YELLOWSTONE CONTROLLED GROUNDWATER AREA, MONTANA LONG-TERM MONITORING PROGRAM: DATA SUMMARY REPORT

Alan English, John LaFave, and Mike Richter

Montana Bureau of Mines and Geology

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Cover photo: Bear Creek Hot Springs, located about 2 miles east of Gardiner, Montana near the confluence of Bear Creek and the Yellowstone River.

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INTRODUCTION AND PURPOSE

History

Yellowstone National Park was created by an act of Congress in 1872, marking establishment of the first national park in the United States. One of the primary reasons for establishing the Park was to protect and preserve the unique geothermal features in the area. In April 1986, the Church Universal and Triumphant (CUT) drilled a 458-ft-deep well about 5 mi northwest of Gardiner, within 2 mi of the Park boundary. The well was drilled on the west side of the Yellowstone River, within 650 ft of La Duke Hot Springs, which is located on the east side of the river. The well (146978) came to be known as the "CUT" well. The CUT well and La Duke Hot Springs are located within an area designated by the U.S. Geological Survey (USGS) as the Corwin Springs Known Geothermal Resource Area (KGRA; Goodwin and others, 1971).

The CUT well intercepted geothermal groundwater at a temperature of 57°C (Norbeck and Kerschen, unpublished report, August 28, 2007). A 13-h pump test of the well, at 1,500 gpm, resulted in a 92% decrease in the discharge from La Duke Hot Springs (Sorey and others, 1991). Concerns raised by the impact pumping the CUT well had on the discharge from La Duke Hot Springs led the U.S. Congress to commission a study by the USGS in 1988. The purpose of the study was to evaluate the potential for development of geothermal resources north of the Park, within the KGRA, to affect geothermal resources within the Park. In completing their study, the USGS concluded that development of geothermal resources within the KGRA could potentially reduce the discharge of geothermal springs in the Mammoth Hot Springs area and other areas in the Park (Sorey and others, 1991).

In 1994 the State of Montana and the National Park Service (NPS) signed a water-rights compact that established Federal reserved water rights for NPS lands in Montana, including Yellowstone National Park (DNRC, 1999; National Park Service Compact, 85-20-401 MCA). The Compact included establishment of the Yellowstone Controlled Groundwater Area (YCGA), encompassing about 1,170 mi^2 of land in Montana adjacent to Yellowstone National Park (fig. 1). The boundary of the YCGA was developed and recommended by a Technical Working Group (Custer and others, 1993) based on the desire "…*to encompass within the Controlled Groundwater Area all regions that might reasonably be expected to influence the Yellowstone National Park hydrothermal systems….*" To aid in protecting the geothermal resources in the Park, Article IV, Section H.2 of the Compact provided for a groundwater monitoring program to be implemented by the Montana Bureau of Mines and Geology (MBMG), in consultation with a Technical Oversight Committee (TOC) composed of representatives for the State of Montana, the USGS, and the NPS.

In accordance with the Compact, the MBMG established the Long-Term Monitoring Program (LTMP) in 2006. Since inception, the TOC has provided oversight of the LTMP, and funding has been provided by the NPS. Prior to establishment of the LTMP, between 1996 and 2003, the MBMG completed inventories of wells and springs within the YCGA. These inventories aided in selecting and obtaining access to monitoring sites selected for the LTMP.

Purpose

The purpose of this report is to compile, present, and summarize data collected at the LTMP sites through 2013. This report also describes site improvements made or planned in 2014, and provides recommendations for future improvements to the LTMP. The monitoring data summarized include groundwater levels, spring flow rates, water-temperature patterns, and water-quality sampling results. An overview of the well and spring inventory results is also provided to show the spatial relationships between inventoried sites and the LTMP sites.

Report Format

The LTMP sites are organized into four watershed areas focused around populated areas within the YCGA (fig. 2). We provide a map of each watershed area, a summary of the geologic setting, and a summary of the water-quality data collected in each watershed area. Detailed descriptions of each of the monitoring sites, summaries of the water level or discharge, and water-temperature data collected at each site are provided in appendix A. An overview of the well and spring inventory work completed within the YCGA is presented first to show the relationships between the LTMP monitoring sites and the inventoried wells and springs.

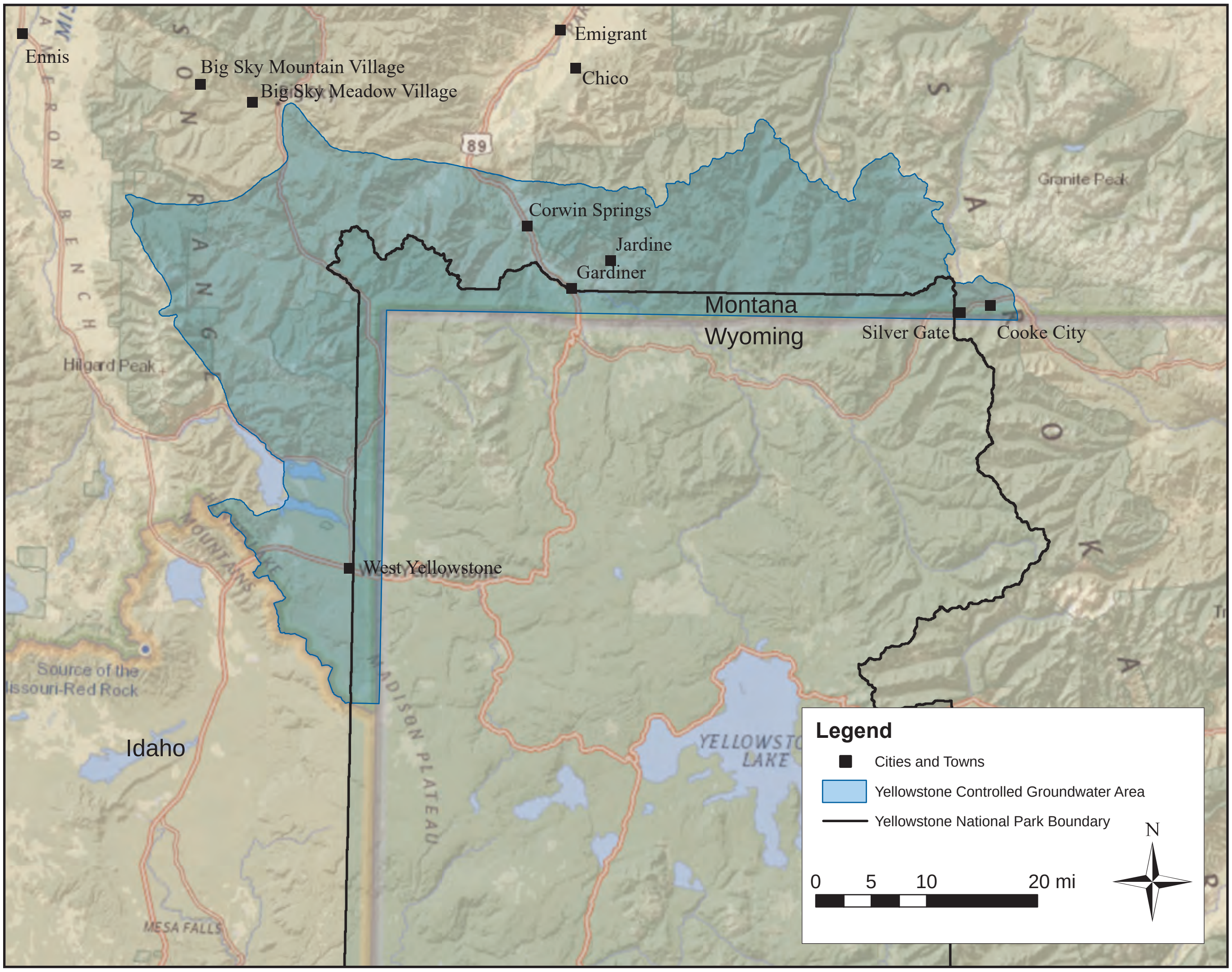


Figure 1. The Yellowstone Controlled Groundwater Area encompasses about 1,300 mi^2 within Montana, adjacent to Yellowstone National Park.

WELLS AND SPRINGS IN THE CONTROLLED GROUNDWATER AREA

Inventoried Wells and Springs

The MBMG inventoried all reasonably accessible wells within the YCGA between 1996 and 1999 and collected baseline water-quality samples from select wells (Metesh and Kougioulis, 1999). Since 1999 additional wells in the area have been inventoried by the MBMG Ground Water Characterization Program. The MBMG also inventoried all reasonably accessible springs within or near the YCGA and collected baseline water-quality samples from selected springs (Metesh, 2004). Locations of inventoried wells and springs within or near the YCGA are shown in figure 3. As of 2013, 718 wells and 118 springs have been inventoried within or near the YCGA.

Non-Inventoried Wells

New wells have been drilled within the YCGA since the MBMG completed the initial well inventory in 2000. While a few of these new wells were inventoried by the MBMG Ground Water Characterization Program while working in Gallatin and Park Counties, there are many new wells that have not been inventoried. A review of the MBMG Groundwater Information Center (GWIC) database in early 2014 indicated that at least 330 wells had been drilled within the YCGA since it was created that had not been inventoried (fig. 3). Many of these wells have DNRC water rights, in compliance with the YCGA guidelines; however, some do not.

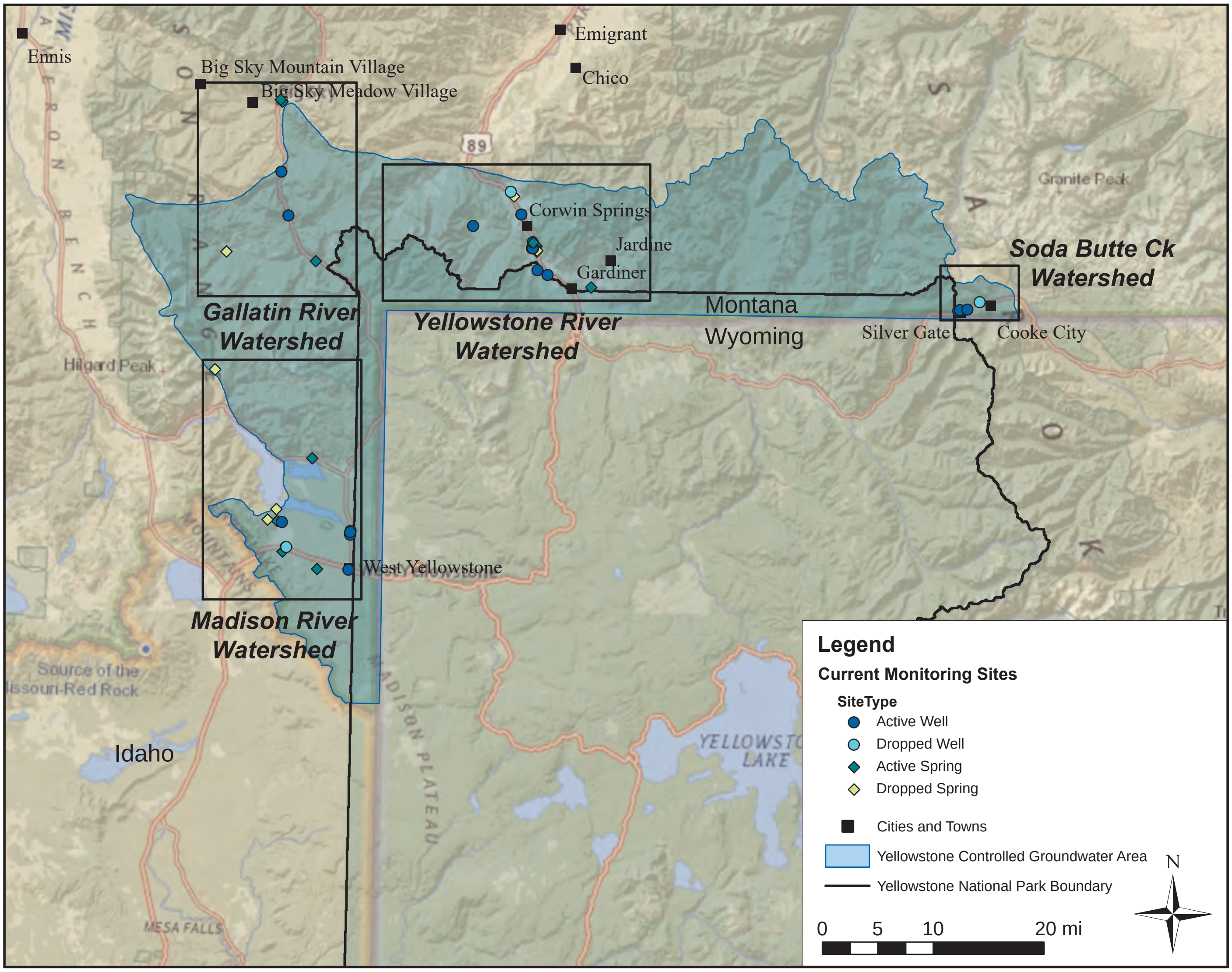


Figure 2. Long-Term Monitoring Program sites within the Yellowstone Controlled Groundwater Area (shaded area) are organized by watershed. All of the monitoring sites are located within the Madison, Gallatin, and Yellowstone River, and Soda Butte Creek watersheds. All but five of the monitoring sites that were active at the end of 2013 are in the Yellowstone and Madison River watersheds.

METHODS

Long-Term Monitoring Sites

Table 1 provides a summary of the monitoring sites in the YCGA; the general locations of the sites are shown in figure 2. The monitoring sites are classified as *cold* (<15°C), *warm* (15° to 25°C), or *hot* (>25°C), based on average water temperature, and include wells, springs, and spring creeks. The spring creek sites (Anceny and Ryberg) are co-located with monitored springs and are used to obtain flow data for the springs. The combined flow at Snowflake Springs, located on the southwest side of the Gallatin River (see cover photo), is also measured in a channel formed at the base of the springs. However, the flow measuring location has not been established as a separate spring creek site.

At the end of 2013 there were 30 active monitoring sites that included 17 wells, 11 springs, and 2 spring creeks. Most of the monitoring sites are either cold (n = 15), or warm (n = 12). There are 3 hot water sites, all located in the Yellowstone River watershed near Gardiner, Montana. Two of the hot water sites are springs (La Duke and Bear Creek), and one is a 2-in-diameter monitoring well located within 20 ft of the spring box at La Duke Hot Springs.

Eight monitoring sites were established but later dropped for various reasons (table 1). The Kloster well (162539), located in the Soda Butte Creek watershed, was dropped after the well casing failed and the owner abandoned the well. A replacement well was drilled, but the owner declined to allow the MBMG to monitor the new well. McPherson Spring (182012) and Spera-

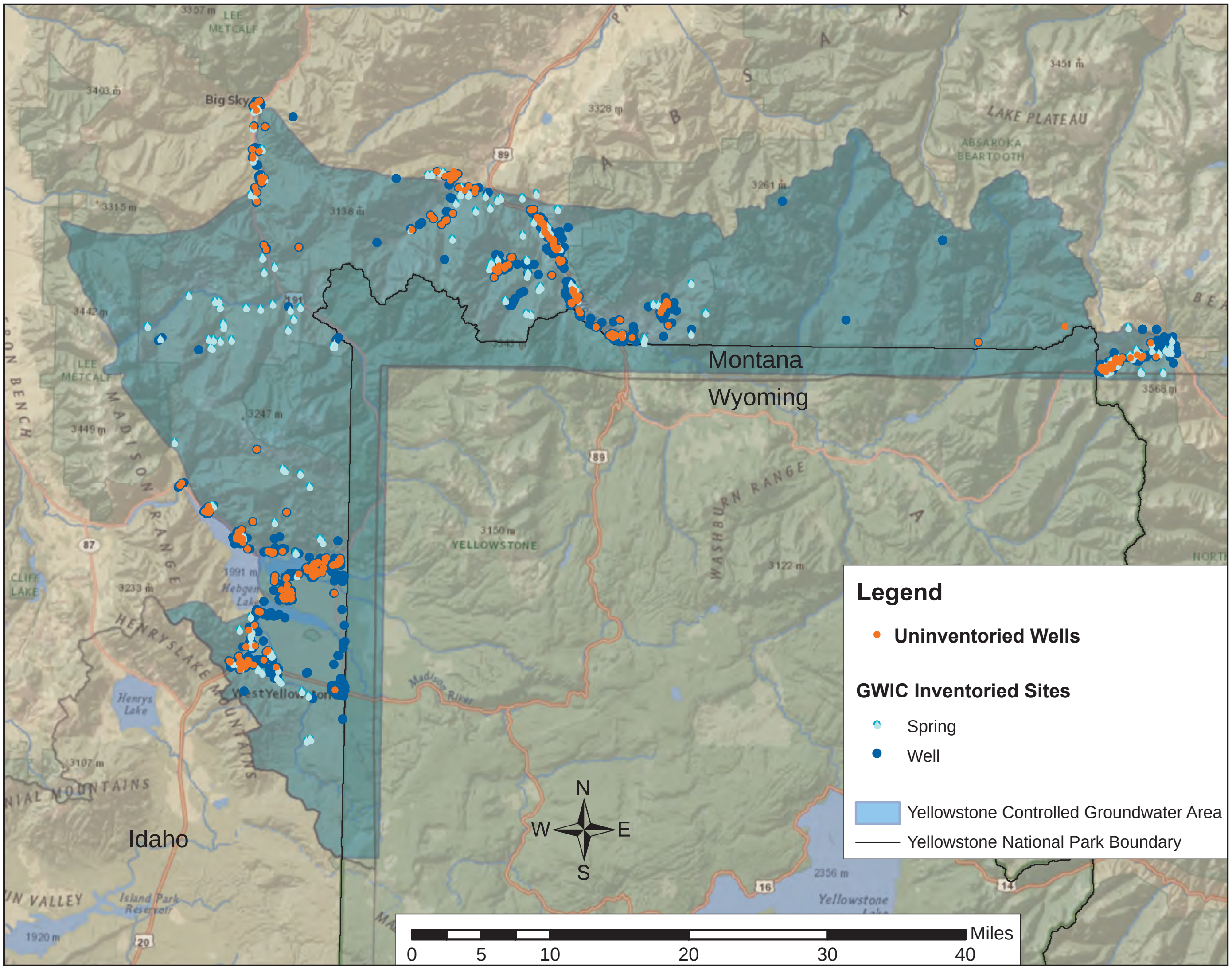


Figure 3. Inventoried and non-inventoried wells and springs in or near the YCGA (shaded).

no Spring (181621), located in the Yellowstone River watershed, were dropped after the owners removed the monitoring equipment and declined access for monitoring. The Sphinx Mountain Mobile Home Park well (140974), located in the same watershed, was dropped due to difficulties with accessing the well for monitoring. Sheep Camp Spring (183236), in the Gallatin River watershed, was dropped because it had a very low flow (2 to 4 gpm) that was intermittent (June through October), and the spring area was subject to runoff during snowmelt or storm events. Beaver Creek Spring (181930), in the Madison River watershed, was dropped for the same reasons. The West Yellowstone KOA well (8935) was dropped because it was difficult to access, was in almost continuous use in the summer, and was redundant with the backup well for the campground's water system (165852). Lonesomehurst Spring (164216), also located in the Madison River watershed, and developed by a water users' association, was dropped because the flow of the spring could not be reliably measured.

Monitoring Methods and Equipment

Table 1 provides a summary of the monitoring equipment installed at the active monitoring sites as of the end of 2013. More detailed information on the monitoring methods and equipment used at each site is provided in appendix A. The monitoring sites are visited at least three times per year (May, August, and November), unless site conditions prevent access. This schedule is used, rather than a quarterly schedule, due to heavy winter snowpack at many of the monitoring sites. Some of the sites, including spring sites with flumes, are visited more frequently to check and clean the monitoring equipment.

Table 1. Active and discontinued YCGA LTMP sites (2005–2013).

GWIC ID	Site Name	Site Type	Status	*H_2O Temp	Period of Record (through 2013)	Monitoring Equipment and Methods**
SODA BUTTE CREEK WATERSHED—*COOKE CITY–SILVER GATE AREA*						
106030	Silvergate	Well	Active	Cold	Sept 2006→	WL/T &, BARO
162539	Kloster	Well	Abandoned	Cold	Aug 2007–Sept 2013	WL/T
YELLOWSTONE RIVER WATERSHED—*GARDINER BASIN–CORWIN SPRINGS AREA*						
171215	La Duke Hot Spring	Spring	Active	**Hot**	July 2005→	TEMP (High)-Data from CUT
256421	LA Duke LD-1	Well	Active	**Hot**	Nov 2013→	Manual WL
197921	Bear Ck. Hot Spring	Spring	Active	**Hot**	July 2009→	TEMP & WL/T w/Flume
184260	Powell	Spring	Active	**Cold**	Oct 2008→	TEMP, Flow Meter
171229	Sirr	Spring	Active	**Cold**	April 2009→	WL/T w/Flume
181620	Cole	Spring	Active	**Cold**	May 2007→	TEMP, Flow Meter
138764	Cole	Well	Active	**Warm**	Oct 2006→	WL/T
252314	Shooting Star Ranch	Flowing Well	Active	**Warm**	Nov 2009→	Manual Pressure
145529	Yellowstone Basin Inn	Well	Active	**Warm**	May 2007→	WL/T
105959	Strauss	Well	Active	**Warm**	May 2007→	WL/T
146967	Galloway	Well	Active	**Cold**	Aug 2005→	WL/T
105980	Gardiner Airport	Well	Active	**Cold**	Sept 2006→	WL/T
152216	Miller	Well	Active	**Warm**	August 2005→	WL/T, BARO
182012	McPherson	Spring	Discontinued	**Cold**	Oct 2009–Nov 2010	
140974	Sphinx Mountain	Well	Discontinued	**Cold**	May 2009-–May 2010	
181621	Sperano	Spring	Discontinued	**Cold**	June 2008–May2010	
GALLATIN RIVER WATERSHED—*BIG SKY AREA–UPPER GALLATIN*						
258715	Anceny	Spring	Active	**Warm**	Oct 2010→	TEMP
304093	Anceny Spring Ck.	Stream	Active	**Cold**	May 2012→	WL/T w/Staff Gage, Manual Flow
171216	Snowflake Springs	Spring	Active	**Cold**	April 2010→	TEMP, Manual Flow
215333	Altman	Well	Active	**Cold**	July 2010→	WL/T
183236	Sheep Camp (USFS)	Spring	Discontinued	**Cold**	July 2007–Nov 2011	
MADISON RIVER WATERSHED—*HEBGEN BASIN–WEST YELLOWSTONE*						
182014	Corey	Spring	Active	**Cold**	July2010→	TEMP, Manual flow
183268	Stinky (USFS)	Spring	Active	**Warm**	Oct 2005→	TEMP, WL/T w/Flume
183242	Black Sand (USFS)	Spring	Active	**Cold**	May 2010→	TEMP, Manual Flow
106775	Baker Hole S.	Flowing Well	Active	**Warm**	May 2007→	TEMP, Manual Pres., Flow Meter
8943	Baker Hole N.	Flowing Well	Active	**Warm**	May2007→	TEMP, Flow Meter
106778	Keland	Flowing Well	Active	**Warm**	Nov 2006→	TEMP, Flow Meter
230654	Ryberg	Flowing Well	Active	**Warm**	Nov 2011→	Manual Pressure
8930	Ryberg #4	Undeveloped	Active	**Cold**	Aug 2011→	TEMP
277397	Ryberg Spring Ck.	Stream	Active	**Cold**	Aug 2011→	WL/T w/Staff Gage, Manual Flow
247335	Hebgen Fire Sta. 3	Well	Active	**Cold**	July 2010→	WL/T
106842	3 Bears Lodge	Well	Active	**Cold**	March 2006→	WL/T, BARO
165852	W.Y. KOA Backup	Well	Active	**Cold**	May 2010→	WL/T
8935	W.Y. KOA	Well	Discontinued	**Cold**	March 2006–Aug 2010	
164216	Lonesomehurst WUA	Spring	Discontinued	**Cold**	Aug 2008–May 2012	
181930	Beaver Ck. (USFS)	Spring	Discontinued	**Cold**	May 2007-–Nov 2011	

*Sites are classified as cold (<15°C), warm (15° to 25°C), or hot (>25°C).
**WL\T, Water level and temperature logger; TEMP, Water-temperature logger; BARO, Barometric Pressure Logger.

Wells

During each site visit manual water-level measurements are made using a water-level meter (e-tape) or steel tape. Many of the wells are equipped with non-vented pressure transducers (water-level loggers) that record and store water-level and water-temperature data. The loggers are either hung in the well using a cord, and then removed for downloading, or hung on a dedicated communication cable that allows for downloading without removing the logger. Most loggers are set to record data on an hourly basis. Barometric pressure transducers (barologgers) are maintained in each of the watershed subareas and record the barometric pressure on an hourly basis. The barologger data are used to correct the non-vented water-level logger data for barometric pressure. The manual water-level measurements are used to check the water-level logger data, and if necessary, correct the logger data for drift between site visits.

Several monitoring sites are flowing wells that are either free-flowing or shut-in. The free-flowing well sites are all located in the Madison River watershed, in the area of the West Yellowstone Airport. The flow from these wells is routed to the Madison River via discharge pipes. Flows are monitored using in-line flowmeters installed on the discharge pipes. During site visits the flowmeter reading is recorded, and the flow rate is measured using the meter and a stopwatch. The flowmeters have been equipped with pulse loggers that record the rotation rate of the flowmeter dials. However, these pulse loggers have proven difficult to maintain and are prone to failure. Temperature loggers are also installed in the discharge lines and are co-located with the flowmeters. The temperature loggers record the water temperature on an hourly basis. Flowing wells that are shut-in are monitored by measuring the shut-in pressure using a digital pressure gage each time the site is visited. Water temperature at these sites can only be measured when the well is purged for water sampling, and is measured using a flow-through cell and a temperature probe.

Springs and Spring Creeks

The spring sites are challenging to monitor because each spring has a unique hydrogeologic setting and flow rates are highly variable (2 to 5,000 gpm). The large springs have multiple discharge points within a general discharge area, and the water either collects in a pond or in a channel (spring creek), while the small springs usually have well-defined discharge points. Several of the small springs in the Yellowstone River watershed have been developed for domestic use and have a collection system with a discharge pipeline. Undeveloped small springs with low flows and a single discharge point are monitored using flumes equipped with water-level loggers (e.g., Bear Creek and Stinky). The flume stage is recorded during each site visit, and hourly water-level data from the loggers are used to record the flow between site visits. The small springs that have been developed are equipped with flowmeters on the discharge pipeline (e.g., Cole and Powel). A flowmeter reading is recorded during each site visit, and the flow is measured using the flowmeter and a stopwatch. At the large spring sites flow is measured using a wading rod equipped with a current velocity meter. These flow measurements are taken either at a restricted flow point near the spring discharge (e.g., Corey and Black Sand), or at co-located spring creek sites (e.g., Anceny and Ryberg). All of the spring sites are equipped with temperature loggers that record the temperature on an hourly basis.

Water-Quality Sampling

Water-quality samples have been collected from the monitoring sites on a 3-yr rotating basis, with one-third of the sites being sampled seasonally (spring, summer, fall) each year. This sampling schedule was used to evaluate seasonal variability in water quality at the sites, while limiting the total number of water-quality samples required each year. As of 2014, all of the LTMP sites had at least 1 yr of seasonal sampling (spring, summer, fall). With approval of the TOC, the MBMG began sampling all sites annually in August to improve identification of long-term trends. Any new sites added to the LTMP will be sampled seasonally for at least 1 yr and then sampled annually in August.

Tritium (^3H), deuterium (^2H), and ^{18}O samples have been collected from most of the monitoring sites at least one time. These samples were analyzed by the University of Waterloo, in Ontario, Canada. Starting in 2013, all LTMP site samples are also being analyzed for stable water isotopes (^2H, ^{18}O) at the MBMG Analytical Laboratory.

Water-quality samples are analyzed for major ions and trace elements at the MBMG analytical laboratory. Samples are collected following MBMG Standard Operating Procedures (SOP). Disposable 0.45-µm filters are used for samples requiring filtration. Samples for trace elements and major cations are filtered and preserved with nitric acid, while samples for nitrate–nitrate analysis are filtered and preserved with sulfuric acid. Samples for anions are filtered but are not acidified, and raw samples are collected for pH, specific conductance, and alkalinity analysis.

Data Access: Groundwater Information Center (GWIC)

All data collected within the YCGA are publicly available via the MBMG Ground Water Information Center at http://mbmggwic.mtech.edu. Data can be retrieved for a site by using its GWIC site identification number, while data for multiple sites may be obtained by selecting "*Projects*" from the GWIC homepage menu, then selecting "*Yellowstone National Park*" within "*Project Groups.*" Table 2 is a screenshot showing data available for projects completed within or adjacent to the YCGA. Data for LTMP sites can be retrieved from GWIC under the project code YNPMON.

SODA BUTTE CREEK WATERSHED

COOKE PASS to SILVER GATE

Monitoring Sites in the Soda Butte Creek Watershed

The LTMP efforts in this watershed focus on the Soda Butte Creek drainage between Cooke Pass and Silver Gate, east of the northeast entrance of the Park (fig. 4). Highway 212 provides access to the area. The two active LTMP sites are both cold water wells located along the northern margin of the valley. No geothermal springs or wells have been identified in the area. The Soda Butte Creek watershed has an extensive history of hard-rock metals mining that has impacted water quality in Miller Creek, north of Cooke City, and Soda Butte Creek (fig. 4; Stoughton and Marcus, 2000).

The Soda Butte Creek Valley is surrounded by steep, rugged mountains, sculpted by glaciation. Most of the area west of Silver Gate and north of Highway 212, between Silver Gate and Colter Pass, burned intensively in 1988. The fire resulted in increased erosion and numerous mudflows along the northern side of the valley. The burn area, visible in figure 4, is west of the McLaren Tailings Reclamation Site, where reclamation of old mill tailings east of Cooke City have involved dewatering, isolating, and lime-stabilizing the tailings.

Geologic Overview of the Soda Butte Creek Monitoring Area

The bedrock geology in the Soda Butte Creek area was mapped by Elliott (1979) at a scale of 1:24,000. The surficial geology of the Soda Butte Creek Valley was mapped by Metesh and others (1999). Lonn and others (2007) combined the data from these two mapping efforts in a geologic map of the entire YCGWA at a scale of 1:100,000. A portion of the geologic map by Lonn and others (2007) is shown in figure 5.

Table 2. Tabular GWIC data available for Yellowstone Controlled Groundwater Area projects.

Project Name	Site Data	Site Visit Data	Water Quality Data	Isotope Data	Surface Water Data	Water Level Data	Photo Data	Weather Data	DocMan Data
SODA BUTTE CREEK. YELLOWSTONE NATIONAL PARK AREA. COOKE CITY AREA (***SODABUT***)	●	●	●			●			
YELLOWSTONE NATIONAL PARK - COOKE CITY AREA (***YNPC***)	●	●	●			●			
YELLOWSTONE NATIONAL PARK - COOKE CITY AREA SPRINGS (***YNPCSPR***)	●	●	●						
YELLOWSTONE NATIONAL PARK - GARDINER AREA (***YNPG***)	●	●	●			●			
YELLOWSTONE NATIONAL PARK - GARDINER AREA SPRINGS (***YNPGSPR***)	●	●	●						
YELLOWSTONE NATIONAL PARK LONG-TERM MONITORING NETWORK (***YNPMON***)	●	●	●	●	●	●			
YELLOWSTONE NATIONAL PARK METERS (***YNPMTR***)	●								
YELLOWSTONE NATIONAL PARK - WEST YELLOWSTONE AREA (***YNPW***)	●	●	●			●			
YELLOWSTONE NATIONAL PARK - WEST YELLOWSTONE AREA SPRINGS (***YNPWSPR***)	●	●	●						

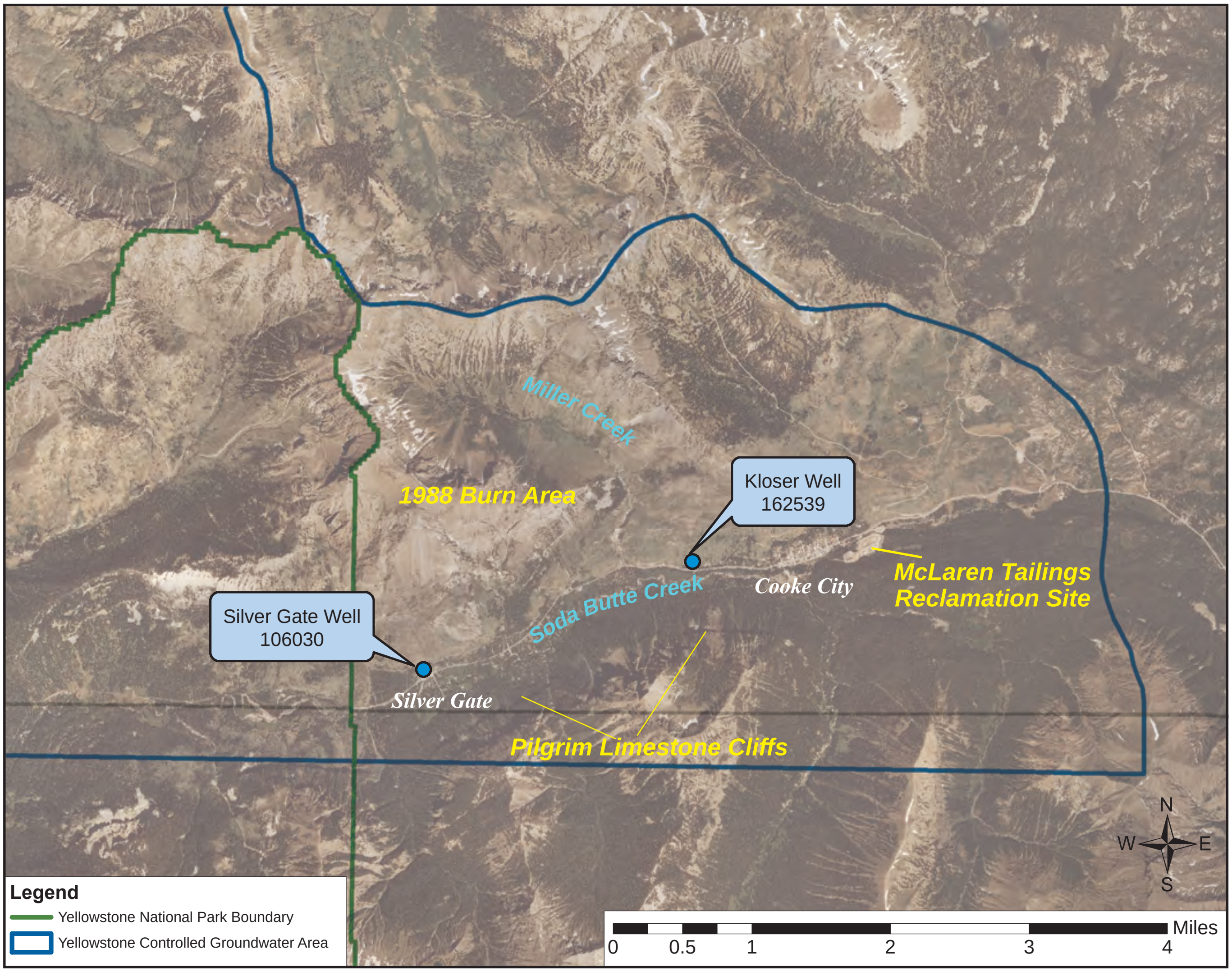


Figure 4. Aerial photograph of the Soda Butte Creek watershed area, showing the locations of the LTMP sites and the steep, rugged terrain in the area. Photograph by USDA Farm Service Agency, August 11, 2011.

Bedrock consists of Archean metamorphic, Paleozoic sedimentary, and Cenozoic volcanic rocks. The Archean metamorphic rocks are composed mainly of gneiss and granite uplifted as part of the Laramide Beartooth uplift. Archean gneiss (Agn) is exposed south and east of Cooke City (fig. 5). Paleozoic rocks were deposited on the Archean basement rock beginning with the middle Cambrian Flathead sandstone. Cambrian through Devonian marine sediments exposed in the area dip gently towards the south and are cut by several extensional faults, but are relatively undeformed. The formations include the Pilgrim Limestone, which forms a prominent cliff along the south wall of the Soda Butte Creek Valley in the Silver Gate area (fig. 4). The Paleozoic formations are overlain by Eocene Absaroka volcanic rocks primarily of andesite composition. The Heart Mountain Detachment fault, a unique feature of the area which dips gently to the southeast, formed in the Eocene during deposition of the Absaroka volcanic rocks. Paleozoic and Mesozoic sedimentary rocks slide towards the south–southeast on the detachment fault surface, leaving a breakaway surface in the early Paleozoic rocks, exposed northwest of Cooke City.

Both of the LTMP well sites in the Soda Butte Creek watershed are completed in surficial deposits along the northern margin of the Soda Butte Creek Valley (figs. 4, 5). Along the north side of the valley, above the valley floor, surficial deposits include a mixture of glacial till, alluvial fan deposits, and landslide deposits. Along the southern valley sidewalls, which have steep north-facing slopes, surficial deposits consist mainly of talus and avalanche deposits. Stream alluvium consisting of sand and gravel, and fine-grained humic-alluvium-containing clay layers, cover the valley floor. The Silver Gate well (106030), completed in fluvial sand and gravel deposits near the

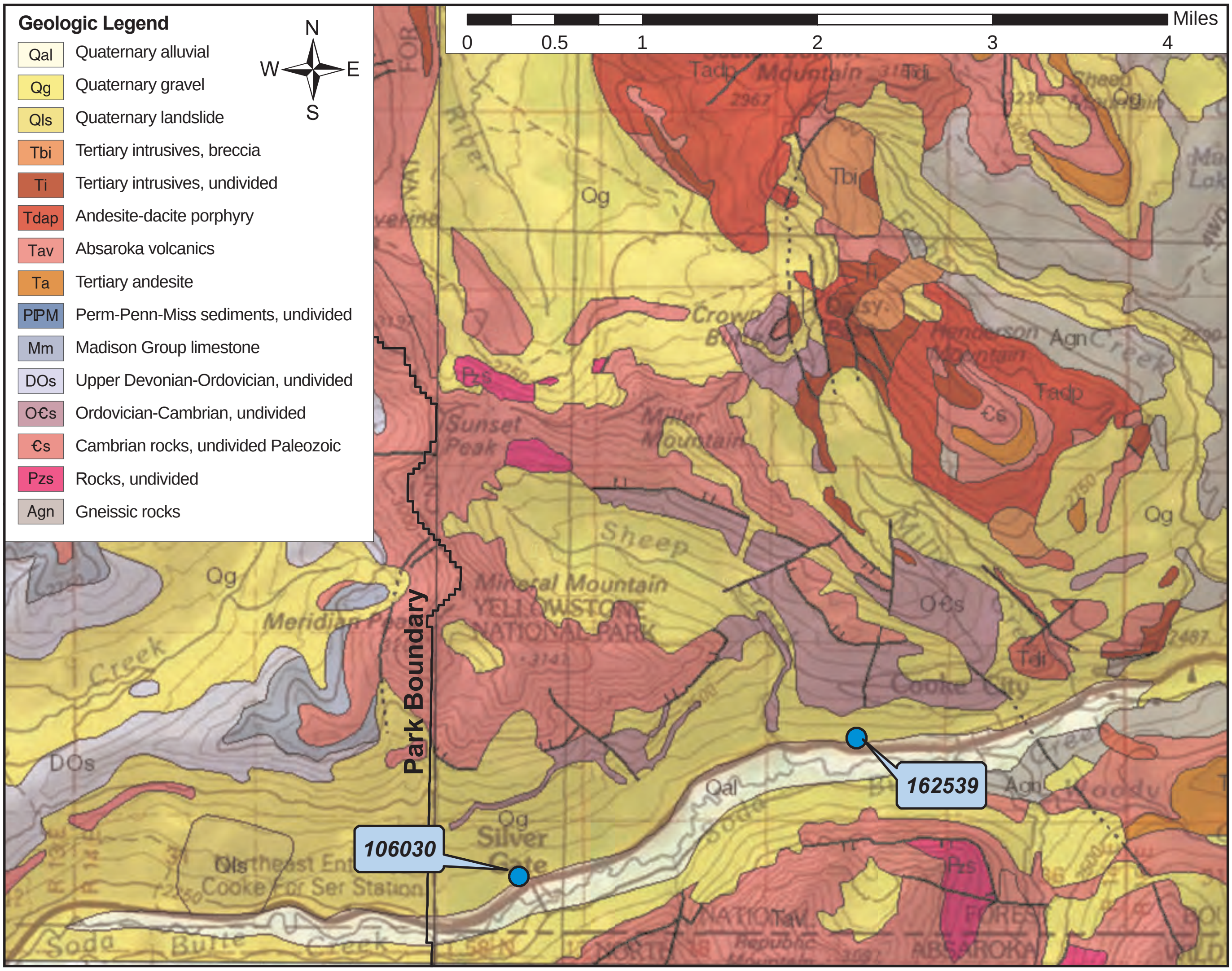


Figure 5. Geologic map of the Soda Butte Creek watershed in the area of Silver Gate and Cooke City, Montana (modified from Lonn and others, 2007). Red line denotes YCGWA boundary.

northern edge of the valley floor, is close to the toe of an alluvial fan and a large landslide deposit to the north (fig. 5). The Kloster well is completed in glacial till deposited on the north side of the valley. Here, the till rests on a south-facing slope carved into Cambrian bedrock by the valley glaciers that occupied the area until as recently as 4,000 to 7,000 years ago (Pierce, 1974).

Drillers' logs for several wells south of Highway 212, in the Silver Gate area, report clay layers over 5 ft thick. English (1999) documented five artesian wells that flow seasonally in the spring in this area. These wells (140290, 106024, 106035, 106037, and 106063) are completed in a confined aquifer below one or more clay layers that range from 3 to 60 ft thick and are often reported as blue clay, or blue-clay-bound sands and gravels. Wells 106024, 106063, and 140290 typically flow during the spring in all or most years, while the other two wells only flow in wetter years (English, 1999). Blue clay is not noted in the Silver Gate well log and the well does not flow, indicating that this well is not completed in the confined aquifer. Establishment of a LTMP site in the confined aquifer area in Silver Gate should be considered so that long-term trends in water levels and water quality can be tracked and compared for confined and unconfined aquifers, which discharge into the Park.

Water-Quality Summary for Soda Butte Creek Sites

Groundwater at both LTMP wells is cold, with an average temperature of less than 5°C. There are no indications that the groundwater has mixed with geothermal groundwater. Water chemistry is similar at the two sites and typical of recently recharged, shallow groundwater. However, the two sites vary with respect to major ions, TDS, trace metals, and isotopes. These

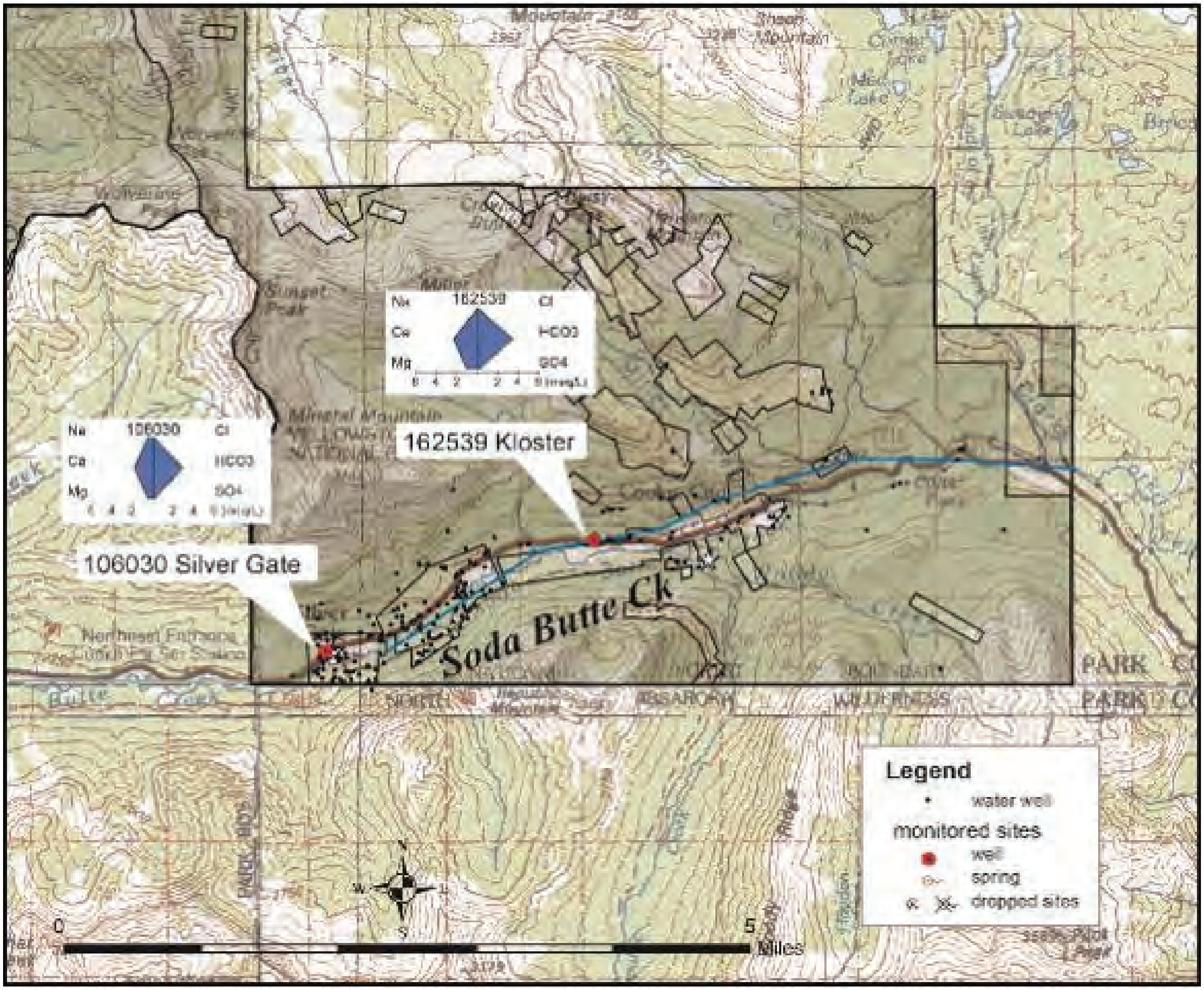


Figure 6. Topographic map of the Soda Butte Creek watershed area with Stiff diagrams representing the dominant major ions in the groundwater at the two LTMP well sites. Both wells produce a calcium-bicarbonate type water (concentrations in meq/L).

differences indicate that despite the close proximity and similarity in geologic setting, the wells produce groundwater from different recharge areas and/or along different subsurface flow paths.

Major Ions and TDS

Stiff diagrams representing the major ion chemistry at the two Soda Butte Creek sites are shown in figure 6, and the major ion chemistry is also summarized on a Piper plot, along with TDS concentrations, in figure 7. The Silver Gate well produces a calcium-sodium-bicarbonate type water, and the Kloster well produces a calcium-magnesium-bicarbonate type water with a slightly higher sulfate concentration. Concentrations of other major ions and TDS are low at both wells, although the Kloster well has slightly higher levels.

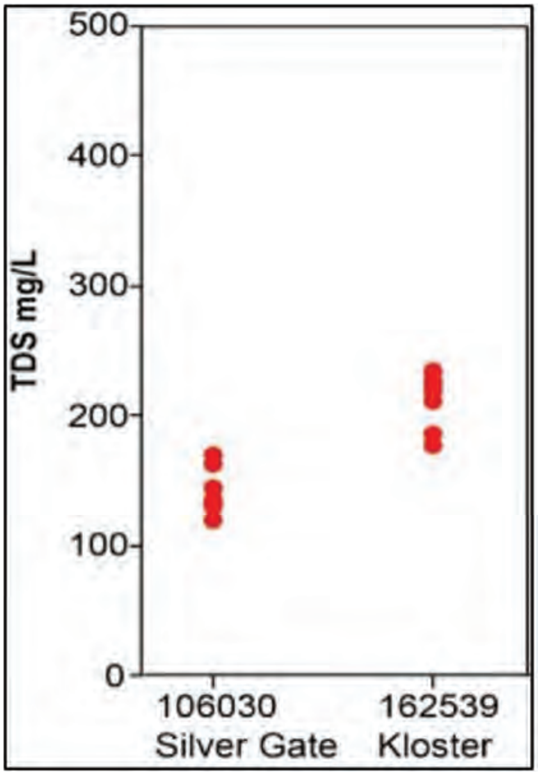
Average Concentrations of Select Major Ions and Trace Metals

Table 3 shows average concentrations of select major ions and trace elements for the Soda Butte

Table 3. Average concentrations of select major ions and trace elements for Soda Butte Creek sites.

GWIC ID	Site Type	*n*	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	SiO_2 (mg/L)	SO_4 (mg/L)	Cl (mg/L)	NO_3 (mg/L)	F (mg/L)	As (µg/L)	B (µg/L)	Ba (µg/L)	Sr (µg/L)	Li (µg/L)	U (µg/L)
162539 Kloster	Well	7	52.7	17.2	1.8	8.9	11.9	0.7	<0.1	0.1	<0.1	5.5	59.8	193	6.4	<1.0
106030 Silver Gate	Well	8	31.1	5.9	12.0	9.3	5.1	2.3	0.8	0.1	0.4	18.9	15.9	251	1.8	<1.0

Note. Based on samples in GWIC through 2013. Blue Highlight indicates cold water sites (<15°C), *n* = number of samples..



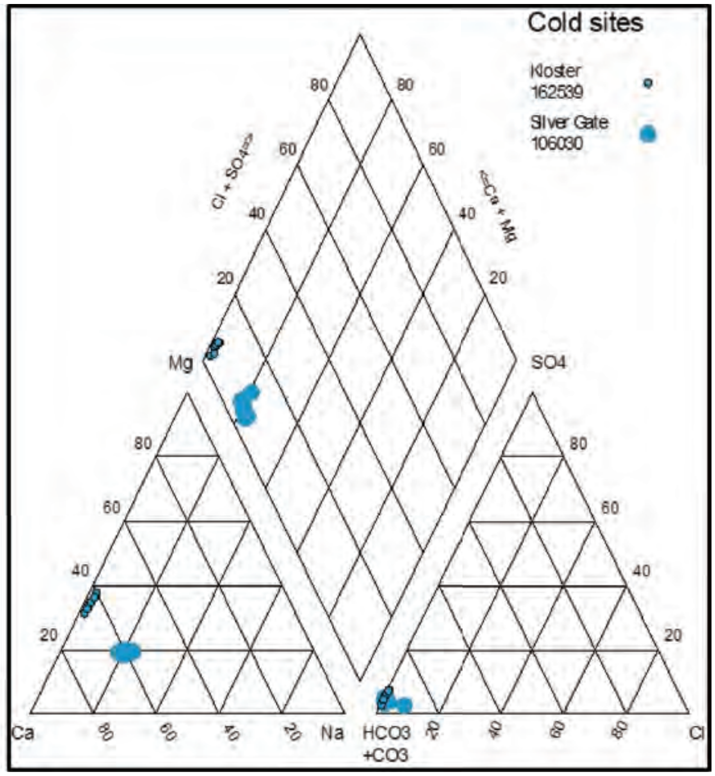


Figure 7. Total dissolved solids (TDS) concentrations and a Piper plot showing major ion chemistry for samples collected from the Soda Butte Creek subarea sites from 2006 through 2013. Major ion concentrations in the Piper plot are expressed as relative percentages in meq/L.

Creek monitoring sites. The Kloster well (162539) has higher concentrations of sulfate, barium, and lithium compared to the Silver Gate well (106030), which has higher sodium, chloride, nitrate, boron, and strontium. While these constituents in the Silver Gate well are relatively low, they are indicators of septic system impacts to water quality and could be related to septic systems in the immediate area of the well.

