75 ft of land surface
	Eocene	Mylonite	East- and southeast-dipping zone of well-foliated, erosionally resistant metamorphic rocks that define the Bitterroot Range front.	Bedrock
Upper Cretaceous to Eocene		Igneous	White to pink, medium- to coarse-grained granular and porphyritic intrusive rocks; lesser amounts of volcanic rocks; where fractured, the rocks can provide adequate supplies of water for household use.	Bedrock
			unconformity	
Paleozoic		Various sedimentary formations	Sandstone, quartzite, shale, limestone, and dolomite of various formations; the rocks provide inadequate to minimally adequate water to wells for household uses.	Bedrock
			unconformity	
Proterozoic		Belt Supergroup	Metamorphosed sandstone, shale, siltstone, limestone, and dolomite of various formations; where fractured, the rocks can provide adequate supplies of water for household use.	Bedrock

Figure 14. Geologic units important to the hydrogeology of the Lolo-Bitterroot Area mostly are unconsolidated sand, gravel, silt, and clay basin-fill within the valleys. The basin-fill deposits contain aquifers and non-aquifer materials (confining units). Fractured bedrock of the Belt Supergroup and igneous rocks locally contain aquifers.

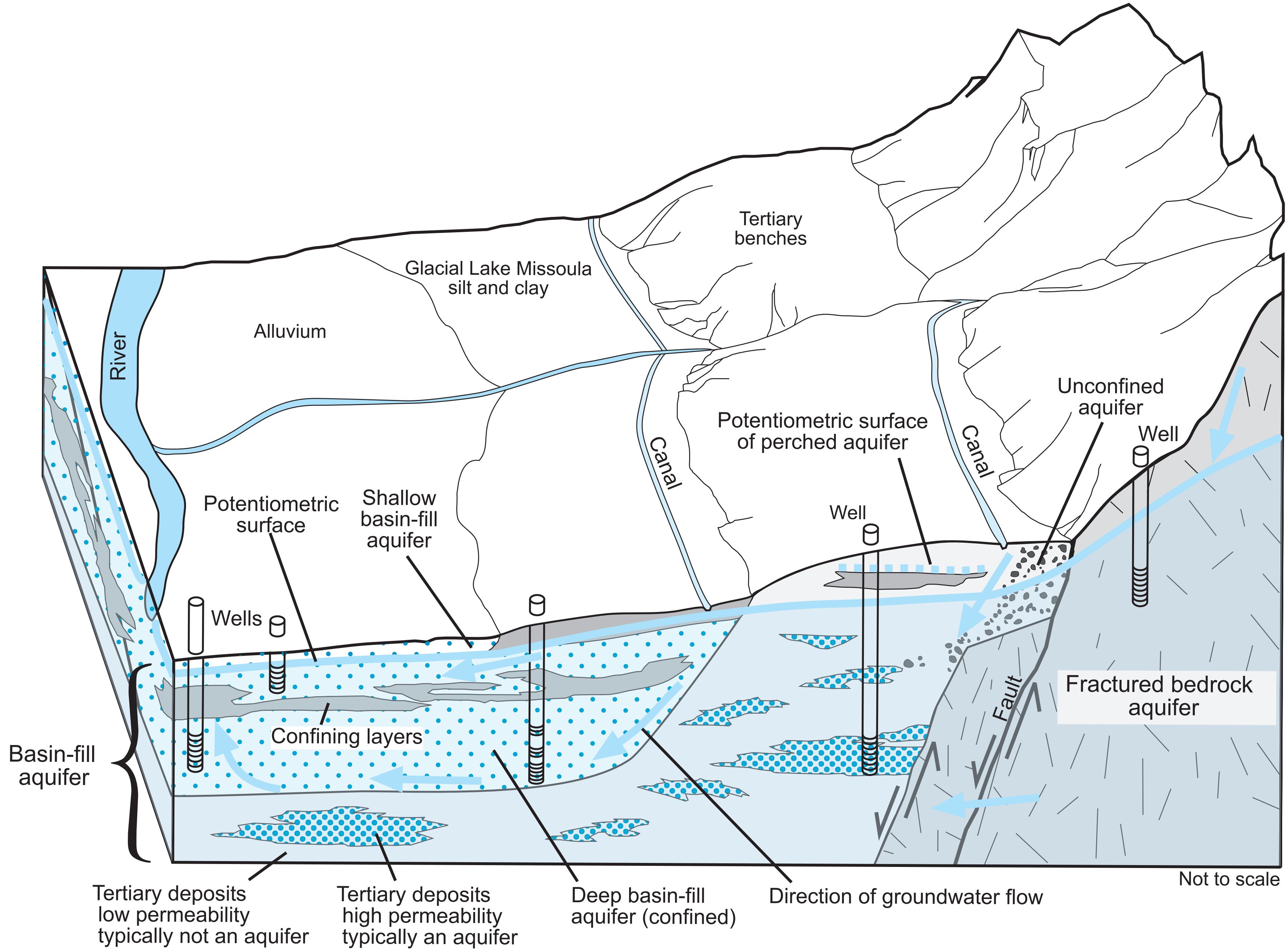


Figure 15. Schematic diagram that shows vertical relationships between the aquifers and non-aquifers in the Lolo-Bitterroot Area. Shallow basin-fill aquifers occur in alluvium at depths less than 75–80 ft below land surface. Confining zones of fine-grained Tertiary-age sedimentary rocks in many areas separate shallow basin-fill aquifers from deep basin-fill aquifers.

Aquifer materials are often highly permeable sand and gravel conducive to rapid movement of water, and any associated contamination, from the land surface to the water table.

Confining units

Confining units near land surface are gravelly and silty till or silt and clay-rich glacial-lake deposits. Deeper confining units are fine-grained silty and clayey Tertiary-age deposits. All confining units have low permeability and impede groundwater movement. Confining units rarely fully seal aquifers; it is more common that the units are partially confining, creating “leaky confined” aquifers.

Deep basin-fill aquifers

Deep basin-fill aquifers are coarse-grained alluvial deposits and Tertiary-age sedimentary rocks at depths greater than 75–80 ft below land surface. The deep basin-fill includes interbedded sand, gravel, silty sand, and local claystone that are widespread but difficult to map with available subsurface data.

Most Tertiary-age basin-fill deposits are shale and/or sandy mudstone and often are confining units or marginal aquifers. However, discontinuous permeable sandstones and conglomerates locally serve as important aquifers, notably in the Bitterroot Valley and St. Regis subareas.

Bedrock aquifers

Most groundwater in the mountainous areas occurs in fractured bedrock. In general, the bedrock contains sufficient fracture permeability to yield water to wells; however, yields are generally low, typically less than 10 gpm. Additionally, the occurrence, size, and orientation of fracture openings are unpredictable, which causes large variations in well yields. In many areas, groundwater occurs under confined conditions where the bedrock is covered by low-permeability deposits or where water-bearing fractures occur at depth. On a regional scale, fractured bedrock aquifers within the mountainous areas are in hydraulic communication with deep basin-fill aquifers (see Part B, maps 6 and 8). Because the mountains receive the majority of precipitation that enters the Lolo-Bitterroot area and occupy most of the study area’s land surface, infiltration of surface water into bedrock aquifers and diffuse flow through fractures becomes an important “mountain-front recharge” component of recharge to basin-fill aquifers.

Water Levels

Between 1997 and 2001, the Groundwater Assessment Program measured groundwater levels at monthly-to-hourly frequencies in 117 wells. Some wells have periods of record extending back to 1956, but most measurements began between 1993 and 1997. Although the Lolo-Bitterroot groundwater assessment groundwater-level data collection ceased in 2001, as of 2011 the statewide Groundwater Monitoring Program and its cooperators still actively monitored 79 wells in the three-county area. Up-to-date groundwater-level data and hydrographs for all historical and currently monitored wells are available online at the GWIC website, http://mbmggwic.mtech.edu.

Annual groundwater-level fluctuation patterns vary across the Lolo-Bitterroot area (Part B, Map 10). Groundwater-level changes are related to seasonal streamflow and climate variability, recharge from irrigation practices, long-term (yearly to decadal) climate variations, and groundwater pumping (usage). Some hydrographs display influences from multiple factors, such as high-frequency seasonal water-level fluctuations superimposed on slowly changing multi-year climate patterns. Common patterns of water-level change that occur in the Lolo-Bitterroot Area include:

(a) The “runoff/stream recharge” response where water levels rise and fall in concert with streamflow and snowmelt runoff (figs. 16a, 17a, and 18). This response, characterized by elevated groundwater levels during high streamflow, is observable in near-stream shallow basin-fill aquifers in non-irrigated areas. An example from the Bitterroot Valley near Florence is the hydrograph for well 136486 (fig. 18), which shows that groundwater levels closely mimic “discharge or runoff” in the nearby Bitterroot River. The pattern suggests that the shallow aquifer near well 136486 responds to the same seasonal hydrologic pulse of spring melt water as does the river, and that the river and the

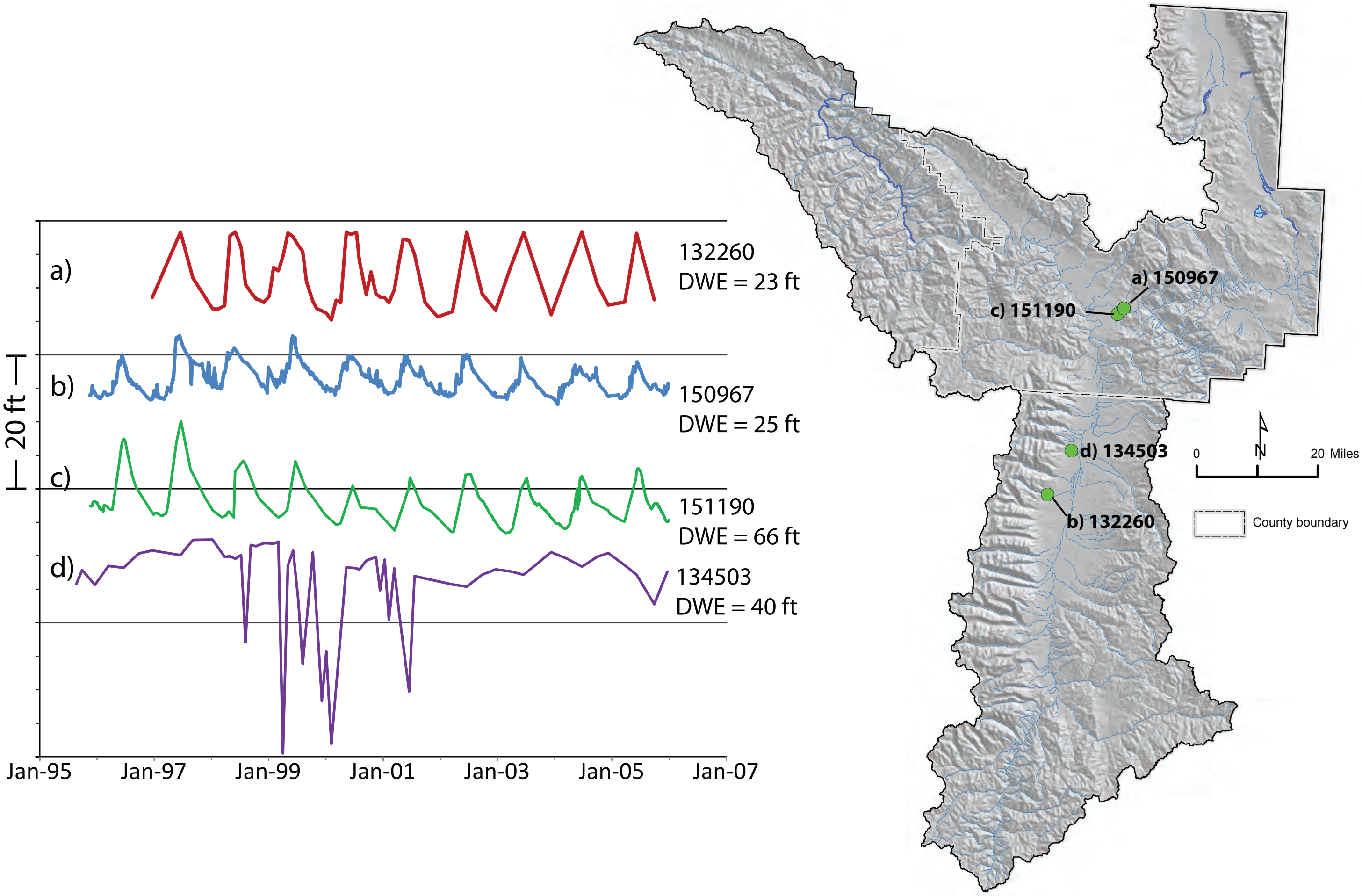


Figure 16. Groundwater hydrographs reveal four types of annual water-level response in aquifers. (a) “Runoff” response that is generally synchronized with annual precipitation and runoff. Water levels increase in April, May, and June, but show a rapid decrease by July, mimicking river stage. (b) “Irrigation” response shows an abrupt increase in water level in April, May, and June, followed by stable water levels throughout the summer and then slowly decreasing water levels through September. (c) “Stream recharge to ground water” responses are similar to a “runoff” response, but with slow water-level decline throughout the summer and fall. (d) “Pumpage” response has an erratic pattern where water levels are affected by slow recovery in the measured well or response to nearby pumping.

shallow aquifer are hydraulically connected. Annual water-level change is generally less than 4 ft.

Hydrographs from wells completed in unconsolidated materials in the Missoula Valley from Hellgate Canyon to Frenchtown show an abrupt groundwater-level rise in April to May coincident with high stream runoff, followed by a steady decline throughout the summer. This response also occurs in many areas where perennial or intermittent streams enter valleys from the surrounding bedrock uplands. In some areas this response occurs near losing streams. In the Missoula Valley, the annual water-level response is as large as 12 ft near where the Clark Fork River enters the valley at Hellgate (fig. 16a).

(b) The “irrigation” response is where groundwater levels abruptly rise in late spring or early summer, stay elevated throughout the summer when irrigation is occurring, and then decline through the winter and into early spring (figs. 16b and 17b; Part B Map 10; McMurtrey and others, 1959). The irrigation response is the most common water-level pattern in the Lolo-Bitterroot area, occurring throughout the Bitterroot and Missoula valleys and in many other areas (fig. 19) where irrigation water is diverted to canals and delivered to fields. The irrigation pattern is not unique to the Lolo-Bitterroot area, and irrigation-derived recharge to groundwater has been recognized in many Montana watersheds (Nicklin and Brustkern, 1983; Osborne and others, 1983; Slagle, 1992; Voeller and Waren, 1997; Uthman and Beck, 1998; Marvin and Voeller, 2000; Roberts and Levens, 2002, Roberts and Waren, 2001; Olson and Reiten, 2002; LaFave and others, 2004). Annual water-level change in irrigation-responsive groundwater systems ranges from a few to tens of feet.

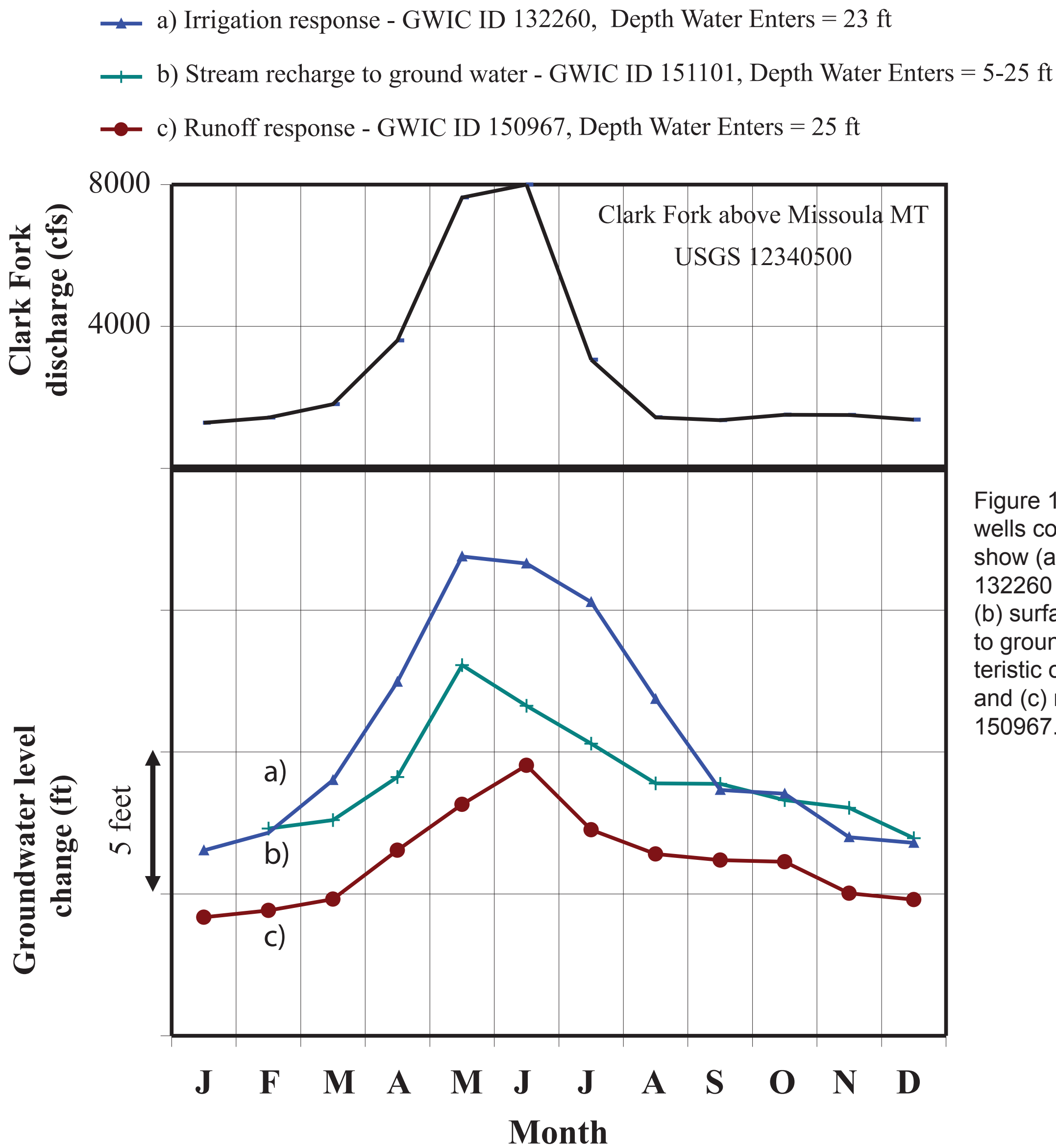


Figure 17. Average monthly water levels from wells completed in shallow basin-fill aquifers show (a) irrigation-based recharge at well 132260 lasting through the summer months; (b) surface-water recharge from stream flow to groundwater pattern at well 151101 characteristic of most Missoula valley alluvial wells; and (c) recharge from springtime runoff at well 150967.

(c) The “pumpage” response occurs where groundwater levels are affected by pumping; the response is characterized by sharply downward groundwater-level changes during summer months, usually in response to irrigation withdrawals. Regional pumpage response may be followed by long recovery periods after pumping ceases (fig. 16d). Pumpage responses may be as little as a few feet in non-pumped wells that provide groundwater data documenting widespread groundwater use across an area, to many feet if the groundwater withdrawals are near or in the measured well. The response is most pronounced and widespread in deep or confined aquifers.

Some hydrographs show multiple-year periods of groundwater rise or decline. Often, irrigation, stream recharge, pumpage, or other high-frequency patterns are superimposed on the long-term trends. Downward long-term trends may be related to groundwater use and pumpage, but in the Lolo-Bitterroot, comparison of the long-term trend components to departures from long-term precipitation averages shows that most long-term variations can be attributed to wet and dry climate cycles. An example of long-term groundwater change related to departures from average precipitation is shown by the hydrograph from well 168180 (fig. 20). Between 1999 and about 2005, water levels declined 5–6 ft overall and then recovered to near 1999 levels, generally coincident with annual departures from average precipitation becoming sharply negative and then returning to normal. Superimposed on the long-term cycle is an annual irrigation response pattern that begins rising in mid-June and peaks in late August (fig. 20).

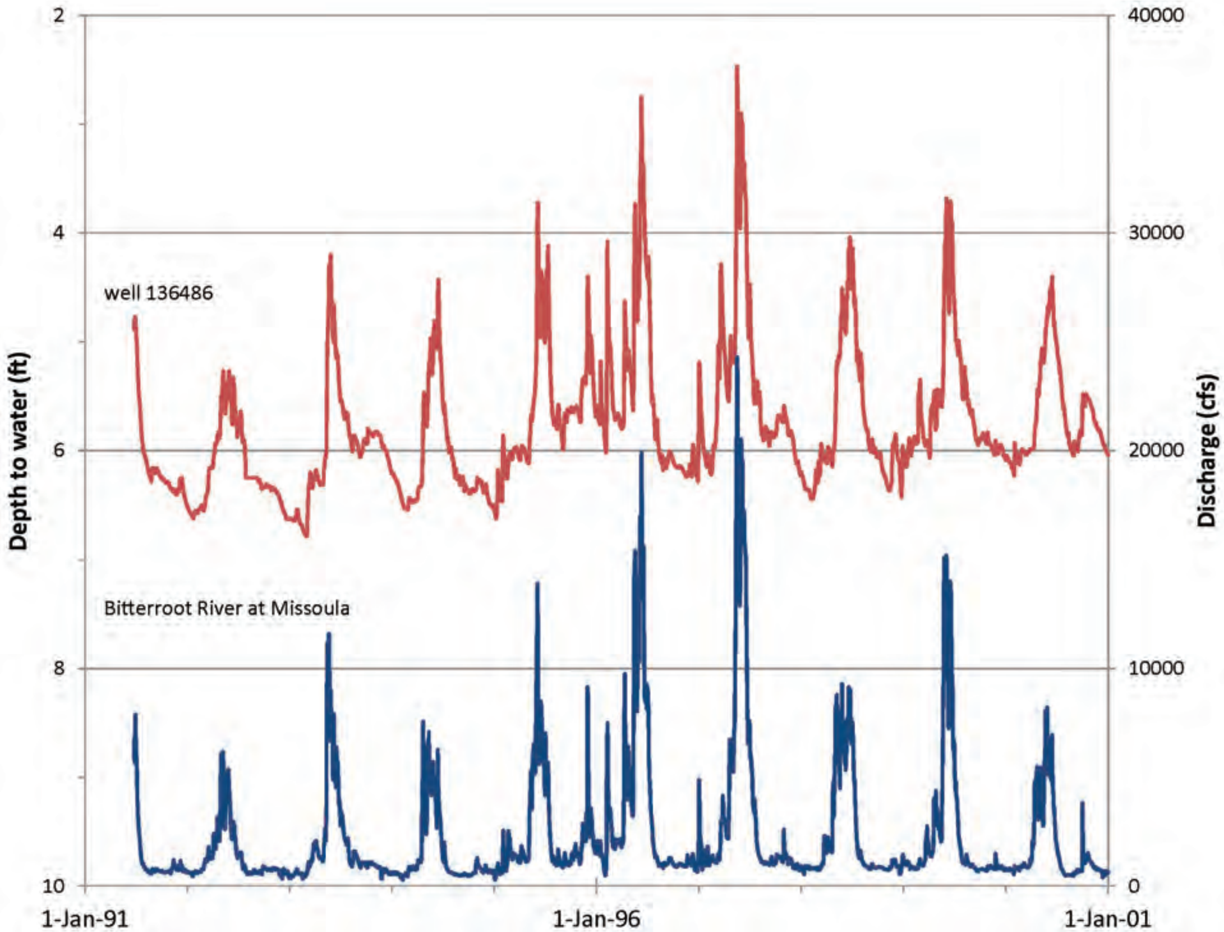


Figure 18. The runoff response groundwater hydrograph for well 136486 closely matches the stream-flow hydrograph in the nearby Bitterroot River.

Groundwater Quality

To evaluate groundwater quality, the Assessment Program collected 305 water samples from 285 wells completed in shallow and deep basin-fill aquifers and fractured bedrock aquifers across the Lolo-Bitterroot area. Most groundwater samples for common inorganic constituents and trace metals (273 samples) were collected between 1997 and 2001 [includes samples collected by Norbeck and McDonald (1999) in the Seeley Lake area and Norbeck and McDonald (2001) in the Florence area]; 32 additional samples were collected from statewide monitoring network wells (17 in 1994, and 15 between 2001 and 2005). Samples for nitrate-only analyses were collected from 52 sites; three of these sites, two near Hamilton and one on the Sunset Bench, had been repeatedly sampled by Briar and Dutton (1999). The Assessment Program continued sampling these sites to increase the time-series record of nitrate concentrations and address local concerns about nutrient concentration trends. Most groundwater samples came from domestic wells, but some samples came from commercial, public water supply, and monitoring wells. Groundwater samples were bottled after purging at least three casing volumes from each well and ensuring that water temperature, pH, specific conductance, and redox potential values were stable and that the bottled water was representative of the aquifer. The MBMG analytical laboratory analyzed samples for major ions, including nitrate, and trace elements. The University of Waterloo Environmental Isotope Laboratory analyzed a subset of 151 samples for tritium (^{3}H). Analytical results are available from the GWIC website (http://mbmggwic.mtech.edu), and detailed discussions of water quality in the Bitterroot Valley are presented in Part B, Map 9; discussions for Missoula and Mineral Counties are presented in Part B, Map 7.

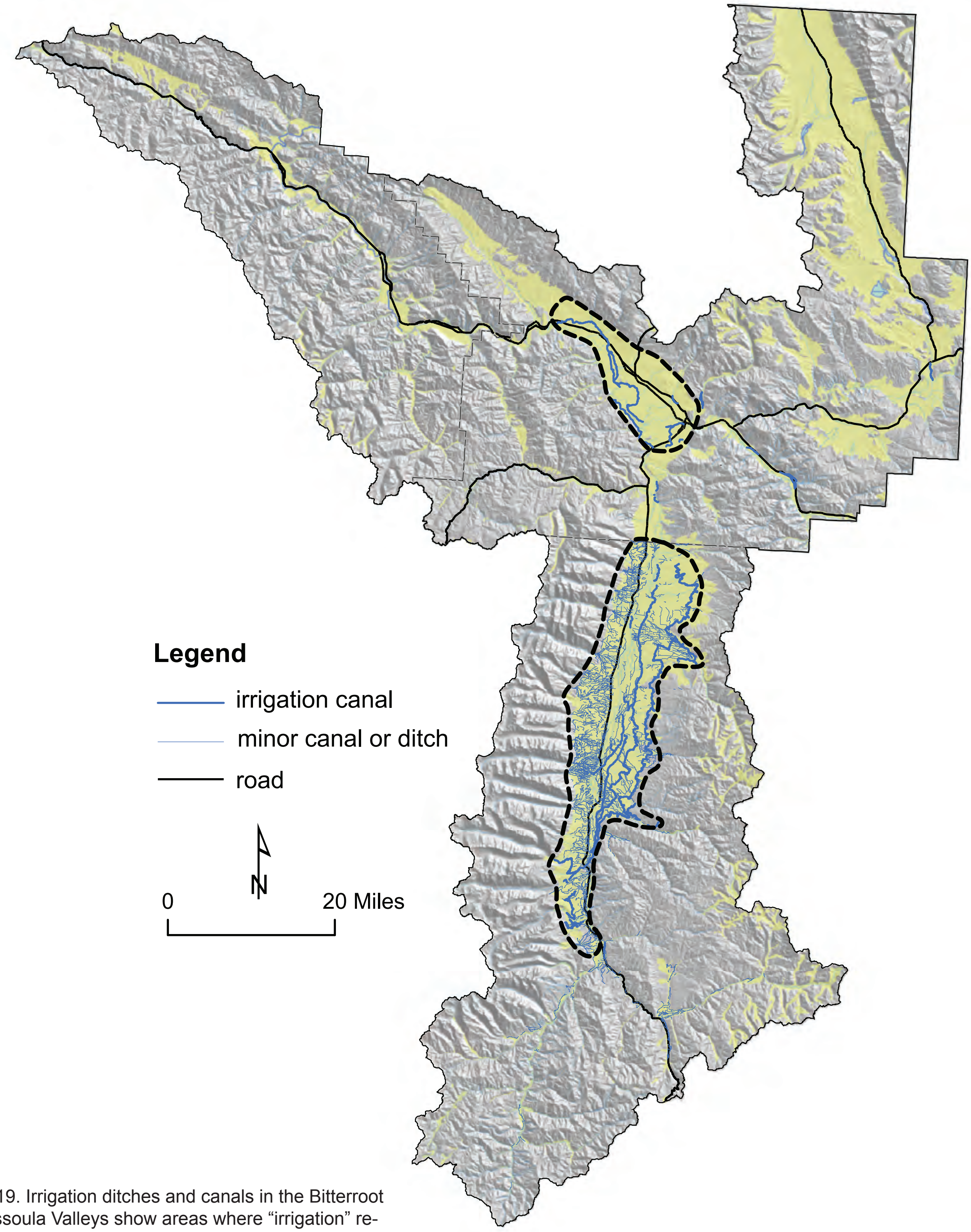


Figure 19. Irrigation ditches and canals in the Bitterroot and Missoula Valleys show areas where "irrigation" recharge to groundwater prevails and where groundwater levels respond to irrigation practices.

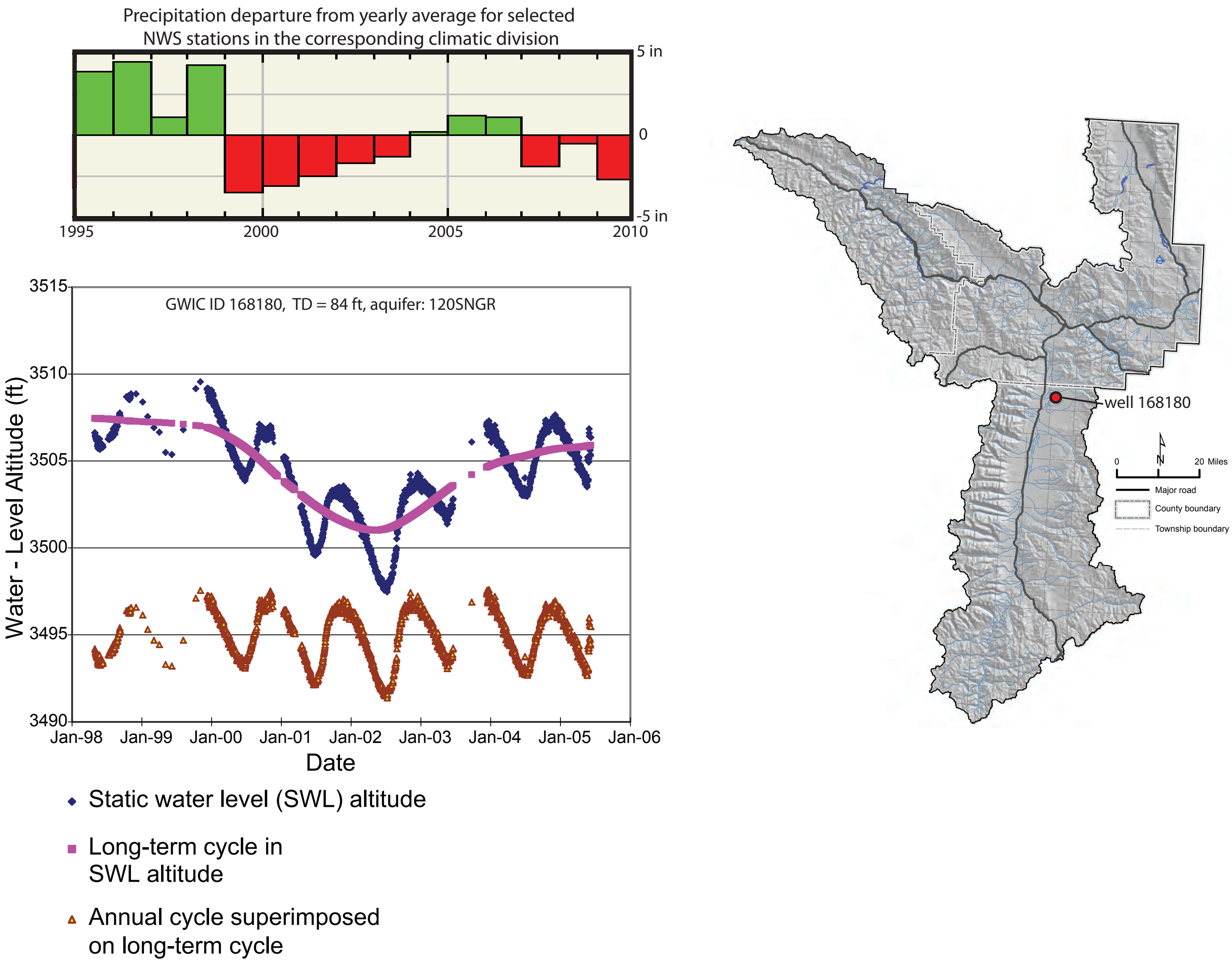


Figure 20. The hydrograph from well 168180 (raw static water-level altitude) includes components of a long-term 6-yr cycle with a superimposed annual cycle of about 5 ft amplitude. Departure from quarterly average precipitation data from nearby National Weather Service stations are shown for comparison to the long-term cycle.

Duplicate samples from six sites were used to assess analytical data quality. Comparison of major-ion concentrations reported for the primary samples and their duplicates show good agreement (fig. 21); the percentage differences for the major ions detected at concentrations greater than 1 mg/L were small (median differences less than 2.5 percent). The charge balances of the major-ion data were also evaluated to ensure data quality. Most charge balance differences were less than 5 percent and no charge balance difference exceeded 15 percent, which was considered acceptable.

The major-ion composition, total dissolved solids (TDS) content, and the levels of certain trace elements can affect the suitability of water for use. The water-quality data were compared to drinking water standards (U.S. EPA, 2002) to assess the general suitability of groundwater for domestic purposes. Although drinking water standards apply only to public water systems, they provide a basis for evaluating the suitability of the groundwater for particular uses. Primary MCLs set concentration limits on certain parameters to protect human health, and SMCLs set concentration limits on parameters that cause aesthetic problems (such as taste, odor, and color) but that do not present a health threat.

Total dissolved solids

Groundwater in the Lolo-Bitterroot area is generally of high quality; analytical results exceeding drinking water standards were few and localized (table 3). TDS (as residue at 180°C) are an indicator of general water quality and suitability for drinking. Of the 305 analyses evaluated, only 11 samples had TDS concentrations exceeding the SMCL of 500 mg/L; the spatial distribution of samples and TDS concentrations from the shallow basin-fill, deep basin-fill, and fractured bedrock aquifers are shown in figures 22–24, respectively. Across the study area, TDS concentrations ranged from 23 to 1,264 mg/L, with a median of 146 mg/L. Samples with TDS greater than 500 mg/L did not appear related either spatially or by aquifer; the wells with elevated TDS are generally near the center of the Lolo-Bitterroot area and were completed in shallow basin-fill (4 samples), deep basin-fill (3 samples), and bedrock aquifers (4 samples) (figs. 22–24). The highest TDS concentration came from a 50-ft-deep domestic well adjacent to a driveway and a county road where the water table is within 10 ft of the land surface. This sample contained elevated concentrations of sodium and chloride, suggesting possible road salt contamination.

