Groundwater Quality in Basin-Fill and Bedrock Aquifers, Deer Lodge, Granite, Powell, and Silver Bow Counties, Montana

By

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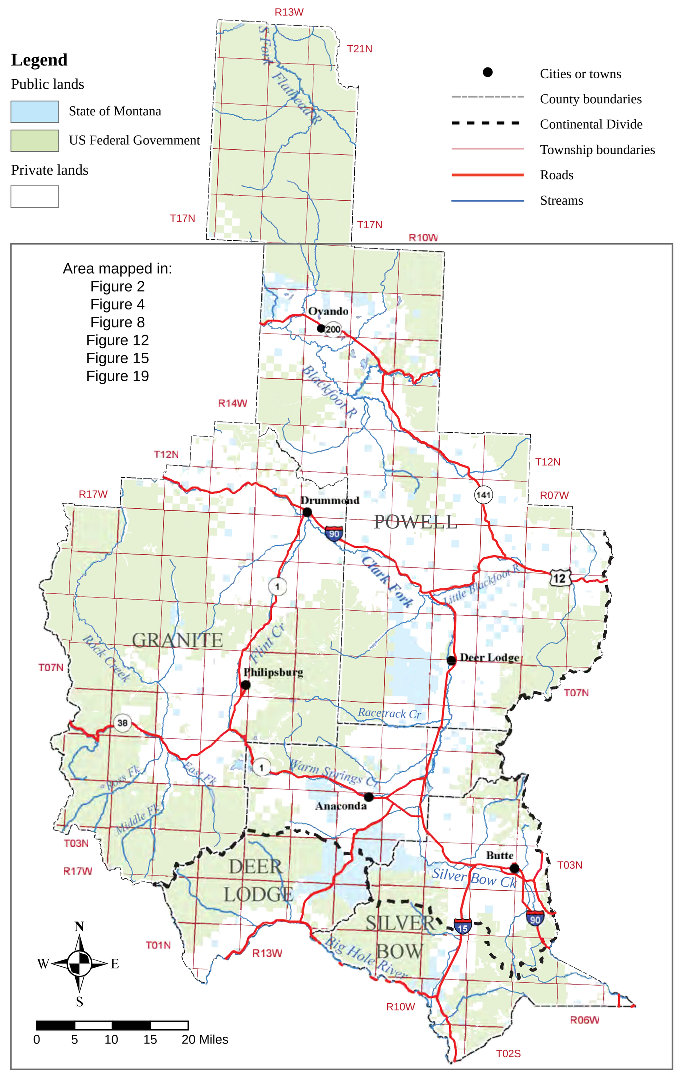


Figure 1. Study area map with land ownership information.

Introduction

This plate describes the quality of water collected from the basin-fill and bedrock aquifers in the Upper Clark Fork Ground Water Characterization area (Granite, Powell, Deer Lodge, and Silver Bow counties, fig. 1). The consolidated-bedrock and basin-fill aquifers provide water for municipal, agricultural, and residential use. The maps and graphs on this plate describe the distribution of total dissolved solids, water types, nitrate, arsenic, and selected environmental isotopes within the principal aquifers. The results presented on this plate are designed to provide baseline data for effective use and management of groundwater resources in the Upper Clark Fork area. The information will be useful for addressing issues such as the effects of land use on groundwater quality, source-water protection, and developing monitoring strategies.

Physical setting

The Upper Clark Fork study area includes Deer Lodge, Granite, Powell, and Silver Bow Counties. The area covers 5,520 square miles; about 62 percent is administered by either Federal or State government, and the remaining 38 percent is privately owned (fig. 1). Much of the Federal and State-administered land is mountainous, undeveloped, and essentially uninhabited. The estimated 2009 population of the study area was about 51,700 people. The four principal population centers, Butte, Anaconda, Deer Lodge, and Phillipsburg, account for 89 percent of the area's residents. The rest of the study area's population occurs in small towns, or is spread across rural acreage. The land-surface altitude ranges from about 3,600 ft where the Clark Fork River crosses the Granite–Missoula county line to more than 10,000 ft in the Highland Mountains along the study area's southeast border.

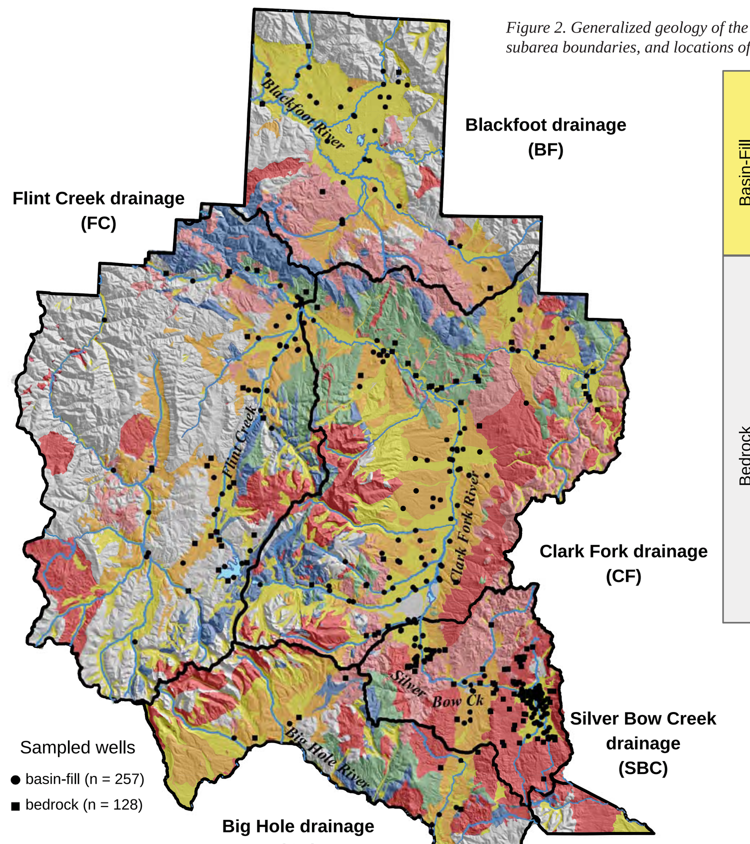
The climate is typical of mountainous areas in southwestern Montana. Temperature generally fluctuates widely between summer and winter. The mountainous areas have long. cold winters and cool summers, whereas the valleys are warmer. Average monthly maximum temperature reaches 84°F in July at Drummond (elevation 3,940 ft), and the average monthly minimum reaches 3°F in February at the Moulton Reservoir (elevation 6,700 ft), north of Butte. Average annual precipitation ranges from more than 40 in in the high mountain areas to less than 11 in on the valley floors. Most of the precipitation falls as snow in the mountains. Snowmelt contributes substantially to spring and summer streamflow.

The Upper Clark Fork Area is part of the Northern Rocky Mountains physiographic province, where north- to northwest-trending mountain ranges separate intermontane valleys. Most of the valleys are drained by the Clark Fork River and its tributaries. The southern edge of the study area is drained by the Big Hole River. The area consists of bedrock-cored mountains that separate large valleys. The principal water-yielding aquifers occur in the basin-fill deposits that range in age from Tertiary to Quaternary. Unconsolidated Quaternary surficial sediments in the floodplains and terraces along modern streams typically include sand, gravel, silt, and lesser amounts of clay; in some areas the deposits are glacially deposited till (gravelly clay, silt, sand, and boulders) and outwash (sand and gravel). These surficial deposits are typically less than 70 ft thick, but in a few places, notably in the Blackfoot River and Nevada Creek, the till and outwash may be more than 200 ft thick. Tertiary sediments typically underlie or flank the Quaternary sediments and are generally layered, poorly consolidated deposits that include clay, silt, sand, gravel, conglomerate, shale, sandstone, and volcanic ash; they may include minor amounts of limestone, coal, and volcanic rock. Typically the materials are more consolidated at depth, and if consolidated, are often fractured.

