HYDROGEOLOGY AND GROUNDWATER AVAILABILITY AT BIG SKY, MONTANA

James Rose and Kirk Waren

Ground Water Investigation Program
Montana Bureau of Mines and Geology

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Cover image: Middle Fork of the West Fork of the Gallatin River at Meadow Village at Big Sky, Montana, elevation 6,234 feet, with Pioneer Mountain on the left (9,860 feet elevation) and Lone Mountain on the right (11,167 feet elevation).

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EXECUTIVE SUMMARY

The resort community of Big Sky, Montana depends on groundwater for all domestic and public water supplies. Many exploratory wells drilled in the area have been abandoned because of inadequate production capacity, and wells drilled for domestic use are often marginally productive. Additional water supplies are needed to meet demand for the water that accompanies the area's growing population and tourism. This report presents results of an assessment of the hydrogeology, available aquifers, water quality, and interactions between surface water and groundwater at Big Sky.

The three most productive aquifers at Big Sky are the sand and gravel aquifer at Meadow Village, glacial and alluvial fan deposits at Mountain Village, and fractured dacite around the core of the Lone Mountain Intrusion. Most of the developments at Big Sky rely on groundwater stored in the Frontier, Muddy, Thermopolis/Kootenai, and Morrison Formations. While these units are composed primarily of low-permeability shale up to 2,000 ft in total thickness, there are thin—on the order of 10 ft or so thick—sandstone layers within these formations that yield water to wells. The number, thickness, and productivity of the sandstone layers vary by location within the Big Sky study area. This heterogeneity in the geologic formations causes difficulty in predicting the productivity of a well prior to drilling a test well at a specific location.

Wells completed in these bedrock formations that are also open to adjacent, fractured intervals of dacite yield more water. Unpredictable distribution of the dacite sills makes locating large, fractured, water-bearing segments difficult. The small and irregular size of many of the sills limits their storage capacity and long-term groundwater productivity. However, two wells located in Mountain Village (identification numbers 103496 and 205931) provide examples of the productivity of the fractured dacite. These wells produce "modern" groundwater based on tritium concentrations. Tritium is a naturally occurring radioactive isotope of hydrogen useful for characterizing groundwater age. The wells completed in the dacite apparently draw water from the heavily fractured, cooled margin of the Lone Mountain Intrusion, which is productive and appears hydrologically connected to recent recharge that infiltrates from the land surface.

The geologic history of the Big Sky region dictates the nature of aquifers and groundwater storage across the study area. Mountain building (tectonic) forces caused movement on the Spanish Peaks Fault (north to south compression), regional west to east compression from the Hilgard Fault, and subsequent extensional faulting that segmented bedrock formations into fault-bounded blocks of steeply dipping, fractured, and folded rock. These tectonic events and intrusion of the Lone Mountain and Pioneer Laccoliths formed discontinuous, local aquifers within the sedimentary layers. This results in variable productivity and storage capacities from wells completed at different locations in the same geologic formation.

There are many examples of the discontinuous and spatially variable properties of the bedrock aquifers across the Big Sky study area. The Frontier Formation is locally absent due to erosion and landslides at Moonlight Basin, Spanish Peaks Mountain Club, and the Yellowstone Club, but is productive in other areas of Moonlight Basin and around Meadow Village. The Kootenai Formation is locally productive at Spanish Peaks Mountain Club and Yellowstone Club but is unsaturated at Moonlight Basin. Low-permeability shale layers and fault displacement can restrict groundwater flow and isolate deeply buried aquifers from recharge. Examples include the Morrison, Kootenai, and Muddy Formations at Moonlight Basin. The Muddy Formation and segments of other aquifers have low transmissivities that limit infiltration of recharge and limit well productivity. In other locations, structural features in the bedrock include transmissive fractures and exposed permeable layers that locally enhance groundwater recharge.

Limestone within the Madison Group has limited viability as a source of groundwater in the Big Sky study area. Over most of the region, the formation is 3,000 to 4,000 ft below the land surface. Of the two wells completed in the Madison Group near Big Sky, a shallow well completed at about 40 ft below ground surface produces high-quality water at a productive rate. In contrast, a well completed at a depth of 1,280 ft in the Madison

Group produced poor-quality (highly mineralized) groundwater at a low production rate. The difference in water quality between these wells indicates that the primary groundwater pathways within the formation are localized; there does not appear to be a continuous flow pathway from recharge in upland areas to lowland discharge areas. Due to its great depth within most of Big Sky, the structural complexity of the geologic setting, and uncertainties related to productivity and water quality, the Madison Group aquifer does not everywhere provide the volume of high-quality water needed for a public water supply system. Incurring the expense of deep test wells may be necessary at each location to evaluate the potential for siting a viable production well in the Madison Group.

Snowmelt provides most of the runoff to surface water and most of the recharge to groundwater at Big Sky. The snowpack melts during a 3- to 4-mo period in the spring. Most snowmelt flows directly to creeks and rivers and subsequently discharges from the watershed. Some meltwater infiltrates to bedrock aquifers where fractures or permeable bedrock close to land surface provide a hydraulic connection to underlying aquifers. Snowmelt can infiltrate directly to the surficial sand and gravel aquifers at Meadow and Mountain Villages. In contrast, wells completed in the Morrison aquifer show limited seasonal change in groundwater levels and produce "old" groundwater with elevated mineral content. These lines of evidence suggest that little recharge reaches the thin sandstone layers within the deeply buried Morrison Formation. Recharge to all aquifers from rainfall appears to be minor, and the groundwater system receives little recharge beyond that provided by snowmelt.

Exchange of water between streams and groundwater in the study area is site specific. Streams are primarily fed by snowmelt during the spring and early summer, and groundwater discharge is the primary source of water to perennial streams at other times of year. Stream gaging conducted during this study showed that some sections of the Middle Fork of the Gallatin River near Meadow Village lose flow and recharge the underlying aquifer at some locations. Overall, we measured a net gain (groundwater discharging to the stream) of 3 cfs or less along the Middle Fork through Meadow Village. Earlier investigations by Van Voast (1972) and Baldwin (1997) reported a gain of 12 cfs along this stretch. The decrease in baseflow to the Middle Fork reflects decades of land-use change in the area. For example, parts of Meadow Village that were historically flood-irrigated grass pasture are now developed. More recently, efforts to reduce water use at the golf course likely reduced the amount of irrigation return water to the underlying aquifer. Such changes may lower the water table and subsequently decrease groundwater discharge to the Middle Fork.

Study results highlight the importance of protecting groundwater and surface-water quality. Research conducted by Montross and others (2013) in the Big Sky region showed that bedrock–groundwater interactions (that is, mineral dissolution) are not a significant source of nitrate to groundwater. Data collected by the MBMG and reported here indicate that anthropogenic contaminants contribute nitrate and chloride to groundwater and surface water in the study area. Naturally occurring nitrate levels in groundwater and springs are low (<0.8 mg/L), but concentrations ranged up to 6.6 mg/L in groundwater from the Meadow Village aquifer. Nitrate in groundwater was highest in wells upgradient of the Meadow Village Golf Course, suggesting that sources of nitrate other than golf course fertilizer and effluent application as irrigation water affect groundwater quality. Elevated nitrate and chloride in Meadow Village surface water and groundwater show that surface water and groundwater are both vulnerable to water-quality degradation from surface activities.

Water use at Big Sky varies seasonally, increasing during the winter and summer months. This is related to high visitation rates, summertime landscape watering, and snowmaking early in the ski season. Water use is lower in spring and fall. During seasonally intensive pumping, hydrographs show groundwater levels decline quickly. This is particularly evident in bedrock wells that reflect groundwater extraction for snowmaking. However, during this study, groundwater levels recovered following the reduction in pumping at the end of high-use periods. Overall, groundwater supplies met the demand for water under the pumping and climate conditions during 2014 to 2016.

The Meadow Village aquifer is one of the most heavily used aquifers at Big Sky. The MBMG evaluated the aquifer and its connectivity to the Middle Fork of the West Fork of the Gallatin River using a groundwater flow model (Waren and others, 2021). Model simulations of water use and hypothetical growth scenarios indicate that high-intensity pumping (up to 75% over 2016 pumping rates) from the aquifer over short time periods will reduce groundwater discharge from the Meadow Village aquifer to the Middle Fork. The groundwater flow model can be used to test various management and water-use scenarios associated with changes in pumping and climatic conditions.

Recommendations developed from results of this study address various aspects of water resources across the Big Sky study area. These include techniques for managing the groundwater system and wells, enhancing water storage facilities, and concepts useful to siting new wells. Recommendations also encompass groundwater-quality protection to ensure its long-term usability for potable supply, and conservation measures to constrain anticipated growth in water use.

PREFACE

The Ground Water Investigation Program (GWIP) at the Montana Bureau of Mines and Geology (MBMG) investigates areas prioritized by the Ground Water Assessment Steering Committee (2-15-1523 MCA) based on current and anticipated growth of industry, housing, and commercial activity, or changing irrigation practices. Additional program information and project-ranking details are available on the GWIP pages at: http://www.mbmg.mtech.edu/.