Isotope Chemistry

Sampling results for stable isotopes of water (^{18}O and ^{2}H) and radioactive tritium (^{3}H) for the Silver Gate and Kloster wells are summarized in table 4, and the $\delta^{18}O$ and $\delta^{2}H$ values are plotted in figure 8. The local meteoric water line (LMWL) is based on samples from the greater Yellowstone National Park area (Kharaka and others, 2002). Stable water isotopes from both wells plot along and slightly below the LMWL, but the values are slightly distinct from each other. Groundwater from the Silver Gate well is slightly enriched (average $\delta^{18}O$ = -18.43‰, average $\delta^{2}H$ = -139.43‰) relative to the Kloster well (average $\delta^{18}O$ = -19.27‰, $\delta^{2}H$ = -146.08‰). The difference most likely reflects higher elevation recharge, hence more depleted, to the Kloster well. The tritium values from each well are consistent with modern recharge within the past 15 to 20 yr (table 4).

YELLOWSTONE RIVER WATERSHED

GARDINER to YANKEE JIM CANYON

Long-term monitoring efforts in the Yellowstone River watershed are focused in the upper watershed, from the Park boundary at Gardiner, Montana, downstream to Yankee Jim Canyon (fig. 9). This area is also

Table 4. Oxygen and hydrogen isotope sampling results for Soda Butte Creek watershed sites.

MBMG Sample ID	GWIC ID	Name	Temp	Site Type	$\delta^{18}O$ Result	$\delta^{2}H$ Result	^{3}H Result	± 1σ	Sample Date
2008R5005	106030	Silver Gate	cold	well	-18.47	-140.11	9.6	0.8	10/16/2007
2011R4967	106030	Silver Gate	cold	well	-18.40	-138.75	7.4	0.7	05/12/2010
2008R5004	162539	Kloster	cold	well	-19.27	-146.19	14.1	1.1	10/16/2007
2009R5002	162539	Kloster	cold	well	-19.71	-145.99	14.4	1.3	10/22/2008
2012R4931	162539	Kloster	cold	well	-18.95	-146.09	6.7	0.6	11/09/2011

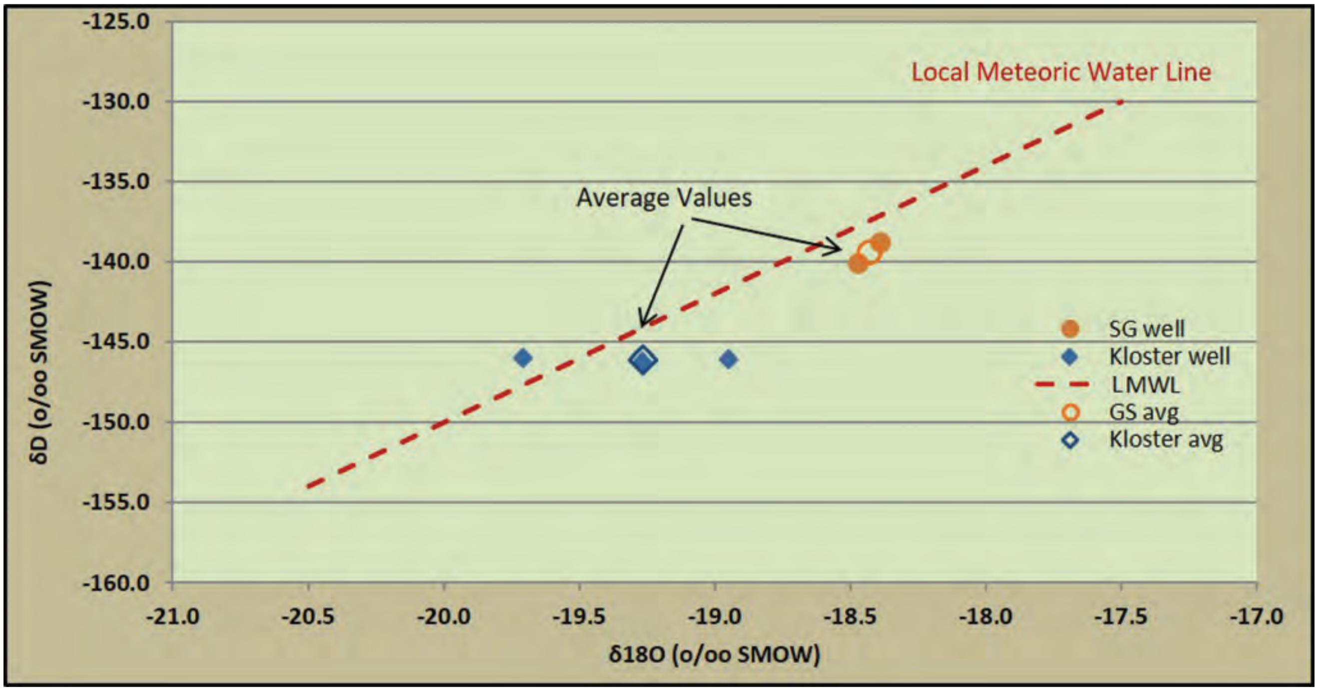


Figure 8. The composition of stable water isotopes show a distinct differences between the Kloster (162539) and Silver Gate (106030) wells. The local meteoric water line is based on samples from the Greater Yellowstone National Park area (Kharaka and others, 2002).

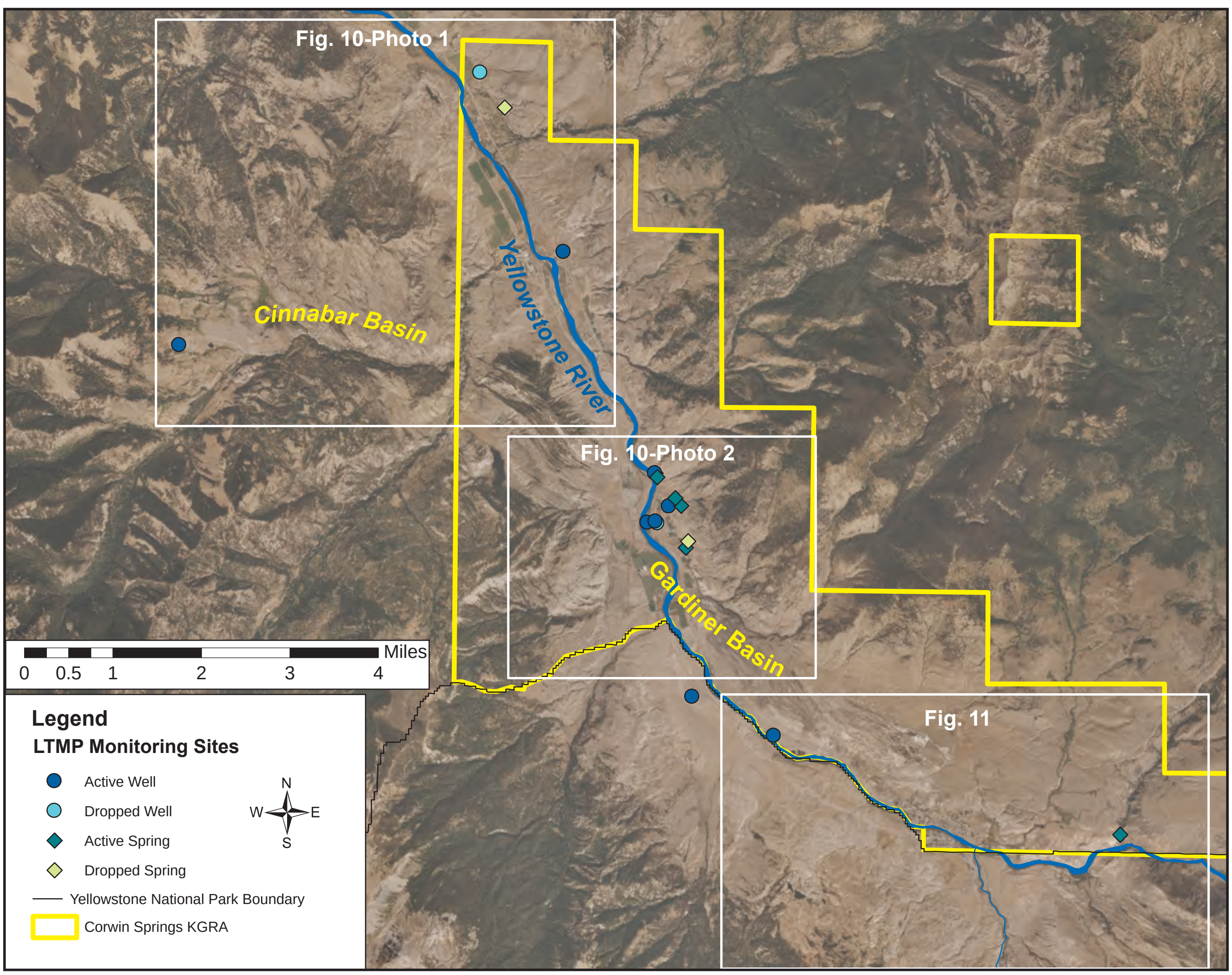


Figure 9. Aerial image showing an overview of the LTMP sites in the Yellowstone River watershed area and the locations of aerial images presented in figures 10 and 11.

commonly referred to as the Gardiner Basin, defined here as the lower elevation slopes and the river valley from Gardiner to Yankee Jim Canyon. The Gardiner Basin is surrounded by mountainous terrain and the climate is semi-arid. Ground cover is mainly dryland grasses, shrubs, and irrigated crops.

Corwin Springs Known Geothermal Resource Area

With the exception of the Shooting Star Ranch well (252314), located in Cinnabar Basin west of the Yellowstone River, all of the LTMP sites in this watershed are in the Corwin Springs KGRA (fig. 9). The USGS defines a KGRA as having favorable geology, known geothermal features, and enough interest in the geothermal resources to warrant development (Goodwin and others, 1971). Known geothermal features within the Corwin Springs KGRA include La Duke Hot Springs (171215), Bear Creek Hot Springs (197921), the Miller well (152216), the CUT well (146978), and the Gay well (266377). La Duke Hot Springs, Bear Creek Hot Springs, and the Miller well are all active LTMP sites, and the CUT well is discussed below.

Church Universal and Triumphant (CUT) Well

The CUT well (146978) was drilled in 1986 to a depth of 458 ft bgs. It is situated near La Duke Hot Springs on the west side of the Yellowstone River (fig. 10, right photo). The well intercepted hot groundwater, with a bottom-hole temperature of about 55°C (130°F). When the well was test pumped, the discharge from La Duke Hot Springs decreased by over 90% (Sorey and others, 1991), indicating a direct hydrologic connection with the flow system for La Duke (Hydrometrics, 1986). Concerns about impacts to geothermal features in the Park from pumping of the CUT well were a primary driver for development of the YCGA. The CUT well was never put into production, and an investigation completed in 2007 found that the casing had failed in several places (Norbeck and Kerschen, 2007). The well was abandoned in 2008.

Monitoring Sites in the Yellowstone River Watershed

There are 13 active LTMP sites in this watershed, consisting of a mix of hot, warm, and cold water sites that include five springs and eight wells (table 1). Locations of the monitoring sites are shown on aerial photographs in figures 10 and 11.

All of the LTMP spring sites are spatially associated with the Gardiner reverse fault, a major geologic structure that is described below. Two of the springs, LaDuke Hot Springs (171215), located northwest of

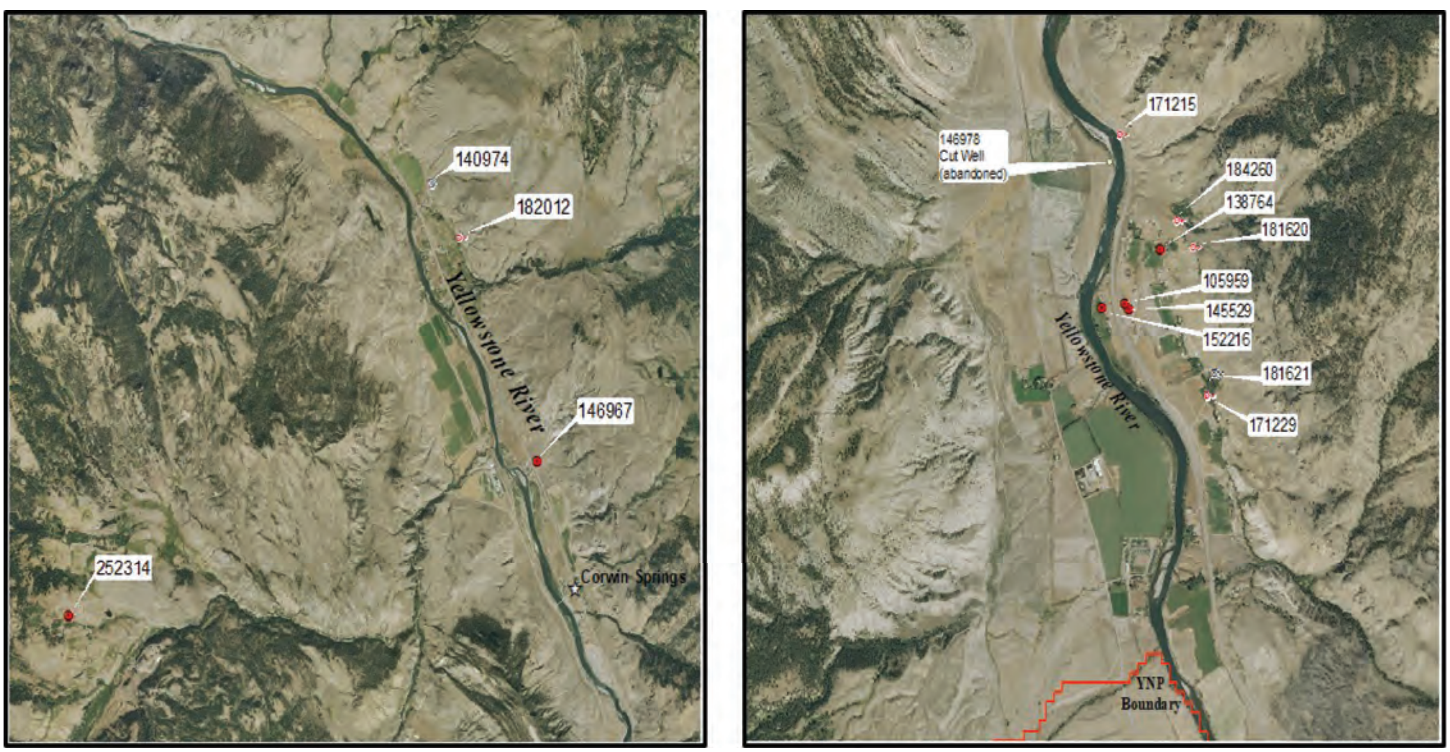


Figure 10. Aerial photographs showing the locations of monitoring sites in the northern portion of the Gardiner Basin. Left photo shows the northernmost sites along the Yellowstone River in the Corwin Springs area. The Shooting Star Ranch well (252314) is located in Cinnabar Basin. Right photo shows the LTMP sites further south, between the Park boundary (red line) and La Duke Hot Spring (171215).

Figure 11. Aerial photographs showing the locations of monitoring sites in the southern portion of the Gardiner Basin, near Gardiner, Montana, and north of the Park boundary. The arid nature of the Gardiner area is shown by the lack of tree cover.

Gardiner (fig. 10, right photo), and Bear Creek Hot Springs (197921), located east of Gardiner (fig. 11, cover photo), discharge hot water and are located along the mapped trace of the Gardiner reverse fault (fig. 12). A monitoring well (LD1, 256421) is co-located with LaDuke Hot Springs (fig. 10, right photo), and is completed in hot, shallow groundwater next to the LaDuke Hot Springs collection system. The three cold water springs (171229, 181620, and 184260) are located north of the Yellowstone River and south of La Duke Hot Springs (fig. 10, right photo), and are also near the mapped trace of the Gardiner reverse fault.

The LTMP well sites include one hot water, five warm water, and two cold water wells. The hot water well (256421) is an 8.7-ft-deep monitoring well that is located about 10 ft west of the spring water collection box for LaDuke Hot Springs (171215). The five warm water wells are thought to produce water that is heated either by the elevated geothermal gradient in the Yellowstone area, or by mixing with hot geothermal groundwater. The Miller well (152216; identified throughout this report as 152216 and also identified as 105960 in MBMG databases), located 5 mi northwest of Gardiner and ½ mi south of La Duke Hot Springs (fig.10, right photo), appears to produce warm water that results from conductive cooling of hot geothermal groundwater, and/or mixing with cold groundwater. In contrast, the Shooting Star Ranch well (252314), located about 10 mi northwest of Gardiner in Cinnabar Basin (fig. 10, left photo), appears to produce warm water that is not associated with a geothermal groundwater system and is simply warmed by the elevated geothermal gradient. This well is over 750 ft deep, completed in volcanic rocks, and is flowing artesian. The remaining warm water wells (138764, 145529, and 105960) are all domestic wells located east of the Yellowstone River between Corwin Springs and Gar-

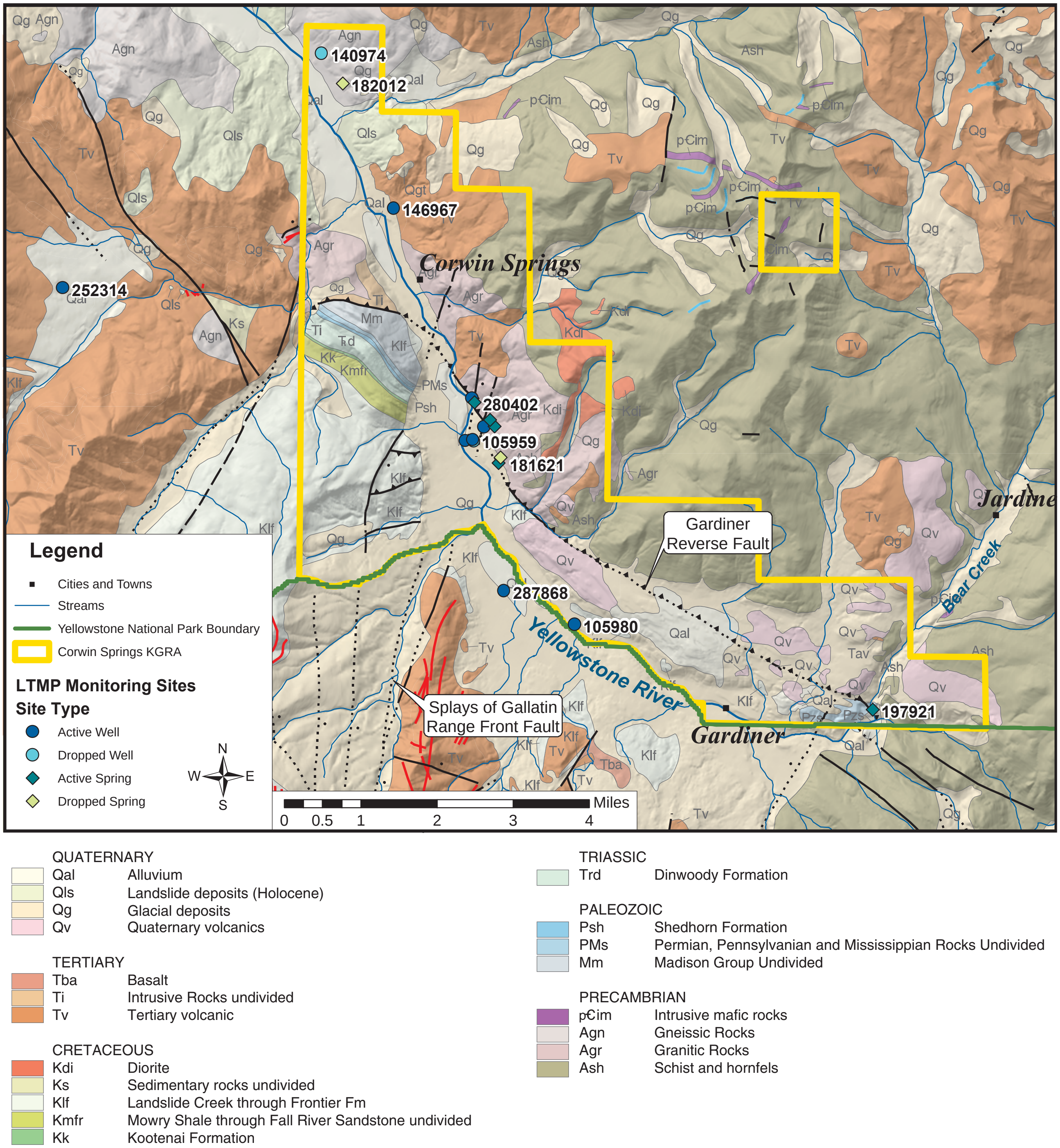


Figure 12. Geologic map of the Yellowstone River watershed monitoring area, showing major structures, geologic units and LTMP sites. Modified from Berg and others (1999).

diner (fig. 10, right photo). The two cold water wells include the Galloway well (146967) located northeast of Corwin Springs (fig. 10, left photo), and the Gardiner Airport well (105980), located along the east bank of the Yellowstone River about 2 mi northwest of Gardiner (fig. 11). Although the Gardiner Airport well is classified as cold, the water chemistry indicates possible mixing of cooled geothermal groundwater with shallow, cold groundwater.

Geologic Overview of the Yellowstone River Watershed Monitoring Area

Numerous authors have mapped the geology in the Yellowstone River monitoring area. Fraser and others (1969) mapped the Gardiner quadrangle at a scale of 1:24,000. Berg and others (1999) mapped the area as part of the Gardiner 30´ x 60´ quadrangle at a scale of 1:100,000, and Lonn and others (2007) combined the previous bedrock mapping with more detailed surficial geology mapping at 1:100:000. Pierce and others (1991) provided a geologic description of the area. Figure 12 shows the geology in the Yellowstone River watershed monitoring area.

The bedrock consists of Archean metamorphic rocks, Paleozoic and Mesozoic sedimentary rocks, and Cenozoic sedimentary and volcanic rocks. The area straddles the southwestern edge of the Beartooth uplift, delineated by the northwest-trending Laramide age Gardiner reverse fault (fig. 12). The Gardiner reverse fault has a stratigraphic offset of at least 3 km (Fraser and others, 1969), placing Archean metamorphic rocks in the hanging wall over and adjacent to Paleozoic and Mesozoic sedimentary rocks in the footwall. Drag along the fault folded and locally overturned the younger sedimentary rocks in the footwall, forming a drag and shear zone, and the Gardiner syncline. The syncline is asymmetric, with a gently dipping southwest limb and a steep to overturned northeast limb. Most of the LTMP sites are located either along the mapped trace of the Gardiner reverse fault or to the west and southwest in the drag and shear zone.

A series of younger, mainly north-trending normal faults extend out of the Park but are not well exposed (fig. 12). These faults merge to the south, inside of the Park, with the Gallatin Range front fault (Pierce and others, 1991). The younger normal faults cut through and offset the Gardiner reverse fault, Gardiner syncline, and other Laramide age structures. Pierce and others (1991) map the Reese Creek fault, one of the normal faults, as intersecting and offsetting the Gardiner reverse fault at La Duke Hot Springs. This fault and others that extend northward out of the Park are possible hydrogeologic connections between the thermal features in the Park and the thermal features in the Corwin Springs KGRA.

Tertiary volcanic rocks of the Absaroka Group (andesite) and younger Tertiary dacite and diorite porphyry overlay and intrude the older sedimentary and metamorphic rocks in the area. Quaternary basalt and travertine deposits cover the slopes along the east side of the valley within much of the area. Pierce (1973, 1979) mapped surficial geology in the area, showing a mantle of thin to thick glacial till and landslide deposits overlying bedrock in many places. Pierce and others (1991) hypothesize that a deep (over 300 ft) scour basin carved by the Pinedale age Yellowstone outlet glacier underlies the Yellowstone River Valley, extending from Gardiner north to Corwin Springs. This scour basin may contain one or more layers of glacial lake sediments that overlie older alluvial sediments and form a confined aquifer. The geothermal water intercepted by the CUT well is thought to be confined geothermal groundwater under the lake sediments.

La Duke Hot Springs (171215), Powell Spring (184260), Cole Spring (181620), Sirr Spring (171229), and Bear Creek Hot Springs (197921) are all located along the mapped trace of the Gardiner reverse fault and appear to somehow be related to the fault. Lithology reported on drillers' logs indicate the Cole well (138764) is completed in the Archean metamorphic rocks in the hanging wall of the Gardiner fault, while the Yellowstone Basin Inn well (145529), Strauss well (105959), and Galloway well (146967) appear to be completed in surficial deposits that cover the Paleozoic and Mesozoic sedimentary formations in the drag and shear zone within the footwall of the Gardiner fault. The driller's log for the Gardiner Airport well (105980) shows that it is completed in sandstones and shales that are interpreted to be Mesozoic bedrock underlying the surficial deposits in the area. A driller's log has not been found for the Miller well (152216), but based on the reported total depth (184 ft), and measured static water levels that range from 9.5 to 3 ft bgs, this well is thought to be completed in a confined aquifer, possibly within the glacial scour basin described by Pierce and others (1991). The Shooting Star Ranch well (252314) is the only monitoring site that is clearly not associated with the Gardiner reverse fault or the sedimentary rocks in the drag and shear zone adjacent to the fault. Instead, this well penetrates a thick sequence of Absaroka volcanic rocks (fig. 12, upper left) that overlie bedrock of unknown type.

Water-Quality Summary for Yellowstone River Watershed Sites

Groundwater quality is variable in the Yellowstone River monitoring area, reflecting differences in geology and groundwater flowpaths. This section summarizes water quality and hydrogeologic conditions at LTMP sites in the Gardiner Basin.

<u>Major Ions</u>

Stiff diagrams highlight the variations in major ion concentrations among the sites (fig. 13). McPherson Spring (182012) is the only site that has a calcium-

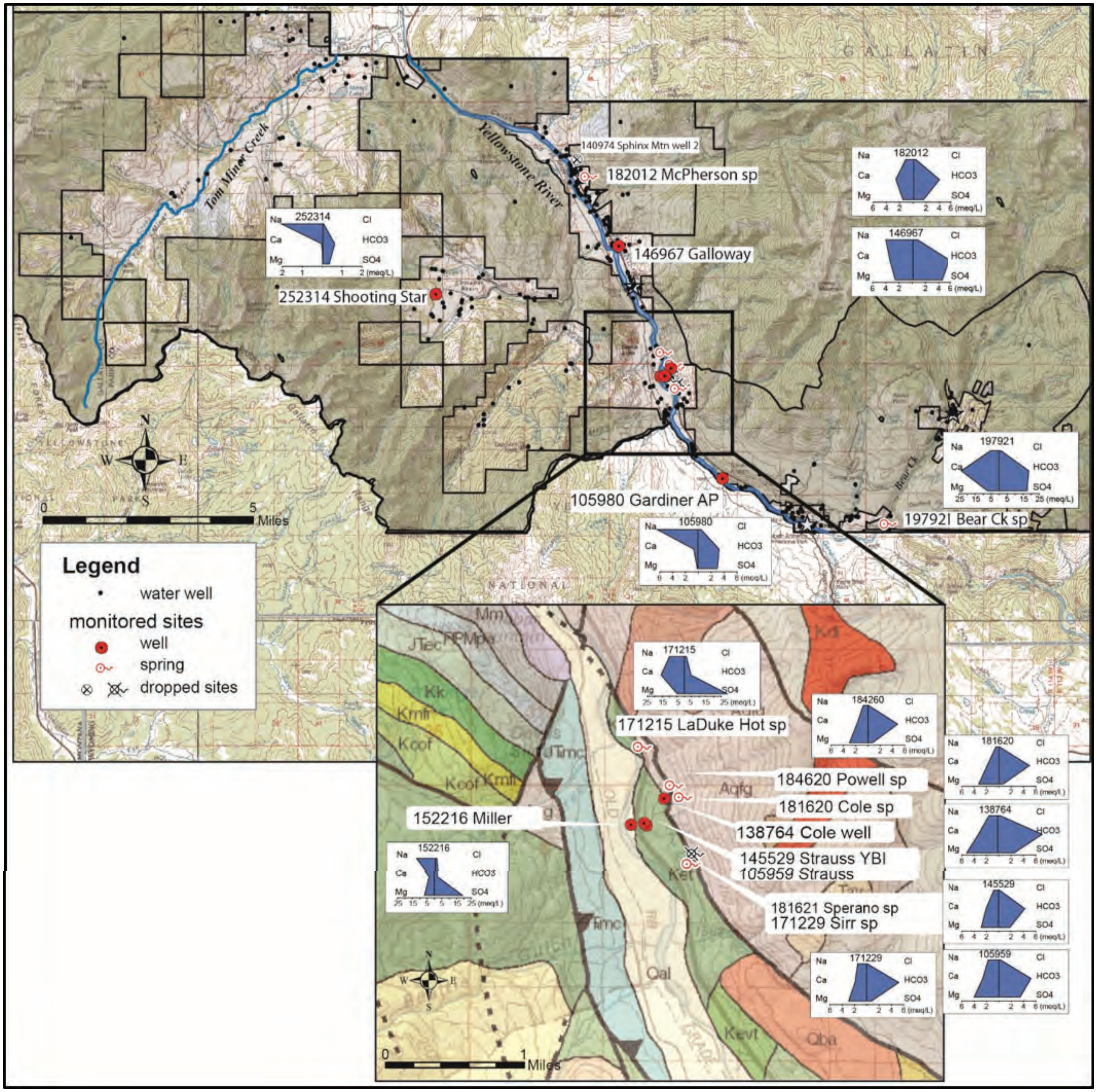


Figure 13. Stiff diagrams show the major ion chemistry for the LTMP sites in the Yellowstone River watershed area. A cluster of sites south of La Duke Hot Springs, shown on the inset map, all have a magnesium-bicarbonate chemistry (e.g., 138764, 181620). The Gardiner Airport well (105980) and the Shooting Star Ranch well (252314) stand out from the other sites with sodium-bicarbonate/sulfate type waters (concentrations in meq per liter).

bicarbonate type water; however, monitoring at this spring was discontinued from the LTMP at the request of the property owner. Six monitoring sites clustered along a bench east of the Yellowstone River and south of La Duke Hot Springs have magnesium-bicarbonate type waters, suggesting a similar hydrogeologic setting. These sites include both springs and wells, as shown with geology, on the inset in figure 13.

The known geothermal monitoring sites (LaDuke Hot Springs, Bear Creek Hot Springs, and Miller well) have elevated major ion concentrations, as shown on the scales for the Stiff diagrams in figure 13, compared to other monitoring sites. Sulfate is typically the dominant anion, but the dominant cation varies. La Duke Hot Springs (171215) has a calcium-sodium-sulfate type water, while Bear Creek Hot Springs (197921) has a calcium-bicarbonate-sulfate type water and the Miller well (152216) has a sodium-magnesium-sulfate type water.

The Gardiner Airport well (105980) and the Shooting Star Ranch well (252314) are distinct in that they have sodium-bicarbonate-sulfate type waters (fig. 13). Although the dominant major ions are similar at these two wells, they differ in hydrogeologic setting and other aspects of water quality. TDS is over 500 mg/L at the Gardiner Airport well, the highest of the cold water well sites in the area, while the Shooting Star Ranch well has a TDS concentration of 150 mg/L, the lowest of any LTMP site in the subarea. The Shooting Star well is unique in that carbonate is the dominant anion due to the elevated pH (9.7 to 10.0). The average bicarbonate concentration (HCO_3^-) is 33 mg/L and the average carbonate (CO_3^{2-}) concentration is 35 mg/L.

Piper plots summarize the major ion chemistry for the Yellowstone River watershed monitoring sites and show the variability among samples from each site. The hot and warm water sites (fig. 14) and cold water sites (fig. 15) are shown separately to show the greater variation in chemistry at hot and warm water sites compared to cold water sites. The Gardiner Airport well (105980) differs from other cold water sites in that sodium is the dominant cation, and it has elevated sulfate. This chemistry suggests that groundwater at the Gardiner Airport well may be a mix of geothermal and fresh groundwater. Major ion chemistry at La Duke and Bear Creek Hot Springs also differs. Sulfate is the dominant anion at La Duke, while Bear Creek has a mixed bicarbonate and sulfate composition.

Total Dissolved Solids

Total Dissolved Solids (TDS) concentrations provide another way to compare the water chemistry among the LTMP sites in the Yellowstone River watershed (fig. 16). La Duke Hot Springs (171215) and Bear Creek Hot Springs (197921) have the highest TDS concentrations, followed by the Miller well (152216). The Miller well has higher TDS concentrations than the other warm or cold water sites, which suggests that the water may be geothermal water that has mixed with cold water. The Shooting Star Ranch well (252314) has the lowest TDS concentrations and also shows the least variability; TDS concentrations for four samples range from 148 to 152 mg/L. The cold water sites show less variability than the warm and hot water sites.

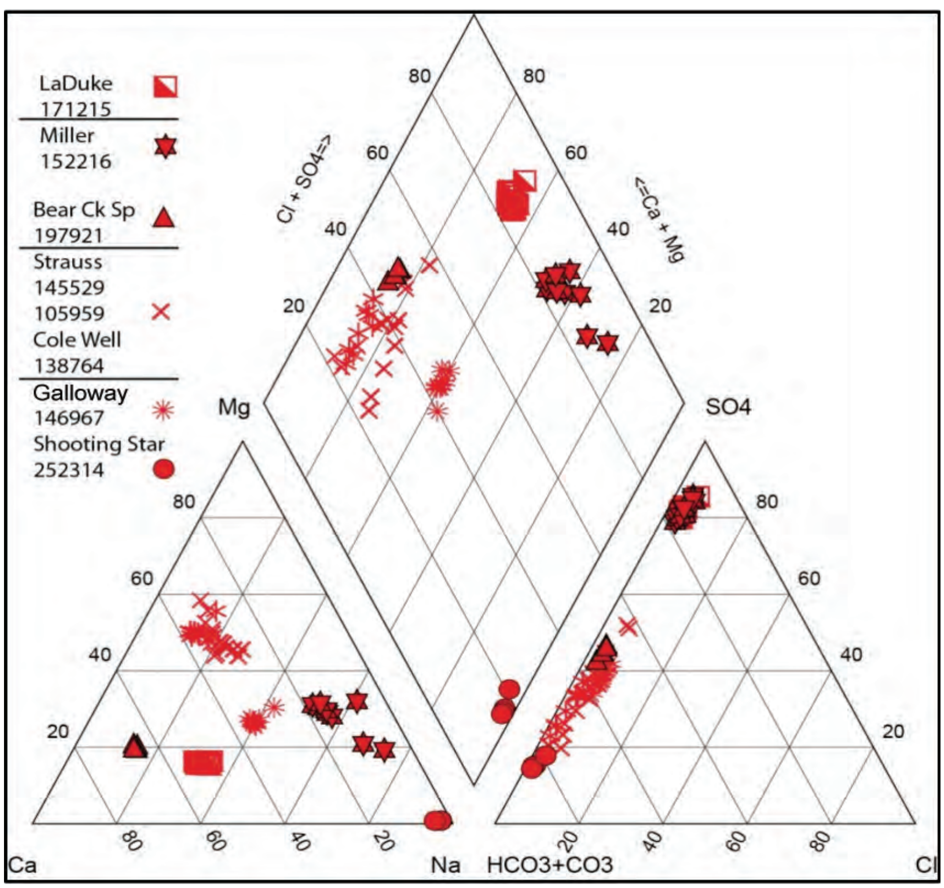


Figure 14. Piper plot for samples from hot (>25°C) and warm (15–25°C) water sites in the Yellowstone River watershed.

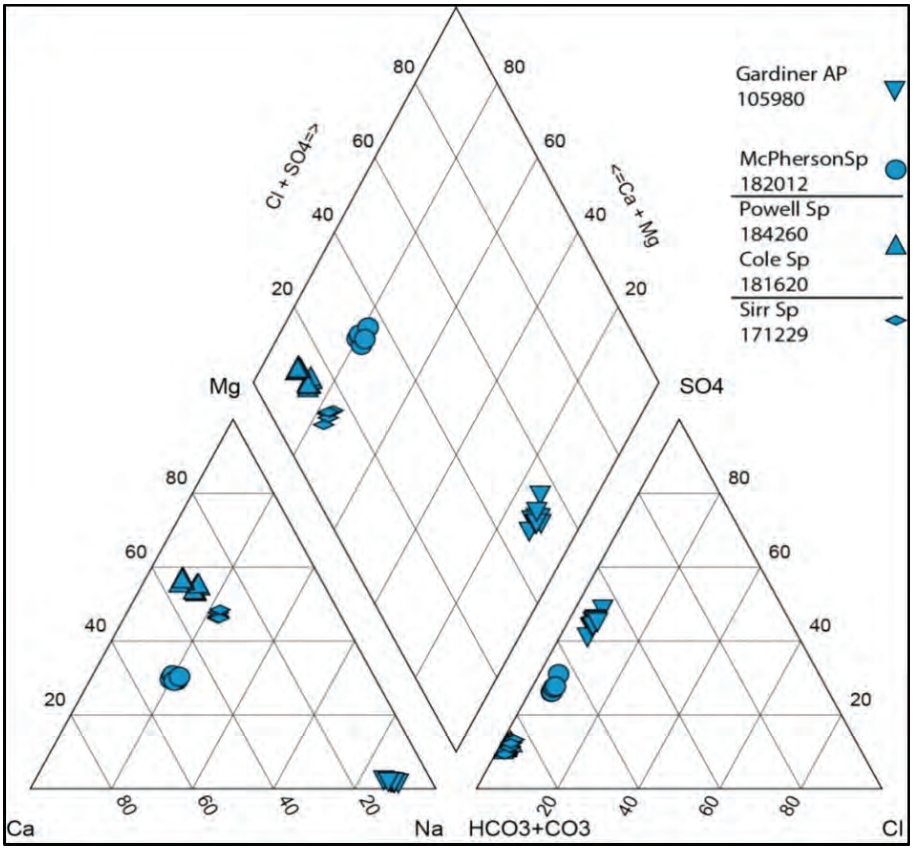


Figure 15. Piper plot for samples from cold water sites (<15°C) in the Yellowstone River watershed. These monitoring sites tend to show less dominance by sodium and sulfate, with the exception of the Gardiner Airport well, compared to the warm and hot water sites (fig, 14).

Average Concentrations of Select Major Ions and Trace Metals

Table 5 shows average concentrations of select major ions and trace elements for the Yellowstone River monitoring sites. La Duke (171215) and Bear Creek (197921) Hot Springs have elevated concentrations of sulfate, chloride, fluoride, arsenic, boron, barium, strontium, and lithium compared to other sites. The Miller well (152216) water chemistry is generally similar to the hot springs water, although concentrations are lower, with the exception of sulfate and iron. The Shooting Star Ranch well (252314) has notably lower concentrations of chloride, barium, stontium, and lithium than other sites. The Gardiner Airport well (105980) is notably different from other cold water sites, with higher concentrations of manganese, sulfate, chloride, fluoride, arsenic, boron, and lithium; this suggests the well produces a mixed thermal/fresh water.

Arsenic

Arsenic concentrations for the Yellowstone River watershed monitoring sites are presented in table 5 and figure 17. Arsenic concentrations generally show a positive correlation with water temperature. The hot water sites have the highest arsenic concentrations, with Bear Creek Hot Springs (197921) at an average concentration of 51 µg/L and LaDuke Hot Springs (171215) at about 18 µg/L. Arsenic in groundwater at the Miller well (152216) is between the two hot springs and varies over time, with a range of 8 to 40 µg/L, possibly due to mixing of geothermal groundwater with cold water. Some of the warm water sites have elevated arsenic, although the Shooting Star Ranch (252314) and Powell wells (184260) do not. The cold water sites have the lowest arsenic concentrations, with the exception of the Gardiner Airport well (105980), which has concentrations between about 9 and 11 µg/L.

Isotope Chemistry

All monitoring sites in the upper Yellowstone River watershed area were sampled at least once for $\delta^{18}O$ and $\delta^{2}H$ (fig. 18, table 6). The data plot along and below the LMWL (Kharaka and others 2002) and the values from the hot and cold sites show a similar

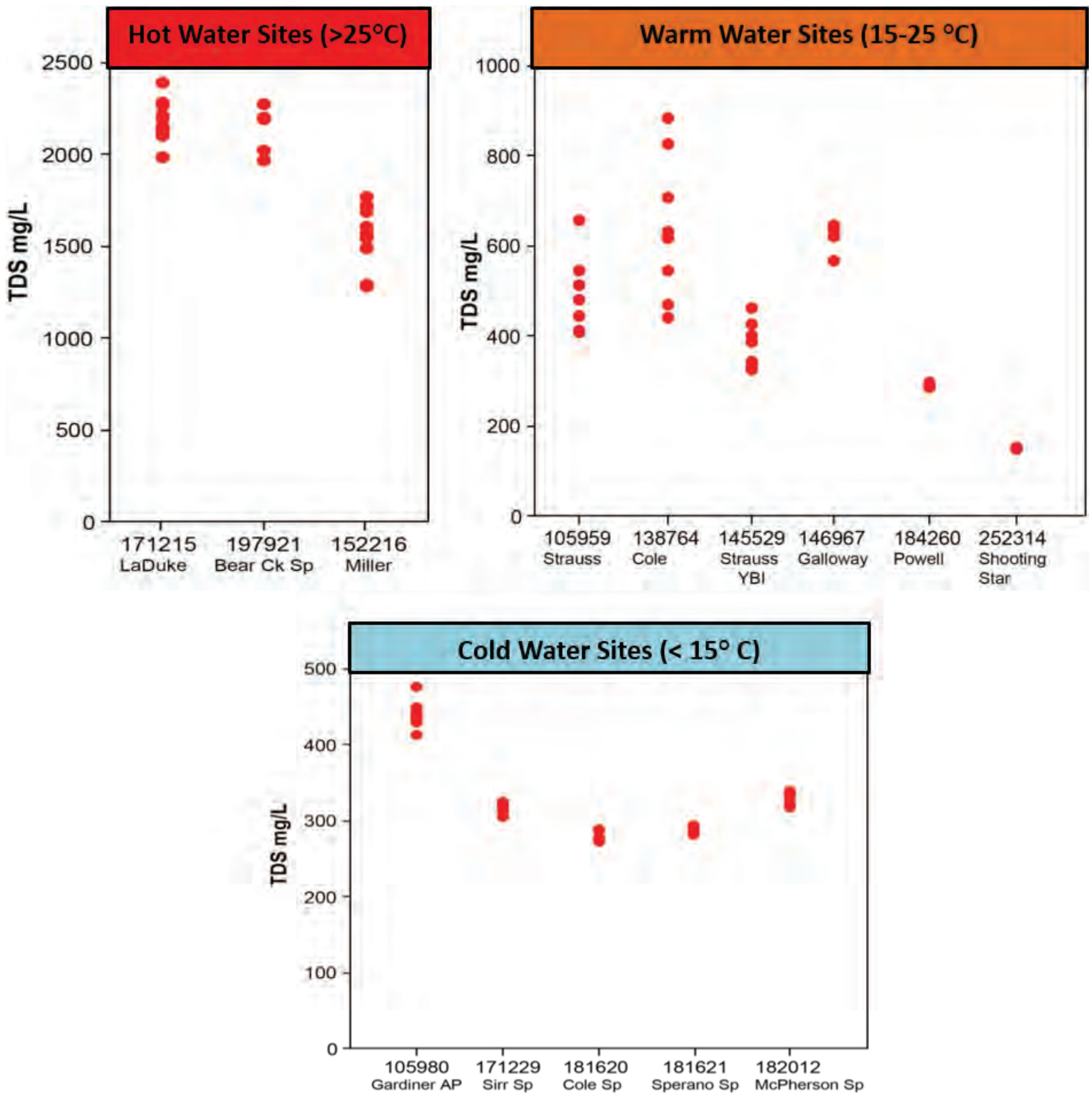


Figure 16. TDS concentrations at monitoring sites in the Yellowstone River watershed.

Table 5. Average concentrations of select major ions and trace elements for Yellowstone River sites.

GWIC ID	Site Type	*n*	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	SiO_2 (mg/L)	SO_4 (mg/L)	Cl (mg/L)	NO_3 (mg/L)	F (mg/L)	As (µg/L)	B (µg/L)	Ba (µg/L)	Sr (µg/L)	Li (µg/L)	U (µg/L)
171215 La Duke	Spring	17	326.1	61.2	235.9	45.1	1278.2	45.1	<0.3	3.7	18.1	454.2	29.2	4236	250.9	<0.5
197921 LD-1	Well	No Data														
197921 Bear Creek	Spring	7	445.4	84.6	109.9	29.4	777.6	37.9	<0.01	2.6	50.5	991.5	23.1	3165	344.0	<1.0
152216 Miller	Well	9	61.7	33.9	298.9	37.5	914.3	33.8	<0.01	1.1	24.2	512.1	15.2	1285	64.3	<1.0
138764 Cole	Well	12	71.6	67.1	44.6	19.0	190.3	17.4	0.6	1.6	10.3	37.7	87.7	2192	41.3	23.3
252314 Shooting Star	Well	4	1.3	ND	48.9	32.1	15.5	1.5	<0.05	0.4	2.7	32.6	2.0	86	4.4	1.0
145529 Y.B. Inn	Well	10	47.7	41.0	20.1	26.5	108.1	6.7	0.5	1.0	3.9	39.6	54.5	739	47.3	3.2
105959 Strauss	Well	9	53.2	49.9	41.8	31.0	156.2	10.3	<0.05	0.8	4.3	59.5	87.1	1107	54.6	4.1
146967 Galloway	Well	10	69.6	33.9	94.9	29.2	191.8	24.1	0.5	0.5	6.0	114.7	62.1	943	53.3	14.0
105980 Airport	Well	11	13.9	1.5	140.7	15.0	151.3	16.8	<0.05	1.0	9.8	259.1	25.8	197	77.5	<0.5
184260 Powell	Spring	8	35.7	37.0	17.6	12.8	32.9	3.5	0.2	0.2	0.5	17.1	73.6	1151	18.0	7.1
171229 Sirr	Spring	6	35.9	34.0	31.5	14.6	34.3	5.1	0.2	0.3	2.1	33.9	53.6	542	38.8	12.7
181620 Cole	Spring	9	37.3	34.0	11.5	13.6	31.4	2.8	0.3	0.3	<1.0	11.1	65.7	1319	15.8	11.8

Note. Red, hot water (>25°C); orange, warm water (15–25°C); blue, cold water (<15°C). Data based on all samples in GWIC collected through 2013. *n* = number of samples.

range. The $\delta^{18}O$ values for the hot sites range from -20.38 to -18.14 with a median of -19.29; values for the cold sites vary from -20.44 to -18.70 with a median of -19.59. There is slightly more variation (difference) in the δ^2H values; hot sites ranged from -152.84 to -143.87 (median = -148.19), whereas the values for the cold sites ranged from -154.35 to -144.00 (median = -151.14). It is notable that the Gardiner Airport well (105980), which has a chemical signature that is distinct from the other cold sites (fig. 15), also has a distinct isotopic signature; the $\delta^{18}O$ and δ^2H values (average of -18.79 and -144.33, respectively) are enriched relative to the other cold springs (average of -19.65 and -151.61).

All the sites with the exception of Bear Creek Hot Springs have been sampled at least once for tritium. Generally, tritium values less than 4 tritium units (TU) suggest a mixture of submodern (recharge prior to 1952) and recent recharge water (Clark and Fritz, 1997). All of the cold water sites have tritium values less than 4 TU with the exception of Gardiner Airport well (105980), which had a value of 7 TU. It is notable that the cold water springs, which have low TDS concentrations (less than 350 mg/L) and a Mg-Ca-HCO_3 chemical signature, suggesting recent recharge, would have tritium concentrations less than 4 TU, suggesting older or mixed water.

The tritium values for the hot sites are either less than 4 TU or greater than 8 TU. La Duke Hot Springs (171215), the Miller well (152216) and the Shooting Star well (252314) did not have detectable tritium, indicating recharge prior to 1952. The Yellowstone Basin Inn wells (105959, 144429) and the Galloway well had tritium concentrations between 8.4 and 12.2 TU, suggesting modern water. The chemical signature of water from these sites is Mg-Ca-HCO_3, also consistent with recent recharge.

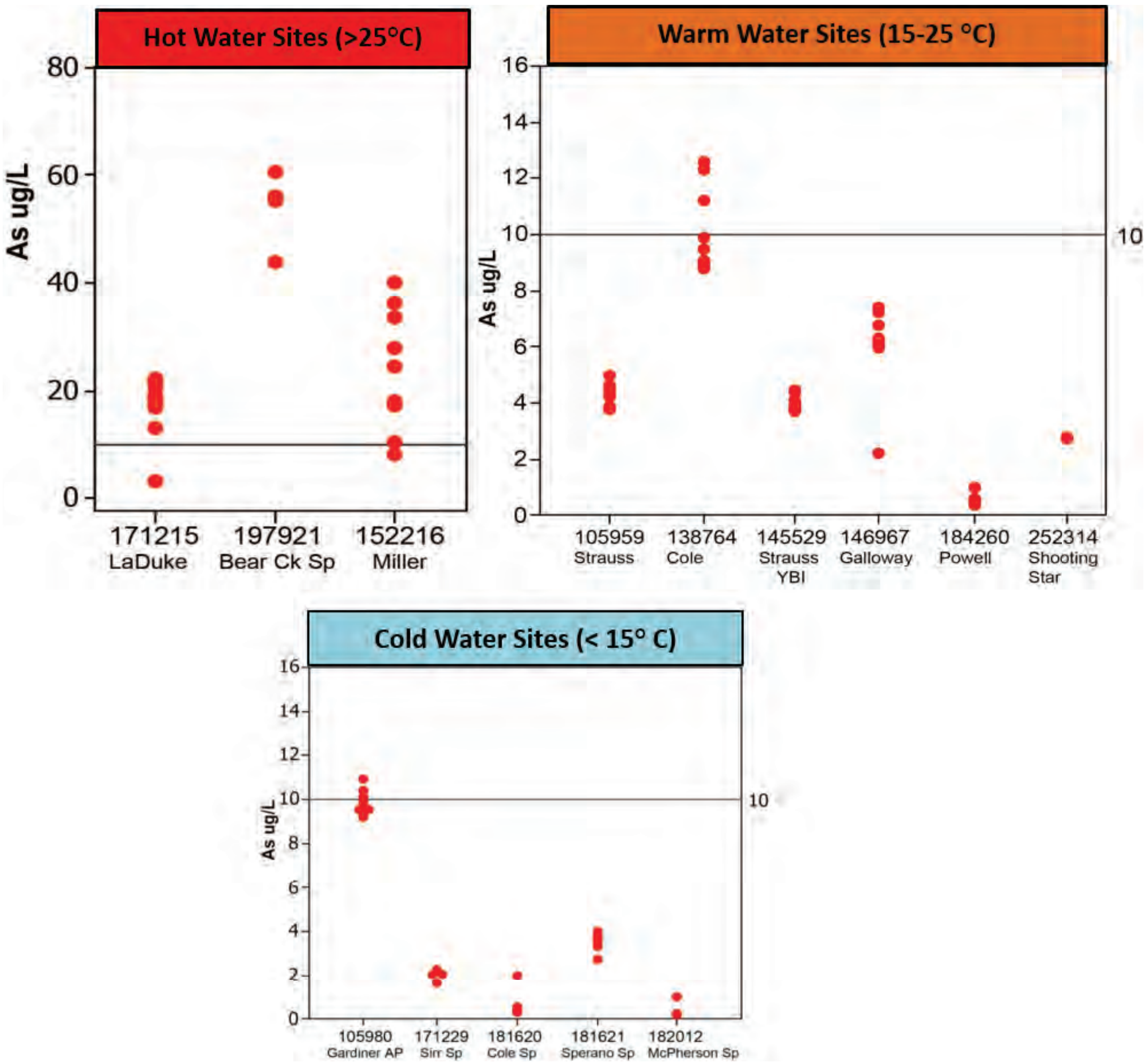
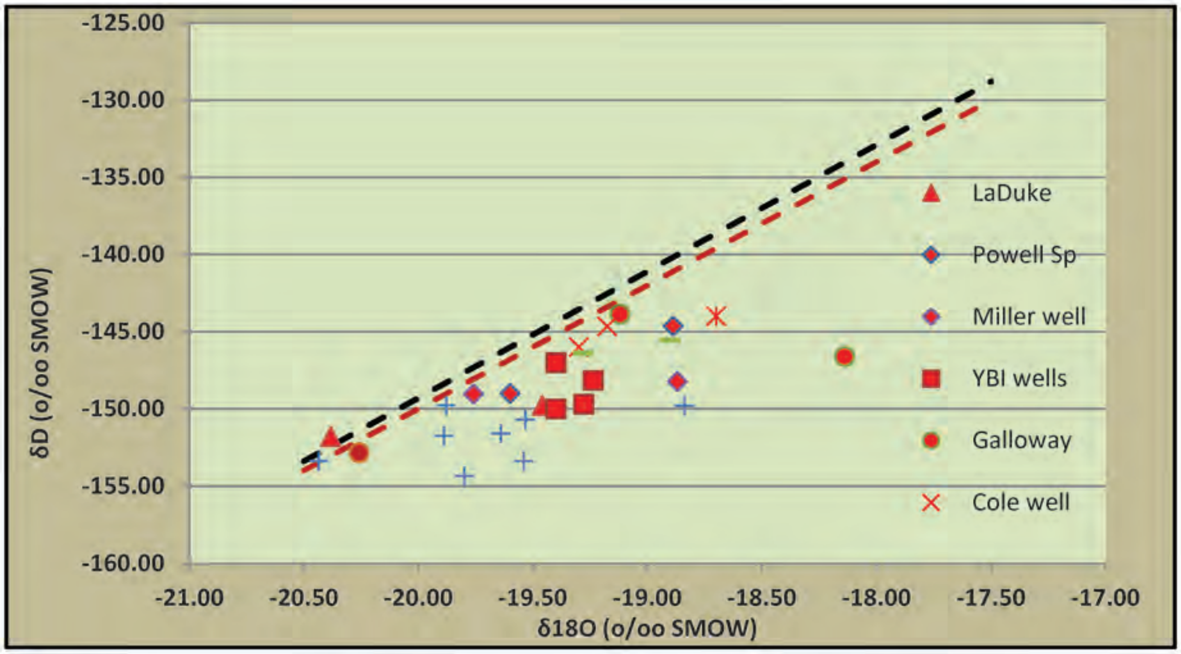


Figure 17. Arsenic concentrations at monitoring sites in the Yellowstone River watershed.