The mountainous areas that surround the valleys are composed of Protozoic meta-sediments of the Belt Supergroup, Paleozoic sandstones and limestones, and volcanic and intrusive rocks of Cretaceous and Tertiary age. A generalized geologic map showing the surficial distribution of major geologic units is presented in figure 2. The geologic setting of the Upper Clark Fork River Groundwater Characterization Area is described in detail in Montana Groundwater Assessment Atlas 5, Map 2 (Smith, 2009).

The principal aquifers that store and yield most of the groundwater used in the Upper Clark Fork Area occur in the unconsolidated basin-fill sediments at various depths within intermontane valleys and in consolidated rocks (bedrock) in the mountains. The basin-fill aquifers were divided into two groups for this analysis: (1) shallow-surficial, unconfined aquifers generally within 60 ft of the land surface, and (2) deep-confined to semi-confined aquifers buried at depths greater than 60 ft. The deep aquifers commonly occur in Tertiary sediments. Fractured bedrock around the valley margins and a few consolidated sedimentary rock units represent secondary aquifers. Groundwater in the mountainous areas is controlled by joints and fractures in the rock. In general, the bedrock has sufficient fracture permeability to yield water to wells; however, the number, size, and orientation of the openings is unpredictable and can change abruptly over short distances, resulting in large variations in well yields and depths. The surficial coarse-grained basin-fill deposits are typically characterized by high permeability and yield, and are strongly connected to surface waters. Permeability in tertiary aquifers varies, with coarse high-yield lenses present within larger sequences of fine-grained deposits with lower permeability and yield. 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. Figure 3 is a diagrammatic cross section through the Deer Lodge Valley showing general relationships between bedrock aquifers and basin-fill aquifers, and general groundwater flow paths. The hydrogeologic setting, groundwater flow, and groundwater fluctuations are described in detail in Map 3 of this series (Waren and LaFave, 2011).

Figure 2. Generalized geology of the Upper Clark Fork Area (modified from Smith, 2009), subarea boundaries, and locations of sample sites.



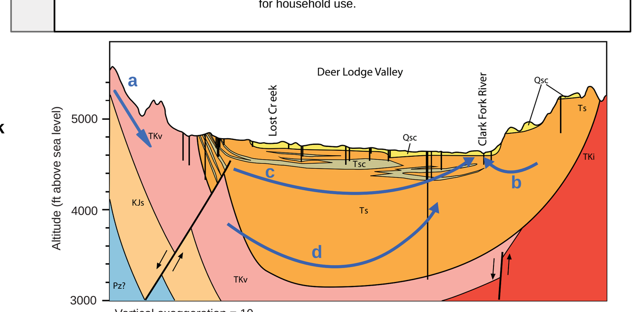


Figure 3. Diagrammatic cross section illustrating stratigraphic relationships between bedrock and basin fill (from Carstarphen and others, 2004) with groundwater flow paths added (blue arrows). The groundwater flow paths shown illustrate example paths of groundwater flowing through bedrock materials (a) and shallow, intermediate, and deep paths through basinfill aquifers (a, b, and c, respectively).

Author's Note: This map is part of the Montana Bureau of Mines and Geology (MBMG) Groundwater Assessment Atlas for the Upper Clark Fork River Area. It is intended to stand alone and describe a single hydrogeologic aspect of the study area, although many of the area's hydrogeologic features are interrelated. For an integrated view of the hydrogeology of the Upper Clark Fork River Area, the reader is referred to other maps and reports of Montana Groundwater Assessment Atlas 5.

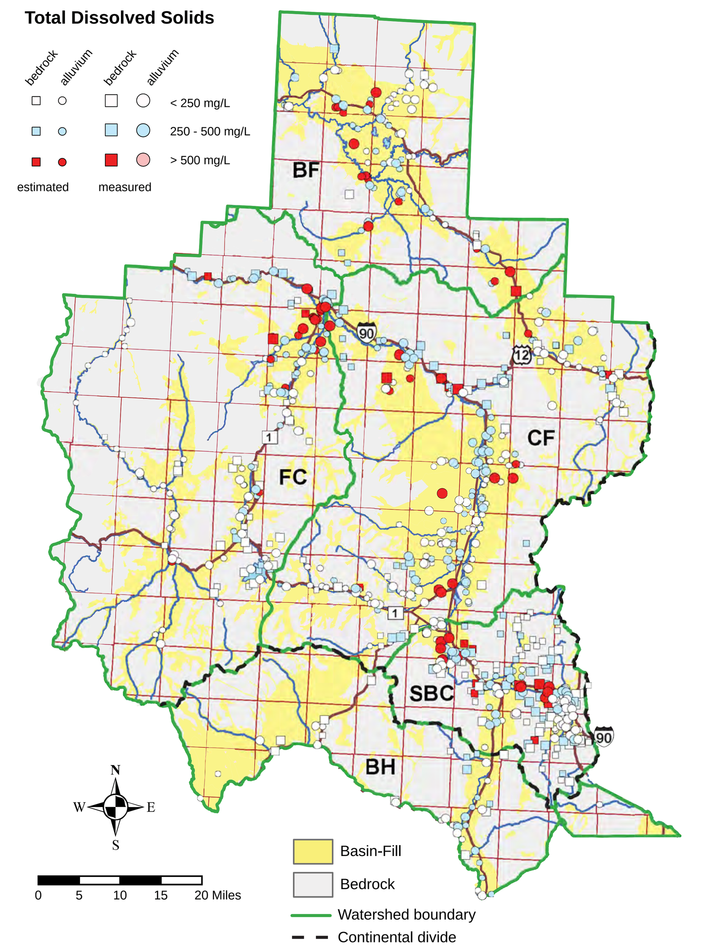
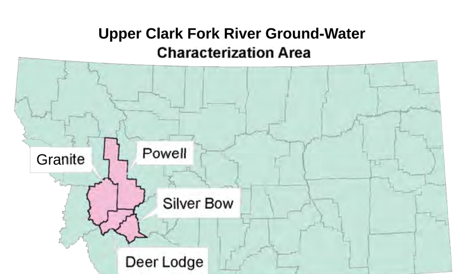


Figure 4. Distribution of dissolved solids in the basin-fill and bedrock aquifers. Map shows measured (large symbols) and estimated (small symbols) concentrations based on field specific conductance measurements .



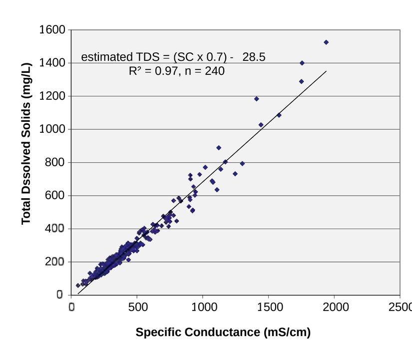


Figure 5. Relationship between field specific conductance and total dissolved solids (TDS) measurements, used to estimate TDS at inventoried sites.