The purpose of the Big Sky project is to provide the hydrogeologic framework for the aquifers in the Big Sky area. Commercial and residential growth in this resort area may result in additional development of water resources. Two reports present findings of the Big Sky GWIP study. This report presents data, addresses questions, offers interpretations, and summarizes project results. The second report, Groundwater Model of the Meadow Village Aquifer at Big Sky (Waren and others, 2021), documents a numerical groundwater flow model developed to assess the effects of groundwater withdrawals from the Meadow Village aquifer.

INTRODUCTION

Background

Big Sky, located in Gallatin and Madison Counties, is a ski resort community in the Madison Range of southwestern Montana about 40 mi south of Bozeman (fig. 1). Established in 1971, Big Sky now includes more than 78 mi^2 with 5,800 acres of skiable terrain. During Big Sky's first 25 yr, development was sporadic; however, since 2013 Big Sky experienced a 21 percent growth in full-time residents, the largest population growth in the State (Big Sky Chamber of Commerce, 2019). Big Sky now has 3,000 full-time residents and a growing seasonal visitor population. During the 2017–2018 ski season Big Sky hosted more than 500,000 skiers, with capacity for many more. According to the 2019 Big Sky, MT Economic Profile (Big Sky Chamber of Commerce, 2019), summer visitations are also increasing. With growth expected to continue, the community is searching for additional sources of groundwater to satisfy the anticipated demand.

Big Sky consists primarily of part-time use vacation homes, condominiums, and hotels located in several developments: Big Sky Resort, (which includes Mountain Village and Meadow Village); Moonlight Basin; Spanish Peaks Mountain Club; Spanish Peaks North, and Yellowstone Club (fig. 2). Except for Spanish Peaks North, each development has its own water distribution system fed by public water supply (PWS) wells. Spanish Peaks North residents are on individual domestic wells.

Water demand fluctuates with the seasonal nature of resort activities and population. Monitoring records at the Big Sky Water and Sewer District (BSWSD), which supplies Meadow Village and supplements Mountain Village and the Yellowstone Club water systems, show water consumption more than doubles during the two-peak tourism seasons; winter (November–April) and summer (June–August). Summer irrigation of lawns and four golf courses add to water demand.

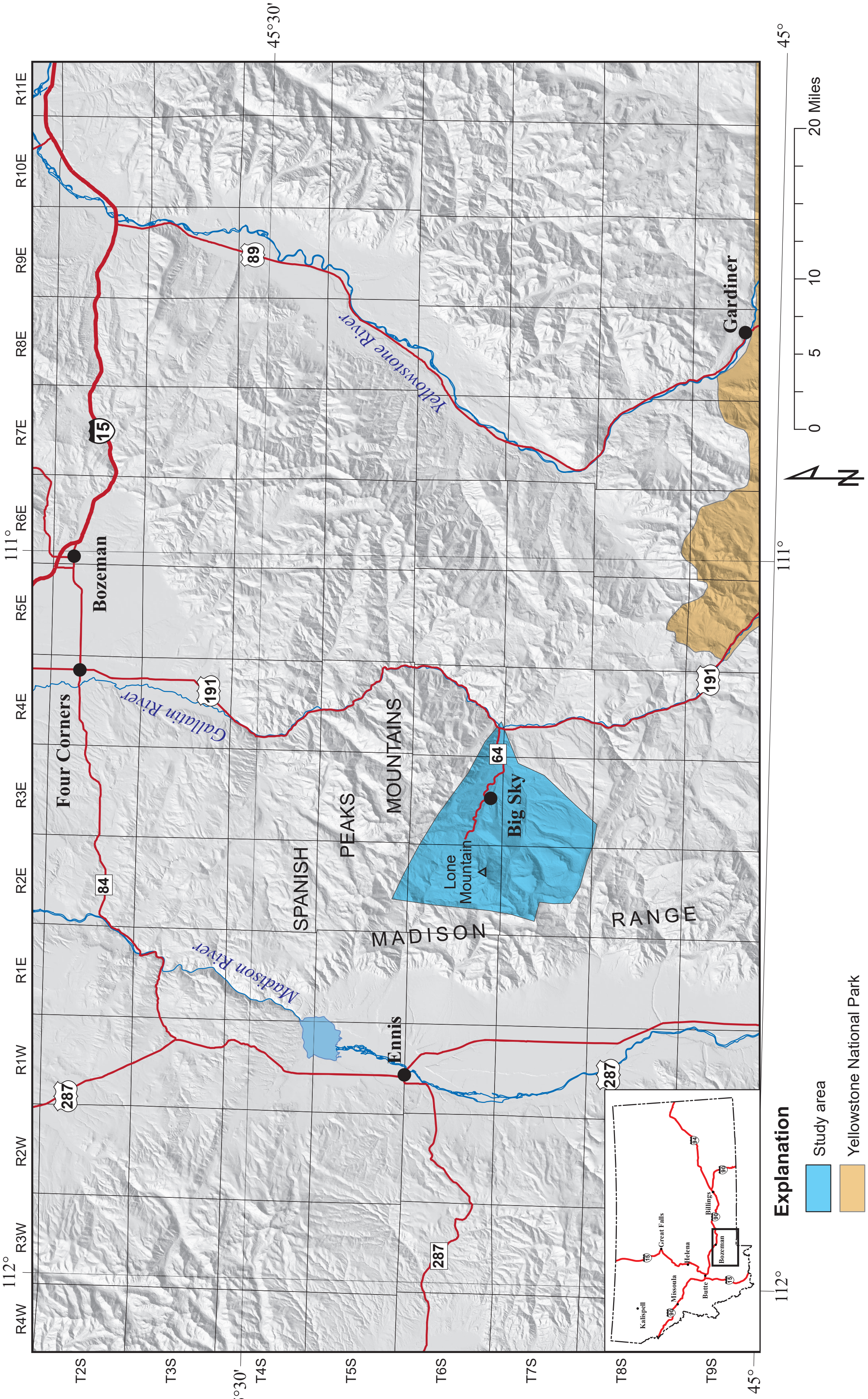


Figure 1. Big Sky Resort is located 40 mi southwest of Bozeman, Montana and 14 mi northwest of Yellowstone National Park.

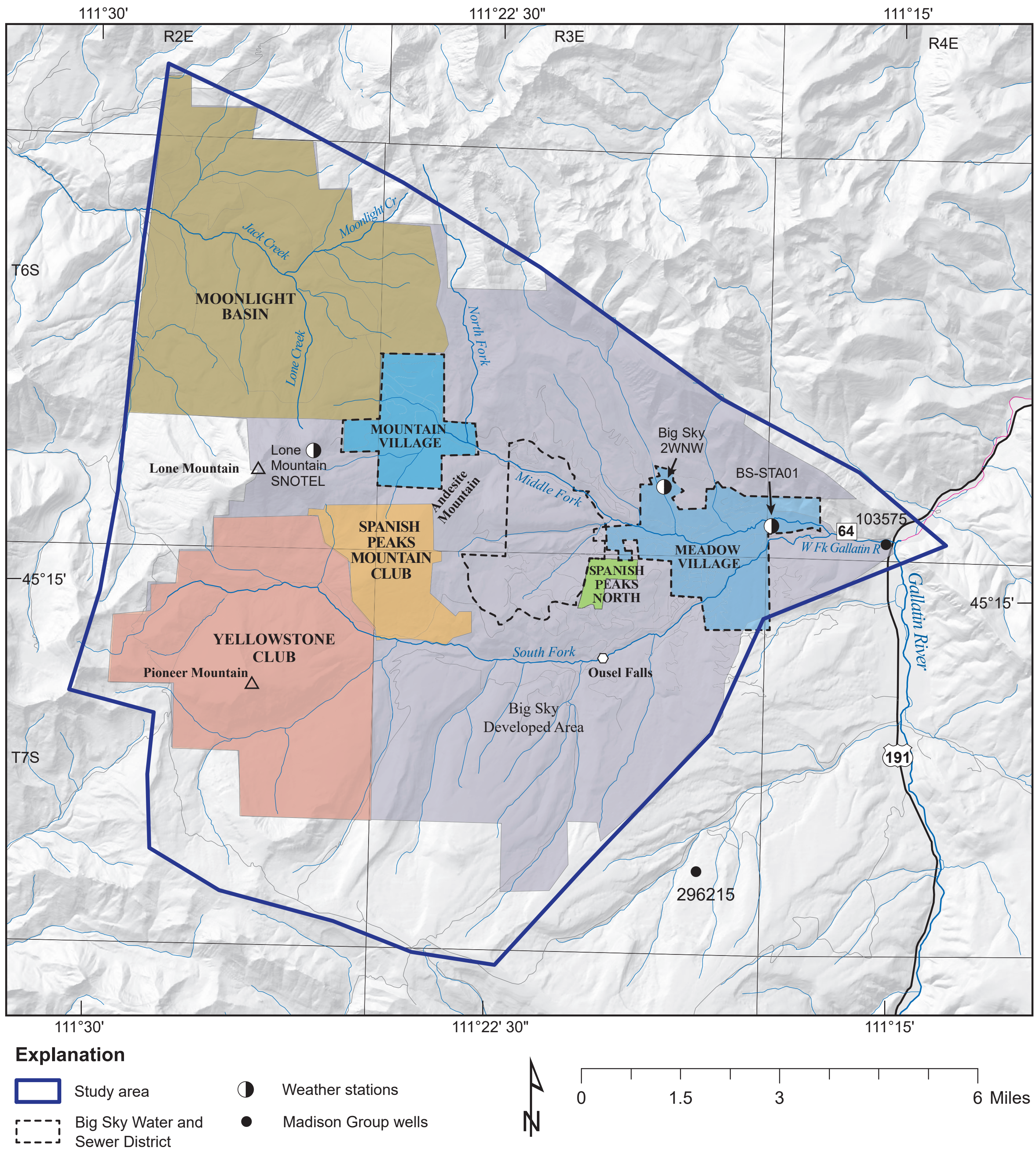


Figure 2. Meadow Village, Mountain Village, Moonlight Basin, Spanish Peaks Mountain Club, Spanish Peaks North, and Yellowstone Club are individual developments within Big Sky. The locations of three weather stations and two Madison aquifer wells are shown.