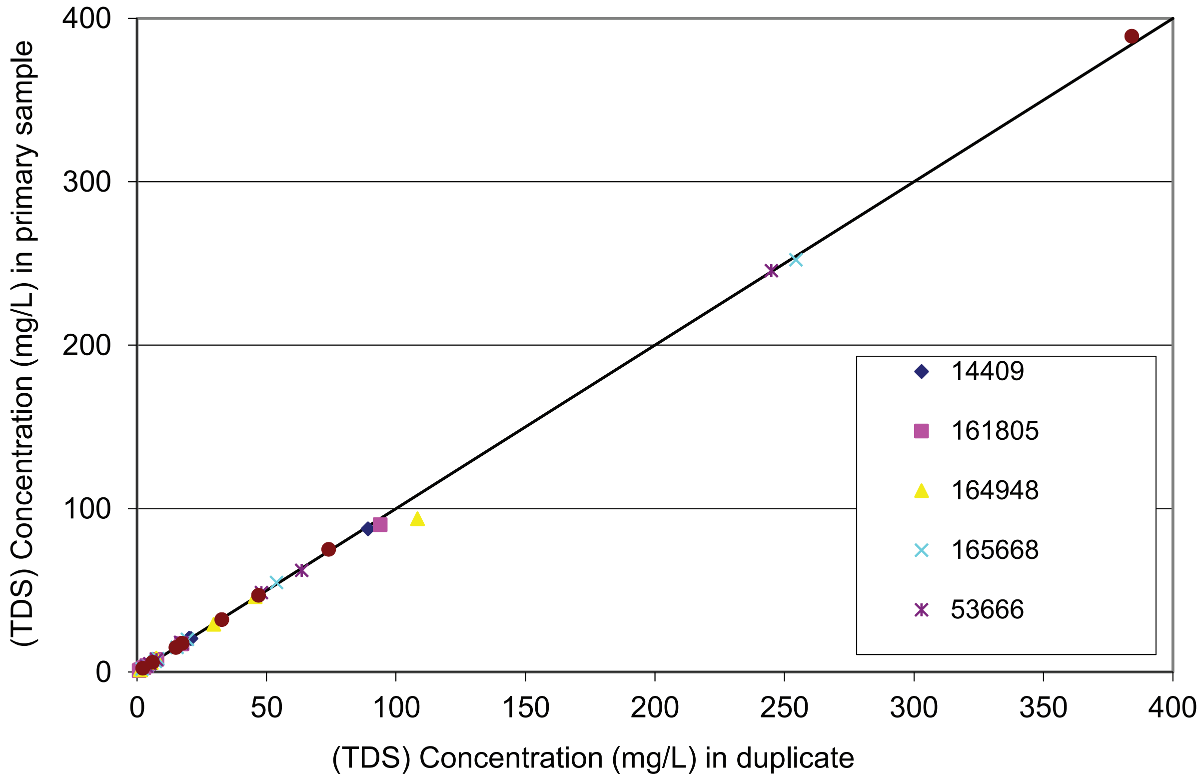


Figure 21. Comparisons of major-ion concentrations between samples and their duplicates show good agreement, indicating good laboratory accuracy.

Table 3. Water-quality data.

		# Samples	% Detect	Min	Median	Max	Exceed SMCL	Exceed MCL	SMCL	MCL
Total	Na mg/L	305	100	1.2	6.5	365.0	2		250	
shallow		113	100	1.44	4.8	365.0	1			
deep		127	100	1.2	6.8	250.6	1			
bedrock		65	100	1.74	15.9	240.0				
Total	Cl mg/L	305	98	<0.2	1.87	686.9	2		250	
shallow		113	96	<0.2	1.84	686.9	2			
deep		127	98	<0.2	1.8	211.5				
bedrock		65	100	0.36	2.3	121.8				
Total	SO_4 mg/L	305	91	<1.0	5.3	224.3			250	
shallow		113	92	<1.0	4.6	40.8				
deep		127	89	<1.0	4.9	208.0				
bedrock		65	95	<1.0	9.4	224.3				
Total	F mg/L	270	79	<0.05	0.11	12.7	4	2	2	4
shallow		89	72	<0.05	0.09	1.36				
deep		119	77	<0.05	0.11	2.87	1			
bedrock		65	91	<0.05	0.2	12.66	3	2		
total	NO_3 mg/L	322	56	<0.25	0.40	27.00		3		10
shallow		116	64	<0.25	0.55	27.00		2		
deep		145	59	<0.25	0.59	6.98				
bedrock		71	37	<0.25	0.25	12.14		1		
Total	Mn mg/L	305	44	<0.001	0.002	1.42	25		0.05	
shallow		113	41	<0.001	0.002	0.87	4			
deep		127	43	<0.001	0.001	1.42	17			
bedrock		65	52	<0.001	0.002	0.57	4			
Total	Fe mg/L	305	47	<0.003	0.006	44.6	21		0.3	
shallow		113	44	<0.003	0.005	44.6	5			
deep		127	50	<0.003	0.007	7.4	13			
bedrock		65	45	<0.003	0.006	1.66	3			
Total	As µg/L	304	34	<1.0		50.06		8		10
shallow		112	16	<1.0		21.5		1		
deep		127	39	<1.0		41.9		3		
bedrock		65	55	<1.0	1.1	50.06		4		
Total	Al µg/L	304	6	<15		4770	3		200	
shallow		112	7	<15		200	1			
deep		127	6	<15		4770	1			
bedrock		65	5	<15		279	1			
Total	Ba µg/L	304	98	<2.0	53.6	4860		2		2000
shallow		112	99	<2.0	30.1	4860		1		
deep		127	98	<2.0	68.8	2411		1		
bedrock		65	98	<2.0	47.7	969.0				
Total	TDS mg/L	305		22	146	1264	11		500	
shallow		113		22	98	1264	4			
deep		128		32	158	795	3			
bedrock		64		31	205	719	4			

Table 3—Continued.

Total	Cr μg/L	304	13		546.7	1		100
shallow		112	17		21.1			
deep		128	16		546.7	1		
bedrock		64	22		22.8			
Total	Cu μg/L	304	42		126.0			1300
shallow		112	43		126.0			
deep		128	39		117.4			
bedrock		64	45		31.0			
Total	Se μg/L	304	5		11.5			50
shallow		112	4		1.5			
deep		128	5		11.5			
bedrock		64	6		10.0			
Total	Zn μg/L	304	91	16	1310		5000	
shallow		112	87	15	546			
deep		128	94	16.8	575			
bedrock		64	92	18	1310			

There are slight differences between median TDS concentrations in groundwater by aquifer; shallow basin-fill aquifers produce water with the lowest TDS. Water from fractured bedrock aquifers contained the highest TDS concentrations, while water from deep basin-fill aquifers had intermediate concentrations (figs. 22–24). Box plots in figures 22–24 show that TDS generally increases with well depth. Spatial variations in TDS in the Bitterroot Valley are discussed in detail in Part B, Map 9. In general, groundwater on the east side of the Bitterroot Valley is slightly more mineralized than it is on the west, but the relative percentages of major ions are similar.

Water types

Groundwater types can be compared by describing the relative percentages of major ions in solution. The quantities and types of dissolved constituents are influenced by:

(1) Differences in bedrock geology and the lithologic composition of basin-fill deposits, which may impart different chemical signatures to groundwater. For example, reactive minerals weathered from bedrock can cause elevated common constituent or trace-metal concentrations.

(2) The velocity of groundwater flow, which controls the contact time between groundwater and aquifer materials. Slow groundwater flow velocities allow groundwater to have more contact time with reactive minerals, potentially causing increased TDS.

(3) The chemical characteristics of recharge water. The chemistry of water in the subsurface will be modified from the initial chemistry of recharge. For example, recharge water derived from irrigation practices may have a different initial chemistry than recharge water derived directly from snowmelt or precipitation.

Most of the sampled groundwater in the Lolo-Bitterroot area is a calcium-bicarbonate (Ca-HCO_3) type (see piper plots in figs. 22–24). The uniform chemical signature across the study area and low TDS concentrations suggest that most aquifer materials are not very reactive. Samples from shallow basin-fill aquifers displayed the most consistent water composition; 106 of 113 samples had a Ca-HCO_3 signature (piper plot in fig. 22). Groundwater from bedrock aquifers displayed the most variability. The piper plot in fig. 24 shows that although bedrock-aquifer water chemistry is primarily a Ca-Mg-HCO_3 type, 17 samples (26 percent) were of sodium bicarbonate (Na-HCO_3) water. Groundwater in deep basin-fill aquifers is predominately Ca-HCO_3 type, but nine samples (7 percent) had a Na-HCO_3 signature (piper plot in fig. 23). The tendency toward Na-HCO_3 waters in deep basin-fill and bedrock aquifers likely reflects longer residence times and slower groundwater flow velocities when compared

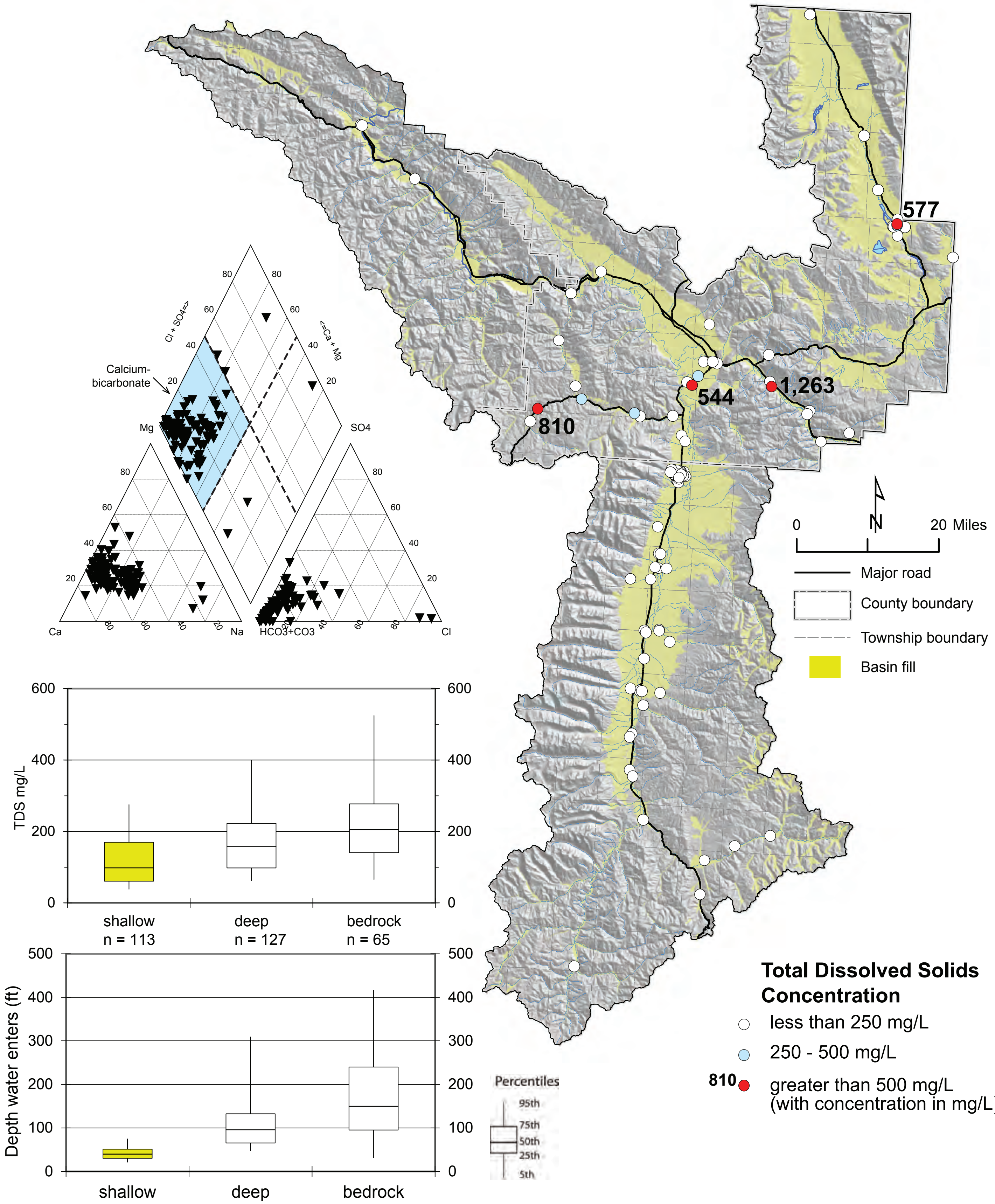


Figure 22. Total dissolved solids concentrations in water from shallow basin-fill aquifers are generally less than concentrations in deep basin-fill and bedrock aquifers. The water is predominately a Ca-HCO_3 type.

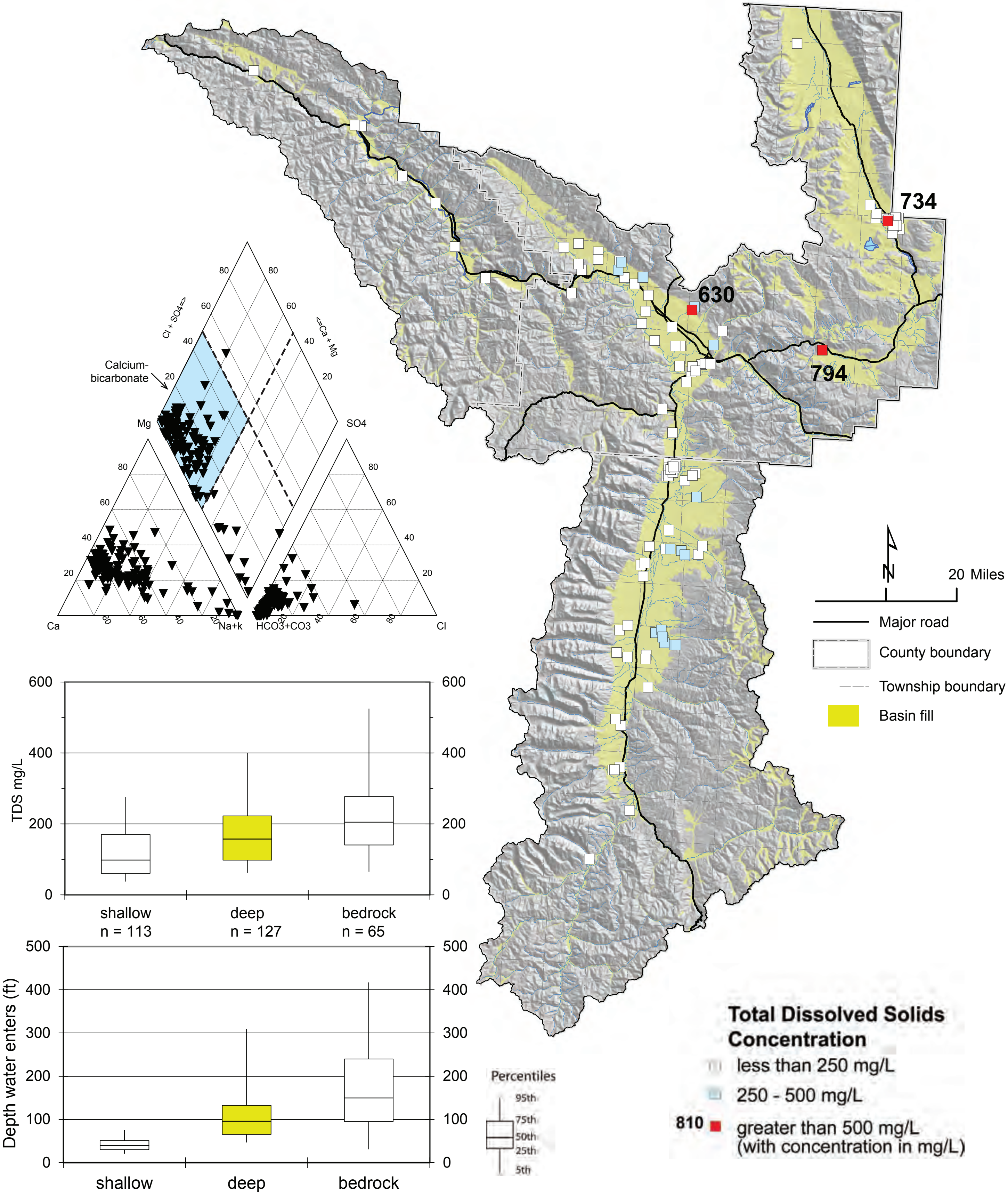


Figure 23. Total dissolved solids concentrations in water from deep basin-fill aquifers are generally intermediate between concentrations in water from the shallow basin-fill and bedrock aquifers. TDS concentrations are typically less than 400 mg/L. The water is predominately a Ca-HCO_3 type; however, a few samples were relatively more enriched in sodium (Na).

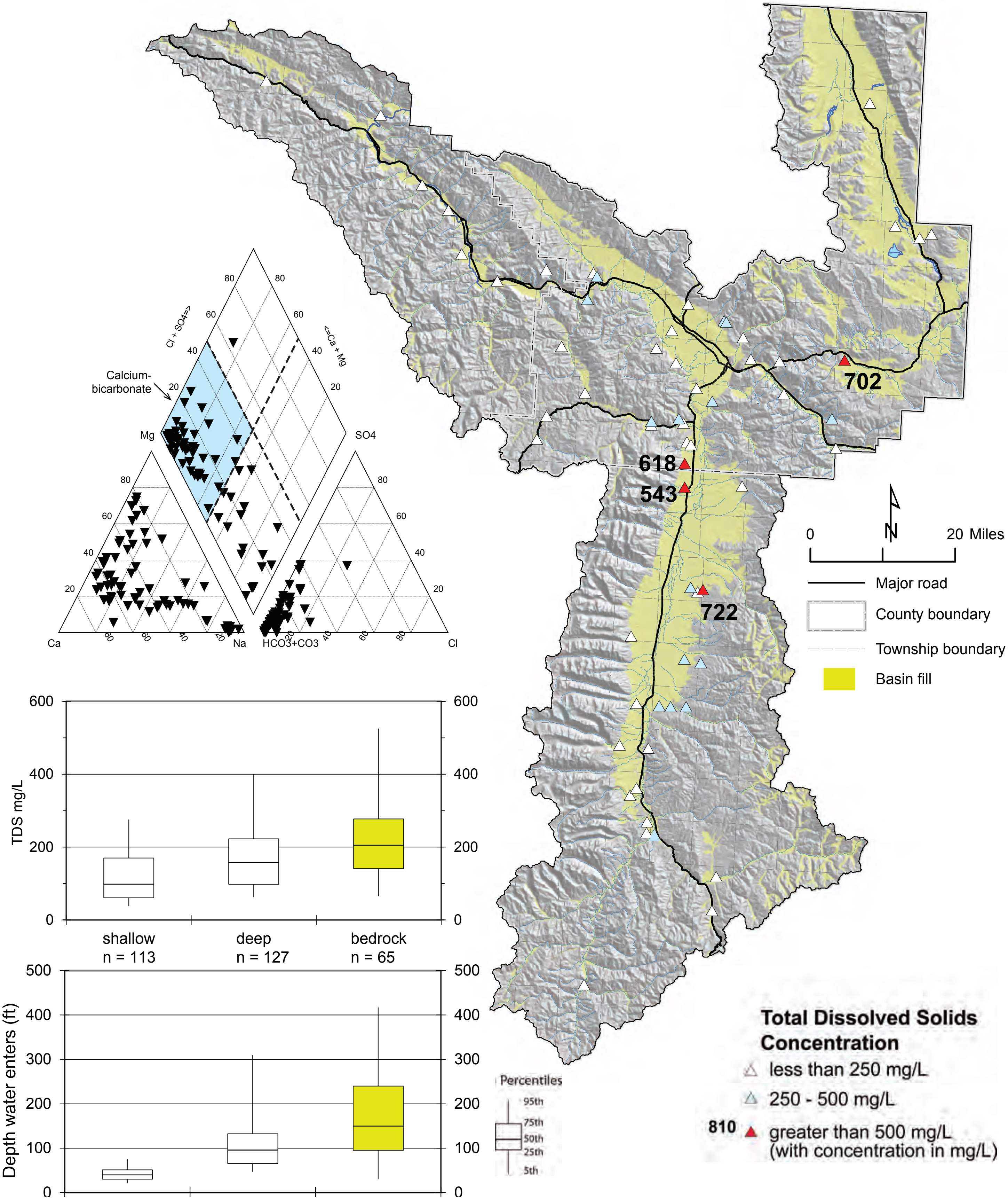


Figure 24. Total dissolved solids concentrations in water from fractured bedrock aquifers were slightly greater than in water from the shallow and deep basin-fill aquifers; however, most concentrations were well below the SMCL for TDS of 500 mg/L. Water from the fractured bedrock aquifers was generally a Ca-HCO_3 type.

to groundwater in shallow basin-fill aquifers. Generally, samples that had greater proportions of sodium also had greater TDS concentrations. Samples with sodium/(calcium+ magnesium) [Na/(Ca+Mg)] ratios greater than unity had a median TDS concentration of 225 mg/L; samples with Na/(Ca+Mg) ratios less than unity had a median TDS concentration of 138 mg/L.

Sodium

Sodium is naturally present in groundwater; it is mostly derived from dissolution of aquifer materials, although elevated sodium concentrations may result from human activities such as application of sodium salts to road surfaces or septic tank effluent. The 250 mg/L sodium SMCL was exceeded in two samples, one from a well completed in a shallow basin-fill aquifer near Clinton (see fig. 2 for location of Clinton) where a surface contamination source is suspected, and one from a well completed in a deep basin-fill aquifer near Potomac (see fig. 2 for location of Potomac; table 3, fig. 25). In all the aquifers, median sodium concentrations were generally less than 20 mg/L; however, sodium concentrations are generally more elevated in samples from deep basin-fill aquifers as compared to samples from shallow basin-fill aquifers, and again in samples from bedrock aquifers as compared to samples from deep basin-fill aquifers (fig. 25). The median concentration from bedrock-aquifer samples (15.7 mg/L) was about three times greater than the median concentration in water from shallow basin-fill aquifers (4.8 mg/L). Boxplots in figure 25 show that 75 percent of samples from shallow basin-fill aquifers had sodium concentrations less than 5 mg/L; 75 percent of samples from deep basin-fill aquifers had concentrations less than 7 mg/L; and 75 percent of samples from bedrock aquifers had concentrations less than 40 mg/L.

Calcium and magnesium

Calcium is one of the most common elements dissolved in natural waters (Hem, 1992) and is the dominant cation in most groundwater samples collected during the Lolo-Bitterroot groundwater assessment (figs. 22–24). Calcium and magnesium-bearing minerals are abundant in rocks and soil, are relatively soluble, and cause hardness that contributes to scale-forming properties of water (Hem, 1992). In the Lolo-Bitterroot assessment area, calcium concentrations were generally less than 50 mg/L and were relatively consistent between the aquifers (fig. 26). Most samples had magnesium concentrations less than 15 mg/L. Median calcium and magnesium concentrations in bedrock aquifer samples were slightly greater than concentrations in samples from the deep and shallow basin-fill aquifers.

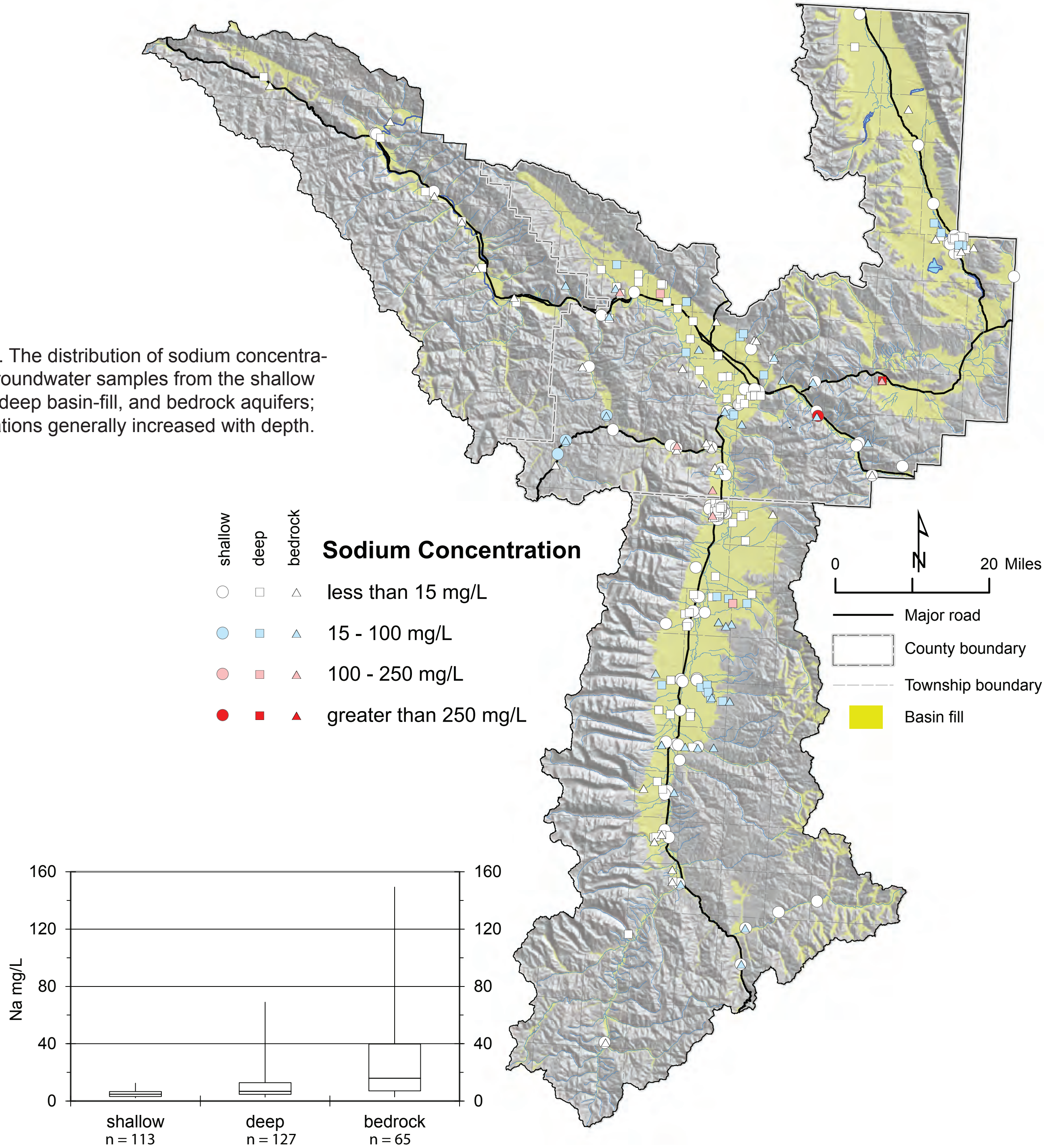
Chloride

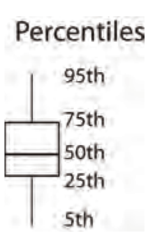
Chloride minerals are extremely soluble and not commonly present in bedrock and basin-fill aquifer materials within the Lolo-Bitterroot study area. Therefore, chloride derived from aquifer materials is limited. The median chloride concentration in groundwater from all aquifers was 2.5 mg/L; concentrations in 75 percent of all samples were less than 5 mg/L. Water samples from bedrock aquifers had more variable and slightly greater chloride concentrations than did water from the other units (fig. 27). Two samples had concentrations that exceeded the 250 mg/L SMCL (table 3); both were from shallow basin-fill aquifers, which suggests possible surface contamination sources (fig. 27). Surface sources of chloride contamination include road salt, fertilizers, and human and animal wastes.

Iron and manganese

Iron and manganese occur naturally in groundwater and are derived from many minerals contained in common rocks. Where iron concentrations in groundwater are near or above the SMCL of 0.3 mg/L, the water will cause aesthetic issues by staining fixtures, clothing, driveways, and houses, if allowed to strike walls. High manganese concentrations have the same objectionable issues as iron. In the Lolo-Bitterroot, iron concentrations exceeded the SMCL of 0.3 mg/L in 21 of 320 samples (7 percent); the manganese SMCL of 0.05 mg/L was exceeded in 25 of 320 samples (8 percent). Co-occurrences were common; 16 samples had both iron and manganese concentrations that exceeded the SMCLs.

Figure 25. The distribution of sodium concentrations in groundwater samples from the shallow basin-fill, deep basin-fill, and bedrock aquifers; concentrations generally increased with depth.





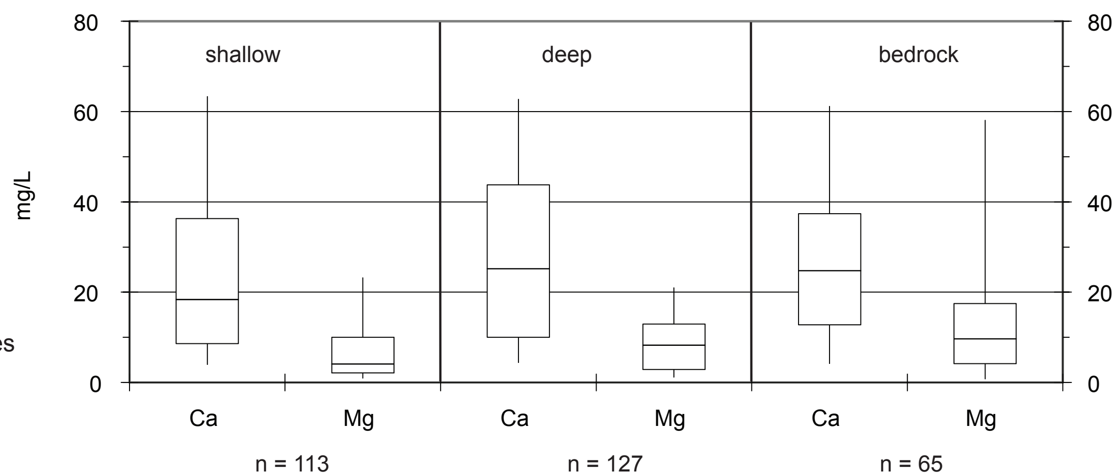


Figure 26. Calcium and magnesium concentrations were consistent in groundwater samples from the shallow basin-fill, deep basin-fill, and bedrock aquifers.

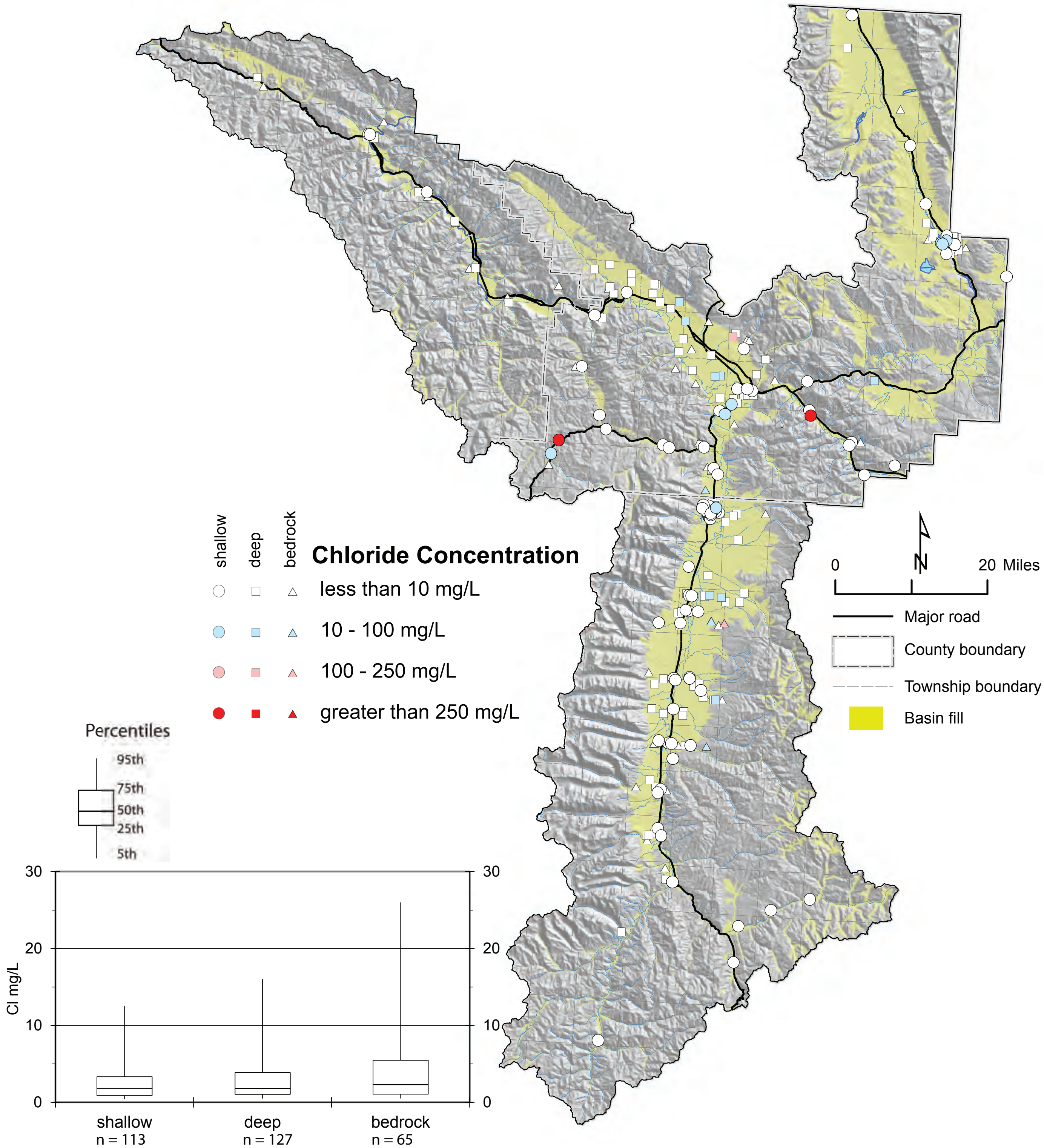


Figure 27. Chloride concentrations in groundwater samples from all Lolo-Bitterroot area aquifers were low, except for samples from two shallow basin-fill wells potentially contaminated by surface activities.

Typically iron and manganese concentrations are strongly related to the oxidation-reduction conditions in groundwater; the more reducing the conditions, the more iron and manganese in solution. Accordingly, exceedances were most common in samples of reduced water from deep basin-fill and bedrock aquifers (table 3). Notable areas that produce groundwater with elevated iron and manganese concentrations include the deep basin-fill aquifer near Seeley Lake, the deep basin-fill and bedrock aquifers along the Missoula Valley's northern margin, and basin-fill aquifers near Florence in the Bitterroot Valley (figs. 28, 29).