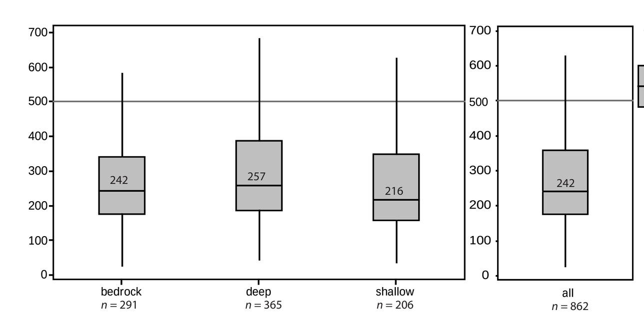


Figure 6. Distribution of measured and estimated dissolved solids concentrations in the basin-fill and bedrock aquifers.

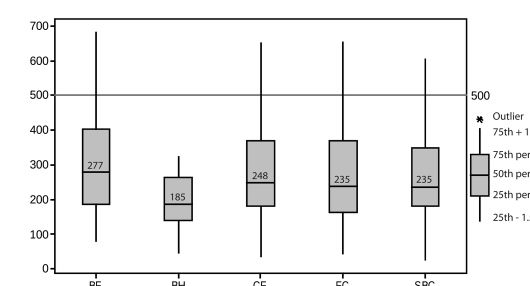


Figure 7. Distribution of measured and estimated dissolved solids concentrations in the subareas of the Upper Clark Fork area.

For this report, the water-quality results are discussed for the: (1) shallow basin-fill, (2) deep basin-fill, and (3) bedrock aquifers. Also, because of differences in the geology and groundwater flow, part of the groundwater-quality discussion is divided into subareas. These subareas are defined by major valleys and/or watershed boundaries (fig. 2) and include:

- Silver Bow Creek • **SBC** (Summit Valley, from the headwaters of Blacktail and Silver Bow Creeks to the confluence with Mill Creek near Warm Springs ponds),
- Clark Fork drainage • **CF** (Deer Lodge Valley from Warm Springs Ponds to the confluence of Clark Fork River and Flint Creek near Drummond),
- Blackfoot drainage • **BF** (including Nevada Creek and the North Fork of the Blackfoot River),
- Flint Creek Drainage • **FC** (including Flint Creek and Rock Creek drainage basins), and
- Big Hole drainage • **BH** (includes the part of the Big Hole basin that is in Silver Bow and Deer Lodge counties).

Sample sites and water-quality data

The data used on this plate to characterize groundwater quality include both new and historical data obtained from the Montana Ground Water Information Center. As part of the Upper Clark Fork Ground-Water Characterization study, MBMG staff sampled 240 wells between 2000 and 2003 (Carstarphen and others, 2004). Groundwater samples were obtained from domestic, stock, municipal, and monitor wells and analyzed for major-ion and trace-metal concentrations by the MBMG Analytical Laboratory. Samples from an additional 8 sites were analyzed for nitrate only. Isotope samples were also obtained from selected wells. A subset of 80 samples was analyzed for tritium, and 14 samples for deuterium and oxygen-18 by the University of Waterloo Environmental Isotope Laboratory. Field measurements of water specific conductance, pH, and temperature also were obtained at the sampled wells. To ensure acquisition of a representative sample, each well was pumped prior to sample collection until the field parameters stabilized and at least three well-casing volumes were removed. Sample sites were selected in an attempt to obtain the best possible areal coverage. Efforts were also made to collect samples along transects of presumed groundwater flow and to sample groups of wells in close proximity completed at different depths.

Data from an additional 145 ground water samples collected by the MBMG or the U.S. Geological Survey between 1980 and 2007 were used to augment the primary data. Most of the additional samples are from residential wells in the Silver Bow Creek watershed. Data from wells in areas of known environmental impacts were not included in this analysis. Historical data included in the study met these basic criteria: (1) a complete determination of major-ion concentrations, (2) charge balance within 10 percent, and (3) known well-completion information. The additional data improve the spatial resolution and enable a more comprehensive interpretation of the distribution of dissolved solids, nitrate, and arsenic in the upper Clark Fork area. All the sample sites are shown on figure 2, and all the data presented in this report are available online from the Montana Ground Water Information Center (http://mbmggwic.mtech.edu/).

Groundwater quality

The total dissolved solids content and the levels of certain major ions and trace elements can affect the suitability of water for use. The U.S. Environmental Protection Agency (2002) has established two types of drinking water standards for public water supply systems, primary and secondary. The primary maximum contaminant levels (MCL) are set to protect human health, the secondary maximum contaminant levels (SMCL) are set for aesthetic reasons (such as taste, odor, color) and do not represent a health threat. The water-quality data used in this study were compared to drinking-water standards as a basis for evaluating the suitability of the sampled groundwater for use. In general, groundwater in the Upper Clark Fork Basin is of excellent chemical quality and consistent in composition; however, in places concentrations of nitrate and arsenic are present that exceed the drinking water standards.

Total Dissolved Solids

The total dissolved solids (TDS) value is the sum of the major cations and anions expressed in milligrams per liter (mg/L). Dissolved solids in groundwater are a result of the initial chemistry of the recharge water and subsequent interactions of that water with soils and aquifer materials. Increased residence time and physical contact between groundwater and the aquifer materials increases the potential for the water to react, resulting in more dissolution of the minerals. The dissolved solids concentration is a general indicator of water quality and suitability for use: the lower the total, the better the water quality. Figure 4 shows the distribution of TDS across the study area. To highlight areal patterns the concentrations are presented in three categories: (1) low (less than 250 mg/L, white symbols), (2) intermediate (between 250 and 500 mg/L, blue symbols), and (3) high (greater than 500 mg/L, red symbols). In all the maps square symbols represent sampled wells in bedrock aquifers and circles represent sampled wells in basin-fill aquifers.

There are 384 sites with a laboratory-measured value of TDS (fig. 4); the laboratory data were supplemented by estimates of TDS derived from field specific-conductance measurements made at an additional 478 sites using the relation shown in figure 5. Overall, concentrations were typically below the 500 mg/L SMCL, indicating good quality water. Of the 862 sites with a measured or estimated value of TDS, concentrations ranged from 26 to 1,646 mg/L with a median of 242 mg/L; about 11%, or 93 samples, had concentrations greater than 500 mg/L, mostly from deep basin-fill aquifers (47), followed by bedrock (26) and shallow basin-fill aquifers (20).

There was little variation in TDS among the three units; in general concentrations were greater in the deep aquifers. Median values ranged from 216 mg/L for shallow to 257 mg/L for the deep basin-fill aquifers; bedrock TDS samples had a median concentration of 242 (fig. 6). TDS concentrations were also consistent among the different subareas (fig. 7). Aquifers in the Big Hole subarea had the lowest TDS concentrations, with a median value of 185 mg/L, and no samples exceeding 500 mg/L. Median values from the other four areas ranged from 235 to 277 mg/L (fig. 7). Aquifers in the Blackfoot subarea had the highest TDS concentrations overall, with 16 percent of the samples (16) exceeding 500 mg/L; most of the samples with elevated TDS (14) were obtained from deep basin-fill aquifers. Samples from the Clark Fork subarea had a median TDS concentration of 248 mg/L, with 7 percent (9) exceeding 500 mg/L. In both the Silver Bow Creek and Flint Creek subareas, the median TDS value was 235 mg/L, and in both areas 13 percent of the samples exceeded 500 mg/L.