Big Sky relies solely on groundwater for its water supply. In 1993, the Upper Missouri River Basin Closure declared that all surface water was allocated in the watersheds of the Missouri River, which includes the West Fork of the Gallatin River at Big Sky. Therefore, surface-water development is restricted, and PWS system growth must come from groundwater unless additional water rights are secured.

There are two sand and gravel aquifers tapped by water wells at Big Sky, the alluvial and glacial outwash deposits of the Mountain Village aquifer and the alluvial deposits of the Meadow Village aquifer. The Meadow Village aquifer is one of the most productive at Big Sky (fig. 2). Due to the importance of the Meadow Village aquifer as a PWS, we assessed its groundwater storage capacity and sustainability through development of a numerical groundwater-flow model (Waren and others, 2021).

Throughout most of Big Sky, some groundwater is available from bedrock aquifers. Most water-supply wells are completed in bedrock and draw groundwater from a few thin sandstones layered within thick shales of four geologic formations. Individually these interbedded sandstones do not produce adequate water to meet PWS system requirements. To enhance groundwater recovery some PWS wells are screened through multiple sandstone beds to increase productive capacity.

The structural geology of the bedrock has a significant influence on groundwater availability. The complex geologic history of the Big Sky area makes locating new water-supply wells challenging, and many wells produce less water than desired. Local planners and well drillers need a better understanding of the geology, physical parameters, and limitations of the available aquifers for locating and developing additional wells.

Purpose and Scope

The Gallatin River Task Force (GRTF), a local non-governmental organization, in cooperation with the BSWSD, proposed this project out of concern for meeting the water needs of additional population growth and the effects of adding more individual septic sewer systems.

Residents and system managers have raised concerns over the potential effects to groundwater, surface-water quality, and fish habitat from septic system discharges throughout the community. Better understanding of groundwater resources and the hydrologic cycle across the study area is crucial to addressing this issue.

This Montana Bureau of Mines and Geology (MBMG) Ground Water Investigation Program (GWIP) project assessed groundwater resources in the Big Sky area to assist residents, resort planners, and regulators in planning for increased water demand. We evaluated aquifer capacity, changes in aquifer storage, effects of pumping, and water chemistry. This investigation had five objectives:

1. Summarize the hydrologic characteristics and water quality of the aquifers in the study area.
2. Define the geographic extent and physiographic controls on the groundwater systems.
3. Develop a groundwater model of the Meadow Village aquifer (MVA) for estimating the long-term capacity as a PWS source.
4. Identify groundwater/surface-water interactions in the MVA to understand sources and rates of recharge and discharge to groundwater.
5. Evaluate potential for development of other groundwater sources, including the Madison Group aquifer.

This report addresses objectives 1, 2, 4, and 5. We reviewed existing groundwater and surface-water data and collected new data from 2014 through 2016. The MVA groundwater model, which addresses objective 3, is presented in Waren and others (2021).

Location

The Big Sky study area includes all developments and individual properties within the Big Sky community, and covers about 78 mi^2 (49,920 acres) on and around Lone Mountain (fig. 2). The study area includes developments that lie within the North, Middle, and South Fork watersheds of the West Fork of the Gallatin River, a tributary of the Gallatin River. The study area extends west into the Jack Creek watershed, a tributary to the Madison River. Both river systems are part of the Upper Missouri River Basin.

The Meadow Village aquifer focus area encompasses 1.7 mi^2. Detailed groundwater and surface-water data were collected in this area to develop the groundwater flow model (Waren and others, 2021).

Previous Investigations

Numerous organizations and agencies have investigated groundwater resources in the Big Sky area. The first such hydrogeologic study was a characterization of the West Fork watershed prior to resort development (Van Voast, 1972). This work established a baseline for groundwater and surface-water conditions.

A regional groundwater characterization study of Gallatin and Madison Counties by the MBMG Ground Water Assessment Program (GWAP) collected data from 2008 to 2012, including sampling for nutrients in groundwater in the MVA (Carstarphen and LaFave, 2018). The project also defined available aquifers (Carstarphen and others, 2015).

Three master's theses from Montana Tech summarized groundwater and surface-water conditions. Baldwin (1997) evaluated the vulnerability of the MVA to contamination. This thesis also included a discussion of the regional geologic setting and the potential geologic structural controls on hydrogeology of the bedrock aquifers at Big Sky. Baldwin speculated that the limited number of major structures throughout the Big Sky community suggests less fracturing of the bedrock and less opportunity for recharge by preferential flow paths. Brown (2014) compiled and evaluated existing water-chemistry data and described variations in the water chemistries between aquifers. Combining the results of Brown (2014) with water-chemistry data obtained from this project, Thomson (2016) summarized the groundwater chemistry of selected aquifers.

MSU students conducted groundwater and surface-water studies at Big Sky. Schaffer (2011) completed a senior paper with estimates of groundwater discharge to the Gallatin River from the Madison Group limestones. Gardner (2010), Gardner and others (2011), and Montross and others (2013) evaluated the relationship between land-use change and nutrient loading in mountain streams. Additional studies on stream health are underway (Robert Payn and Meryl Storb, Montana State University, oral commun., 2021).

Consultant reports, available from the BSWSD library, provided background information on the PWS systems, including details about groundwater availability, and assessments of aquifer productivities. While many of the consultant reports focus on water-supply systems or groundwater sources, a few reports summarize conditions over larger areas. These include:

- Source Water Delineation and Assessment Report [Western Groundwater Service (WGS), 2002].
- Feasibility Study for Drilling a New Water Supply Well in Big Sky, Montana (HKM Engineering and Gallagher, 2005).
- The Water System Source Capacity Plan Update (WGS, draft, 2015).

Physiography

Elevations in Big Sky vary from 6,000 ft above mean sea level (amsl) near the Gallatin River, to 11,162 ft at the top of Lone Mountain, which is the fifth highest peak in the Madison Range. This study focused on areas between 6,000 ft and 8,500 ft amsl where housing and infrastructure development are concentrated. The terrain is mountainous and includes dense residential developments consisting of houses, condominiums and hotels, ski terrain, and undeveloped forested land. Much of the forested land within the study area is platted for development.

Climate

Across Big Sky, conditions range from a dry continental climate at lower elevations, around 6,000 ft, to alpine conditions at the highest elevations, over 11,000 ft. We used rainfall and snowfall data from four weather stations to characterize this range. Snowmelt is reported here as snow water equivalent (SWE), a measurement of the amount of water released when the snow melts.

The three low-elevation stations include BS-STA01 (fig. 2), operated by the BSWSD at Meadow Village, at an elevation of 6,100 ft; Big Sky 2WNW at 6,000 ft (fig. 2); and West Yellowstone SNOTEL 924 at 6,700 ft, which is located 43 mi south of the study area (not shown on figures). Lone Mountain SNOTEL Site 590 at an elevation of 8,880 ft provided a high-elevation dataset (fig. 2).

The lower elevations receive an average annual precipitation of 20.2 in (Big Sky 2WNW; WRCC, 2016; table 1). Precipitation occurs typically as rainfall in the spring and early summer and snow is common from late fall through spring. In 2014 Big Sky 2WNW

Table 1. Precipitation data from four climate stations used in the GWIP investigation.

	Elevation (ft amsl)	Period of 30 yr Average	30 yr Average	2013	2014	2015	2016
BS-STA01	6,100	NA[1]	NA	NA	15.4	16.9	11.2
Big Sky 2WNW	6,590	1981–2010	20.2	20.4	26.7	NA	NA
SNOTEL 924 West Yellowstone	6,700	1981–2010	23.8	19.2	30.4	24.0	26.2
SNOTEL 590 Lone Mountain	8,880	1981–2010	34.0	31.1	38.6	33.7	33.0

[1]Not available.

Note. Precipitation in inches.

received 26.7 inches, an annual high for the period of record. SNOTEL 924 has a 30-yr mean annual precipitation of 23.8 in (table 1; WRCC, 2016). Data records for SNOTEL 924 for the study period (2013–2016) showed precipitation was above average during 3 of the 4 study years.

SNOTEL station data show that precipitation is greater at higher elevations. The 30-yr mean annual precipitation at the Lone Mountain SNOTEL 590 site (8,880 ft elevation) is about 34 in, 10.2 in greater than at SNOTEL 924 at 23.8 in (table 1). At SNOTEL 590, up to 60 percent of the precipitation occurs as snowfall (Gardner, 2010). Precipitation at SNOTEL 590 was about 10 percent below the long-term average during 3 of 4 project years. Precipitation in 2014 was about 15 percent above average (table 1).