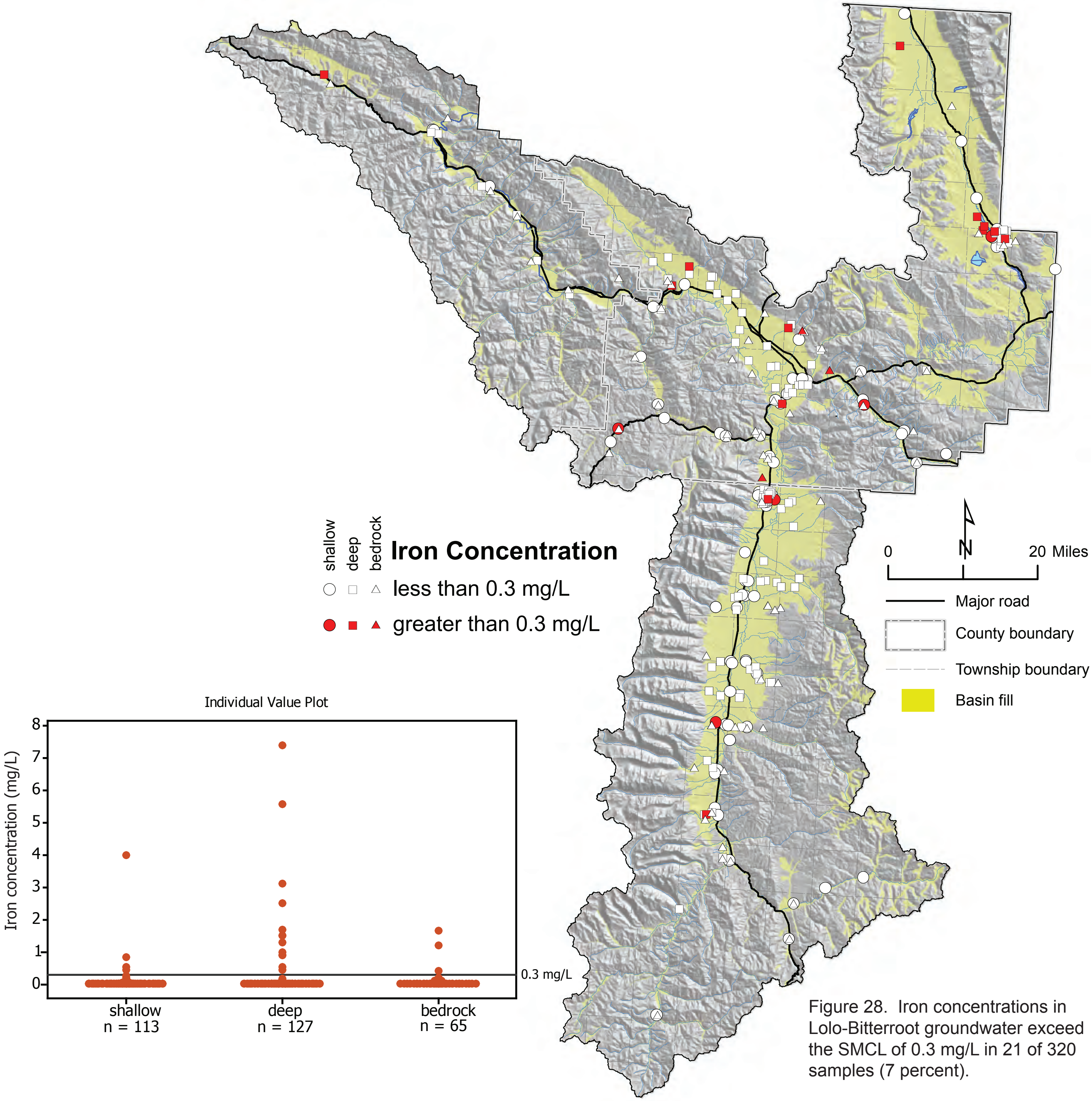
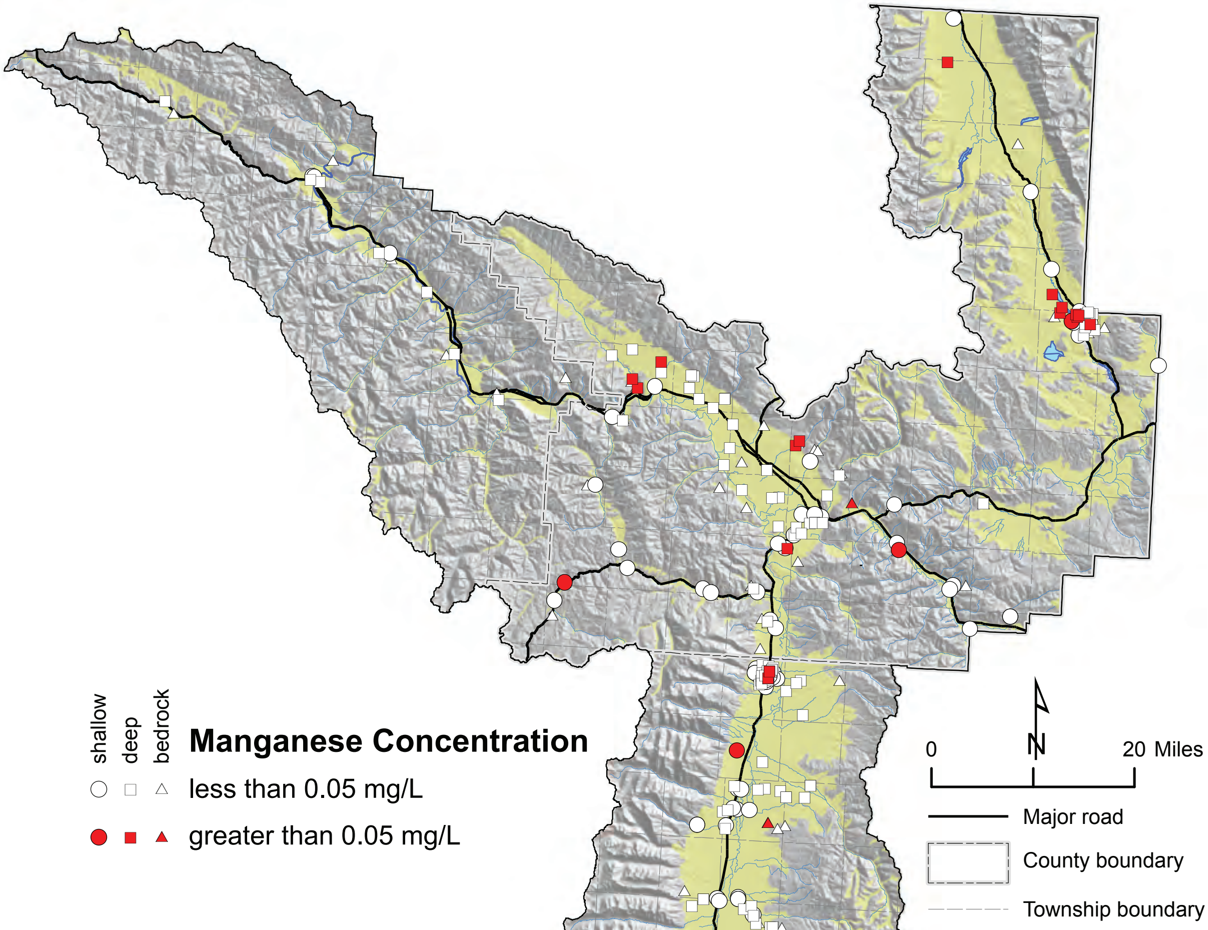


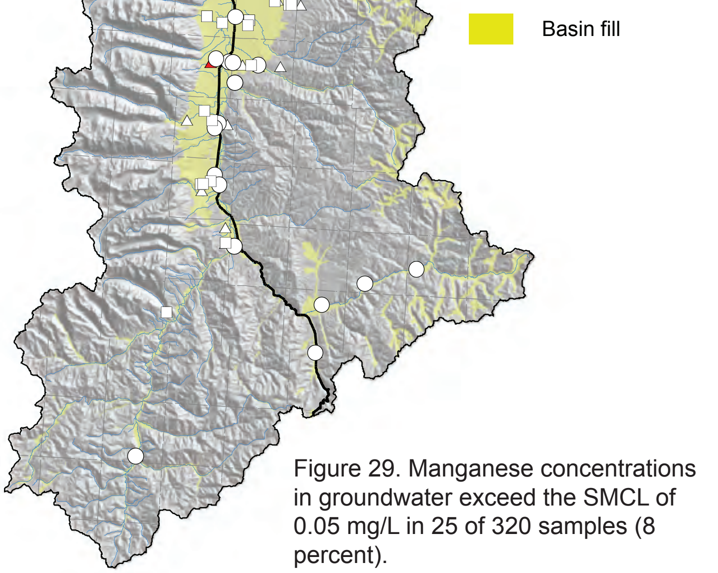
Figure 28. Iron concentrations in Lolo-Bitterroot groundwater exceed the SMCL of 0.3 mg/L in 21 of 320 samples (7 percent).

Fluoride

Fluoride in groundwater occurs naturally and is commonly dissolved in small amounts from minerals found in many igneous and sedimentary rocks; high concentrations may occur in waters related to geothermal resources. Long-term ingestion of drinking water containing fluoride concentrations in excess of the MCL may cause skeletal and dental fluorosis. However, small concentrations of fluoride in drinking water promote strong teeth, and in the United States, fluoride is routinely added to many municipal water supplies.

In the Lolo-Bitterroot, fluoride concentrations in groundwater are generally low; only 35 samples (11 percent) contained fluoride concentrations greater than the detection limit (0.3 mg/L), but less than the SMCL of 2 mg/L. Two samples exceeded the





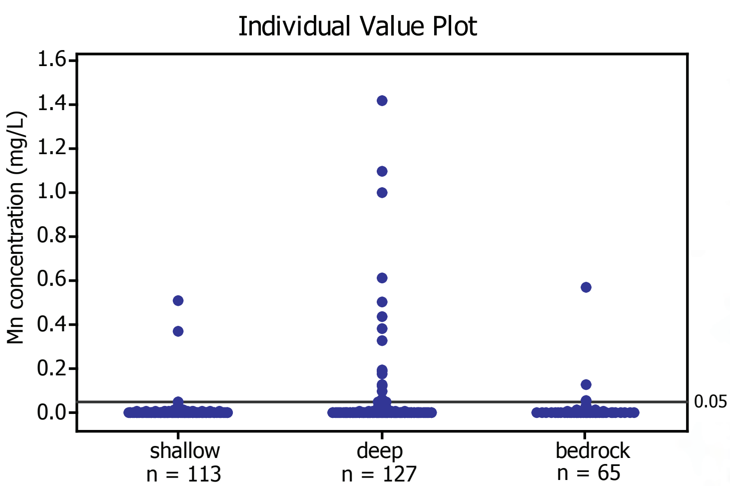


Figure 29. Manganese concentrations in groundwater exceed the SMCL of 0.05 mg/L in 25 of 320 samples (8 percent).

4 mg/L MCL for fluoride, and four samples exceeded the 2 mg/L SMCL (table 3). Fluoride was more commonly detected in water from bedrock and deep-basin fill aquifers; five of the six samples that exceeded either the MCL or SMCL were obtained from bedrock aquifers, and the remaining sample was from a well completed in a deep basin-fill aquifer near Potomac (fig. 30).

Arsenic

Arsenic occurs naturally and is commonly associated with certain igneous (volcanic), metamorphic, and sedimentary rocks, as well as with geothermal environments. It is also associated with metal smelting and some pesticides. Throughout Montana, small concentrations of arsenic in groundwater are common, and the Lolo-Bitterroot is no exception.

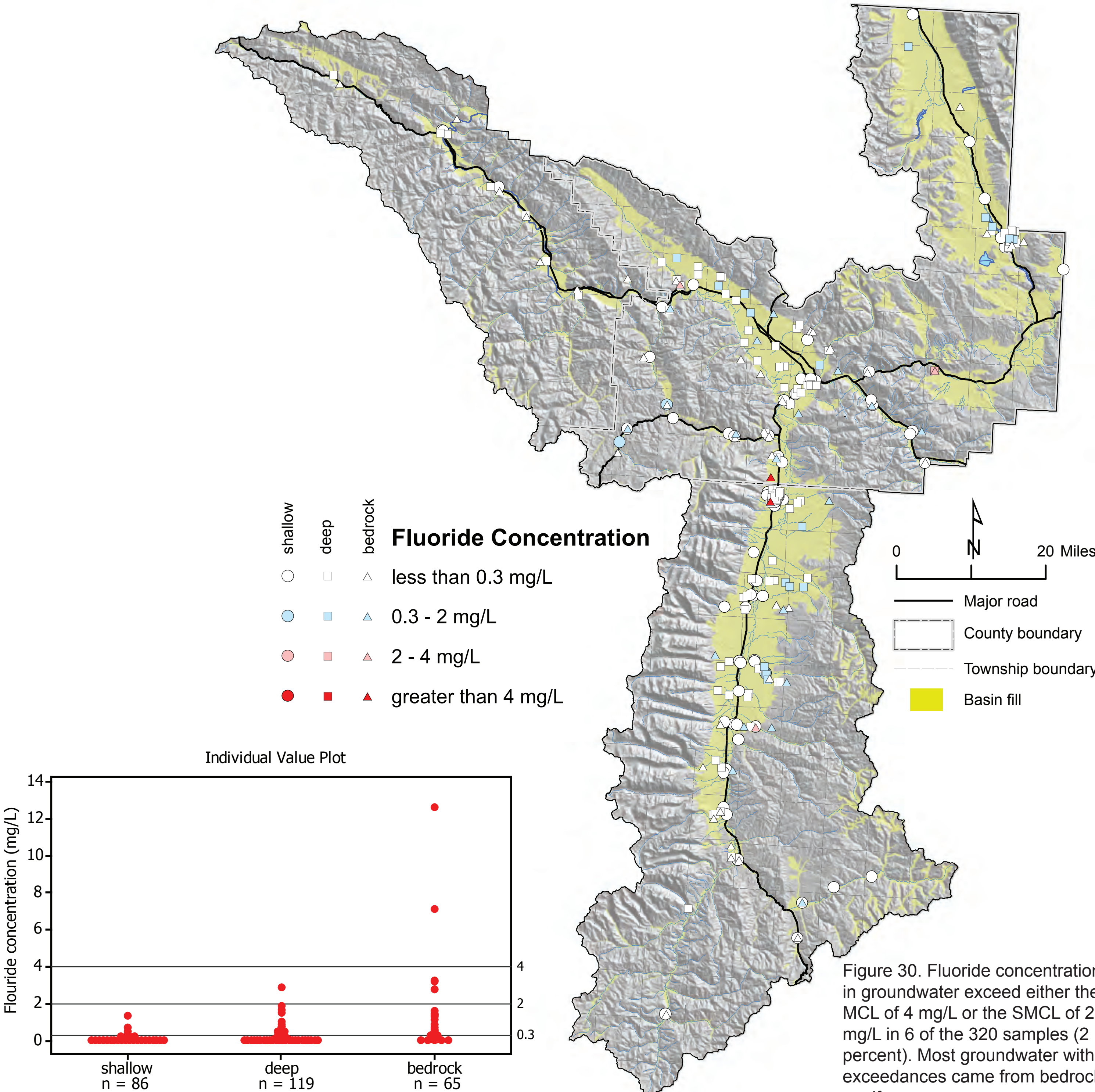


Figure 30. Fluoride concentrations in groundwater exceed either the MCL of 4 mg/L or the SMCL of 2 mg/L in 6 of the 320 samples (2 percent). Most groundwater with exceedances came from bedrock aquifers.

Arsenic was detected in 102 of 320 (32 percent) of samples; concentrations in 8 samples exceeded the 10 µg/L MCL (table 3). Samples containing arsenic concentrations >5 µg/L, but less than the MCL, were mostly from bedrock (25 samples) and deep basin-fill (23 samples) aquifers; only 10 samples from shallow basin-fill aquifers contained elevated arsenic concentrations (fig. 31).

Elevated arsenic concentrations occurred in a cluster of samples from the Willow Creek drainage east of Corvallis in the Bitterroot Valley. The elevated arsenic concentrations in groundwater from this area are discussed in Part B, Map 9. Elevated arsenic concentrations also occur in groundwater from the northern margin of the Missoula Valley, at the lower end of the Ninemile drainage, and near Potomac (fig. 31).

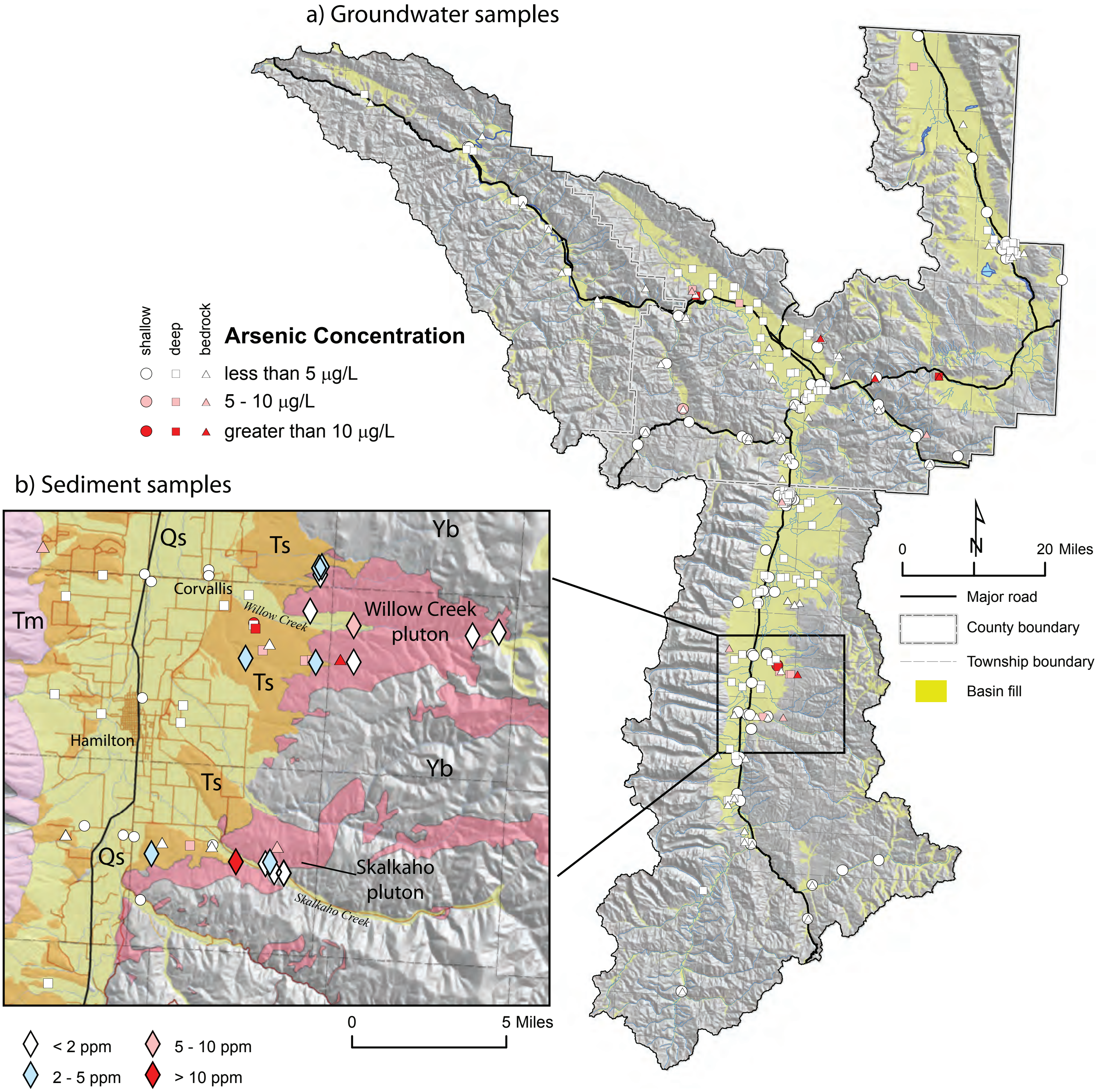


Figure 31. Arsenic concentrations in groundwater exceed the MCL of 10 µg/L in 8 of 320 samples (3 percent); 58 additional samples (18 percent) had elevated values of >5 µg/L. Several samples with elevated concentrations were from sites in the Willow and Skalkaho creek drainages. The inset map shows the distribution of groundwater and sediment samples (diamonds) near Hamilton and Corvallis.

Arsenic in rocks and sediments

In the Lolo-Bitterroot, arsenic is the only trace element that approaches or exceeds its drinking water MCL. Although there are isolated groundwater samples containing elevated arsenic concentrations from wells at locations outside of the Bitterroot Valley, most elevated arsenic concentrations occur in groundwater from shallow and deep basin-fill aquifers, within or downslope of the Willow Creek and Skalkaho granitic rock bodies east of Corvallis (Part B, Map 9; Lonn and Berg, 1996). Likely primary sources of arsenic in earth materials are volcanic rocks or hydrothermally altered granitic rocks (Welch and others, 2000), and the Willow Creek and Skalkaho granitic rocks are suggested as a local source for the arsenic. To test this concept, the Assessment Program collected sand and rock samples from locations near Hamilton and Corvallis and submitted them for arsenic analysis. Locations where the samples were collected are shown by diamond symbols in the figure 31 inset.

Concentrations of arsenic in strong-acid extracts from unconsolidated sediment and Belt bedrock samples ranged from 0.3 to 73.9 parts per million (ppm; appendix C). Arsenic concentrations in strong-acid extracts from igneous rock bodies were consistently far less, at 0.3 to 2.7 ppm. The low concentrations of arsenic in the bedrock samples compared to concentrations from the sediment samples suggest that weathering and local geochemical conditions may have concentrated arsenic in the sedimentary basin-fill aquifers, perhaps incorporated into iron oxide precipitates. The data show that arsenic is available in the aquifer materials and also in the suggested primary source rocks.

The three samples of unconsolidated aquifer materials that produced extracts with the highest arsenic concentrations were also submitted for a "weak acid" leaching extraction (EPA Method 1312 Acid-Rain Simulation) intended to represent the tendency of natural, slightly acidic infiltration from rainfall and snowmelt to incorporate metals from rock and sediment. Arsenic concentrations in the weak-acid extractions of 0.002 to 0.01 ppm were much less than the 0.3 to 73.9 ppm concentrations found in the strong-acid extractions (appendix C). The arsenic values from the relatively non-mineralized aquifer materials east of Hamilton and Corvallis are 2 to 5 orders of magnitude less than arsenic concentrations reported in samples collected during assessments of abandoned mine lands in the Lolo National Forest (Hargrave and others, 2003). However, the highest weak-acid extraction concentrations of 0.01 ppm (10 ppb) are significant because they are equivalent to the arsenic drinking water MCL. Therefore, the evidence suggests that rainwater infiltrating through these aquifer materials could produce arsenic concentrations in groundwater approaching the arsenic MCL. The sample with the highest weak-acid extraction concentration was from near-land-surface fine-grained sand in the Willow Creek drainage (fig. 31).

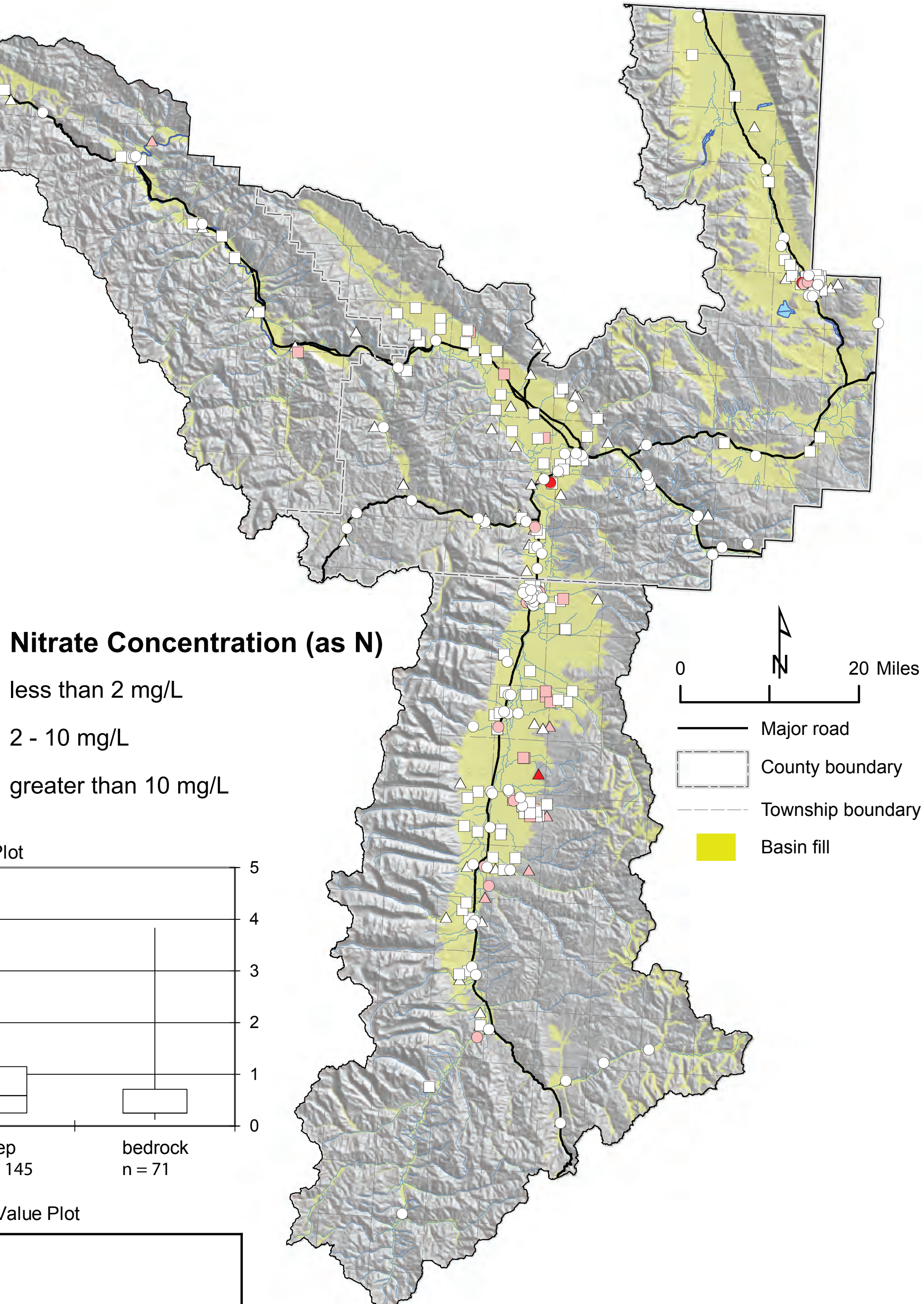
Nitrate

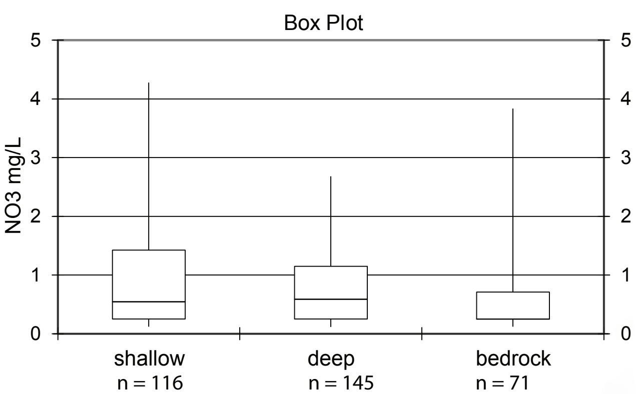
Primary sources for nitrate in groundwater include fertilizers, animal manure, human sewage, wastewater, and in rare cases, geologic sources. Where groundwater has been contaminated by nitrate, the contamination is usually related to a surficial nitrogen source (Madison and Brunett, 1984). During the Lolo-Bitterroot study, Assessment Program staff collected 386 samples from 332 sites; analytical results showed that nitrate concentrations in groundwater ranged from not detected to 27 mg/L (concentrations are nitrate + nitrite, reported as N). Three samples exceeded the 10 mg/L nitrate MCL: two from shallow basin-fill aquifers and one from a bedrock aquifer (table 3). The occurrence and distribution of nitrate in Lolo-Bitterroot groundwater are discussed in detail in Part B, maps 7 and 9.

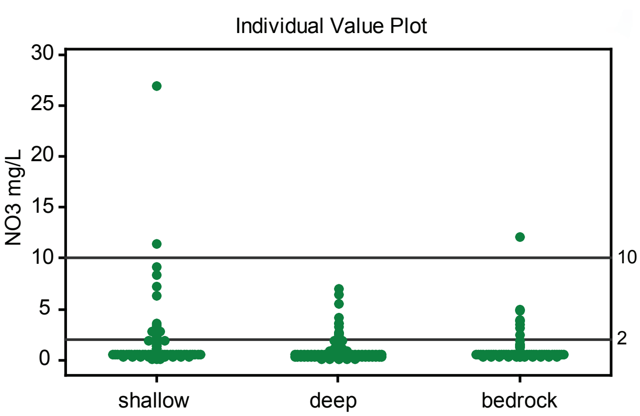
For this summary nitrate concentrations were grouped into three reporting ranges:

(1) Low-level: <0.5 (below detection) to 2 mg/L. Concentrations reflect natural occurrence or minor land-use impacts.
(2) Impacted: 2 to 9.9 mg/L. Elevated concentrations above background that likely reflect general land-use impacts or local contamination at the sample site.
(3) MCL exceedances: ≥10 mg/L. Elevated concentrations that likely present a human health risk.

Nitrate concentrations in the Lolo-Bitterroot area groundwater were generally low (fig. 32). Of the 332 sites sampled, 290 (87 percent) had concentrations either less than 2 mg/L or below the detection limit (table 3). Of the 42 wells that produced water with nitrate concentrations greater than 2 mg/L, 18 were from shallow basin-fill aquifers, 16 were from deep basin-fill aquifers, and 8 were from bedrock aquifers (fig. 32). Although many of the apparently impacted sites occur in highly developed areas in the Bitterroot Valley and near Seeley Lake,







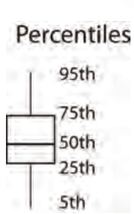


Figure 32. Nitrate concentrations in groundwater were generally low. Only three samples, two from shallow basin-fill aquifers and the other from a fractured-bedrock aquifer, exceeded the 10 mg/L MCL; 39 sites had samples with concentrations greater than 2 mg/L, suggesting possible land-use impacts. Median nitrate concentrations were less than 0.60 mg/L in each aquifer.

some are isolated occurrences in sparsely populated areas. The nitrate concentrations in developed areas may reflect land-use practices, but the isolated elevated nitrate occurrences more likely represent contamination of individual wells from septic or other sources.

To assess seasonal variation of nitrate concentrations in the Bitterroot Valley, the Assessment Program sampled three wells six times between June 1998 and March 2001. Briar and Dutton (1999) had sampled these wells in 1997 on a roughly bi-monthly basis. Two wells were located on the Hamilton Heights Bench and one on the Sunset Bench (fig. 33).

Well 57778 on the Sunset Bench is located downgradient of the Bitterroot Irrigation Canal, and is perforated from 100 to 105 ft below land surface. Between November 1996 and March 2001 the well was sampled 14 times; nitrate concentrations in the samples ranged from not detected (less than 0.5 mg/L) to 5.9 mg/L. Time-series graphs of the concentrations and water-level data are shown in figure 33. There is a noticeable difference in nitrate concentrations between the samples collected in 1997 and the samples collected in 1999–2001; in 1997 all but one of the concentrations were greater than 5 mg/L; concentrations in samples collected after 1999 were less than 4 mg/L (fig. 33). Based on the data set, seasonal fluctuations are erratic, but are generally less than 2.5 mg/L annually. The one sample that did not have detectable nitrate was obtained during the highest recorded water level, but otherwise nitrate concentrations do not appear to correspond to water-level fluctuations.

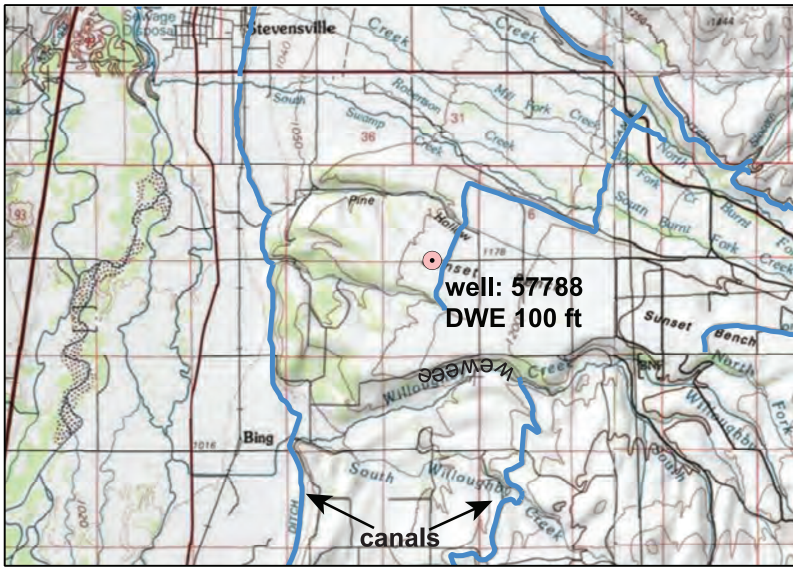
The two wells located on the Hamilton Heights Bench are also downgradient of the Bitterroot Irrigation canal. Well 53992 is easternmost, located at a higher elevation, and perforated from 130 to 160 ft below the surface in the deep basin-fill aquifer; well 126820 is westernmost, near the base of the bench (about 160 ft lower in elevation), and perforated from 50 to 55 ft below the surface in the shallow basin-fill aquifer (fig. 33). Water-level records for both wells show an annual irrigation response (Part B, Map 10). Well 53992 was sampled 13 times and well 126820 sampled 14 times between January 1997 and March 2001; nitrate concentrations in samples ranged from not detected to 2.85 mg/L. In general, concentrations were slightly greater in water from well 126820 than in water from the deeper well 53992 (fig. 33). Although nitrate concentration trends in water from both wells were not upward or downward during the sampling period, their seasonal fluctuations were contradictory. The annual variation in both wells was about 1 mg/L per year; however, high nitrate concentrations in well 126820 correspond to low nitrate concentrations in well 53992. In well 126820 low nitrate concentrations occur midsummer when water levels are high; correspondingly, nitrate concentrations are high midwinter when water levels are low. The pattern suggests that at this location irrigation recharge may dilute nitrate concentrations. In well 53992 the pattern is reversed, with nitrate concentrations high when water levels are high; nitrate concentrations in samples dropped below detection limits in June 1999 and May 2000, when water levels in the well were at seasonal lows (fig. 33). This pattern suggests that at this location seasonal recharge may be flushing nitrogen into the aquifer.