In the Silver Bow Creek watershed, values greater than 500 mg/L are clustered in the northwest part of the Summit Valley (fig. 4), where Silver Bow Creek exits the valley through a bedrock canyon cut through granite of the Boulder Batholith, and further downstream near Fairmont Hot Springs where Silver Bow Creek emerges from a bedrock canyon cut through the Lowland Creek Volcanics (fig. 2). Values greater than 500 mg/L are also clustered around the town of Drummond near the confluence of Flint Creek and the Clark Fork River, and near Garrison Junction where Paleozoic sedimentary rocks are exposed at the surface (figs. 2, 4).

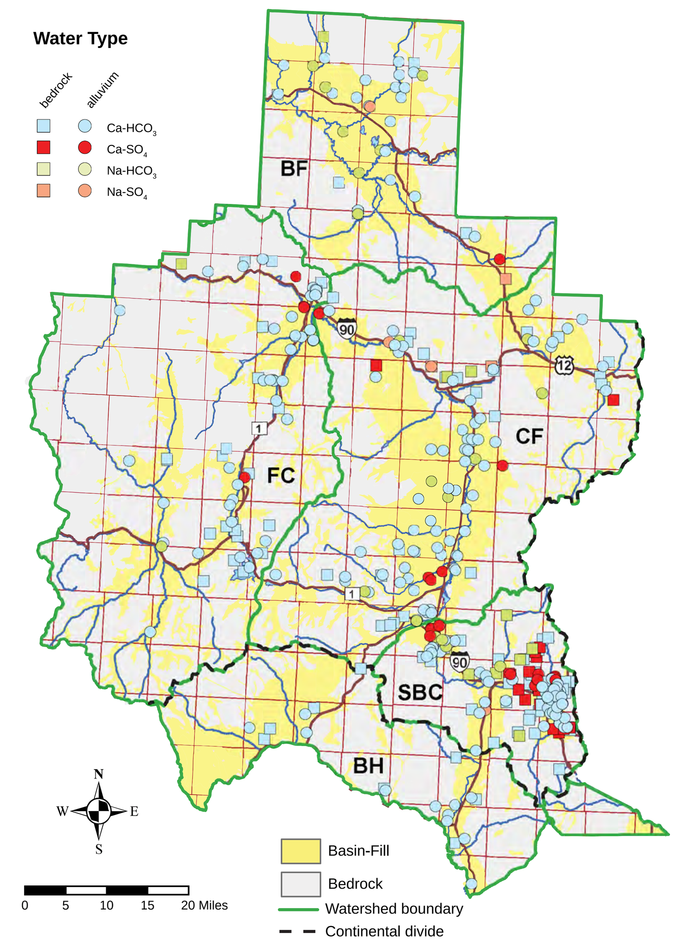


Figure 8. Distribution of water types; most of the sampled groundwater in the bedrock and basin-fill aquifers is a $Ca-HCO_3$ type water.

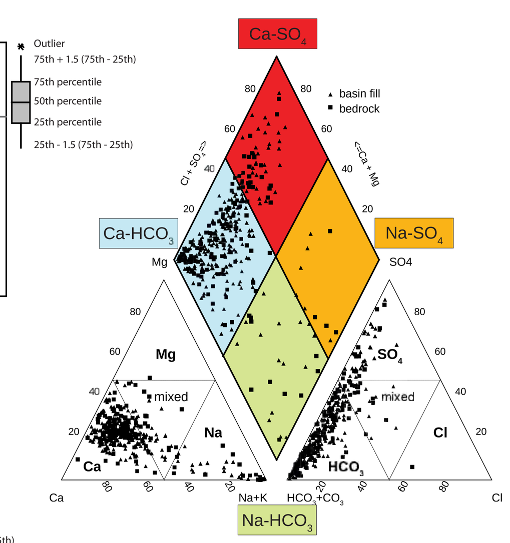


Figure 9. Piper diagram showing the relative major-ion composition of basin-fill and bedrock groundwater samples. The relative ion composition (in milliequivalents) is used to determine water types. Most of the groundwater samples are a calcium-bicarbonate ($Ca-HCO_3$) type water.

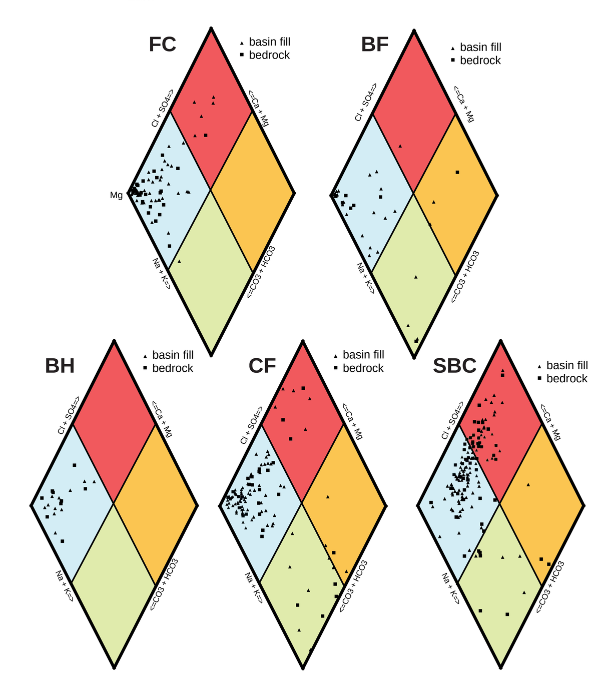


Figure 10. Water types for groundwater samples from each of the subareas. Groundwater from the Silver Bow Creek subarea (SBC) showed the most variability.

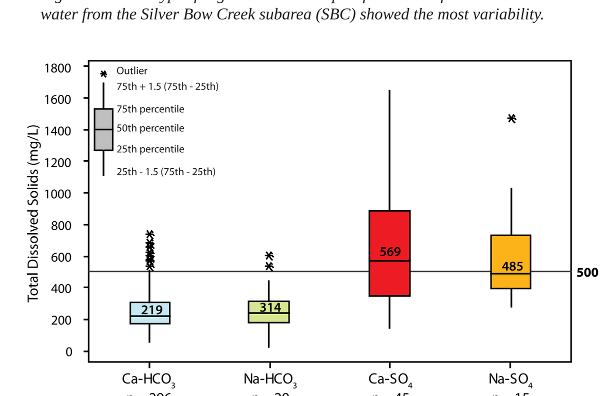


Figure 11. The calcium-bicarbonate and sodium-bicarbonate water is generally low in TDS, with concentrations typically well below the U.S. EPA 500 mg/L secondary MCL. The TDS of the calcium-sulfate and sodium-sulfate type water is much greater; the median concentrations for both types are very close to or exceed 500 mg/L.

Groundwater Types

Groundwater can be classified or "typed" by the relative percentages of major ions in solution. The quantities and types of major ions are influenced by: (1) differences in aquifer mineralogy and basin-fill composition, (2) the rate of groundwater flow, which controls the contact time between the water and aquifer materials; and (3) the chemical characteristics of water from the recharge areas. Based on the 384 groundwater analyses evaluated for this study, calcium (Ca) and sodium (Na) are the main cations, and bicarbonate (HCO_3) and sulfate (SO_4) are the main anions; magnesium (Mg) and chloride (Cl) were typically minor constituents. Therefore, sample results were grouped into four main water types: (1) $Ca-HCO_3$, (2) $Ca-SO_4$, (3) $Na-HCO_3$, and (4) $Na-SO_4$. The distribution of water types is shown in figure 8.