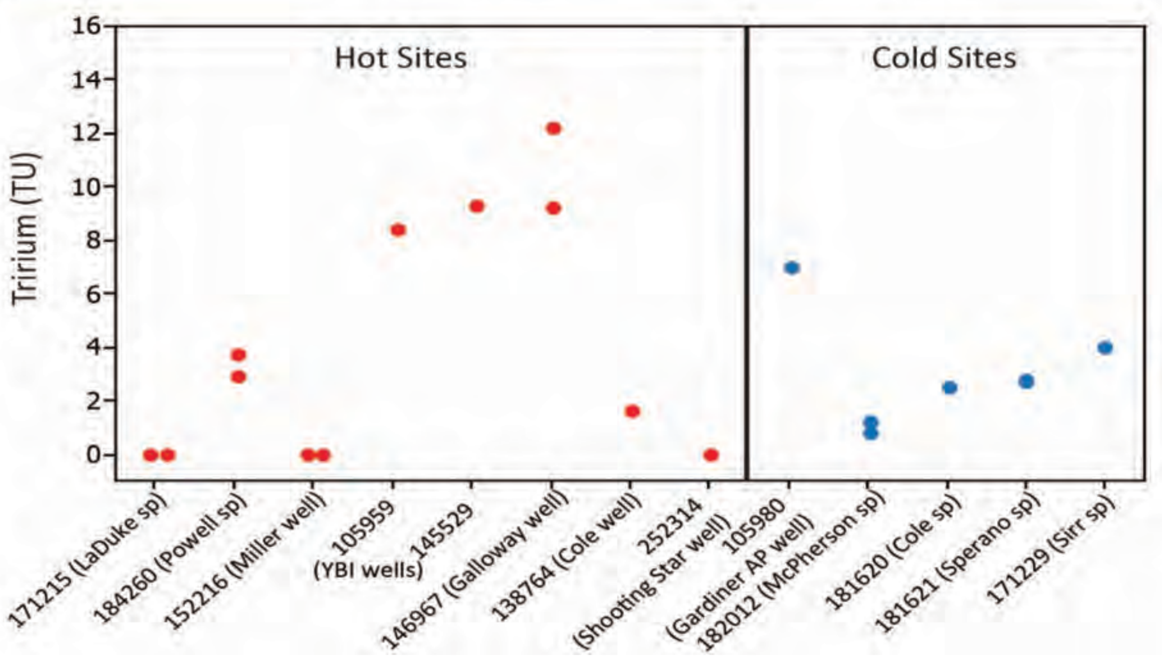


Figure 18. Chart showing the composition of stable isotopes for the monitoring sites in the Yellowstone River watershed, and plots showing the tritium concentrations for hot (and warm) water sites and cold water sites in the Yellowstone subarea. The local meteoric water line is based on samples from the Greater Yellowstone National Park area (Kharaka and others, 2002).

Table 6. Oxygen and hydrogen isotope sampling results for Yellowstone River Watershed sites.

MBMG Sample ID	GWIC ID	Name	Temp Class	Site Type	$\delta^{18}O$ Result	$\delta^{2}H$ Result	3H Result	± 1σ	Sample Date
2010R5099	171229	Sirr	Cold	Spring	-19.5	-153.4	4.00	0.5	11/12/09
2008R5010	181620	Cole	Cold	Spring	-19.5	-150.70	2.50	0.4	10/18/07
203865	181620				-19.5	-151.0			05/21/13
204758	181620				-19.9	-152.0			08/19/13
205516	181620				-19.2	-154.0			11/26/13
2009R5003	181621	Sperano	Cold	Spring	-20.4	-153.4	2.8	0.8	10/23/08
2010R5101	181621				-19.9	-149.8	2.7	0.4	11/12/09
2009R5005	182012	McPherson	Cold	Spring	-19.9	-151.7	<0.8	0.8	10/24/08
2010R5106	182012				-18.8	-149.8	1.2	0.3	11/12/09
2010R5107	252314	Shooting Star	Warm	Well	-20.3	-152.8	<0.8	0.3	11/17/09
2006R5000	171215	La Duke	Hot	Spring	-18.9	-145.6	<0.8	0.7	03/22/06
2010R5104	171215				-19.3	-146.4	<0.8	0.3	11/12/09
2011R5068	171215				-19.5	-148.9	<0.8		04/12/11
2009R5004	184260	Powell	Cold	Spring	-20.4	-151.8	2.9	0.8	10/24/08
2010R5103	184260				-19.5	-149.8	3.7	0.5	11/12/09
203760	197921	Bear Creek	Hot	Spring	-19.6	-149.0			05/14/13
204762	197921				-19.7	-149.0			08/21/13
2014R5011	197921				-19.0	-150.0	2.7		11/14/13
2008R5008	105980	Airport	Cold	Well	-18.9	-144.7	7.0	0.6	10/17/07
203868	105980				-18.7	-144.0			05/21/13
204756	105980				-19.1	-145.0			08/19/13
205515	105980				-18.2	-147.0			11/20/13
2008R5007	105959	Strauss Res.	Warm	Well	-19.2	-148.2	8.4	0.7	10/17/07
203867	105959				-19.4	-147.0			05/22/13
204761	105959				-19.7	-148.0			08/20/13
205518	105959				-19.0	-150.0			11/26/13
2008R5009	138764	Cole	Warm	Well	-19.3	-149.7	1.6	0.3	10/18/07
203864	138764				-19.4	-150.0			05/21/13
204757	138764				-19.7	-151.0			08/19/13
205519	138764				-19.3	-153.0			11/26/13
2008R5006	145529	Strauss YBI	Warm	Well	-19.2	-144.7	9.3	0.8	10/17/07
203866	145529				-19.3	-146.0			05/22/13
204759	145529				-19.6	-147.0			08/20/13
205517	145529				-19.2	-150.0			11/26/13
2006R5002	146967	Galloway	Warm	Well	-18.1	-146.6	12.2	1.1	03/22/06
2010R5105	146967				-19.1	-143.9	9.2	1.4	11/12/09
2006R5001	152216	Miller	Warm	Well	-18.9	-148.2	<0.8	0.6	03/22/06
2010R5102	152216				-19.8	-149.1	<0.8	0.3	11/12/09

GALLATIN RIVER WATERSHED

PARK BOUNDARY to BIG SKY SPUR ROAD

Monitoring Sites in the Gallatin River Watershed

Long-term monitoring efforts in the Gallatin River watershed focus on the upper Gallatin River from the Park boundary downstream to the Big Sky spur road area (junction Highway 191 and Route 61). Figure 19 shows the entire Gallatin River monitoring area, and figures 20 and 21 show more detailed aerial imagery of the monitoring sites. Excluding the river valley, the area is mountainous, with steep forested slopes along both sides of the valley.

Four active LTMP sites in this subarea include two large springs, a spring creek, and a deep bedrock well (see table 1). A fifth site, Sheep Camp Spring (183236), located in the Taylor Fork of the Gallatin River, was monitored between July 2007 and November 2011. Monitoring at Sheep Camp Spring was discontinued because of a low discharge rate and intermittent seasonal flow. Since there are only a few sites in this watershed area, the following section includes a summary of the water-chemistry data obtained from Sheep Camp Spring.

Geologic Overview of the Gallatin River Monitoring Area

The geology in the Gallatin River watershed monitoring area was mapped at a scale of 1:100,000 by Kellogg and Williams (2000, 2006) and Lonn and others (2007). Figure 22 shows a geologic map of the northern portion of the monitoring area, focused on the area around the Anceny Spring (258715) and Anceny Spring Creek (304093) monitoring sites near Big Sky. The geology in the southern portion of the monitoring area, which includes the Altman well (215333), Snowflake Springs (171216), and Sheep Camp Spring (183236), is shown in figure 23.

The oldest rocks in the area are Archean metamorphic rocks, which are the basement rocks in this

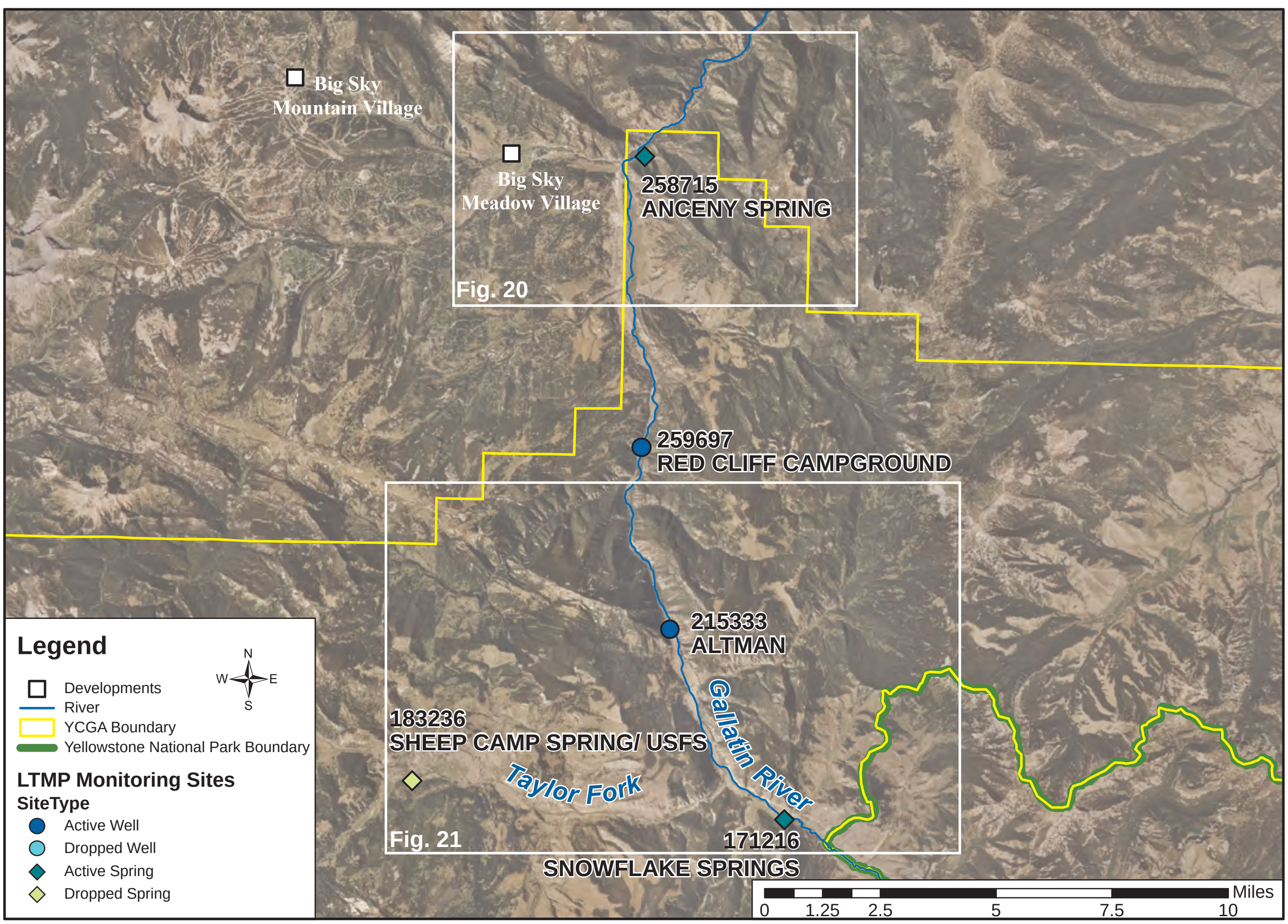


Figure 19. Overview of the Gallatin River Watershed LTMP area showing the monitoring sites, and the locations of figures 20 and 21.

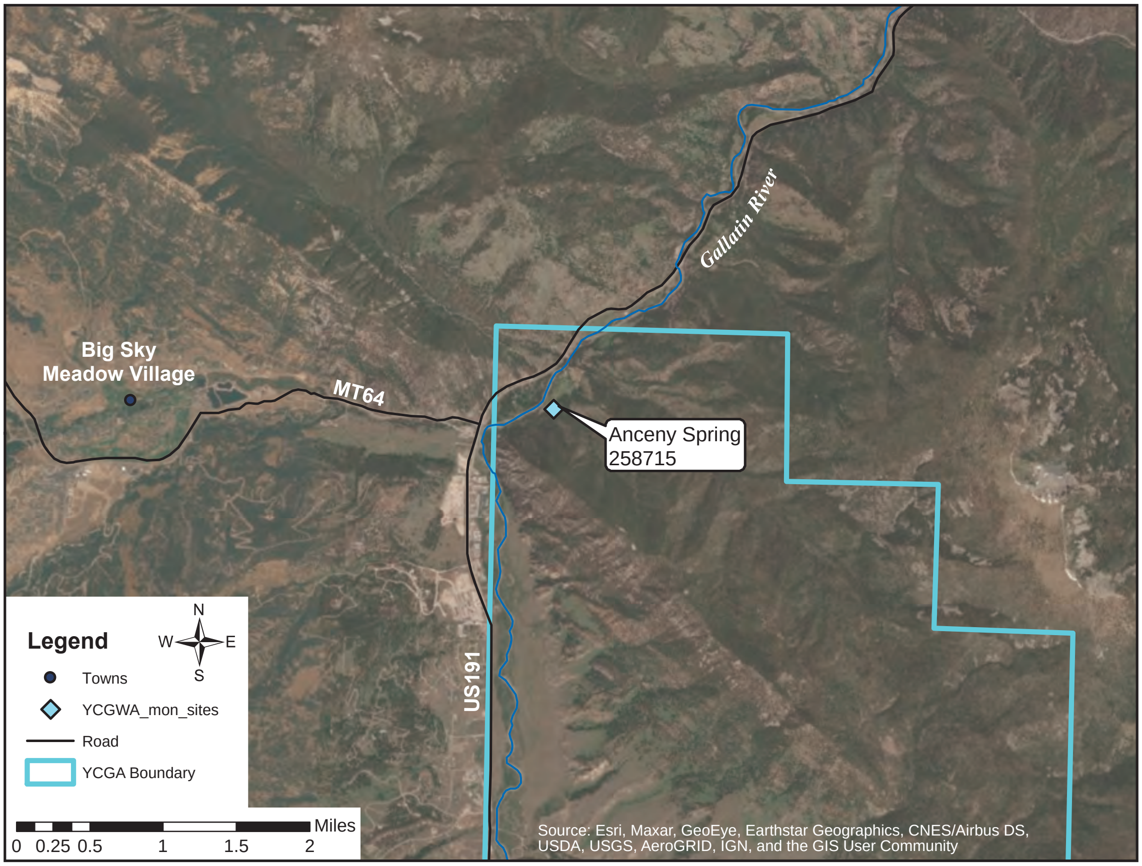


Figure 20. Location of Anceny Spring in the northern portion of the Gallatin River watershed monitoring area. Modified from aerial imagery provided by the USDA National Agricultural Inventory Program (NAIP, 2015).

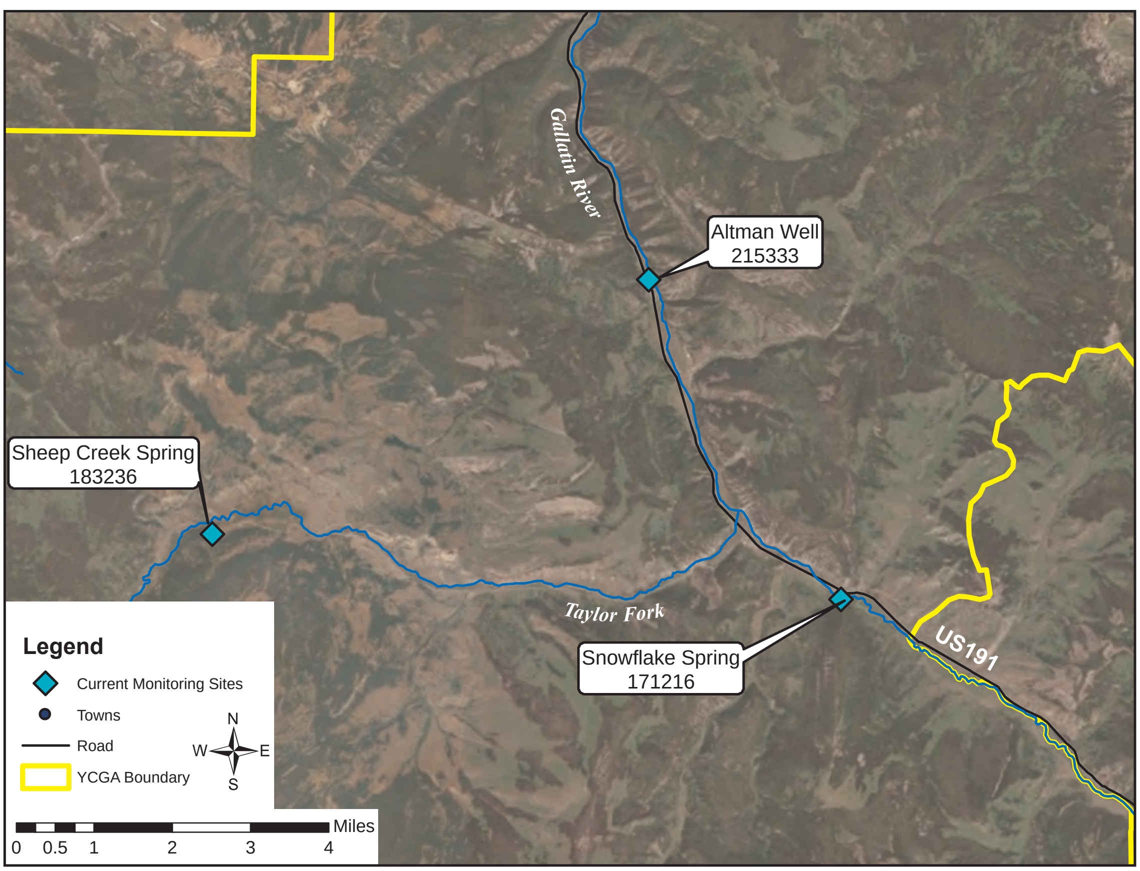


Figure 21. Map showing the location of monitoring sites in the southern portion of the Gallatin River watershed monitoring area. Modified from aerial imagery provided by the USDA National Agricultural Inventory Program (NAIP, 2015).

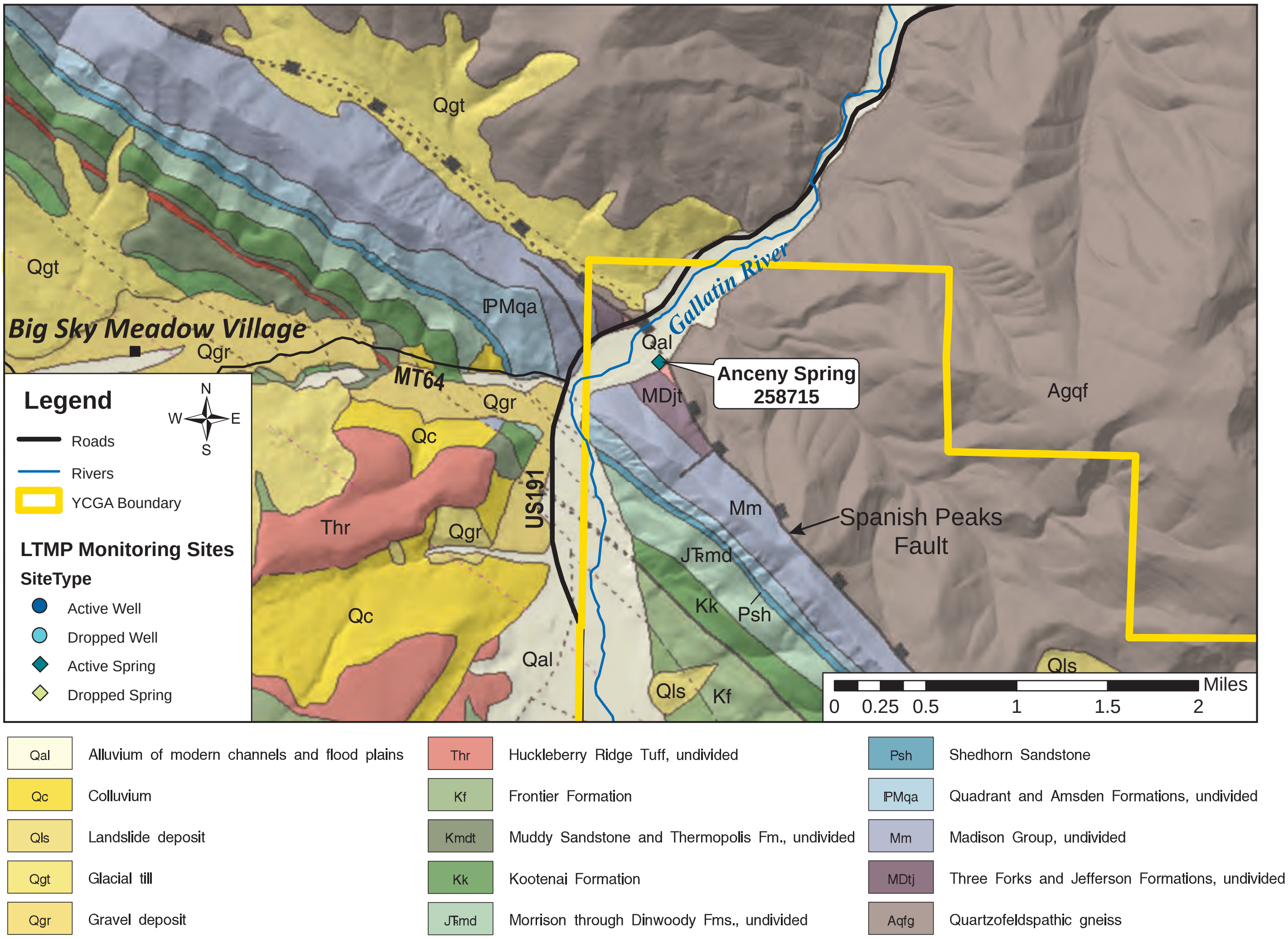


Figure 22. Geologic map of the northern portion of the Gallatin watershed showing the location of Anceny Spring. The spring surfaces from folded and faulted Paleozoic carbonates on the footwall side of the Spanish Peaks thrust fault (Modified from Kellogg and Williams, 2005).

area. The basement rocks are unconformably overlain by Paleozoic and Mesozoic sedimentary rocks, and Cenozoic sedimentary and volcanic rocks. The basement rocks are only exposed in the northeastern portion of the monitoring area, on the northeast side of the Spanish Peaks fault (fig. 22). Compressive forces during the late Cretaceous Laramide Orogeny formed the Spanish Peaks fault, along with other reverse faults and thrust faults, and extensively folded the Paleozoic and Mesozoic formations.

Anceny and Snowflake Springs both surface from folded and faulted Madison Group limestone adjacent to major faults. Anceny Spring surfaces adjacent to the Spanish Peaks fault, a major reverse fault, which extends southeastward from Ennis Lake through the Big Sky area and continues southeast, where it is covered by Eocene Absaroka volcanic rocks. Lonn and others (2007) speculate that the Spanish Peaks fault may continue southeast under the volcanic cover and be a continuation of the Gardiner reverse fault in the Yellowstone River watershed. The Spanish Peaks reverse fault and the Gardiner reverse fault both thrust Archean metamorphic and igneous basement rocks southwestward, over Paleozoic and Mesozoic formations. Snowflake Spring surfaces adjacent to an unnamed north–south-trending thrust fault, where folded Paleozoic formations were thrust eastward over folded younger Paleozoic and Mesozoic formations (fig. 23).

Volcanic and volcaniclastic rocks of the Absaroka Volcanic Group (Eocene), the Huckleberry Ridge Tuff (Pliocene), and Quaternary surficial deposits partially cover the Paleozoic and Mesozoic formations in the monitoring area. The Quaternary surficial deposits include colluvium, alluvium, glacial till, and landslide deposits (figs. 22, 23). The landslide deposits are extensive in the monitoring area, and generally occur along the margins of the Gallatin River Valley and other slopes, where bedrock consists of Cretaceous

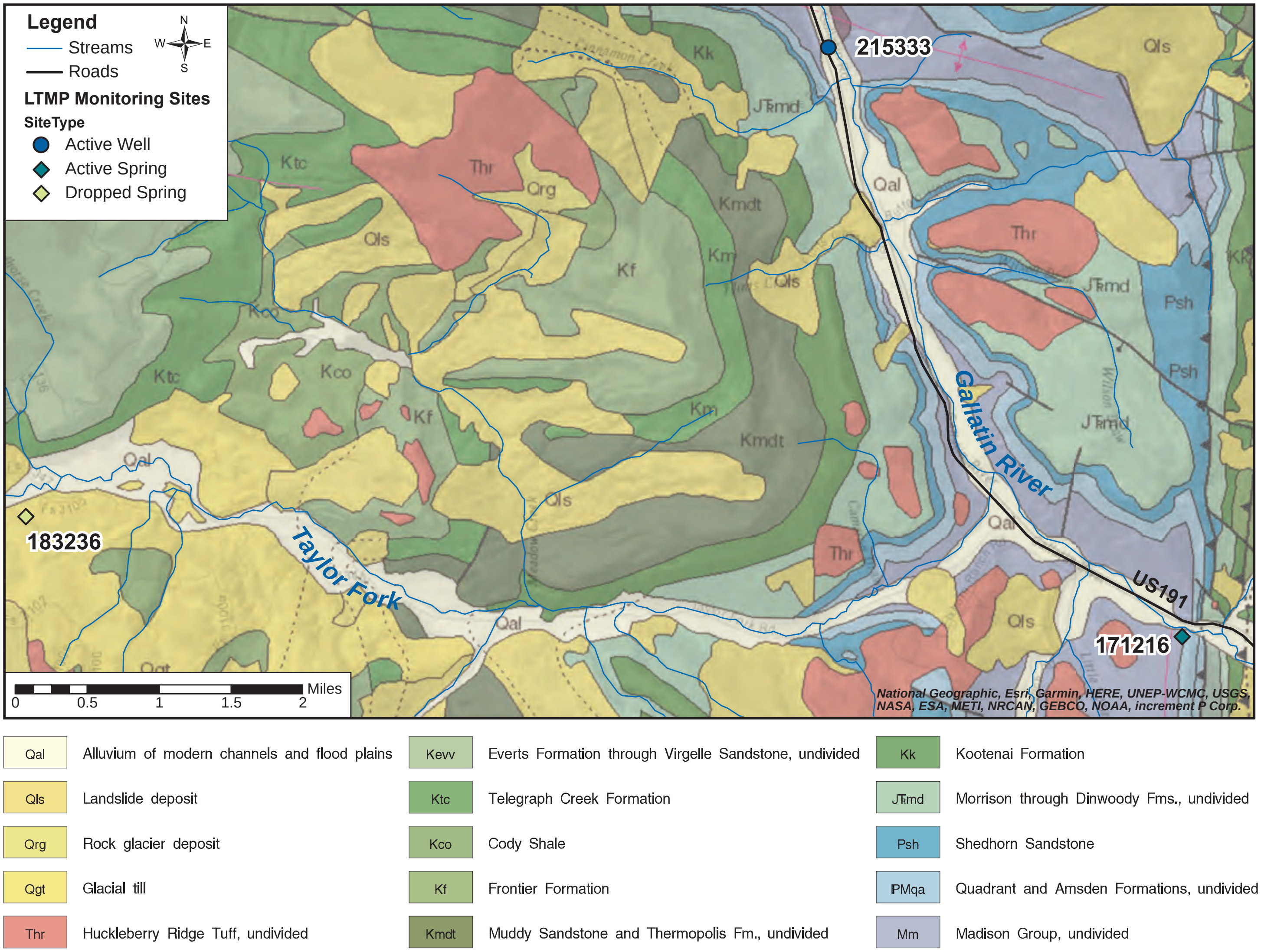


Figure 23. Geologic map of the southern portion of the Gallatin River watershed showing the locations of Snowflake and Sheep Camp Springs (modified from Kellogg and Williams, 2005). Snowflake Spring surfaces from folded Paleozoic rocks on the hanging wall side of a thrust fault.

shale and sandstone. Patches of glacial till are found throughout the area, with thick deposits covering some of the higher elevation ridges. Thin, isolated patches of glacial till are present along the Gallatin River Valley, but the valley floor is primarily covered by alluvial fan deposits, fluvial clays, sands and gravels, and landslide deposits.

Normal faults, which formed as a result of extensional forces active since the end of the Cretaceous, crisscross the area. These faults offset the Paleozoic and Mesozoic formations, and the Absaroka Group, but are not shown on the geologic maps as offsetting the younger Huckleberry Ridge tuff and the Quaternary surficial deposits.

Water-Quality Summary for Gallatin River Watershed Monitoring Sites

Anceny Spring is a warm water spring with an average temperature of 17.3°C, while Snowflake and Sheep Camp Springs are cold water springs with average temperatures of 12.4 and 5.9°C, respectively. Anceny and Snowflake Springs have similar major ion chemistry, but there are some differences in trace element chemistry. The water quality at Sheep Camp Spring differs from that at Anceny and Snowflake Springs, but the three springs have similar water isotope chemistry. Water quality is not monitored at the Anceny Spring Creek site, and the Altman well has not been sampled because there is no pump in the well and the water level in the well is over 300 ft bgs.

Major Ions and Total Dissolved Solids

Stiff diagrams (fig. 24) and a Piper plot (fig. 25) highlight the major ion chemistry of the Gallatin River watershed monitoring sites. TDS concentrations

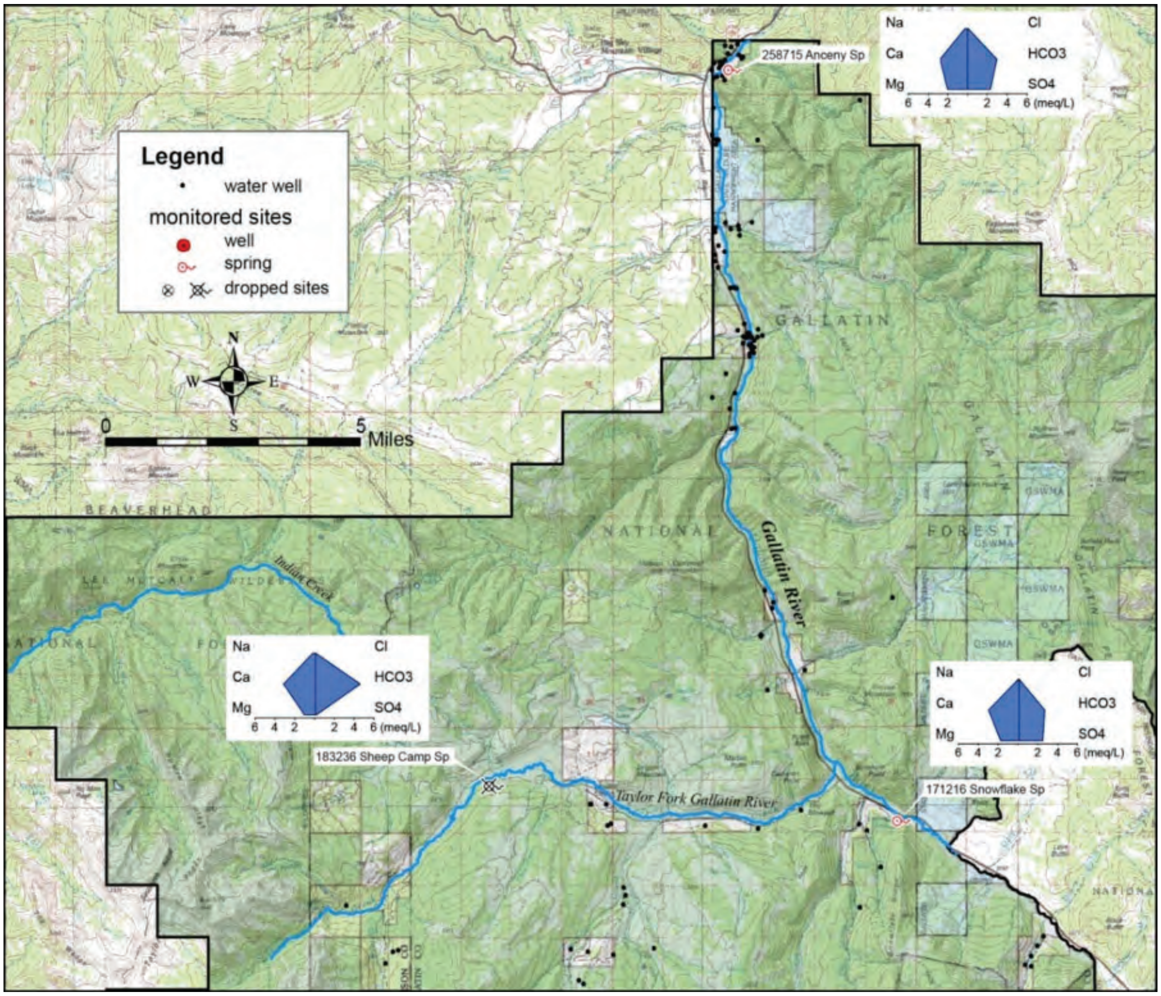


Figure 24. Stiff diagrams summarizing major ion chemistry for the Gallatin monitoring sites show the similarity in major ion chemistry at Anceny and Snowflake Springs.

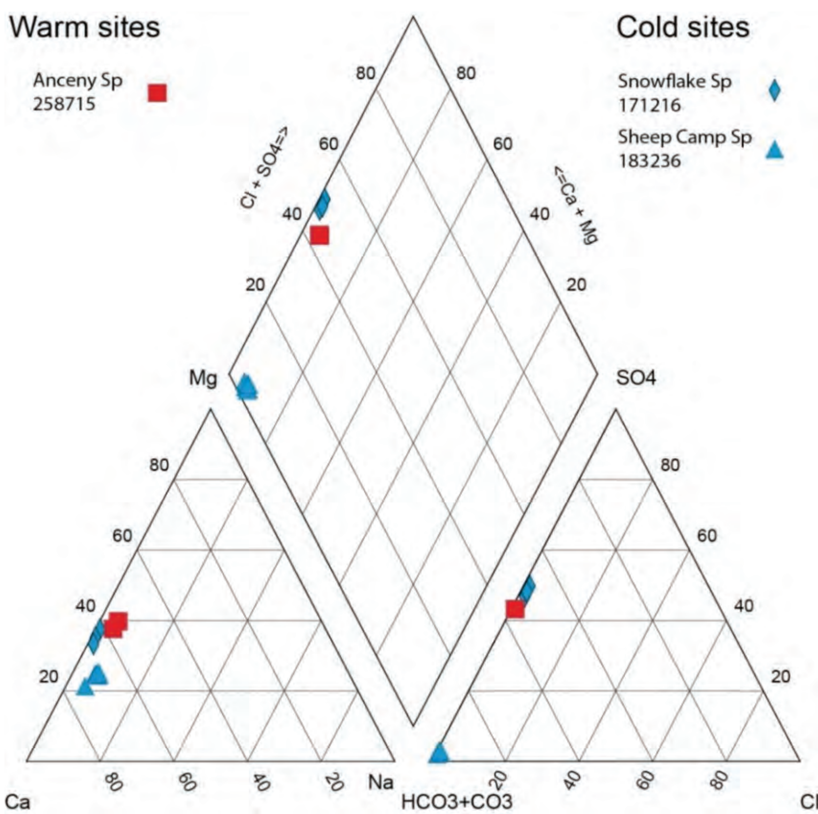


Figure 25. Piper plot for the three Gallatin River springs shows the chemistry is relatively consistent over time at each site. The Piper plot also highlights low sulfate concentrations in the Sheep Creek Spring.

are summarized in figure 26. Anceny and Snowflake Springs both discharge a calcium-magnesium-bicarbonate-sulfate type water. Anceny Spring has slightly higher ratios of calcium to magnesium, and bicarbonate to sulfate, than Snowflake Springs (fig. 25). Sheep Camp Spring discharges a calcium-bicarbonate type water that is low in sulfate and TDS, and distinct from Anceny and Snowflake Springs. None of the sites have elevated levels of sodium or chloride. While Anceny and Snowflake Springs both have TDS concentrations around 300 mg/L, Sheep Camp Spring has an average TDS concentration of less than 240 mg/L (fig. 26).

Average Concentrations of Select Major Ions and Trace Elements

Table 7 shows the average concentrations of select major ions and trace elements for the Gallatin River monitoring sites. Of the two large springs, Anceny Spring (258715) has higher concentrations of sodium, chloride, boron, and strontium than Snowflake Springs (171216), and lower concentrations of sulfate, barium, and lithium (table 7). These differences are noteworthy given they both appear to discharge from Madison Group limestone. Sheep Camp Spring (183236), a small intermittent spring in a different hydrogeologic setting, differs in water quality compared to the two large springs, with higher concentrations of silica and barium, and lower concentrations of sulfate and strontium.

Isotope Chemistry

Values for $\delta^{18}O$ and $\delta^{2}H$ in water samples collected from the Gallatin River monitoring sites are shown in figure 27 and summarized in table 8. The data plot close to the local meteoric water line, and there is little difference isotopically between the two cold springs and the warm spring (Anceny). The median $\delta^{18}O$ value for the cold springs is -19.6; the median value for Anceny Spring (258715) is -19.4. The median $\delta^{2}H$ value for the cold springs is -146.5, and the median value

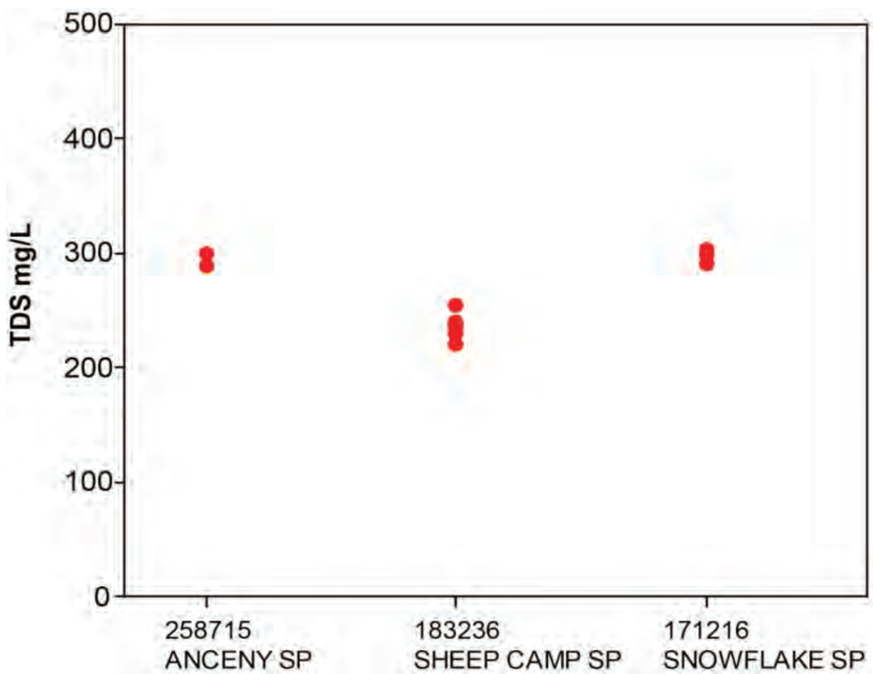


Figure 26. TDS concentrations for all samples collected from the Gallatin River subarea. Anceny and Snowflake Springs have nearly identical TDS concentrations, while Sheep Camp Spring has an average TDS concentration about 50 mg/L lower.

Table 7. Average concentrations of select major ions and trace elements for Gallatin River monitoring sites.

GWIC ID	Site Type	*n*	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	SiO_2 (mg/L)	SO_4 (mg/L)	Cl (mg/L)	NO_3 (mg/L)	F (mg/L)	As (µg/L)	B (µg/L)	Ba (µg/L)	Sr (µg/L)	Li (µg/L)	U (µg/L)
258715 Anceny	Spring	4	57.8	23.3	5.4	8.6	110.1	2.0	0.1	0.6	1.2	17.6	27.3	427.7	7.7	< 1.0
171216 Snowflake	Spring	5	64.1	21.7	1.5	8.3	121.3	0.8	<0.2	0.6	2.9	8.2	33.8	332.9	11.7	0.6
183236 Sheep Camp	Spring	8	64.3	13.7	7.0	13.7	5.6	0.9	<0.1	0.1	0.4	20.0	95.4	215.4	6.9	<0.5

Note. Orange, warm water (15–25°C); blue, cold water (<15°C). Data based on all samples in GWIC collected through 2013.

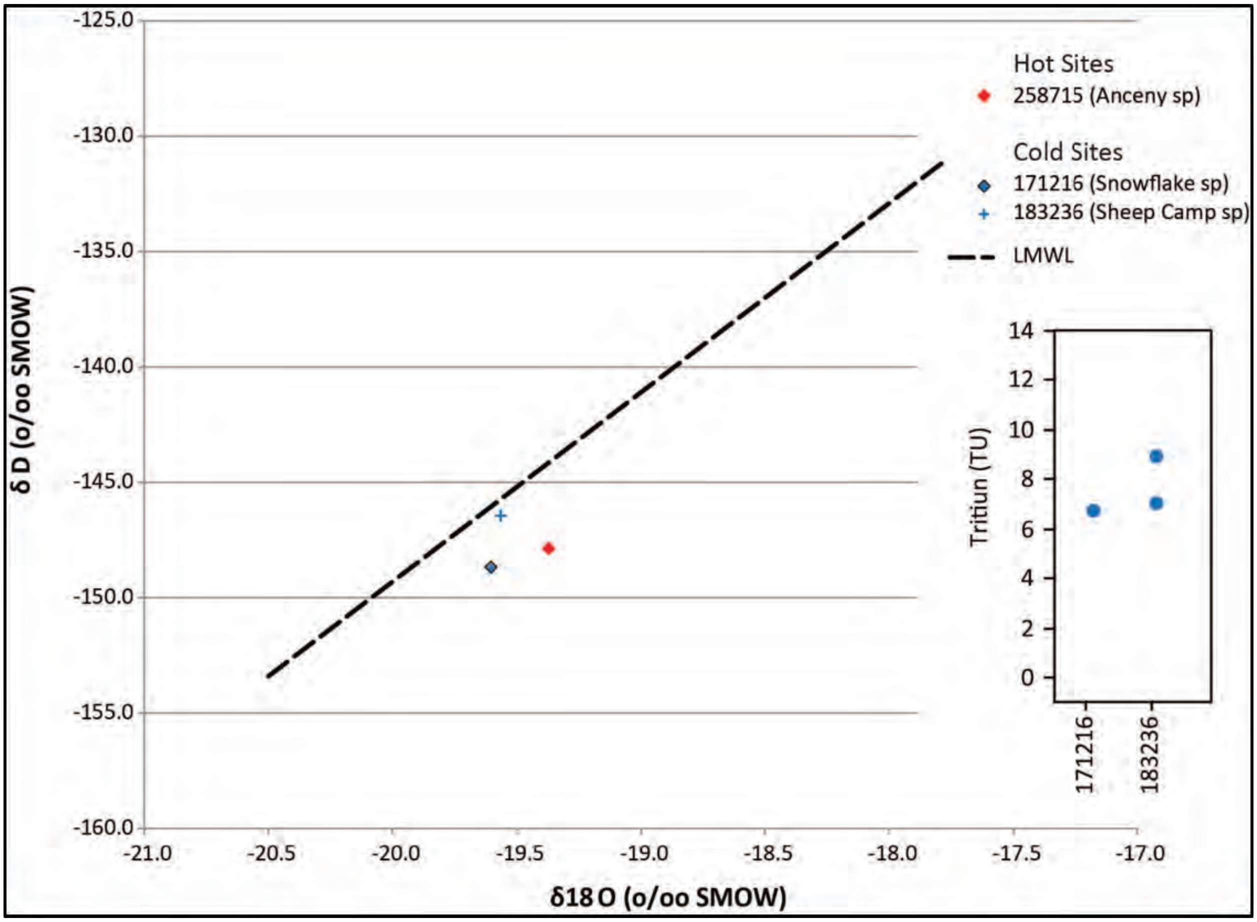


Figure 27. The composition of stable isotopes and tritium for the warm (Anceny) and cold (Snowflake and Sheep Camp) springs in the Gallatin River watershed. Values are similar for all three sites. The local meteoric water line is based on samples from the Greater Yellowstone National Park area (Kharaka and others, 2002).

Table 8. Oxygen and hydrogen isotope sampling results for Gallatin River monitoring sites.

Sample ID	GWIC ID	Name	Temp	Site Type	$\delta^{18}O$ Result	$\delta^{2}H$ Result	^{3}H Result	± 1σ	Sample Date
2010R5109	171216	Snowflake	Cold	Spring	-19.6	-148.6	6.7	0.6	4/27/10
2012R4940	171216				-19.6	-148.6	6.7		5/23/12
203683	171216				-19.7	-148.0			5/6/13
204750	171216				-20.0	-150.0			8/13/13
205457	171216				-19.6	-152.0			11/6/13
2008R5003	183236	Sheep Camp	Cold	Spring	-19.0	-146.4	8.9	0.8	10/04/07
2009R5001	183236				-20.2	-146.5	7.0	0.9	10/21/08
203684	258715	Anceny	Warm	Spring	-18.8	-147.0			5/6/13
204751	258715				-19.9	-149.0			8/13/13
205456	258715				-19.5	-151.0			11/6/13

from Anceny Spring is -148.0. Tritium concentrations from the cold springs range from 6.7 to 8.9 TU (fig. 27), consistent with a source of modern recharge. Anceny Spring (258715) has not yet been sampled for tritium.

MADISON RIVER WATERSHED

HEBGEN BASIN and WEST YELLOWSTONE AREA

Monitoring Sites in the Madison River Watershed

Monitoring activities in this watershed are focused in the Hebgen Basin, in the upper Madison River watershed. There are 12 active LTMP sites in the watershed that include cold and warm water wells and springs, and one spring creek (see table 1). With the exception of Corey Spring (182014), located along the north shore of Hebgen Lake (fig. 28), the monitoring sites are focused in the southern portion of Hebgen Basin, south of Hebgen Lake and north and west of the town of West Yellowstone (fig. 29). Stinky Spring (183268) is the only monitoring site that may be associated with a geothermal groundwater reservoir. There are several flowing-artesian wells in the southern portion of the Hebgen Basin, and four of these are LTMP sites.

Monitoring was discontinued at three LTMP sites in this area for various reasons. Lionshead Spring (181626; fig. 29) flows year-round and serves as a public water supply for numerous cabins along Hebgen Lake. A cracked and leaky concrete spring box covers the spring and precludes accurate flow and temperature monitoring. Monitoring of Lonesomehurst Spring (164216; fig. 29) was dropped due to intermittent flow and difficulty maintaining a flume due to snow and ice accumulation. Monitoring at Beaver Creek Spring (181930), located northwest of Hebgen Lake at the U.S. Forest Service Beaver Creek Cabin, was discontinued because of low and intermittent spring flow.

Geologic Overview of the Madison River Monitoring Area

The geology of the Hebgen Basin area was mapped by O’Neill and Christiansen (2002) at a scale

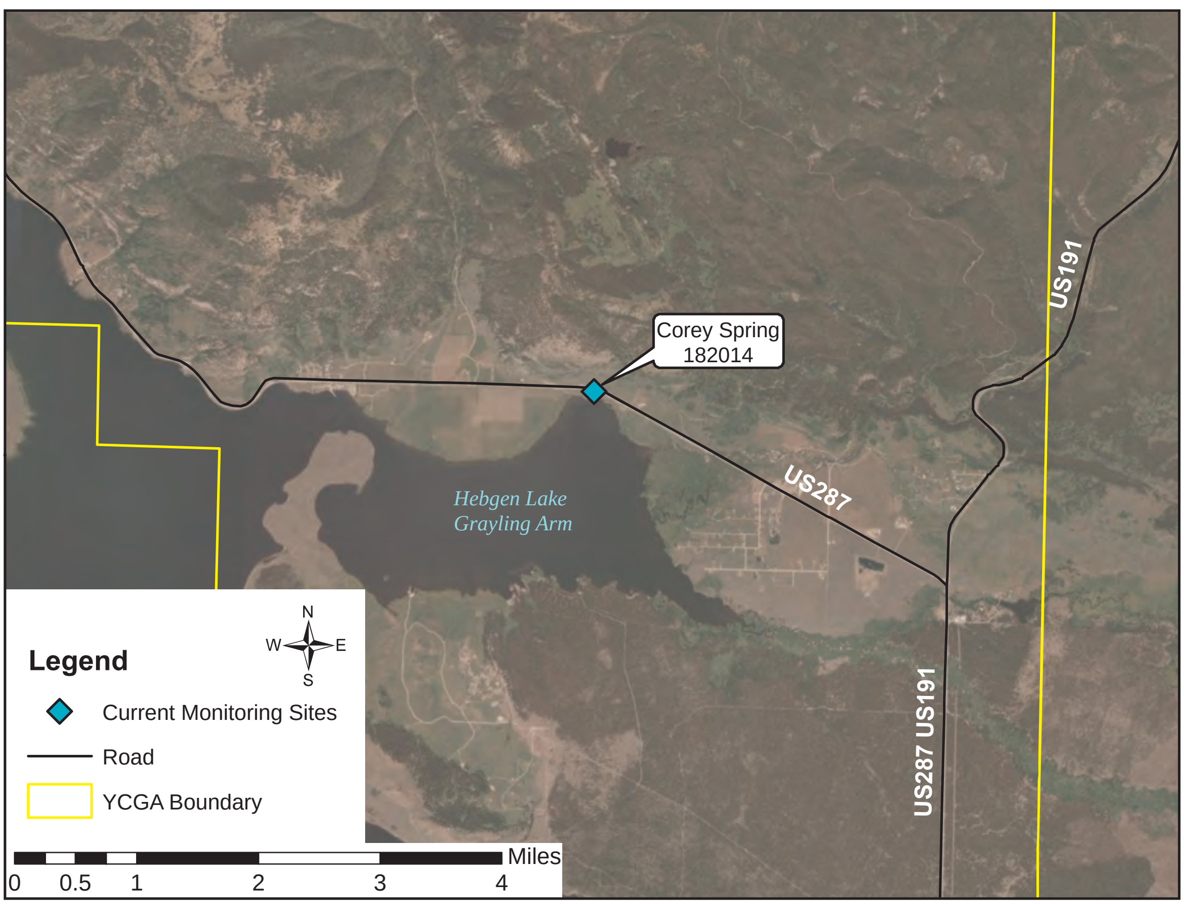


Figure 28. Aerial image showing the location of Corey Spring along the north shore of Hebgen Lake. Corey Spring discharges from under highway fill, into a large pole area, and then flows into Hebgen Lake.