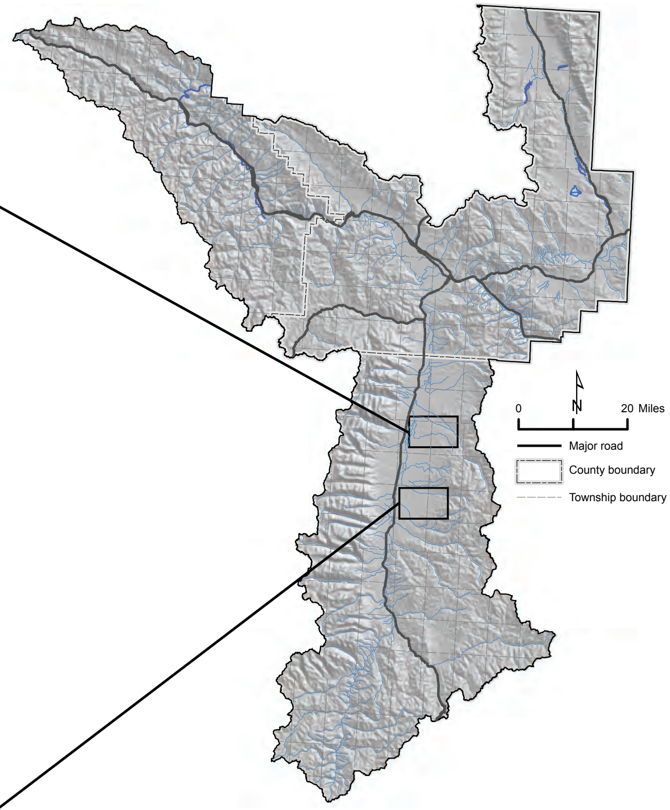
Tritium

Tritium is a naturally occurring radioactive isotope of hydrogen that has a half-life of 12.43 years. It is produced in the upper atmosphere where it is incorporated into water molecules, and therefore is present in precipitation that becomes groundwater recharge. Tritium concentrations are expressed in tritium units (TU), where one TU is equal to one tritium atom in 10^{18} atoms of hydrogen. Before the atmospheric nuclear weapons testing began in 1952, natural tritium concentrations in precipitation were 2 to 8 TU (Plummer and others, 1993). Atmospheric testing of nuclear weapons between 1952 and 1963 released large amounts of tritium into the atmosphere, overwhelming the natural production; in North America, tritium concentrations in precipitation peaked at several thousand TU in 1963–1964 (Hendry, 1988).

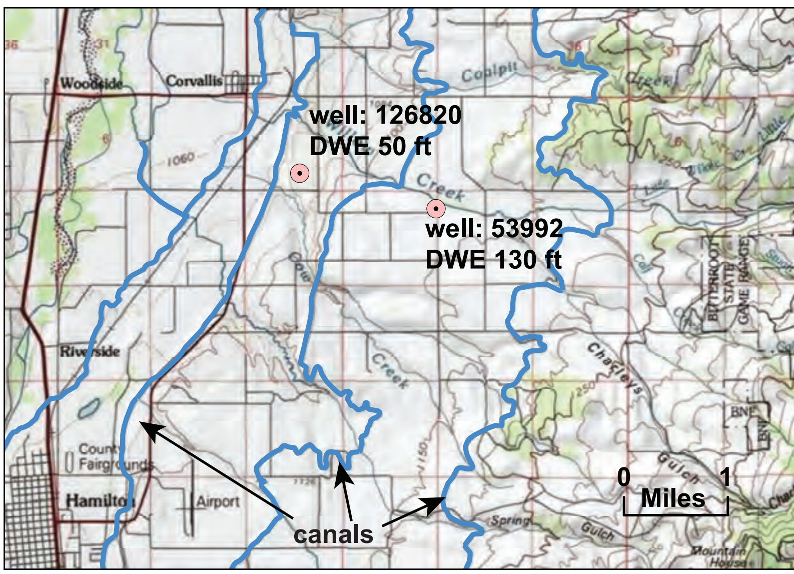
Because of its short half-life, tritium is an ideal marker of post-1952 groundwater recharge; groundwater recharged prior to 1952 will not have detectable tritium (less than 0.8 TU). Groundwater recharged by precipitation during or after the advent of above-ground nuclear testing will have detectable tritium.

Sunset Bench

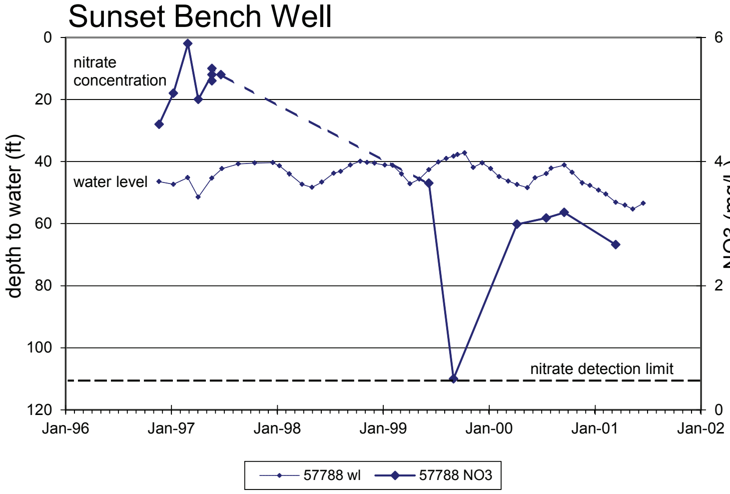




Hamilton Heights



Sunset Bench Well



Hamilton Heights wells

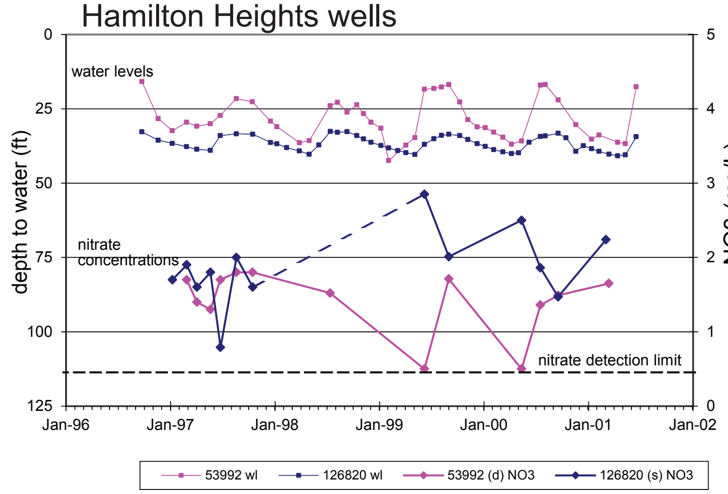


Figure 33. Nitrate as N concentrations in groundwater were measured multiple times in one well on the Sunset and two wells on the Hamilton Heights benches. On the Sunset bench, values generally decreased between 1997 and 1999–2001. The two wells on the Hamilton Heights Bench show seasonal variation.

Clark and Fritz (1997) present a qualitative interpretation of tritium in groundwater for continental regions:

- less than 0.8 TU—submodern (recharged before 1952)
- 0.8–5 TU—mixture between submodern and recent recharge
- 5–15 TU—modern (recharged since 1985)
- 15–30 TU—modern with some “bomb” tritium

For this report, the Clark and Fritz classification is simplified so that “submodern” will refer to tritium concentrations less than 5 TU, and “modern” will refer to tritium concentrations greater than 5 TU.

Tritium was analyzed in 151 water samples from the Lolo-Bitterroot area. Samples were obtained from fractured bedrock aquifers (40 samples), deep basin-fill aquifers (61 samples), and shallow basin-fill aquifers (50 samples). In the analytical results, tritium concentrations ranged from less than 0.8 TU to 22.8 TU. The distribution of sampled sites is shown in figure 34. The distribution of tritium concentrations in the analytical results is bimodal, with a peak in the number of samples with tritium below detection and a peak in the number of samples with concentrations between 8 and 12 TU (fig. 35).

About 74 percent (111 of 151) of samples contained tritium at concentrations between 5 and about 23 TU. Tritium in groundwater concentrations in this range are consistent with modern precipitation and suggest that the water was recharged within the past 5 to 10 years (Clark and Fritz, 1997). The remainder of the samples (about 26 percent) contained tritium at concentrations less than 5 TU, indicating little or no modern water; most of the samples in this group (25 of 37) did not have detectable tritium (fig. 35).

There were notable differences in the tritium distribution between the different hydrologic units. Most shallow basin-fill aquifer (generally less than 75–80 ft deep) samples are from the Bitterroot and Missoula valleys (fig. 34), and most of the samples (37 of 50) had tritium concentrations between 8 and 12 TU, indicating modern water or recharge since the mid-1990s (fig. 35). One sample from a 56-ft-deep well about 5 miles north of Darby had a tritium concentration of 71 TU, suggesting a recharge date of early to mid-1960s when atmospheric tritium concentrations peaked.

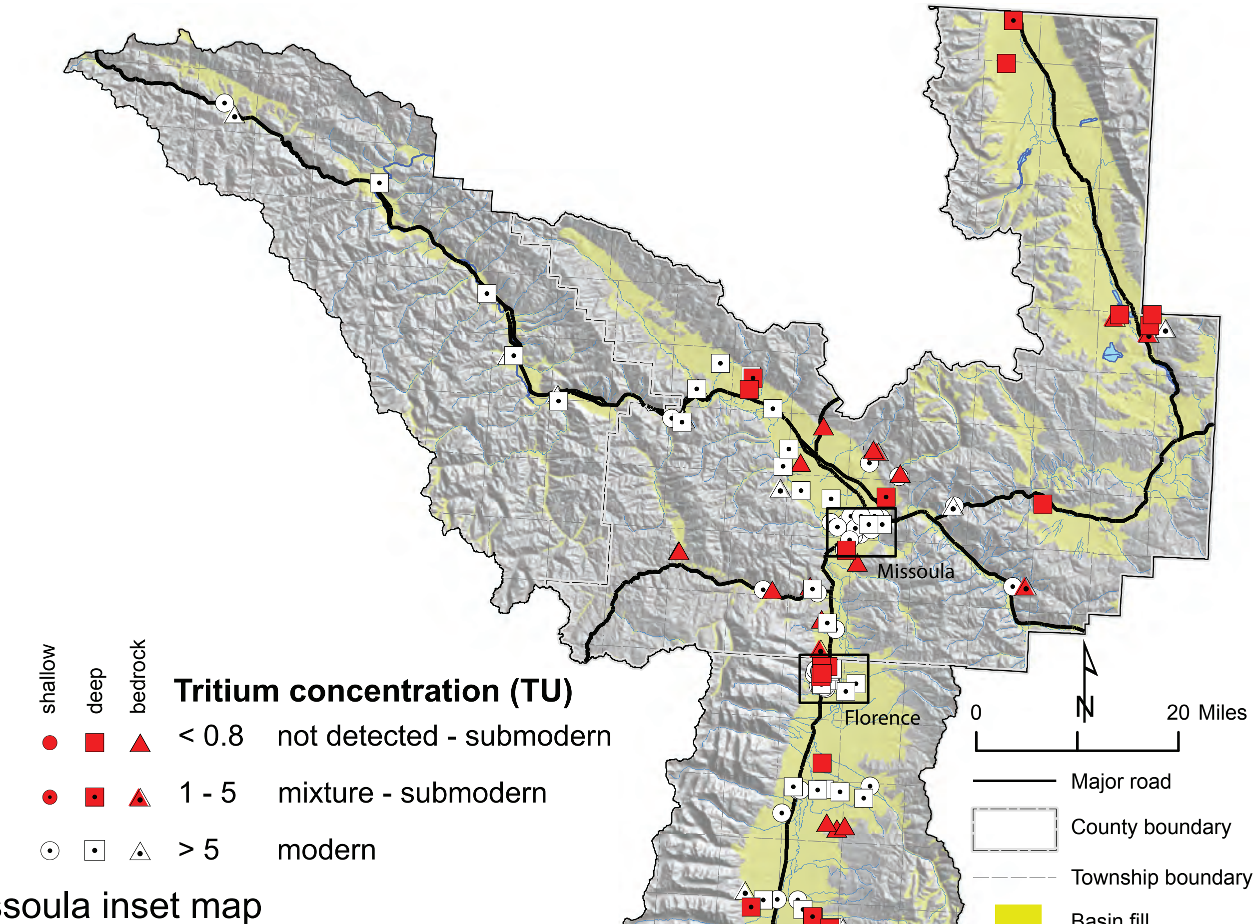
About one-third of the samples (19 of 61) collected from deep basin-fill aquifers had tritium concentrations of less than 5 TU, suggesting submodern water; the other 42 samples had concentrations that ranged from 5.5 to 21.5 TU, suggesting modern water (fig. 34). The distribution of submodern and modern water in deep basin-fill aquifers was not uniform. In the Bitterroot and Missoula Valleys, about 25 percent of the samples contained submodern water, but all samples from deep basin-fill aquifers from the Canyons subarea downstream from Missoula were of modern water. In the Seeley Lake subarea, all deep basin-fill aquifer samples contained submodern water (fig. 34). In general, greater well depths decreased the likelihood that water samples would contain modern water. The median depth water enters for the deep-basin fill wells that produced submodern water was 133 ft below land surface, whereas the median depth for the samples that contained modern water was 99 ft (fig. 35). This suggests that relatively young water is present in the upper parts of deep basin-fill aquifers.

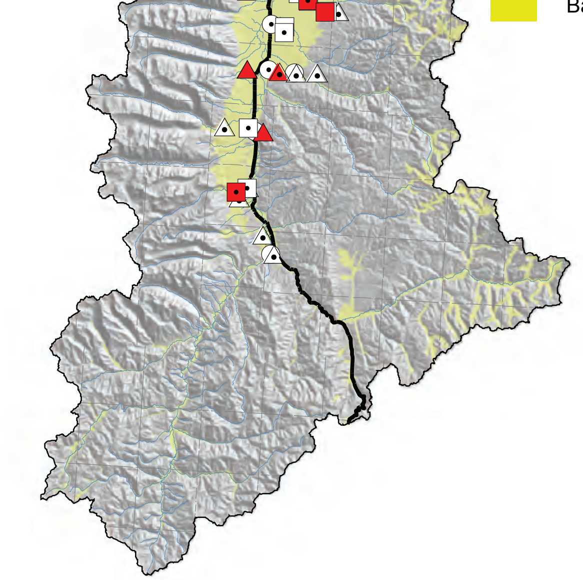
Samples from bedrock aquifers were nearly evenly split between submodern and modern waters; 21 samples had tritium concentrations less than 5 TU, and the other 19 had concentrations between 5.2 and 22.8 TU (fig. 35). In general, deep wells were more likely to produce submodern water (9 of the 12 samples from wells with depths water enters greater than 250 ft below the land surface had concentrations less than 5 TU). However, samples with submodern water were also obtained from some relatively shallow bedrock wells with depths water enters as shallow as 36 ft below land surface (fig. 35). About two-thirds of the bedrock aquifer samples from the Missoula and Bitterroot Valleys and the Seeley Lake subarea contained submodern water, whereas all the bedrock samples from the Canyons subarea contained modern water (fig. 34).

HYDROGEOLOGY OF SUBAREAS

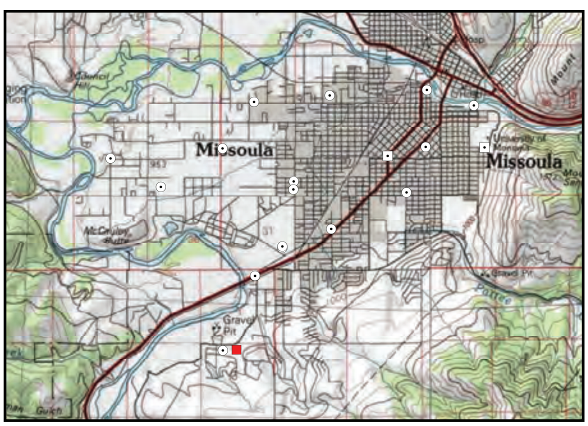
Bitterroot Valley

The Bitterroot Valley subarea (figs. 2, 36) is a north-trending intermontane basin between the Bit-





Missoula inset map



Florence inset map

Figure 34. Maps of tritium concentrations in groundwater samples show that submodern water dominates the deep basin-fill and bedrock aquifers (red symbols), and modern water is in all shallow basin-fill aquifers.

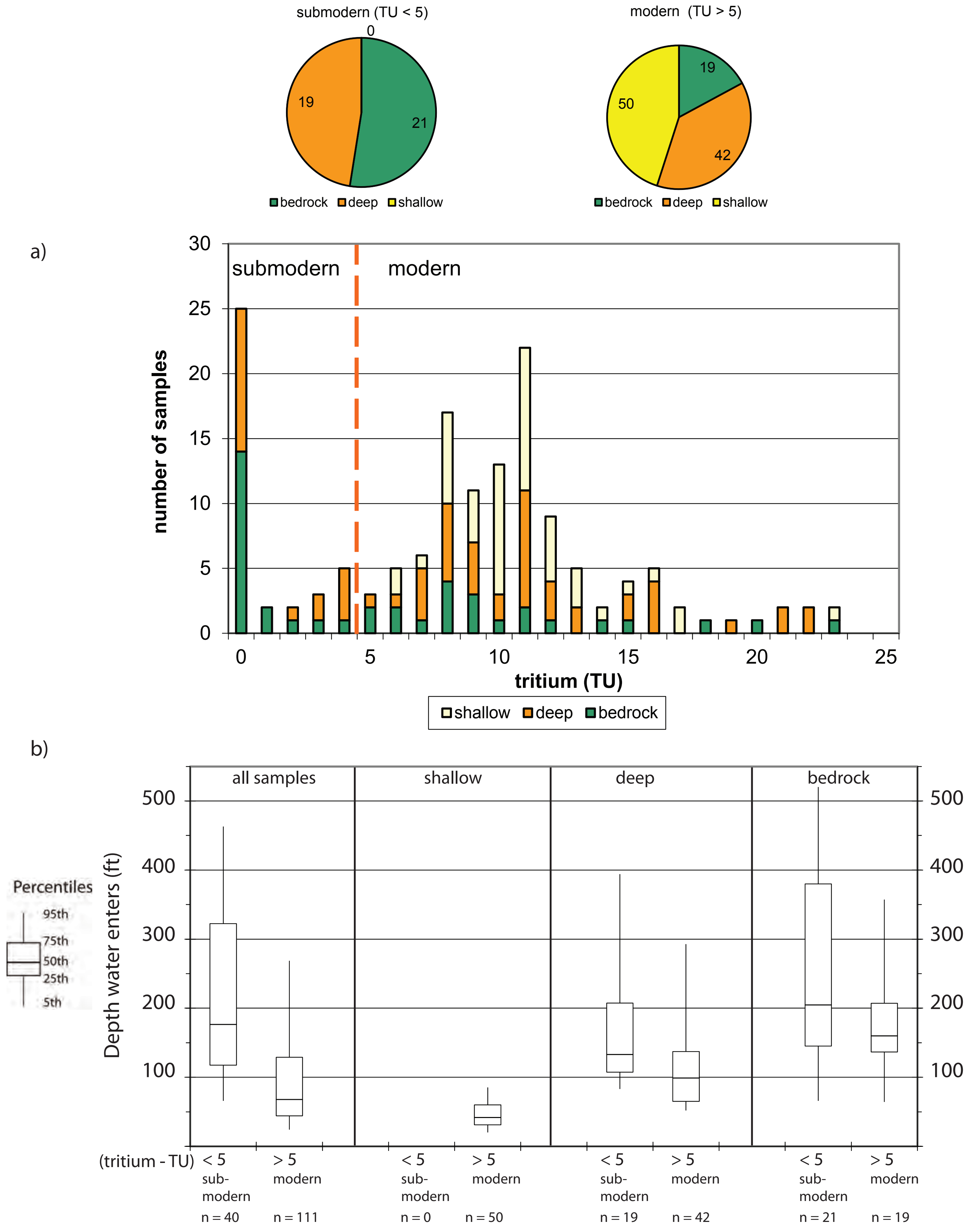
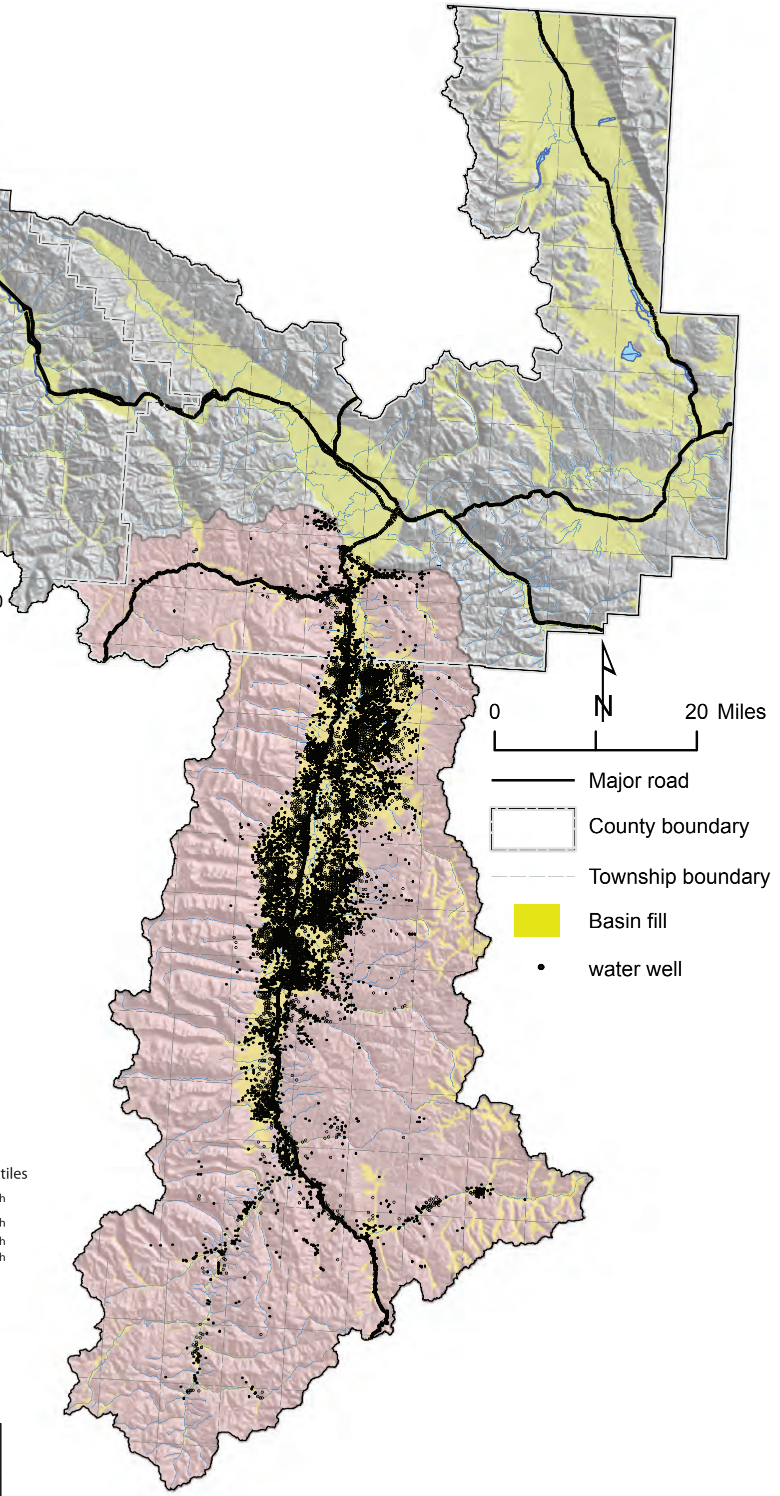


Figure 35. (a) A histogram of tritium concentrations in groundwater samples shows a bimodal distribution. Most samples had tritium values between 8 and 12 TU; all of the water sampled from shallow basin-fill aquifers was modern (TU > 5). (b) Box and whisker plots of the depths water enters in wells sampled for tritium show that wells with modern water are consistently shallower than those with submodern water.



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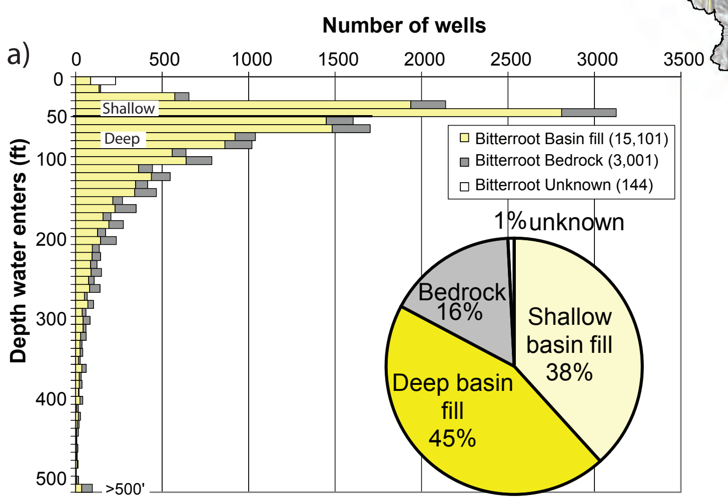

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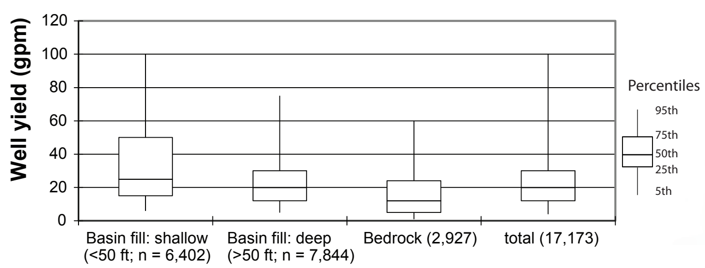

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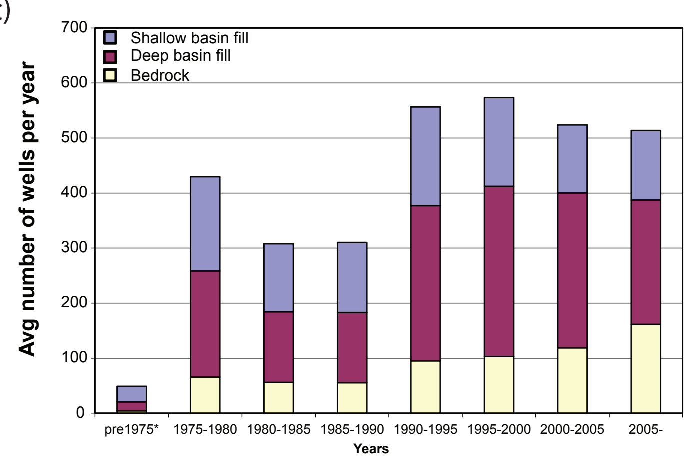


Figure 36. There are records for more than 18,000 wells in the Bitterroot Valley subarea (Bitterroot watershed). (a) The histogram shows the depth water enters vs. number of wells and a pie chart showing relative development by aquifer. (b) Reported yields are greatest in shallow basin-fill aquifers and lowest in bedrock aquifers. (c) Ground-water development (as measured by the number of wells) has increased rapidly since 1970.

terroot Range and Sapphire Mountains and approximately defined by the Bitterroot River's drainage basin boundaries. It is the Lolo-Bitterroot's largest subarea, covers about 2,800 square miles, and is one of the fastest growing regions in Montana. Between 1990 and 2000, the subarea's population (Ravalli County) grew almost 44 percent to about 50,520. Groundwater extracted from basin-fill and fractured bedrock aquifers serves all municipal and domestic uses; the amount of groundwater used to supply irrigation and stock water is relatively minor. Nearly all wells have been constructed within the 6.5 percent of the Bitterroot Valley that is privately owned.

The Bitterroot Range, with peaks of more than 9,000 ft above mean sea level, rises abruptly from the west side of the Bitterroot River Valley floor. The Sapphire Mountains form a less rugged eastern boundary; peaks in the Sapphires are generally between 7,800 and 8,500 ft above mean sea level. The Bitterroot River Valley's land surface elevation rises from about 3,100 ft near Missoula to 3,940 ft above mean sea level at Darby. Near Darby, the Bitterroot River flows northward though a steep-sided valley less than 1 mile wide. Between about 4 miles south of Hamilton and Florence, the valley is about 7 miles wide. The floodplain of the Bitterroot River is flanked by numerous low-relief terraces between 10 and 20 ft above the current river channel. These terraces in turn are flanked by prominent basinward-sloping high "benches" 30 to 300 ft above the adjacent floodplains, low terraces, and nearby valley bottoms (McMurtrey and others, 1972; Briar and Dutton, 2000). Well known "high-bench" examples include the Hamilton Heights and Sunset Benches.

In the Bitterroot Valley most near-surface, recent, alluvial sediments are sand and gravel along floodplains and low-relief stream terraces. Other surficial deposits such as till, glacial-lake deposits, and outwash occur only in localized areas near stream valley mouths along the Bitterroot Range front (see Part B, Map 2). Weakly consolidated Tertiary-age mudstones, sandstones, and local conglomerates are exposed in road and stream cuts at the sides of high benches on the western and eastern valley sides. The contact between the Tertiary-age sand and gravel and overlying alluvium is sometimes difficult to recognize in water well logs. As estimated from geophysical surveys and a few deep water wells, basin-fill deposits are about 3,000 ft thick; the deposits fill two structural subbasins, one centered below Hamilton and the other below Stevensville (see Part B, Map 5).

There are more wells in the Bitterroot Valley subarea than in all the other Lolo-Bitterroot subareas combined (fig. 36a). Most Bitterroot Valley wells are completed in unconsolidated to weakly consolidated shallow (≤50 ft below land surface) and deep (50 to 2,600 ft below land surface) basin-fill aquifers (38 and 45 percent, respectively). Bedrock aquifers on either side of the Bitterroot Valley and in areas south of Darby account for 16 percent of wells. The median depth of all wells is 60 ft. As discussed below and in Part B, Map 8, potentiometric-surface analysis and water-level altitudes show that all aquifers in the subarea are generally connected. Generalized water-level altitudes and directions of groundwater flow for basin-fill and bedrock aquifers in the Bitterroot Valley are shown in Part B, Map 8.

Shallow basin-fill aquifers

Alluvium associated with the Bitterroot River and its tributaries forms a nearly continuous shallow basin-fill aquifer that supplies water to many communities and individuals. Shallow basin-fill aquifers may also cap the high benches on either side of the Bitterroot River Valley where leakage from irrigation practices or other recharge may saturate permeable sand and gravel within about 50 ft of land surface. Groundwater flow in shallow basin-fill aquifers is from local topographic highs toward nearby surface streams; discharge from shallow basin-fill aquifers capping high benches may appear as springs and wetlands along the bench edges.

Yields from shallow basin-fill aquifers are greater than those from other units, but vary more (fig. 36b). The median reported yield from 5,696 wells is 25 gallons per minute (gpm), and the average reported yield is 40 gpm. Yields of more than 100 gpm have been reported for 8 percent (493 wells), but yields of more than 1,000 gpm have been reported for only 8 wells.

Figure 36c shows the annual average number of wells drilled during 5-year periods since 1975. The number of wells drilled into shallow basin-fill aquifers has been steady at about 150 per year since 1990. More than 2,500 wells were completed in shallow basin-fill aquifers between 1990 and mid-2007.

Deep basin-fill aquifers

Coarse-grained basin-fill deposits, generally at depths greater than 50 ft below land surface, form deep basin-fill aquifers that provide significant domestic and stock water supplies within the Bitterroot Valley. Throughout the valley, multiple discontinuous layers of low-permeability silt and clay locally confine discrete water-bearing sand and gravel intervals. The water-bearing intervals locally may have differing groundwater head elevations, suggesting partial hydraulic separation from surrounding materials. On a regional, valley-wide scale, however, head differences are minor and the deep basin-fill aquifers can be considered a single groundwater unit.

Water-level data from the east- and west-side high benches show that important recharge sources to the deep basin-fill aquifer include downward leakage from shallow basin-fill aquifers found along tributary streams entering the basin or that may locally cap high benches along the valley sides, as well as mountain-front recharge from fractured bedrock aquifers surrounding the intermontane basin. The deep basin-fill aquifer's geologic framework, groundwater flow characteristics, and groundwater quality are discussed in detail in Part B, maps 2, 6, 7, 8, 9, and 10.

About 45 percent of wells in the Bitterroot Valley subarea are completed in deep basin-fill, making it the most utilized aquifer (fig. 36a). Most deep basin-fill aquifer completions are located in high-bench areas east and west of the central Bitterroot River valley axis in areas where the shallow basin-fill aquifers may not be available (fig. 36 and Part B, Map 5). The median reported yield for wells completed in the deep basin-fill aquifer is about 20 gpm (fig. 36b); 4 percent (326 wells) have reported yields of greater than or equal to 100 gpm, and 11 wells have reported yields of 1,000 gpm or more.

Prior to 1975, only about 1,200 wells had been completed in the deep basin-fill aquifer. Drilling into this aquifer more than doubled between 1985 and 1990; since 1990, the annual drilling rate has been steady at about 300 wells (fig. 36c).

Bedrock aquifers

Fractures within Belt Supergroup, intrusive granitic, and metamorphic rocks (see fig. 14) in mountainous areas surrounding the Bitterroot River Valley form the bedrock aquifer. The bedrock aquifer's hydraulic character notably differs from that of the basin-fill aquifers; groundwater is stored and transmitted through secondary fractures (see fig. 9), rather than through primary intergranular space (see fig. 13 for example). The rock's fracture density and the degree of interconnection between fractures control the bedrock aquifer's water-bearing properties.

Extensive bedrock aquifer development may eventually be problematic as the relatively low storage available in fractures makes the aquifer more susceptible to impacts by groundwater withdrawals and decreased recharge during dry climate periods (see Part B, Map 8). Additionally, bedrock aquifer fractures that intercept the land surface can act as conduits to transmit surficial contamination to groundwater. Potentiometric and water-quality data show that the bedrock aquifer is in hydraulic connection with the deep basin-fill aquifer (see Part B, Map 8).

The irregular fracture distribution in the bedrock aquifer can make groundwater difficult to locate, as is reflected in the widely varying depths and yields of bedrock aquifer wells. Most bedrock wells are between 50 and 200 ft deep (fig. 36a), although there are 54 wells with reported depths of more than 500 ft. Reported well yields from bedrock are typically lower than for wells completed in the shallow or deep basin-fill aquifers; the maximum reported yield is 300 gpm (as compared to 3,000 gpm in the basin-fill), and the median bedrock aquifer yield is 10 gpm (average 15 gpm; fig. 36b).

The bedrock aquifer has become more utilized in recent years. In 1975, only 320 wells had been completed in bedrock, roughly 9 percent of all wells completed in the Bitterroot Valley. Since 1990, about 20 percent of new wells have been bedrock aquifer completions along the valley perimeter. About 100 wells per year were completed in the bedrock between 1990 and 2005 (fig. 36c). The emergence of the bedrock aquifer as an important groundwater source reflects current interest in developing home sites in the mountainous perimeter surrounding the Bitterroot River Valley.

Missoula Valley

The northwest-trending Missoula Valley subarea contains the towns of Missoula, Frenchtown, Huson, and numerous other small communities (figs. 2, 37). The subarea covers about 105 square miles and had a 2005 population estimated at about 83,000; the subarea experienced a 22 percent population growth between 1990 and 2000 (U.S. Census Bureau data). Groundwater has supplied all municipal, domestic, commercial, and industrial water in the subarea since 1983 when surface-water supplies in the Rattlesnake Creek watershed (City of Missoula public water supply) were found to contain giardia (Mountain Water Company). After the Rattlesnake Creek supply was taken offline, the city of Missoula continued to develop municipal water supplies from sand and gravel zones within basin-fill aquifers.

The Missoula Valley subarea is defined here to include the Miller Creek Valley on the southeast and the Ninemile Valley on the northwest. Mount Jumbo, Mount Sentinel, and Hellgate Canyon border the valley on the east; the Grave Creek Range borders on the southeast, and the Rattlesnake Mountains and Reservation Divide border on the northwest. Altitudes along drainage divides are about 6,500 ft above mean sea level, except in the Rattlesnake Mountains, where some peaks exceed 8,000 ft above mean sea level. The Missoula Valley floor generally slopes to the northwest between the Bitterroot and Clark Fork Rivers.