Trilinear Piper diagrams provide a way to graphically compare the relative percentages of major-ion concentrations for numerous samples. As shown in figure 9, most of the sampled groundwater (77 percent of samples) in the Upper Clark Fork area is a calcium-bicarbonate ($Ca-HCO_3$) type, followed by calcium-sulfate ($Ca-SO_4$) type. The uniform chemical signature and the low TDS concentrations suggest that recharge water is of good quality and that the aquifer materials are not very reactive. Samples from the shallow basin-fill displayed the most consistent water composition; 83 percent of the samples were $Ca-HCO_3$ type water, followed by 77 percent of the deep basin-fill samples and 71 percent of the bedrock samples.

Water from the Silver Bow Creek subarea displayed the most variability (fig. 10); 67 percent of the samples were a $Ca-HCO_3$ type, while 25 percent had a $Ca-SO_4$ signature. Most of the $Ca-SO_4$ type water was detected in the bedrock and basin-fill near where Silver Bow Creek exits the Summit Valley, west–southwest of Butte, and in the bedrock along the southern margin of the Summit Valley. A cluster of four shallow basin-fill wells upgradient of the Warm Springs ponds also had a $Ca-SO_4$ signature. In the Clark Fork and Flint Creek subareas, 12 and 9 percent, respectively, of the samples had a $Ca-SO_4$ signature; four of the samples were from deep basin-fill aquifers near Drummond, and three were from the deep basin-fill near the Warm Springs Ponds (figs. 8, 10).

Groundwater enriched in sulfate ($Ca-SO_4$ and $Na-SO_4$ types) also had greater TDS concentrations (fig. 11). The median TDS concentration of the samples with a Ca-SO4 signature was 569 mg/L, and those with a $Na-SO_4$ signature had a median TDS concentration of 485 mg/L. The samples with a $Ca-HCO_3$ signature had a median TDS of 218 mg/L, less than half that of the sulfate-dominated water.

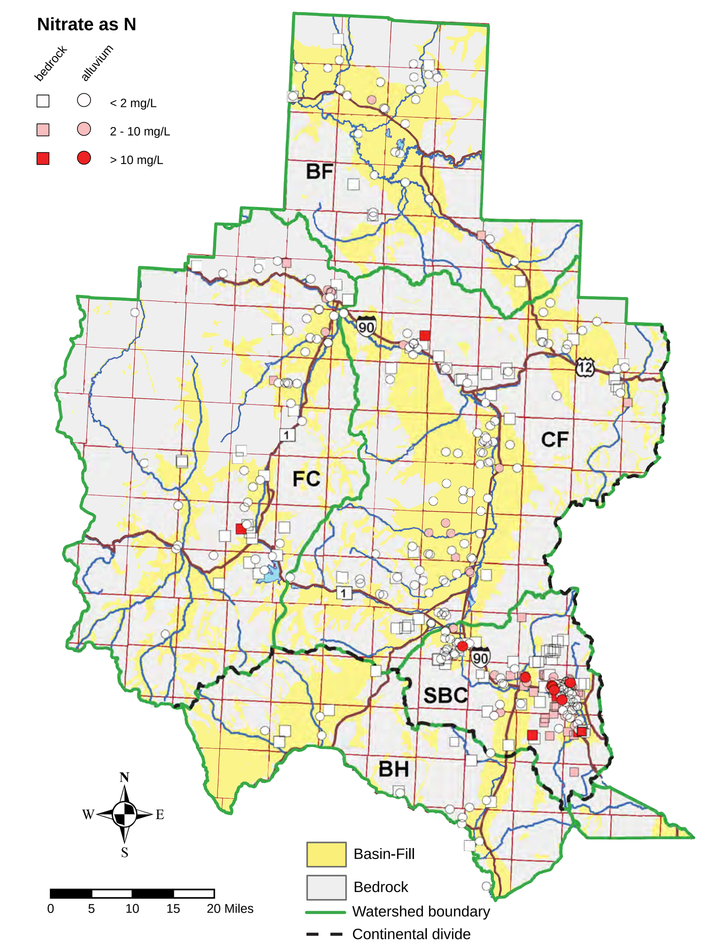


Figure 12. Distribution of nitratein the basin-fill and bedrock aquifers; concentrations were low except for the Silver Bow Creek subarea.

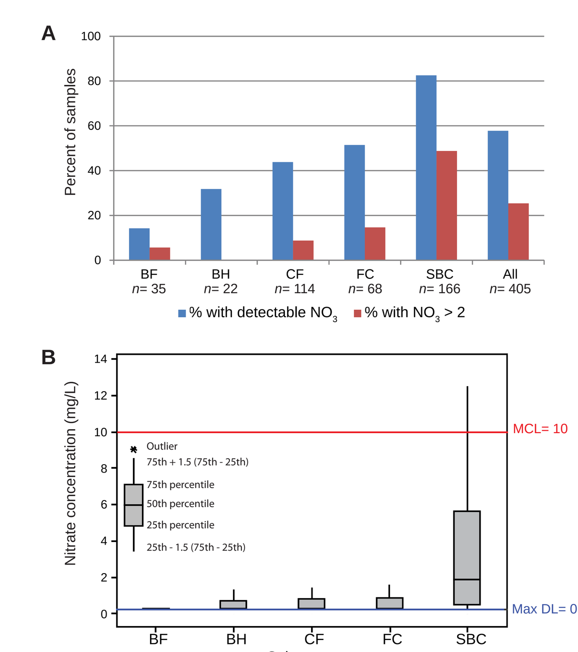


Figure 13. (A) The percent of samples with detectable nitrate, and the percent detected above 2 mg/L. (B) Summary of nitrate concentrations by subarea. Nitrate was detected more frequently and at higher concentrations in the Silver Bow Creek subarea.

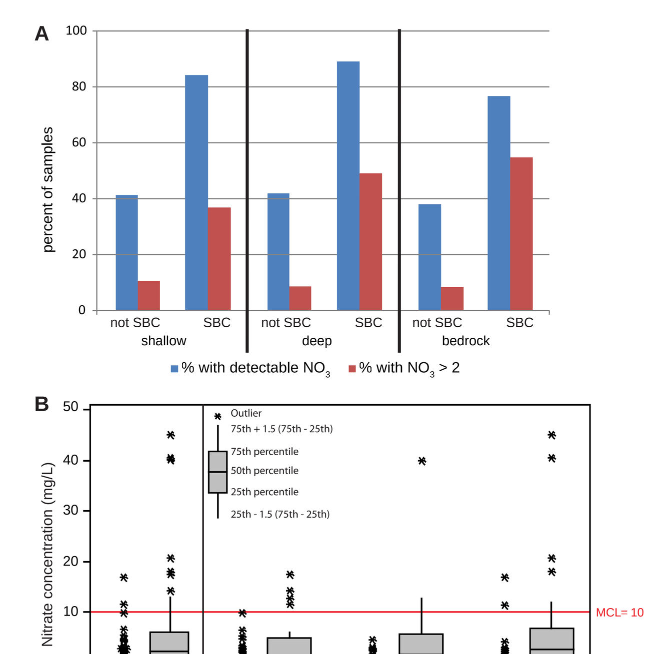


Figure 14. (A) The percent of samples with detectable nitrate, and the percent detected above 2 mg/L, and (B) Summary of nitrate concentrations by aquifer. The results are also grouped as to whether or not the samples are within or not within the Sliver Bow Creek (SBC) subarea. Nitrate concentrations were generally consistent between the different units but more elevated in the Silver Bow Creek subarea.