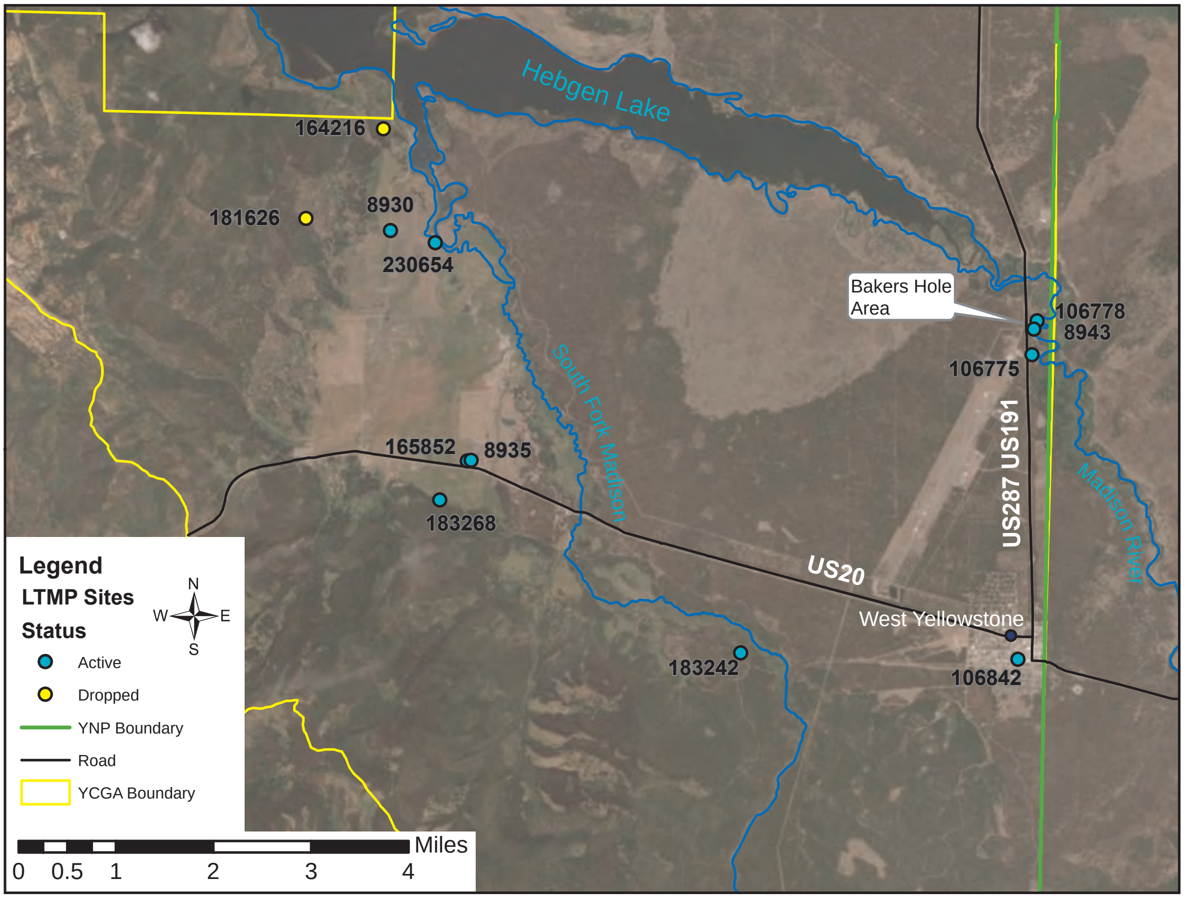


Figure 29. Aerial image showing the locations of active and discontinued monitoring sites in the southern portion of Hebgen Basin.

of 1:100,000 as part of the Hebgen Lake 30´ x 60´ quadrangle. Lonn and others (2007) mapped the geology of this area at a scale of 1:100,000 during geologic mapping of the YCGA. The geology in the area of the monitoring sites is shown in figures 30 and 31.

Hebgen Basin is a structural and topographic basin formed in a half-graben created by northeast–southwest extension. The northwestern, western, and southwestern margins of the basin are bounded by normal faults. O'Neill and Christiansen (2002) have also mapped several northwest-trending normal faults in the interior of the basin, south and southeast of Hebgen Lake. The Hebgen Basin area has probably gone through several periods of extension since the beginning of the Tertiary period (Janecke, 2007), and is still undergoing extension as evidenced by the 1959 Hebgen Lake earthquake. Fault scarps from this earthquake, where the Red Canyon fault ruptured to the surface, are visible just north of Corey Spring (fig. 30). Trilateration surveys completed between 1973 and 1987 in the Hebgen Lake area by Savage and others (1993) indicate that the area is currently undergoing significant extension in a N. 15° E. direction at a rate of up to 8 mm/y.

Along the northwestern margin of the basin, in the Corey Spring area, the exposed bedrock consists of folded and faulted Paleozoic and Mesozoic sedimentary formations that were thrust northeastward during the Cretaceous Laramide Orogeny (fig. 30). Bedrock exposed along the north–northeast and south margins of the Madison Valley consists almost entirely of volcanic rocks, including the Tertiary Huckleberry Ridge rhyolite tuff, Quaternary Lava Creek rhyolite tuff, and Quaternary rhyolite flows (O'Neill and Christiansen, 2002). Numerous isolated outcrops of Archean amphibolite, schist, granite gneiss, and marble are exposed under the volcanic rocks along the north–northeastern margin of the basin (fig. 30), indicating that most or all of the Paleozoic and Mesozoic sedimentary formations in this area were removed by erosion prior to deposition of the volcanic rocks. The western margin of Hebgen Basin is bounded mainly by Archean gneiss, schist, and quartzite, and the Tertiary Huckleberry Ridge rhyolite tuff (fig. 31). The Archean bedrock extends northward into and across Hebgen Lake, and is exposed in the Horse Butte area.

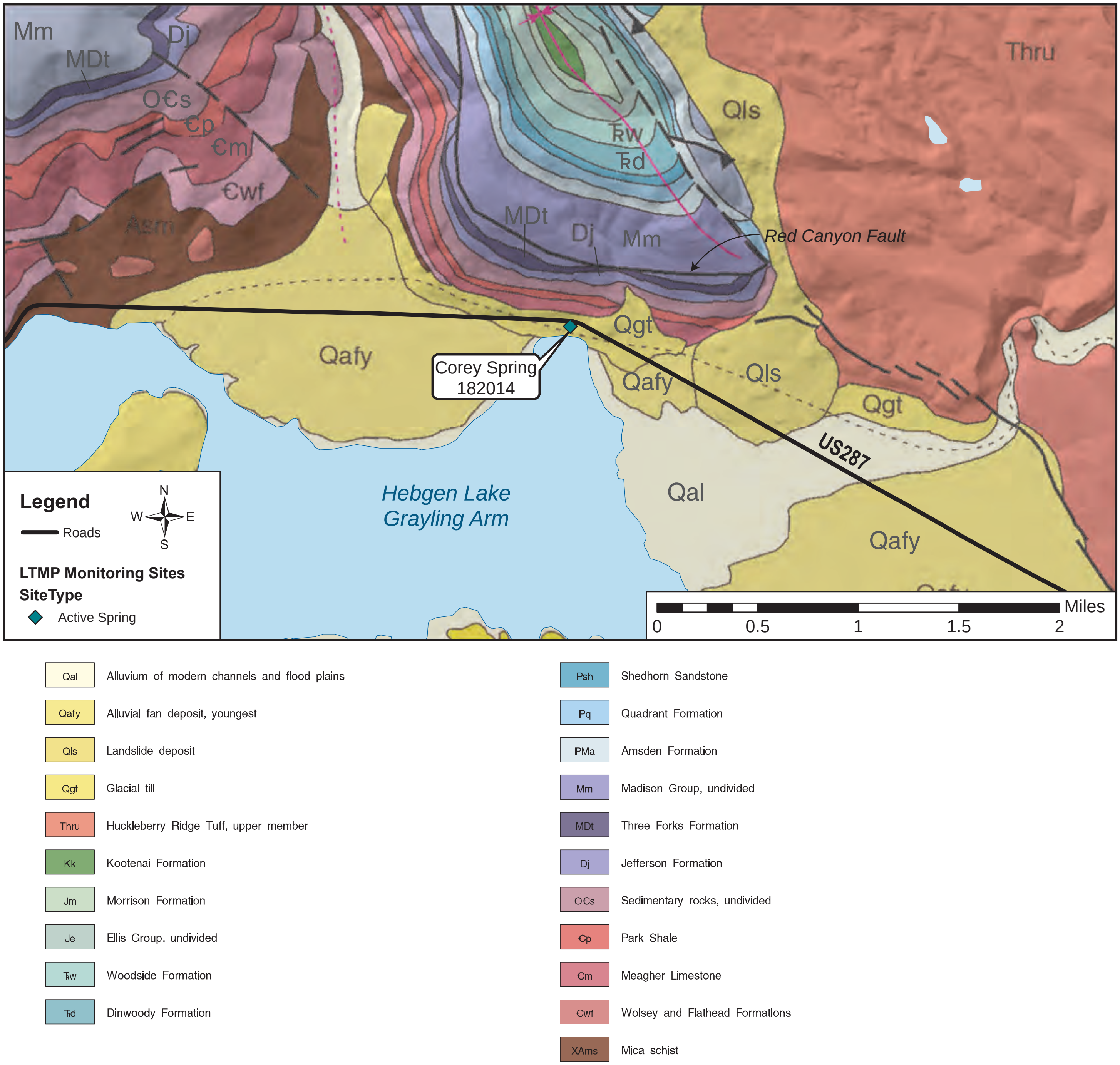


Figure 30. Geologic map of the northern portion of the Hebgen Basin showing the location of the Corey Spring. Modified from O'Neill and Christiansen (2002).

A large expanse of Quaternary (Pleistocene) glacial outwash sands and gravels cover the valley floor in the southern portion of Hebgen Basin, with the exception of Holocene fluvial deposits along the rivers and streams within the valley (O'Neill and Christiansen, 2002). The glacial outwash deposits, commonly referred to as the Obsidian Sand Plain, contain a high percentage of obsidian grains, which give the sandy deposits a gray to black color.

Flowing Artesian Wells

The Hebgen Basin contains numerous flowing artesian wells. Located within the Obsidian Sand Plain, these wells vary in depth, with some completed in the glacial outwash deposits and some completed in the underlying bedrock. A cluster of flowing wells occurs in the Bakers Hole area, north of West Yellowstone (fig. 31). These relatively shallow wells are completed in the sandy glacial outwash deposits, and three of

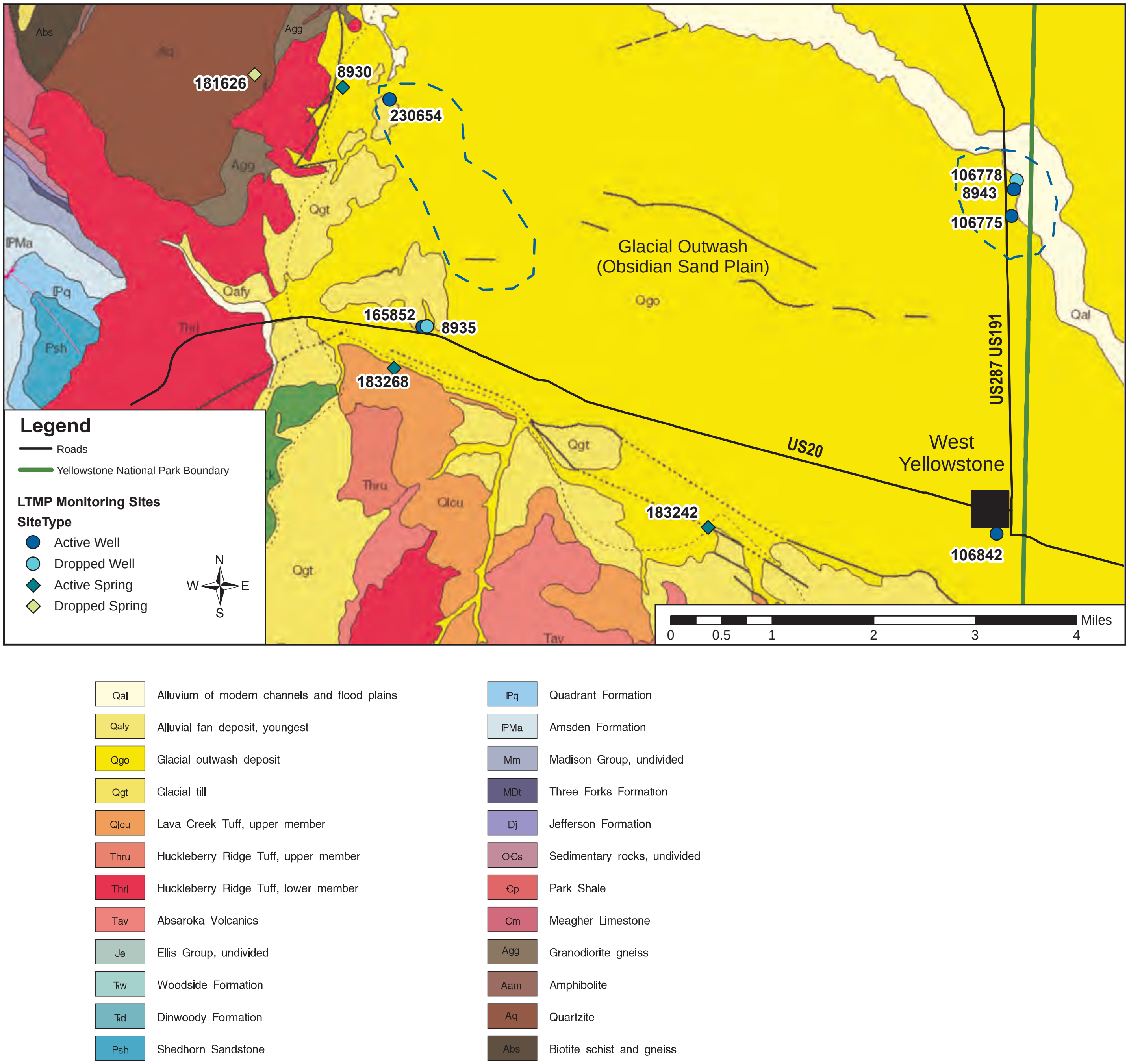


Figure 31. Geologic map of the southwestern portion of the Hebgen Basin with locations of LTMP sites and area of known flowing artesian wells (red lines). Modified from O'Neill and Christiansen (2002).

them are active monitoring sites: Bakers Hole North (8943), Bakers Hole South (106775), and Keland (106778). The Keland well is surrounded by other shallow flowing wells to the west (106779), north (8942), and south (unknown ID).

A flowing well that was owned by Montana Fish Wildlife and Parks, located about 600 ft northeast of the Keland well, was abandoned after the Madison River channel migrated over the well site during spring flooding in 2011. The channel migration left the well in the middle of the active river channel. The original well logs for this well (8941) reported artesian flow at 100 gpm. The well abandonment log (264107) includes a remark that the well flowed in excess of 250 gpm. The original driller's log reported sand to 40 ft, a 7-ft-thick clay and sand layer, and then sand and gravel with flowing water from 47 to 48 ft bgs. Logs for other flowing wells in this area also indicate about 40 ft of sand overlying a clay layer, with artesian conditions underlying the clay. All of the logs for flowing wells in this area indicate confined conditions under one or more clay layers within the glacial outwash deposits.

At least two flowing wells are located along the west side of Hebgen Basin, south of Hebgen Lake (fig. 31). One of these is the Ryberg well (230654), an LTMP well that is 119 ft deep. Although not an LTMP site, the Deep Well Ranch well (106763) is located about 1 mi southeast of the Ryberg well. Drilled in 1940 to a depth of 500 ft, it flows continuously at about 150 gpm and forms a large pond. A number of springs and at least one other flowing well (161092) occur in the vicinity of the Deep Well Ranch. Well 161092 was drilled to 100 ft, completed at 97 ft, and is screened from 75 to 97 ft. The well log does not indicate that the well intercepted bedrock, but several clay layers are noted within the glacial outwash deposits.

Confining conditions generated by laterally extensive clay layers within the outwash extend across this area, but flowing wells are found only within the areas depicted in figure 31. The Three Bears Lodge well (106842), an LTMP site located in the town of West Yellowstone, is 140 ft deep with a static water level around 40 ft bgs. In contrast, the Ryberg well is an artesian well that encountered volcanic bedrock at 113 ft bgs and was advanced to a depth of 172 ft into this bedrock. These two examples illustrate the local nature of artesian conditions in the valley.

Water-Quality Summary for Madison River Watershed Monitoring Sites

Water quality is monitored at 11 of the 12 LTMP sites in this watershed; water samples are not collected

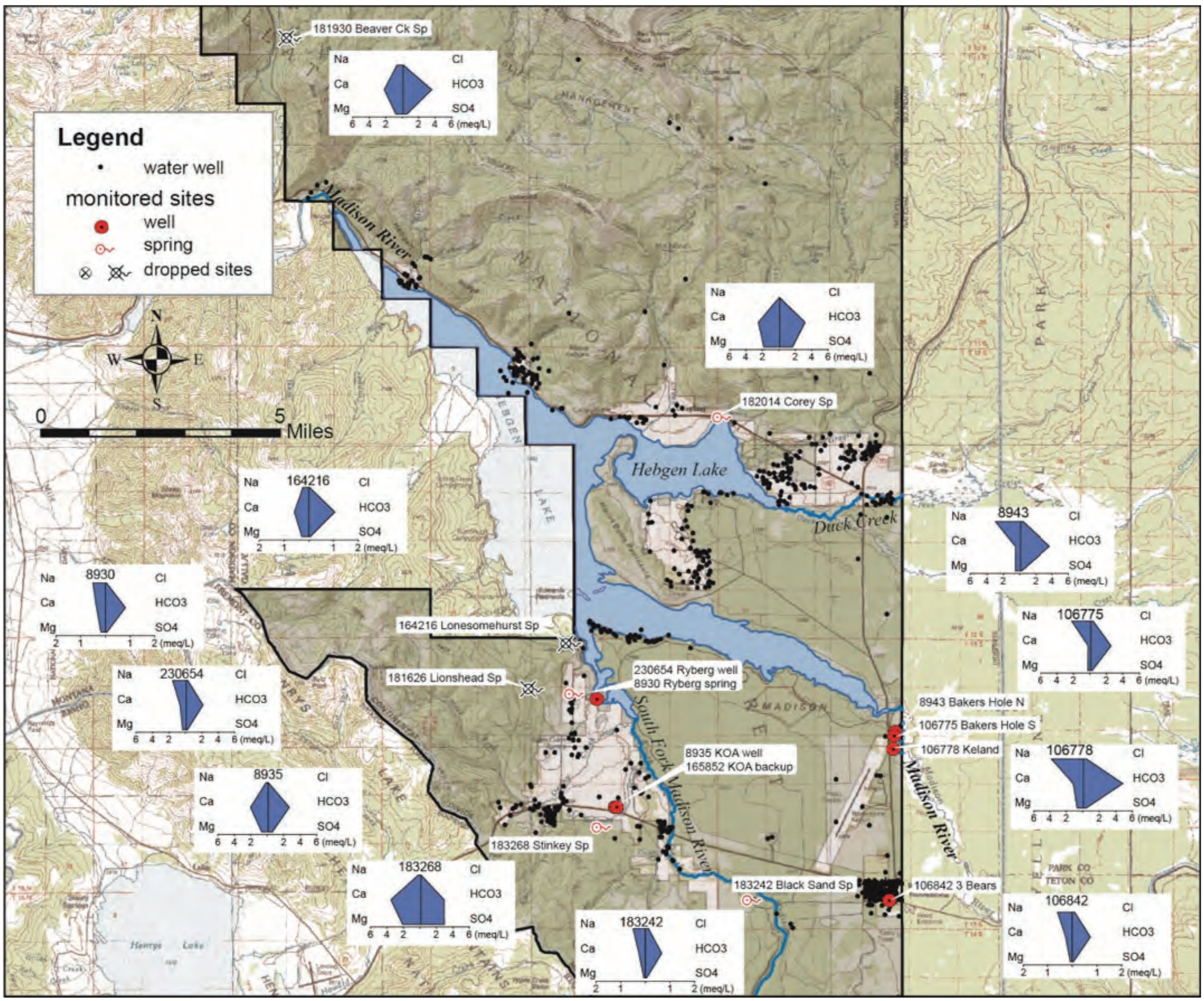


Figure 32. Stiff diagrams representing the major ion chemistry at LTMP sites in the Madison River watershed (concentrations expressed as meq/L).

at the Ryberg Spring Creek site (277397). Water quality varies among the LTMP sites in the Madison River watershed, but not to the same extent as the LTMP sites in the Yellowstone River watershed. Combining the many geologic maps and investigations in the area with the water-quality data and well logs from the LTMP sites allows for interpretation of the hydrogeologic settings and groundwater flow paths at the sites.

Major Ions

Stiff diagrams highlight the variations in major ion chemistry for the LTMP sites in the Madison River watershed (fig. 32). Seven of the 12 wells and springs have a sodium-bicarbonate type water, including all 4 of the flowing wells (8943, 106775, 106778 and 230654). The same sodium-bicarbonate type water also discharges from Ryberg Spring (8930) and Black Sand Spring (183242). Common features of the sites that discharge sodium-bicarbonate type water is their association with volcanic bedrock or sediments derived from volcanic bedrock and their relatively high silica concentrations. Stinky Spring (183268) discharges a calcium-bicarbonate-sulfate type water. Corey Spring (182104), which discharges from Madison Group limestone, produces a calcium-magnesium-bicarbonate water that is similar to the water from Anceny Spring in the Gallatin River watershed.

A Piper plot showing the ratios of the major ions for the cold water sites in the Madison River watershed is shown in figure 33, and for warm and hot water sites in figure 34. These diagrams include results for all samples collected at each site to illustrate temporal variability in water chemistry. The cold water sites vary mainly in terms of the cations but have similar proportions of anions. Sodium is the dominant cation at four of the seven cold water sites, but figure 33 shows a wide spread of calcium to sodium ratios. The cold water sodium-dominated sites include Ryberg Spring (8930), Black Sand Spring (183242), the Keland well (106778), and the Three Bears Lodge well (106842). Bicarbonate is the dominant anion at all sites, but Corey Spring (182014) contains higher concentrations of sulfate. The main KOA Campground well (8935) also has slightly elevated levels of sulfate. Figure 34 shows that Stinky Spring (183268), a warm water site, stands out from the other three sites, which are all warm water flowing artesian wells.

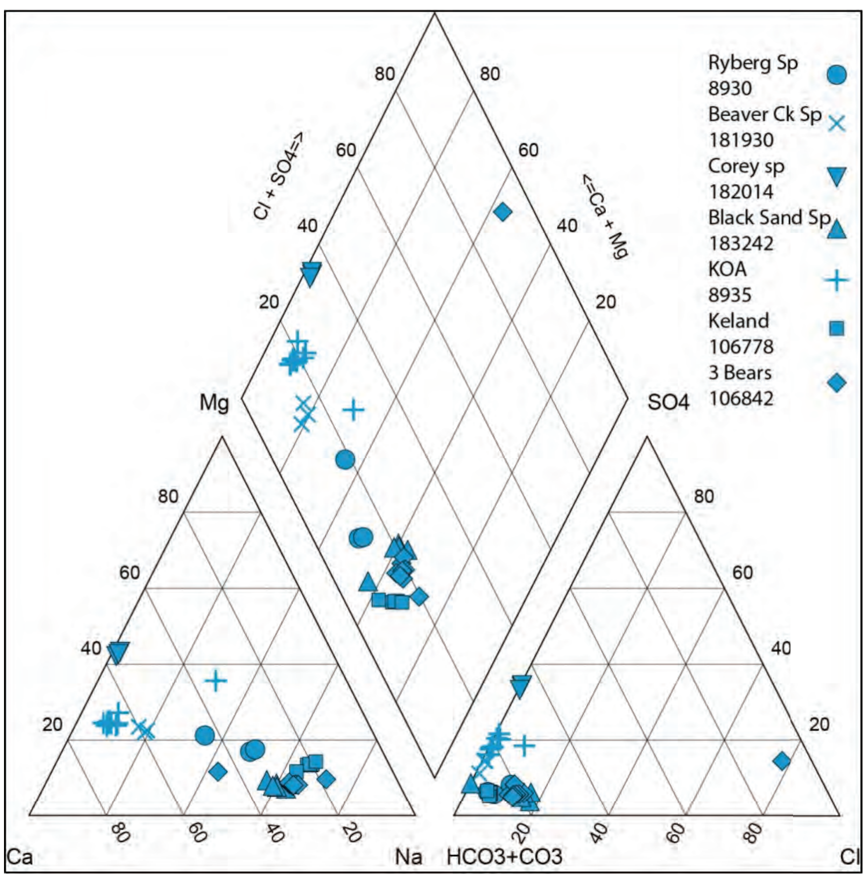


Figure 33. Piper plot showing the ratios of major cations and anions for cold water sites (<15°C) in the Madison River watershed.

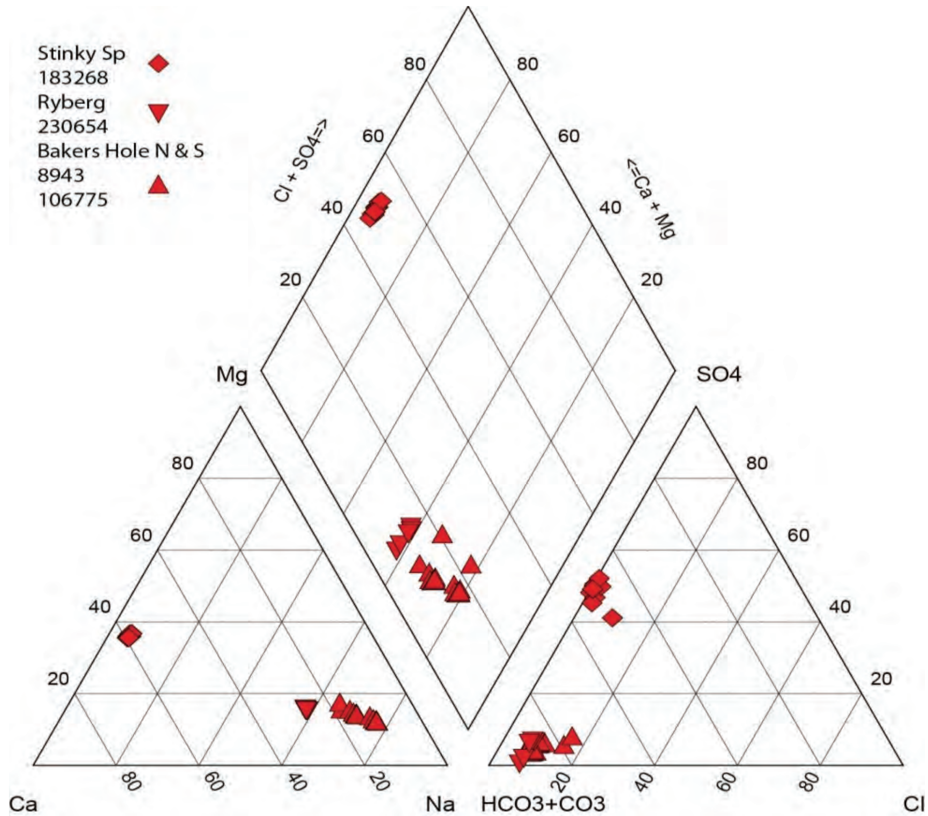


Figure 34. Piper plot showing the ratios of major cations and anions for hot (>25°C) and warm (15–25°C) water sites in the Madison River watershed.

Total Dissolved Solids Concentrations

Total Dissolved Solids (TDS) concentrations for all of the samples collected in the Madison River watershed are summarized in figure 35, which illustrates the variability within and between sites. The warm and hot water sites have generally higher TDS concentrations and show more variation within each site. The Beaver Creek cold water spring, which also shows wide variation, is an exception. However, this site, which is no longer an active LTMP site, is susceptible to snowmelt and stormwater runoff. Stinky Spring (183268) has the highest TDS concentrations. The cold water sites have TDS values below 200 mg/L with the previously noted exception of Beaver Creek, and Corey Spring (182014). The higher TDS at Corey Spring is attributed to its discharge from Madison group limestone. TDS is very stable at the two large springs, Corey Spring and Black Sand Spring.

Average Concentrations for Select Major Ions and Trace Elements

Table 9 shows average concentrations of select major ions and trace elements at Madison River watershed LTMP sites. The warm water sites tend to have higher concentrations of silica, arsenic, lithium and fluoride. The flowing wells monitored in the Bakers Hole area (106775, 8943, and 106778), in the eastern portion of the basin, exceed the 10 µg/L drinking water standard for arsenic, and all have elevated concentrations of chloride, fluoride, boron, and lithium. These wells all exceed or nearly exceed the secondary drinking water standard of 4 mg/L for fluoride, along with the Ryberg well (230654) in the western portion of the basin, and Black Sand Spring (183242) in the southern portion of the basin. Stinky Spring, Corey Spring, and the wells at the KOA campground (183268, 182014, 165842 and 8935) all have higher levels of strontium, along with barium and sulfate.

Arsenic

Figure 36 shows arsenic concentrations at LTMP sites in the Madison River watershed. All the warm water well sites are flowing wells used for drinking water, and exceed the EPA drinking water standard for arsenic of 10 µg/L. The Bakers Hole Campground wells (8943, 106775) are public water supply wells. The Ryberg well (230654) is a private water supply,

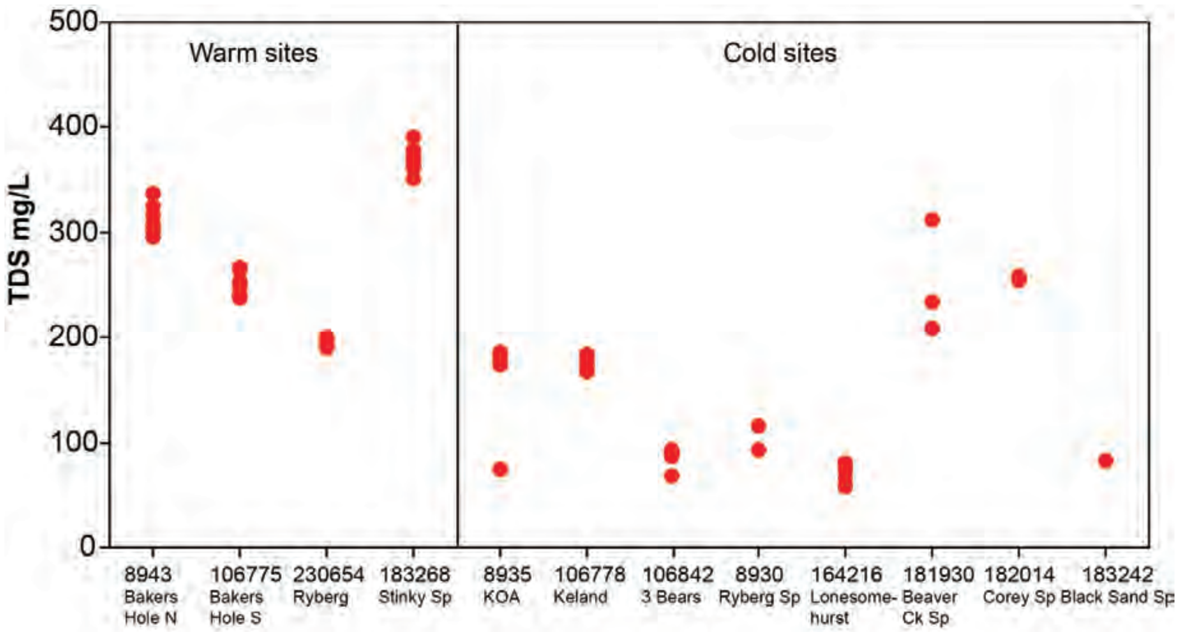


Figure 35. Total dissolved solids (TDS) concentrations for the LTMP sites in the Madison River watershed.

Table 9. Average concentrations of select major ions and trace elements for Madison River monitoring sites.

GWIC ID	Site Type	*n*	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	SiO_2 (mg/L)	SO_4 (mg/L)	Cl (mg/L)	NO_3 (mg/L)	F (mg/L)	As (µg/L)	B (µg/L)	Ba (µg/L)	Sr (µg/L)	Li (µg/L)	U (µg/L)
183268 Stinky	Spring	11	73.3	27.3	7.5	12.5	145.9	3.8	<0.1	1.1	11.0	40.8	23.6	711.6	40.0	<0.1
106775 Bakers S.	Well	11	6.2	4.2	53.8	81.7	7.6	10.5	0.1	4.7	27.8	92.8	5.3	11.7	158.7	<1.0
8943 Bakers N.	Well	11	12.8	7.6	67.1	75.2	8.4	12.9	<0.1	4.4	27.1	112.1	5.1	27.7	156.8	1.2
106778 Keland	Well	7	8.5	3.1	30.4	66.6	5.3	4.2	<0.1	3.8	18.6	46.8	3.6	20.2	99.0	<1.0
230654 Ryberg	Well	5	14.6	5.2	36.7	48.2	7.9	6.6	<0.1	3.9	7.0	71.5	7.4	38.2	95.7	1.1
182014 Corey	Spring	5	51.3	24.3	1.8	7.6	75.3	0.7	0.1	0.3	0.5	10.0	28.8	343.2	4.4	0.7
183242 Black Sand	Spring	7	5.6	0.9	11.7	34.6	2.2	3.8	<0.5	3.5	0.9	50.6	<1.0	5.5	33.9	0.6
8930 Ryberg #4	Spring	3	8.8	2.7	12.5	33.7	3.7	3.3	0.3	1.5	5.0	32.6	8.5	22.6	39.1	0.6
106842 3 Bears	Well	8	5.0	1.0	14.0	35.9	3.4	3.9	0.2	2.9	1.8	44.0	3.9	7.7	49.9	<0.3
165852 KOA BU	Well	3	40.1	9.0	7.6	17.1	32.6	1.0	0.3	0.1	<0.4	15.9	20.6	241.4	<0.4	0.6
8935 KOA Main	Well	7	42.0	9.4	6.0	18.3	26.8	1.1	0.3	0.3	0.4	17.0	25.7	266.5	6.7	0.6

Note. Blue, cold water (<15°C); orange, warm water (15–25°C). Data based on all samples in GWIC collected through 2013.

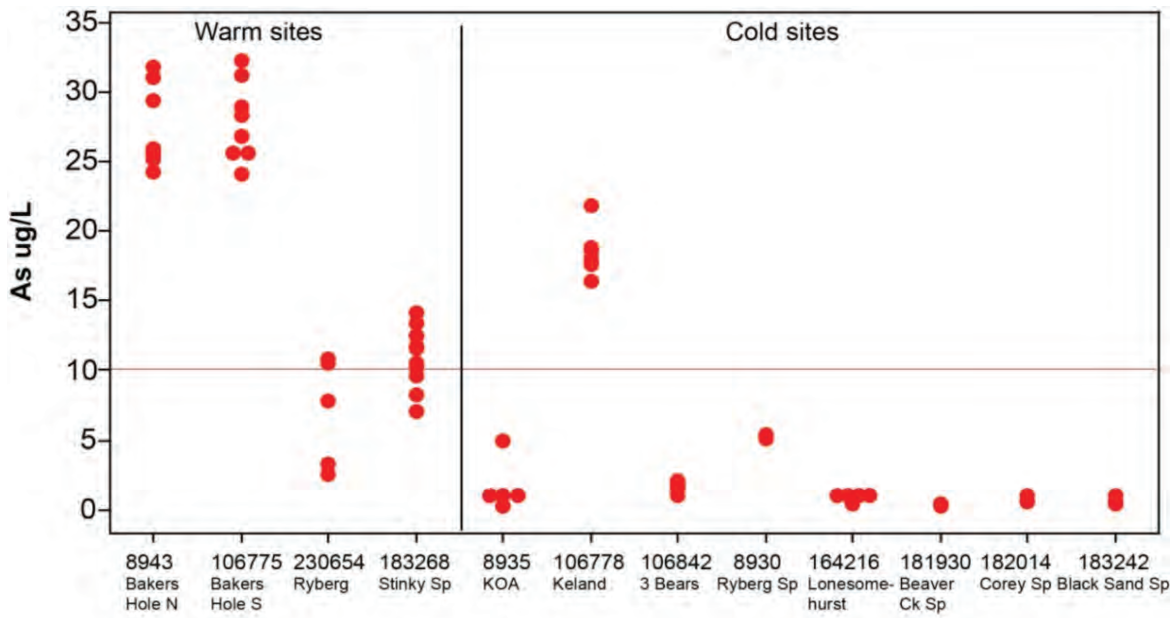


Figure 36. Plotted arsenic concentrations for all samples collected from LTMP sites in the Madison River subarea. The red line denotes the EPA drinking water standard for arsenic.

and while it has an average arsenic concentration of 7 µg/L (table 9), two of the samples collected have exceeded the arsenic standard (10.6 and 10.9 µg/L). Although plotted with the cold water sites, the Keland well (106778) is considered a warm water site (table 1) and is similar in all other respects to the other wells in the Bakers Hole area. The temperatures recorded at the Keland well are cooler due to heat loss prior to measurement, which is made in a shallow discharge pipe more than 50 ft from the wellhead. The wellhead is under a cabin and cannot be accessed. The source aquifer for the Keland well is the same as the other flowing wells in the Bakers Hole area.

Isotope Chemistry

Values for $\delta^{18}O$ and $\delta^{2}H$ in groundwater samples collected from the warm and cold water sites in the Madison River subarea are shown in figure 37 and table 10. All the data plot along and slightly below the local meteoric water line of Karaka and others (2002). The cold water sites show more variation in isotopic composition, with $\delta^{18}O$ values ranging from -19.45 to -17.74 with a median of -18.68; the $\delta^{2}H$ values range from -147.13 to -130.57, with a median of -141.51. The variation of the isotopic signature reflects the variation of the chemical signature. The water chemistry of the cold sites varies from calcium-magnesium-bicarbonate to a sodium-calcium-bicarbonate type (fig. 32). In general, sites with calcium-magnesium-bicarbonate type water are more enriched in $\delta^{18}O$ and $\delta^{2}H$ (e.g., Beaver Creek Spring, 181930, and KOA well, 8935), whereas the sites with sodium-calcium-bicarbonate type water are relatively depleted in $\delta^{18}O$ and $\delta^{2}H$ (e.g., Black Sand Spring, 183242, and Three Bears, 106842).

The values from the warm water sites are more consistent with overall median values that are slightly more depleted than the cold water sites. The warm water site $\delta^{18}O$ values ranged from -19.60 to -18.44 with a median of -19.32; the $\delta^{2}H$ values ranged from -146.97 to -141.55, with a median of -148.00. Stinky Spring (183268) is isotopically and chemically distinct from the other warm water sites.

Tritium values from the warm and cold water sites are shown in figure 37. Cold water site values ranged from 5.2 to 16.4 TU, with a median of 7.9 TU (table 10), and are consistent with modern recharge. The warm water site tritium values have a bimodal distribution. The samples from Stinky Spring (183268) did not contain detectable tritium, and the sample from the Ryberg well (230654) had a concentration of 1.2 TU, suggesting most of the recharge to these sites is submodern water (prior to 1952). The Bakers Hole wells (8943 and 106775) had similar tritium concentrations (5.1 and 6.2 TU, respectively) that suggest a large component of modern recharge.

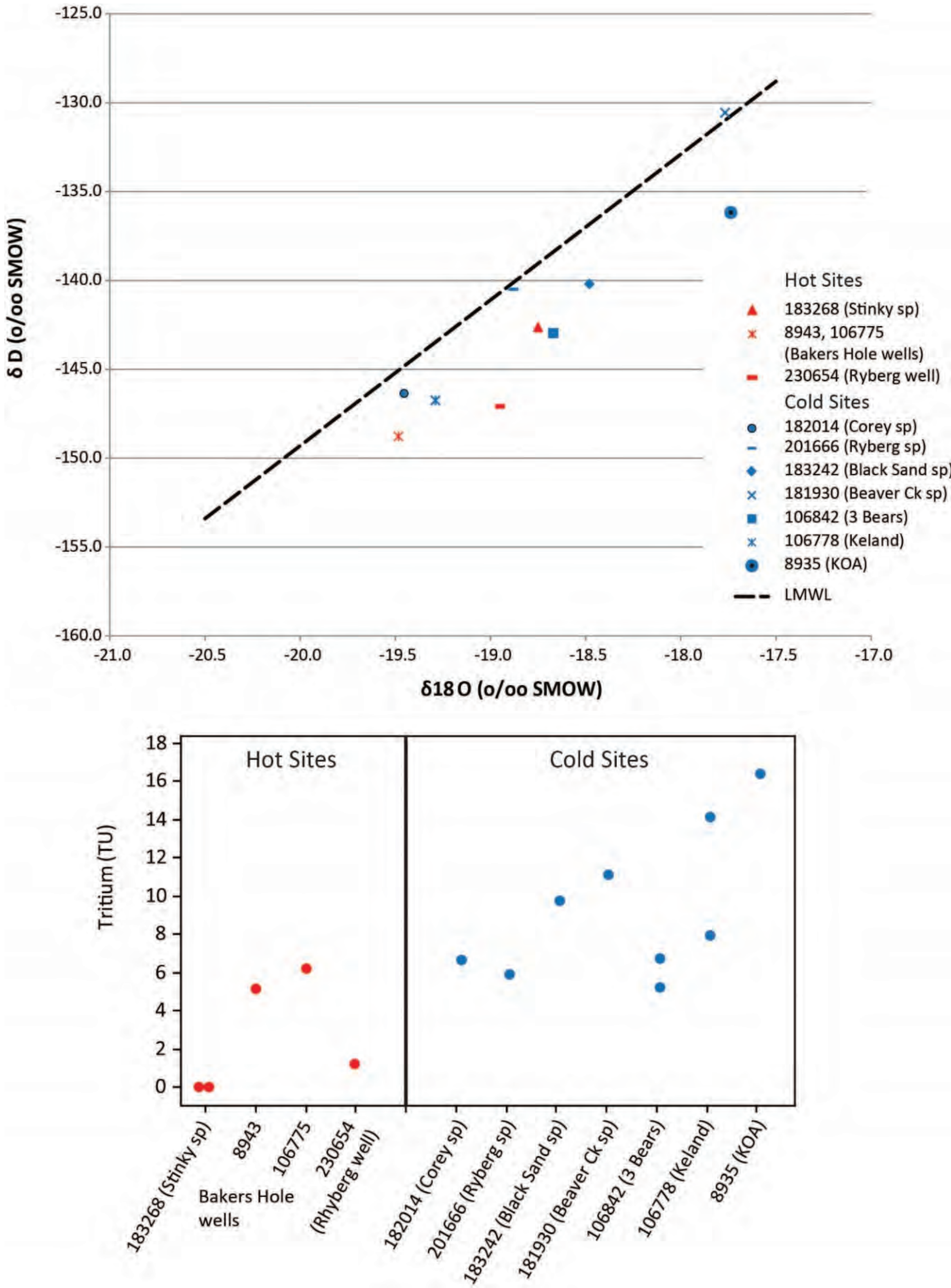


Figure 37. The composition of stable isotopes and tritium for the warm (hot) and cold sites in the Madison River subarea.

Table 10. Oxygen and hydrogen isotope sampling results for Madison River sites.

Sample ID	GWIC ID	Site Name	Site Type	Temp	$\delta^{18}O$ Result	$\delta^{2}H$ Result	^{3}H Result	± 1σ	Sample Date
2009R5000	181930	Beaver Ck	Spring	Cold	-17.8	-130.6	11.1	1.1	10/20/08
2011R4961	182014	Corey	Spring	Cold	-19.5	-146.3	6.6	0.6	07/08/10
2012R4934	182014				-19.5	-146.3	6.6		09/01/11
203761	182014				-19.5	-145.0			05/15/13
204755	182014				-19.6	-146.0			08/15/13
205479	182014				-19.3	-148.0			11/18/13
2010R5110	183242	Black Sand	Spring	Cold	-18.5	-140.2	9.7	0.8	05/27/10
2012R4933	183242				-18.5	-140.2			08/30/11
203869	183242				-18.9	-141.0			05/28/13
204754	183242				-19.1	-141.0			08/14/13
205485	183242				-18.8	-143.0			11/07/13
2011R4969	8930	Ryberg	Spring	Cold	-18.9	-140.5	5.9	0.6	05/28/11
2006R5005	8935	WY KOA	Well	Cold	-17.7	-136.2	16.4	1.4	03/24/06
2008R5001	106778	Keland	Well	Warm	-19.2	-146.4	14.1	1.1	10/04/07
2011R4968	106778				-19.3	-147.1	7.9	0.7	05/17/11
2006R5004	106842	3 Bear Lodge	Well	Cold	-18.5	-142.5	6.7	0.8	03/24/06
2010R5097	106842				-18.9	-143.4	5.2	0.6	11/11/09
203758	165852	WY KOA Backup	Well	Cold	-18.4	-137.0			05/08/13
204753	165852				-18.6	-138.0	8.9		08/14/13
2006R5003	183268	Stinky	Spring	Warm	-18.4	-143.7	<0.8	0.4	03/23/06
2010R5096	183268				-19.1	-141.6	<0.8	0.3	11/10/09
2008R5002	8943	Bakers Hole North	Well	Warm	-19.5	-150.0	5.1	0.5	10/04/07
203756	8943				-19.6	-149.0			05/09/13
204749	8943				-19.8	-150.0			08/13/13
205460	8943				-19.0	-151.0			11/06/13
2008R5000	106775	Bakers Hole South	Well	Warm	-19.3	-148.2	6.2	0.6	10/04/07
203757	106775				-19.5	-148.0			05/09/13
204764	106775				-19.7	-149.0			08/14/13
205459	106775				-19.0	-147.0			11/06/13
2010R5098	230654	Ryberg	Well	Warm	-19.0	-147.1	1.2	0.3	11/11/09

LTMP UPDATES AND RECOMMENDATIONS

Yellowstone Controlled Groundwater Area Well Inventory and Permitting

- Records in the GWIC database indicate that more than 330 wells have been drilled in the YCGA since the MBMG completed the initial well inventory. We recommend completing inventories on as many of these new wells as is practical.

Long-Term Monitoring Program

- With approval of the TOC at the October 2014 meeting, the water-quality sampling schedule was modified to collect samples from all LTMP sites yearly in August. Previously, samples were collected on a 3-yr rotating basis from one-third of the sites, which were sampled three times (spring, summer, fall) to evaluate the seasonal variability in water quality. Any new sites added to the LTMP will be sampled seasonally for 1 yr to evaluate seasonal water-quality variability.

- All of the LTMP monitoring sites should be sampled for radon to provide additional water-quality data to aid in interpreting hydrogeologic settings and groundwater flowpaths.

Soda Butte Creek Watershed

- The Soda Butte Creek watershed is the only developed watershed within the YCGA that drains into the Park. There are numerous abandoned mines, a mill tailings reclamation site, and numerous domestic wells and septic systems in this area that have the potential to impact water quality in the Park.

- Although Metesh and others (1999) found only minor impacts to groundwater quality and quantity in the Cooke City–Silver Gate area, we recommend updating this work to determine if changes have occurred since 1999.

- No geothermal resources have been identified in the YCGA portion of the Soda Butte Creek watershed. However, Soda Butte, a geothermal feature in the Park that lends its name to the creek, is only 12 mi southwest of the town of Silver Gate.

- The MBMG attempted to replace the failed and abandoned Kloster well (162539) with the replacement well (275365) drilled by the owner. The new well was monitored for 1 yr, from November 2013 to November 2014. However, the well owner decided not to participate with the LTMP and the monitoring equipment was removed in November 2014. A replacement well for the original Kloster well should be considered.

- The active Silver Gate well (106030) is completed in the shallow, unconfined alluvial aquifer along the north side of the Soda Butte Creek Valley. A deeper (<200 ft) confined aquifer has been identified in the Silver Gate town site area, south and southeast of the Silver Gate well (English, 1999). Several wells in this confined aquifer flow seasonally, in the spring. An additional LTMP well site is recommended in the confined aquifer to document and compare water levels and water quality in the unconfined and confined aquifers at Silver Gate. Both aquifers discharge into the Park along Soda Butte Creek.

- Groundwater in the bedrock formations that surround and underlie the Soda Butte Creek Valley probably contribute recharge to both the shallow unconfined aquifer(s) in the valley and the shallow confined aquifer in the Silver Gate area. A monitoring well completed in bedrock within this watershed is also recommended.

Yellowstone River Watershed

- The Shooting Star Ranch well (252314) is a 757-ft-deep flowing-artesian well with significant shut-in pressure (46 to 50 psi). We recommend this site be evaluated to determine if a pressure transducer can be installed in the water line at the wellhead, to allow continuous measurement of pressure in the deep aquifer system. Manual measurements of shut-in pressure would still be taken during site visits.

- Cole Spring (181620) and Powell Spring (184260) were originally equipped with in-line flowmeters that are installed more than 100 ft from the spring discharge points. Temperature loggers were co-located with the flowmeters when the sites were established. During the 2014 field season the temperature loggers at both springs were moved to the spring discharge points to obtain more accurate water-temperature data.

- The Yellowstone Basin Inn well (145529) and the Strauss well (105959) are within 150 ft of each other in the same aquifer, and both are 100 ft deep. The sites provided redundant data, so the MBMG discontinued monitoring of the Yellowstone Basin Inn well in 2014, with approval of the TOC. This well was selected to be discontinued because it is a public water supply well and the monitoring required routinely removing the sanitary well cap to access the data logger and measure the water level.

- Three shallow 2-in PVC piezometers were installed around the La Duke Hot Springs collection box in the spring of 2010. Two of these (LD-2 and LD-3) were usually dry (above the water table), but LD-1 is in good condition and is completed in geothermal groundwater within 20 ft of the collection box. In August 2014, with approval of the TOC and CUT, the MBMG installed a surface casing with a locking well cap on LD-1 and added it to the LTMP network. Piezometers LD-2 and LD-3 were properly abandoned.

- Site improvements are needed at Sirr Spring to prevent water from the irrigation ditch from backing up into the flume. Water-temperature data are currently collected by the water-level logger installed in the flume. A separate temperature logger should be installed in the main spring discharge area to obtain more accurate temperature data.

Gallatin River Watershed

- Monitoring sites in this subarea include two large springs (Anceny and Snowflake) that discharge from Madison Group limestone. These sites provide good water-quality and water-temperature data. However, obtaining accurate flow measurements is difficult due to the diffuse nature of the spring discharge. Currently the discharge at both springs is measured in adjacent spring creeks by wading the streams and measuring flow with a current meter. We recommend these sites be evaluated to see if improvements can be made to collect better spring discharge data.