Temperature records from 1967 to 2016 at Big Sky 2WNW ranged from an average daily minimum of about -7.0°F (-22°C) in January, to an average daily maximum of about 84.9°F (29°C) in July (WRCC, 2016). The mean annual temperature was 37°F (2.8°C). Temperatures at Lone Mountain (SNOTEL 590) are cooler, reaching the upper 70s °F (20s °C) in July and August, dropping to single digits above or below 0°F (-18°C) in February.

Geologic Setting

Many geologic events contributed to the landforms at Big Sky (fig. 3). Geologic mapping by Tysdal (1991), Kellogg and Williams (2006), and Vuke (2013a) show bedrock in the area is composed of thick sequences of Cretaceous through Upper Jurassic marine and non-marine shales that were uplifted and tilted by local intrusions and regional faulting. The shale bedrock contains thin interbeds of siltstone, mudstone, sandstone, and limestone. Glacial till, glacial outwash, debris flows, landslide deposits, alluvium, and colluvium cover much of the land surface. Bedrock is exposed on steep hillsides, but landslide and erosional sediment obscure the surface in many areas, making detailed subsurface geologic interpretations difficult. Most of the development in the study area rests on unconsolidated sediment that overlies shale bedrock.

Several significant Late Cretaceous and younger geologic events influenced aquifer characteristics and shaped the topography at Big Sky. Late Cretaceous movement on the Spanish Peaks Fault steeply tilted Mesozoic and Paleozoic formations in the footwall of the fault (fig. 3). West to east compression of the bedrock from the Hilgard Thrust System west of Big Sky (fig. 3) formed northeast–southwest-oriented folds, such as the Andesite Mountain anticline. The intersecting structures of the two fault systems produced an orthogonal pattern intruded by Late Cretaceous laccoliths (Tysdal and others, 1986). Normal faulting during Cenozoic extension enhanced the structural pattern and resulted in aquifer segmentation. Glaciation subsequently reshaped the surface terrain followed by numerous landslide occurrences throughout the area (Vuke, 2013b).

Spanish Peaks Fault

The Spanish Peaks Fault is an extensive northwest–southeast-striking regional tectonic structure. The southwest-directed reverse fault overrode and tilted Paleozoic and Mesozoic bedrock in the footwall as it moved along planes of weakness in Archean basement rock, offsetting at least 10,000 vertical feet

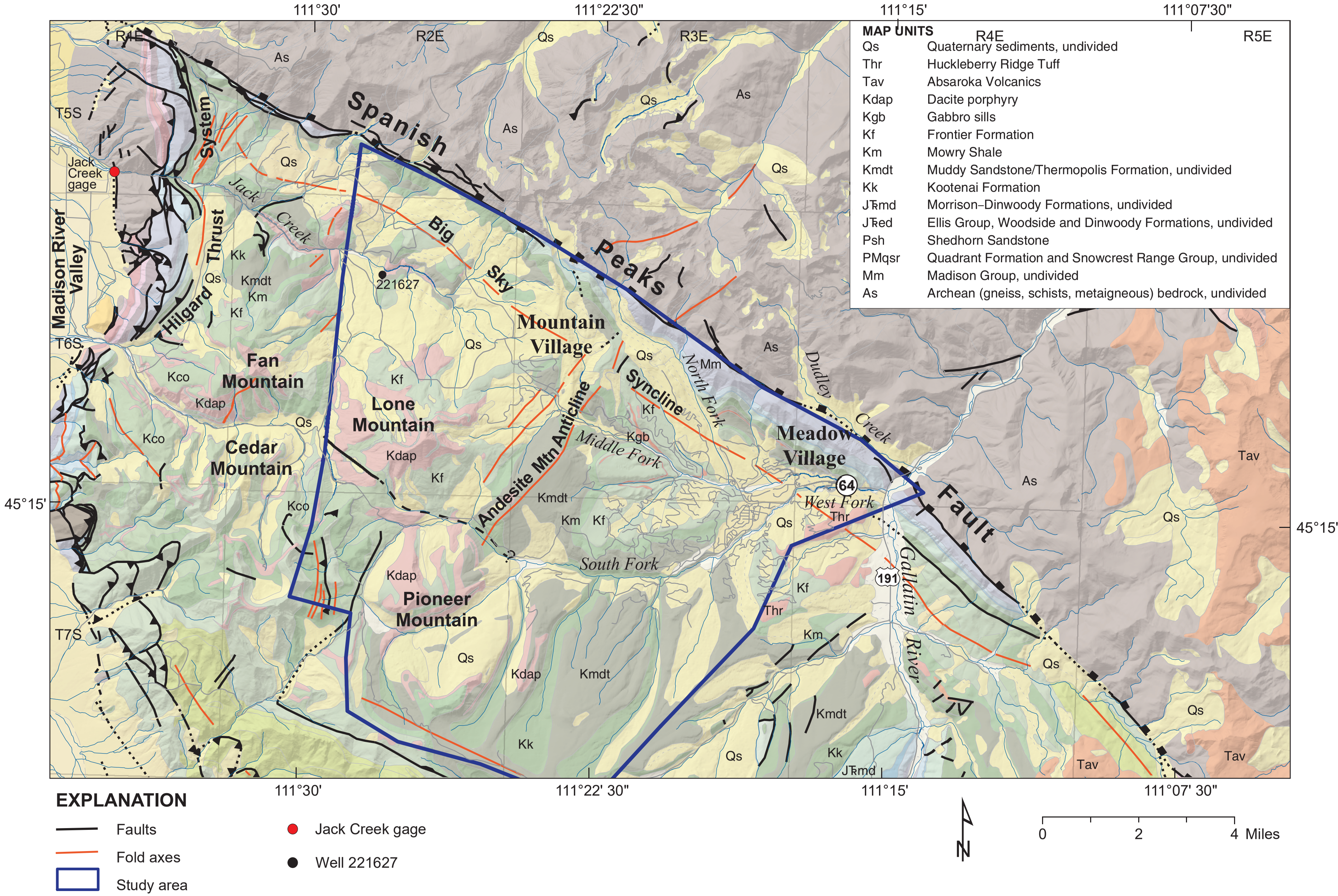


Figure 3. Map of the surface geology at Big Sky (after Kellogg and others, 2006), showing major geologic structures including faults and fold axes. Lone Mountain is cored by an igneous dacite intrusion, and landslide debris covers much of the land surface. The USGS Jack Creek stream gage, site 06040300, is shown in the upper left. Well 221627 is completed in the Kootenai Aquifer.

(3,050 m) of bedrock (McMannis and Chadwick, 1964; Garihan and others, 1983). Fault movement tilted the footwall rocks to the southwest, forming the ridge 3,000 ft above Meadow Village that defines the north boundary of the study area (fig. 3). Bedrock formation outcrops along the ridge dip steeply and in some places are overturned.

Mississippian Madison Group limestone is prominent along the ridgeline as gray, steeply dipping bare-rock cliffs. The Gallatin River incised into the bedrock perpendicular to the Spanish Peaks Fault, forming the Gallatin Canyon. The river canyon exposes the Spanish Peaks Fault and southwest-dipping footwall rock just north of the State Route 64 junction with U.S. Highway 191 (fig. 3).

Crustal compression during uplift created the Big Sky Syncline (WGS, 2008), a fault-parallel synclinal fold in the bedrock less than 1 mi south of the Spanish Peaks fault trace (fig. 3). The fold axis passes through the study area. The steeply tilted formations of the north ridge form the north limb of the fold. In the southern three-quarters of the study area, bedrock layers on the south limb of the fold dip gently at about 10° to the north. The shallow north dip is prevalent in bedrock through much of the Meadow Village area.

Hilgard Thrust

During the Late Cretaceous, eastward compression of the bedrock occurred as the result of east-directed movement of the Hilgard Thrust System west of Big Sky (fig. 3). Tysdal and others (1986) and McMannis and Chadwick (1964) attribute this faulting and folding to regional adjustment to the displacement along the Spanish Peaks Fault.

Dacite Laccoliths

Also during the Late Cretaceous, magma intruded vertically through the sedimentary formations, producing dacite laccolith cores of the conical Lone and Pioneer Mountains in the study area and Cedar and Fan Mountains, located just west of the study area (fig. 3). Swanson (1950) interpreted the igneous rocks as “Christmas tree” laccoliths intruded as a central pipe (trunk) from which sills (branches) emanated along bedding planes into the sedimentary host rock (fig. 4; unit Kdap). The dacite is heavily fractured around the margins of the intrusions and in some of the sills encountered in wells.

Host rocks near the intrusions typically exhibit a thin zone of contact metamorphic alteration associated with heat from the intrusion. These rocks show a partially re-melted and brittle character. The partial re-melting reduced primary porosity of the host rock, especially the sandstones, but fracturing of these brittle rocks increased secondary porosity.

Landslides

Several features of the Big Sky area promote landslide development. These include steep mountain slopes, dipping weak sedimentary bedding planes, relatively heavy annual snowfall, and landslide triggers such as earthquakes (Vuke, 2013b).