Nitrate

Nitrate concentrations in the Upper Clark Fork area are shown in figure 12. Nitrate (NO_3) is an essential nutrient for plant life, yet is potentially toxic to humans (especially infants) when present in drinking water at excessive concentrations. High levels of nitrate in well water typically indicate seepage from septic tanks, fertilizers, land application of animal wastes, or other nonpoint sources. On this map nitrate is reported as the sum of nitrite and nitrate as nitrogen. Naturally occurring or "background" concentrations in groundwater are less than 2 mg/L; concentrations greater than 2.0 mg/L may indicate effects of human activities (USGS, 1999).

On the map, concentrations were grouped into three reporting ranges:

(1) Low level—[nitrate not detected (less than 0.25 mg/L) or detected at concentrations less than 2 mg/L]: may reflect natural occurrence or minor land-use impacts (white symbols),
(2) Impacted—(nitrate detected at concentrations between 2 and 9.9 mg/L): elevated concentrations probably reflecting land-use impacts (pink symbols), and
(3) MCL exceedances—(nitrate detected at concentrations greater than or equal to 10 mg/L): elevated concentrations that represent a human-health risk (red symbols).

In general, nitrate concentrations were low. They ranged from less than the method detection limit of 0.25 to 44.7 mg/L, the median value was 0.53, and the mean was 2.02 mg/L. Of the 393 samples, 58 percent had nitrate concentrations above the method detection limit of 0.25 mg/L; 25 percent exceeded the 2 mg/L background concentration. However, the results varied considerably among the subareas. Concentrations in the Silver Bow Creek subarea were markedly higher than in the other areas, and skew the overall results (fig. 13). Outside of the Silver Bow Creek subarea, 91 percent of the samples were at or less than 2 mg/L; only two of the 239 samples exceeded the 10 mg/L MCL (fig. 12).

The overall concentrations and the frequency of nitrate detection within the Silver Bow Creek subarea were greater than in the other areas; only 51 percent of the samples were at or less than 2 mg/L, 13 samples exceeded the 10 mg/L health standard, and the median concentration was 1.9 mg/L, almost 15 times the median of the other areas. Most of the elevated concentrations are clustered in the upper part of the Silver Bow Creek subarea in the Summit Valley around the city of Butte (fig. 12). The elevated concentrations in and around Butte are likely caused by high nitrogen inputs related to septic discharge, leaking sewer pipes, and fertilizers applied to lawns and gardens, and natural conditions that favor transport such as soils with low organic carbon content and high infiltration capacities. See LaFave (2009) for a more detailed treatment of nitrate in the Summit Valley.

There was little variation in nitrate concentrations among the shallow and deep basin-fill and bedrock aquifers (fig. 14). Outside of the Silver Bow Creek subarea, the percent of samples with detectable nitrate ranged between 38 and 42% in the three units, and the percent of samples with concentrations greater than background (> 2 mg/L) ranged from 8 to 11% (fig. 14). Within the Silver Bow Creek subarea the concentrations were also consistent among the different units; however, the percentage of detections and the concentrations were considerably greater than in the other subareas. The percentages of samples with detectable nitrate ranged from 77 to 89%, and the percentage of samples greater than background ranged from 37 to 55% (fig. 14).

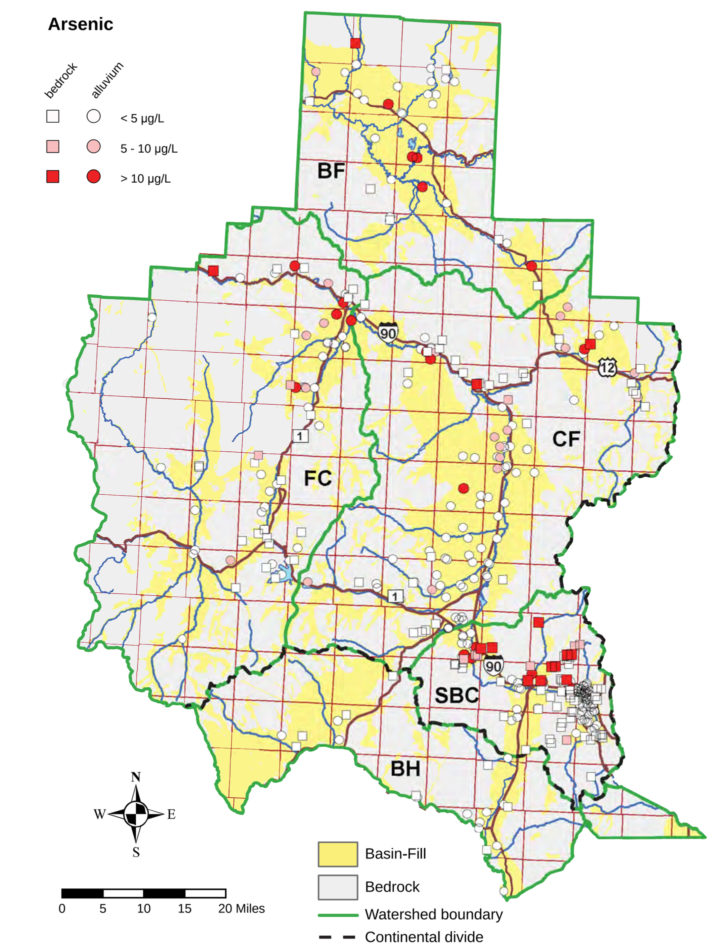


Figure 15. Distribution of arsenic in the basin-fill and bedrock aquifers.

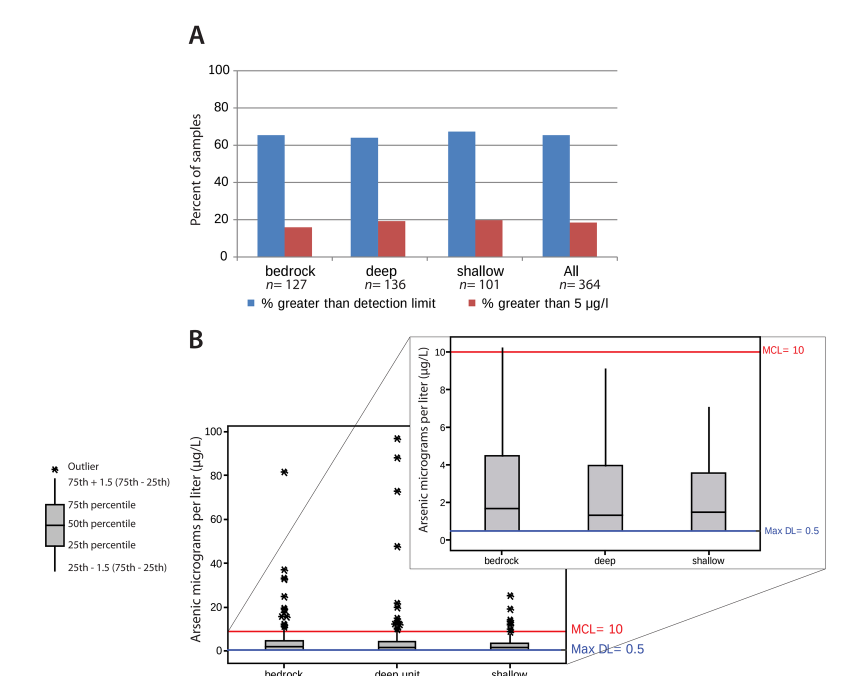


Figure 16. (A) The percent of samples with detectable arsenic, and the percent detected above 5 µg/L in each aquifer. (B) Summary of arsenic concentrations by aquifer. Arsenic detections and concentrations were uniform between the different units.