- The YCGA boundary in this area was drawn in part to include Madison Group limestone because it may provide a hydrogeologic connection between the Big Sky area and the Park. If this connection exists there is potential for development in the Big Sky area to impact thermal resources in the Park. The USFS Red Cliff Campground well (259697) is located between Big Sky and the Park boundary along the Gallatin River. The well is 703 ft deep and completed in the Madison Group limestone. To improve monitoring in the Madison Group limestone in the Gallatin watershed, the MBMG added the well to the LTMP network in the fall of 2014.

- The Altman well (215333) is also located between Big Sky and the Park boundary and appears to be completed in Cambrian limestone or dolomite, within 100 ft of the Gallatin River. In 2014 the well was added to the LTMP and a pressure transducer was installed to obtain hourly water-level data. Due to the depth to water, the MBMG has not been able to collect water-quality samples. Once the well owner installs a pump system the MBMG will begin monitoring water quality at this site.

Madison River Watershed

- Three of the LTMP sites in this subarea are flowing wells located in or near the USFS Bakers Hole campground: Bakers Hole Campground South (106775), Bakers Hole Campground North (8943), and Keland (106778). These sites have similar hydrogeologic settings and similar water chemistry. In 2014 the Keland well was dropped from the LTMP network because it provided redundant information.

- Flowmeters installed in the discharge lines for the Bakers Hole Campground wells were originally installed with pulse loggers to record hourly flow rates. However, these pulse loggers have failed numerous times. We recommend that improvements to the flowmeters at these two sites be made to allow for continuous (hourly) flow monitoring.

- We recommend installing a dedicated monitoring well in the Bakers Hole area as an alternative to the existing sites at the Bakers Hole Campground. This well could be located at a higher elevation, to the west by the airport, which would allow for continuous monitoring of the head in the artesian aquifer.

- A 500-ft-deep flowing-artesian well (106763), located about 5 mi northwest of West Yellowstone in the Hebgen Basin, appears to flow at a rate of at least 100 gpm. The GWIC records report the well yield at 150 gpm. Water from the well forms a pond around the well. The free-flowing well connects a confined aquifer with the shallow alluvial aquifer underlying the pond. The well owner has declined to allow MBMG access to inventory the well and collect a water-quality sample.
- Black Sand Spring (183242), located about 2.5 mi west of West Yellowstone along the south side of the Hebgen Basin, is a large spring (>10 cfs) that has been visited by USFS, USGS, and MBMG staff many times for various projects, dating back to at least 1977. The MBMG inventoried the spring in 2000 and measured the flow with a wading current meter in 2011. In 2013 the spring was added to the LTMP network with approval from the TOC. A hydrogeologic investigation of this spring is recommended to determine if the spring discharge is associated with a fault (deeper water source) or shallow groundwater–surface water interaction.
- Temperature monitoring at Stinky Spring (183268) was improved in 2014 by installing a temperature logger in the central upwelling area of the spring pool. The temperature was previously measured at the edge of the pool where a flume is installed to measure flow.

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APPENDIX A

APPENDIX A
LONG-TERM MONITORING PROGRAM
MONITORING SITE OVERVIEWS AND DATA SUMMARIES

Table of Contents

SODA BUTTE CREEK WATERSHED MONITORING SITES

Silver Gate Well (106030)

Site Description

The Silver Gate well is located in the town of Silver Gate, north of Highway 212. It is 51 ft deep and constructed with 6-in-diameter steel casing that extends to the bottom of the borehole. The Silver Gate Water Users Association drilled the well in 1976 for use as a public water supply. However, the well was never used due to suspected fecal-coliform bacteria contamination. The well has been used by the MBMG for monitoring since 1998. The MBMG inventoried this well in September 1996, first sampled it in July 1998, and added it to the LTMP in September 2006.

Hydrogeologic Setting

The well is completed in Quaternary alluvium deposited by Soda Butte Creek (Metesh and others, 1999). The alluvial deposits are up to 150 ft thick in the area; however, the Silver Gate well is located near the northern edge of the alluvium, where the thickness is probably less. The depth to bedrock is unknown, but two nearby wells drilled to 71 ft (148102) and 80 ft (148102) did not reach bedrock.

Water-Level and Water-Temperature Monitoring Summary

This site has been monitored since September 2006. A water-level logger is installed in the well and collects hourly water-level and water-temperature data. Manual water-level measurements are made during site visits, and temperature measurements are made when the well is purged for sampling. Figure A1 summarizes the water-level and water-temperature data collected, and statistics for the water-level logger data are provided in table A1.

The lowest water levels usually occur in late March to mid-April. Water levels rise rapidly in mid-April, in response to spring runoff. The water-temperature and water-level data display an inverse relationship. Water temperatures recorded by the pressure transducer do not reflect the bottom-hole groundwater temperature because the transducer is installed about 20 ft bgs, and the well is not pumped. Rather, the temperature pattern is interpreted as being reflective of groundwater temperatures 20 ft bgs, and the pattern suggests that cold recharge water cools the shallow groundwater during spring runoff, but once runoff stops the groundwater system slowly heats back up due to geothermal heat flow. As illustrated in figure A1, water temperatures following purging for water-quality sampling are usually slightly warmer than temperatures recorded by the water-level logger, and are considered representative of groundwater temperatures at the bottom of the well (51 ft bgs).

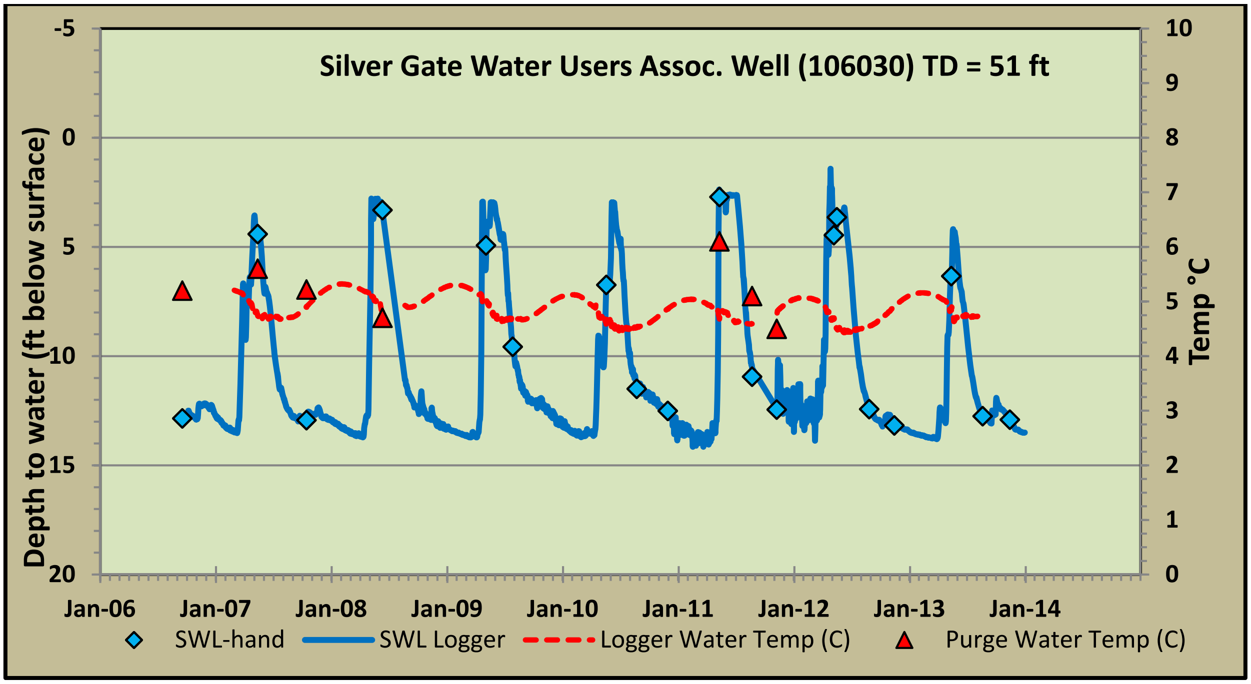

Figure A1. Hydrograph for the Silver Gate well showing daily midnight-hour water levels and water temperatures recorded by the water-level logger, and manual measurements obtained during site visits.

Table A1. Water-Level Logger Statistics for the Silver Gate Well

Statistic	Water Level (ft bgs)	Water Temp. (°C)	Comments
Mean	10.94	4.9	✓ Based on daily midnight-hour readings from September 2006 through December 2013 ✓ Temperature measured by logger about 20 ft bgs and 12–17 ft below the water surface ✓ Purge-water temp. 4.5 to 6.1°C, Avg. 5.1 (*n*=8) ✓ Water classified as Cold (<15°C)
Median	12.51	4.9	
Maximum	14.15	5.3	
Minimum	1.42	4.4	
# Readings	2,512	2,512	

Water-Quality Sampling Summary

There is no pump in the well so water-quality samples are collected using a portable pump system. The well has been sampled eight times for major ions and trace elements between July 1998 and December 2013. This includes sampling for seasonal variation (spring, summer, and fall) in 2011. Average concentrations of select major ions and trace elements are presented in table A2. The well produces a calcium/bicarbonate type water with a near neutral pH, low TDS, and low levels of chloride, nitrate, fluoride, and arsenic, and does not exceed and EPA inorganic drinking water standards.

Table A2. Average Concentrations of Select Major Ions and Trace Elements for Silver Gate Well

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
141	7.2	31.1	5.9	12.0	9.3	5.1	2.3	0.8	0.1	0.3	18.9	15.9	251.	1.8	<1.0

A radon sample collected in April 1995 showed a radon (^{222}R) concentration of 30.0 pC/L. In 1998 a water sample age-dated with a tritium-helium method (Poreda and others, 1988) yielded an apparent groundwater age of 1.59 +/- 0.1 years. The well was sampled for the stable isotopes oxygen (^{18}O) and deuterium (^{2}H), and the radioactive isotope tritium (^{3}H), in October 2007 and November 2011 (see report, fig. 8, table 4). The measured tritium concentrations are consistent with recently recharged groundwater and the groundwater age obtained from the tritium-helium sample.

Kloster Well (162539)

Site Description

The Kloster well was located along the north side of Highway 212 on a south-facing slope, about 1 mi west of Cooke City. It was 78 ft deep and constructed with 6-in-diameter steel casing that extended to the bottom of the borehole. The well was drilled in 1996 and provided water for a private cabin, typically only used in the summer. The well was inventoried, sampled, and added to the LTMP in August 2007. In September 2013 the well failed due to sediment buildup inside the well casing. The owner had the well properly abandoned and drilled a replacement well (275365) about 75 ft to the southwest.

Hydrogeologic Setting

Quaternary (Pindale) glacial till covers bedrock at the Kloster well site (Metesh and others, 1999). The underlying bedrock consists of near-horizontal Cambrian sedimentary formations, which are exposed on the slopes directly above the well (Elliot 1979). West of the well, the Cambrian Meagher Limestone is exposed at the mouth of Sheep Creek canyon, at about the same elevation as the well, and probably also underlies the glacial till at the Kloster well site. The well log indicates the well did not reach the underlying bedrock, and was completed in the glacial till. Recharge to the till is primarily from infiltration of precipitation and snowmelt on the slope above the well. Groundwater flow from the bedrock may also recharge the glacial till at this site.

Water -Level and Water-Temperature Monitoring Summary

The Kloster well was monitored from August 2007 through September 2013. A water-level logger was maintained in the well and collected hourly water-level and water-temperature data. Manual water-level measurements were made during site visits, and temperature measurements were made when the well was purged for water-quality sampling. In January 2013 the water level in the well dropped below the depth of the logger (55 ft bgs) for the first time since monitoring began. This was discovered during the May 2013 site visit, and data collection began again with the logger reinstalled at 65 ft bgs. Figure A2 summarizes the water-level and water-temperature data collected. Statistics for the water-level logger data are summarized in table A3.

The water-level logger was removed by the driller when the well was abandoned and was found on the ground during the November 2013 site visit. The data from the logger were retrieved, and the logger was installed in the new well (275365) on November 14, 2013. The logger was maintained in the new well through November 13, 2014, when it was removed at the request of the well owner. The intent was to use well 275365 as a replacement, but the new well was never officially added to the LTMP due to the owner's request to discontinue monitoring.

The Kloster well had an unusual water-level and water-temperature pattern. Springtime water-level rise was initially rapid and then slowed. These two distinct segments are apparent in the spring of 2008 and 2009 (fig. A2). After the water levels peak, typically in mid-June, the declining limb of the hydrograph also has two pronounced segments. Water levels decline rapidly and then the rate of decrease abruptly slows and becomes linear until the next spring. A sharp drop in temperature coincided with the abrupt rise in spring water levels, immediately followed by a sharp rise in temperature as the water levels peaked. The water temperatures fluctuated 8° to 10°C within a few weeks. In between these unusual seasonal temperature spikes, the water temperature remained stable at about 4.5°C.

One potential explanation for these water-level and temperature patterns is that the casing was compromised and allowed surface runoff to short circuit, entering the casing above the water table and exiting from the bottom of the casing. The buildup of sediment in the well casing indicated that the casing was somehow compromised. Since the well has been abandoned, the cause of the unusual water levels and temperature patterns can't be further evaluated.

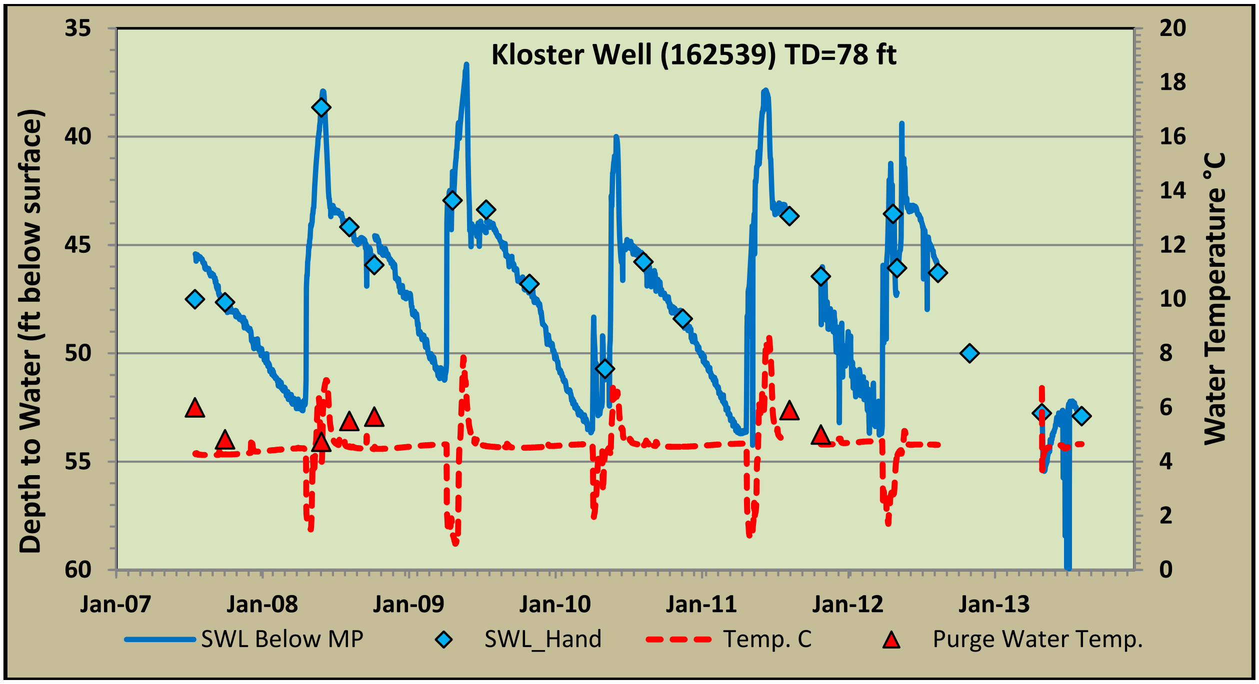

Figure A2. Hydrograph for the Kloster well showing daily water levels and water temperatures recorded by the water-level logger, and manual measurements made during site visits.

Table A3. Water-Level Logger Statistics for the Kloster Well

Statistic	Water Level (ft)	Water Temp. (°C)	Comments
Mean	47.63	4.5	✓ Water level in ft below ground surface ✓ Statistics based on hourly reading during the 3:00 am hour, from August 2007 through August 2013 ✓ Temperature measured by logger about 55 ft bgs and 2 to 18 ft below the water surface ✓ Purge-Water Temp. 4.7 to 6.0°C, Avg. 5.4 (*n*=7) ✓ Water classified as Cold (<15°C)
Median	47.62	4.6	
Maximum	59.95	8.6	
Minimum	36.60	1.0	
# Readings	1,848	1,848	

Water-Quality Sampling Summary

Water-quality samples are collected from a frost-free hydrant located at the wellhead. The well was sampled seven times for major ions and trace metals between August 2007 and November 2011. This includes sampling for seasonal variation (spring, summer, and fall) in 2008. Average concentrations of select major ions and trace elements are presented in table A4. It produced a calcium-magnesium/bicarbonate type water with a basic pH (7.7), low TDS, and low concentrations of sodium, chloride, nitrate, fluoride and arsenic. The water did not exceed any EPA inorganic drinking water standards

Table A4. Average Concentrations of Select Major Ions and Trace Elements for Kloster Well

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
212	7.5	52.7	17.2	1.8	8.9	11.9	0.7	<0.1	0.1	0.4	5.5	59.8	192.	6.4	<1.0

The well was sampled three times for the stable isotopes oxygen (^{18}O) and deuterium (^{2}H), and the radioactive isotope tritium (^{3}H) (see report, fig. 8, table 4). Like the Silver Gate well, concentrations of tritium are consistent with recently recharged groundwater.

YELLOWSTONE RIVER WATERSHED MONITORING SITES

LaDuke Hot Spring (171215)

Spring Description

LaDuke Hot Spring is located 5 mi north of Gardiner, Montana on the east side of Highway 89. It has a long history of development, research, and monitoring beyond the scope of this report. LaDuke is a developed spring that is maintained by the Church Universal and Triumphant (CUT). The CUT owns the spring collection system and water rights for the geothermal discharge, but the land is owned by the U.S. Forest Service.

LaDuke is part of a larger geothermal discharge area that includes several small seeps and another hot spring. However, it produces most of the observable thermal discharge (100 to 150 gpm) in the area. The other hot spring is an undeveloped spring that also surfaces along the east side of Highway 89, about 250 ft south of LaDuke Hot Spring. This small spring is on U.S. Forest Service land and is commonly referred to as the "Forest Service Spring." Discharge from the Forest Service Spring is difficult to measure because the water surfaces on the side of the barrow pit along the highway and ponds in the bottom of the barrow pit. The discharge has been estimated at 10 gpm. Other geothermal features in the LaDuke area include several travertine deposits, and several warm water seeps that surface along the east bank of the Yellowstone River, below LaDuke Hot Spring and the Forest Service Spring. The seeps along the bank of the river extend southward along the river bank for over 3,500 ft into the area of the Miller geothermal well.

The spring water at LaDuke Hot Spring is collected in a rectangular concrete spring box that is oriented roughly north–south, parallel to Highway 89. The spring box consists of two chambers. The southernmost chamber is the original, older part of the spring box; it is about 4.5 ft wide and 4.5 ft long. The second, newer chamber is about 60 ft long, 3.5 ft wide, and about 6.5 to 7 ft deep. Water enters the box through an open bottom and holes along the concrete wall on the uphill side.

For many years, probably since Highway 89 was constructed in the late 1930s, water discharged from a hole at the south end of the spring box. The water was routed under the highway through a culvert, and then flowed down the bank and into the Yellowstone River. In April 2010, CUT used a vacuum truck to rehabilitate the spring box, removing mineral deposits, and conducted a pumping test on the spring box. In 2012 the CUT installed a discharge line at the north end of the spring box, a control valve, a pumping vault, and an insulated underground discharge line. This system was installed to divert the flow from LaDuke Hot Spring to a wading pool at Corwin Springs, 2 mi north of the LaDuke. The CUT began diverting the flow in 2013, but the pumping system has run intermittently. When the system is operating no spring water flows through the flume and the CUT collects the flow data.

Hydrogeologic Setting

LaDuke Hot Spring surfaces along the northeast side of the Gardiner basin, at the base of a steep southwest-facing mountain slope that generally marks the southwestern edge of the Beartooth Uplift, which is bounded by the northwest-trending Gardiner reverse fault. The surface trace of the Gardiner fault is obscured by alluvium and colluvium in the LaDuke Hot Spring area, but is mapped as crossing through the LaDuke area (Berg and others, 1999). Berg and others (1999) also show two northeast-trending normal faults that intersect the Gardiner reverse fault in the LaDuke area. These normal faults are thought to be northeast-trending splays of the Reese Creek Fault, which extends northward out of the Park.

Discharge and Water-Temperature Monitoring Summary

As part of their investigation of the Corwin Springs known geothermal resource area (KGRA), the USGS installed a flume on the east bank of the river in 1987 to measure the flow coming out of the culvert. The USGS monitored the flow from September 1987 to August 1994. The site has been monitored by the MBMG as part of the LTMP since July 2005. Monitoring by the MBMG has consisted of manual flume readings during site visits, and hourly temperature readings using a temperature logger designed for high temperatures. Flow monitoring by the MBMG ceased in August 2012 when the CUT began diverting the flow to Corwin Springs. The CUT collects data from the pumping system and spring box and has agreed to provide the data to the MBMG. Figure A3 summarizes the flow data and temperature data collected by the MBMG. Table A5 shows statistics for water-temperature data collected by the MBMG and the USGS.

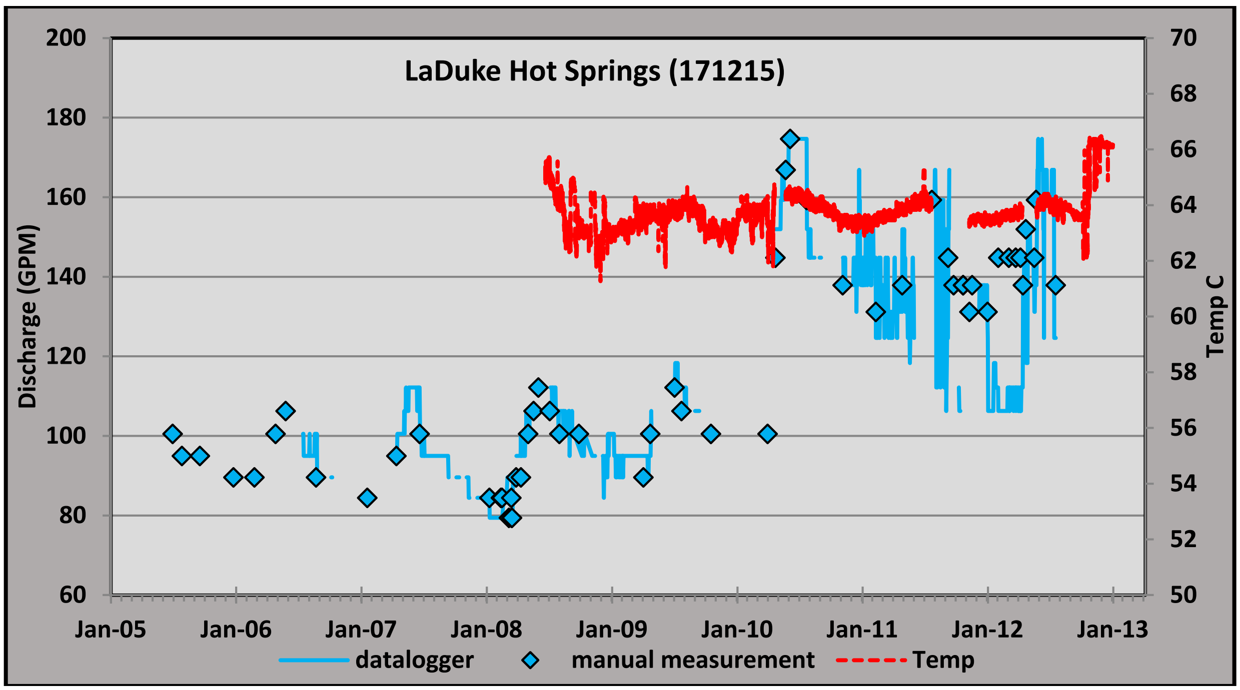

Figure A3. Hydrograph for LaDuke Hot Spring showing average daily discharge and water-temperature data. Manual measurements of discharge through the flume averaged 95 gpm from July 2005 to April 2010. In April 2010 the spring box was rehabilitated, resulting in increased flow. After May 2010 discharge averaged 145 gpm.

Table A5. Water-Temperature Statistics for La Duke Hot Spring

Statistic	MBMG Water Temp. (°C-logger)	USGS Water Temp. (°C-Field)	Comments
Mean	63.8	62.4	✓ Logger temperature data collected inside the spring box at the south end between July 2008 and January 2013. ✓ Manual measurements made by the USGS between September 1988 and August 1994. ✓ Water classified as Hot (>25°C)
Median	63.6	62.4	
Maximum	66.5	65.4	
Minimum	61.3	60.4	
# Readings	35,132	58	

Water-Quality Sampling Summary

Water-quality samples at LaDuke have been collected either as grab samples from the spring discharge, or by pumping water out of the spring box using a portable peristaltic pump. The spring has been sampled by the MBMG 17 times for major ions and trace elements between July 1975 and April 2011. This includes sampling for seasonal variation (spring, summer, and fall) in 2006, 2009, and 2010. The first sample was collected in 1975 as part of an assessment of geothermal resources in Montana. Average concentrations of select major ions and trace elements in the spring water are presented in table A6.

The spring water is a highly mineralized calcium-sodium/sulfate type water with a near neutral pH, very high TDS concentration, high concentrations of sulfate and strontium, and elevated concentrations of fluoride and arsenic. Fluoride and arsenic concentrations exceed drinking water standards.

Table A6. Average Concentrations of Select Major Ions and Trace Elements for LaDuke Hot Spring

TDS	pH	Ca mg/L	Mg mg/	Na mg/L	SiO_2 mg/	SO_4 mg/L	Cl mg/	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
2161	7.3	326.1	61.2	235.9	45.1	1278.2	45.1	<0.3	3.7	18.1	454.2	29.2	4236	250.9	<0.5

In March 2006 and November 2009 the spring was sampled for the stable isotopes oxygen (^{18}O) and deuterium (^{2}H), and the radioactive isotope tritium (^{3}H) (see report, fig. 18, table 6). The water from La Duke Hot Spring does not contain detectable levels of tritium, indicating the water entered the groundwater system prior to 1952.

LaDuke Hot Spring Monitor Well LD1 (256421)

Site Description

Monitor well LD1 is located about 10 ft west of the spring box at LaDuke Hot Spring. The well is 8.7 ft deep, and is constructed with 2-in-diameter PVC pipe that is perforated from 2.0 to 8.7 ft. This well and two others (LD2 and LD3) were installed around the LaDuke spring box in May 2010 for a drawdown test conducted by the CUT (McNabb and Weight, 2011). Wells LD1 and LD3 were installed in the shallow alluvium/colluvium around the spring box to monitor drawdown in the spring area during the 2010 drawdown test. LD2 did not penetrate shallow groundwater and was never used.

In 2013 the MBMG inspected the wells and found that LD1 was still in good condition and had water in the casing, but LD2 and LD3 were dry. With approval from the CUT and the TOC, the MBMG abandoned wells LD2 and LD3 and installed a 6-in-diameter protective steel casing over the wellhead. The well was added to the LTMP in November 2013.

Hydrogeologic Setting

The geologic setting is the same as described for LaDuke Hot Spring. Well LD1 is completed in alluvium and/or colluvium and the well log reports the material as reddish-brown silty sand with a travertine matrix. The thickness of the surficial deposits around the LaDuke Hot Spring collection system is unknown, as is the depth and type of underlying bedrock.

Water-Level and Water-Temperature Monitoring Summary

The water level in this well was monitored during the drawdown test completed on the LaDuke Hot Spring collection box on May 10, 2010 by the CUT. During the pumping test the water level varied from 4.34 to 5.56 ft bgs. The lowest value was reported when the spring box was pumped to the bottom. A measurement of 4.87 ft bgs was measured on August 18, 2010.

On November 20, 2013, after the well was added to the LTMP, a water level of 5.76 ft bgs was recorded. The MBMG plans to install a temperature logger in the well and monitor the water level manually during site visits.

Water-Quality Sampling Summary

No water-quality samples have been collected from this well. However, during the drawdown test the temperature and specific conductance of the well water were measured at 64.1°C and 2,380 µmhos/cm, respectively, similar to the LaDuke Hot Spring values.

Shooting Star Ranch Well (252314)

Site Description

The Shooting Star Ranch well is located 10 mi northwest of Gardiner, in Cinnabar Basin. This privately owned well is used for fire protection, irrigation, and domestic purposes. It was drilled in September 2009 to a depth of 757 ft bgs, and is screened from 727 to 757 ft bgs. It is a flowing artesian well, but it is connected to a distribution system and is shut-in unless the well is in use. The well was inventoried and sampled by the MBMG in November 2009 and added to the LTMP.

The well produces warm water, which raised concerns when the YCGA permit application was being processed. The TOC reviewed the YCGA permit application and determined the warm water was due to the well depth and the elevated geothermal gradient in the Park area, rather than interception of a geothermal groundwater reservoir.

Hydrogeologic Setting

Glacial kame and glacial lake deposits mantle underlying Eocene Absaroka Group volcanic rocks at this site (Lonn and others, 2007). Lithology reported on the driller's log notes silt, sand, gravel, and cobles to 6 ft bgs, with alternating layers of black, brown, gray, and green siltstone to a depth of 757 ft. We interpret this as a thin, 6-ft layer of glacial till overlying Absaroka Group volcanic and/or volcaniclatic rocks. Although the driller's log does not clearly identify a confining unit, it describes bentonite stringers that could explain the artesian conditions at this site. The artesian conditions could also be due to a strong upward vertical gradient in the volcanic deposits.

Water-Level and Water-Temperature Monitoring Summary

A 3-in-diameter fire hydrant is located about 10 ft from the wellhead. The fire hydrant is used to measure the shut-in pressure and to purge the well prior to collecting water samples. Eighteen shut-in pressure measurements have been obtained from the well between May 2010 and September 2013 (fig. A4). The pressure readings, converted to feet of head above ground surface (ags), have varied from 102 to 112 ft ags (45.9 to 50.2 psi) and average 107.8 ft ags. The water-level values account for the difference in elevation (-3.92 ft) between the fire hydrant and the ground surface at the wellhead.

Water temperature has been measured six times, during two site visits and four sampling events (fig. A4). There is most likely some cooling as the water flows up the casing and discharges from the fire hydrant during well purging. An initial temperature reading of 15.8°C, obtained when the well was inventoried and first sampled in November 2009, was lower than subsequent measurements, which range from 20.7° to 21.0°C. The driller reported a temperature of 20°C after allowing the well to flow for 24 h. The 15.8 measurement is believed to be in error due to cooling during purging, and possibly due to cold air temperatures during the sampling, in November.

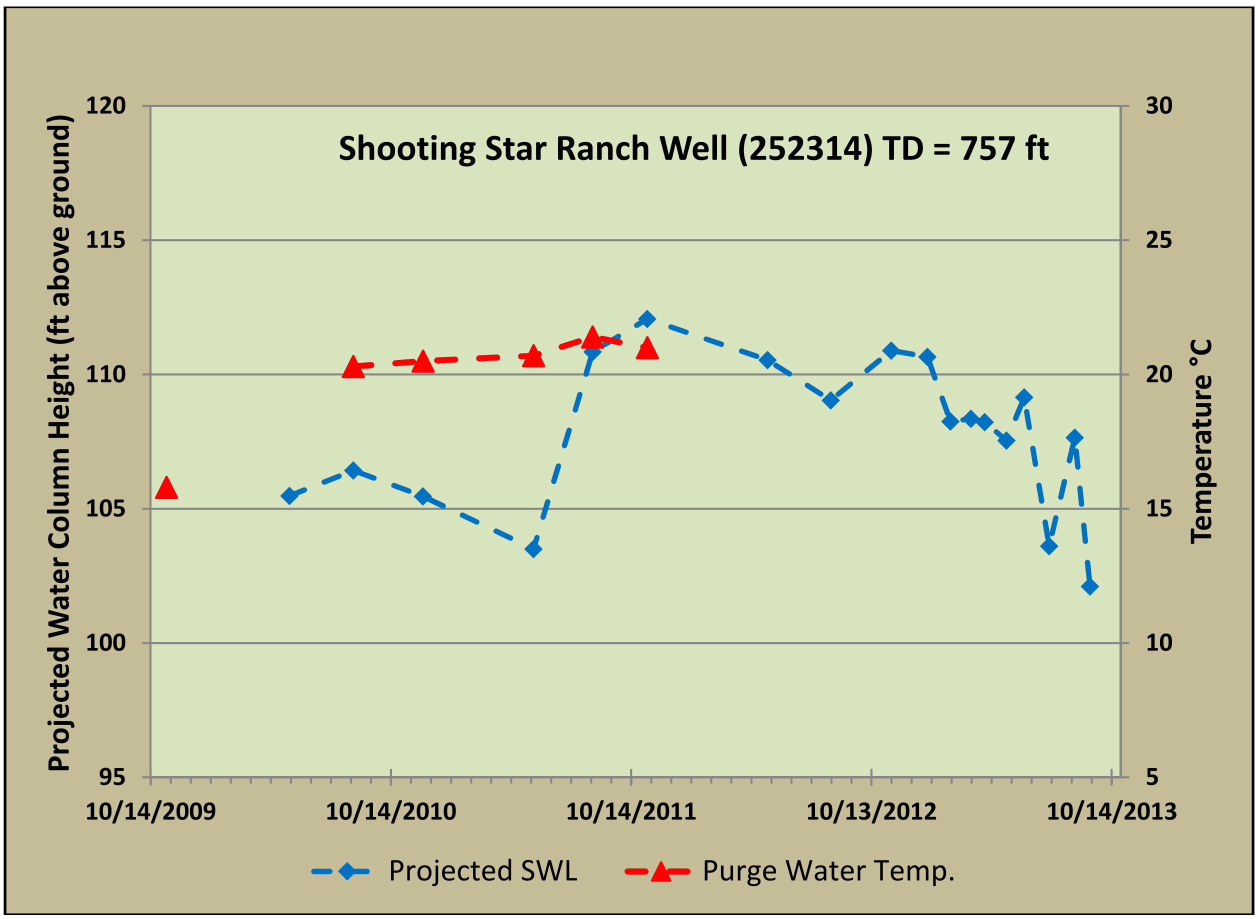

Figure A4. Shut-in pressures and water temperatures measured in the Shooting Star Ranch well.

Water-Quality Sampling Summary

Water samples are collected from a fire hydrant next to the wellhead. The well has been sampled four times for major ions and trace metals between November 2009 and November 2011. This includes sampling for seasonal variation (spring, summer, and fall) in 2011. Average concentrations of select major ions and trace elements are presented in table A7.

Water quality at this site is unusual: the water is a sodium/carbonate-bicarbonate type water with very high pH, a low TDS concentration, and generally low concentrations of dissolved major ions and trace elements. The water is extremely soft (<4 mg/L as $CaCO_3$) due to the low concentrations of calcium and magnesium. The water does not exceed any primary EPA drinking water standards for inorganics, but does exceed the secondary drinking water standard for pH of 6.5 to 8.5.

Table A7. Average Concentrations of Select Major Ions and Trace Elements for Shooting Star Well

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
150	9.8	1.3	<0.0	48.9	32.1	15.5	1.5	<0.0	0.4	2.7	32.6	2.0	85.8	4.4	1.0

The well was sampled in 2009 for stable water isotopes (^{18}O and ^{2}H) and the radioactive isotope tritium (^{3}H) (see report, fig. 18, table 6). The water sample did not contain detectable levels of tritium, indicating the water entered the groundwater system prior to 1952.

Gardiner Airport Well (105980)

Site Description

The Gardiner Airport well is located 1.5 mi north of Gardiner, Montana on the west side of Highway 89. The airport is jointly owned by the City of Gardiner and Park County, and the well provides water for a small amount of landscape irrigation, a mobile home, and several airport buildings. It was drilled in 1989, inventoried in February 1995, first sampled in May 1998, and added to the LTMP in September 2006.

The well is 263 ft deep and is constructed with 6-in-diameter steel casing down to 177 ft and perforated 4-in PVC casing from 177 to 263 ft. The well log does not indicate if a packer or other type of seal was installed between the steel casing and the PVC casing.

Hydrogeologic Setting

The Gardiner Airport is situated on a gravel covered bench about 250 ft northeast of, and 109 ft higher in elevation than, the northeast bank of the Yellowstone River. A northeast–southwest cross section drawn south of the airport shows steeply dipping to overturned Paleozoic and Mesozoic formations within a drag and shear zone in the footwall (southwest side) of the Gardiner reverse fault (Fraser and others, 1969). The Gardiner reverse fault is mapped about 4,000 ft northeast of the airport, and overturned beds of sandstone and siltstone of the Cretaceous Landslide Creek Formation are exposed directly across Highway 89 from the airport (Fraser and others, 1969; Berg and others 1999). These observations indicate that the shear and drag zone in the footwall of the Gardiner reverse fault underlies the airport, and the Landslide Creek Formation probably underlies the surficial deposits that cover the bench. The well log is interpreted as follows: glacial till or reworked glacial till (0–20 ft); glacial outwash deposits (20–156 ft); Landslide Creek Formation (156–263 ft). The 6-in steel surface casing extends to 177 ft, fully penetrates the surficial deposits, and extends 21 ft into the Landslide Creek Formation.

Water-Level and Water-Temperature Monitoring Summary

The Gardiner Airport well has been monitored since September 2006. A water-level logger is maintained in the well and collects hourly water-level and water-temperature data. Manual water-level measurements are made during site visits using an e-tape and water-temperature measurements are obtained when the well is purged for sampling. Figure A5 summarizes the water-level and water-temperature data collected, and statistics for the water-level logger data are summarized in table A8.

We used the river stage recorded at the Corwin Springs gaging station (06191500), located about 5.5 river mi downriver from the Airport, to evaluate the relationship between the water level in the well and the stage of the Yellowstone River. The datum for the Corwin Springs gage station is 5,079 ft and the elevation of the river surface just east of the Airport is about 5,155 ft. To approximate the river stage near the airport, 76 ft was added to the Corwin Springs gage readings (fig. A5).

Water levels in the well follow the same pattern as the river stage. However, while the water levels in the well are based on a surveyed elevation, the river stage altitudes are approximate and cannot be used to determine if groundwater elevations are above or below the river stage. To better evaluate this relationship, a stage gage with a stilling well and a water-level logger could temporarily be installed in the river adjacent to the airport.

Regardless of the relative altitudes of the water levels in the well and the river stage, the hydrograph patterns do show that the river stage somehow influences water levels in the well. The well log indicated the airport well is completed in sandstone and shale bedrock and the surface casing extends 21 ft into the bedrock. If the lithology reported on the driller's log extends to the river, the river channel should be in the sand and gravel deposits, at least 30 ft above the bedrock. It could be that groundwater in the bedrock is hydrologically connected to the groundwater in the surficial deposits, and when river levels rise and recharge the sand and gravel deposits, the increased head in the sand and gravel is rapidly transmitted to the groundwater in the bedrock. Water-quality data from the well (described below) indicates that the water quality is distinct from that of the river. More work is needed to better understand the hydrogeologic setting at this monitoring site.

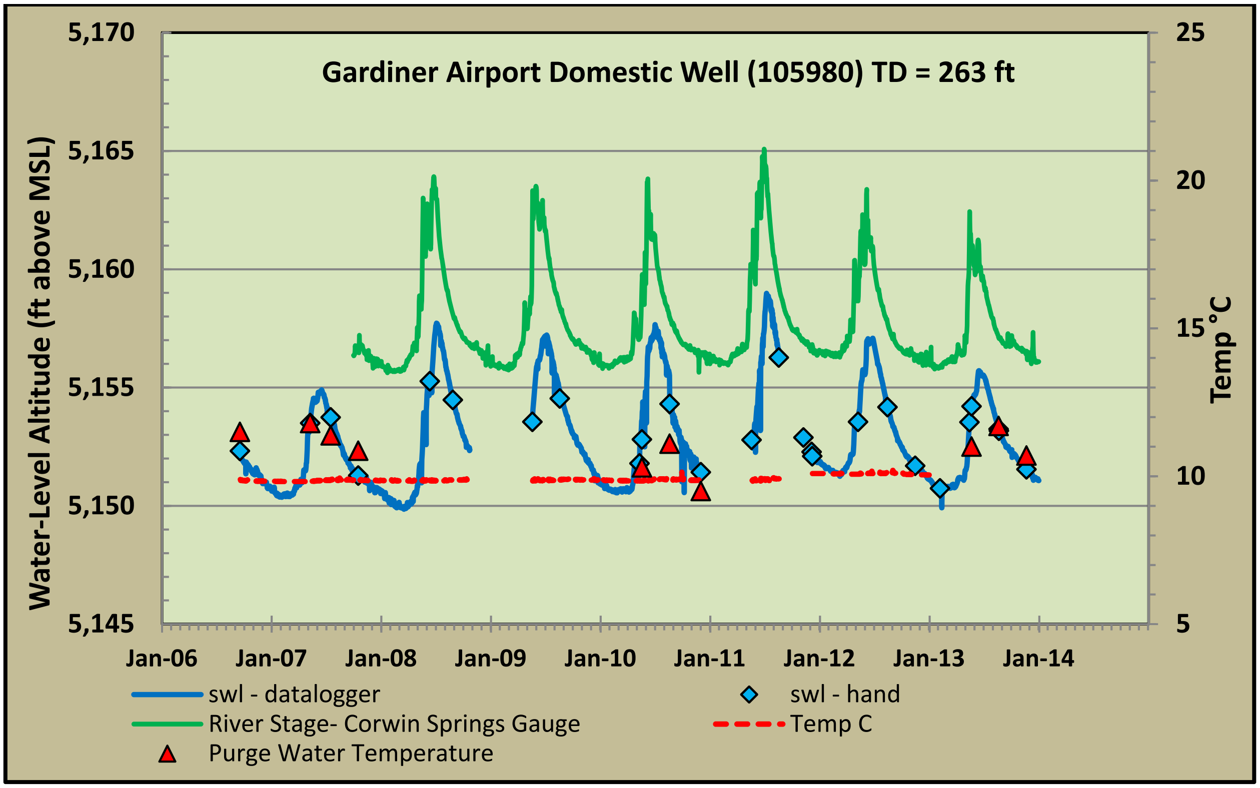

Figure A5. Hydrographs for Gardiner Airport well and the Yellowstone River, showing water levels and water temperatures recorded by the water-level logger, and adjusted river stage based on the Corwin Springs gage (station 06191500). All values are daily midnight-hour readings. Manual measurements obtained during site visits are also shown.

Water temperatures recorded by the water-level logger are about 10°C and have varied by less than 1°C with no apparent seasonal variation. Manual water temperatures measured after purging the well average 11°C, and appear to follow the water levels in the well. The manual measurements likely reflect the temperature of groundwater entering the perforated portion of the well casing from 177 to 262 ft bgs. The stable water temperatures suggest the well is not under the direct influence of the river.

Table A8. Water-Level Logger Statistics for Gardiner Airport Well

Statistic	Water Level (ft bgs)	Water Temp. (°C)	Comments
Mean	107.1	9.9	✓ Temperature measured by logger hanging about 132 ft bgs and 20-30 ft below water surface ✓ Based on daily midnight-hour measurements from September 2006 through December 2013 ✓ Purge-water temp.9.5 to 11.8°C, AVG 11.0°C (*n*=10) ✓ Water classified as Cold <15°C)
Median	107.9	9.9	
Maximum	101.0	9.8	
Minimum	110.1	10.2	
# Readings	2,019	2,012	

Water-Quality Sampling Summary

A frost-free hydrant, located 100 ft north of the well, is used to purge the well and collect water-quality samples. The well has been sampled 11 times for major ions and trace elements between May 1998 and November 2013. This includes sampling for seasonal variation (spring, summer, and fall) in 2007, 2010, and 2013. Average concentrations of select major ions and trace elements are presented in table A9. The airport well produces a sodium/bicarbonate-sulfate type water that has a basic pH, and a TDS that is higher than other cold-water monitoring sites in the Yellowstone River watershed (see report for TDS data). The water is soft due to low levels of calcium and magnesium, with an average hardness of 41 mg/L as $CaCO_3$. The average arsenic concentration is very close to the EPA drinking water standard of 10 µg/L, and three samples have slightly exceeded the standard (10.1 to 10.9 µg/L).

Table A9. Average Concentrations of Select Major Ions and Trace Elements for the Airport Well

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
445	8.2	13.9	1.5	140.	15.0	151.	16.8	<0.0	1.0	9.8	259.	25.8	197.	77.5	<0.5

A radon sample collected in August 1998 had an elevated concentration of 1,100 (Rn^{222}-pC/l). The well has also been sampled for stable water isotopes (^{18}O and ^{2}H) and the radioactive isotope tritium (^{3}H). The tritium sample, collected in October 2007, has a concentration of 7.0 TU (see report, fig. 18, table 6).

Cole Well (138764)

Site Description

The Cole well is located 5 mi northwest of Gardiner on a bench northeast of Highway 89. The privately owned well is used for landscape irrigation and livestock. It was drilled in 1992, inventoried by the MBMG in November 1995, and first sampled in June 1996. The well was added to the LTMP in October 2006. The borehole was drilled to 280 ft bgs but the borehole collapsed upon removal of the drill stem and the well was completed at 143 ft bgs. Water enters the well's perforated casing between 120 and 143 ft bgs. If vertical hydraulic gradients are upward at this site, deeper groundwater may flow up through the collapsed portion of the borehole and into the well.

Hydrogeologic Setting

The Cole well is situated on a bench between the Yellowstone River to the west and a steep mountain slope to the east. The bench surface is about 500 ft wide and 120 to 140 ft higher in elevation than the river. The well is located at the east edge of the bench and is about 1,000 ft east of the river.

The base of the mountain slope generally defines the southwest edge of the Beartooth Uplift, which is bounded by the northwest-trending Gardiner fault. The Gardiner fault is a regional scale reverse fault formed during the Late Cretaceous Laramide orogeny. The fault transported Archean igneous and metamorphic basement rocks southwestward, up and over Paleozoic and Mesozoic sedimentary rocks to the southwest. Geologic mapping by Berg and others (1999) show the trace of the Gardiner fault passing along the base of the steep slope, within about 200 ft east of the Cole well. Mapping also shows two northeast-trending normal faults near the Cole well. These down-to-the-southeast normal faults are Tertiary extensional faults and they cut across the Gardiner reverse fault and offset it. The Cole well is positioned between the two normal faults, in a graben structure.

The bench at the Cole Well is on the southwest (footwall) side of the Gardiner reverse fault. Archean granitic rocks are mapped on the northeast (hanging wall) side of the fault. The bench is mantled with glacial till and the underlying bedrock is not exposed. However, the Cretaceous Landslide Creek Formation is mapped to the east and south of the Cole well (Berg and others, 1999), and is thought to underlie the bench. The driller's log reports the following lithology for the Cole well: sand and pea gravel (0–30 ft); hard quartz (31–125 ft); soft quartz layers and clay (126–142 ft); and hard quartz and clay (143–280 ft).

The driller also noted that the borehole collapsed, from 143 to 280 ft, when the drill stem was pulled. Based on the geologic mapping and the information on the well log, the upper 30 ft is interpreted as glacial outwash. The deeper intervals with hard and soft quartz and clay are interpreted as Archean granitic or metamorphic rock, possibly sheared and faulted. The 18 ft of soft quartz and clay from 126 to 142 bgs may represent a shear zone associated with the Gardiner Fault. The collapse of the bore hole below 143 ft also hints at subsurface shearing and possibly fault gouge. For these reasons the well is interpreted to be completed in the Archean granitic rocks either within the Gardiner fault zone or in the hanging wall of the fault.

Water-Level and Water-Temperature Monitoring Summary

The Cole irrigation well has been monitored since September 2006. A water-level logger is installed in the well and collects hourly water-level and water-temperature data. Manual water-level measurements are made during site visits, and temperature measurements are made when the well is purged for sampling. Figure A6 summarizes the water-level and water-temperature data collected, and statistics for the water-level logger data are summarized in table A10.

Water levels are erratic and show numerous downward spikes during the irrigation season, due to pumping from the well. The hydrograph does not show a typical annual pattern with a sharp rise in the spring followed by a gradual decline. Instead, peak water levels occur anywhere from February through July, and water levels do not show a consistent annual pattern. In April 2013 the water levels rose about 6 ft higher than previous years.

Water temperature varies seasonally and is generally inverse to water levels. The temperature fluctuates about 4°C annually, and peak in late July to late August. Water levels and water temperatures were anomalous in 2013, with the lowest recorded temperature coinciding with high water levels (fig. A6). Manual water temperatures measured during sampling are slightly warmer (table A10). These measurements are likely more representative of *in situ* conditions near the well screen, at 120–143 ft bgs. The spikes in water temperature coincide with short-term decreases in water levels associated with pumping.

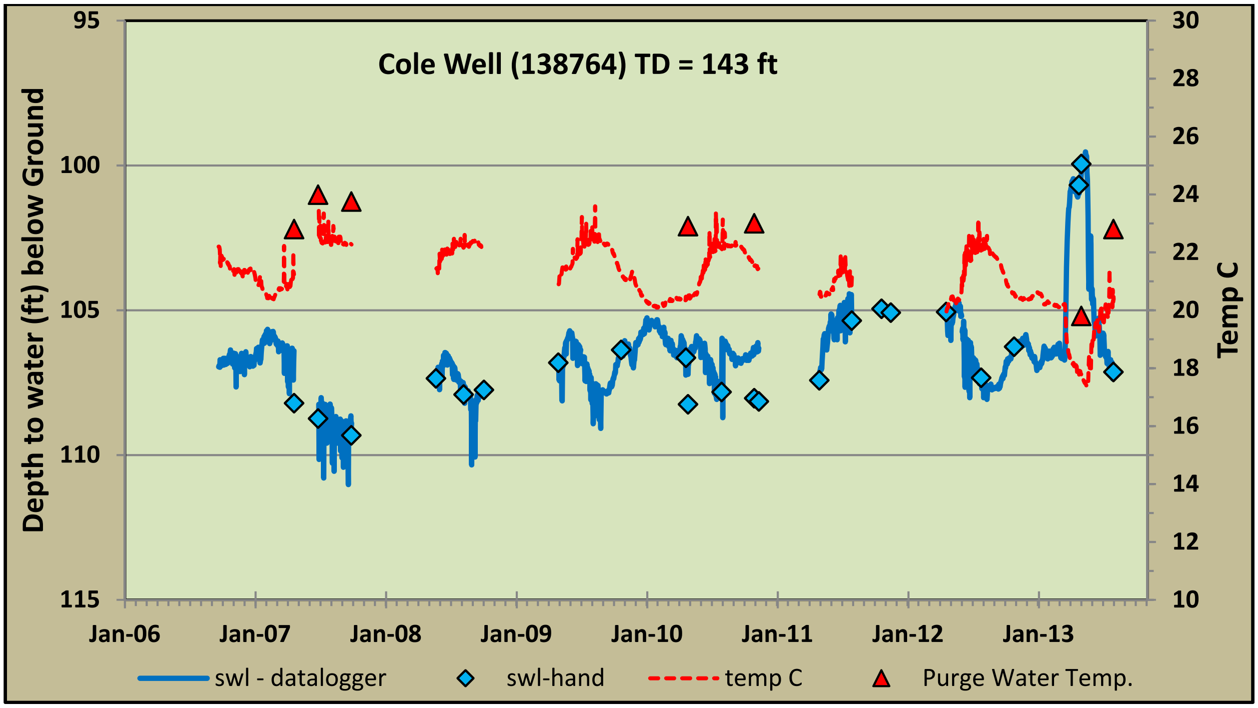

Figure A6. Hydrograph for the Cole well showing daily midnight-hour water-level and water-temperature data recorded by a water-level logger, and manual water-level and water-temperature measurements made during site visits.