The Cretaceous formations that extensively underlie the Big Sky area contain alternating permeable sandstone and impermeable mudstone, including shale. Erosion-exposed sandstone beds allow infiltration of precipitation that can saturate weak bentonitic and other clay-rich zones. This reduces friction and facilitates landslide movement along the weakened planes. Ground movement may be slow—less than an inch a year—or rapid, such as when earthquakes or increased loading of saturated bedrock trigger sudden landslide development. Geotechnical studies have confirmed that landslides in the area are still active.

Hydrogeologic Setting

The geologic setting described above, including the formations, the relative orientations of their bedding, geologic processes, and tectonic structures, is important in understanding the availability, productivity, and extent of groundwater at Big Sky.

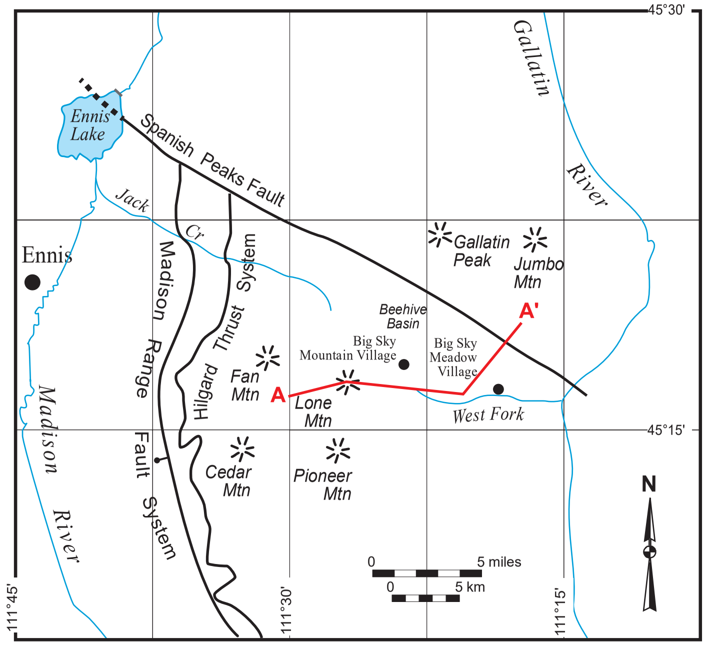
At Meadow Village wells draw groundwater from the unconsolidated MVA. At Mountain Village wells draw from the Mountain Village aquifer, and from the fractured dacite intrusive. Wells in these aquifers are the most productive wells in the Big Sky community. However, the unconsolidated MVA, Mountain Village aquifer, and the fractured bedrock dacite aquifer are location-specific and not present everywhere.

The MVA is a locally important, unconfined aquifer composed of unconsolidated glacial outwash and modern (Quaternary) sand and gravel alluvium. The Mountain Village aquifer consists of glacial till and alluvial fan deposits. Productivity in the dacite aquifer is dependent on wells intersecting heavily fractured zones that are difficult to identify from the land sur-

CROSS SECTION EXPLANATION

Qgt	Glacial till
Kdap	Dacite porphyry and related compositions
Kgb	Gabbro
Ks	Everts through Thermopolis Formations
Kk	Kootenai Formation
Jm	Morrison Formation
JTRed	Ellis Group and Dinwoody Formation
IPq	Quadrant Formation
IPMqsr	Quadrant Formation and Snowcrest Range Group
Mm	Madison Group, undivided
MDtj	Three Forks and Jefferson Formations
MDt	Three Forks Formation, undivided
Dj	Jefferson Formation
Ob	Beartooth Butte Formation
€s	Sedimentary rock, undivided
Amt	Archean metamorphic rock, undivided

The original map for Cross Section A–A' is a 1:36,360-scale geologic map of part of the Virginia City and Eldridge 15' quadrangles (Swanson, 1950).
The line for the cross section is only indicated on the inset map, because the cross-section (1:48,000 scale) is not necessarily coincident with the current geologic map.



Cross Section A–A'

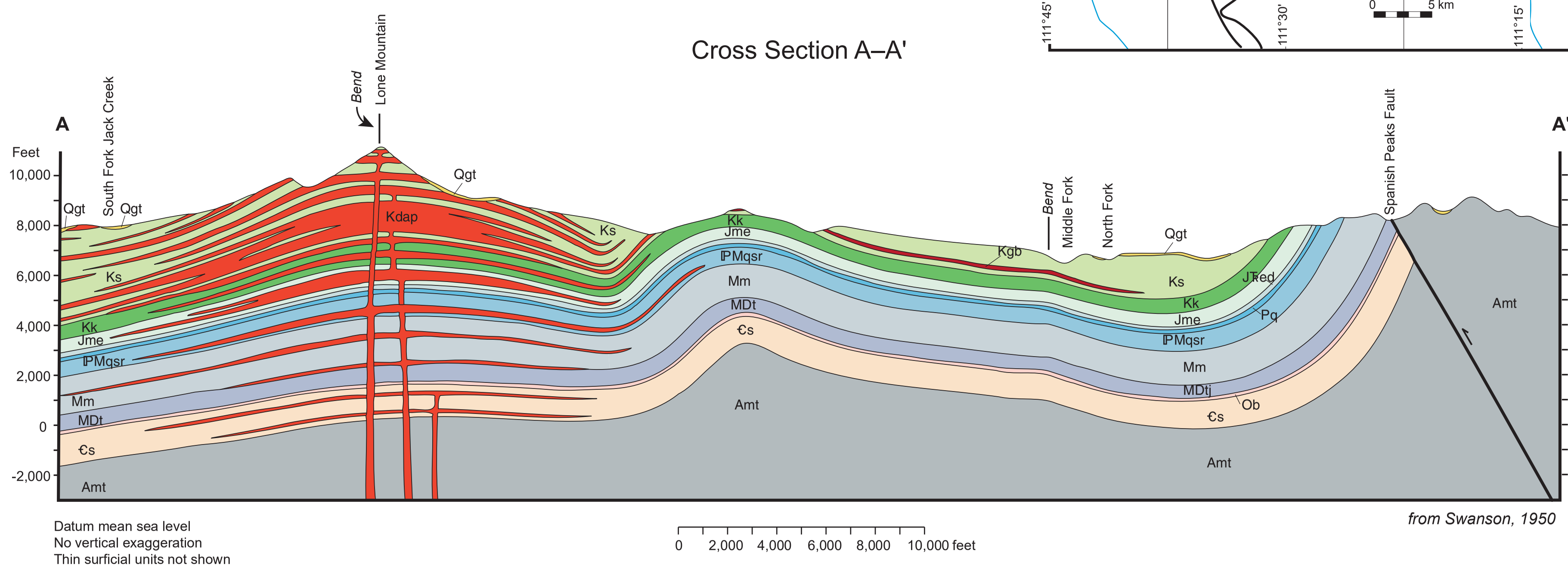


Figure 4. A generalized geologic cross-section at Big Sky (Vuke, 2013, after Swanson, 1950). The cross-section shows the relative thickness of the geologic formations, the effects of regional faulting and igneous intrusions on the local geology, and the dacite sills that extend out from Lone Mountain along contact and bedding planes of the Cretaceous sedimentary formations.

face. All three aquifers are productive sources of high-quality water with low mineral content.

Bedrock aquifers are prevalent throughout the study area. Sandstone beds in the Frontier, Muddy, Kootenai, and Morrison Formations (figs. 3, 4) yield groundwater to wells.

In the search for additional groundwater, Big Sky community planners are considering development of the Madison Group limestone. The Madison Group is composed of the Lodgepole and Mission Canyon limestones found in much of central Montana. In some locations, Madison Group limestones have karstic solution features such as large cavities and enlarged fractures. At some locations in Montana, the Madison Group provides abundant, high-quality groundwater within typical water-well drilling depths (on the order of 1,000 ft or less). The Madison Group is the source of several of the largest springs in the State: Great Falls' Giant Springs, Lewistown's Big Spring, and Toston's Big Springs (Van Voast, 1972).

Within the Big Sky area, measured thicknesses (Tysdal, 1991; Vuke, 2013a) and well records of formations that overlie the Madison Group (GWIC, 2020) suggest this limestone lies 3,000 to 4,000 ft below ground surface at Meadow Village. This exceeds the depth of conventional water-well drilling. In contrast, the Madison Group outcrops at the land surface in the Gallatin River Canyon near the Highway 191 and State Road 64 intersection, a result of uplift along the Spanish Peaks Fault. Within the Canyon, springs that discharge from the Madison Group supply substantial baseflow to the Gallatin River.

Surface-Water Hydrology

Big Sky is situated on a hydrologic divide between two watersheds. The West Fork flows east to the Gallatin River, and Jack Creek flows west out of Moonlight Basin into the Madison River near Ennis, Montana (fig. 2).

The West Fork of the Gallatin River drains an 80-mi^2 watershed above its confluence with the Gallatin River. The West Fork consists of three tributary branches that drain the east, north, and south sides of Lone Mountain. The Middle Fork originates on the north slope of Lone Mountain in Moonlight Basin just west of Mountain Village (fig. 2). The North Fork joins the Middle Fork 0.3 mi upstream of the Meadow Village Golf Course. The Middle Fork then continues east through the Meadow Village Golf Course and through the sand and gravel of the MVA. The South Fork and Middle Fork merge 1 mi below the golf course to form the West Fork. The West Fork flows 0.9 mi east where it joins the Gallatin River near the intersection of State Road 64 and Highway 191 (fig. 2).