Shallow basin-fill aquifers in the Missoula Valley and along modern streams include coarse-grained sand and gravel with interbeds of minor silt and clay. The shallow basin-fill aquifers are between 20 and 80 ft thick, but based on driller's lithologic logs, their basal contact with deep basin-fill aquifers can be difficult to determine. Many logs describe clean sand and gravel to about 80 ft below land surface; at this depth there is a transition to primarily clay-rich sand and gravel with relatively few beds of clean sand and gravel. The top of the clay-rich sediments is usually considered to be the base of the shallow basin-fill aquifer (see Part B, maps 2 and 3, and fig. 8). The thinly bedded Glacial Lake Missoula sediments below the shallow basin-fill aquifer were deposited as fine-grained particles settling through the lake's water column.

In the Missoula Valley, Glacial Lake Missoula sediments overlie deep basin-fill aquifer materials deposited at times when Glacial Lake Missoula was drained (Smith, 2006c). The upper part of the deep basin-fill aquifer consists of gravelly alluvium and minor silt at depths between 80 and 200 ft below land surface. Few wells have been drilled through the upper deep basin-fill aquifer materials into more deeply buried deep basin-fill aquifers within Tertiary-age semi-consolidated silt, clay, sandstone, and conglomeritic deposits, or into the bedrock aquifer (Part B, Map 2). Most wells are completed only 10 to 20 ft below the top of the deep basin-fill aquifer.

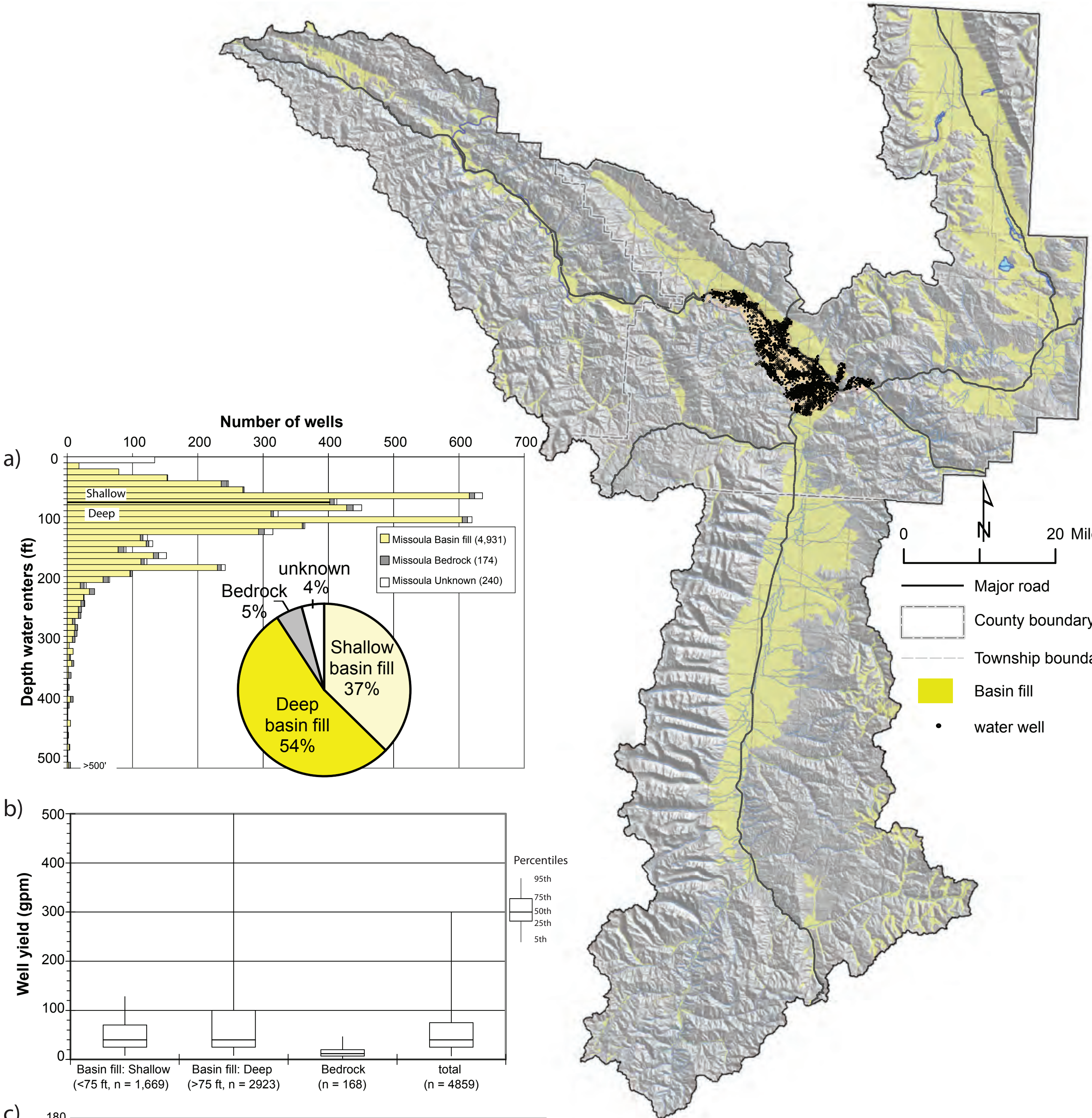
The GWIC database contains records for about 6,000 wells completed in the Missoula Valley subarea; about 5,300 of these wells are completed in the Missoula Valley itself. The remainder are completed in outlying areas, including about 470 wells in the Ninemile Valley. Most wells (91 percent) are completed in unconsolidated deposits (shallow and deep basin-fill aquifers) and about 5 percent are completed in bedrock aquifers. Driller-reported well yields for the unconsolidated sand and gravel units in the Missoula Valley are some of the highest in the Lolo-Bitterroot study area.

Hydrographs from wells completed in the shallow and deep basin-fill aquifers within the Missoula Valley show a seasonal "stream recharge to groundwater" response related to leakage during high flows from the Clark Fork River (Woessner, 1988; Part B, Map 10). Generalized water-level altitudes and directions of groundwater flow for basin-fill aquifers in the Missoula Valley subarea are shown in Part B, Map 6.

Shallow basin-fill aquifers

In the Missoula Valley subarea, 37 percent of wells are completed in shallow basin-fill aquifers (fig. 37a). The median reported yield is 35 gpm; about 75 percent of reported yields exceed 20 gpm, and 25 percent of well logs report yields of greater than 60 gpm (fig. 37b). The median driller-reported yield for shallow basin-fill aquifers in the Ninemile Valley is 20 gpm, about half that of Missoula Valley shallow basin-fill aquifers.

About 40 wells annually were drilled into the shallow basin-fill aquifers between 1990 and 2005



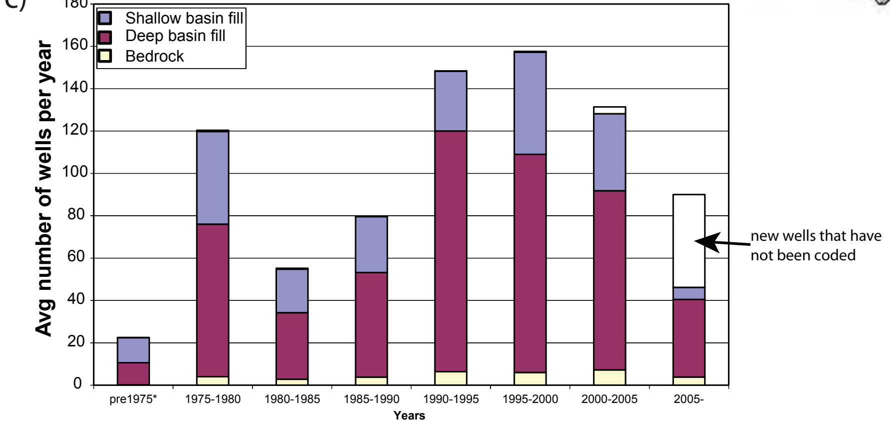


Figure 37. There are records of more than 6,000 wells in the Missoula Valley subarea. The histogram shows the depth water enters vs. number of wells. (a) Most of the wells are completed in shallow and deep basin-fill aquifers (pie chart); (b) the median reported yield for shallow and deep basin-fill aquifers is 40 gpm, greater than any of the other subareas. (c) The rate of well development in the Missoula subarea has slowed since 2000 (bar chart).

(fig. 37c). The rate of shallow basin-fill aquifer development increased beginning in 1980–1985 and appeared to peak in 1995–2000. Since then, the rate of development appears to decline (fig. 37c). The decreased development rate could be related to concerns about potential local contamination of shallow basin-fill aquifers and near-surface groundwater, extension of the Missoula municipal water system into areas previously served by wells, or the desire of many to live outside of the Missoula Valley where shallow basin-fill aquifers are not available.

Deep basin-fill aquifers

Deep basin-fill aquifers underlie almost the entire Missoula Valley, including many areas where Tertiary sedimentary rocks outcrop. Important sources of recharge to deep basin-fill aquifers are leakage from shallow basin-fill aquifers, neighboring mountain range fronts, and leakage from the Clark Fork River downstream of Hellgate Canyon. Overlying silty and clayey Glacial Lake Missoula sediments cause groundwater in most deep basin-fill aquifers to be confined to semi-confined. Groundwater flow is generally toward the west–northwest as shown on potentiometric surface maps contained in Part B, Map 6.

Depending on locations within the Ninemile Valley, alluvial sand and gravel within deep basin-fill aquifers rests on bedrock, Tertiary-age clayey gravel deposits, and some Glacial Lake Missoula silts and clays. The alluvial deep basin-fill aquifer is as much as 150 ft thick near the confluence of Ninemile Creek and the Clark Fork River, but thins rapidly to the northwest up the Ninemile Valley; within a few miles of the confluence, alluvium in the deep basin-fill aquifer is generally less than 50 ft thick, near land surface, and effectively merges with shallow basin-fill aquifers (Part B, Map 3). Most of the deep basin-fill aquifer materials in the Ninemile Valley are partially consolidated Tertiary-age silty sandstones found beneath the alluvial materials.

Fifty-five percent of wells in the Missoula Valley subarea are completed in deep basin-fill aquifers (fig. 37a) and are some of the most productive wells within the Lolo-Bitterroot study area; the median reported yield is 40 gpm (fig. 37b), and 24 percent (735 of the 3,077 wells that have yield information) have reported yields of greater than 100 gpm; 76 wells have reported yields greater than 1,000 gpm. In the Ninemile Valley, wells completed in deep basin-fill aquifers are much less productive, with a median reported yield of 5 gpm. Many of these wells are completed in low-yielding Tertiary-age sediments on the valley's northeastern side.

Since 1990, 90 to 120 wells annually have been drilled into the Missoula Valley subarea's deep basin-fill aquifer (fig. 37c).

Bedrock aquifers

Fractured bedrock aquifers are important in the Missoula Valley subarea near the edges of the Clark Fork River Valley and in the Ninemile, where about 25 percent of wells obtain water from bedrock. Subarea-wide, about 290 wells (5 percent) get water from bedrock aquifers (fig. 37a). Across the subarea, about 60 percent of wells completed in bedrock are more than 150 ft deep and depths vary from about 40 to more than 500 ft.

There are about 10 reported yields of greater than 50 gpm from bedrock-completed wells within the Missoula Valley subarea; the median bedrock-aquifer yield is 10 gpm (fig 37b). Ninety-five percent of bedrock-completed wells produce less than 40 gpm. If the Ninemile is excluded, Missoula Valley subarea bedrock wells have a driller-reported median yield of 12 gpm, and about 25 percent of wells produce more than 20 gpm. In comparison, the median yield for bedrock wells in the Ninemile is 4 gpm, and only about 5 percent produce more than 20 gpm (fig. 37b).

Annual construction of new wells in the bedrock aquifer increased between 1980 and 1990 and then remained steady between 1990 and 2005 at about 10 wells per year. Since 1990, bedrock wells in the Ninemile Valley make up about one-third of all wells drilled, which represents development in the foothills surrounding the valley.

Seeley–Swan

The Seeley–Swan subarea includes the southern Swan Valley, drained by the north-flowing Swan River, and the Seeley/Placid Lake region, characterized by a series of lakes along the Clearwater River drainage (figs. 2, 38). The eastern edge of the subarea is marked by the Swan Mountains that abruptly rise as much as 4,000 ft from the valley floor. In the southern Swan Valley, the Mission Mountains define the subarea's western edge; west of the Seeley/Placid Lake region relatively low-relief mountains with peaks between 4,500 and 5,500 ft above mean sea level separate the Seeley–Swan subarea from the Potomac and Missoula Valley subareas. The largest community in the subarea is Seeley Lake.

The sculpted land surface south of the Swan/Clearwater River drainage divide shows typical evidence of south-to-north movement of glacial ice; deglaciation left extensive but relatively thin deposits of till and outwash that rest on older alluvial materials and some Tertiary-age rocks (fig. 39). In the Placid Lake area and the adjacent Clearwater River drainage, multiple bedrock exposures at land surface and some drillhole data indicate that the glacial, alluvial, and Tertiary-age deposits are relatively thin and bedrock is mostly within 300 ft of land surface (fig. 39). Ten to 200 ft of till and gravel, and a northward-thickening section of Tertiary-age rocks, underlie the southern Swan River Valley (Part B, maps 2 and 4).

Shallow basin-fill, deep basin-fill, and bedrock aquifers

The glacial deposits, alluvial sand and gravel, and Tertiary-age rocks host shallow and deep basin-fill aquifers that provide water to almost 80 percent of the 1,220 wells drilled in the Seeley–Swan subarea. In the southern Swan Valley, shallow basin-fill aquifers serve about half of the wells, deep basin-fill aquifers provide water to another 40 percent, and bedrock aquifers serve the remainder (fig. 38a). In the Seeley/Placid Lake region, the percentage of deep basin-fill completions is similar to that in the southern Swan Valley, but shallow basin-fill aquifers (aquifer materials at less than 75 ft below ground surface) account for only 25 percent of well completions. Because glacial, alluvial, and Tertiary-age deposits are relatively thin and bedrock is near land surface at many locations (fig. 39), about 30 percent of wells in the Seeley/Placid Lake region are completed in bedrock aquifers, making it an important source of water. Generalized water-level altitudes and directions of groundwater flow for basin-fill aquifers near the Seeley–Swan subarea are shown in Part B, Map 6.

Median reported well yields for shallow and deep basin-fill in the southern Swan Valley and the Seeley/Placid Lake regions vary from 12 to 20 gpm (fig. 38b). About 75 percent of Seeley–Swan subarea shallow basin-fill aquifer wells produce less than 30 gpm, but wells in shallow basin-fill in the Seeley/Placid Lake region are more likely to produce smaller yields; 75 percent of wells in the southern Swan shallow basin-fill produce more than 12 gpm, but 75 percent of wells in the Seeley/Placid Lake region produce more than 8 gpm (fig. 38b). Only 4 percent of wells in the Seeley–Swan subarea basin-fill aquifers are more than 250 ft deep.

Median yields from bedrock aquifers in the southern Swan Valley and Seeley/Placid Lake region are 10 and 11 gpm, respectively (fig 38b). In both areas, 75 percent of bedrock aquifer wells produce less than 20 gpm and 25 percent produce less than 7 gpm. Because water production from bedrock aquifers depends on fracture density and interconnection, the potential for non-productive wells is greater than that for the basin-fill aquifers. About 25 percent of bedrock aquifer wells are more than 250 ft deep.

Between 1990 and 2005, well-completion rates increased in all aquifers, but more than doubled in bedrock aquifers between 1995 and 2000 (fig. 38c). Increased bedrock-aquifer usage signifies the expansion of subdivisions into mountainous regions, particularly in the Seeley/Placid Lake region.

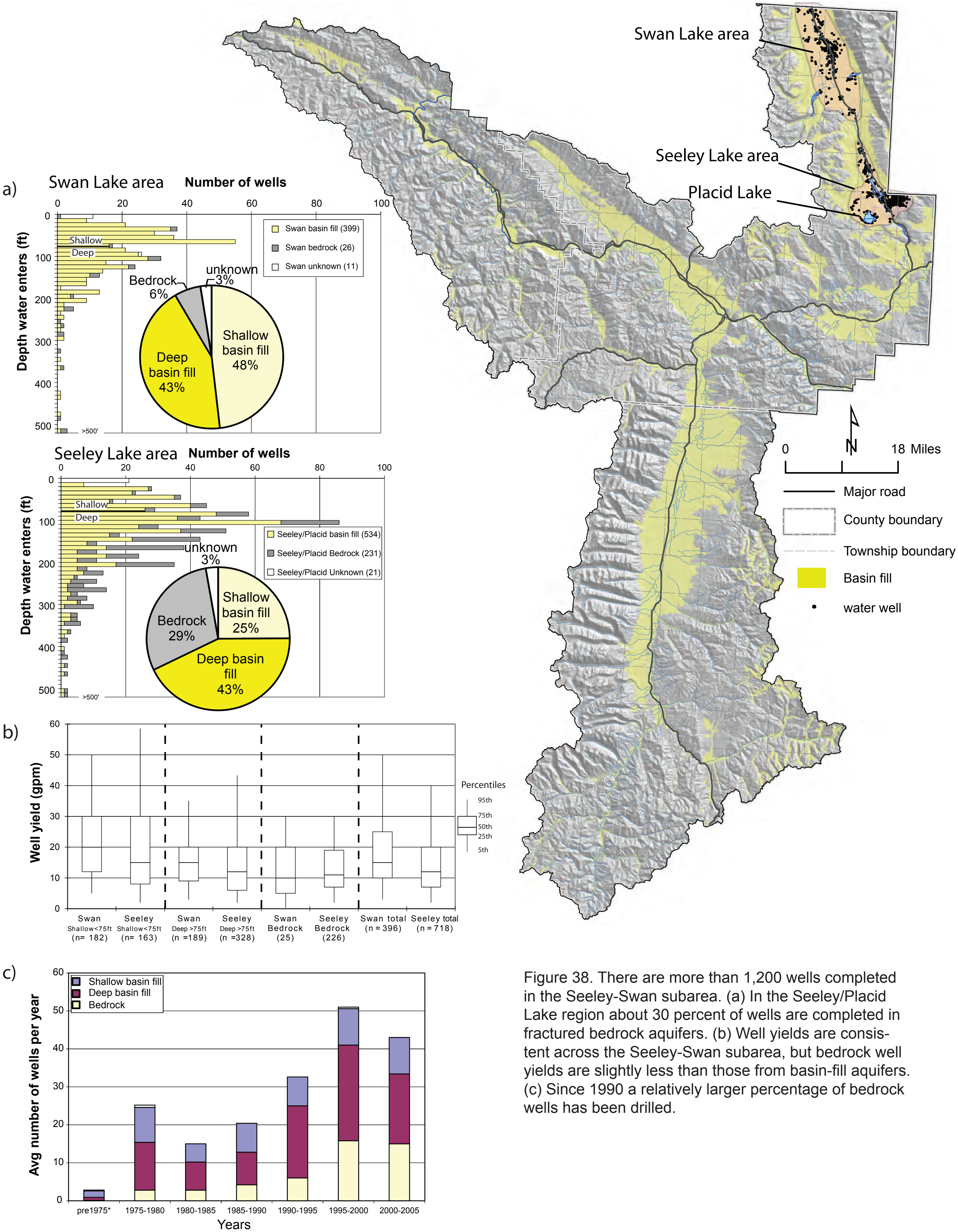
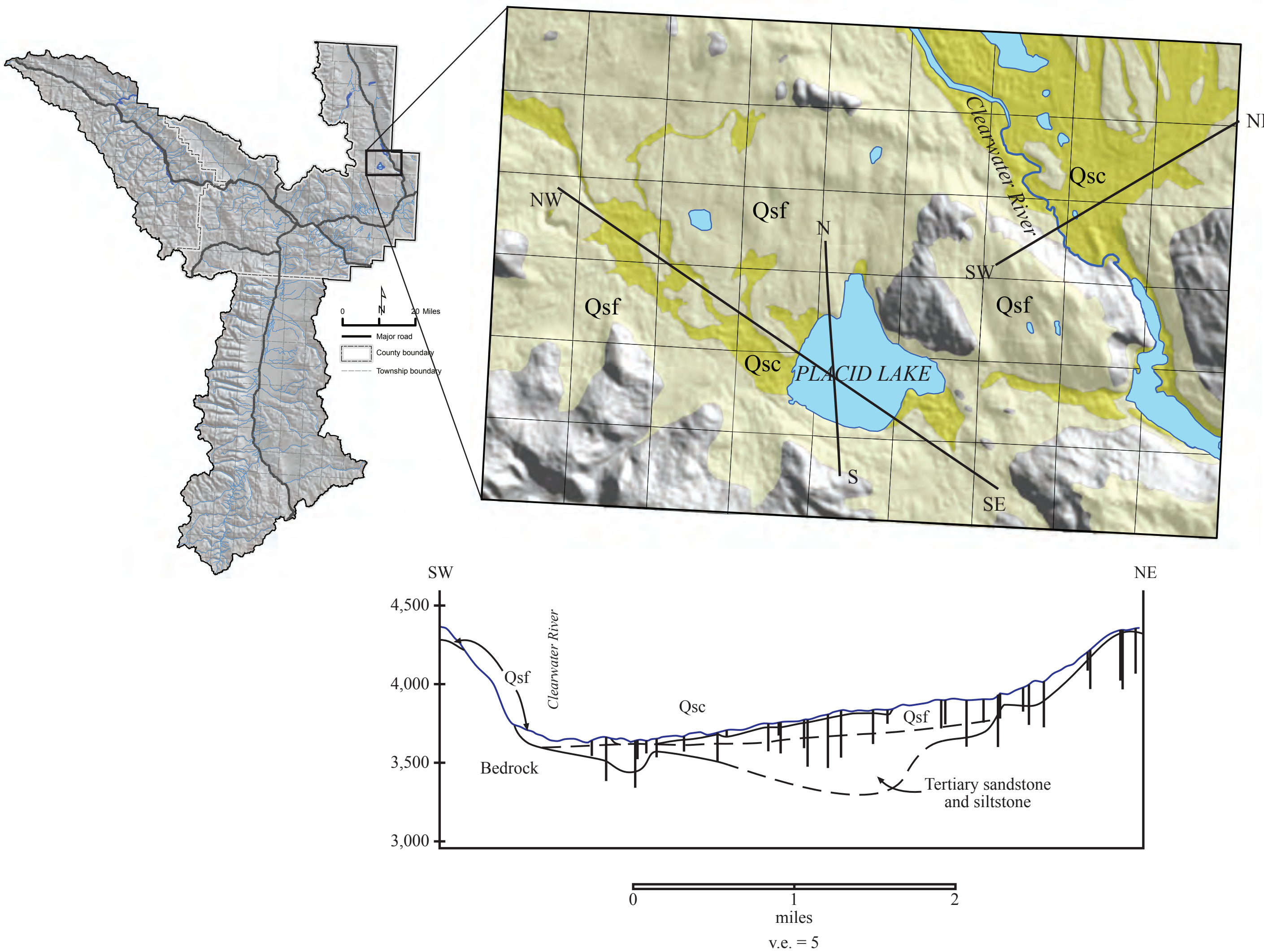


Figure 38. There are more than 1,200 wells completed in the Seeley-Swan subarea. (a) In the Seeley/Placid Lake region about 30 percent of wells are completed in fractured bedrock aquifers. (b) Well yields are consistent across the Seeley-Swan subarea, but bedrock well yields are slightly less than those from basin-fill aquifers. (c) Since 1990 a relatively larger percentage of bedrock wells has been drilled.



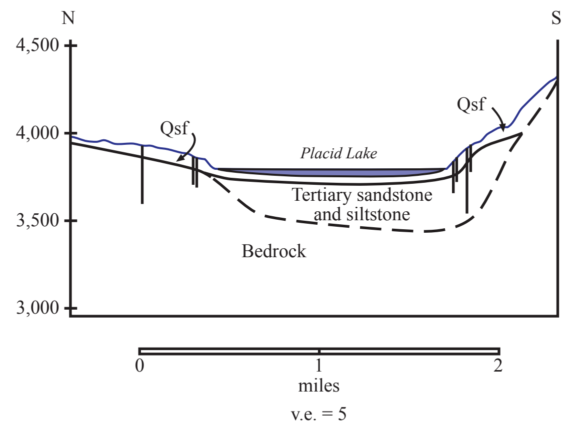
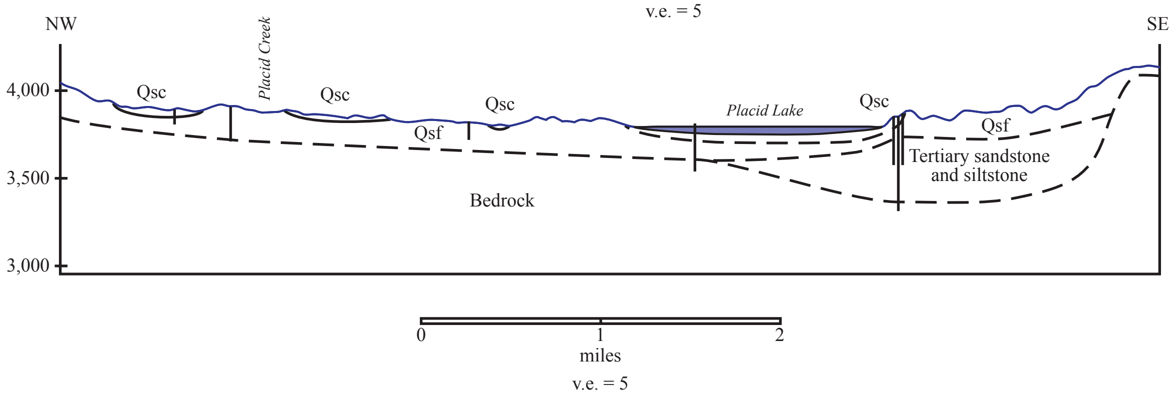


Figure 39. In the Seeley/Placid Lake region fine-grained till (Qsf) and coarse-grained alluvium (Qsc) directly overlie Tertiary-age basin-fill or bedrock aquifers. In this area the bedrock is generally within 300 ft of the land surface and is an important aquifer.



Canyons

The Canyons subarea includes the Clark Fork River canyon upstream to the Granite County line and Blackfoot River canyon upstream to the Potomac Valley (figs. 2, 40), but excludes the Clark Fork River Valley near St. Regis. The Canyons subarea includes segments of populated side-drainage valleys near the Clark Fork River, including much of the Petty Creek drainage, south of Alberton.

The Clark Fork River canyon floor upstream of East Missoula contains about 50 ft of unconsolidated sand and gravel that becomes as much as 200 ft thick between Turah and East Missoula. The valley-fill is about 50 ft thick near Milltown on the Blackfoot River, but thins rapidly to almost nothing immediately upstream at Bonner (Part B, Map 3).

The Clark Fork River Valley floor, downstream from the river's confluence with Ninemile Creek, is between 0.3 and 2 miles wide and is underlain by up to 450 ft of unconsolidated silt, sand, and gravel. Within the canyon are gently sloping uplands that accommodate agriculture and residential development, bedrock knobs, and terrace surfaces. The Clark Fork River flows across bedrock along about 40 percent of its valley; in other areas, surficial sediments cover the canyon floor (Lewis, 1998; Lonn and McFaddan, 1999; Lonn and others, 2007). Gravelly alluvium occurs along floodplains, beneath stream terraces, and at depth beneath silt and clay deposits. The bench-forming sequences of laminated silt, clay, and minor sand deposits have been widely recognized as Glacial Lake Missoula deposits.

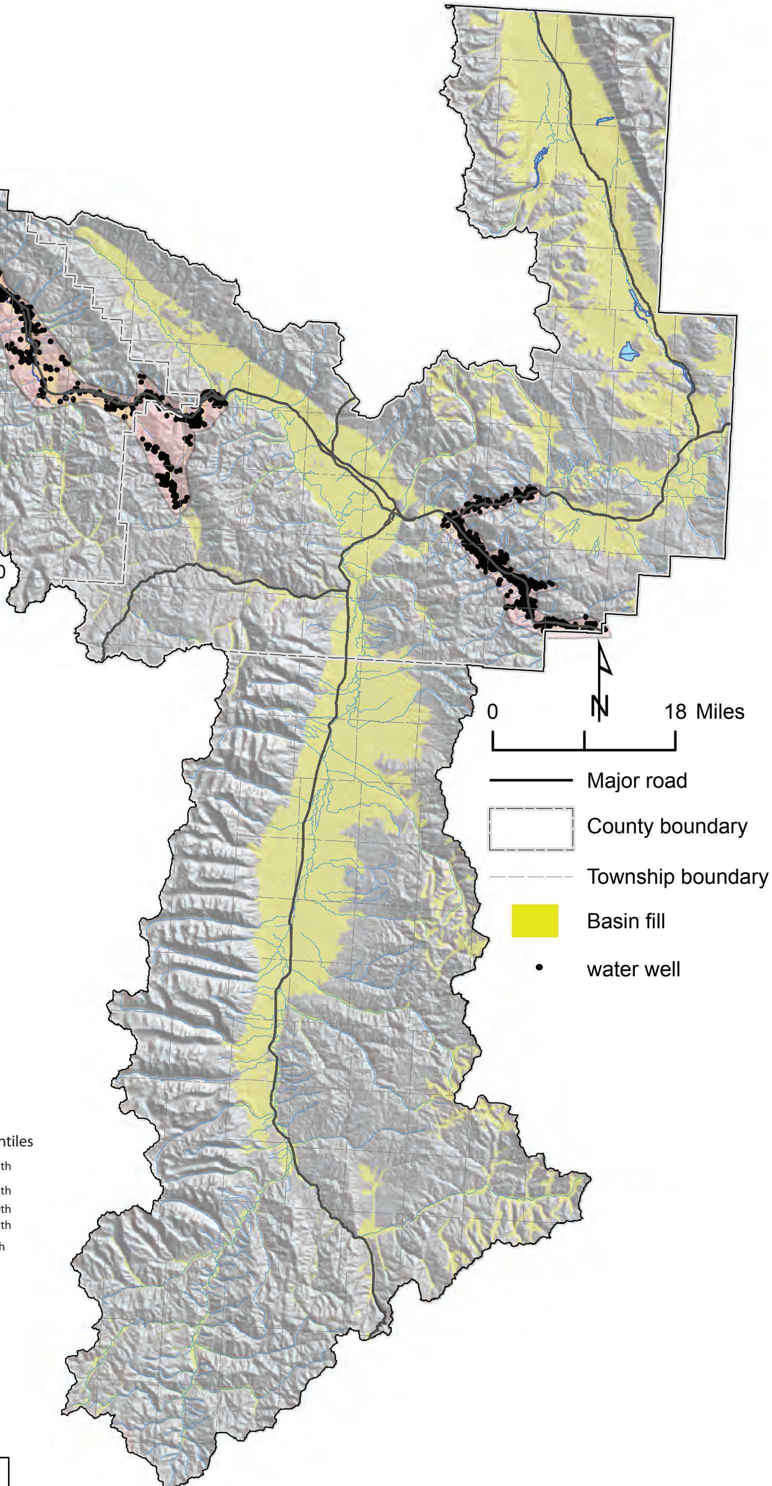
Regional geologic mapping in the Canyons subarea shows that segments of the thick basin-fill gravelly alluvium were deposited as gravel bar segments downstream of narrow gorges in the Clark Fork River canyon, such as near Tarkio below the Alberton gorge. Large-scale cross-stratification, block-sized boulders, and the large-scale gravel bars indicate that much of the alluvium along the Clark Fork River was deposited by high-velocity, high-discharge flows during Glacial Lake Missoula drainage events (Smith, 2006c). The well-sorted, coarse-grained gravels host productive aquifers.

Shallow basin-fill, deep basin-fill, and bedrock aquifers

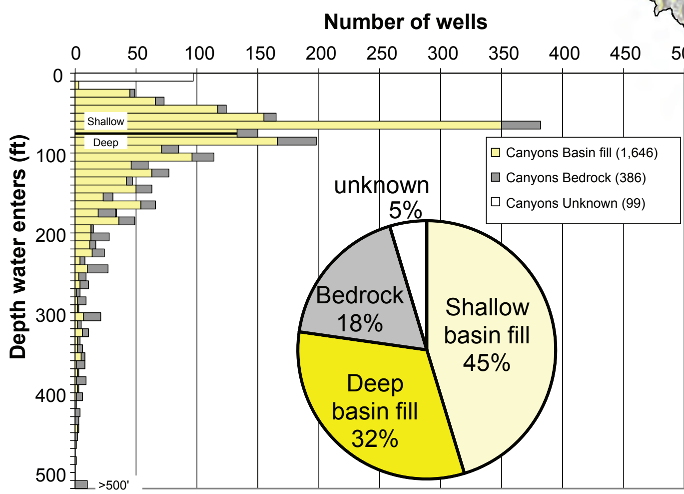
Shallow basin-fill aquifers (≤80 ft below land surface) occur where the Clark Fork River is less incised, such as near Clinton and Superior, and where stream terraces are near the river and its tributaries. Shallow basin-fill aquifers account for 43 percent of the subarea's 2,200 wells; wells in deep basin-fill aquifers total 34 percent (fig. 40a). Median reported yields from the shallow and deep basin-fill are 30 gpm, making basin-fill aquifers in the Canyons subarea among the Lolo-Bitterroot's most productive (fig. 40b); reported yields for 10 percent of the shallow basin-fill wells (78 wells) and 6 percent of the deep basin-fill wells (44 wells) were greater than 100 gpm. Reported yields for six basin-fill aquifer well completions were greater than 1,000 gpm. Generalized water-level altitudes and directions of groundwater flow for basin-fill aquifers in the Canyons subarea are shown in Part B, Map 6.

About 18 percent of wells (386 wells) in the Canyons subarea were completed in fractured bedrock aquifers (fig. 40a). Bedrock well depths vary widely but have a median depth of 150 ft and a maximum depth of 760 ft. The bedrock is much less productive than the basin-fill aquifers; reported yields have a median of only 7 gpm, and only 1 percent (4 wells) report yields >100 gpm (fig. 40).