Table A10. Water-Level Logger Statistics for Cole Well

Statistic	Water Level (ft)	Water Temp. °C	Comments
Mean	106.47	21.14	✓ Temperature measured by logger about 117 ft bgs and 6–18 ft below the water surface ✓ Based on daily midnight-hour readings from October 2006 through August 2013 ✓ Purge-water temp. 20 to 24°C, Avg. 22.6°C (*n*=7) ✓ Water classified as Warm (15–25°C)
Median	106.56	21.27	
Maximum	111.02	23.59	
Minimum	99.53	17.38	
# Readings	1552	1558	

Water-Quality Sampling Summary

Water-quality samples are collected from a frost-free hydrant located at the wellhead. The Cole well has been sampled 11 times for major ions and trace elements between June 1998 and November 2013. This includes sampling for seasonal variation (spring, summer, and fall) in 2007, 2010, and 2013. Average concentrations of select major ions and trace elements are presented in table A11. The well produces a magnesium-calcium/bicarbonate-sulfate type water that is distinct from other monitoring sites in the Yellowstone River watershed. The water is very hard (average of 465 mg/L as Ca CO_3), and has elevated concentrations of sulfate, strontium, and arsenic. Arsenic concentrations slightly exceed the of 10 µg/L drinking water standard.

Table A11. Average Concentrations of Select Major Ions and Trace Elements for Cole Well

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
621	7.5	71.6	67.1	44.6	19.0	190.	17.4	0.6	1.6	10.3	37.7	87.7	2192	43.1	23.3

The well was sampled for stable water isotopes (^{18}O and ^{2}H) and tritium (^{3}H) in October 2007, and again for stable water isotopes in May 2013 (see report, fig. 18, table 6).Tritium was detected at a low concentration (1.6 TU).

Cole Spring (181620)

Site Description

Cole spring is located about 5 mi northwest of Gardiner on the steep southwest-facing slope above the previously described Cole well. The elevation of the spring is about 200 ft above the bench where the Cole well is located. The area around the spring is covered with tin, rocks, and brush, and the collection system design is not known. The spring serves as a domestic water supply for the owners and a neighboring residence. A plastic discharge line conveys water from the spring to a cistern. The spring was inventoried and sampled by the MBMG in June 2000 and added to the LTMP in May 2007.

Hydrogeologic Setting

Based on the 1:100,000-scale map (Berg and others, 1999), the Cole spring appears to discharge from Archean granitic rocks, either in the hanging wall of the Gardiner reverse fault, or from the fault zone itself (see hydrogeologic setting for Cole well). The location of the spring is thought to be fault controlled, as there are several other springs that surface along the slope or along the base of the slope near the Cole Spring. Colluvium and vegetation obscure the bedrock at the spring but granitic rocks crop out less than 100 ft upslope. The Gardiner reverse fault likely consists of several shears and fault splays, and the spring location may be controlled by one of these shears or faults within the Archean granitic rocks. More detailed geologic mapping in the Cole Spring area is needed to help interpret the geologic setting.

Discharge and Water-Temperature Monitoring Summary

Discharge and water temperature at Cole Spring have been monitored since October 2007. Hourly discharge data have been collected using an in-line flowmeter installed on the discharge line about 150 ft downslope from the spring collection point. The flowmeter is equipped with an externally mounted pulse logger that records the number of rotations of the meter dial. Daily discharge readings for the 3:00 am hour are presented in figure A7. The hourly discharge data are discontinuous because the pulse logger system has been unreliable. The flowmeter is also prone to clogging when debris from the collection system gets into the discharge line. Discharge averaged 2.3 gpm during periods of successful monitoring. Manual discharge measurements are also made during site visits by timing readings from the flowmeter dial. The manual flowmeter readings have varied from 1.8 to 4.7 gpm and average 2.5 gpm, in general agreement with the pulse logger data (fig. A7).

Hourly water-temperature data are collected using a Tidbit® temperature logger installed in the discharge line at the flowmeter. Daily water temperatures measured during the 3:00 am hour are shown in figure A7, and summary statistics for the daily data are presented in table A12. The discharge line lies on the ground near the collection area and is buried a few lines under the surface further down, where the flowmeter is installed. Heating and cooling of the ground likely modifies the water temperature in the discharge line, and the annual fluctuations in water temperature probably reflect shallow ground temperature patterns. Moving the temperature logger to the head of the spring would provide more accurate temperature measurements.

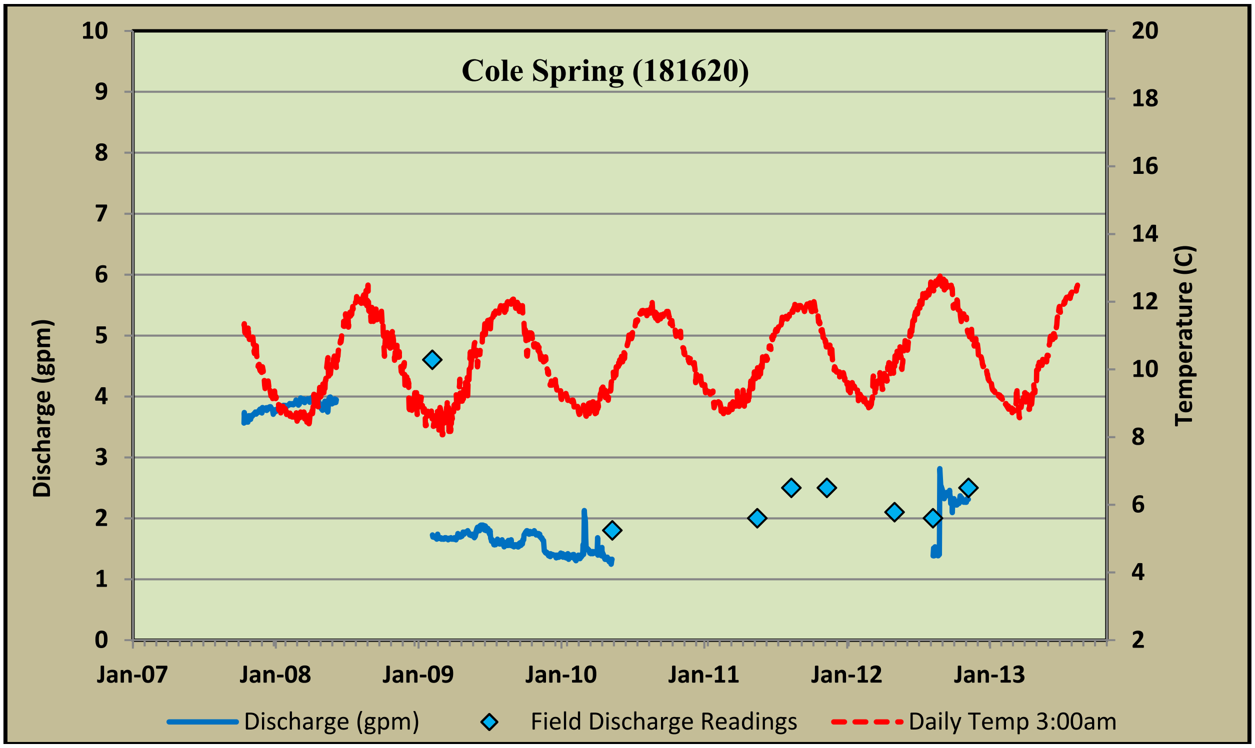

Figure A7. Discharge and water-temperature data obtained from Cole Spring using an inline flowmeter equipped with a data logger, and a Tidbit® temperature logger. Manual flow measurements made during site visits are also shown. Failure of the data logger on the flowmeter has resulted in several gaps in the discharge record.

Table A12. Water-Temperature Statistics for Cole Spring

Statistic	Water Temp. (°C)	Comments
Mean	10.3	✓ Temperature measured by temperature logger installed in discharge line at flowmeter. ✓ Based on daily 3:00 am hour measurements ✓ Water classified as Cold (15°C)
Median	10.2	
Maximum	12.8	
Minimum	8.1	
# Readings	2,028	

Water-Quality Sampling Summary

Water samples are collected from the collection system at the head of the spring. Cole Spring has been sampled 8 times for major ions and trace metals between May 2007 and November 2013. This includes sampling for seasonal variation (spring, summer, and fall) in 2007 and 2013. Average concentrations of select major ions and trace elements are presented in table A13. The spring discharges a magnesium-bicarbonate type water that is similar to water from the Cole well, but has lower concentrations of major ions and trace elements. The spring does not exceed any inorganic drinking water standards, but does have a high concentration of strontium.

Table A13. Average Concentrations of Select Major Ions and Trace Elements for Cole Spring

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
286	7.5	37.3	40.0	11.5	13.6	31.4	2.8	0.3	0.3	< 1.0	11.1	65.7	1319	15.8	11.8

Cole Spring has been sampled four times for stable water isotopes (^{18}O and ^{2}H) between October 2007 and November 2013. The spring was sampled for tritium (^{3}H) in October 2007 and had a concentration of 2.7 TU (see report, fig. 18, table 6).

Powell Spring (184260)

Site Description

Powell Spring is located 5 mi northwest of Gardiner, and is about 700 ft northwest of Cole Spring, on the same steep west-facing slope. However, Powell Spring is about 150 ft lower on the slope, near the base. The privately owned spring is used for domestic water supply. The spring consists of a several discrete discharges and numerous small seeps. A perforated pipe buried in the largest discharge at the top of the spring area collects water which is piped to an underground 2,000-gallon cistern and gravity-fed to multiple residences. The spring was inventoried in May 2000, and was sampled and added to the LTMP in October 2008.

Hydrogeologic Setting

The hydrogeologic setting for Powell Spring is generally the same as for Cole Spring. However, based on the 1:100,000-scale geologic mapping by Berg and others (1999), Powell Spring plots on the trace of the Gardiner reverse fault, where a northeast-trending normal fault intersects and offsets the Gardiner fault. The spring location is likely fault controlled, but at the scale of the geologic mapping, it is not clear if the spring surfaces along Gardiner fault, the normal fault, or the intersection of the two. Like Cole Spring, colluvium and vegetation obscure the bedrock, and more detailed geologic mapping is needed to help interpret the geologic setting.

Discharge and Water-Temperature Monitoring Summary

Discharge at Powell Spring has been monitored since April 2009. In July 2009 an in-flowmeter was installed on the discharge line, about 200 ft downslope from the collection point. The flowmeter was equipped with an externally mounted pulse logger that records the number of rotations of the meter dial. Daily discharge readings for the midnight hour are presented in figure A8 and statistics for the flow logger data are provided in table A14. Manual discharge measurements are also made during site visits by timing readings from the flowmeter dial. The manual flowmeter readings have varied from 7 to 9 gpm and average 7.9 gpm, in general agreement with the pulse logger data (fig. A8, table A14).

Manual water-temperature measurements have been made since October 2008 and have ranged from 11.9 to 17.2°C and average 14.7°C (n=10; fig. A8). A Tidbit® temperature logger was installed in the discharge line at the flowmeter in May 2012. The temperature-logger data is summarized in figure A8 and statistics for the data are provided in table A14. Like Cole Spring, the discharge line from the spring is buried just under the surface, and shallow ground temperatures likely modify the water temperature before it is measured at the flowmeter. The spring water-temperature pattern is limited to just over one year, but the pattern is similar to the pattern seen in the nearby Cole Spring. The temperature pattern is most likely reflective of the annual pattern of shallow ground temperatures. Although the hydrogeologic setting for Powell and Cole springs are similar and they are near each other, Powell Spring produces water that is about 5° to 6°C warmer than Cole Spring.

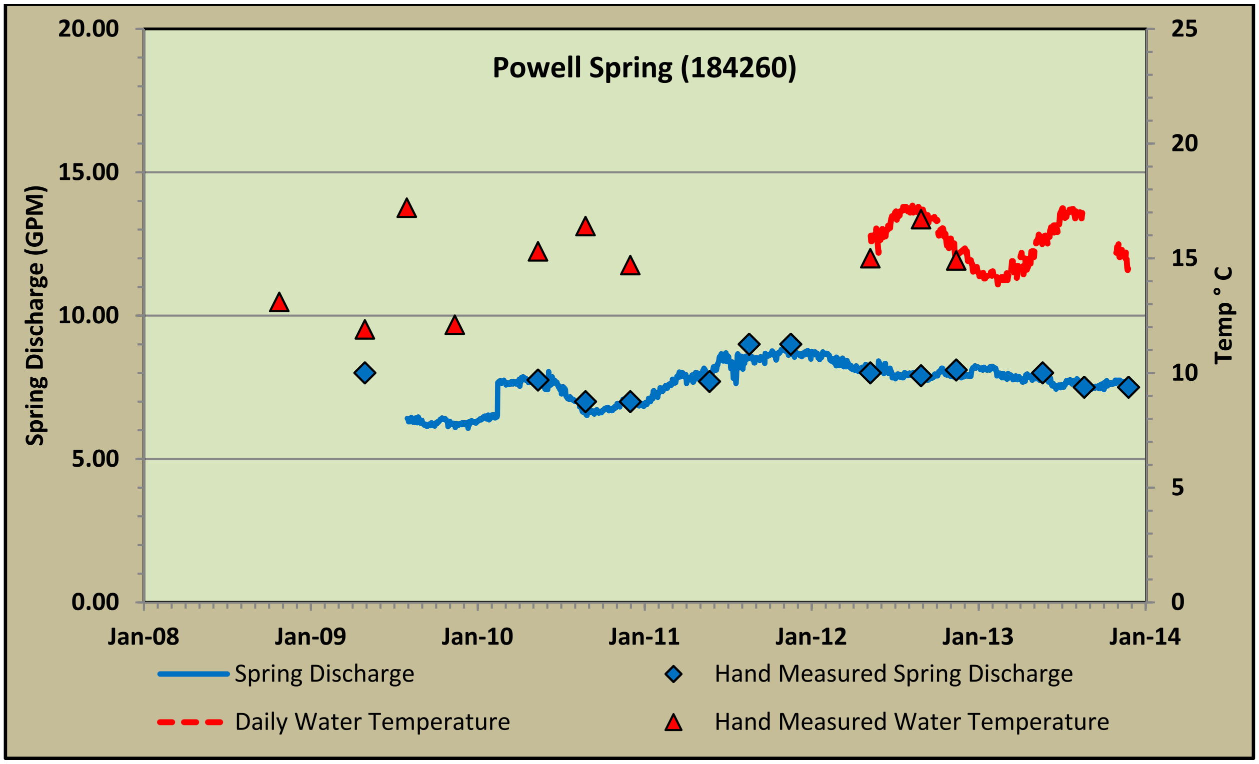

Figure A8. Discharge and water-temperature data obtained from Cole Spring using an inline flowmeter equipped with a data logger, and a Tidbit® temperature logger. Manual flow measurements made during site visits are also shown.

Table A14. Discharge and Water-Temperature Statistics for Powell Spring

Statistic	Discharge (gpm)	Water Temp. (°C)	Comments
Mean	7.6	15.8	✓ Discharge recorded by pulse logger during the midnight hour from 7/31/2009 to 11/25/2013 ✓ Manual discharge measurements range from 7 to 9 gpm and average 7.9 gpm ✓ Temperature measured by Tidbit® temperature logger at midnight from 5/10/2012 to 8/20/2013 ✓ Manual temperature measurements range from 11.9 to 17.2°C and average 14.7°C (Oct. 2008–Nov 2012)
Median	7.8	15.9	
Maximum	8.8	17.3	
Minimum	6.1	13.9	
# Readings	1579	478	

Water-Quality Sampling Summary

Water samples are collected from the head of the spring where the upper end of the discharge pipe is buried. Powell Spring has been sampled 8 times for major ions and trace metals between October 2000 and November 2012. This includes sampling for seasonal variation (spring, summer, and fall) in 2009 and 2012. Average concentrations of select major ions and trace elements are presented in table A15. Powell Spring discharges a magnesium-bicarbonate type water that is similar to the water produced by Cole Spring. The spring water has a basic pH, is hard (avg. = 241 mg/L as $CaCO_3$), and has an elevated strontium concentration, but does not exceed any drinking water standards.

Table A15. Average Concentrations of Select Major Ions and Trace Elements for Spring 184260

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
290	7.8	35.7	37.0	17.6	12.8	32.9	3.5	0.2	0.2	<0.5	17.1	73.6	1151	18.0	7.1

Powell Spring has been sampled four times for stable water isotopes (^{18}O and ^{2}H) between October 2007 and November 2013. The spring was sampled for tritium (^{3}H) in October 2007 and had a concentration of 2.5 TU (see report, fig. 18, table 6).

Yellowstone Basin Inn Well (145529)

Well Description

The Yellowstone Basin Inn well, located 4.5 mi northwest of Gardiner along the east side of Highway 89, is used as a public water supply for the Inn. Drilled in 1994, the well is 100 ft deep and constructed with 6-in-diameter steel casing that extends to the bottom of the borehole. MBMG inventoried the well in February 1995, collected a water-quality sample in July 1998, and added it to the LTMP in May 2007.

Hydrogeologic Setting

The Yellowstone Basin Inn well is situated on a river terrace about 70 ft above and 850 east of the Yellowstone River. The terrace is bounded on the east by the higher bench that the Cole well is located on. Glacial deposits are mapped on the terrace (Berg and others, 1999). The driller's log reports the following lithology: gravel and boulders (0–8 ft), sand and a little gravel (8–96 ft), and gravel (96–100 ft). Based on the geologic mapping and the information on the well log, the upper 8 ft is interpreted as glacial outwash or flood deposits, and the underlying sand and gravel is interpreted as glacial outwash or fluvial deposits.

Water-Level and Water-Temperature Monitoring Summary

The Yellowstone Basin Inn well has been monitored since May 2007. Hourly water-level and water-temperature measurements are obtained using a water-level logger. Manual water-level measurements are made during site visits and manual water-temperature measurements are obtained when the well is purged for sampling. Figure A9 shows the midnight water-level and water-temperature measurements obtained from the Yellowstone Basin Inn well since monitoring began in May 2007. Table A16 shows summary statistics for the logger data.

We used the river stage recorded at the Corwin Springs gaging station (USGS Station 06191500), located about 2.4 river mi downriver from the Inn, to evaluate the relationship between the water level in the well and the stage of the Yellowstone River. The datum for the Corwin Springs gage station is 5,079 ft and the elevation of the river surface just east of the Inn is about 5,125 ft. To approximate the river stage near the Inn, 46 ft was added to the Corwin Springs gage readings (fig. A9). The results show that groundwater levels at the well site are close to and generally follow the river stage. Since the river elevation near the well is estimated, results cannot be used to determine if groundwater elevations are above or below the river stage.

Groundwater levels and river stage peak at almost the same time, and then both decline through February each year. The amplitude of the annual fluctuations in groundwater levels is about 1 ft less than the amplitude of the annual river stage fluctuations. Small spikes in river stage hydrograph do not show up on the well hydrograph. Water levels in the well peak in mid-June to early July: the earliest measured peak occurred on June 11, 2007 and the latest occurred on July 7, 2008. Water levels decrease about 6 ft following the seasonal peak, through the end of February. The lowest water level measured at this site occurred on February 27, 2008. Water-temperature data obtained from the water-level logger deployed in this well were erratic and considered unreliable. The well water is classified as warm based on manual temperature measurements made during site visits (fig. A9, table A16).

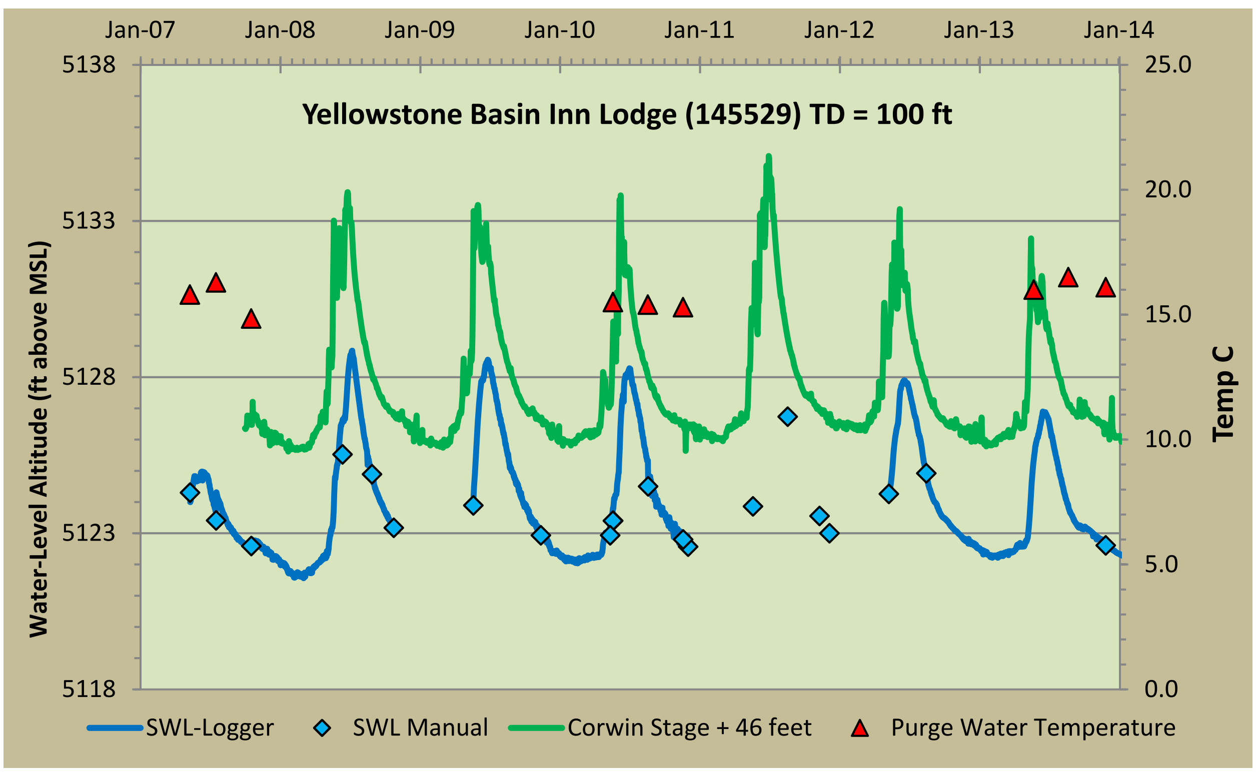

Figure A9. Hydrograph for the Yellowstone Basin Inn well and the Yellowstone River, along with manual water-level and water-temperature readings obtained from the well during site visits. Stage elevations for the Yellowstone River are adjusted to show the approximate stage elevation near the well.

Table A16. Water-Level Statistics for the Yellowstone Basin Inn Well

Statistic	Water Level (ft bgs	Water Temp. (°C)	Comments
Mean	68.3	No Data	✓ Thermistor in water-level logger failed ✓ Purge-water temp. 14.8–16.5°C, Avg. 15.7 (*n*=9) ✓ Water is classified as Warm (15–25°C)
Median	68.8	No Data	
Maximum	70.7	No Data	
Minimum	63.5	No Data	
# Readings	1548		

Water-Quality Sampling Summary

The Yellowstone Basin Inn well has been sampled 9 times for major ions and trace metals between 1998 and 2013. This includes sampling for seasonal variation (spring, summer, and fall) in 2007, 2010, and 2013. Average concentrations of select major ions and trace elements are presented in table A17. The well produces a magnesium-calcium/bicarbonate-sulfate type water with a basic pH, and an average hardness of 275 mg/L as $CaCO_3$. The water does not exceed any EPA drinking water standards for inorganics. The well was sampled for stable water isotopes (^{18}O and ^{2}H) and the radioactive isotope tritium (^{3}H) in October 2007, and three more times for stable water isotopes in 2013 (see report, fig. 18, table 6).

Table A17. Average Concentrations of Select Major Ions and Trace Elements for Inn Well

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
394	7.7	47.7	41.0	21.0	26.5	108.	6.7	0.5	1.0	3.9	39.6	54.5	739	47.3	3.2

Strauss Well (105959)

Site Description

The Strauss well is located 4.5 mi northwest of Gardiner, about 140 ft northwest of the Yellowstone Basin Inn well. The well, drilled in 1981, is 100 ft deep and constructed with a 6-in-diameter steel casing that extends to the bottom of the borehole. It provides domestic and irrigation water for a residence next to the Inn. It was inventoried by the MBMG in November 1995 and sampled and added to the LTMP network in May 2007.

Hydrogeologic Setting

The Strauss well and Yellowstone Basin Inn well (145529) have the same hydrogeologic setting (see previous description). The well log reports granite boulders and clay to 16 ft, which is interpreted as glacial till. Alternating sand and gravel layers from 16 to 100 ft bgs are interpreted as fluvial or glaciofluvial sands and gravels. The driller's log reports "quicksand" from 80 to 95 ft bgs, which is also commonly reported for wells on the bench east of the terrace.

Water-Level and Water-Temperature Monitoring Summary

This site has been monitored by the MBMG since May 2007. Hourly water-level and water-temperature measurements are made using a water-level logger. Manual water-level measurements are made during site visits and manual temperature measurements are obtained when the well is sampled. Figure A10 summarizes water-level and water-temperature data obtained from the well during the midnight hour, and statistics for the water-level logger data are provided in table A18.

The Strauss and Yellowstone Basin Inn (145529) wells are at the same elevation, and have similar water levels. We used the same method to compare the water level in the Strauss well to the Yellowstone River stage, adding 46 ft to the river stage recorded at the Corwin Springs USGS gage station (06191500). The water-level pattern for the Strauss well shows a typical spring recharge peak followed by a slow decline through late January and February. Similar to the Yellowstone Basin Inn well, peak groundwater levels occur in mid-June to early July and the lowest levels occur in February (figs. A9, A10). Water-level altitudes in the Strauss well are close to the estimated river stage altitudes and the water levels closely follow the river stage (fig. A10). The water levels in the well peak at almost the same time as the Yellowstone River, but then lag behind the river levels as they both decline through February each year. Small spikes in river stage hydrograph do not show up on the well hydrography.

Water temperatures in the Strauss well show a low amplitude pattern that follows the water levels, with the highest temperatures occurring just before peak water levels. The data logger was originally installed about 68 ft bgs. It was replaced in May 2012 and reinstalled on a direct read cable at a depth of 72 ft bgs, which resulted in an increase in the *in situ* water temperatures recorded by the logger (fig. A10). Manual temperatures measured after purging and sampling the well are consistently warmer than the logger measurements (table A18).

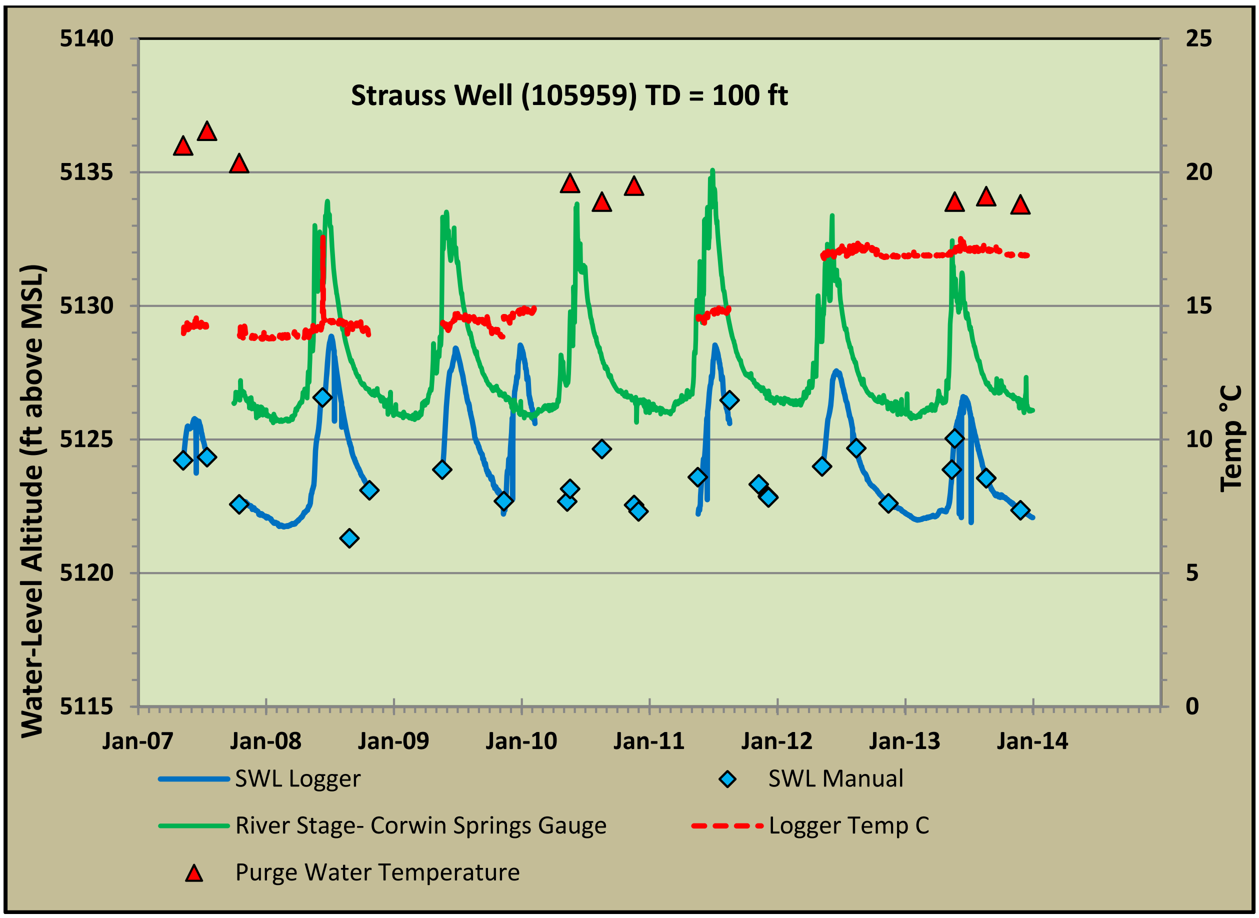

Figure A10. Hydrograph for the Strauss well and the Yellowstone River, along with manual water-level and water-temperature readings obtained from the well during site visits are also shown. Stage elevations for the Yellowstone River are adjusted to show the approximate stage elevation near the well.

Table A18. Water-Level Logger Statistics for the Strauss Well

Statistic	Water Level (ft bgs)	Water Temp. (°C)	Comments
Mean	65.7	17.0	✓ Water levels based on midnight-hour readings from May 2007 through December 2013 ✓ Temperatures based on daily midnight-hour readings from May 2012 through December 2013 ✓ Temperature measured by logger about 72 ft bgs, and 5-12 ft below the water surface ✓ Purge-water temp. 17.7- 21.6°C, Avg. 19.5 (n=8) ✓ Water is classified as warm (15-25°C)
Median	66.3	16.9	
Maximum	68.3	17.5	
Minimum	61.1	16.8	
# Readings	1,396	600	

Water-Quality Sampling Summary

Water samples at this site are collected from a frost-free hydrant located about 50 ft west of the well. The well has been sampled 9 times for major ions and trace elements between May 2007 and November 2013. This includes sampling for seasonal variation (spring, summer, and fall) in 2007, 2010, and 2013. Average concentrations of select major ions and trace elements are presented in table A19. The well produces a magnesium-calcium/bicarbonate-sulfate type water that is very hard (average of 338 mg/L as $CaCO_3$) and has a basic pH. Even though the Strauss well is the same depth at the Yellowstone Basin Inn well (145529) and only 140 ft away, the water is more mineralized. The average TDS concentration is over 100 mg/L higher, and most major ion and trace element concentrations are higher (tables A17, A19). Manganese exceeds the secondary EPA drinking water standard of 0.05 mg/L, with an average value of 0.10 mg/L, but does not exceed any primary EPA drinking water standards. The Strauss well has been sampled four times for stable water isotopes (^{18}O and ^{2}H), and was also sampled for tritium ^{3}H in October 2007 (see report, fig. 18, table 6).

Table A19. Average Concentrations of Select Major Ions and Trace Elements for Struss Well

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
513	7.7	53.2	49.9	41.8	30.9	156.	10.3	<0.1	0.8	4.3	59.5	87.1	1106	54.6	4.1

Miller Well (152216)

Site Description

The Miller well is located about 5 mi northwest of Gardiner. Drilled in 1971 for a domestic water supply, the well is not used due to poor water quality. It was monitored by the USGS as part of the study of the Corwin Springs KGRA (Sorey, 1991). In September 1995 the MBMG inventoried the well, and in March 2006 the well was sampled and added to the LTMP. The well was drilled to a depth of 195 ft and completed at 190 ft. Steel casing (6-in diameter) was installed down to 178 ft, and a screen was installed from 178 to 190 ft. The remaining 5 ft of the borehole probably collapsed during well completion. However, the MBMG sounded the well in November 2012, and documented the pump at 170 ft, and the bottom of the well at 184 ft. The difference in total depth is attributed to buildup of sediment in the bottom of the well casing.

Hydrogeologic Setting

The Miller well is located in the floodplain of the Yellowstone River, on a river terrace on the east side of the river. The well is about 250 ft east of the river, and the elevation of the terrace is about 15–20 ft higher than the river surface. The driller's log reports alternating layers of sand, sand and gravel, and clayey sand and gravel. Black sands are noted in several intervals from 104 to 195 ft. The well is located about 0.4 mi south of the CUT well (146978; see report). A description of the CUT well lithology includes reference to "Unconsolidated lake sediments with sand layers, as noted in the nearby Miller well" (Pierce and others, in Sorey 1991, Chapter 3, page C-24). The Miller well is thought to be completed in the Yellowstone River Valley glacial scour basin postulated in the Sorey report. This scour basin is thought to be filled with fine-grained silt (lake sediments) deposited in a deep scour basin carved by the Yellowstone outlet glacier (Pierce and others, in Sorey 1991, Chapter 3).

Water-Level and Water-Temperature Monitoring Summary

The Miller well has been monitored since August 2006. A water-level logger is installed in the well and collects hourly water-level and water-temperature data. Manual water-level measurements are made during site visits, and temperature measurements are made when the well is purged for sampling. Figure A11 summarizes the water-level and water-temperature data collected, and statistics for the water-level logger data are provided in table A20. We used the river stage recorded at the Corwin Springs gaging station (06191500), located about 2.4 mi downriver from the Miller well, to evaluate the relationship between the water level in the well and the stage of the Yellowstone River. The Corwin Springs gage station datum is 5,079 ft and the elevation of the river surface just east of the Miller well is about 5,124. To approximate the river stage near the well, 45 ft was added to the Corwin Springs gage readings (fig. A11).

Water levels in the well have ranged from about 3 to 10 ft bgs. The levels usually peak in late June to early July, and the lowest levels occur in late February to early March. The water levels follow the same general pattern as the river stage, but the seasonal peaks in the well hydrograph lag behind the peaks in the river stage by 2 to 4 weeks, and the falling limb of the well hydrograph deceases at a slower rate. However, while the water levels in the well are based on a surveyed elevation, the river stage altitudes are approximate and cannot be used to determine if groundwater elevations are above or below the river stage. To better evaluate this relationship, a stage gage with a stilling well and a water-level logger could temporarily be installed in the river adjacent to the Miller well. This temporary staff gage could also be used to better evaluate the Strauss (105959) and Yellowstone Basin Inn (145429) monitoring sites, which are about 500 ft due east of the Miller well.

Temperature patterns in the Miller well do not correlate with the water level in the well. The water-level logger is installed 30 ft bgs, nearly 154 ft above the bottom of the well, and the well is not pumped; the water temperatures recorded by the water-level logger probably reflect ambient groundwater temperatures around the well at 30 ft bgs. Water temperatures measured following well purging are about 7°C warmer, and ranged from 23.0° to 25.3°C with an average of 24°C (fig. A11). The spikes in the water temperature coincide with site visits when the well is purged for sampling. Review of these data shows that it takes 1 to 3 days for the water in the casing to reequilibrate to the cooler groundwater temperatures, 30 ft bgs, after pumping.

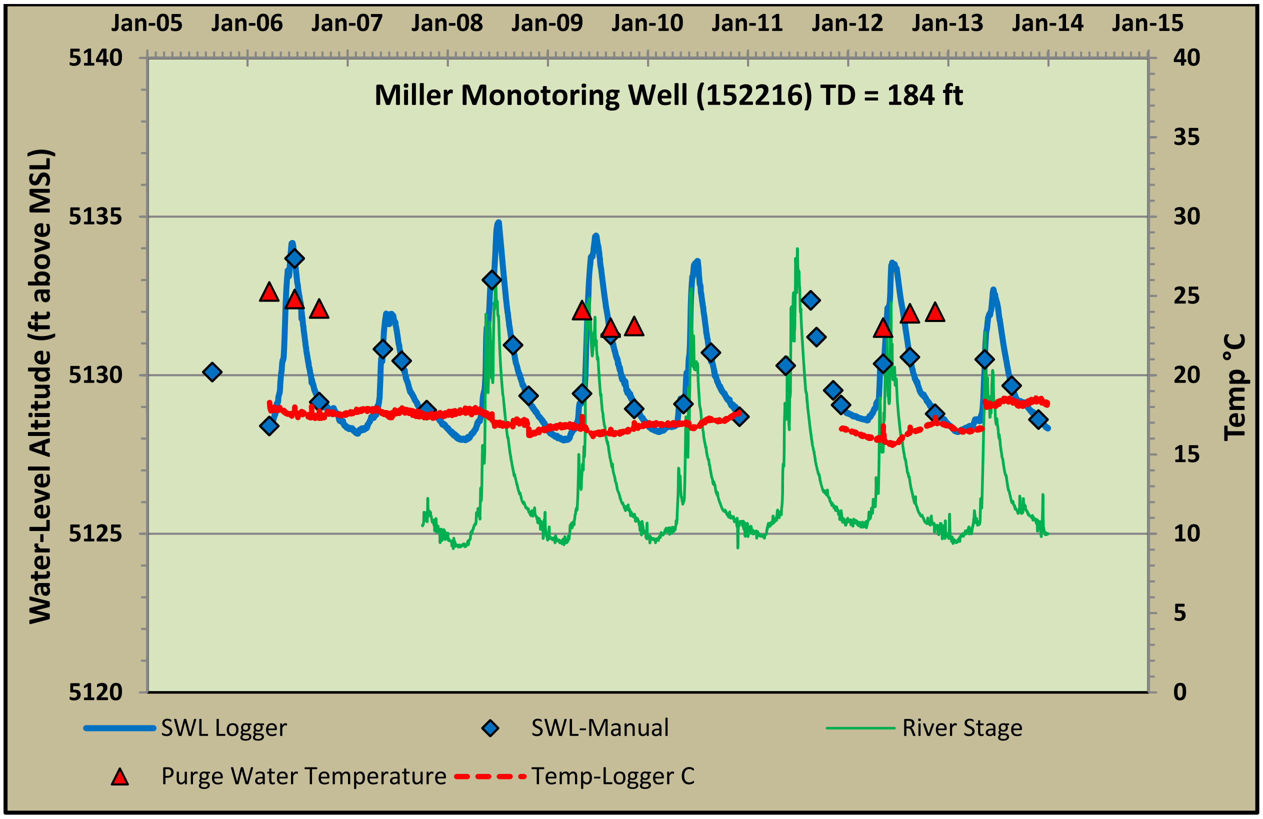

Figure A11. Hydrograph for the Miller well showing daily midnight-hour water levels and water temperatures recorded by the water-level logger, and approximate elevations of the Yellowstone River stage. Manual measurements made during site visits are also shown.

Table A20. Water-Level and Water-Temperature Statistics for the Miller Well

Statistic	Water Level (ft bgs)	Water Temp. (°C-logger)	Comments
Mean	7.9	17.1	✓ Daily midnight-hour readings 3/26/2006 to 12/31/2013) ✓ Temperature measured by water-level logger hanging in well 30 ft bgs and 21–27 ft below the water surface in the well. ✓ Average temperature measured when the well is purged for sampling = 24° C ✓ Well water classified as warm (15°–25° C)
Median	8.5	17.0	
Maximum	9.7	18.6	
Minimum	2.8	15.6	
# Readings	2,470	2,469	

Water-Quality Sampling Summary

A faucet at the wellhead is used to purge and sample the Miller well. The well has been sampled 9 times for major ions and trace metals between 2006 and 2013. This includes sampling for seasonal variation (spring, summer, and fall) in 2006, 2009, and 2012. Average concentrations of select major ions and trace elements are presented in table A21. The well produces a sodium-magnesium/sulfate type water with a basic pH and high concentrations of TDS, sodium, sulfate, arsenic, boron and strontium (table A21). The arsenic concentration exceeds EPA drinking water standards. The water is also very hard, with an average of 474 mg/L as $CaCO_3$. Chloride concentrations are elevated relative to other LTMP sites in the Yellowstone River watershed;

only LaDuke and Bear Creek Hot Springs have higher chloride concentrations. The Miller well was sampled for stable water isotopes (^{18}O and ^{2}H), and the radioactive isotope tritium (^{3}H) in March 2006 and November 2009 (see report, fig. 18, table 6). Both samples showed tritium concentrations below detection at <0.8 TU.

Table A21. Average Concentrations of Select Major Ions and Trace Elements for the Miller Well

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
1551	8.0	61.7	77.6	299	37.5	914	33.8	<0.0	1.1	24.2	512	15.2	1,28	64.3	<0.2

Galloway Well (146967)

Site Description
The Galloway well is located about 7.5 mi northwest of Gardiner, at the northwest end of the Gardiner Basin. Here the Yellowstone River Valley narrows, south of Yankee Jim Canyon. The site is located on the east side of the narrow river valley, and east of Highway 89. Drilled in 1979 for domestic use and irrigation, the well is 200 ft deep and is constructed with 6-in-diameter steel casing. The casing extends to the bottom of the borehole and is not perforated or screened. The well was inventoried by the MBMG in February 1995, first sampled in July 1998, and added to the LTMP network in March 2006.

Hydrogeologic Setting
The Galloway well is situated on the south flank of a Quaternary debris-flow-dominated alluvial fan that emanates from Horseshoe Canyon, to the east. An active ephemeral channel on the fan passes about 175 ft northeast of the Galloway well and, in the summer of 2013, a debris flow from the canyon flowed by the Galloway residence, plugged a culvert under Highway 89, and blocked the highway for a short time. Horseshoe Gulch drains an area northeast of the well that is underlain by volcanic rocks of the Tertiary (Eocene) Absaroka Volcanic Group. Volcanic rocks exposed in the walls of the gulch are mapped as Tertiary felsic pyroclastics (volcanic ash) and andesite epiclastic rocks (Lonn and others, 2007). Archean metamorphic basement rocks or Absaroka Group volcanic rocks probably underlie the alluvial fan, and are mapped in areas surrounding the alluvial fan. The driller's log reports sand and gravel to 204 ft bgs, indicating the Galloway well did not reach bedrock.

Water-Level and Water-Temperature Monitoring Summary
The Galloway well has been monitored since October 2005. A water-level logger is installed in the well and collects hourly water-level and water-temperature data. Manual water-level measurements are made during site visits, and manual temperature measurements are made when the well is purged for sampling. Figure A12 summarizes the water-level and water-temperature data collected, and statistics for the water-level logger data are provided in table A22.

Water levels rise rapidly in late April to early May and usually peak in mid- to late June. An exception is 2011, when the highest peak recorded did not occur until mid-July. Water levels then decline to the lowest levels in late February to mid-March. The magnitude of seasonal water-level fluctuations is 6 to 8 ft.

Annual water-temperature fluctuations at the depth of the logger (130 ft) are less than 2°C. Water temperatures measured during well purging also show less than a 2° fluctuation and are about 1.5° warmer than the logger temperatures (fig. A12, table A22). The logger temperatures do show a low-amplitude pattern that generally follows the water levels with a lag time of a few months: water temperatures usually peak in mid-August to mid-September (fig. A12). Although a few manual water-temperature measurements have been above 15°C, the water is classified as cold (<15°C) based on average temperatures.

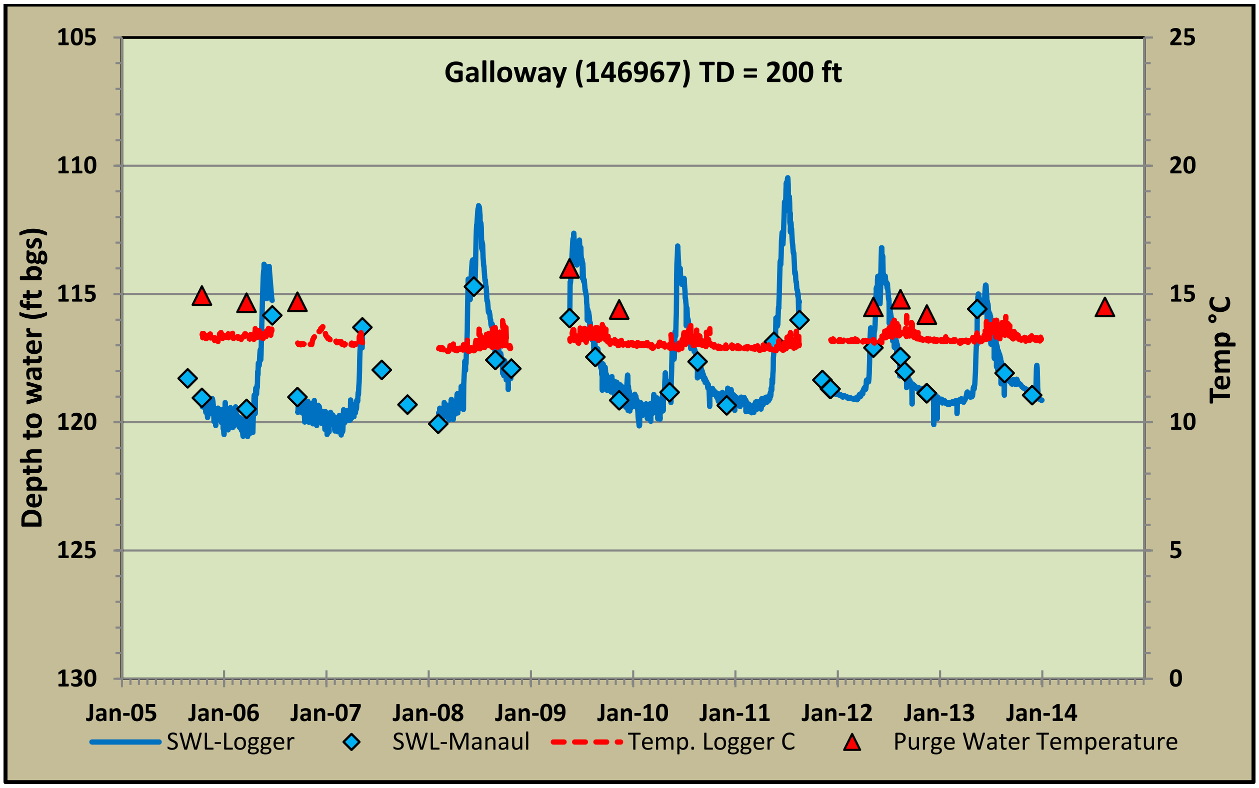

Figure A12. Hydrograph for the Galloway well showing daily midnight-hour water levels and water temperatures recorded by the water-level logger, and manual measurements made during site visits.

Table A22. Daily Water-Level and Water-Temperature Statistics for the Galloway Well

Statistic	Water Level (ft)	Water Temp. (°C-logger)	Comments
Mean	118.0	13.2	✓ Based on daily midnight-hour readings from October 2005 through December 2013 ✓ Temperature measured by logger about 133 ft bgs and 13–23 ft below the water surface ✓ Purge-water temps. 14.2 to 16.0°C, Avg. 14.8 (*n*=8) ✓ Water classified as Cold (<15°C)
Median	118.9	13.2	
Maximum	120.6	14.2	
Minimum	110.5	12.8	
# Readings	2,301	2,299	

Water-Quality Sampling Summary

Water samples are collected from a frost-free hydrant located next to the Galloway well. The well has been sampled 10 times for major ions and trace elements between July 1998 and November 2012. This includes sampling for seasonal variation (spring, summer, and fall) in 2006, 2009, and 2012. Average concentrations of select major ions and trace elements are presented in table A23. The well produces a sodium-calcium/bicarbonate type water with a basic pH and elevated concentrations of sodium, chloride, and boron, in comparison to other LTMP sites in the Yellowstone River watershed (see report, table 5). The water does not exceed any EPA inorganic drinking water standards. The Galloway well was sampled for the stable water isotopes (^{18}O and ^{2}H), and the radioactive isotope tritium (^{3}H) in March 2006 and November 2009 (see report, fig. 18, table 6).

Table A23. Average Concentrations of Select Major Ions and Trace Elements for the Galloway Well

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
629	7.6	69.6	33.9	94.9	29.2	191.	24.1	0.5	0.5	6.0	114.	62.1	943	53.3	14.0

Sirr Spring (171229)

Site Description

Sirr Spring is located about 4 mi northwest of Gardiner, on the northeast side of the Yellowstone River Valley. This undeveloped spring is on private land. Spring discharge forms a small pond that drains into an irrigation ditch that flows along the southwest side of the pond. The spring was first inventoried and sampled by the MBMG in July 1999, and was added to the LTMP network in March 2009.

Hydrogeologic Setting

Sirr Spring surfaces at the base of the same steep southwest-facing slope that Cole and Powell Springs discharge from, and is situated along the northeast side of the same bench that the Cole well is on. Here the bench is also about 500 ft wide and 120 to 140 ft higher in elevation than the river. Surficial geology on the bench surface is mapped as glacial till and the slope northeast of the spring is mapped as Archean granitic rocks (Berg and others, 1999). The spring is either located along the trace of the Gardiner reverse fault, or just southwest of it, on the footwall side (see report, figure 12). However, the underlying bedrock cannot be determined due to the overlying glacial deposits and colluvium. A small debris-flow fan that is not mapped emanates from the steep slope and Sirr Spring appears to discharge from the toe of the fan.

Discharge and Temperature Monitoring Summary

Sirr Spring has been monitored since April 2009. Monitoring discharge and temperature has been difficult due to ponding of the spring water in the discharge area, and interconnection of the spring discharge with the irrigation ditch that flows along the southwest side of the pond. Initial monitoring from April 2009 through May 2012 consisted of manual temperature measurements made where the spring water flows out of the pond and into the irrigation ditch. A flume installed at the outlet of the pond in August 2010 was unsuccessful in capturing all of the flow from the pond. In May 2012 the flume was replaced and a water-level logger was installed in the flume.

There was still some discharge that was not captured by the flume, so in August 2012 more work was completed to seal the perimeter of the pond near the flume. This was successful in capturing as much of the pond discharge as possible. Even with these improvements, problems still occur when the irrigation ditch is full because the ditchwater backs up into the tailwater side of the flume and floods it out.

Discharge and water-temperature data are summarized in figure A13. The flume data collected between August 2010 and August 2012 were deemed unusable due to leakage around the flume. The discharge and temperature data collected from August 2012 through August 2013 show a possible seasonal pattern (fig. A13) but more data is needed to evaluate this pattern. Also, the water-temperature data collected at the outlet of the pond are likely affected by ambient air temperature. More improvements are needed at this site to resolve the problem with the ditchwater backing up into the flume, and to obtain more accurate water-temperature data by installing a temperature logger in the main spring discharge area rather than at the outlet.