Although there are no continuous discharge measurements on the West Fork, stage data from a station about 0.6 mi below the golf course (site 274333) indicate that lower stages and lower flows occur from August to April and higher flows occur during spring runoff from April to July (fig. 5).

Jack Creek is formed by the convergence of Lone Creek and Moonlight Creek on the west side of Lone Mountain. It drains a 51.5-mi^2 watershed that includes Moonlight Basin (fig. 2). Mean monthly flows in Jack Creek were measured by the USGS from 1976 to 1985 at a gaging station located about 6 mi west of the study area boundary (fig. 3).

Snowmelt is the primary water source to streams during the spring and early summer. During other times of the year groundwater discharge is the primary source of water to perennial streams. Previous work suggests that groundwater discharge to streams is 6 to 14 percent of average annual precipitation (Van Voast, 1972; WGS, 2002).

METHODS

Data Management

GWIP Big Sky project data are housed in the MBMG's Ground Water Information Center Database (GWIC, 2020). The database contains well location and completion information, aquifer designation, groundwater levels, water chemistry, aquifer test data, and other information. Appendix A lists GWIC identification numbers (GWIC ID) for project surface-water and monitoring well sites. Sites referred to in this report are denoted by the GWIC ID for wells (e.g., well 219966) and for surface water (e.g., site 274333).

Geologic Information

We developed several geologic cross-sections to better understand the local geologic and hydrogeologic settings. Surface geology from maps by Tysdal (1991), Kellogg and Williams (2006), and Vuke (2013a), and water-well lithology logs from the GWIC database (GWIC, 2020) were used to construct the cross sec-

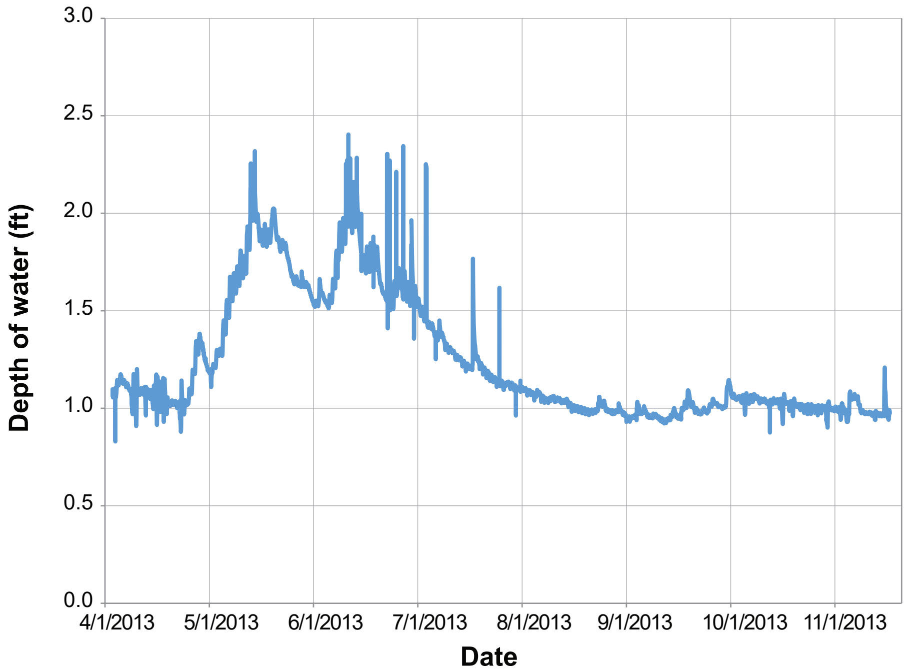


Figure 5. Stage of the Middle Fork measured below the Meadow Village Golf Course at Gallatin River Task Force site 274333 (fig. 6), in 2013. The river stage reflects spring runoff, peak flow, and decline through the summer into winter typical to the area.

tions using GMS software (Aquaveo, 2017). A stratigraphic column was created to combine geologic and hydrogeologic descriptions and cross-section information from other authors (Dixon, 2002), from consultants' reports (WGS, 2002; HKM and Gallagher, 2005), and from this investigation.

The configuration of the MVA was determined by constructing a series of cross-sections based on drillers' logs from 17 existing monitoring wells and 15 new monitoring wells drilled for this project. The well data were processed with GMS software to define the orientation of geologic strata and the aquifer thickness.

Monitoring

Surface Water

Surface-water monitoring and sampling sites were established on the mainstem of the West Fork, and on its three principal tributaries: the North, Middle, and South Forks (fig. 6). Monitoring locations were also established on Jack Creek and at spring sites. Surface-water monitoring included stage measurements and stream gaging to estimate discharge, water-quality parameters (e.g., temperature, specific conductance, and pH), and water sampling for chemical analysis (appendix A, table A1). One-time measurements of discharge and water-quality parameters were collected from other streams in the project area (fig. 6).

Ten stream gaging sites were established on the Middle Fork in the Meadow Village area to measure stream discharge and stage in conjunction with the MVA assessment (fig. 6, inset; appendix A, table A1). For comparison to historic data, eight of the gaging sites were reestablished as close as possible to sites used by previous investigators (Van Voast, 1972; Baldwin, 1997). Six of the gaging sites are within MVA model boundaries (Waren and others, 2021). The six sites were located along a 2.1-mi stretch of the Middle Fork between Two Moon Bridge (site 275228) at the upstream boundary of the Meadow Village Golf Course and the culvert site beneath State Road 64 (275238), about 1 river-mile downstream of the golf course (fig. 6). All gaging sites were surveyed by a licensed surveyor for location and elevation. A staff gage and pressure transducer installed at each site recorded stage over time. Discharge was measured monthly at six sites, as ice cover allowed, using a Flowtracker handheld Doppler flow meter. Four additional sites were gaged in spring, summer, and/or fall.

The GRTF has maintained four stream monitoring stations in the MVA area since 2003 (sites: 274335 (North Fork); 274333 (Middle Fork); 274334 (South Fork); and 274332 (West Fork; fig. 6). Data from these sites collected during this project are available in GWIC (2020). Historic data from these sites are avail-

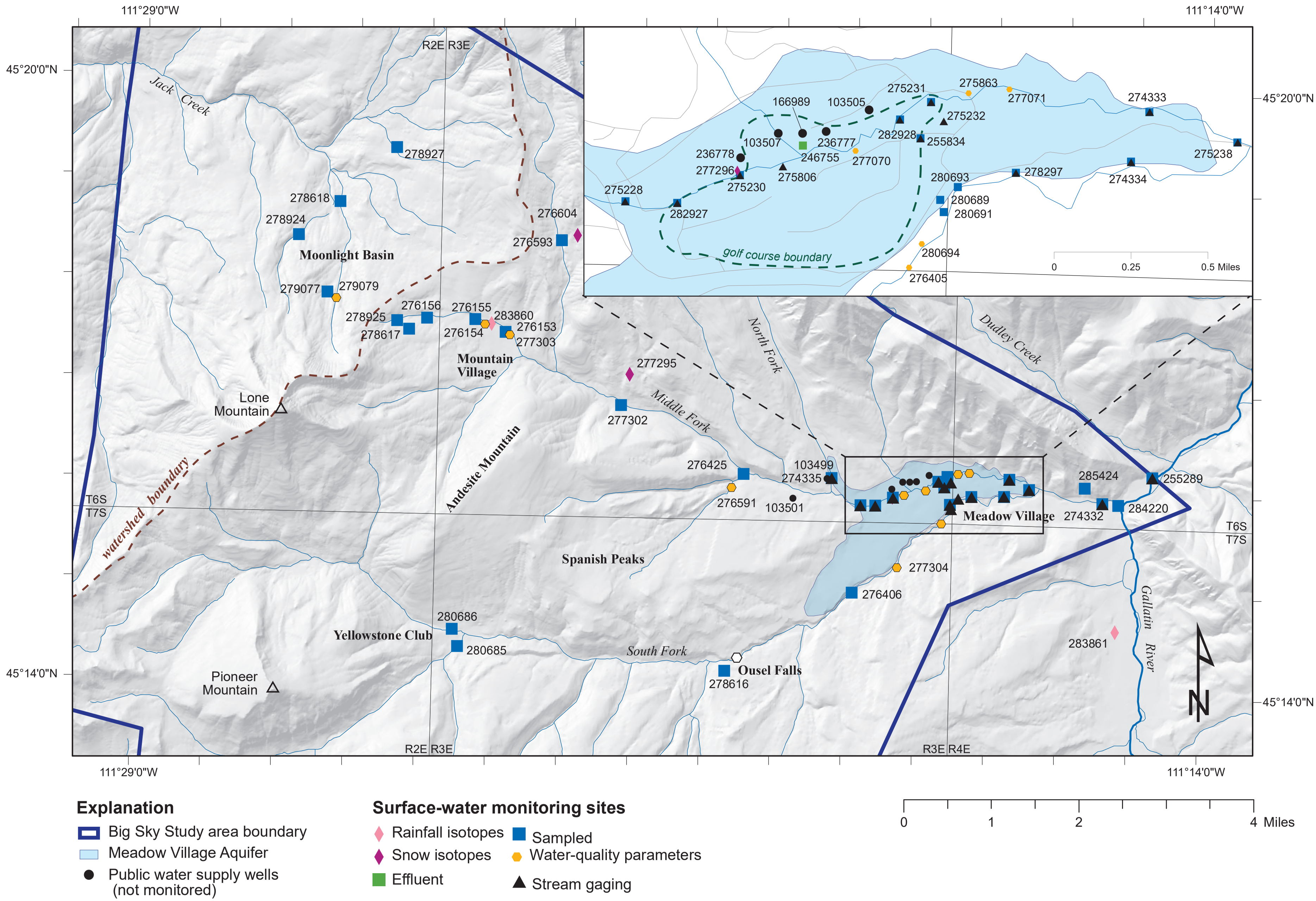


Figure 6. Locations of surface-water monitoring and sampling sites. The boundaries of the Meadow Village Aquifer are based on the mapped edges of the Quaternary glacial outwash (Qgo) and the Quaternary alluvium (Qal) along the river and on well logs of now abandoned wells to the south GWIC (2020). These units are the host material of the aquifer.

able through the GRTF (K. Gardner, Gallatin River Task Force, oral commun.).