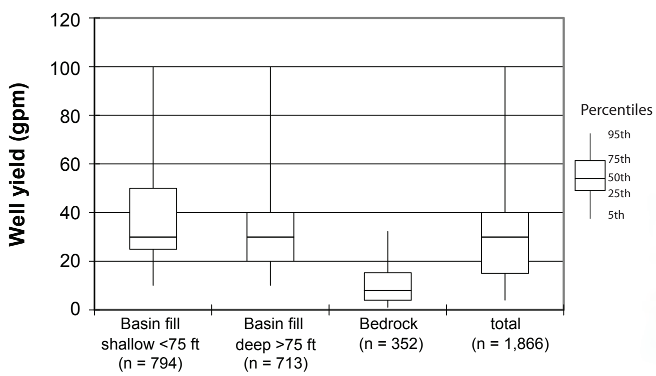
Well development in the Canyons subarea increased from the 1980s to the 1990s; however, a significant number of wells (37 percent) pre-date 1980, indicating the long-term settlement in the subarea, especially in areas with shallow groundwater supplies.



a)



b)



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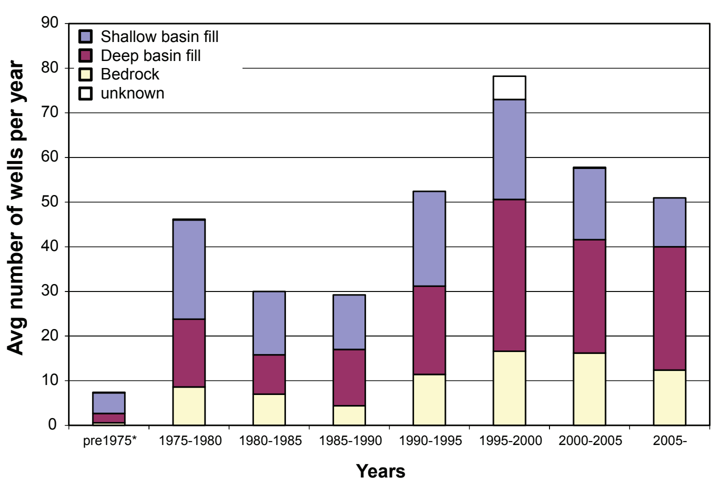


Figure 40. There are more than 1,200 wells completed in the Canyons subarea. (a) Most of the wells are completed in the shallow alluvium. (b) The median reported yield (30 gpm) from shallow and deep basin-fill aquifers is considerably greater than that of bedrock aquifers (8 gpm). (c) A relatively larger percentage of wells have been drilled in the deep and bedrock aquifers since 2000.

Potomac

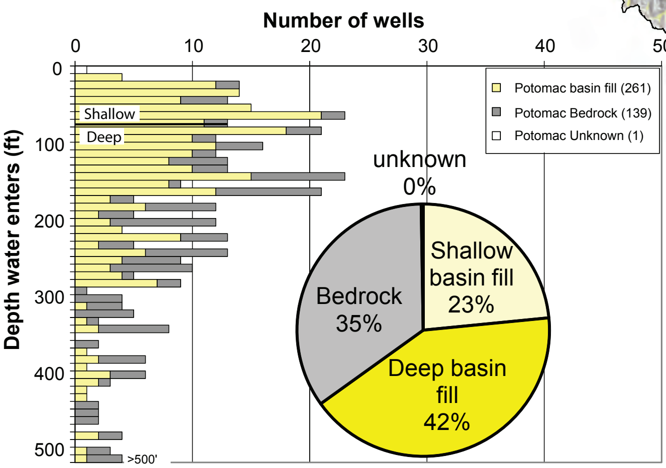
The Potomac subarea lies in a small intermontane basin about 15 miles west of Milltown, on state Highway 200. The area is unincorporated, supports several large agricultural operations, and serves as a bedroom community for Missoula. In the Potomac subarea (figs. 2, 41), up to 30 ft of alluvial deposits overlie several hundred feet of Tertiary-age siltstones and minor sandstones. The Tertiary-age rocks thicken from south to north. Water wells are completed in shallow basin-fill and deep basin-fill aquifers in the partially consolidated Tertiary-age sedimentary rocks, as well as bedrock aquifers within the adjacent uplands. Because many wells have been drilled through the Tertiary-age sediments into the bedrock, the thickness of unconsolidated to semi-consolidated basin-fill above bedrock is better known in the Potomac subarea than in the other subareas that include large intermontane valleys (Part B, Map 4).

Shallow basin-fill, deep basin-fill, and bedrock aquifers

Shallow basin-fill, deep basin-fill, and bedrock aquifers all provide water to wells within the Potomac subarea (fig. 41). About 23 percent of the wells are completed in shallow basin-fill aquifers at depths below about 80 ft below land surface (fig. 41a). The number of wells completed in deep basin-fill and bedrock aquifers is approximately equal (fig. 41a); wells completed in deep basin-fill aquifers have a median depth of 200 ft and wells completed in bedrock aquifers have a median depth of 260 ft. Generalized water-level altitudes and directions of groundwater flow for basin-fill aquifers in the Potomac subarea are shown in Part B, Map 6.

The shallow basin-fill aquifers are the most productive, with a median reported yield of 15 gpm (fig. 41b). The median reported yield for deep basin-fill aquifers is 9 gpm, which is similar to the 10 gpm median for bedrock aquifer wells (fig. 41b).

The number of wells has increased since 1990 due to residential development (fig. 41c). New bedrock-aquifer development has resulted in 10–15 wells per year, reportedly all for domestic use.

a)


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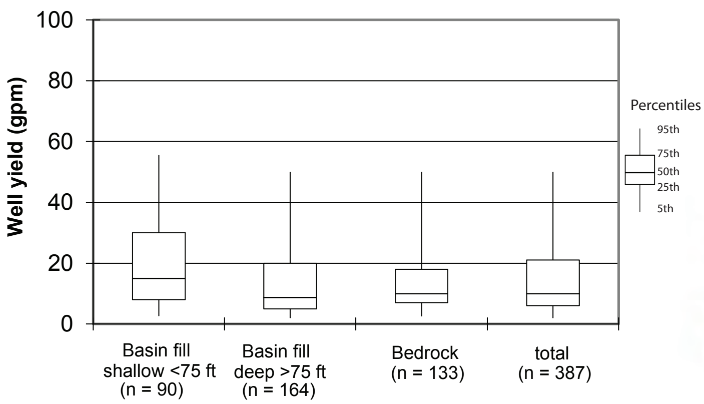

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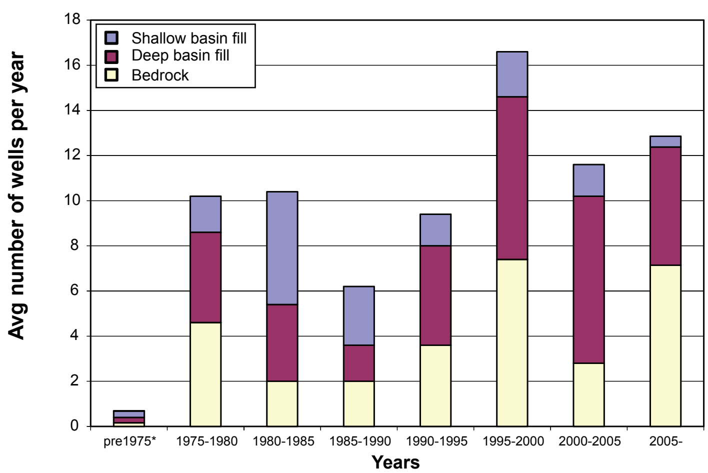


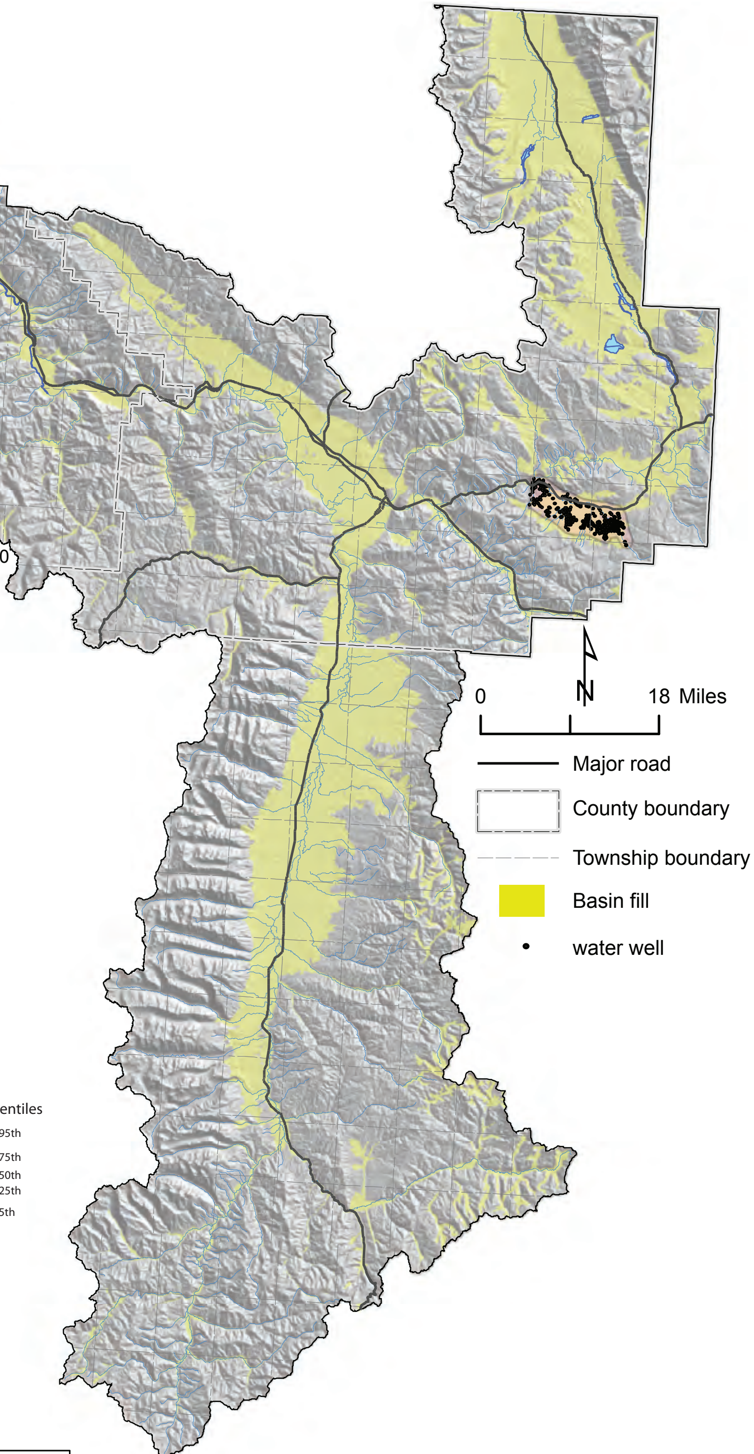


Figure 41. There are more than 400 wells in the Potomac subarea. (a) Most wells are completed in deep basin-fill and bedrock aquifers. (b) The reported yields are similar for each subarea aquifer but generally lower than yields from similar aquifers in the other subareas. (c) Most wells drilled since 2000 have been completed in deep basin-fill and bedrock aquifers.

St. Regis

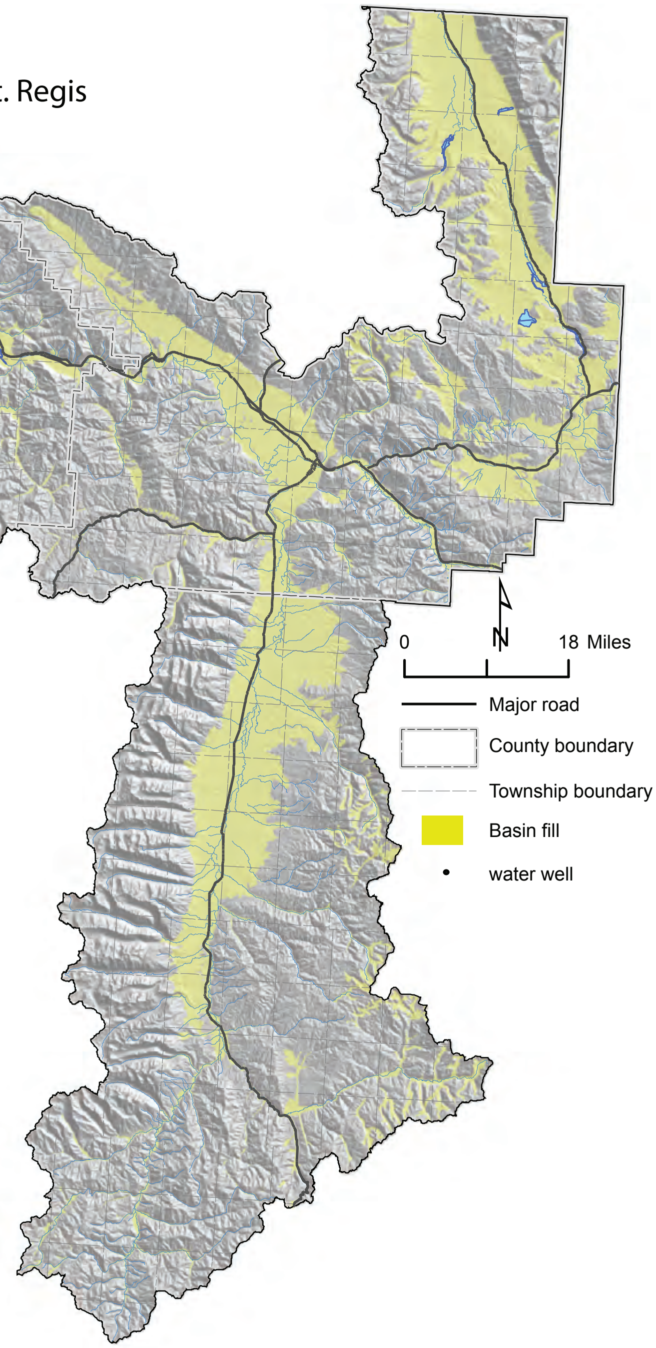
The St. Regis subarea is located at the confluence of the Clark Fork and St. Regis Rivers (figs. 2, 42). The area covers only about 19 mi^2; it is bounded on the south by mountainous uplands cored by complexly folded and faulted Precambrian Belt bedrock. At St. Regis, the Clark Fork River leaves the fault-controlled valley it has been following northwest of Alberton and turns to the northeast, and then east before joining the Flathead River at Paradise, Montana. For about 5 miles up and downstream along the south side of the Clark Fork River, a narrow wedge of Tertiary-age deposits consisting of sandstone, conglomerate, and siltstone are near land surface (Part B, Map 2). These sediments were deposited by the ancient Clark Fork River system and dip northeastward into the trace of the Boyd Mountain Fault (Lonn and McFaddan, 1999). Tertiary-age deposits of composition similar to those near St. Regis are shown in figure 10.

In the St. Regis subarea, driller logs show that Tertiary-age deposits are covered by up to 200 ft of gravelly alluvium and laminated silt and clay deposited by Glacial Lake Missoula (Part B, Map 4 and Part B, Map 2). Shallow and deep basin-fill aquifers occur in the Quaternary-age gravelly alluvium and Tertiary-age sandstone and conglomerate.

Shallow basin-fill, deep basin-fill, and bedrock aquifers

Wells in the St. Regis subarea are mostly completed in the productive basin-fill aquifers (fig. 42a). Shallow basin-fill aquifers in the Clark Fork River Valley alluvium account for 30 percent of wells. Their median reported yield is 30 gpm (fig. 42b); 10 percent of wells (7 wells) have reported yields greater than 100 gpm. About 60 percent of wells are completed in productive deep basin-fill aquifers and have a median reported yield of 41 gpm; 26 wells (21 percent) have reported yields greater than 100 gpm, and 5 wells have reported yields greater than 1,000 gpm (fig. 42b). Generalized water-level altitudes and directions of groundwater flow for basin-fill aquifers near St. Regis are shown in Part B, Map 6. Wells completed in the deep basin-fill Tertiary-age sandstones and conglomerates are typically confined and have static water levels near ground surface or produce artesian flow.

A small percentage of wells in the St. Regis subarea (5 percent) are completed in fractured bedrock, mostly north of St. Regis, and near bedrock outcrops. Reported well yields are low; the median is 7 gpm. Well drilling in the subarea has remained steady from 1975 to 2005, with about 4 to 5 wells being drilled annually (fig. 42c). In 2005, deep basin-fill aquifers were the most common completion target.



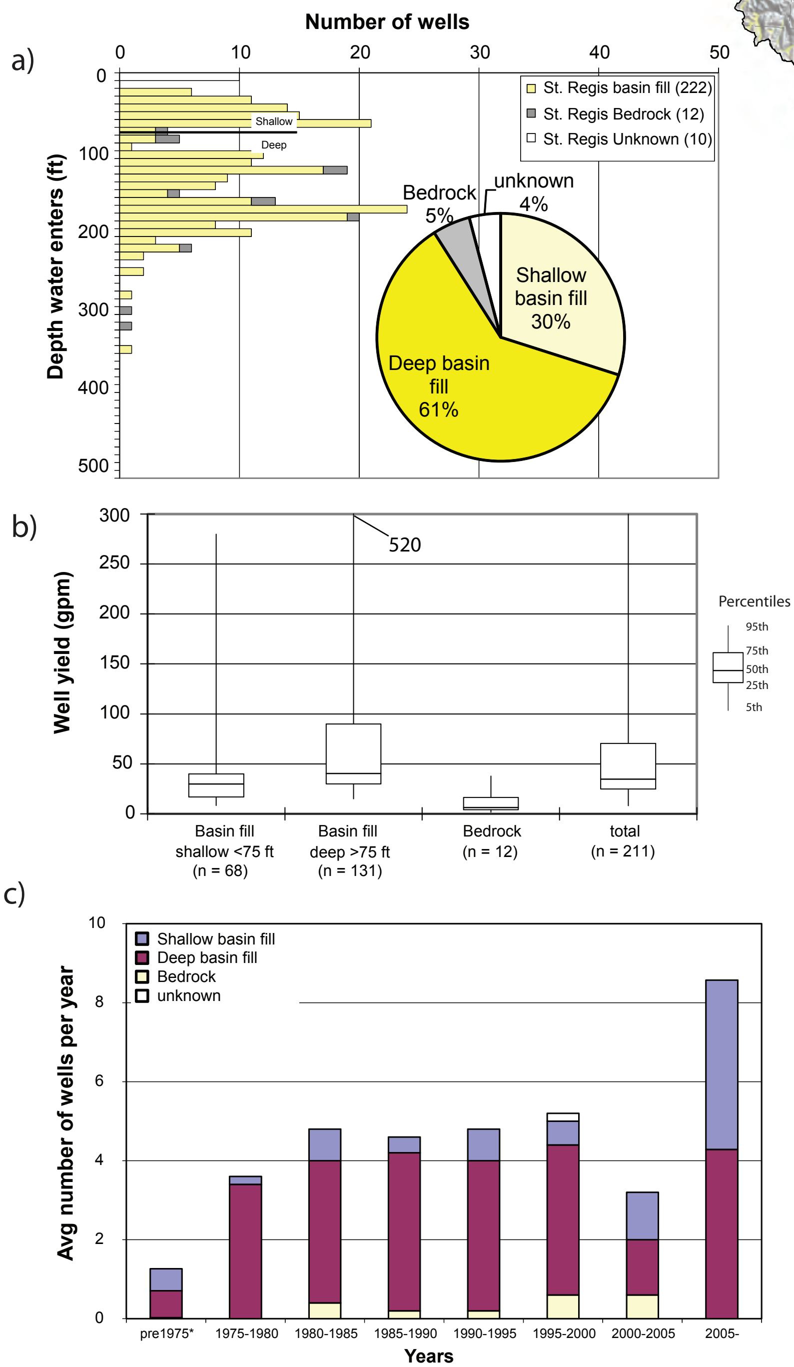


Figure 42. St. Regis is the smallest subarea. (a) Most wells are completed in productive deep basin-fill aquifers. (b) The median reported well yield for deep basin-fill aquifers is 40 gpm, with several wells reporting yields greater than 1,000 gpm.

Mountains

About 2,550 mi^2 within the Lolo-Bitterroot groundwater assessment area, not included in the already named subareas, is called the Mountains subarea. The subarea's 1,300 wells are mostly in mountainous valleys drained by Clark Fork River tributaries upgradient of the Missoula, Canyons, and St. Regis subareas. The area also includes the Blackfoot River drainage between the Potomac and Seeley–Swan subareas (fig. 2). Surficial sand and gravel and Tertiary-age basin-fill sediments occur in valley bottoms; bedrock aquifers are found primarily in Belt bedrock in the upland areas. Based on driller logs, basin-fill materials have a median thickness of 62 ft; however, at some locations their thickness exceeds 500 ft (fig. 43a).

Shallow basin-fill, deep basin-fill, and bedrock aquifers

Wells in the Mountains subarea are completed nearly equally among the shallow and deep basin-fill and bedrock aquifers (fig. 43a). Wells in shallow basin-fill aquifers have a median reported yield of 20 gpm, with 19 wells (4 percent) reported to produce more than 100 gpm. Wells in deep basin-fill aquifers had a median reported yield of 15 gpm and 15 wells (5 percent) had reported yields of more than 100 gpm. The median yield from fractured bedrock aquifers was 9 gpm (fig. 43). Well development in the Mountains subarea has doubled between 1990 and 2005 (fig. 43c). Well completions increasingly favor fractured bedrock aquifers as residential development of mountain front and mountain locations continues.

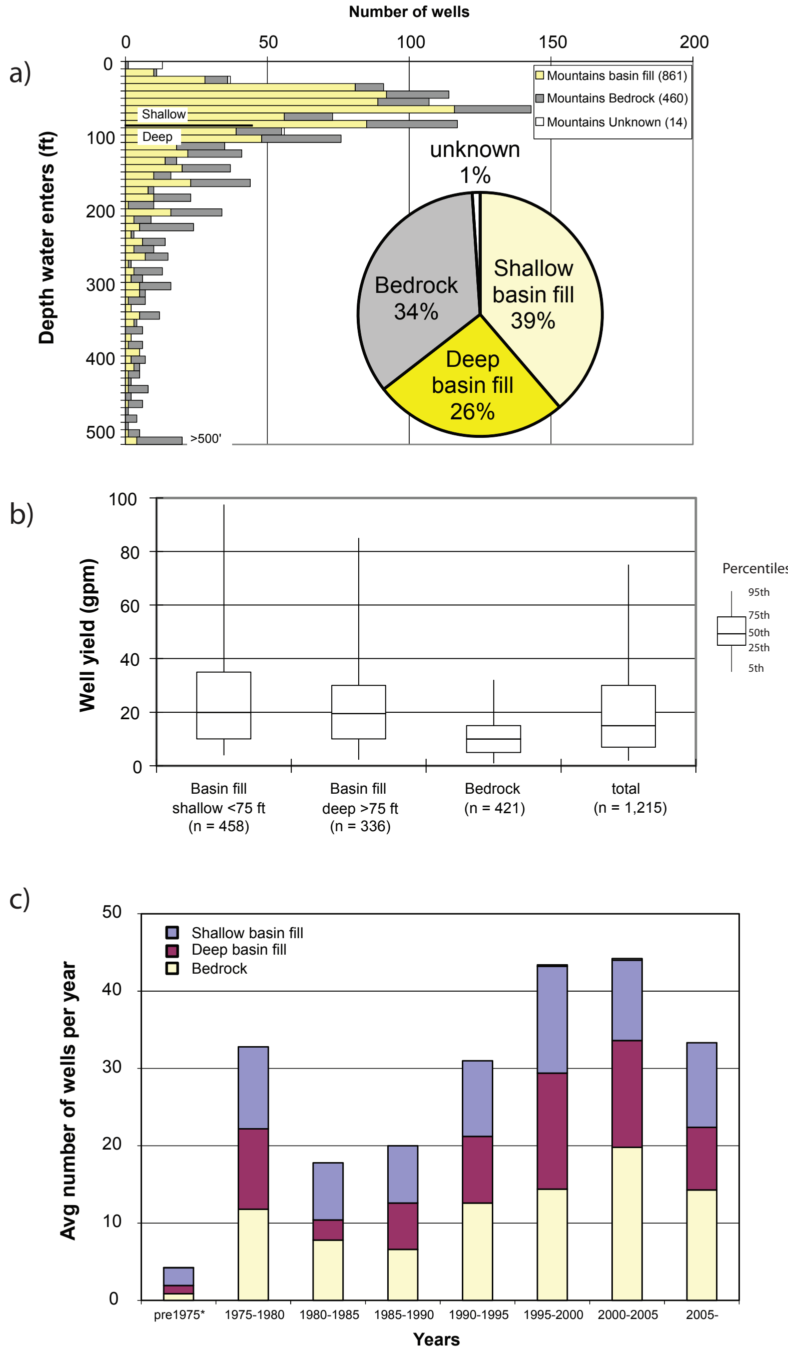


Figure 43. There are more than 1,300 wells at scattered locations within the Mountains subarea. Well development has been evenly distributed among shallow basin-fill, deep basin-fill, and bedrock aquifers. The median reported yield for wells completed in the shallow and deep basin-fill aquifers is 20 gpm; the median reported yield for the bedrock wells is 10 gpm. Since 2000, a greater relative percentage of wells have been completed in fractured bedrock aquifers.

LOLO-BITTERROOT AREA SUMMARY

Sources of groundwater in the Lolo-Bitterroot area are unconsolidated to semi-consolidated basin-fill deposits within the major valleys, and fractured bedrock along valley perimeters and in mountainous areas. The unconsolidated deposits consist primarily of Pleistocene and Holocene alluvium along modern stream valleys (fig. 14). Near-surface and deeply buried unconsolidated to semi-consolidated Tertiary-age sediments are locally important basin-fill aquifers.

Unconfined shallow basin-fill aquifers, generally <75–80 ft below land surface, are present in most Lolo-Bitterroot subareas and supply water to 34 percent of the assessment area's wells. Shallow basin-fill aquifers include the alluvium along the Bitterroot River, the Missoula Valley aquifer, and alluvium along the Clark Fork River and its tributaries. Driller-reported well yields in shallow basin-fill aquifers reportedly can be more than 1,000 gpm (the median yield is 25 gpm); however, these aquifers are often susceptible to surface sources of contamination and can be sensitive to wet/dry climate cycles.

Deep basin-fill aquifers occur in sand and gravel deposits at depths >75–80 ft below land surface. Based on the wells drilled to date, deep basin-fill aquifers in the Missoula Valley and St. Regis subareas are the most productive groundwater sources within the Lolo-Bitterroot area. The deep alluvial aquifers are as much as 200 ft thick in the Missoula Valley and St. Regis subareas and more than 2,000 ft thick in the Bitterroot Valley subarea. Reported well yields from deep alluvial aquifers are as great as 1,000 gpm, but the median yield is 25 gpm.

Bedrock, almost entirely made up of the Belt Supergroup and a few intrusive igneous rocks, forms the mountains that frame the valleys and underlie the basin-fill deposits. The bedrock is an aquifer because it generally contains sufficient fracture permeability to yield water to wells. However, the yields are variable due to irregular fracture distribution and differing fracture permeability. Therefore, groundwater availability in the bedrock can be unpredictable; well depths and yields can vary widely across short distances. In the Lolo-Bitterroot area, reported well yields from bedrock aquifers are generally lower than in basin-fill aquifers; they range from less than 1 to 400 gpm, with a median yield of 8 gpm. Well depths in bedrock aquifers can exceed 2,400 ft; the median depth is 180 ft.

Since the 1980s the number of wells drilled into fractured bedrock has steadily increased. There are about 6,700 productive bedrock aquifer wells; most (60 percent) have been installed since January 1990. The emergence of the fractured bedrock as an important aquifer results from residential development in mountainous areas and along valley margins.

Water Quality

Groundwater in the Lolo-Bitterroot area is of high quality and is generally suitable for domestic consumption, crop irrigation, and most other uses. There is little discernible difference in the water chemistry among shallow basin-fill, deep basin-fill, and bedrock aquifers. The TDS of groundwater samples from all aquifers was generally less than 500 mg/L; the median TDS concentration in samples evaluated for this study was 146 mg/L. Only 4 percent of the water samples (11 of 305) exceeded the SMCL for TDS. In general, the shallow basin-fill aquifer had the lowest, fractured bedrock the highest, and the deep basin-fill aquifers intermediate TDS concentrations. The major ions in solution are calcium, bicarbonate, and sodium. Exceedances of the iron SMCL in 7 percent of the samples (21) and of the manganese SMCL in 8 percent of the samples (25) is associated with reducing conditions in some of the deep basin-fill aquifers.

Nitrate concentrations in groundwater were generally low. The MCL of 10 mg/L was exceeded in only 3 of the 386 samples collected for this study. Of the sites producing groundwater with nitrate concentrations greater than 2 mg/L, suggesting surface impacts, 18 samples were from shallow basin-fill wells, 16 were from deep basin-fill wells, and 8 were from bedrock wells. Concentrations of chloride, likely derived from human-caused surface contamination, exceeded the SMCL for public drinking water supplies in two samples.

Arsenic was detected in 33 percent of samples, and concentrations exceeded the 10 µg/L MCL in 8 samples. Elevated arsenic was detected in a cluster of samples from wells in the Bitterroot Valley adjacent to the Willow Creek and Skalkaho igneous plutons near Corvallis. A few samples with elevated arsenic also occurred in the north part of the Missoula Valley and in the lower Ninemile Valley.

Selected groundwater samples from the shallow and deep basin-fill and bedrock aquifers were analyzed for tritium. Tritium was detected at concentrations indicative of recent recharge (less than 50 years) in all the samples from the shallow basin-fill aquifers, and in about 75 percent of the samples from deep basin-fill aquifers in the Missoula Valley and Bitterroot Valley subareas. All deep basin-fill samples from the Canyons subarea contained tritium. The deep basin-fill samples in the Seeley Lake area contained submodern (greater than 50 years old) water, indicating relative isolation from modern recharge. Samples from the bedrock aquifers were nearly evenly split between submodern and modern water. In general, deep wells were more likely to produce submodern water.

ACKNOWLEDGMENTS

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GLOSSARY

(Modified from Gary and others, 1972)

Alluvium Sand, gravel, outwash, silt, or clay deposited during recent geological time by a stream or other form of running water.

Anion See Ion.

Aquifer Geologic materials that have sufficient permeability to yield usable quantities of water to wells and springs. Spaces between the sedimentary grains (pore spaces) or openings along fractures provide the volume (porosity) that stores and transmits water within aquifers (fig. G-1). Aquifers are either unconfined or confined. The water table forms the upper surface of an unconfined aquifer; below the water table the pore spaces of the aquifer are completely water-saturated. A layer of low-permeability material such as clay or shale marks the upper surface of a confined aquifer. This low-permeability layer is called the confining unit. Below the confining unit the aquifer is completely saturated and the water is under pressure (fig. G-2).

Artesian Aquifer An artesian or confined aquifer contains water that is under pressure. To be classified as artesian, the pressure must be adequate to cause the water level in a well to rise above the top of the aquifer (fig. G-2). Flowing wells, or flowing artesian conditions, occur in areas where the potentiometric surface is higher than the land surface (fig. G-3).

Bedrock A general term for consolidated geologic material (rock) that underlies soil or other unconsolidated material.

Carbon-14 A naturally occurring radioactive isotope of carbon, denoted as ^{14}C, with a half-life of 5,730 years. ^{14}C, with six protons and eight neutrons, is heavy compared with the most common isotope of carbon (^{12}C); see Environmental isotopes.

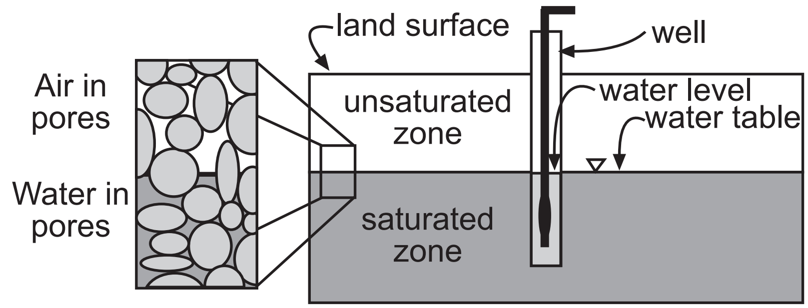


Figure G-1. In the unsaturated zone the pores (openings between grains of sand, silt, and clay and cracks within rocks) contain air and water. In the saturated zone the pores are completely filled with water. The water table is the upper surface of the saturated zone. Wells completed in unconfined aquifers are commonly referred to as water-table wells.

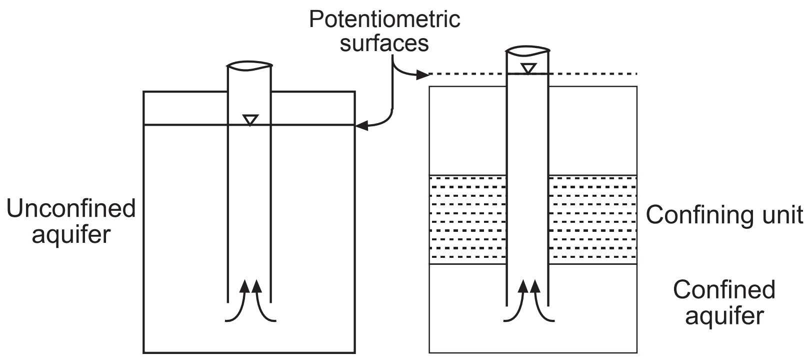


Figure G-2. In an unconfined aquifer, the water table represents a free upper surface. Therefore, water-level changes in an unconfined aquifer will increase or decrease the saturated thickness of the aquifer. In a confined aquifer, the water level in a well will rise to the potentiometric surface, above the top of the aquifer. Water-level changes in a confined aquifer do not change the saturated thickness.

Cation See Ion.

Cone of Depression See Well hydraulics.

Confined Aquifer See Aquifer.

Deuterium A stable isotope of hydrogen, with one neutron and one proton, denoted as D or ^{2}H. Deuterium has approximately twice the mass of the most common isotope of hydrogen, protium (^{1}H); see Environmental isotopes.

Aquifer Sensitivity

Aquifer sensitivity describes the potential for an aquifer to be contaminated based on its intrinsic geologic and hydrogeologic characteristics; it is a measure of the relative quickness with which a contaminant applied on or near the land surface could infiltrate to the aquifer of interest (usually, the aquifer of interest is the uppermost aquifer, directly below the water table). The faster water moves from the land surface to the water table, the more sensitive the aquifer is to potential contamination. The recognition of potentially sensitive groundwater areas is a critical first step in action to prevent groundwater contamination. Preventing contamination is less costly and easier than cleaning up the contamination after the fact.

The primary factors in assessing aquifer sensitivity are the depth and the permeability of geologic materials above it. Areas characterized by rapid infiltration and a shallow basin-fill aquifer at the water table are more sensitive than others. Examples of such areas are surficial alluvium and outwash with sandy soils, or sand and gravel at the surface. Areas with poorly drained soils and/or low-permeability material will restrict infiltration of water, and any associated contamination, providing a protective layer to underlying aquifers. Thus the sensitivity in these areas is lower. Also, a deep water table affords more of an opportunity for contaminants to be naturally attenuated or “filtered” before reaching the groundwater system.

The following procedure can be used to compare the relative sensitivity of broad areas given the range of conditions present in the study area. The procedure only considers the physical hydrogeologic characteristics of the study area. The steps include: (1) estimate the depth to water; (2) determine the surficial geology; (3) make a relative judgment based on range of conditions.

(1) Estimate depth to water. If shallow wells are in the area of interest, the depth to water can be measured or there may be records of measurements in the GWIC database. If site-specific data do not exist, the depth to water could be estimated by subtracting the water-table altitude from the land-surface altitude as determined from a topographic map.

(2) Determine the surficial geology. If site-specific data for near-surface geologic conditions are available, such as lithologic descriptions from well logs, assess whether the materials contain much sand and gravel (permeable) or silt and clay (less permeable). If site-specific data are not available, use a geologic map to assess the type and thickness of surficial materials. As discussed in the Geologic Framework part of this report, the materials in the surficial deposits are variable, but usually unconsolidated deposits are more permeable than consolidated deposits. Therefore, an area with unconsolidated sand and gravel at the land surface would be more sensitive than an area with clay-rich sediment at the surface.