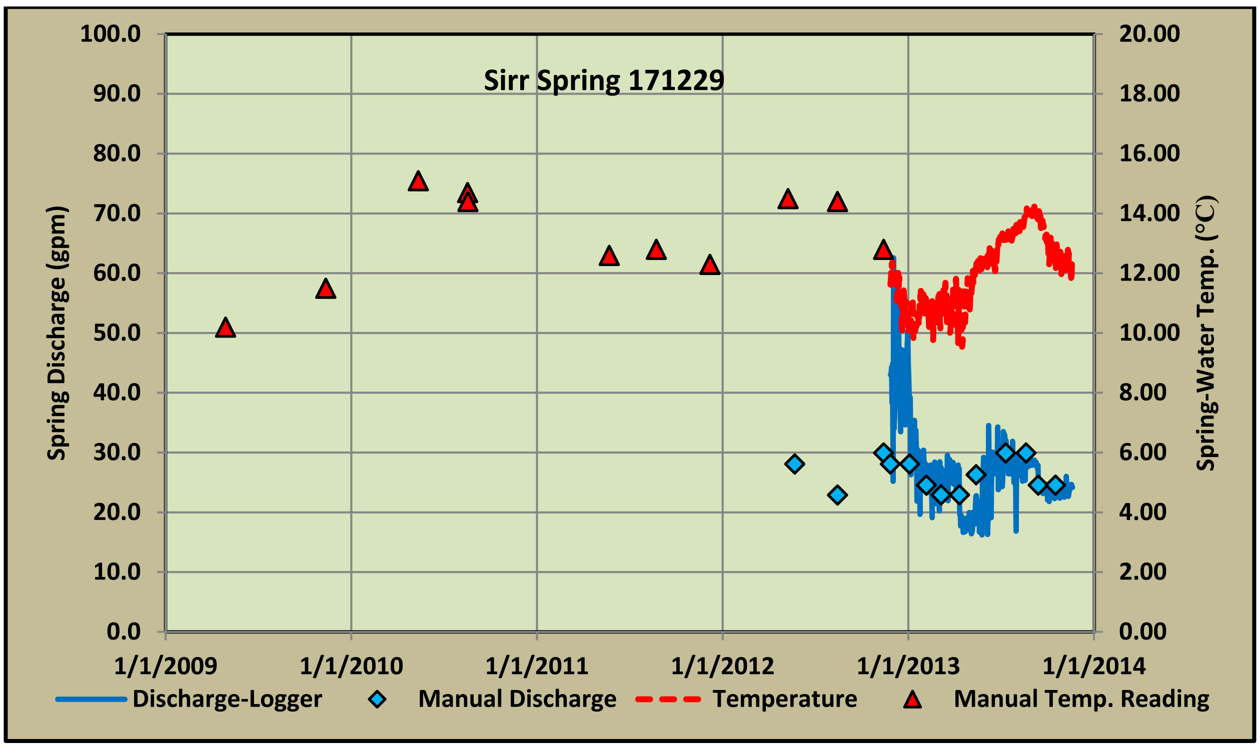

Figure A13. Hydrograph for Sirr Spring showing daily midnight-hour spring discharge and water-temperature data obtained from the water-level logger in the flume, and manual flume readings and temperatures obtained during site visits.

Water-Quality Sampling Summary

Water samples are collected at the flume using a peristaltic pump. Sirr Spring has been sampled 6 times between April 2009 and November 2012. This includes sampling for seasonal variation (spring, summer, and fall) in 2009 and 2012. Average concentrations of select major ions and trace elements are presented in table A24. The spring produces a magnesium/bicarbonate type water; concentrations of calcium, magnesium, and sodium are about the same, but magnesium dominates in terms of mg/L. The spring water is basic, and has low concentrations of chloride, nitrate, and arsenic. Uranium concentrations are elevated and higher than the other Yellowstone River watershed sites, excluding the Cole and Galloway wells (see report, table 5). The water does not exceed any EPA drinking water standards for inorganics. Sirr Spring was sampled for stable water isotopes (^{18}O and ^{2}H), and the radioactive isotope tritium (^{3}H) in November 2009 (see report, fig. 18, table 6).

Table A24. Average Concentrations of Select Major Ions and Trace Elements for Sirr Spring

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
316	8.0	35.9	34.0	31.5	14.6	34.3	5.4	0.2	0.3	2.1	33.9	53.6	542	38.8	12.7

Bear Creek Hot Spring (197921)

Site Description

Bear Creek Hot Spring is located about 1.75 mi east of Gardiner. The spring is situated along the west bank of Bear Creek, about 900 ft upstream of the confluence with the Yellowstone River, and about 6 ft above Bear Creek. Access to the site is by foot, using a trail that descends down to the spring from the Eagle Creek Campground area along the Jardine Road. The monitored spring site is one of several springs and seeps that discharge within an area covering almost 8 acres, delineated by travertine deposits. It was inventoried in September 2002, was added to the LTMP in July 2009, and first sampled in May 2010.

Hydrogeologic Setting

The extensive travertine deposits at Bear Creek Hot Spring form a large mound that covers the bedrock at the monitored site. The monitored spring is one of the largest and most localized modern discharge points, but the travertine deposits indicate that spring discharge was probably much higher in the geologic past. Geologic mapping by Fraser and others (1969), at a scale of 1:62,500, shows the Gardiner reverse fault passing directly through the travertine deposits. The fault places Archean metamorphic basement rocks in direct contact with Madison Group limestone. A vertical cliff along the west bank of Bear Creek, at the monitoring site, exposes sheared basement rocks, and the Madison Limestone crops out on the hillside west and north of the travertine mound. Based on the geologic mapping and exposed bedrock in the area, the spring appears to discharge directly from the Gardiner fault.

Discharge and Water-Temperature Monitoring Summary

Bear Creek Hot Spring has been monitored since July 2009. A water-temperature logger installed in the spring discharge collects hourly data. A flume was installed in June 2012 to capture and measure the spring discharge. A cement dam was installed around the spring discharge area to direct the flow through the flume. The cement dam and flume form a small (2-ft diameter) pool. Some leakage occurred after installation of the flume, and in August 2012 the cement seal was improved to stop the leakage. This repair held until early 2013 when leakage occurred again. In June 2013 the cement dam was increased in height and thickness and all of the flow was again captured. Manual discharge measurements from the flume are obtained during site visits and manual temperature measurements are obtained when the spring is sampled. Figure A14 summarizes the water-temperature and discharge data collected, and statistics for the water-temperature logger data are provided in table A25.

Water temperatures have varied by less than 2°C. The temperature logger data appear to show a seasonal pattern with peak temperatures in July and August, and lows in February and March. However, because of equipment malfunctions, temperature data are missing from December 2010 through August 2012. Discharge data are limited and flume measurements prior to June 2013 did not capture all of the spring flow. The discharge data collected since June 2013 are considered the most reliable, but a longer period of record is needed to evaluate discharge patterns.

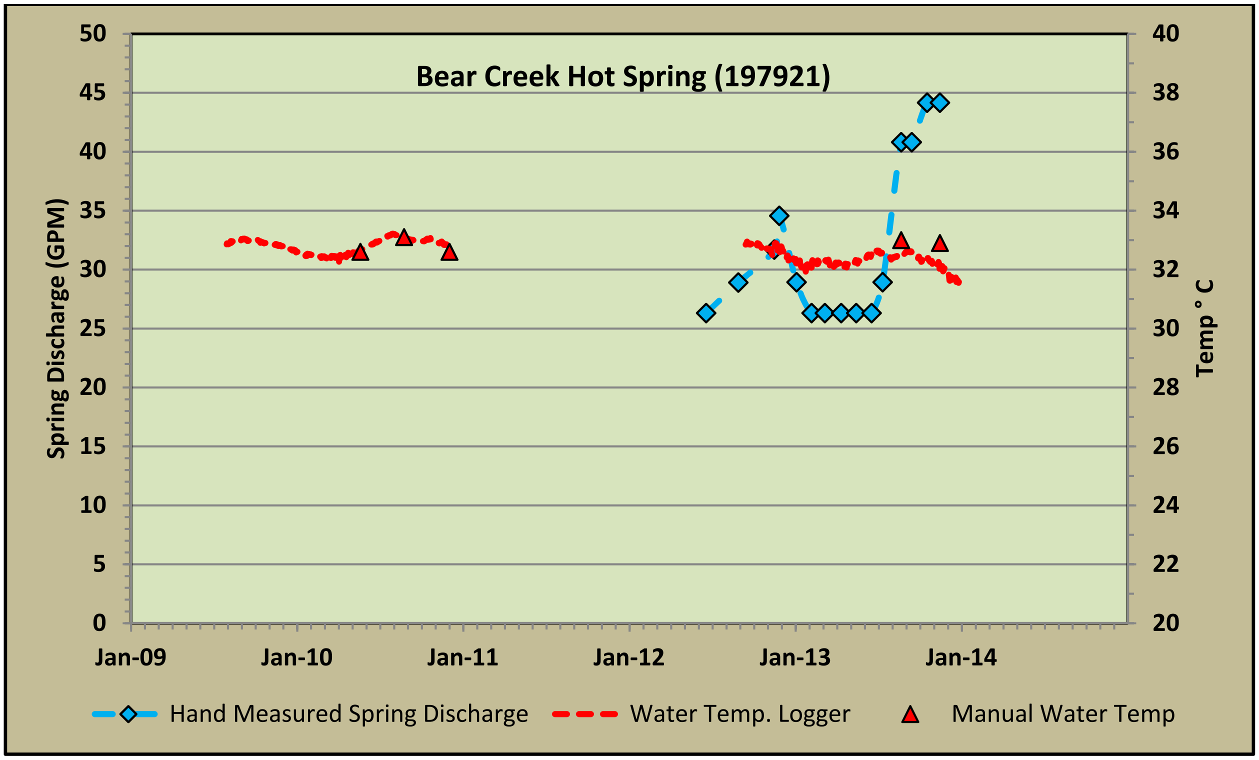

Figure A14. Hydrograph for Bear Creek Hot Spring showing daily midnight-hour water temperatures and manual discharge and water-temperature measurements obtained during site visits.

Table A25. Water-Temperature Statistics for Bear Creek Hot Spring

Statistic	Water Temp. Logger (°C)	Comments
Mean	32.6	✓ Based on daily midnight-hour readings from July 2009 through December 2013 ✓ Temperature measured by logger in bottom of spring pool ✓ Manual Water Temp. 32.6 to 33.1°C, Avg. 32.8 (*n*=5) ✓ Water classified as Hot (>25°C)
Median	32.6	
Maximum	33.2	
Minimum	31.5	
# Readings	950	

Water-Quality Sampling Summary

Water samples are collected from the small pool at the spring using a peristaltic pump. The spring has been sampled seven times for major ions and trace elements between September 2002 and December 2013. This includes sampling for seasonal variation (spring, summer, and fall) in 2010 and 2013. Average concentrations of select major ions and trace elements are presented in table A26. The spring produces a highly mineralized calcium/bicarbonate-sulfate type water with a slightly acidic pH. Calcium, magnesium, arsenic, boron, and lithium concentrations are the highest of any of the LTMP sites in the YCGA.

Table A26. Average Concentrations of Select Major Ions and Trace Elements for Bear Creek

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
2091	6.5	445.	84.6	109.	29.3	777.	37.9	<0.0	2.6	50.5	991.	23.1	3,16	344.	<1.0

The spring was sampled for stable water isotopes (^{18}O and ^{2}H) in May, August, and November 2013. The November sampling event also included sampling for tritium (^{3}H) (see report, fig. 18, table 6 for isotope data)

GALLATIN RIVER WATERSHED MONITORING SITES

Anceny Spring (258715) and Anceny Spring Creek (304093)

Spring Description

Anceny Spring is located on private land 0.5 mi northeast of the intersection of Highway 191 and the Big Sky Spur Road. The spring is situated along the southeastern edge of Gallatin Canyon and discharges from the mouth of a gully at the edge of the canyon floor. Spring water discharges from multiple locations adjacent to and within a small pond and wetland. Anceny Spring Creek drains the pond area, flows north through a wet meadow to another larger pond, and then into the Gallatin River. Some of the spring water is used for pasture irrigation. The spring was first inventoried and sampled by the MBMG, and added to the LTMP network, in October 2010.

Hydrogeologic Setting

Anceny Spring surfaces just southwest of the Spanish Peaks thrust fault (fig. A15). Based on review of aerial photographs and 1:100,000-scale geologic mapping by Kellogg and Williams (2005), Anceny Spring appears to surface from the contact area between steeply southwest-dipping Madison Group (undivided) carbonates and the Three Forks and Jefferson Formations (undivided) on the footwall side of the Spanish Peaks thrust fault.

Spring Discharge and Water-Temperature Monitoring Summary

Anceny Spring has been monitored since October 2010. Because the spring discharges from multiple locations in and around the pond, there is no practical way to measure discharge at the spring. Instead, discharge measurements are obtained from the Anceny Spring Creek site (304039), located about 600 ft downstream of the spring. Manual discharge measurements have been made during site visits using a Marsh-McBirney® flowmeter. In June 2012 a staff gage and stilling well was installed at Anceny Spring Creek, and a water-level logger was installed in the stilling well to obtain hourly stage data. However, as of December 2013 a rating curve had not yet been developed to convert the stage data to discharge. Figure A15 summarizes the discharge and water temperature data collected, and statistics for the temperature data are provided in table A27.

The limited periodic discharge measurements appear to show a seasonal variation of 300–400 gpm, with peak flows in August, and an overall decline during the period of record. Water temperature has been monitored hourly since September 2011 using a temperature logger. The first temperature logger had a lower resolution and was replaced in November 2012. The logger was initially installed in the pond close to the main discharge point, but in August 2013 it was moved into the main discharge at the head of the spring to try and avoid solar radiation. Overall, the water temperature is very stable and has varied by less than 1°C during the period of record.

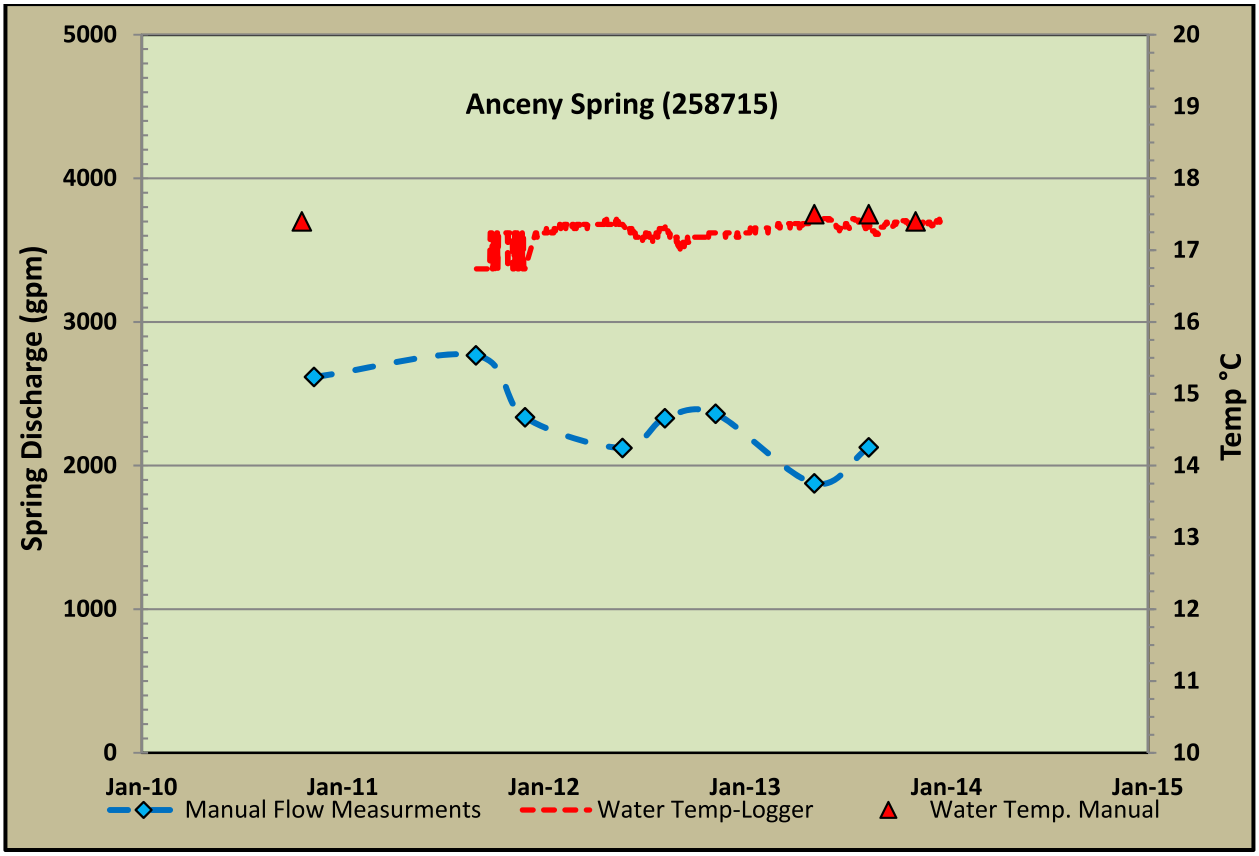

Figure A15. Hydrograph for Anceny Spring showing midnight-hour water temperatures recorded by the temperature logger, and manual flow and discharge measurements made during site visits.

Table A27. Water-Temperature Logger Statistics for Anceny Spring

Water Temp. Statistics	Water Temp. (°C-logger)	Comments
Mean	17.3	✓ Based on daily midnight-hour temperatures from September 2011 through December 2013 ✓ Temperature measured by temperature logger installed in a discharge area at the head of the spring. ✓ Spring water classified as Warm (15–25°C)
Median	17.3	
Maximum	17.5	
Minimum	16.7	
# Readings	816	

Water-Quality Sampling Summary

Water samples are collected from the main discharge at the head of the spring using a peristaltic pump. The spring has been sampled 4 times for major ions and trace metals between October 2010 and November 2013. This includes sampling for seasonal variation (spring, summer, and fall) in 2013. Average concentrations of select major ions and trace elements are presented in table A28. The spring discharges a calcium-magnesium/bicarbonate-sulfate type water with a slightly basic pH, and low concentrations of sodium, chloride, nitrate, and arsenic. Sulfate and strontium concentrations are somewhat elevated, but the water does not exceed any EPA drinking water standards for inorganics. The spring has been sampled twice for the stable isotopes of oxygen (^{18}O) and deuterium (^{2}H), but not for radioactive isotope tritium (^{3}H) (see report, fig. 27 and table 8).

Table A28. Average Concentrations of Select Major Ions and Trace Elements for Anceny Spring

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
298	7.5	57.8	23.2	5.4	8.6	110.	2.0	0.1	0.6	1.2	17.6	27.3	428	7.7	<1.0

Snowflake Springs and Spring Creek (171216)

Spring Description

Snowflake Springs is located 14 mi southeast of Big Sky on the west side of Highway 191 and the Gallatin River, and 1.2 mi south of the intersection with the Taylor Fork Road. The undeveloped spring is on U.S. Forest Service land, but the Elkhorn Ranch, which owns land adjacent to the spring to the north, diverts some spring water for pasture irrigation using irrigation pipe to capture the water. This spring was first inventoried and sampled by the MBMG in July 1999 and added to the LTMP network in August 2011.

Hydrogeologic Setting

Numerous springs and seeps surface within a 1.5-acre area near the base of a north-facing mountain slope, formed where the Gallatin River has cut through a north–south-trending ridge. The ridge extends southward from the springs and forms the eastern boundary of the discharge area. The springs surface 10 to 75 ft above river level, and 180 to 450 ft south of the river. The discharge collects at the base of the slope and forms a spring creek that flows northward for about 1,200 ft, parallel to and then into the river. The largest and highest discharge point, used as the LTMP monitoring site, is located near the west edge of the discharge area. Multiple anastomosing channels flowing down the slope have formed a fan-shaped travertine deposit.

Based on 1:100,000-scale geologic mapping by Kellogg and Williams (2006), Snowflake Springs discharge from Madison Group limestone in the hanging wall of a north–south-trending thrust fault. The thrust fault places Paleozoic rocks over Mesozoic rocks. The Paleozoic rocks in the hanging wall are near vertical to overturned and include the Madison Group and the Quadrant and Amsden Formations undivided. The ridge along the east side of the spring area is thought to be held up by the Quadrant Formation, and the thrust fault is mapped along the base of the ridge on the east side. The formations on the footwall side of the thrust fault are also near vertical and include the Triasic Dinwoody and Woodside Formations and the Jurassic Morrison Formation.

Spring Discharge and Water-Temperature Monitoring Summary

There is no practical way to measure the discharge of all the individual springs and seeps at this site. MBMG hydrologists have gaged the Gallatin River above and below the spring area to measure the discharge of the springs, but inherent errors in these measurements were too large to obtain an accurate discharge from the springs. Discharge has been monitored each time the site is visited by gaging the spring creek formed by the spring flows at a location 900 ft northwest of the springs. Water temperature at Snowflake Springs has been continuously monitored since September 2011. Manual temperature measurements have been made when water-quality samples are collected. All temperature data are collected from the main discharge at the head of the spring area. Figure A16 summarizes the discharge and water-temperature data collected, and statistics for the temperature logger data are provide in table A29.

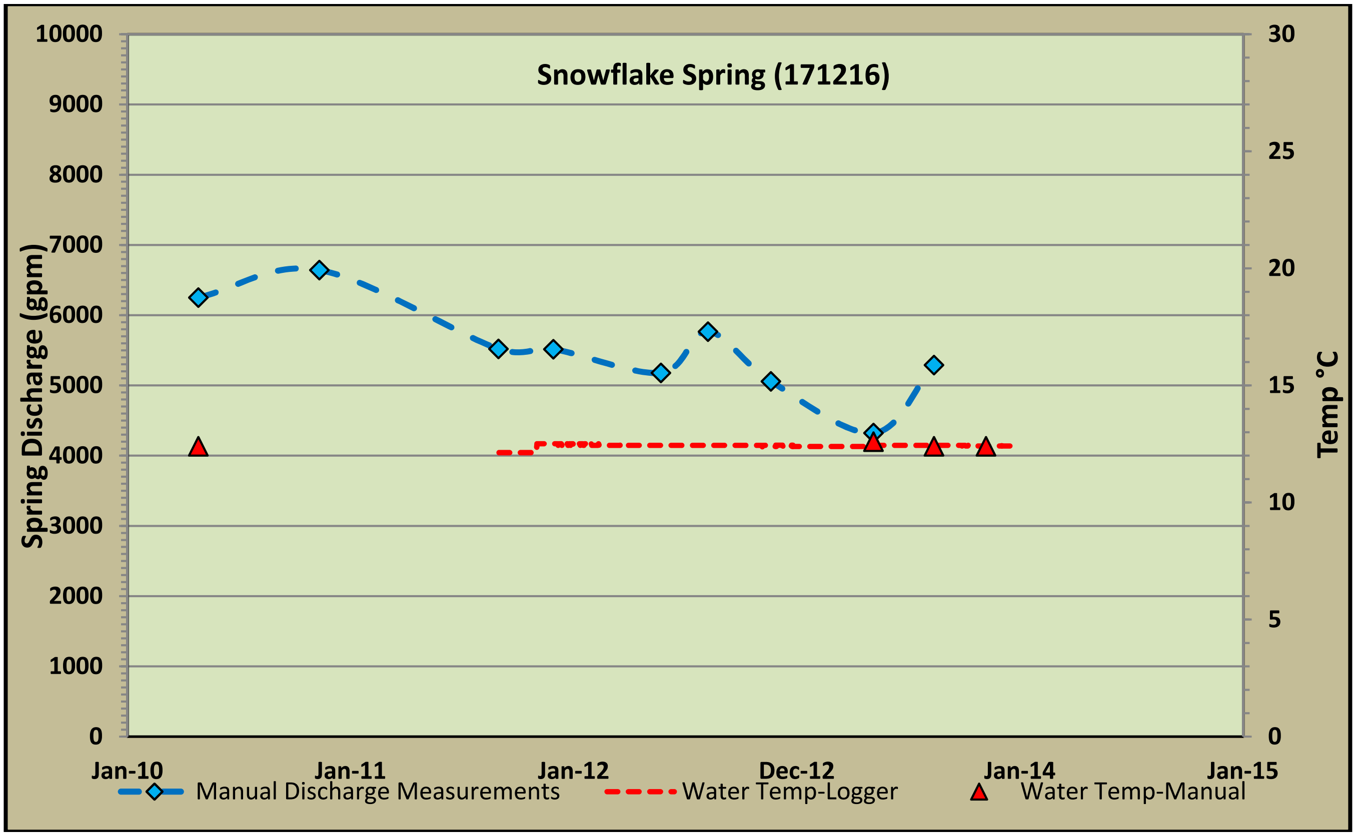

Figure A16. Hydrograph for Snowflake Springs showing midnight-hour water temperatures recorded by the temperature logger, and manual flow and discharge measurements made during site visits.

Table A29. Water-Temperature Logger Statistics for Snowflake Spring

Statistics	Water Temp. (°C-logger)	Comments
Mean	12.4	✓ Based on daily midnight-hour readings from September 2011 through December 2013 ✓ Temperature measured by water-level logger installed at the head of the main spring discharge at the top of the discharge area ✓ Manual temperature readings have ranged from 12.3 to 12.6 and average 12.4 (*n*=5) ✓ Spring water classified as Cold (<15°C)
Median	12.4	
Maximum	12.5	
Minimum	12.1	
# Readings	844	

Water-Quality Sampling Summary

Water quality samples are collected from the head of the spring using a peristaltic pump. The spring was sampled 5 times for major ions and trace elements between July 1999 and November 2013. This includes sampling for seasonal variation (spring, summer, and fall) in 2013. Average concentrations of select major ions and trace elements are presented in table A30. The spring produces a calcium-magnesium/bicarbonate-sulfate type water, similar to Anceny Spring, with a slightly basic pH, and low concentrations of sodium, chloride, nitrate, and arsenic. Sulfate and strontium concentrations are somewhat elevated, but the water does not exceed any EPA drinking water standards for inorganics. The spring was sampled for the stable water isotopes (^{18}O and ^{2}H) and the radioactive isotope tritium (^{3}H) in April 2010 (see report, fig. 27, table 8).

Table A30. Average Concentrations of Select Major Ions and Trace Elements for Snowflake Spring

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
299	7.6	64.1	21.7	1.5	8.3	121.	0.8	0.1	0.6	2.9	8.2	33.8	333	11.7	<1.0

Altman Well (215333)

Site Description

The Altman well is located about 10 mi south of the Big Sky area in the Gallatin River canyon. The well is just off the east side of Highway 191, and west of the Gallatin River. The well was drilled in 2004 for a new home site, but as of the end of 2013 the well has not been used and there is no pump installed in the well.

The borehole was drilled to 520 ft, and the well was cased and completed at 470 ft. The well is completed with 4.5-in PVC casing from 10 to 470 ft and the casing is perforated from 430 to 470 ft. The driller’s log reports yellow-brown dolomite with poor to no circulation and lots of dolomite crystals from 448 to 520 ft.

Hydrogeologic Setting

The 1:100,000-scale geologic map by Kellogg and Williams (2006) shows alluvium covering Paleozoic formations at the site. The contact between the Madison Group limestone and the underlying Three Forks and Jefferson Formations (undivided) is mapped just north of the site and the well appears to be completed in the Jefferson Formation based on review of the driller’s log and the thickness of the Three Forks and Jefferson Formations (Kellogg and Williams, 2006). More detailed geologic evaluation is need to determine what formation the well is completed in, and it may be completed in the deeper Red Lion or Pilgrim Formations. The Gallatin River is about 120 ft east of the well.

Water-Level and Water-Temperature Monitoring Summary

The Altman well has been monitored since July 2010. Water levels are generally over 350 ft bgs, even though the well is only 120 ft west of the Gallatin River. Water levels have been manually measured using either a sonic water-level sounder or an E-Tape sounder. We plan to install a water-level logger in the well in 2014. Figure A17 summarizes the manual water-level data obtained through December 2013. No water-temperature data have been collected.

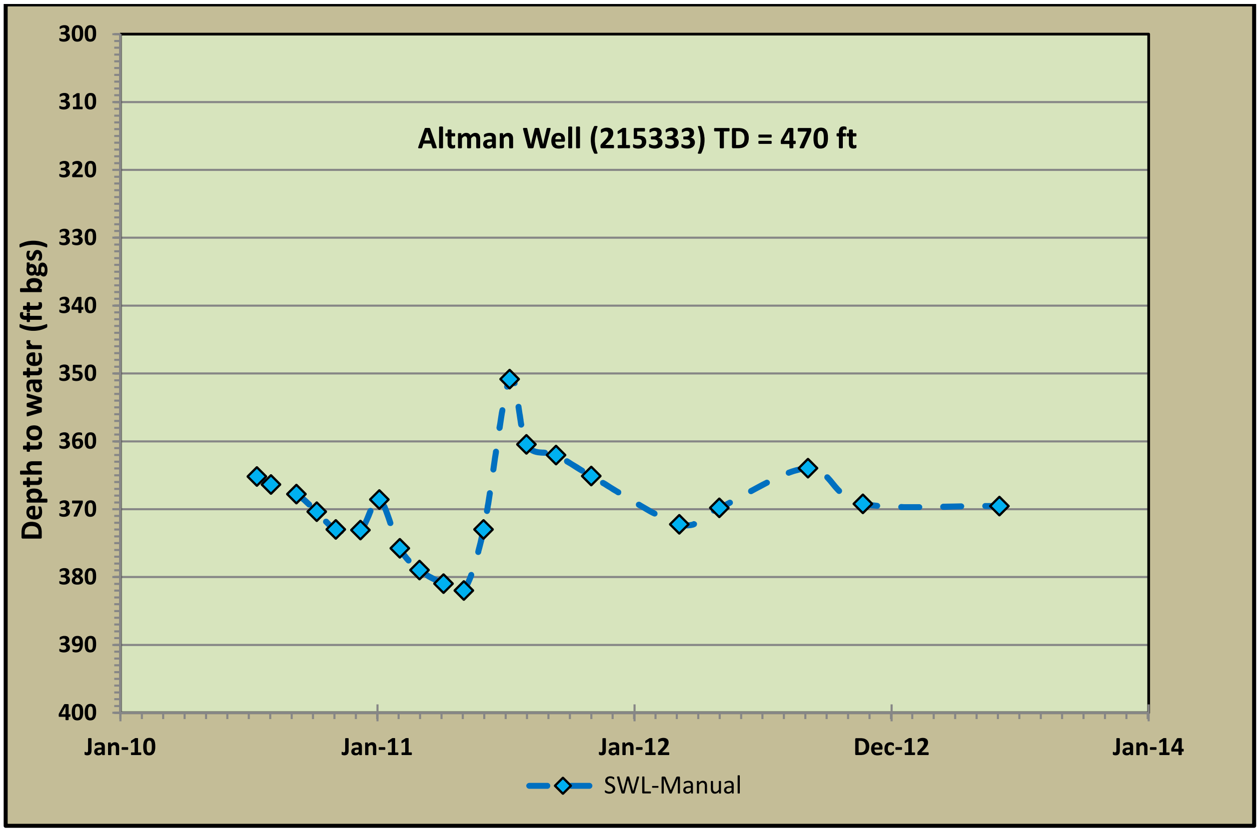

Figure A17. Hydrograph for the Altman well showing manual water levels obtained through December 2013.

Water-Quality Sampling Summary

The Altman well has not been sampled because the depth to water exceeds the pumping capacity of any portable pumps that MBMG has. Plans are to collect water-quality samples once the owner installs a pump in the well.

MADISON RIVER WATERSHED MONITORING SITES

Bakers Hole Campground North Well (8943)

Site Description
The Bakers Hole Campground is located 3.3 mi north of West Yellowstone, on the east side of Highway 191. The U.S. Forest Service owns the campground and operates this well as a public water supply for the campground (MT PWS#62308002). Drilled in 1964, it is a shallow (58 ft) flowing artesian well that was first visited and sampled by the MBMG in 1979 as part of a project to assess geothermal resources throughout Montana. It was inventoried and sampled again by the MBMG in July 1996, and added to the LTMP network in May 2007. The wellhead is located inside a concrete well house at the north end of the campground.

Hydrogeologic Setting
Bakers Hole Campground is situated adjacent to the Madison River on a broad, flat plain near the center of the Madison Valley, southeast of Hebgen Lake (fig. 29). The surficial geology, mapped as glacial outwash by O'Neill and Christiansen (2002), is commonly referred to as the obsidian sand plain due to the predominance of this material in the outwash deposits (fig. 31). At the well site, the glacial outwash consists of stratified, moderately well sorted, fine to coarse gray sand. The Madison River incises the sand plain and actively reworks and erodes the outwash material. In the Bakers Hole area, the river forms a meander corridor up to several thousand feet wide. The well is located about 100 ft west of the Madison River along the outside bank of a large meander. The river incises the bank in the campground area.

The well log reports lithology of fine to coarse obsidian sand to 50 ft and notes a trace of water from 12 to 50 ft bgs. A yellow clay layer extends from 50 to 54.5 ft bgs, and is underlain by a 2-ft layer of "very loose sands" followed by 2.5 ft of coarser sand. The well was completed in the lower coarse sand. Information from the well log suggests the well is completed in a shallow confined aquifer in the glacial outwash deposits. The flowing artesian conditions could also be due to a combination of thin, discontinuous confining clay layers and a strong upward vertical gradient in the outwash deposits. The well water is warm, which suggests either a relatively deep flow path, or mixing with thermal groundwater. When the well was investigated by the MBMG in 1979, a reservoir temperature of 45°C was calculated for the well, water based on the major ion chemistry (Sonderegger and others, 1981).

Discharge and Water-Temperature Monitoring Summary
The well discharges year round to the Madison River. A buried discharge line extends from the well house towards the Madison River and daylights about 30 ft east of the well house. An in-line flowmeter has been installed where the discharge pipe is exposed, housed in a plastic landscape irrigation box. A data logger is installed on the flowmeter to obtain continuous flow data but has had maintenance issues. A second irrigation box installed next to the flowmeter houses a water-temperature logger. Water exiting the discharge line runs into a small channel and flows to the river.

The Bakers Hole North well has been monitored since May 2007. Figure A18 summarizes the flow and temperature data collected through December 2013. Manual flow measurements are made during site visits using the in-line flowmeter and a stop watch. Hourly water-temperature readings are taken by the temperature logger, and manual temperature measurements are made when water-quality samples are collected. Flow measurements have varied from 30 to 38 gpm, and water temperatures fluctuate less than 2°C. The temperature logger data in figure A18 are based on daily midnight-hour readings, to minimize fluctuations caused by ground heating around the discharge pipe. Statistics for the temperature logger data are provided in table A31. Flow measurements taken during the summer season may be altered by campground water use at the time of measurement.

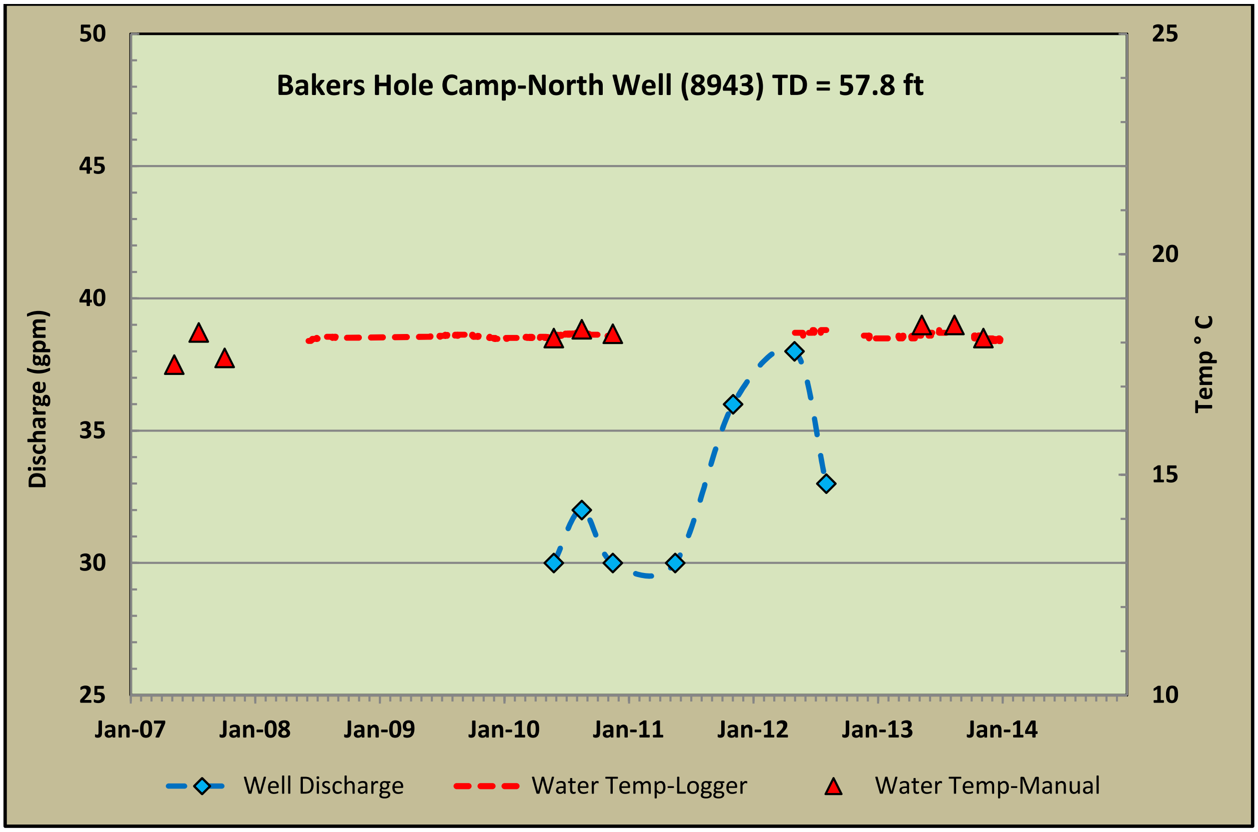

Figure A18. Hydrograph for the Bakers Hole Campground North well showing daily midnight-hour water-temperature readings and manual water-temperature and flow measurements made during site visits.

Table A31. Daily Water-Temperature Statistics for Bakers Hole Campground North Well

Water Temp. Statistics	Water Temp. (°C-logger)	Comments
Mean	18.1	✓ Based on daily midnight-hour readings from June 2008 through December 2013 ✓ Temperature measured in discharge line about 30 ft east of the well, buried at shallow depth. ✓ Manual temperature measurements have ranged from 17.5 to 18.4°C and average 18.1°C (*n*=9) ✓ Well water classified as warm (15–25°C)
Median	18.1	
Maximum	18.3	
Minimum	18.0	
# Readings	1,181	

Water-Quality Sampling Summary

Water samples are collected from the discharge line at the flowmeter using a peristaltic pump. The well has been sampled 11 times for major ions and trace elements between August 1979 and December 2013. This includes sampling for seasonal variation (spring, summer, and fall) in 2007, 2010, and 2013. Average concentrations of select major ions and trace elements are presented in table A32.

The well produces a sodium/bicarbonate type water with a slightly acidic pH, and elevated concentrations of sodium, silica, fluoride, arsenic and lithium. Nitrate and sulfate concentrations are low. The water exceeds EPA drinking water standards for fluoride and arsenic; fluoride concentrations have exceeded 5 mg/L in 3 of the 11 samples collected. Compared to other LTMP sites in the area, the water has notably low concentrations of calcium and strontium, suggesting the groundwater has not interacted with carbonate rocks. Due to low levels of calcium and magnesium, the water is soft, with an average hardness of 63 mg/L (as $CaCO^3$). Overall the water chemistry is interpreted as being reflective of interaction with siliceous volcanic rocks. The well has been sampled four times for stable water isotopes (^{18}O and ^{2}H) and once for tritium (^{3}H). The isotope data are summarized in figure 37 and table 10 of the report.

Table A32. Average Concentrations of Select Major Ions and Trace Elements for North Well

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
306	6.9	12.8	7.6	67.1	75.2	8.4	12.9	<0.1	4.4	27.1	112.	5.1	27.7	157	1.2

Bakers Hole Campground South Well (106775)

Site Description

The Bakers Hole Campground south well, located 3 mi north of West Yellowstone, is about 1,400 ft south of the Bakers Hole Campground north well (8943), near the south end of the campground. Owned by the U.S. Forest Service, it serves as a backup public water supply well for the Bakers Hole Campground. There is no known driller’s log for the well, but a Declaration of Vested Water Right filed on the well in 1963 by the U.S. Forest Service reports an estimated drilling date in 1948, though there are no well construction or lithology records. A 6-in-diameter steel surface casing extends above a concrete pad around the wellhead. Like the north well, this is a flowing artesian well that discharges continuously into the Madison River. It was first inventoried by the MBMG in August 1996, first sampled in June 1998, and added to the LTMP network in November 2006.

Hydrogeologic Setting

Located about 75 ft west of the Madison River, the hydrogeologic setting for this well is likely the same as that for the north well. Discharge from this well is less than the Bakers Hole Campground north well (8934), which may indicate completion at a shallower depth or lower hydraulic conductivity aquifer sediment. However, the well condition is unknown and the lower flow rate could be related to well casing or piping issues.

Discharge and Water-Temperature Monitoring Summary

This well discharges yearround to the Madison River. A flowmeter and a temperature logger are installed on the discharge line between the well and the river. The discharge pipe consists of 1.5-in plastic pipe that is exposed along the river bank. A valve at the wellhead allows the well to be shut-in for periodic pressure measurements. Like the campground north well, attempts to continuously monitor flow with a data logger on the flowmeter have not been successful. Site visits included both manual measurement of flow with the flowmeter and reading shut-in pressure using a digital pressure gage. Flow measured since May 2010, summarized in figure A19, varied from 16.5 to 17.5 gpm.

The water temperature at the south well has been continuously monitored since November 2006 at hourly intervals, using a temperature logger installed on the discharge line. Data summarized in figure A19 are based on midnight-hour reading to minimize effects of ground heating around the shallow discharge pipe. The variation in water temperature exceeds that at the north well, possibly due to the lower discharge rate, that allows more heating and cooling by the ground surface. Water temperatures appear slightly higher in warmer months with cooling in winter months.

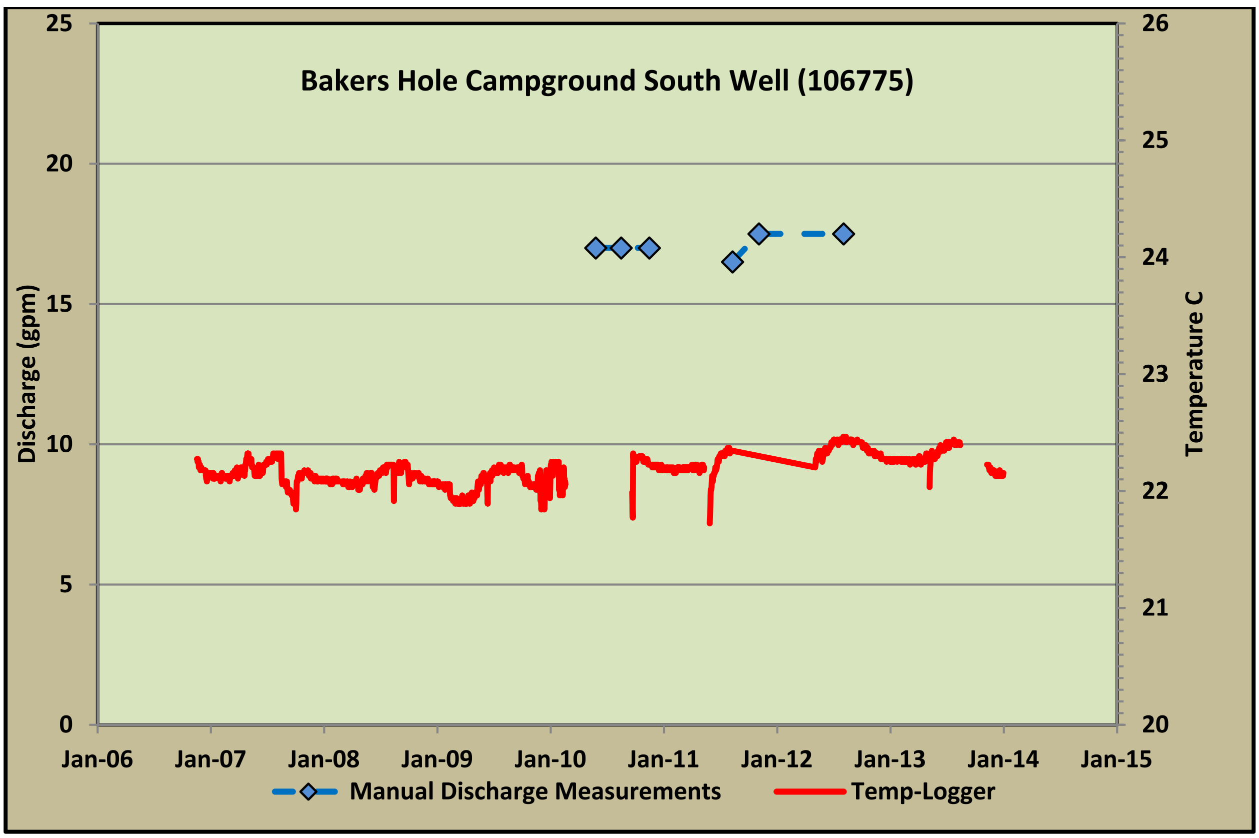

Figure A19. Hydrograph for the Bakers Hole Campground South well showing daily midnight-hour water-temperatures and manual flow measurements made during site visits.

Table A33. Water-Temperature Statistics for Bakers Hole Campground South Well

Water Temp. Statistics	Water Temp. (°C-logger)	Comments
Mean	22.2	✓ Based on daily midnight-hour readings from November 2006 through December 2013 ✓ Temperature measured by logger installed in discharge line at flowmeter. ✓ Well water classified as warm (15–25°C)
Median	22.2	
Maximum	22.5	
Minimum	21.7	
# Readings	1,999	

Water-Quality Sampling Summary

Samples are collected from a faucet at the wellhead. The Bakers Hole Campground south well has been sampled 11 times for major ions and trace elements between June 1998 and December 2013. This includes sampling for seasonal variation (spring, summer, and fall) in 2007, 2010, and 2013. Average concentrations of select major ions and trace elements are presented in table A34.

The well produces water that is very similar to the Bakers Hole Campground north well (8943), with the exception of strontium, which is about double the average concentration of the north well (see report, table 9). Like the north well, the water is a sodium/bicarbonate type water with a slightly acidic pH, and elevated concentrations of sodium, silica, fluoride, arsenic, and lithium. Nitrate and sulfate concentrations are low. The water exceeds EPA drinking water standards for fluoride and arsenic; fluoride concentrations have exceeded 5 mg/L in 3 of the 11 samples collected. Compared to other LTMP sites in the area, the water has notably low concentrations of calcium and strontium, suggesting the groundwater has not interacted with carbonate rocks. Due to low levels of calcium and magnesium the water is soft, with an average hardness of 33 mg/L (as $CaCO^3$). Overall the water chemistry is interpreted as being reflective of interaction with siliceous volcanic rocks.

Table A34. Average Concentrations of Select Major Ions and Trace Elements for South Well

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
248	6.9	6.2	4.2	53.8	81.7	7.6	10.5	0.1	4.7	27.8	92.8	5.3	11.7	159	<1.0

A radon sample collected in August 1998 had a concentration of 280 pCi/L (Rn222). The well has been sampled 4 times for stable water isotopes (^{18}O and ^{2}H) between October 2007 and December 2013. The October 2007 sampling also included the radioactive isotope tritium (^{3}H), which showed a tritium concentration of 6.2 TU (see report, fig.37 and table 10 for isotope data).

Keland Well (106778)

Site Description

The Keland well, located 3.5 mi north of West Yellowstone, Montana, is situated about 700 ft east of Highway 191 and about 700 ft north of the Bakers Hole Campground north well (8943). Like the campground wells, it is a flowing artesian well. The well, drilled in 1954, is 48 ft deep and provides water for a cabin. The cabin and well are privately owned but the land is leased from the U.S. Forest Service. The well is located in a pit under the cabin and the wellhead is not accessible. It was first visited by MBMG in 1979 as part of a project assessing geothermal resources throughout Montana. In June 1998 MBMG inventoried and sampled the well, and it was added to the LTMP network in November 2006.

Hydrogeologic Setting

The Keland well is about 100 ft west of a slough formed by an abandoned meander channel of the Madison River. There is another flowing well 350 ft south of the Keland well that serves the adjacent “Surfing Buffalo” cabin. The Keland well driller’s log reports sand from 0 to 42 ft bgs with a clay layer extending from 42 to 48 ft bgs. Based on the shallow well depth, and well logs for other flowing wells in the Bakers Hole area, the Keland well likely completed in a shallow confined aquifer within the glacial outwash that is capped by a clay layer.

Discharge and Water-Temperature Monitoring Summary

The Keland well has been monitored since November 2006. An in-line flowmeter and a temperature logger are installed on the discharge line between the cabin and the Madison River. During site visits manual discharge readings are taken using the flowmeter and a stop watch, and the flowmeter accuracy is checked by measuring the flow at the end of the discharge line using a bucket and stop watch. Figure A20 summarizes the discharge and water-temperature data collected from the well. Daily midnight-hour temperature data were used to minimize noise in the temperature data caused by heating or cooling of the ground surface around the discharge line. Statistics for the daily temperature data are presented in table A35.

The artesian flow at this well site is the lowest of any of the flowing wells in the Bakers Hole area, with measured discharges ranging from 1.5 to 1.6 gpm This flow seems low considering that the shut-in pressure reported by the driller in 1954 was 15 psi (34.6 ft of water). For comparison, the flowing well at the cabin to the south is only 8 ft deeper, but flows at about 50 gpm. The reason for the low flow at the Keland well has not been determined, but could be due to some restriction or valve in the discharge line or at the wellhead. The flow measurement data are limited and more data are needed in order to determine if there is a seasonal pattern to the discharge.

The temperature data obtained from the well show a seasonal pattern, which is attributed to heating and cooling of the well water in the discharge line, which is buried just below the surface. Observations at site visits indicate that with a thin snow cover, the heat from the buried discharge line melts the snow along the trace of the line. The bottom hole water temperature cannot be obtained in this well, but it is likely that the bottom hole water temperature is several degrees warmer than the measured water temperature.

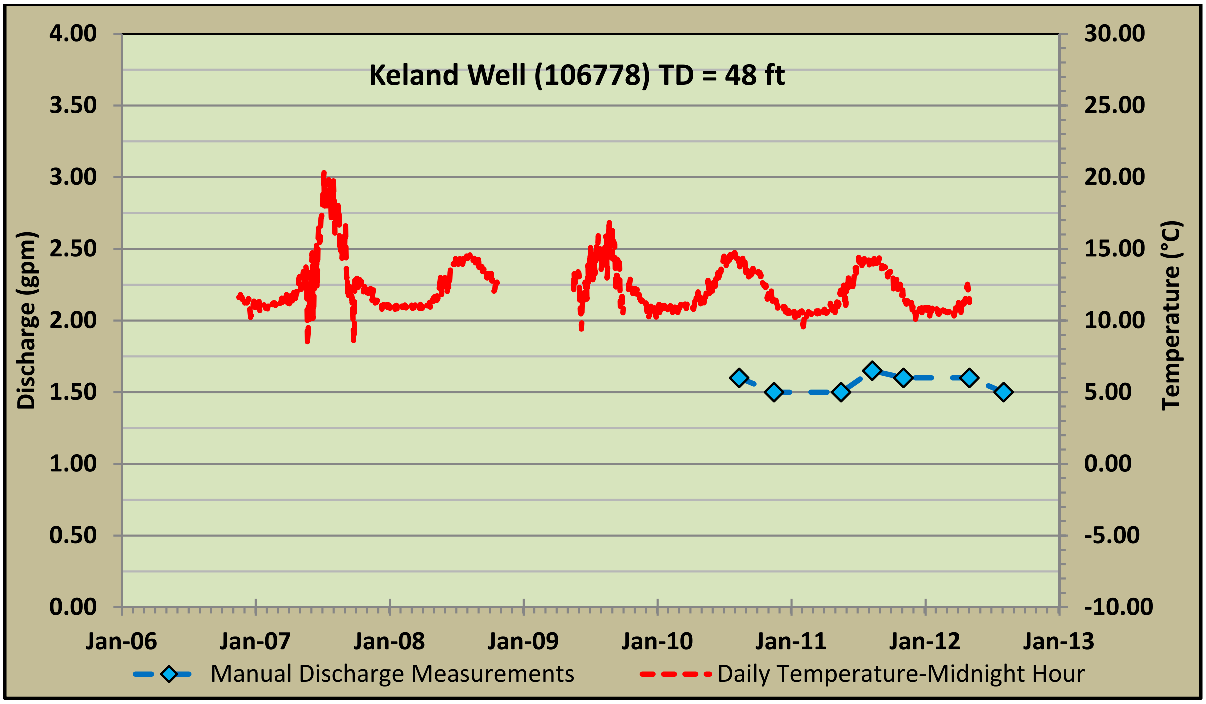

Figure A20. Hydrograph for the Keland well showing daily midnight-hour water temperatures and manual flow measurements made during site visits.