The GRTF continuously monitors river stage at the Middle Fork site 274333 using a sonic distance sensor and data recorder located over the river. The sensor measures the distance to the water surface from a fixed reference point to determine river stage. The design of this sensor allowed measurements to the water surface, but also to river ice cover and the accumulated snow depth on top of the ice during the winter. Waren and others (2021) relied on these data to determine the timing of spring snowmelt when constructing the MVA model.

Groundwater

Well Inventory

Ninety-four wells were "inventoried" for this investigation, which included locating the well record and evaluating the condition of the well for monitoring (appendix A; table A2). Data from these wells, including water-level measurements, well completion details, lithologic logs, and water analyses, are available in the GWIC database (GWIC, 2020). Well locations were determined by MBMG staff using a handheld GPS and map-derived elevations to within ±10 ft accuracy.

Monitoring Well Network

Pressure transducers were installed in 44 of the 94 inventoried wells (fig. 7; appendix A, table A2). Unvented In-Situ RuggedTroll 100s or LevelTroll 300s, and two Solinst transducers with specific conductance sensors, recorded hourly water levels in these wells. Data from four barometric pressure transducers located throughout the study area were used to correct the unvented transducer measurements. Water levels in the remaining 50 wells were measured manually each month as snow cover allowed (appendix A, table A2). Groundwater hydrographs for select wells (fig. 8) were compared to snowmelt, rainfall, stream stage, and to pumping from nearby wells.

Meadow Village Focus Area

Forty wells were monitored in the Meadow Village area (appendix A, table A2). Thirty of the wells were monitored specifically to support the MVA groundwater model. Of these, 27 were completed in the MVA (alluvium), and 3 wells—103557, 104510, and 220659—were completed in sandstone within the underlying Frontier Formation. Fifteen monitoring wells in the MVA were drilled for this project, including 3 nested well pairs. Transducers recorded hourly water levels in 23 wells in the MVA and 7 were manually measured each month (fig. 7, inset; appendix A, table A2).

Aquifer Test Data

Aquifer test data for wells in the study area were compiled from consultants' reports, published literature, and DNRC records, and were matched to the appropriate GWIC ID (appendix B, table B1). A summary table of aquifer test analyses from WGS (2008) provided transmissivity (T) and specific yield (S_y) values for the five BSWSD pumping wells completed in the MVA.

Water Chemistry

Sampling

Water chemistry samples collected from surface water (fig. 6) and wells (fig. 9) were analyzed for major ions (appendix C), trace elements (GWIC, 2020), stable isotopes (appendix E), and tritium (appendix F). Sampling results from previous studies (Van Voast, 1972; Baldwin, 1997; Carstarphen and others, 2015, 2018) were incorporated into the dataset for water chemistry classification. Samples were collected for this study in accordance with MBMG standard operating procedures (Gotkowitz, 2022) and preserved as described in Timmer (2020).

Surface Water

Seven streams and three springs were sampled for major ions, trace metals, and/or stable isotopes (fig. 6; appendix C, table C1). Snow samples from the full accumulated snowpack depth were composited at three sites representing elevations of 8,080 ft, 7,240 ft, and 6,260 ft. Rainwater samples were collected at 7,575 ft and at 6,080 ft elevation from a single storm event (appendix E, table E2). These samples were collected directly into sampling containers for stable isotopes.

Water from the Meadow Village Golf Course sprinkler system (site 246755) was sampled for major ions, trace metals, nitrate, and stable isotopes. This sprinkler water is pumped from the treated effluent holding ponds of the BSWSD wastewater treatment plant.

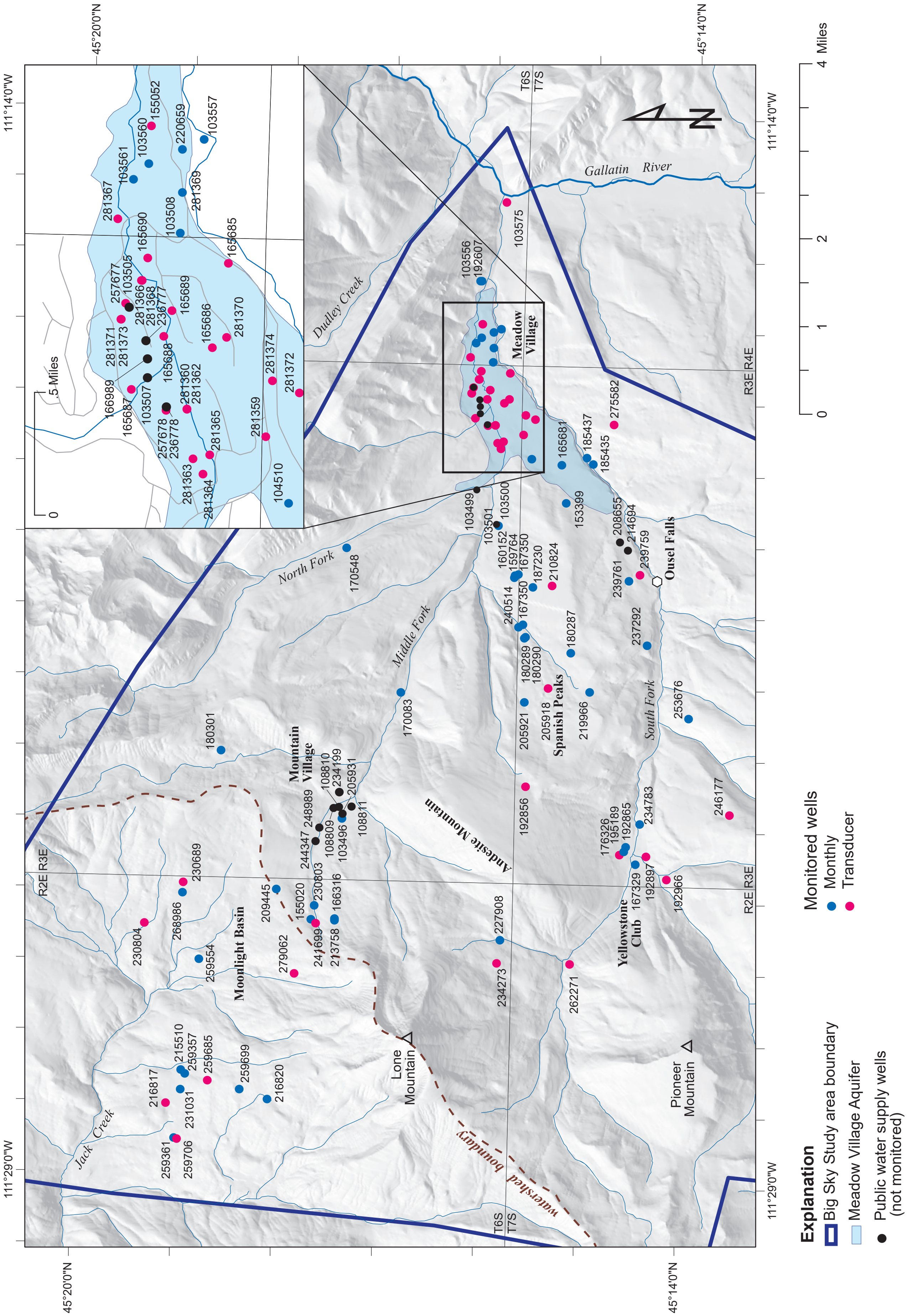


Figure 7. Location of groundwater wells monitored for this project. Wells are identified by hourly or monthly water-level measurements.