(3) Judge the sensitivity. With the information generated in steps 1 and 2, a relative assessment of aquifer sensitivity can be made using a simple matrix that incorporates the relative permeability range of geologic material present in the unsaturated zone and the depth to water. Three classifications of sensitivity (low, medium, and high) are presented based on subdivisions of the depth to water and the surficial geology. The geologic subdivisions are based on the relative permeability of the unconsolidated deposits compared with the consolidated bedrock formations. The classifications are relative terms and not absolute indicators of aquifer sensitivity.

This method of evaluating sensitivity provides a generalized assessment that addresses the relative potential for vertical movement of contaminants to the water table. It must be recognized that the factors affecting aquifer sensitivity commonly vary considerably over short distances and the accuracy of any assessment will depend on the amount and quality of available data. Projects that require precise resolution of aquifer sensitivity will require site-specific investigation. For more detailed discussions and procedures concerning aquifer sensitivity, see Aller and others (1985), National Research Council (1993), and Vrba and Zoporozec (1994).

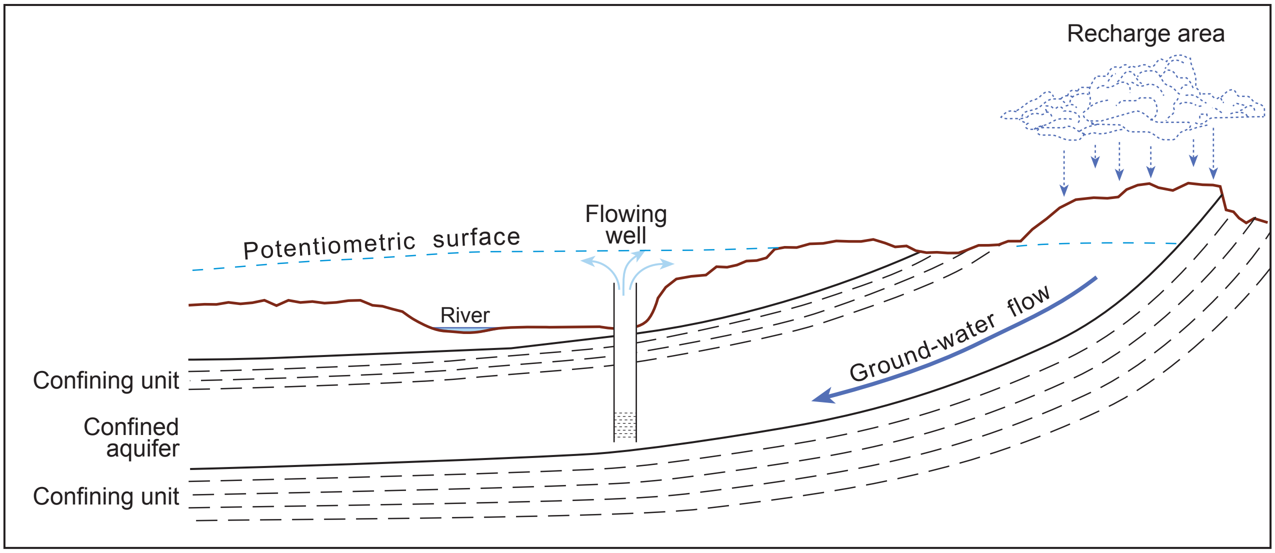


Figure G-3. Artesian conditions develop in confined aquifers when the aquifer, overlain by a low-permeability unit, dips or tilts away from its recharge area. Water percolates down to the water table in the recharge area and moves beneath the confining unit. The artesian pressure is caused by the difference in the level of the water table in the recharge area and at the top of the aquifer. Flowing wells, or flowing artesian conditions, occur in areas where the potientometric surface is higher than the land surface.

Discharge Area An area where groundwater is released from an aquifer, generally characterized by water moving toward the land surface. Springs or gaining streams (fig. G-4) may occur in groundwater discharge areas.

Dissolved Constituents The quantity of dissolved material in a sample of water expressed as milligrams per liter. The value is calculated by summation of the measured constituents, which include major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}, Fe^{2+}, Mn^{2+}) and anions (HCO_{3-}, CO_3^{2-}, SO_4^{2-}, Cl^-, NO_{3-}, F^-, SiO_{3-}) expressed in milligrams per liter (mg/L). See related sidebar, page 70.

Environmental Isotopes Globally distributed isotopes that occur in nature are called environmental isotopes. See related sidebar, page 71.

Flow System The aquifers and confining beds that control the flow of groundwater in an area constitute the groundwater flow system (fig. G-3). Groundwater flows through aquifers from recharge areas, which commonly coincide with areas of high topography, to discharge areas that are topographically low. The relative length and duration of the groundwater flow paths are used to classify groundwater systems. A regional system generally consists of deep groundwater circulation between the highest surface drainage divides and the largest river valleys. Local and intermediate flow systems consist of shallow groundwater flow between adjacent recharge and discharge areas superimposed on or within a regional flow system.

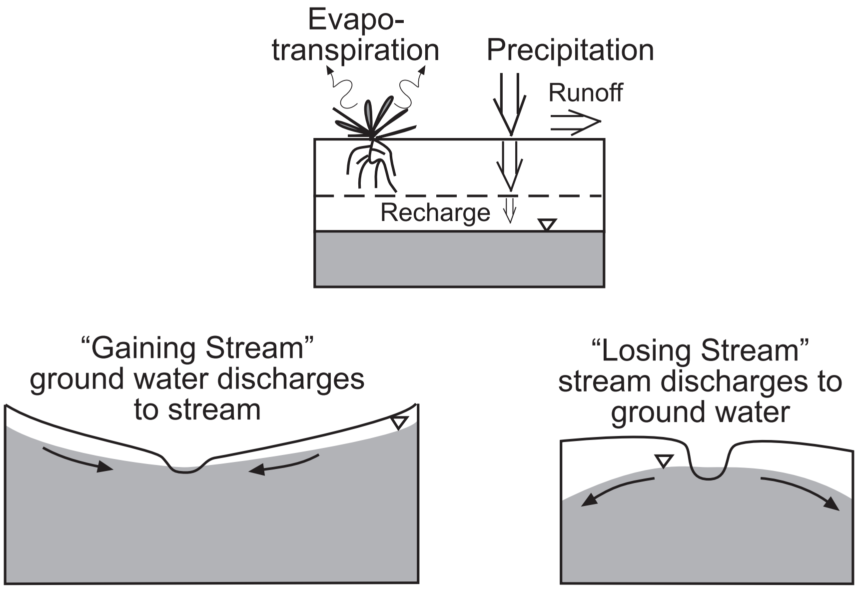


Figure G-4. Water that percolates through the unsaturated zone to the water table is said to recharge an aquifer. Recharge can also occur from the surface-water bodies (losing streams) where the water levels are higher than those in neighboring aquifers. In contrast, in a gaining stream water levels in the aquifer are above those in the stream and flow is maintained by groundwater discharge.

Dissolved Constituents

The amount of dissolved matter in water is commonly reported either as “Total Dissolved Solids” (TDS) or the “Sum of Dissolved Constituents,” or simply “dissolved constituents.” The dissolved constituents are the sum of the major cations (Na, K, Ca, Mg, Fe, Mn) and anions (HCO_3, CO_3, SO_4, Cl, SiO_3, NO_3, F) expressed in milligrams per liter (mg/L). Dissolved constituents in groundwater are a result of the initial chemistry of the recharge water and subsequent interactions of that water with soils and aquifer materials. The total concentration of dissolved matter provides a general indicator of water quality: the lower the total concentration the better the water quality.

Reported values of “dissolved constituents” differ slightly from reported values of TDS, which are also commonly reported. Total dissolved solids were traditionally measured by weighing the residue remaining after evaporating a known volume of water. However, during evaporation about half the bicarbonate (HCO_{3-}) is converted to carbon dioxide gas (CO_2), which escapes to the atmosphere and does not appear in the residue (Hem, 1992). Therefore, TDS underestimates total dissolved-ion concentration in solution, especially where bicarbonate concentrations are high. For this report the actual concentrations reported for the major constituents are summed and reported as dissolved constituents (rather than TDS), giving a more accurate measure of the total ions in solution. Typically, water does not become too salty to drink until the concentration of dissolved constituents reaches about 2,000 mg/L.

Laboratory-measured dissolved constituent concentrations can be supplemented by estimating dissolved constituent concentrations from field measurements of specific conductance made during visits to wells. Hem (1992) showed that dissolved constituents (DC) can be estimated from specific conductance (SC) according to the relationship: DC = A x SC, where A is a constant. Based on a straight-line regression between field conductances and laboratory dissolved constituents values for samples collected in the Lolo-Bitterroot Area, A = 0.92. Specific conductance data are more commonly collected than samples for analyses, and the dissolved constituents concentrations estimated from the SC data can also be used to better understand the spatial distribution of water quality.

Nitrate

Nitrate (NO_{3-}) is an essential nutrient for plant life, yet it is a potentially toxic pollutant when present in drinking water at excessive concentrations. Pregnant women and infants less than 1 year of age are most commonly at risk from nitrate poisoning if they ingest water with nitrate concentrations more than 10 mg/L. Nitrate poisoning can result in methemoglobinemia, or “blue-baby” syndrome, in which the ability of the individual’s blood supply to carry oxygen is reduced to the point that suffocation can occur.

Nitrate has natural and human-related sources. However, where nitrate contamination of groundwater has been identified, it is usually related to a known or suspected surface-nitrogen source (Madison and Brunett, 1984). It can occur naturally in groundwater through the interaction of recharging water with atmospheric nitrogen (nitrogen fixation). It also can be derived from nitrogen-rich geologic deposits (generally marine-deposited shales). Significant human sources of nitrate to groundwater include septic systems, agricultural activities (fertilizers, irrigation, dryland farming, livestock wastes), land disposal of wastes, and industrial wastes.

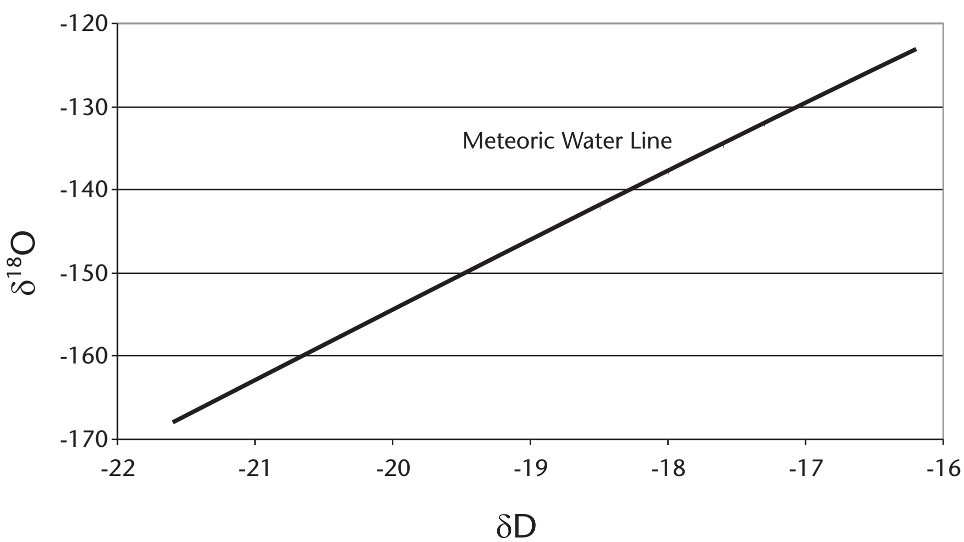


Figure G-5. Values of $\delta^{18}O$ and δD in precipitation from around the world plot linearly along a line known as the global meteoric water line (Craig, 1961). Groundwater that originates as precipitation should also plot along the global meteoric water line.

Environmental Isotopes

Isotopes of hydrogen, oxygen, and carbon in groundwater can provide insight into hydrologic process and provide independent confirmation of interpretations of groundwater flow made from other hydrologic and chemical data. Isotopic data can also help estimate the age of groundwater.

Tritium

Tritium is a naturally occurring radioactive isotope of hydrogen that has a half-life of 12.43 years. It is produced in the upper atmosphere where it is incorporated into water molecules and therefore is present in precipitation and water that recharges aquifers. Concentrations of tritium are measured in tritium units (TU), where one TU is equal to one tritium atom in 1,018 atoms of hydrogen. Before the atmospheric testing of nuclear weapons began in 1952, natural concentrations of tritium in precipitation were 2 to 8 TU (Plummer and others, 1993). Atmospheric testing of nuclear weapons between 1952 and 1963 released large amounts of tritium into the atmosphere, overwhelming the natural production of tritium; in North America tritium concentrations in precipitation peaked at several thousand TU in 1963–1964 (Hendry, 1988). Because of its short half-life, bomb-derived tritium is an ideal marker of recent (post-1952) groundwater recharge. Groundwater recharged by precipitation before 1952 will have tritium concentrations reduced because of radioactive decay to less than 1.0 TU, which is at or below the analytical detection limit. Therefore, a groundwater sample with detectable tritium (greater than 0.8 TU) includes water that must have been recharged since 1952 and would be considered “modern.” Tritium-free groundwater infers recharge before 1952 and is considered “sub-modern” or “older” (Clark and Fritz, 1997).

Oxygen and hydrogen isotopes

Ratios of the stable isotopes of oxygen ($^{18}O/^{16}O$) and hydrogen ($^{2}H/^{1}H$) in groundwater help evaluate recharge conditions and can sometimes be used to confirm age estimates for water from other methods. Concentrations of each isotope are reported as delta (δ) values in per mil (parts per thousand) relative to a standard known as Vienna Standard Mean Ocean Water (VSMOW). These values are denoted as $\delta^{18}O$ and δD for oxygen and hydrogen, respectively. A positive delta value means that the sample contains more of the isotope than the standard; a negative value means that the sample contains less of the isotope than the standard.

When water evaporates from the ocean, the water vapor will be depleted in oxygen-18 (^{18}O) and ^{2}H [or deuterium (D)] when compared with the ocean water because molecules of the lighter isotopes (^{16}O and ^{1}H) more readily evaporate than molecules containing the heavier isotopes. As air masses are transported away from the oceans, the isotopic character of the water vapor will sequentially change because of condensation, freezing, melting, and evaporation of molecules of the different isotopes. The two main factors that affect isotopic content of precipitation are the condensation temperature and how much water has already condensed from the initial water in the air mass. The isotopic composition of water that condenses at cooler temperatures (commonly associated with higher altitudes, higher latitudes, or cooler climatic conditions) is lighter than that of water that condenses at warmer temperatures (commonly associated with lower altitudes, lower latitudes, or warmer climatic conditions). Therefore, at a given locality the $\delta^{18}O$ and δD in the precipitation will depend on factors such as distance from the ocean, altitude, and temperature. Because the isotopic composition of groundwater generally reflects the average isotopic composition of precipitation in a recharge area, spatial and temporal variations in the isotopic content of precipitation can be useful in evaluating groundwater recharge sources. Craig (1961) observed another useful relationship, namely that values of $\delta^{18}O$ and δD of precipitation from around the world plot linearly along a line known as the global meteoric water line (fig. G-5). Groundwater that originates as precipitation should also plot along the global meteoric water line. The departure of $\delta^{18}O$ and δD values from the meteoric water line may suggest that the water has been subject to evaporation or geothermal processes. ^{18}O and deuterium can be used to help delineate different sources of water to a groundwater flow system.

Carbon

^{14}C is a naturally occurring radioactive isotope of carbon (C) produced in the upper atmosphere, and has a half-life of 5,730 years. Carbon atoms (99 percent are ^{12}C and the remaining atoms are ^{13}C and ^{14}C) combine with oxygen to form carbon dioxide (CO_2), which travels throughout the atmosphere and biosphere. Carbon dioxide containing ^{14}C travels throughout the atmosphere and biosphere in the same way as CO_2 that contains other carbon isotopes (Bowman, 1990). A dynamic equilibrium exists between formation and decay of ^{14}C that results in a relatively constant amount of ^{14}C in the atmosphere and biosphere.

Recharge waters dissolve atmospheric ^{12}C, ^{13}C, and ^{14}C, present in the soil-zone CO_2, and move it through the unsaturated zone. As groundwater moves below the water table and is cut off from soil-zone CO_2, no new ^{14}C can be added to the water. The radioactive carbon at this point in the system is part of the carbonate and bicarbonate anions that are in solution. Radioactive decay will cause the ^{14}C content of the carbon in these anions to decline at a known rate. The basic principle of ^{14}C dating of groundwater is to measure the ^{14}C activity in the dissolved inorganic carbon (HCO_{3-} and CO_{32-}) and relate that activity to an age. If soil-zone CO_2 were, in fact, the only source of dissolved inorganic carbon in groundwater, then the technique could be used to assign accurate numerical dates (ages) to the water. Unfortunately, other processes add old, non-radioactive carbon to groundwater, such as dissolution of carbonate minerals where the carbon has been locked up in molecules remote from the atmosphere for long periods. The added “dead carbon” dilutes the concentration of ^{14}C, increasing the apparent groundwater age. However, measured values of ^{14}C can still convey significant information about relative groundwater ages between pairs of samples along flow paths. ^{14}C is measured as percent modern carbon (PMC) relative to a 1950 A.D. standard (Bowman, 1990); water with a higher PMC value would be younger than water with lower PMC values.

Groundwater Strictly speaking, all water below land surface is "groundwater." The water table defines the boundary between the unsaturated (air in pores) and saturated (water in pores) zones (fig. G-1). It is the water from saturated zones that supplies water to wells (and springs) that will be called groundwater in this atlas.

GWIC The Groundwater Information Center (GWIC) is a repository for water well logs and groundwater information at the Montana Bureau of Mines and Geology, http://mbmg-gwic.mtech.edu; 1300 W. Park St, Butte, MT 59701; (406) 496-4336; GWIC@mtech.edu.

Hydraulic Conductivity Measure of the rate at which water is transmitted through a unit cross-sectional area of an aquifer under a unit gradient; commonly called permeability. The higher the hydraulic conductivity of the aquifer (the more permeable it is), the higher the well yields will be. The hydraulic conductivity of geologic material ranges over 14 orders of magnitude (fig. G-6).

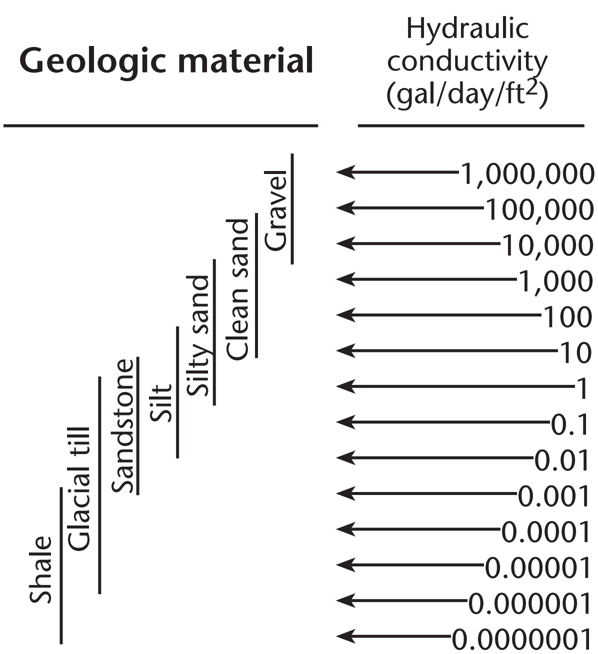


Figure G-6. The range of hydraulic conductivity values for typical geologic materials ranges over several orders of magnitude. Hydraulic conductivities not only differ in different rock types but may also be different from place to place in the same rock (modified from Freeze and Cherry, 1979).

Hydrologic Cycle The constant circulation of water among the ocean, atmosphere, and land is called the hydrologic cycle. The notion of the hydrologic cycle provides a framework for understanding the occurrence and distribution of water on the earth. The important features of the hydrologic cycle are highlighted in figure G-7. The hydrologic cycle is a natural system powered by the sun and is quantified by the hydrologic budget. Evaporation from the ocean and other surface bodies of water and shallow groundwater, and transpiration from plants, bring "clean" water (because most dissolved constituents are left behind) into the atmosphere where clouds may form. The clouds return water to the land and ocean as precipitation (rain, snow, sleet, and hail). The precipitation may subsequently follow many different pathways. Some may be intercepted by plants, may evaporate, may infiltrate the ground surface, or may run off (overland flow). The water that infiltrates the ground contributes to the groundwater part of the cycle, a small but critical item in the hydrologic budget. Groundwater flows through the earth until it discharges to a stream, spring, lake, or ocean. Runoff occurs when the rate of infiltration is exceeded. This water contributes directly to streams, lakes or other bodies of surface water. Water that reaches streams flows to the ocean where it becomes available for evaporation again, perpetuating the cycle.

Hydrologic Unit A body of geologic materials that functions regionally as a water-yielding unit.

Ion An atom or group of atoms that carries a positive (cation) or negative (anion) electric charge. Atoms in liquid solutions are typically ions; the atoms are said to have been ionized.

Isotopes Atoms of the same element that differ in mass because of differing numbers of neutrons in their nuclei. Although isotopes of the same substance have most of the same chemical properties, their different atomic weights allow them to be separated. For example, ^{18}O is heavier than ^{16}O, so water molecules containing ^{16}O evaporate from a water body at a greater rate; see Environmental isotopes.

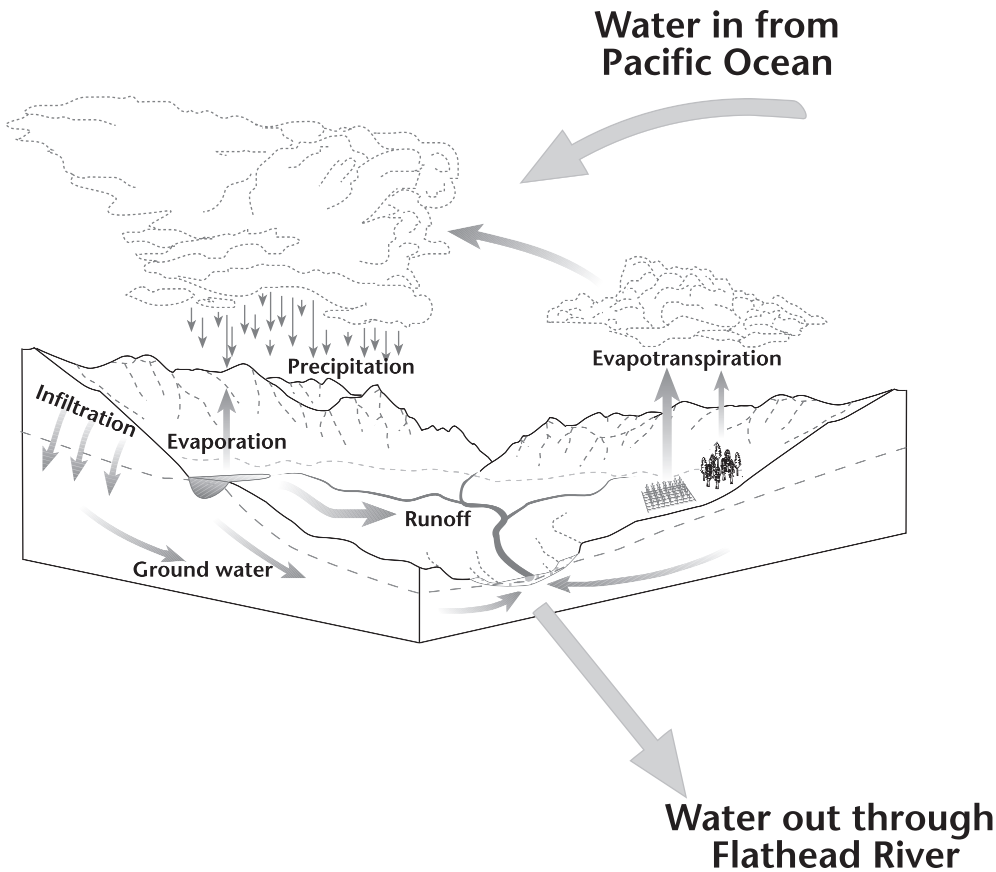


Figure G-7. The constant circulation of water among the ocean, atmosphere, and land is referred to as the hydrologic cycle. In the Flathead Lake area, most of the precipitation that enters the area is returned to the atmosphere by evaporation and evapotranspiration.

Radioactive Half-Life The time over which half of a radioactive material decays to another elementary material from a parent to a daughter product.

Radon Radon is a colorless, odorless gas produced by the radioactive decay of uranium found naturally in rocks and soil, and has been linked to lung cancer in humans (EPA, 1999). Radon in indoor air poses a health risk and accumulates by seepage into a structure from the soil and rock beneath its foundation. Water that contains radon is also a source of radon in indoor air, but the U.S. Environmental Protection Agency estimates that radon released from drinking water accounts for less than 2 percent of that in indoor air. Currently no drinking water standard for radon exists. However, the U.S. Environmental Protection Agency has proposed a 300 picoCuries per liter (pCi/L) MCL for community water systems, and an alternative 4,000 pCi/L MCL for community systems that have a U.S. Environmental Protection Agency-approved Multimedia Mitigation Program (EPA, 1999). The proposed MCLs for radon will not apply to private wells.

Nitrate A mineral compound described by the anionic structure of NO_{3}^{-} that is soluble in water and stable in oxidized environments. Common analysis of the concentration is reported as milligrams per liter (mg/L) of nitrogen (N). Common sources of nitrate are decaying organic matter, sewage, natural nitrate in soil, and fertilizers. See related sidebar, page 70.

Overdraft Long-term withdrawal of water at rates greater than long-term recharge.

^{18}O A stable isotope of oxygen, denoted as ^{18}O, with 8 protons and 10 neutrons. ^{18}O is heavy compared with the common isotope of oxygen (^{16}O); see Environmental isotopes.

Permeability The capacity of a geologic material to transmit fluid (water in this report); also called hydraulic conductivity.

Potentiometric Surface A surface defined by the level to which water will rise in tightly cased wells (figs. G-1 and G-2). The water table is a potentiometric surface for an unconfined aquifer.

Recharge Area An area where an aquifer receives water, characterized by movement of water downward into deeper parts of an aquifer (fig. G-3).

Sediment Solid fragments of rocks deposited in layers on the earth's surface and commonly classified by grain size (clay, silt, sand, gravel) and mineral composition (e.g., quartz, carbonate, etc.).

Storativity The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. In an unconfined aquifer the storativity is nearly equivalent to how much water a mass of saturated geologic material will yield by gravity drainage.

Surface Water Water at the earth's surface, including snow, ice, and water in lakes, streams, and oceans.

Transmissivity The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Transmissivity is equivalent to the hydraulic conductivity times the aquifer thickness.

Tritium A naturally occurring radioactive isotope of hydrogen, denoted as ^3H, with a half-life of 12.43 years. Tritium, with 1 proton and 2 neutrons, has approximately three times the mass of the most common isotope of hydrogen, protium (^1H); see Environmental isotopes.

Unconfined Aquifer See Aquifer.

Unconsolidated Sediment that is not generally cemented or otherwise bound together.

Unsaturated Zone The subsurface area above the water table where the pores are filled by air or partly by water and partly by air (see fig. G-1).

Water Quality The fitness of water for use, affected by physical and chemical factors. EPA water-quality standards: U.S. Environmental Protection Agency (EPA) primary, secondary, and proposed maximum contaminant levels (MCL, SMCL, and PMCL) for drinking water. These standards are the permissible levels allowable in a public water-supply system. Constituents for which MCLs have been set may pose a health threat at elevated concentrations. Secondary levels are set for aesthetic reasons; elevated concentrations of these constituents may be a nuisance (bad taste, odor, or staining) but do not normally pose a health risk. See related sidebar on Major Ions and Constituents.

Water Table The upper surface of the saturated zone, often the surface of an unconfined aquifer; occurs where the pressure of the water is equal to atmospheric pressure. Below the water table the pore spaces are completely saturated.

Major Ions and Constituents

The major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}, Fe^{2+}, Mn^{2+}) and anions (HCO_{3-}, CO_3^{2-}, SO_4^{2-}, Cl^-, NO_{3-}, F^-, SiO_{3-}) derived from soil and rock make up most of the dissolved materials in groundwater.

Bicarbonate (HCO_{3-}) and **carbonate** (CO_3^{2-}) occur naturally; bicarbonate is the dominant anion in groundwater. Bicarbonate and carbonate are typically derived from dissolution of common carbonate minerals such as calcite and dolomite. Carbonate will only be present as a parameter in groundwater when the water's pH is greater than about 8.3.

Sulfate (SO_4^{2-}) is dissolved from rocks and soils containing gypsum, iron sulfides, and other sulfur compounds. Sulfate can be present in some industrial wastes.

Chloride (Cl^-) occurs in rocks and soils and is easily dissolved from those sources. It is also present in sewage and is found in natural and industrial brines.

Nitrate (NO_{3-}) is a natural constituent in groundwater and can come from decaying organic matter and natural accumulation of nitrogen in soils. Elevated concentrations of nitrate can come from infiltration of sewage effluent and leaching of fertilizers.

Fluoride (F^-) is dissolved in low concentrations from most rocks and soils. Elevated concentrations are found in some formations and near hot and warm springs where groundwater can contain more than the recommended concentration of fluoride.

Silica (SiO_{3-}) is generally derived from the breakdown of quartz (SiO_2) and other silicate minerals, which form the bulk of the grains in most sand and gravel deposits (Hem, 1992).

Sodium (Na^+) and **potassium** (K^+) are metals present in many feldspar and clay minerals that occur in alluvial and glacial deposits. Sodium in water may also be associated with septic effluent, road salt, and industrial discharges. When combined with chloride in water, sodium may impart a salty taste.

Calcium (Ca^{2+}) and **magnesium** (Mg^{2+}) are metals that are also commonly dissolved in natural water. Calcium and magnesium are typically derived from dissolution of common carbonate minerals such as calcite and dolomite. Magnesium is chemically similar to calcium and is found in dolomite and in ferro-magnesium minerals common in metamorphic rocks. Calcium and magnesium have no health standards and elevated concentrations do not pose health risks. However, calcium, magnesium, and bicarbonate contribute to the hardness of water.

Iron (Fe^{2+}) and **manganese** (Mn^{2+}) are essential to plants and animals, but may cause unpleasant taste, odor, and staining of plumbing fixtures, clothing, or buildings sprayed by irrigation water. Primary sources of iron and manganese in groundwater are the dissolution of iron-bearing minerals in aquifers. Iron concentrations in well water may also be increased by corrosion of steel well casings and by bacterial activity in and around well screens or perforations.

Well A hole drilled or dug to produce groundwater or to monitor groundwater levels or quality. A properly designed production well for domestic, stockwatering, or municipal purposes should produce good-quality, sand-free water with proper protection from contamination. The basic elements of a properly constructed well are shown below (fig. G-8).

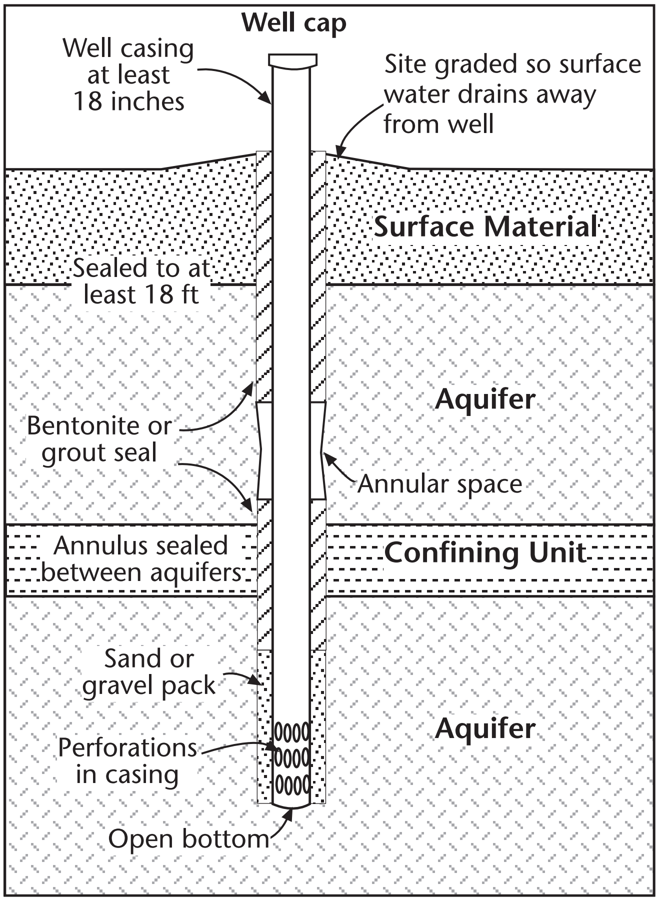


Figure G-8. Properly constructed wells are completed in single aquifers. In order to protect groundwater quality and maintain artesian pressures, wells should not serve as conduits from the surface to groundwater or connect separate aquifers.

Well Hydraulics The withdrawal of water from a well causes the water level within the well to drop below the static water level in the producing aquifer. The lowering of the water level in the well induces groundwater to move from the aquifer to the well. As pumping continues, the water levels in the well and the producing aquifer continue to decline until the rate of inflow equals the rate of withdrawal. The radial decline in the water level of a producing aquifer response to pumping is called the cone of depression. The limit of the cone of depression is called the zone of influence. The geographic area containing groundwater that flows toward the well is the zone of capture (fig. G-9).

Wellhead Protection Area Zone around a public water supply that is managed to prevent contamination of the water supply. The area typically is delineated based on geologic and hydraulic factors and includes the zone of capture within about a mile of the well (fig. G-9).

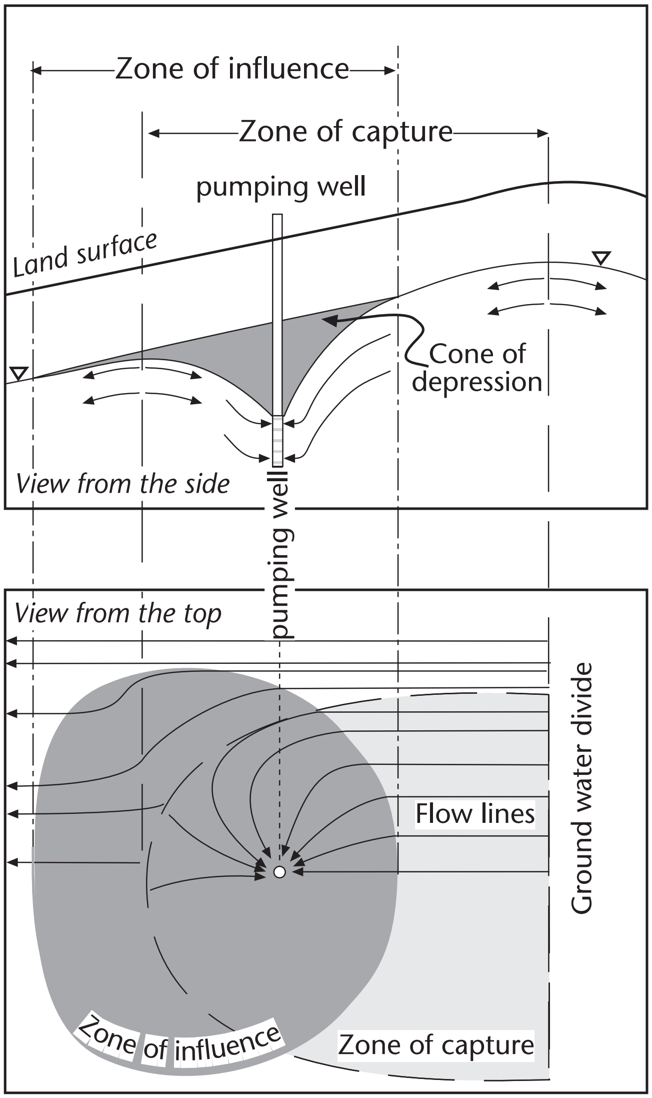


Figure G-9. Withdrawal of groundwater will temporarily depress the water level (potentiometric surface) in the region surrounding the well, creating a "cone of depression." The dimensions of the cone of depression, zone of influence, and zone of contribution depend on hydraulic characteristics of the aquifer, potentiometric surface, and discharge rate of the well.