Table A35. Water Temperature Statistics for the Keland Well

Water Temp. Statistics	Water Temp. (°C-logger)	Comments
Mean	12.3	✓ Based on midnight-hour readings from November 2006 to May 2012. ✓ Temperature measured by Tidbit® temperature logger installed in discharge line at flowmeter. ✓ Well water classified as Cold (<15°C) but temperature data is probably altered by heating and cooling of the ground along the discharge line.
Median	11.6	
Maximum	20.3	
Minimum	8.3	
# Readings	1,769	

Water-Quality Sampling Summary

Water samples are collected from the end of the discharge line at the Madison River. The well has been sampled 7 times for major ions and trace elements between June 1998 and August 2011. The well was sampled for seasonal variation (spring, summer, and fall) in 2007. Average concentrations of select major ions and trace elements are presented in table A36. The well produces a sodium/bicarbonate type water with a slightly acidic pH and elevated concentrations of sodium, silica, fluoride, and arsenic. The water exceeds the EPA drinking water standard of 10 µg/L for arsenic, and the secondary standard of 2.0 mg/L for fluoride. One of the samples exceeded the primary fluoride standard of 4.0 mg/L. Due to the low concentrations of calcium and magnesium, the water is soft (avg.= 34 mg/L as $CaCO_3$). Overall, the inorganic chemistry is similar to the other flowing wells in the Bakers Hole area and is interpreted as being reflective of interaction with silicic volcanic rocks.

Table A36. Average Concentrations of Select Major Ions and Trace Elements for Keland Well

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
177	6.7	8.5	3.1	30.4	66.6	5.3	4.2	<0.1	3.8	18.6	46.8	3.6	20.2	99.0	<1.0

The Keland well was sampled for stable isotopes of oxygen (^{18}O) and hydrogen (^{2}H) and the radioactive hydrogen isotope tritium (^{3}H) in October 2007 and May 2011. The tritium concentrations were 14.1 and 7.9 TU, respectively (see report, fig. 37 and table 10 for isotope data).

3 Bears Lodge Well (106842)

Site Description

The 3 Bears Lodge is located in the town of West Yellowstone. The well is privately owned and is used for landscape irrigation. Drilled in 1966, the well is 140 ft deep and constructed with 6-in steel casing that extends to the bottom of the well. The casing is not perforated or screened. The area around the wellhead is covered by pavement and buildings. The MBMG inventoried the well in August 1995, first sampled it for major ions and trace elements in June 1998, and added to the LTMP network in October 2005.

Hydrogeologic Setting

The surficial geology at the 3 Bears Lodge site is concealed by urban development, but the site lies within the area mapped as glacial outwash by O'Neill and Christiansen (2002), commonly referred to as the obsidian sand plain. The driller reported sand from the surface to 102 ft bgs, followed by a 23-ft-thick layer of yellow clay down to 125 ft bgs. The driller reported 10 ft of "sloppy sand and lava dust" under the clay layer, followed by 5 ft of coarse sand. The driller did not indicate where water was first intercepted. The driller's log is interpreted as showing that the well is completed in the glacial outwash deposits, but also possibly in a locally confined water-bearing zone under the clay layer.

Clay and "yellow" clay layers are commonly reported in other wells in the area that are completed in the glacial outwash deposits of the obsidian sand plain, including the shallower flowing artesian wells in the Bakers Hole area. The lithology at this site is similar to the lithology reported on well logs in the Bakers Hole Campground area. Although the 3 Bears Lodge well does not flow, water levels are typically 35 to 40 ft bgs, well above the clay layer. The sloppy sand under the clay suggests heaving sand due to high pore pressure.

Water-Level and Water-Temperature Monitoring Summary

The 3 Bears Lodge well has been monitored since October 2005. A water-level logger is installed in the well and collects hourly water-level and water-temperature data. Manual water-level measurements are made during site visits, and temperature measurements are made when the well is purged for sampling. Figure A21 summarizes the water-level and water-temperature data collected, and statistics for the water-level logger data are provided in table A37.

The water-level patterns are noisy due to pumping of the well for irrigation, but an annual pattern can still be seen. Water levels usually peak in late May to mid-June, and reach their lowest levels in April through mid-May. The declining limbs of the annual patterns are linear, and in some years water levels do not seem to recover in the spring (e.g., 2010 and 2013). The reason for the unusual amount of pumping from June 2006 through January 2008 is unknown. Although the well is reported to only be used for irrigation, it may have also been used to supply water for the lodge during this period.

The temperature patterns for the water-level logger data show upward spikes when the well is being pumped, but still do not vary more than about 1°C. The pattern shows that water temperatures at the bottom of the well (140 ft) are slightly warmer than those at the depth of the logger (60 ft). Temperatures measured when the well is purged for sampling are significantly higher, and probably best reflect the groundwater temperature at 140 ft bgs.

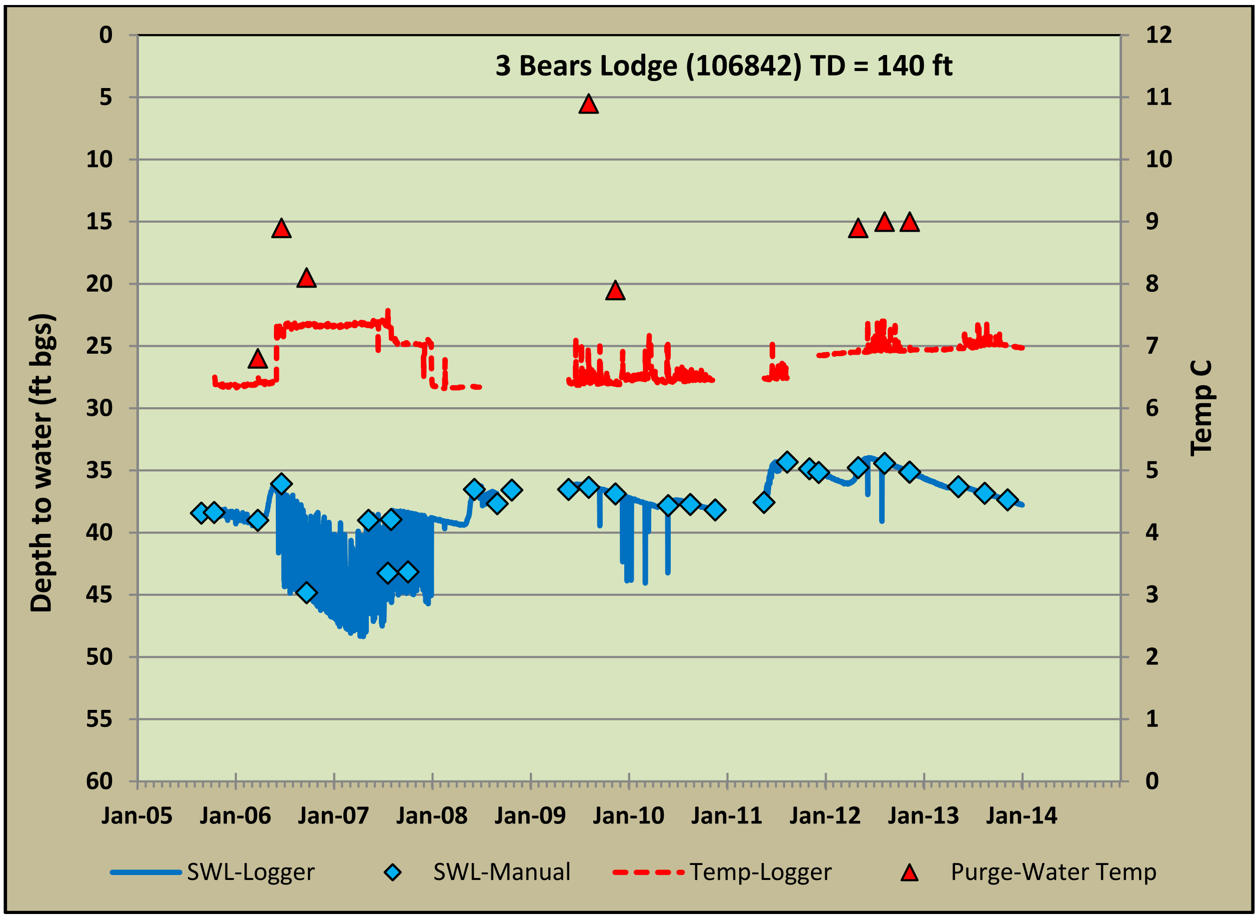

Figure A21. Hydrograph for the 3 Bears Lodge well showing daily midnight-hour water levels and water temperatures recorded by the water-level logger, and manual measurements obtained during site visits.

Table A37. Water-Level Logger Statistics for the 3 Bears Lodge Well

Statistics	Water Level (ft bgs)	Water Temp. (°C)	Comments
Mean	38.4	6.8	✓ Based on daily midnight-hour readings from Oct 2005 through December 2013 ✓ Temperature measured by water-level logger hanging in well 60 ft bgs and 10 to 25 ft below the water surface ✓ Purge-water temp. 6.8 to 10.9°C, Avg. 8.7 (*n*=9) ✓ Water classified as Cold (<15°C)
Median	37.4	6.9	
Maximum	48.4	7.6	
Minimum	34.0	6.3	
# Readings	2,436	2,370	

Water-Quality Sampling Summary

Samples are collected from an outside faucet on the north side of the 3 Bears Lodge. This well has been sampled 8 times for major ions and trace elements between June 1998 and November 2012. This includes sampling for seasonal variation (spring, summer, and fall) in 2012. The well was also sampled twice in 2006 (June and September) and 2009 (August and November). Average concentrations of select major ions and trace elements are presented in table A38. The well produces a sodium-calcium/bicarbonate type water with a near neutral pH, low TDS, and low levels of sulfate, chloride, and nitrate. Fluoride concentrations exceed the EPA secondary drinking water standard of 2.0 mg/L, and a have ranged from 2.62 to 3.15 mg/L. The well was sampled for the stable water isotopes (^{18}O and ^{2}H), and the radioactive isotope tritium (^{3}H) in October 2007 and November 2011 (see report, fig. 37 and table 10 for isotope data).

Table A38. Average Concentrations of Select Major Ions and Trace Elements for 3 Bears Well

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
86.7	6.9	118.	1.0	14.0	35.9	3.4	3.9	0.2	2.9	1.8	44.0	3.9	7.7	49.9	<0.3

West Yellowstone KOA Campground Well (8935)

Site Description

The West Yellowstone KOA well is located 5.5 mi west of West Yellowstone along U.S. Highway 20. The privately owned well supplies drinking and irrigation water for the campground and is classified as a public water supply. Drilled in 1972, the well is 225 ft deep and is constructed with 8-in-diameter steel casing that extends to 213 ft. The remainder of the borehole has probably caved in. There are no perforations or screens in the casing. The well was first visited and sampled by the MBMG in August 1979 as part of an assessment of geothermal resources in the area. It was inventoried by the MBMG in August 1995, and was added to the LTMP network in June 2006. Well construction includes an 8-in borehole drilled to 225 ft and completed with steel casing to 213 ft bgs. There is no screen or perforations in the casing, and water enters the well through the open bottom at 213 ft bgs. The remainder of the borehole has probably caved in.

Hydrogeologic Setting

The KOA well is situated near the southwestern margin of the Hebgen Basin. Based on 1:100,000-scale geologic mapping by O'Neill and Christiansen (2002), the well is located on the southern edge of an outcrop of Quaternary glacial till of Bull Lake age that is surrounded by Pinedale age glacial outwash deposits of the obsidian sand plain. Bull Lake till crops out in several other locations near the KOA well and on the hills to the south. In this area of the basin the outwash deposits of the obsidian sand plain thin out, and Bull Lake till probably underlies the outwash deposits.

The lithology reported on the driller's log for the KOA well shows numerous layers of clay described as yellow clay, gray clay, sandy clay, and clay-bound gravels down to 205 ft. The thickness of the clay layers varies from 4 to 27 ft. A 5-ft-thick fine gravel layer reported 165–170 ft reportedly produced 25 gpm. The log reports "clay & soft shale sand" from 205 to 215 ft, "sandstone w/water" from 215 to 224 ft, and "clay" from 224 to 225 ft. The KOA well is cased to 213 ft and the casing is not perforated or screened. It is unknown why the casing was not extended to the top of the sandstone at 215 ft, but it appears the water produced from the well comes from the sandstone layer.

The well log is interpreted as showing glacial till interbedded with layers of sand and gravel down to 205 ft. Below that, the "clay & soft shale sand" from 205 to 215 ft and the "sandstone w/water" from 215 to 224 ft is interpreted as till or compacted till, and "clay" from 224-225 ft is also probably till.

This KOA well is artesian, with a static water level of 8 ft bgs reported after completion of the well. The well log contains a remark that the well is artesian part of the year, which is interpreted as meaning it is a flowing artesian well part of the year. The artesian pressures in the aquifer are most likely due to confining condition created by the thick sequence of clay layers noted on the well log. The source of recharge into the glacial deposits at this site is unknown, but given the amount of clay noted in the till, it is more likely from the underlying bedrock rather than infiltration of precipitation or surface waters in the area.

Water-Level and Water-Temperature Monitoring Summary

The wellhead is located in a pit and is difficult to access. In addition, the well serves as a public water supply well for the campground and is in almost constant use during the summer. For these reasons, a water-level logger has not been installed in the well, and monitoring is limited to water-quality sampling.

Water-Quality Sampling Summary

Water samples have been collected from a sampling tap in the well pit. The well has been sampled 7 times for major ions and trace elements between August 1979 and August 2010. Sampling to evaluate seasonal variability in water quality (spring, summer, and fall) was completed in 2006 and 2009, but the fall samples (November) could not be collected because the well was shut down for the winter season. Average concentrations of select major ions and trace elements are presented in table A39. The well produces a calcium/bicarbonate type water with a slightly basic pH and low concentrations of sodium, chloride, nitrate, fluoride, and arsenic. Excluding Corey and Stinky Springs, strontium levels are elevated in comparison to other LTMP sites in the Hebgen Basin (see report, table 9). The well was sampled for stable water isotopes

(^{18}O and ^{2}H) and the radioactive hydrogen isotope tritium (^{3}H) in March 2006 (see report, fig. 37 and table 10 for isotope data).

Table A39. Average Concentrations of Select Major Ions and Trace Elements for KOA Well

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
181	7.5	42.0	9.4	6.0	18.3	26.8	1.1	0.3	0.3	0.4	17.0	25.7	266	6.7	0.6

West Yellowstone KOA Backup Well (165852)

Site Description
The West Yellowstone KOA Backup well is located 5.5 mi west of West Yellowstone on the north side of U.S. Highway 20, about 175 ft southwest of the West Yellowstone KOA Campground well (8935) described above. The Backup well is situated on a low hill about 100 ft north of the highway and just west of the campground entrance. The MBMG inventoried and sampled this well in May 2010, and added to the LTMP network so water-level data could be collected at the campground. The well was drilled in 1997 to provide a backup water supply for the campground and is currently used on an emergency basis. The well is constructed with 8-in steel casing that has a screen from 240 to 260 ft bgs.

Hydrogeologic Setting
The surficial geology of the KOA Backup Well site is the same as for the main water supply well (8935). However, the driller's log reports purple, gray, and brown "basalt volcanic" rocks from 242 to 260 ft bgs, suggesting the well may have penetrated volcanic bedrock under the glacial till deposits. Absaroka Group volcanic rocks are mapped in the mountains south of the campground by O'Neill and Christiansen (2002). If the volcanic rocks described on the driller's log are Absaroka volcanic rocks, the well is screened in, and producing from the volcanic rocks.

Water-Level and Water-Temperature Monitoring Summary
The KOA Backup Well has been monitored by the MBMG since August 2005. Current monitoring consists of hourly monitoring of water level and water temperature using a water-level logger. Manual water-level measurements are made during site visits using an e-tape and temperature is measured after purging the well for sampling. Figure A22 summarizes the water-level and water-temperature data collected, and statistics for the water-level logger data are provided in table A40. Equipment that failed in August 2011 was replaced in December 2011. The replacement logger was installed at a shallower depth, which resulted in cooler water temperature readings since that time. Figure A22 and table A40 summarize daily water-level and temperature data from August 2005 to August 2013. Temperatures recorded at the two different depths are reported separately because the average temperature decreased by 0.7°C at the shallower depth.

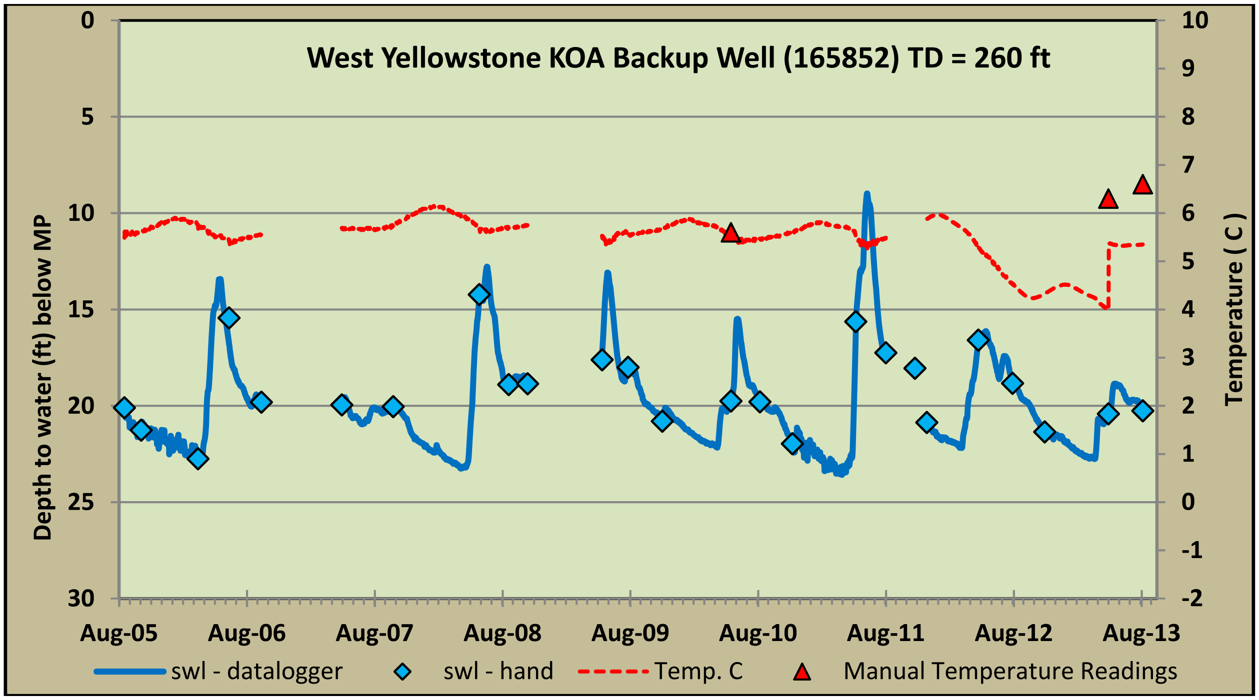

Figure A22. Hydrograph for the KOA backup well showing daily midnight-hour water levels and water temperatures recorded by the water-level logger, and manual measurements obtained during site visits.

Water levels rise sharply in late March to mid-April and peak in late May to mid-June. Water temperature inversely correlates with water levels. However, while minimum temperatures occur at about the same time as peak water levels, maximum water temperatures usually occur in early February, about 2 mo earlier than minimum water levels (early April).

Table A40. Water-Level Logger Statistics for KOA Campground Backup Well

Statistics	Water Level (ft)	Temp C Silver	Temp C Edge	Comments
Mean	19.95	5.70	4.96	✓ Based on daily midnight-hour readings from Oct 2005 through August 2013. ✓ Levelogger-**Silver**® hung @ 30.2 ft bgs (8/26/05 to 12/6/11) ✓ Older model logger replaced on 12/6/11 ✓ Levelogger **Edge**® hung @ 23.4 ft bgs (8/26/05 to 12/6/11) ✓ Well water classified as Cold (<15°C)
Median	20.44	5.67	4.76	
Maximum	23.58	6.94	6.33	
Minimum	8.98	4.98	3.99	
# Readings	2352	34337	10247	

Water-Quality Sampling Summary

The KOA backup well was sampled 3 times for major ions and trace metals between May 2010 and August 2013. Sampling requires the system operator to shut off the main campground well and adjust valves to purge the backup well. In addition, like the main KOA well (8935), the well is not accessible in the late fall when the campground is closed. For these reasons, seasonal sampling has not been conducted. Average concentrations of select major ions and trace elements are presented in table A41. The well produces a calcium/bicarbonate type water with a slightly basic pH and low concentrations of sodium chloride, nitrate, fluoride, arsenic, and lithium. Overall the water is very similar to the main KOA well, with the notable exceptions that lithium concentrations are below detection, and sulfate concentrations are slightly higher (see report, table 9). The well was sampled for stable water-isotopes (^{18}O and ^{2}H) in May 2013 but was not sampled for tritium (^{3}H) (see report, table 10 for isotope data).

Table A41. Average Concentrations of Select Major Ions and Trace Elements for KOA Backup Well

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
185	7.3	40.1	9.0	7.6	17.1	32.6	1.0	0.3	0.1	<0.4	15.9	20.6	241.	<0.4	0.6

Black Sand Spring (183242)

Site Description
The undeveloped Black Sand spring is located about 2.5 mi west of the town of West Yellowstone, along the southern margin of the Hebgen Basin on U.S. Forest Service land. A parking area constructed at the spring makes for easy access. The spring discharge of about 16 to 25 cfs forms a spring creek that flows to the northwest, forming a tributary of the South Fork of the Madison River. The MBMG inventoried the spring and sampled it for major ions and trace elements in May 2000, and it was sampled again, and added to the LTMP, in May 2010.

Hydrogeologic Setting
Black Sand Spring surfaces along the southern margin of the Madison Valley. Topographically, the spring emanates from the northeastern edge of a low, forested plateau area that is bounded to the west and south by the Continental Divide and to the east by the South Fork of the Madison River. The low plateau surface is a northwestern extension of the Madison Plateau in the Park. Bedrock in the vicinity of the spring, to the south, consists of Eocene volcanic rocks of the Absaroka Group that are overlain by the Pliocene Huckleberry Ridge, and Pleistocene Lava Creek tuffs (O'Neill and Christiansen, 2002). The volcanic rocks overlie older, folded and faulted Paleozoic and Mesozoic sedimentary formations. In the spring area the bedrock is covered by glacial till and glacial outwash deposits of the obsidian sand plain, and appears to discharge from the surficial deposits. Several northwest-trending normal fault are mapped near the spring, and the spring is believed to discharge from one of the faults. Several other cold water springs surface along or near the projected trace of this normal fault further northwest, including springs on the Diamond P Ranch (184430), and Madison Fork Ranch (181919, 182691, 181928), supporting the hypothesis that the Black Sand Spring is structurally controlled by faulting.

Discharge and Water-Temperature Monitoring Summary
Monitoring at Black Sand Spring has been limited to manual measurements of discharge by gaging at the head of the spring creek, and manual measurements of water temperature during site visits. Data are shown in figure A23. The limited data preclude evaluation of trends or seasonality. Based on eight monitoring events between May 2010 and December 2013, discharge has varied from about 7,300 to 11,300 gpm and average 8,700 gpm. Temperatures have varied from 8.3 to 9.7°C and average 8.9 ° C.

The spring creek channel near the point of discharge is wide and shallow, with a width of about 40 ft and a water depth ranging from about 0.2 to 1.3 ft. The flat, shallow nature of the channel makes establishment of a gage difficult, because large changes in spring flow would result in small changes in stream stage. This, coupled with the inherent errors associated with measuring discharge, make this a difficult site for continuous flow monitoring. However, continuous water-temperature monitoring is possible, and the MBMG installed a temperature logger at the spring in May 2014.

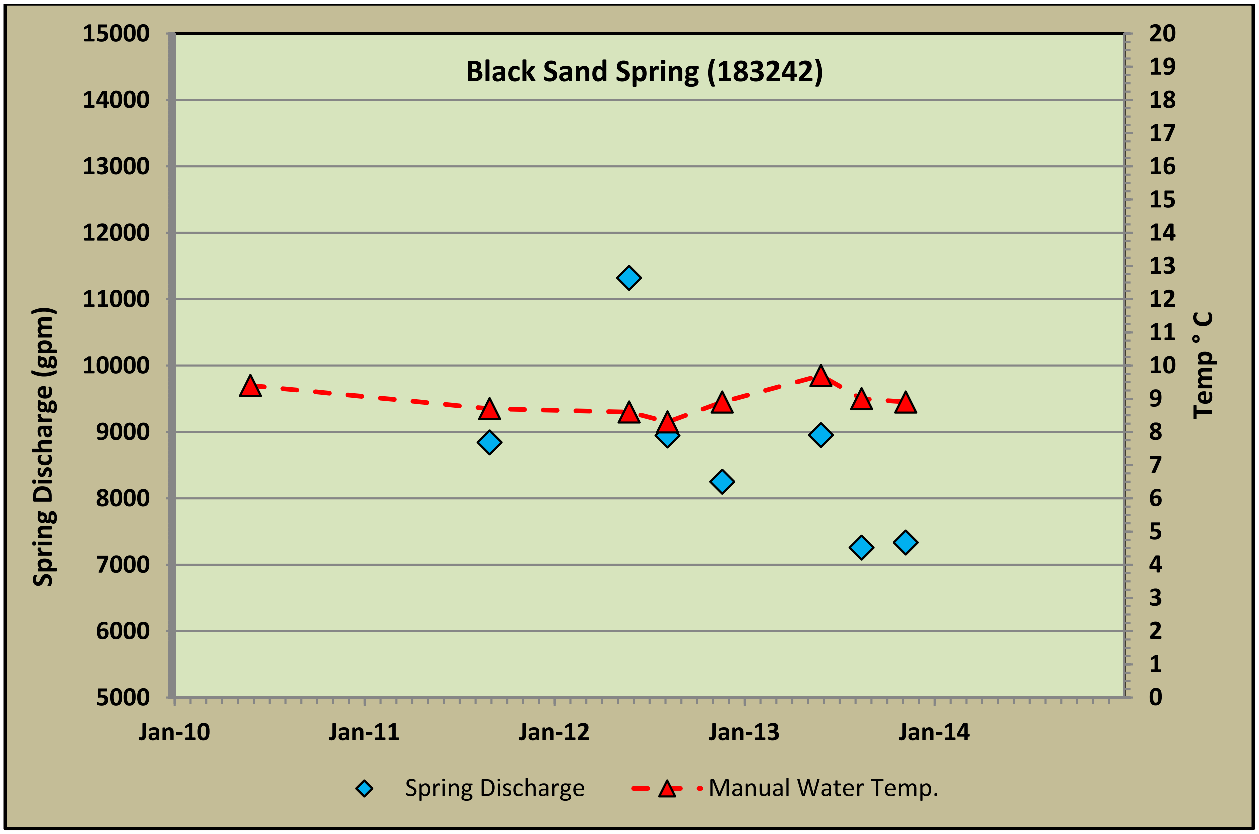

Figure A23. Hydrograph for Black Sand Spring showing manually measured discharge and water-temperature data obtained from the spring.

Water-Quality Sampling Summary

Water samples are collected from the spring discharge area at the east end of the pool formed at the head of the spring creek, using a peristaltic pump. Black Sand Spring has been sampled seven times since 1977, including sampling for major ions by the USGS in August 1977, and by the MBMG in June 1979, as part of an assessment of geothermal resources in the area. The spring has been sampled five times for major ions and trace elements between October 2000 and December 2013. This includes sampling for seasonal variation (spring, summer, and fall) in 2013. Average concentrations of select major ions and trace elements are presented in table A42. The spring produces a sodium-calcium/bicarbonate type water with a slightly acidic pH, a low TDS concentration, and low levels of magnesium, sulfate, chloride, nitrate, arsenic, strontium, and uranium. Silica, fluoride, and lithium levels are elevated, and the water exceeds the secondary EPA drinking water standard of 2.0 mg/L for fluoride.

Table A42. Average Concentrations of Select Major Ions and Trace Elements for KOA Backup Well

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
82	6.9	5.6	0.9	11.7	34.6	2.2	3.8	<0.5	3.5	0.9	50.6	<1.0	5.5	33.9	0.6

Stinky Spring (183268)

Site Description

Stinky Spring is located about 6 mi west of the town of West Yellowstone, on U.S. Forest Service land. The spring is situated along the south side of a pack trail, where it forms a small pool that flows through a culvert under the trail and discharges into a marshy area to the north, along the southwest margin of the Hebgen Basin. A small flume is installed at the outlet of the spring pool, just before the culvert. This site was inventoried by the MBMG in August 2000, sampled in October 2000, and added to the LTMP network in October 2005.

Hydrogeologic Setting

The hydrogeologic setting for Stinky Spring is similar to that for Black Sand Spring described above. The spring surfaces along the northern edge of a low, forested plateau area that is bounded to the west and south by the Continental Divide and to the east by the South Fork of the Madison River. The low plateau surface is a northwestern extension of the Madison Plateau in the Park. Bedrock in the vicinity of the spring, to the south, consists of Eocene volcanic rocks of the Eocene Absaroka Group that are overlain by the Pliocene Huckleberry Ridge, and Pleistocene Lava Creek tuffs (O'Neill and Christiansen, 2002). The Lava Creek tuff is exposed on the east side of the spring pool. A northwest-trending normal fault is mapped through the spring area and is thought to control the location of the spring. Targhee Sulphur Spring (8940) surfaces about ½ mi southeast of Stinky Spring, along the trend of the same fault, and the two springs have similar water chemistry.

Discharge and Water-Temperature Monitoring Summary

Stinky Spring has been monitored since October 2005 using a small flume installed at the outlet of the spring pool. A water-level logger was installed in the flume in June 2006 to record hourly stage and water temperature. Manual discharge measurements from the flume, between October 2005 and June 2006, were impacted by leakage around the flume and deemed unreliable. From June 2006 through June 2013 monitoring consisted of hourly temperature readings with the water-level logger installed on the flume. Although the logger also recorded the stage in the flume, plant material and other debris often clogged the flume between site visits, altering the water level. Thus, continuous discharge measurements were unreliable and are not presented in this report. In July 2013, a logger was installed with a staff gage in the pool and improvements were made to try and prevent clogging. These improvements have helped, but clogging of the flume is still an issue. Discharge and temperature data collected from the spring are summarized in figure A24, and statistics for the water-level logger temperature data and the manual measurements are provided in table A43.

Manual discharge measurements average 34.3 gpm (n=27). For the short period in 2013 when discharge data were obtained from the water-level logger installed in the pool, the discharge averaged 40.7 gpm. Water temperatures measured by the logger installed in the flume average 14.2°C, which classifies the spring water as cold (<15°C). However, manual readings obtained by the MBMG have ranged from 15.1 to 18.3°C and average 16.3°C. This difference is attributed the location of the temperature logger in the flume and cooling of the water during the winter season; manual readings are all obtained after snowpack has melted in the late spring, summer, and early fall. For this reason, and also because of the unique water chemistry of the spring water (described below), Stinky Spring is classified as a warm (15–25°C).

The water-temperature data do show an annual pattern with a fluctuation of about 6°, but given the site characteristics and location of the logger, this may reflect heating and cooling of the water by the surrounding air and ground surface. The MBMG installed a separate temperature logger in the upwelling spring water in the center of the pool in June 2014 to try and obtain more accurate data.

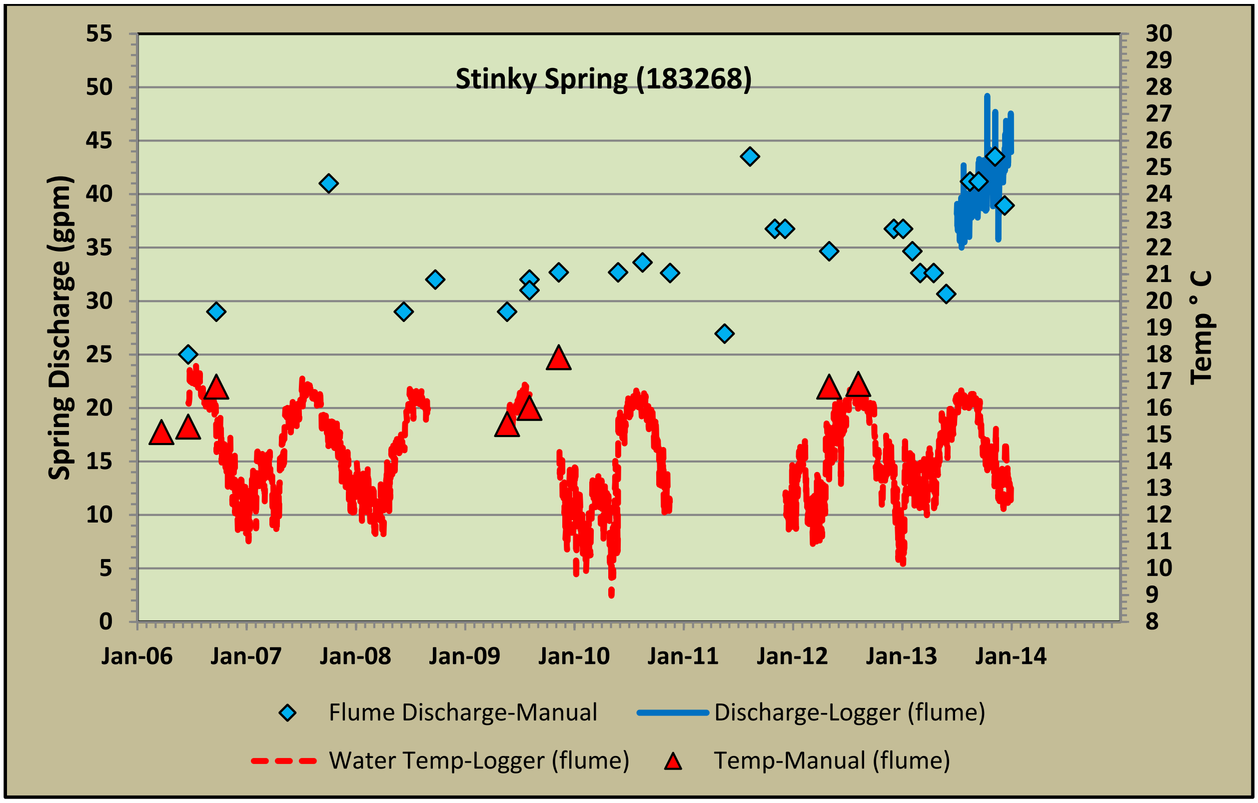

Figure A24. Hydrograph for Stinky Spring showing discharge and water-temperature data collected from data loggers, and manual discharge and temperature data obtained from the spring.

Table A43. Statistics for Water Temperature and Discharge Measurements at Stinky Spring

Statistics	Discharge (gpm)	Water Temp. (°C-logger)	Comments
Mean	34.3	14.2	✓ Temperature data based on daily midnight-hour readings from June 2006 through December 2013. ✓ Temperature measured by water-level logger installed in flume. ✓ Discharge data are based on manual readings of the flume during the same period. ✓ Water classified as Warm (15 to 25°C)
Median	32.7	14.1	
Maximum	43.5	21.2	
Minimum	27.0	8.9	
# Readings	27	1,849	

Water-Quality Sampling Summary

Water samples are collected from the flume using a peristaltic pump. Stinky Spring has been sampled 11 times for major ions and trace metals between October 2000 and November 2012. Seasonal sampling (spring, summer, and fall) to evaluate variations in water chemistry was completed in 2006, 2009 and 2012. The spring produces a calcium-magnesium/bicarbonate-sulfate type water. Average concentrations of select major ions and trace elements are presented in table A44. The relative dominance of bicarbonate and sulfate are almost equal. The water has basic pH, and low concentrations of sodium and chloride; uranium concentrations are below detection. Lithium, sulfate, arsenic, and strontium concentrations are elevated, and arsenic exceeds the EPA drinking water standard of 10 mg/L for arsenic. Concentrations of TDS, calcium, sodium, sulfate, and strontium are the highest of any of the LTMP sites in the Madison River Watershed (see report, table 9).

Table A44. Average Concentrations of Select Major Ions and Trace Elements for Stinky Spring

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
369	7.5	73.3	27.3	7.5	12.5	145.	3.8	<0.0	1.1	11.0	40.8	23.6	711.	40.0	<0.1

While the strontium concentration at Stinky Spring is higher than at any other monitoring site in the Madison River watershed, it is significantly lower than many of the monitoring sites in the Yellowstone River watershed, including cold, warm, and hot water sites (see report, table 5). The unique water chemistry at Stinky Spring suggests that the water is either a geothermal groundwater that has cooled prior to discharge, or a mix of geothermal groundwater with cold, shallow groundwater.

Stinky Spring was sampled for stable water isotopes (^{18}O and ^{2}H), and the radioactive isotope tritium (^{3}H) in March 2006 and November 2009 (see report, fig.37, table 10 for isotope data). Stinky Spring does not stand out from other monitoring sites in the Madison Valley in terms of the stable isotopes of oxygen and hydrogen. The spring water had no detectable concentrations of tritium, indicating that the water discharging at the spring entered the groundwater flow system prior to the early 1950s.

Ryberg Well (230654)

Site Description

The Ryberg well is located 7 mi northwest of the town of West Yellowstone, near the South Fork of the Madison River, and the western margin of the Hebgen Basin. The privately owned well supplies domestic water and landscape irrigation water for a summer cabin. Drilled in 2004, the well is a flowing artesian well that is shut-in. The well was drilled to a depth of 172 ft but was only cased to 119 ft with 6-in steel casing. There are no perforations or screens reported in the well casing. The driller’s log does not indicate if a PVC liner was installed in the lower portion of the borehole, and the condition of the borehole from 119 to 172 ft bgs is unknown. The well was inventoried and sampled by the MBMG in November 2009, and added to the LTMP at that time.

Hydrogeologic Setting

The surficial geology mapped by O’Neill and Christiansen (2002) indicates the well is located on the north flank of an outcrop of Bull Lake-age glacial till, surrounded by Pinedale-age glacial outwash deposits of the obsidian sand plain. The setting is similar to the KOA campground LTMP sites (8935 and 203758). Bedrock exposed along the western margin of the basin, about ½ mifrom the well, consists of the lower member of the Pliocene Huckleberry Ridge tuff, overlying Archean quartzite and granitic gneiss.

Lithology reported on the driller's log shows gravel and cobblestones down to 13 ft bgs, then a 100-ft-thick sequence of alternating layers of gravel, sand, and clay. Included in this sequence is a 44-ft-thick layer of gray clay from 39 to 83 ft. Below the sequence of gravel, sand, and clay the log reports brown rhyolite with black silt from 113 to 172 ft bgs. The driller's log is interpreted as showing glacial till interbedded with glacial outwash and glacial lake sediments down to 113 ft. Below the glacial deposits the "brown rhyolite with black silt" could be the lower member of the Huckleberry Ridge tuff, but the tuff does not contain any minerals that would make "black silt" in the well cuttings. An alternative interpretation is the volcanic rock could be a rhyolite flow that contains obsidian, or pre-Pinedale age glacial outwash deposits derived from the obsidian-bearing rhyolite flows to the east or south. Regardless, the well casing appears to extend 6 ft into the volcanics, and since the casing is not screened or perforated, water entering the well appears to be coming from the volcanics.

Water-Level and Water-Temperature Monitoring Summary

Monitoring has consisted of manual measurements of the shut-in pressure during site visits, and manual measurements of water temperature when the well is purged for sampling. Shut-in pressures, converted to feet of water above ground surface, and water temperatures obtained from the Ryberg well, are summarized in figure A25. Calculated water levels, feet above ground, have ranged from 9.2 to 29.7 ft. Temperatures have ranged from 13.4 to 14.7°C.

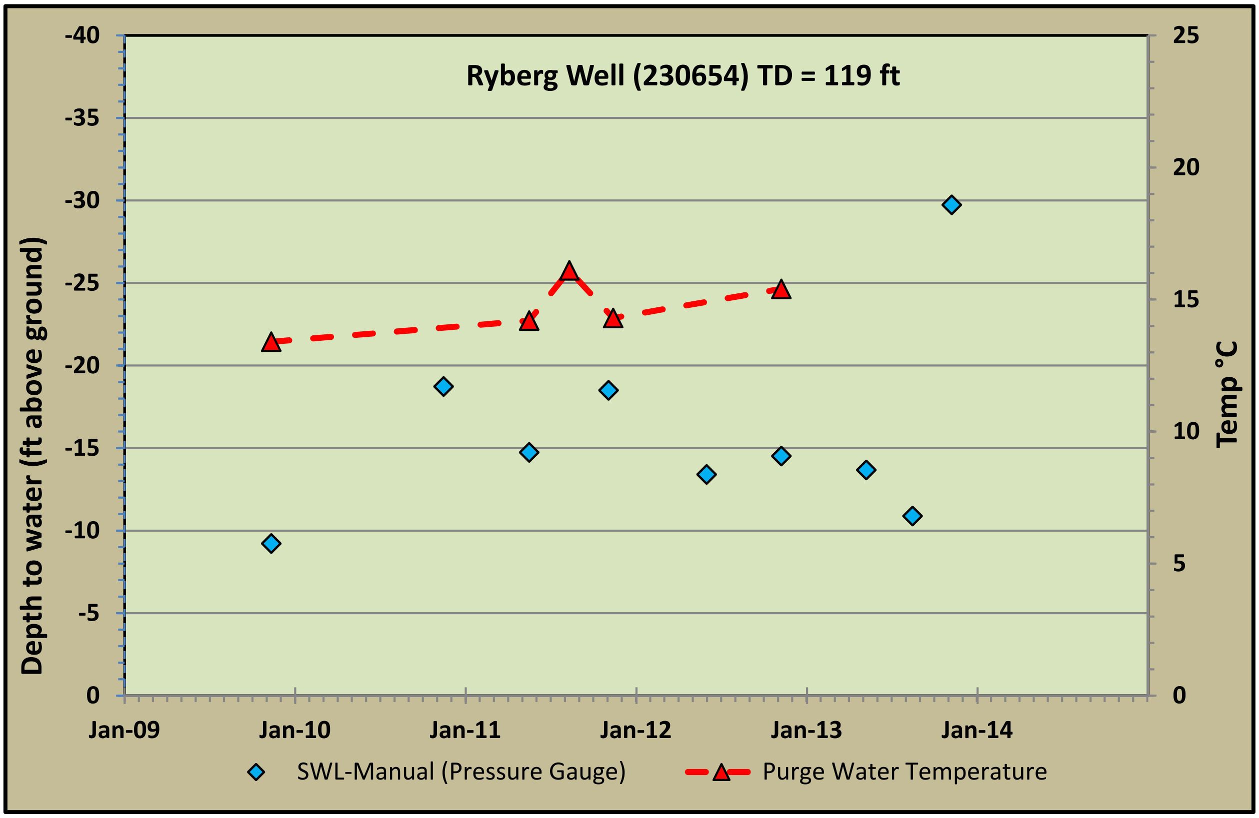

Figure A25. Hydrograph for the Ryberg well showing manual shut-in pressure readings converted to feet above ground, and water temperatures measured when the well has been purged for sampling.

Water-Quality Sampling Summary

Samples from the Ryberg well are collected from a frost-free hydrant at the wellhead. The well has been sampled 5 times for major ions and trace elements between November 2009 and November 2012. This includes sampling for seasonal variation (spring, summer, and fall) in 2011. Average concentrations of select major ions and trace elements are presented in table A45. The well produces a sodium/bicarbonate type water with a slightly basic pH and low concentrations of sulfate, chloride, and nitrate. Silica, fluoride, and lithium concentrations are elevated. Two of the samples have exceeded the primary EPA drinking water standard of 4 mg/L for fluoride (4.12 and 4.23), and all samples exceed the secondary standard of 2 mg/L. While the average arsenic concentration in the samples is below the EPA drinking water standard of 10 µg/L, two of the samples have exceeded the standard (10.6 and 10.9).

Overall, the water chemistry is similar to the chemistry for the flowing wells in the Bakers Hole area, the 3 Bears Lodge well, and Black Sand Spring. The hydrogeologic setting for these sites consist of glacial outwash deposits derived from obsidian bearing rhyolite flows, with the exception of Black Sand Spring, which is believed to discharge from a rhyolite flow. The similarities in water chemistry between the Ryberg well and these sites suggests the Ryberg well is completed in a rhyolite flow or deposits derived from rhyolite flows, rather than the Huckleberry Ridge tuff.

The Ryberg well was sampled for stable water isotopes (^{18}O and ^{2}H), and the radioactive isotope tritium (^{3}H) in November 2011 (see report, fig. 37, table 10 for isotope data).

Table A45. Average Concentrations of Select Major Ions and Trace Elements for Ryberg Well

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
195	7.2	14.6	5.2	36.7	48.2	7.9	6.6	<0.1	3.9	7.0	71.4	7.4	38.2	95.7	1.1

Corey Spring (182014)

Site Description

Corey Spring is located along the north shore of Grayling Arm of Hebgen Lake, about 10 mi north–northwest of the town of West Yellowstone (see report, fig. 28). The spring surfaces at the base of fill material used to construct the roadbed for Highway 287, and the original spring discharge area may have been covered or modified by the highway construction. The spring is on private property, and a large pond has been constructed below the head of the spring. The spring discharge flows into the pond and then overflows directly into Hebgen Lake.

Hydrogeologic Setting

Corey Spring has a geologic setting that is unique from the other Madison River watershed sites. The original spring area has been covered by fill placed during construction of Highway 287, and the spring water now discharges from the base of the highway fill. Directly north of the spring, relatively horizontal Paleozoic and Mesozoic formations are mapped along the southwest limb of a northwest-trending syncline. These formations have been highly modified by both thrust faulting and extensional faulting (normal faults).The Red Canyon fault runs along the base of the slopes north of the spring, and recent fault scarps from the 1959 Hebgen Lake earthquake are visible. The structural geology at the Corey Spring site is complex; detailed mapping would be needed to help determine the source of the spring water. However, the flow is relatively large and the water quality is similar to Anceny and Snowflake Springs, so the Madison Group limestone is the suspected source of spring water.

Water-Level and Water-Temperature Monitoring Summary

Corey Spring has been monitored since October 2010, with continuous measurement of temperature using a temperature logger installed in the spring discharge area since September 2011. Discharge measurements are made during site visits using a Marsh-McBirny ® flowmeter, and manual water-temperature readings are obtained when samples are collected. Discharge and temperature data obtained from Corey Spring are summarized in figure A26, and statistics for the temperature logger data are provided in table A46. The temperature of the spring water is very stable, varying by less than 1°C. Manual discharge measurements have ranged from 3,627 to 6,019 gpm and average 4,663 gpm (n=10).

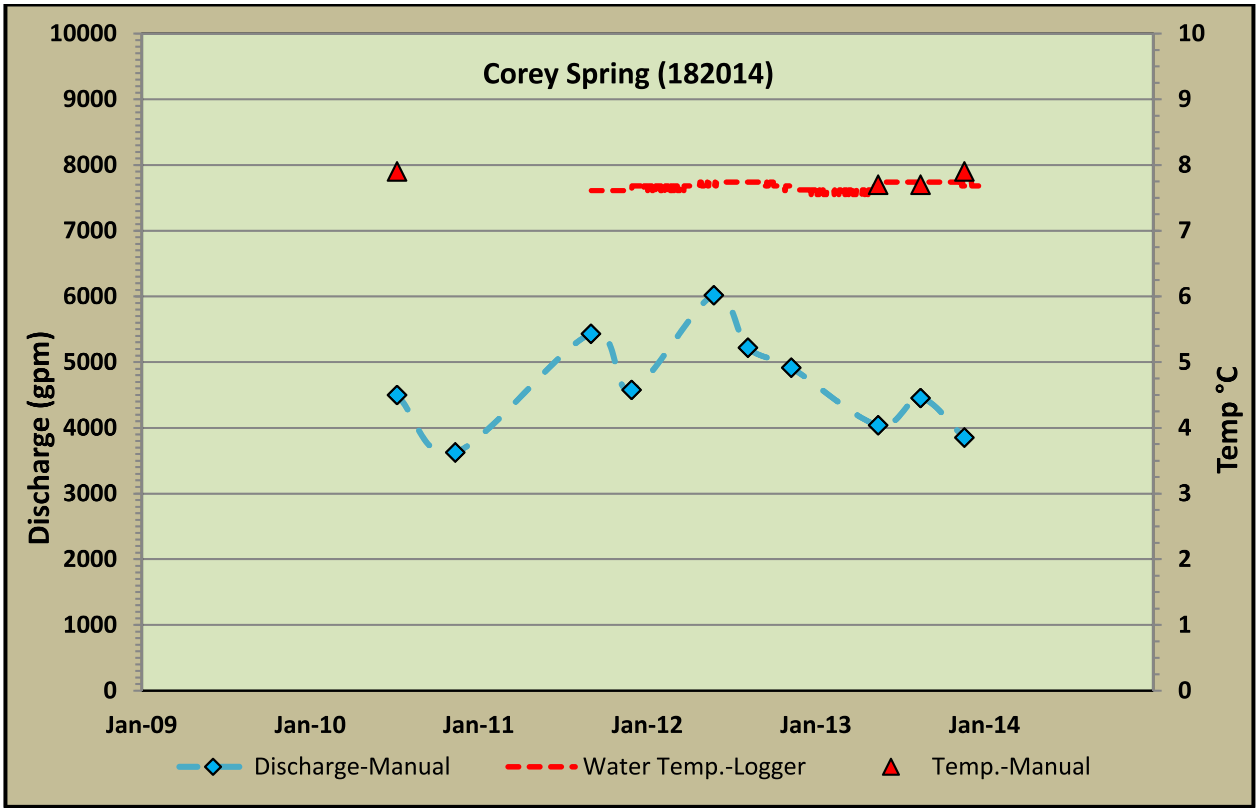

Figure A26. Hydrograph for Corey Spring showing daily midnight-hour water-temperature readings obtained from the temperature logger, and manual discharge measurements made during site visits.

Table A46. Statistics for Water Temperature Data from Corey Spring

Statistics	Water Temp. (°C-logger)	Comments
Mean	7.7	✓ Based on daily midnight-hour temperature readings from June 2006 through December 2013. ✓ Temperature measured logger installed at head of spring discharge area. ✓ Manual temperatures have ranged from 7.6 to 7.9°C and average 7.7°C ✓ Water classified as Cold (<15°C)
Median	7.7	
Maximum	7.7	
Minimum	7.6	
# Readings	804	

Water-Quality Sampling Summary

Samples are collected from the head of the spring using a peristaltic pump. Corey Spring has been sampled 5 times for major ions and trace metals between October 2000 and December 2013. This includes seasonal sampling (spring, summer, and fall) in 2013. Average concentrations of select major ions and trace elements are presented in table A47. The spring discharges a calcium-magnesium/bicarbonate-sulfate type water with a basic pH, and low concentrations of silica, chloride, nitrate, arsenic, lithium, and fluoride. Sulfate, barium, and strontium concentrations are elevated in comparison to other monitoring sites in the Madison River watershed. The water does not exceed any drinking water standards. The spring was sampled for stable water isotopes (^{18}O and ^{2}H), and the radioactive isotope tritium (^{3}H) in July 2010 (see report, fig. 37, table 10 for isotope data).

Table A47. Average Concentrations of Select Major Ions and Trace Elements for Corey Spring

TDS	pH	Ca mg/L	Mg mg/L	Na mg/L	SiO_2 mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L	F Mg/L	As µg/L	B µg/L	Ba µg/L	Sr µg/L	Li µg/L	U µg/L
255	7.6	51.3	24.3	1.8	7.6	75.3	0.7	0.1	0.3	0.5	10.0	28.8	343.	4.4	0.7