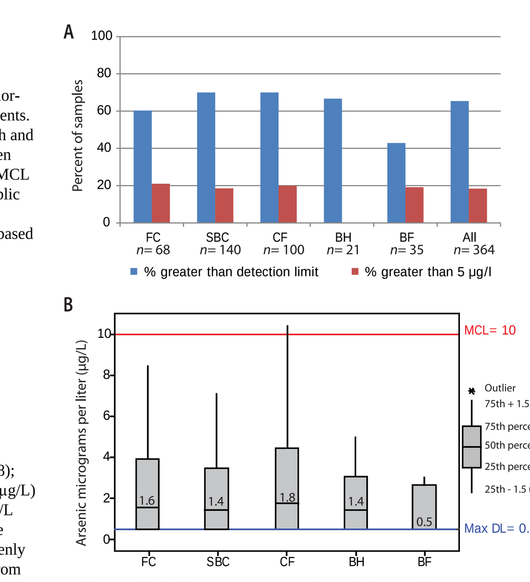


Figure 17. (A) The percent of samples with detectable arsenic, and the percent detected above 5 µg/L in each subarea. (B) Summary of arsenic concentrations by subarea.

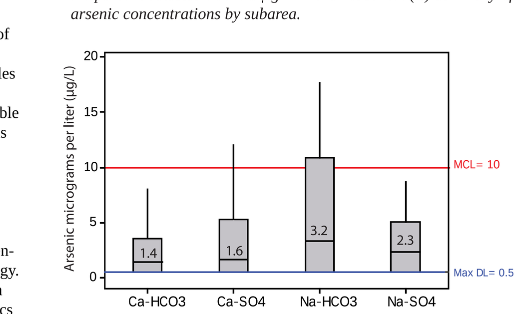


Figure 18. Arsenic concentrations were generally higher in water with sodium as the dominant cation.

Arsenic

Arsenic is a naturally occurring trace element that is commonly associated with certain igneous (volcanic), metamorphic, and sedimentary rocks, as well as geothermal environments. It is also associated with smelting and some pesticides (Welch and others, 1988). Arsenic can adversely affect human health when ingested at elevated concentrations; the U.S. EPA has set an MCL of 10 micrograms per liter (µg/L) for dissolved arsenic in public drinking water supplies.

Arsenic distribution is shown in figure 15; the map is based on concentrations from 364 sites. The concentrations were grouped into three reporting ranges:

(1) low level (not detected or less than 5 µg/L, white symbols),
(2) elevated (5 to 10 µg/L, pink symbols), most likely due to natural or geologic sources, and
(3) MCL exceedence (greater than 10 µg/L, red symbols), which are concentrations greater than the health standard for public drinking water.

Arsenic was detected in 65 percent of the samples (238); concentrations ranged below the method detection limit (0.5 µg/L) up to 96.8 µg/L and; 35 samples exceeded the MCL of 10 µg/L (figs. 15, 16). The median concentration was 1.5 ug/L and the mean was 4.4 ug/L. Samples with detectable arsenic were evenly distributed among the three main hydrologic units, ranging from 64 percent of the deep basin-fill aquifer samples to 67 percent of the bedrock aquifer samples (fig. 16). Elevated concentrations (greater than 5 µg/L) were somewhat more prevalent from bedrock aquifer samples (fig. 16A); the median concentration of the bedrock samples was 1.7 µg/L, slightly higher than the shallow (1.5 µg/L) and deep (1.3 µg/L) basin-fill aquifer samples (fig. 16).

The Blackfoot subarea had the lowest percent of detectable arsenic (43 percent); in the other subareas the arsenic detections ranged from 60 to 70 percent (fig. 17). There were no samples with elevated arsenic (greater than 5 µg/L) in the Big Hole subarea; in the other subareas 19 to 21 percent had elevated arsenic (fig. 17A), and median concentrations were less than 2 µg/L (fig. 17B).

In the Silver Bow Creek subarea, elevated arsenic concentrations (fig. 15) are associated with the igneous bedrock geology. Most of the samples that exceeded 10 µg/L were obtained from wells located near the contact between Lowland Creek Volcanics and the Boulder Batholith (Tertiary extrusive igneous rocks and Cretaceous intrusive igneous rocks; fig. 2).

Elevated arsenic concentrations were generally associated with sodium-bicarbonate or sodium-sulfate water (fig. 18).

Environmental Isotopes

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). Above-ground 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 1963–64 (Clark and Fritz, 1997).

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.

Tritium was analyzed in 79 water samples from the Upper Clark Fork area. Samples were obtained from fractured bedrock aquifers (33 samples), deep basin-fill aquifers (37 samples), and shallow basin-fill aquifers (9 samples). The tritium values ranged from less than 0.8 to 30.9 TU. The distribution of sampled sites is shown in figure 19. A qualitative interpretation of tritium "ages" based on Clark and Fritz (1997) was used to group the results into four reporting ranges on the map:

< 0.8 TU—sub-modern (pre-bomb)—recharged before 1952 (white symbols with a dot)
0.8–5 TU—sub-modern or a mixture of pre-bomb and recent recharge (white symbols)
5–15 TU—modern—recharged since 1990 (pink symbols)
> 15 TU—modern with some "bomb" tritium (red symbols)

Values for samples from each unit are shown in figure 20. There were notable differences in the tritium distribution among the different hydrologic units (fig. 20). The nine shallow-basin fill samples had tritium concentrations between 6 and 20 TU (median of 12.2 TU), a range that is most likely made up of water recharged within the past 15 years. Tritium was not detected (< 0.8 TU) in 9 of the 36 samples from the deep basin-fill, indicating groundwater in the vicinity of these wells was recharged prior to the early 1950s. Eight deep basin-fill samples had tritium values between 0.8 and 5 TU, indicating water recharged between the early 1950s and early 1960s, or a mixture of "older" and "younger" water. Nine deep basin-fill samples had modern tritium values, and 12 samples had tritium values greater than 15 TU, suggesting some component of recharge since the mid- to late-1960s when atmospheric tritium concentrations peaked. Samples from fractured bedrock aquifers showed the most variability, ranging from <0.8 to 30.90 TU. Seven samples did not contain detectable tritium, and six samples had tritium values between 0.8 and 5 TU. Fourteen of the bedrock samples were in the modern range (between 5 and 15 TU), and 6 were greater than 15 TU.

In the deep basin-fill and bedrock aquifers, tritium concentrations decrease with depth (fig. 21). With one exception, samples obtained from depths greater than 220 ft were a mixture of old and young water (0.8–5.0 TU) or submodern (< 0.8 TU), indicating that little or no or post-1950s recharge water has penetrated below 220 ft in the deep basin-fill and bedrock aquifers.