APPENDIX A

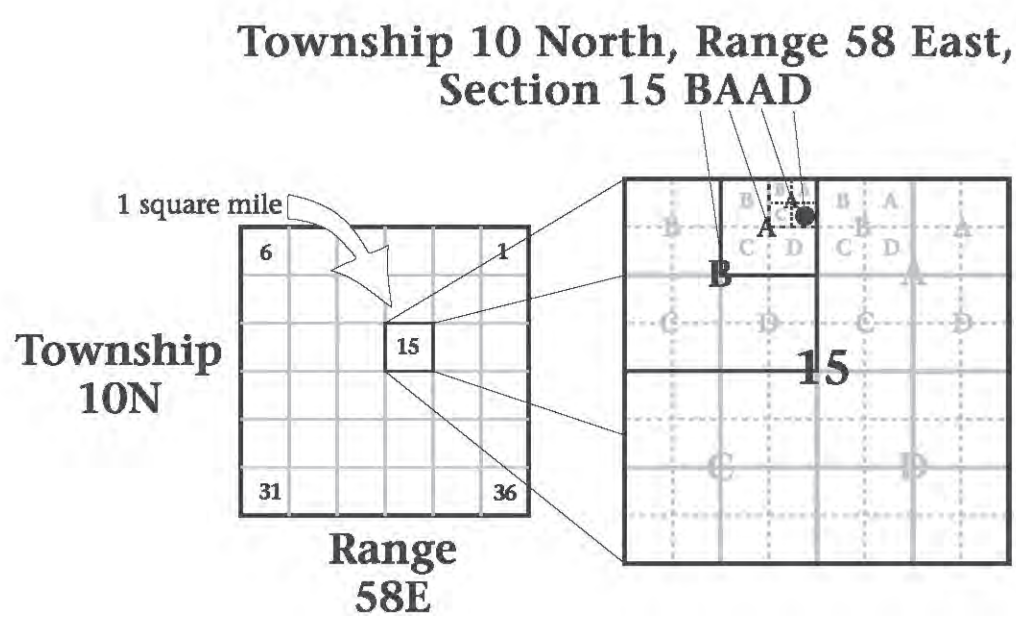
Site Location System for Points in the Public Land Survey System

GWIC locations are read from left to right, largest tract to smallest, which is the opposite of legal land descriptions.

GWIC description: 10N 58E 15 BAAD

Legal land description: SE¼ NE¼ NE¼ NW¼ Sec. 15 T. 10 N., R. 58 E.

For example: to find a well located in 10N 58E 15 BAAD, read the tract designations from left to right, largest tract to smallest tract.



APPENDIX B

Tritium Data

Tritium Data

Sample	GWIC ID	Latitude	Longitude	Location (TRS)	County	TOTAL_DEPT	AQUIFER	UNIT	TRITIUM	+/-
1999Q0292	168150	47.587	-113.7692	21N17W10CDCB	MISSOULA	66	112ALVM	shallow	3.1	0.6
2000Q0502	67257	46.8183	-114.0596	12N20W12BBAD	MISSOULA	45	111ALVM	shallow	6.0	0.7
1999Q0349	152725	47.3968	-115.4171	19N30W21ABDA	MINERAL	85	111ALVM	shallow	6.0	0.7
1999Q0838	123115	46.4716	-114.1221	08N20W08ABAB	RAVALLI	37	111ALVM	shallow	6.6	0.7
1999Q0747	57128	46.3133	-114.1571	07N21W36DDDD	RAVALLI	31	112TRRC	shallow	7.4	0.8
1998Q0861	123152	46.6407	-114.0913	10N20W10ADBD	RAVALLI	51	112ALVF	shallow	7.4	0.6
1998Q0867	123569	46.645	-114.0725	10N20W11ABADBC	RAVALLI	70	112ALVF	shallow	7.6	0.6
1999Q0731	128782	46.4376	-114.1579	08N21W24ADCD	RAVALLI	33	120SNGR	shallow	7.7	0.8
1998Q0857	63977	46.6444	-114.1051	10N20W10BBDB	RAVALLI	26	112ALVF	shallow	7.8	0.6
1998Q0868	139841	46.6431	-114.0973	10N20W10ABCC	RAVALLI	34	112ALVF	shallow	7.8	0.6
1998Q0869	166186	46.6301	-114.0753	10N20W14ABCB	RAVALLI	50	112ALVF	shallow	7.8	0.6
2000Q0326	144409	45.9277	-114.1279	02N20W18BADB	RAVALLI	42	112TRRC	shallow	8.2	0.8
1999Q0850	151143	46.868	-114.0291	13N19W20CDDA	MISSOULA	45	111ALVM	shallow	8.7	
1998Q0865	63988	46.6381	-114.1073	10N20W10CBBD	RAVALLI	50	112ALVF	shallow	8.8	0.7
1999Q0841	69055	46.8691	-114.0014	13N19W21DABC	MISSOULA	57	112ALVM	shallow	8.9	
1999Q0752	57724	46.4719	-114.1271	08N20W08BAAB	RAVALLI	50	112ALVF	shallow	9.3	0.9
1998Q0863	147580	46.6365	-114.0835	10N20W11CBCD	RAVALLI	67	112ALVF	shallow	9.5	0.7
2000Q0424	67425	46.7542	-114.1109	12N20W33DABA	MISSOULA	68	120SNGR	shallow	9.6	0.9
2000Q0204	141342	46.8502	-114.0773	13N20W25CCDB	MISSOULA	99	112ALVM	shallow	9.6	0.8
2000Q1216	136964	46.2552	-114.1536	06N20W19CCCC	RAVALLI	40	112TRRC	shallow	9.7	0.9
2000Q0042	52909	46.1898	-114.1538	05N20W18CBBB	RAVALLI	40	112TRRC	shallow	10.0	0.9
2000Q0421	67961	46.8894	-113.8365	13N18W14ABCC	MISSOULA	58	111ALVM	shallow	10.0	0.9
2000Q0509	143740	46.8497	-114.0395	13N19W30DDDD	MISSOULA	99	112ALVM	shallow	10.0	0.9
2000Q0327	131025	46.9906	-114.4357	14N22W07BBAD	MISSOULA	80	111ALVM	shallow	10.2	0.9
2000Q0209	66652	46.7792	-113.7063	12N17W23CCDB	MISSOULA	100	111ALVM	shallow	10.3	0.9
2000Q0096	67551	46.7544	-114.2242	12N21W34BDDC	MISSOULA	44	111ALVM	shallow	10.3	0.9
2000Q1166	57525	46.4831	-113.979	08N19W04BDAA	RAVALLI	59	112ALVF	shallow	10.4	0.9
1999Q0839	157331	46.1882	-114.1003	05N20W16DBBD	RAVALLI	38	112ALVF	shallow	10.4	0.9
1998Q0902	121919	46.6212	-114.085	10N20W14CBCDA	RAVALLI	50	112ALVF	shallow	10.5	0.9
2000Q1159	56528	46.3142	-114.1138	07N20W32DDDA	RAVALLI	40	111ALVM	shallow	10.9	0.9
1999Q0835	157210	46.8386	-114.0426	13N19W31DDBA	MISSOULA	97	112ALVM	shallow	10.9	
2000Q0201	70904	46.9269	-113.9562	14N19W35DADB	MISSOULA	79	112ALVM	shallow	11.0	0.9
2000Q0564	69344	46.842	-114.0287	13N19W32BDDD	MISSOULA	126	112ALVM	shallow	11.2	

Tritium Data

Sample	GWIC ID	Latitude	Longitude	Location (TRS)	County	TOTAL_DEPT	AQUIFER	UNIT	TRITIUM	+/-
2000Q0281	70892	46.9445	-114.0181	14N19W29ADDB	MISSOULA	56	111ALVM	shallow	11.2	1.0
1999Q0825	151191	46.8661	-113.988	13N19W22CDABD	MISSOULA	53	111ALVM	shallow	11.2	
1998Q0908	130928	46.6227	-114.0978	10N20W15DBBD	RAVALLI	60	112ALVF	shallow	11.3	1.0
1998Q0899	64163	46.6188	-114.0822	10N20W14CCDA	RAVALLI	39	112ALVF	shallow	11.7	1.0
1999Q0821	151201	46.8383	-114.0426	13N19W31DDBA	MISSOULA	51	112ALVM	shallow	12.1	
1999Q0840	151190	46.858	-114.0018	13N19W28ACDAA	MISSOULA	76	112ALVM	shallow	12.4	
2000Q0384	66057	46.7036	-114.0694	11N20W23AAAB	MISSOULA	75	111ALVM	shallow	14.4	1.2
1998Q0657	163262	46.6379	-114.0754	10N20W11DBB	RAVALLI		110ALVM	shallow	15.9	1.1
1998Q0904	166834	46.6363	-114.0723	10N20W11DBDAC	RAVALLI	40	112ALVF	shallow	16.3	1.3
1998Q0898	166833	46.6411	-114.077	10N20W11BDDA	RAVALLI	58	112ALVF	shallow	16.4	1.3
1997Q0804	64025	46.6405	-114.0758	10N20W11ACCBA	RAVALLI	44	112ALVF	shallow	22.6	1.7
2000Q0137	51547	46.1018	-114.175	04N21W14CBAD	RAVALLI	56	112TRRC	shallow	71.0	0.7
1999Q0351	67827	46.8992	-113.653	13N16W08CABB	MISSOULA	205	120SDMS	deep	< 0.8	0.6
1999Q0830	71782	47.0391	-114.2789	15N21W20DCDD	MISSOULA	250	120SICL	deep	< 0.8	0.6
1999Q0206	72526	47.1621	-113.4495	16N15W12BBCB	MISSOULA	330	112ALVM	deep	< 0.8	0.6
1998Q0905	136362	46.6352	-114.0933	10N20W10DCAACB	RAVALLI	115	120SNGR	deep	< 0.8	0.5
1999Q0207	140822	47.1778	-113.4453	16N15W01BABB	MISSOULA	130	112ALVM	deep	< 0.8	0.5
1999Q0238	146741	47.1758	-113.5132	16N15W04BBCD	MISSOULA	108	112ALVM	deep	< 0.8	0.6
2000Q0499	164425	46.8184	-114.0557	12N20W12BAAD	MISSOULA	185	112ALVM	deep	< 0.8	0.5
1999Q0291	169130	47.5253	-113.7788	20N17W04BBDB	MISSOULA	440	120SDMS	deep	< 0.8	0.6
1999Q0057	54043	46.2772	-114.0454	06N20W13BCDC	RAVALLI	190	120SDMS	deep	< 0.8	0.6
2000Q1210	60137	46.5123	-114.0809	09N20W26BACC	RAVALLI	552	120SNGR	deep	< 0.8	0.5
1998Q0856	157453	46.6397	-114.0919	10N20W10ADCC	RAVALLI	138	120SNGR	deep	< 0.8	0.2
2000Q0249	134716	46.8973	-113.9794	13N19W10DADB	MISSOULA	98	120SICL	deep	1.9	0.6
1999Q0749	71735	47.0559	-114.2716	15N21W17DADA	MISSOULA	170	120SDMS	deep	2.1	0.5
2000Q1212	54854	46.3008	-114.2096	06N21W03CDAC	RAVALLI	320	120SDMS	deep	2.1	0.5
1999Q0059	84910	46.2925	-114.0816	06N20W10BDDA	RAVALLI	240	120SDMS	deep	3.2	0.6
1998Q0872	63950	46.6502	-114.0933	10N20W03DBDD	RAVALLI	94	120SNGR	deep	3.3	0.4
1998Q0858	63933	46.65	-114.0805	10N20W02CDBABC	RAVALLI	130	120SNGR	deep	3.9	0.4
2000Q0250	50846	46.0135	-114.2054	03N21W16DABC	RAVALLI	93	120SNGR	deep	4.4	0.6
2000Q0099	71258	46.9575	-114.1881	14N21W24DAAB	MISSOULA	151	112ALVM	deep	5.5	0.7
2000Q0377	139851	46.7127	-114.0877	11N20W14BCCB	MISSOULA	144	120SNGR	deep	6.3	0.7
2000Q1215	163226	46.2447	-114.127	06N20W29CACC	RAVALLI	160	120SNGR	deep	6.4	0.7

Tritium Data

Sample	GWIC ID	Latitude	Longitude	Location (TRS)	County	TOTAL_DEPT	AQUIFER	UNIT	TRITIUM	+/-
1998Q0855	124587	46.6472	-114.0708	10N20W02DDCC	RAVALLI	64	112ALVF	deep	6.8	0.6
2003Q1060	73642	47.2987	-115.0801	18N27W30ABBA	MINERAL	192	112ALVM	deep	7.0	0.8
1998Q0854	64208	46.6239	-114.0921	10N20W15DABB	RAVALLI	60	112ALVF	deep	7.2	0.6
1999Q0350	141918	46.2909	-114.0801	06N20W10ACCC	RAVALLI	67	120SNGR	deep	7.4	0.8
2000Q0246	50814	46.0193	-114.1845	03N21W15ADBB	RAVALLI	49	120SNGR	deep	7.5	0.7
1998Q0864	136269	46.6428	-114.0775	10N20W11BADCDD	RAVALLI	80	120SNGR	deep	7.5	0.6
1999Q0733	72114	47.0348	-114.3881	15N22W28BADC	MISSOULA	138	112ALVM	deep	7.8	0.8
1999Q0824	157533	47.0739	-114.3421	15N22W11ACDC	MISSOULA	445	120SICL	deep	7.8	0.7
1999Q0744	136050	46.3118	-114.1856	06N21W02ABBD	RAVALLI	84	120SDMS	deep	8.1	0.8
1999Q0829	144517	46.4757	-114.1369	08N20W06DADD	RAVALLI	44	120SNGR	deep	8.4	0.8
2000Q0141	161907	46.473	-114.087	08N20W03CDCC	RAVALLI	61	112TRRC	deep	8.8	0.7
2000Q0130	51560	46.1055	-114.1894	04N21W15ACBA	RAVALLI	65	120SNGR	deep	8.8	0.8
2000Q0510	69147	46.8562	-114.0126	13N19W28CBAA	MISSOULA	78	112ALVM	deep	9.5	
2000Q0284	57788	46.472	-114.0407	08N20W12ABBB	RAVALLI	108	120SDMS	deep	9.5	0.9
2000Q0798	121525	46.8579	-113.985	13N19W27ACBC	MISSOULA	198	112ALVM	deep	10.1	0.9
2000Q0511	127578	47.1519	-114.8397	16N26W14AAAB	MINERAL	119	112ALVM	deep	10.1	0.9
1998Q0903	64178	46.6297	-114.0815	10N20W14BACBAC	RAVALLI	59	112ALVF	deep	10.5	0.9
2000Q0140	142278	46.8991	-114.1575	13N20W08DBBA	MISSOULA	110	112ALVM	deep	10.6	0.8
1997Q0793	160812	46.6302	-114.0789	10N20W14BACAAB	RAVALLI	54	112ALVF	deep	10.6	1.0
2000Q0494	72198	47.0659	-114.7741	15N25W09CCCA	MINERAL	296	112ALVM	deep	10.9	0.9
2000Q0420	151004	47.0051	-114.675	14N24W06AACD	MINERAL	440	112ALVM	deep	11.0	1.0
2000Q0138	163303	46.8897	-114.0942	13N20W14BACA	MISSOULA	119	112ALVM	deep	11.0	0.9
1998Q0866	136423	46.6363	-114.0865	10N20W11CBCBCA	RAVALLI	56	112ALVF	deep	11.0	0.8
1998Q0900	166835	46.637	-114.0828	10N20W11CBDB	RAVALLI	60	112ALVF	deep	11.3	1.0
1999Q0748	145891	47.0578	-114.2768	15N21W17DBAD	MISSOULA	79	120SNGR	deep	11.8	1.0
1998Q0859	166188	46.6281	-114.0936	10N20W15ACAD	RAVALLI	90	112ALVF	deep	11.9	0.9
2000Q0320	71326	46.9866	-114.4143	14N22W08BCDA	MISSOULA	100	112ALVM	deep	13.0	1.1
2000Q0325	63651	46.6158	-114.0408	10N19W19BBAD	RAVALLI	55	120SNGR	deep	13.0	1.0
2000Q1168	54272	46.2528	-114.1259	06N20W29BADB	RAVALLI	85	120SDMS	deep	14.4	1.1
1999Q0729	71955	47.0131	-114.2272	15N21W35CBCD	MISSOULA	180	112ALVM	deep	14.5	1.2
2000Q0095	67420	46.7596	-114.1215	12N20W33BACA	MISSOULA	120	112ALVM	deep	15.7	1.2
1999Q0753	63567	46.6277	-114.0204	10N19W17BCAA	RAVALLI	135	120SNGR	deep	15.8	1.2
2000Q0330	136174	46.4744	-114.0735	08N20W03DDAD	RAVALLI	162	120SNGR	deep	15.8	1.2

Tritium Data

Sample	GWIC ID	Latitude	Longitude	Location (TRS)	County	TOTAL_DEPT	AQUIFER	UNIT	TRITIUM	+/-
2000Q0132	145761	46.4652	-113.9901	08N19W08DAAA	RAVALLI	234	120SNGR	deep	16.0	1.2
1999Q0061	162912	46.2777	-114.0407	06N20W13BDDC	RAVALLI	120	120SDMS	deep	18.2	1.4
1999Q0060	141917	46.3009	-114.1022	06N20W04DCBC	RAVALLI	140	120SNGR	deep	20.1	1.6
1998Q0853	160354	46.6423	-114.0817	10N20W11BCAAA	RAVALLI	90	112ALVF	deep	20.3	1.4
1998Q0910	64023	46.6408	-114.0745	10N20W11ACBDD	RAVALLI	98	112ALVF	deep	21.1	1.6
2000Q0097	141877	46.9324	-114.1981	14N21W36BDAB	MISSOULA	99	112ALVM	deep	21.5	1.6
2000Q0207	57977	46.4198	-114.0427	08N20W25CAAC	RAVALLI	225	400BELT	bedrock	< 0.8	0.4
2000Q0203	70861	46.9635	-114.0117	14N19W21BABC	MISSOULA	560	400BELT	bedrock	< 0.8	0.4
2000Q0383	122445	46.7176	-114.0998	11N20W15BAAA	MISSOULA	380	120PLNC	bedrock	< 0.8	0.5
2000Q0090	127530	46.7547	-114.2058	12N21W35BDCC	MISSOULA	180	400BELT	bedrock	< 0.8	0.5
1999Q0746	130860	46.4275	-114.0639	08N20W26BAAC	RAVALLI	440	400BELT	bedrock	< 0.8	0.5
2000Q0133	130960	46.7635	-114.1271	12N20W28CCCB	MISSOULA	320	400BELT	bedrock	< 0.8	0.5
2000Q0136	140560	46.1013	-114.1582	04N21W13CBBC	RAVALLI	160	400BELT	bedrock	< 0.8	0.4
2000Q0100	143747	46.9929	-114.1195	14N20W10BBAC	MISSOULA	440	400BELT	bedrock	< 0.8	0.4
2000Q0206	145762	46.4244	-114.0275	08N19W30BBCA	RAVALLI	120	120PLNC	bedrock	< 0.8	0.4
1999Q0848	146109	46.803	-114.4052	12N22W18AACB	MISSOULA	420	400BELT	bedrock	< 0.8	0.5
2000Q0098	155963	46.939	-114.1626	14N20W29CBCD	MISSOULA	404	400BELT	bedrock	< 0.8	0.5
2000Q0093	164948	46.1889	-114.1989	05N21W15DABA	RAVALLI	199	211DBTL	bedrock	< 0.8	0.7
2000Q0047	171600	46.8023	-114.4045	12N22W18AACD	MISSOULA	38	400BELT	bedrock	< 0.8	0.5
2000Q0493	66911	46.8019	-114.0324	12N19W18ACBA	MISSOULA	800	400BELT	bedrock	0.8	0.5
2000Q0205	141347	46.9319	-113.9533	14N19W36BCBB	MISSOULA	281	400BELT	bedrock	0.9	0.5
2000Q0500	158514	46.7807	-113.6817	12N17W24CACB	MISSOULA	244	400BELT	bedrock	1.0	0.5
2000Q0418	153246	46.6747	-114.1009	11N20W34BABB	MISSOULA	600	400BELT	bedrock	1.6	0.5
1999Q0239	151056	47.1713	-113.5259	16N15W05DBBB	MISSOULA	375	400BELT	bedrock	2.1	0.6
2000Q0040	129284	46.188	-114.1348	05N20W18DADA	RAVALLI	210	120PLNC	bedrock	3.8	0.7
2000Q0202	70841	46.9614	-114.005	14N19W21ABCC	MISSOULA	110	400BELT	bedrock	4.2	0.5
1999Q0730	139304	47.0371	-114.39	15N22W28BAAB	MISSOULA	200	400BELT	bedrock	5.2	0.7
1999Q0058	154007	46.3234	-114.2272	07N21W33ACBB	RAVALLI	300	211DBTL	bedrock	5.2	0.7
2000Q0328	141343	46.9007	-114.2048	13N21W12BCBD	MISSOULA	300	400BELT	bedrock	6.7	0.7
2000Q1116	140366	45.9543	-114.1499	02N21W01CDBA	RAVALLI	280	211DBTL	bedrock	7.3	0.7
1999Q0240	143756	47.1591	-113.4196	16N14W07BDDA	MISSOULA	155	400BELT	bedrock	7.4	0.8
1999Q0348	74215	47.3818	-115.3984	19N30W27ABCD	MINERAL	350	400BELT	bedrock	7.5	0.8
2000Q0501	166075	47.1501	-114.8385	16N26W13BBCC	MINERAL	295	400BELT	bedrock	7.8	0.8

Tritium Data

Sample	GWIC ID	Latitude	Longitude	Location (TRS)	County	TOTAL_DEPT	AQUIFER	UNIT	TRITIUM	+/-
1998Q0906	64209	46.6273	-114.0974	10N20W15ACBBCC	RAVALLI	270	211DBTL	bedrock	8.4	0.8
2000Q0422	67966	46.8893	-113.8434	13N18W14BACC	MISSOULA	203	400BELT	bedrock	8.6	0.8
2000Q0247	162608	46.0202	-114.1855	03N21W15ABDA	RAVALLI	133	211DBTL	bedrock	8.6	0.9
2000Q0248	143019	46.0052	-114.2029	03N21W21AACD	RAVALLI	178	211DBTL	bedrock	9.9	0.9
2000Q0048	143685	46.1894	-114.057	05N20W14DBAB	RAVALLI	300	120PLNC	bedrock	10.1	0.9
2000Q0419	71300	46.9908	-114.4141	14N22W08BABC	MISSOULA	219	400BELT	bedrock	10.2	0.9
2000Q0208	173458	46.1048	-114.2417	04N21W17BCBB	RAVALLI	133	211DBTL	bedrock	11.5	0.9
1999Q0831	52804	46.1876	-114.101	05N20W16DBCA	RAVALLI	200	120PLNC	bedrock	13.2	1.1
2000Q0496	72209	47.0647	-114.7912	15N25W17BABC	MINERAL	235	400BELT	bedrock	14.4	1.1
2000Q0495	165985	47.0151	-114.6811	15N24W31ACDA	MINERAL	440	400BELT	bedrock	17.7	1.4
1999Q0745	164714	46.2787	-114.0216	06N19W18BDDC	RAVALLI	68	120PLNC	bedrock	19.1	1.4
2000Q0322	172449	45.9278	-114.1251	02N20W18AACD	RAVALLI	150	211DBTL	bedrock	22.8	1.7

APPENDIX C

Trace Element Data

Trace Element Data

Sample No.	latitude	longitude	Sample description	As_ppm	Ag_ppm	Al %	B_ppm	Ba_ppm	Be_ppm
2006-25	46.18189	-114.06133	Skalkaho granite	2.7	0.01	0.29	<10	10	0.35
2006-26	46.18101	-114.06423	Skalkaho granite	0.9	0.02	0.35	<10	10	0.33
2006-27A	46.17713	-114.05144	Apilite dike in meta-belt	1	0.01	0.99	<10	20	1.12
2006-27C	46.17714	-114.05150	Leucocratic granite	0.5	0.02	0.31	<10	20	0.2
2006-29	46.18250	-114.14146	Taf-Grantsdale Cem	3.2	0.75	1.53	<10	70	0.71
2006-30	46.18114	-114.08433	Taf-Bitt Irr Ditch	73.9	0.24	1.44	<10	140	2.18
2006-31	46.29338	-113.93320	Willow Cr pluton-fresh	0.7	0.01	0.51	<10	70	0.14
2006-33	46.29578	-113.91559	Willow Cr pluton-nr contact	0.7	0	0.58	<10	180	0.15
2006-34	46.29500	-114.01392	Eolian or Qglm beach	9.1	0.08	1.67	10	150	0.69
2006-35	46.30060	-114.04384	Willow Cr pluton	0.3	0	0.38	<10	70	0.09
2006-36B	46.32111	-114.03977	Taf (or Qt)-high in section	2	0.04	1.25	<10	100	0.62
2006-36C	46.32185	-114.03763	Taf-low in section	2.6	0.06	2.61	<10	110	1.29
2006-36D	46.31787	-114.03841	Willow Cr pluton-weathered	0.4	0.03	0.57	<10	60	0.1
2006-37	46.27664	-114.03806	Taf-rdcut nr Charley Gulch	3	0.08	3.27	<10	450	2.13
2006-38	46.27795	-114.01245	Willow Cr pluton nr Calf Cr	0.8	0.03	0.63	<10	90	0.3
2006-39	46.27670	-114.08562	Taf (Qao?)- Ham Heights	2.4	0.07	2.44	<10	100	1.85
2006-40	46.17740	-114.05801	Skalkaho granite	1.1	0	0.41	<10	20	0.15

Trace Element Data, *Continued, part 2*

Sample No.	Bi_ppm	Ca %	Cd_ppm	Ce_ppm	Co_ppm	Cr_ppm	Cs_ppm	Cu_ppm	Fe %	Ga_ppm	Ge_ppm	Hf_ppm
2006-25	0.03	0.07	0.05	43.3	0.5	3	0.38	3.7	0.78	1.5	0.05	0.04
2006-26	0.03	0.09	0.04	31.5	0.5	3	0.46	3.1	0.68	2.05	0	0.03
2006-27A	0.03	1.08	0.05	51.2	1.8	1	2.71	30.2	0.96	3.68	0.09	0.02
2006-27C	0.03	0.42	0.03	38.8	0.8	5	0.98	8.4	0.75	2.12	0.07	0.03
2006-29	0.22	0.26	0.14	36.3	5.1	11	2.36	12.2	1.44	4.98	0.09	0.35
2006-30	0.24	0.43	0.04	23.2	5.2	17	1.79	21.3	4.32	5.41	1.33	0.64
2006-31	0.03	0.19	0.03	37	1.3	6	1.13	2.9	1.01	3.38	0.06	0.02
2006-33	0.02	0.16	0.04	41.5	1.6	6	2.67	5.6	1.19	4.4	0.06	0.04
2006-34	0.15	5.56	0.11	30.5	5.1	12	2.22	12.8	1.63	5.82	0.13	0.14
2006-35	0.01	0.06	0.04	17.35	0.9	5	0.35	3.3	0.71	1.94	0	0.09
2006-36B	0.14	4.69	0.04	26.4	3.7	12	3.35	7.5	1.19	4.16	0.17	0.15
2006-36C	0.29	0.69	0.1	33.4	4.9	20	4.68	10.5	2.17	8.58	0.19	0.39
2006-36D	0	0.17	0.05	33.9	1.4	4	0.72	3.5	1	3.34	0.08	0.03
2006-37	0.35	0.98	0.13	56.1	6.6	10	2.12	19.5	2.77	10.05	0.21	1.14
2006-38	0.02	0.07	0.03	17.25	1.2	4	0.6	3.5	0.93	3.01	0	0.04
2006-39	0.26	0.47	0.02	55.8	9.7	12	2.74	10.7	2.44	8.99	0.15	0.85
2006-40	0.04	0.11	0.03	24.7	0.6	3	0.27	2.8	0.84	2.29	0	0.02

Notes. Qglm, Quaternary glacial Lake Missoula sediments (fine-grained); Qt, Quaternary talus; Taf, Tertiary alluvium, fine-grained; Bitt Irr Ditch, Bitterroot Irrigation big ditch; Ham Heights, Hamilton Heights.

Trace Element Data, *Continued, part 3*

Sample No.	Hg_ppm	In_ppm	K %	La_ppm	Li_ppm	Mg %	Mn_ppm	Mo_ppm	Na %	Nb_ppm	Ni_ppm
2006-25	0.02	0.006	0.08	24.6	2.6	0.05	88	0.24	0.03	0.51	0.8
2006-26	0.01	0.006	0.12	15.3	4.9	0.08	173	0.8	0.03	0.72	0.6
2006-27A	0.03	0.01	0.15	28.9	9.4	0.49	92	0.09	0.02	0	0.7
2006-27C	0.02	0.019	0.15	19.6	7.1	0.12	165	0.19	0.04	1.52	0.9
2006-29	0.02	0.022	0.27	18.9	9.7	0.33	258	0.22	0.01	0.98	6.5
2006-30	0.16	0.031	0.1	14.8	20	0.65	127	0.86	0.01	0.38	11.2
2006-31	0.01	0.006	0.24	18.8	17.6	0.22	228	0.15	0.04	0.98	0.8
2006-33	0.01	0.009	0.35	20.9	16.8	0.25	204	0.21	0.05	1.38	1.3
2006-34	0.02	0.02	0.43	16.2	17.4	0.78	254	0.28	0.06	2.23	9.6
2006-35	0	0.005	0.18	8.5	7.1	0.13	74	0.11	0.04	0.58	0.6
2006-36B	0.02	0.02	0.47	13.9	15.9	0.77	123	0.11	0.03	1.51	7.3
2006-36C	0.03	0.044	0.65	23.6	21.9	1.01	179	0.14	0.02	1.99	12
2006-36D	0.01	0	0.25	19.4	7.6	0.21	129	0.24	0.03	0.67	1.7
2006-37	0.08	0.073	0.21	36.7	17.3	0.83	501	0.19	0.02	0.14	8.8
2006-38	0.01	0	0.26	7.9	13.9	0.16	224	0.47	0.03	1.82	0.8
2006-39	0.15	0.041	0.29	26	13.4	0.65	172	0.1	0.01	0.13	8.2
2006-40	0	0.005	0.13	12	7.4	0.09	242	0.96	0.03	1.75	0.8

Trace Element Data, *Continued, part 4*

Sample No.	Pb_ppm	Rb_ppm	Re_ppm	S %	Sb_ppm	Sc_ppm	Se_ppm	Sn_ppm	Sr_ppm	Ta_ppm	Te_ppm	Th_ppm
2006-25	8.2	7.2	<0.001	0	0.11	0.5	0	0.3	5.8	<0.01	0.01	10.5
2006-26	13.2	10.6	<0.001	0	0.08	0.5	0	0.3	5.7	<0.01	0	8.7
2006-27A	6.1	15.4	<0.001	0.01	0.14	1	0	0.2	21.6	<0.01	0.01	6.8
2006-27C	7	17	<0.001	0.01	0.15	2.2	0	1	6.2	<0.01	0.01	9.2
2006-29	7.7	35.9	<0.001	0.01	0.15	3.7	0.3	0.8	25.1	<0.01	0.02	4.1
2006-30	5.1	17.8	<0.001	0.01	0.69	5.3	0.7	0.8	52.5	<0.01	0.03	6.7
2006-31	4.3	24.1	<0.001	0	0.08	1	0	0.4	17.6	<0.01	0	5.8
2006-33	4.6	33.6	<0.001	0.01	0.1	2.3	0	0.7	16.3	<0.01	0	4.9
2006-34	5.4	39.3	<0.001	0.06	0.39	3.6	0.5	0.8	130.5	<0.01	0.03	4.1
2006-35	3.1	15.3	<0.001	0	0	1.1	0	0.4	18.4	<0.01	0	2.6
2006-36B	2.7	45.2	<0.001	0.02	0.11	3	0.5	0.8	58	<0.01	0.03	4.6
2006-36C	6	70.5	<0.001	0.02	0.13	5	0.5	1.6	14.2	<0.01	0.02	6
2006-36D	3	23.5	<0.001	0	0.07	1.6	0.3	0.5	14.6	<0.01	0	4
2006-37	12.8	29.4	<0.001	0.01	0.67	10.5	1	1.9	47.5	0.01	0.05	8.8
2006-38	8.3	21.6	<0.001	0.01	0.07	0.8	0	0.3	18.7	<0.01	0.01	4.2
2006-39	8.5	43.3	<0.001	0	0.34	6.7	0.4	1.4	37.2	<0.01	0.02	8.9
2006-40	9.5	12.2	<0.001	0.02	0.1	0.7	0	0.4	7.5	<0.01	0	9.5

Trace Element Data, *Continued, part 5*

Sample No.	Tl_ppm	U_ppm	V_ppm	W_ppm	Y_ppm	Zn_ppm	Zr_ppm
2006-25	0.03	0.65	3	1.25	10.35	28	1.2
2006-26	0.05	0.69	2	0.23	4.51	29	1
2006-27A	0.04	0.46	7	0.26	8.23	28	0
2006-27C	0.09	0.73	2	0.28	5.53	24	1.1
2006-29	0.19	1.17	26	0.09	10.25	40	13.1
2006-30	0.14	7.06	128	1.94	17.75	34	25.7
2006-31	0.11	1.25	6	0.07	3.56	38	0.8
2006-33	0.15	0.58	13	0.15	7.64	33	1.2
2006-34	0.16	1.08	38	0.37	9.49	46	7.1
2006-35	0.06	0.38	5	0	2.89	20	2.3
2006-36B	0.18	0.53	19	0.16	9.29	15	6.6
2006-36C	0.33	0.65	26	0.08	20.9	36	16.2
2006-36D	0.13	0.8	11	0.1	5.15	33	1.1
2006-37	0.27	0.7	41	0.17	47.4	55	54.6
2006-38	0.12	0.61	6	0.08	2.19	35	1.5
2006-39	0.22	1.91	36	0.06	14.85	45	29.9
2006-40	0.04	0.41	2	0.32	5.05	30	0.9

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