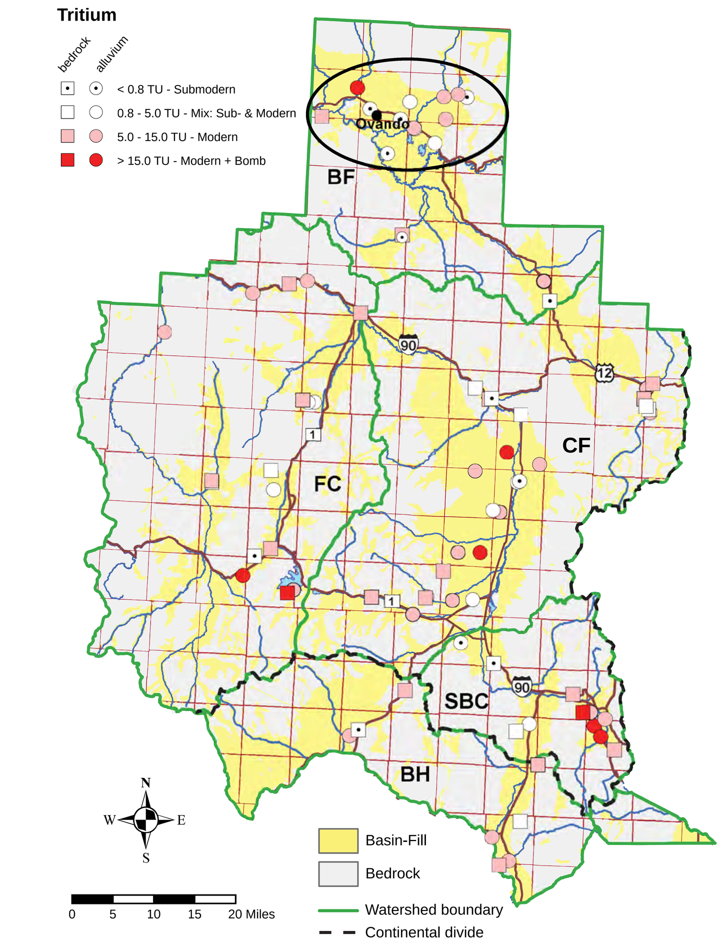


Figure 19. Distribution of tritium in the basin-fill and bedrock aquifers.

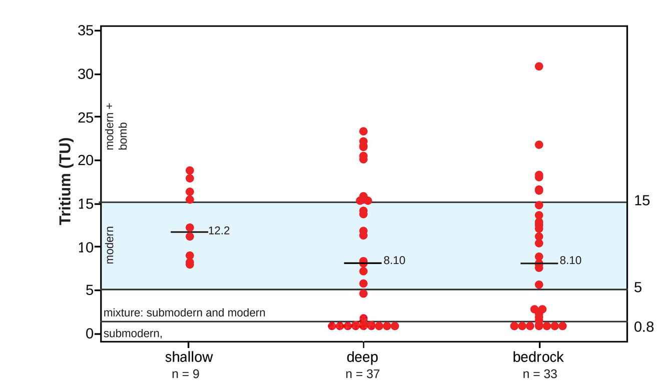


Figure 20. Tritium concentrations in the shallow basin-fill, deep basin-fill and bedrock aquifers. Median concentrations for each unit are indicated.

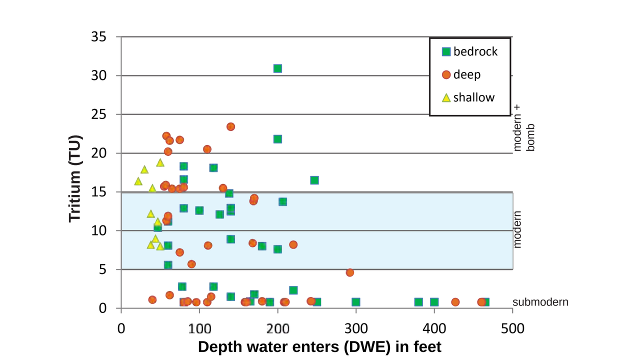


Figure 21. Tritium concentrations as a function of sample depth and aquifer. In general, tritium concentrations decrease with depth. There was no modern water detected below 250 ft.

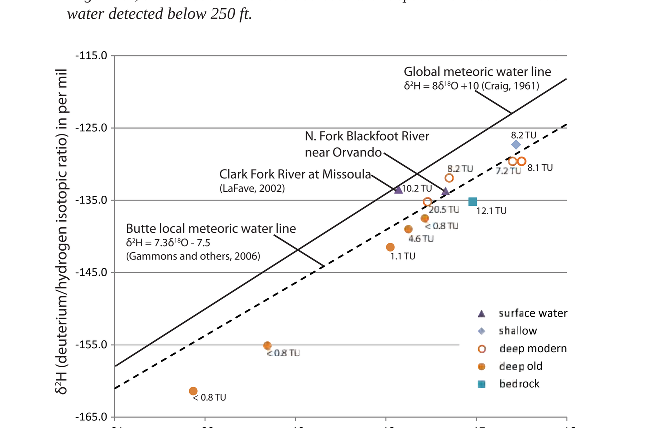


Figure 22. The relation between $\delta^{18}O$, δ^2H, and tritium for groundwater samples from the Ovando area. The samples plot close to the local meteoric water line for Butte, MT. In general, samples with little or no tritium had more negative $\delta^{18}O$ and δ^2H values.

Oxygen-18 and hydrogen-2

Groundwater from 11 wells located near Ovando (fig. 20) and a surface-water sample from the North Fork of the Blackfoot river were analyzed for ratios of the stable isotope of oxygen ($^{18}O/^{16}O$) and hydrogen ($^2H/H$). The isotopic ratio is expressed as the difference between the measured ratios of the samples and the reference water, divided by the ratio of the reference water. Vienna Standard Mean Ocean Water (VSMOW) is the standard reference for ^{18}O and deuterium (^2H) isotopes. The ratio is known as delta (δ) and is expressed in units of parts per thousand, or per mil (‰). For additional background on the utility isotopes in groundwater see Clark and Fritz (1997).

The $\delta^{18}O$ and δ^2H were plotted and compared to the Global Meteoric Water Line (Craig, 1961), and the local meteoric water line for Butte, MT (Gammons and others, 2006, fig. 22). Nine of the groundwater samples were from deep basin-fill aquifers, and sample depths ranged from 40 to 427 ft; one sample was from the shallow basin-fill (sample depth 38 ft) and one from a bedrock aquifer (sample depth 126 ft). All of the $\delta^{18}O$ and δ^2H results plot near the local water meteoric line, and most of the results are grouped together ($\delta^{18}O$ between -18 and -16, and δ^2H between -145 and -125), indicating a common meteoric origin of the groundwater. The surface-water sample from the Little Blackfoot River, and the results from a Clark Fork River sample near Missoula, also plot close to the local meteoric water line and the groundwater samples. However, two of the samples from the deep basin-fill are more depleted (more negative) in $\delta^{18}O$ and δ^2H and plot off the meteoric water line; these two samples also did not have detectable tritium (fig. 22). In general, samples with pre-bomb or submodern tritium values were more negative (fig. 22).

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DATA SOURCES

Base layers of physiography, hydrology, and cultural features were derived from the Montana State Library Natural Resources Information System, Helena, Montana.

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