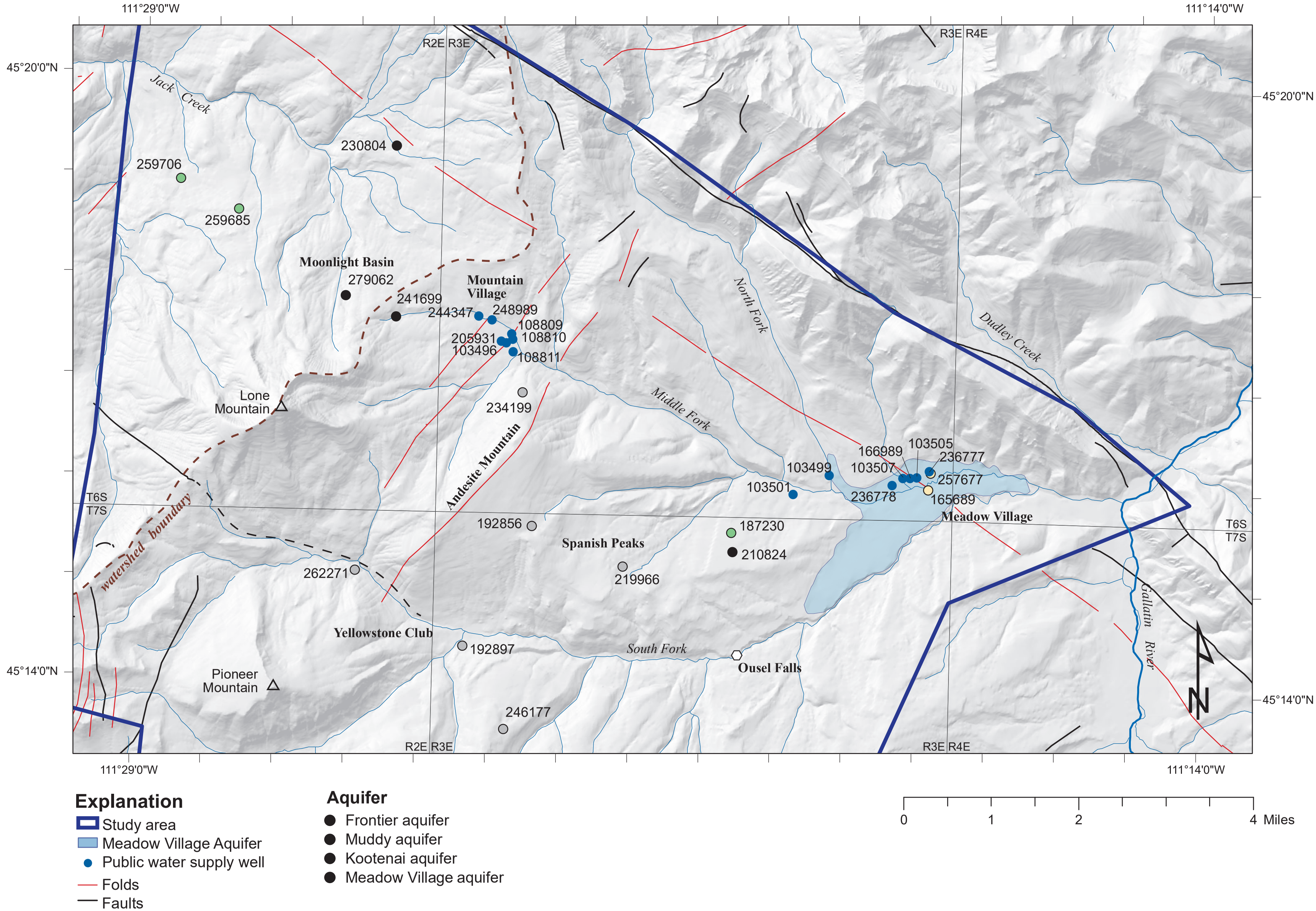


Figure 8. Location of wells with groundwater hydrographs used in this report. Wells are identified by aquifer.

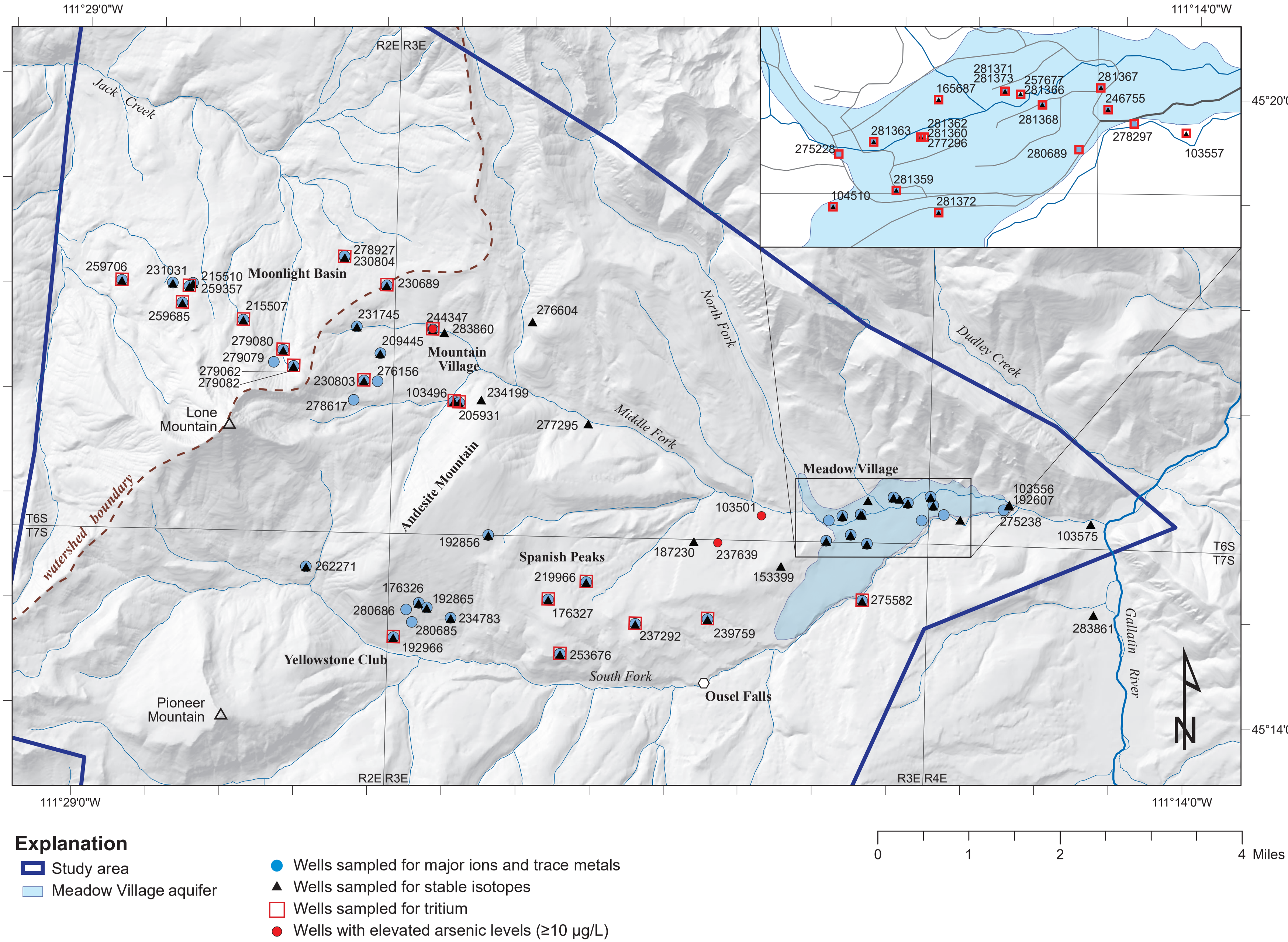


Figure 9. Location of groundwater wells sampled for major ions, water isotopes, and tritium. Wells 103501, 237639, and 244347 showed elevated arsenic (>10 µg/L) when sampled in 2011. Well 244347 was sampled in 2015 for this project and again showed elevated arsenic.

Temperature, pH, specific conductance (SC), and dissolved oxygen (DO) of sampled water were measured in the field at the time of sample collection and monthly (when accessible) at 18 surface-water sites (GWIC, 2020).

Groundwater

Forty wells were sampled for major ion, trace metal, and stable isotopes. Wells were completed in different aquifers and located throughout the study area (fig. 9). Wells were sampled following purging of three well volumes and the stabilization of pH, SC, temperature, and DO in the purge water. Twenty-one of the well samples were also analyzed for tritium (described below).

Isotopes

Selected groundwater, surface water, snowmelt, and precipitation samples were analyzed for stable isotope ratios of oxygen-18 and hydrogen (deuterium) (^{18}O/D; fig. 9). The samples were collected directly into sample containers with zero headspace. The MBMG Laboratory in Butte, MT analyzed water samples for oxygen and hydrogen isotopes on a Picarro Isotope Analyzer (Timmer, 2020; appendix E, tables E1–E3). These data are provided for the interested readers but are not discussed further in this report.

Tritium

Tritium (^3H) is a naturally occurring radioactive isotope of hydrogen that decays to helium; tritium has a half-life of 12.3 yr. Typically present in the atmosphere at very low concentrations, tritium was also introduced into the atmosphere as a byproduct of atmospheric nuclear testing between 1951 and 1976 (Nikolov and others, 2019). These tests increased the tritium incorporated into the water molecules in precipitation. This bomb-tritium signature is imparted in groundwater that originated as precipitation recharge within the last 70 yr.

For this study, water samples from 21 wells (fig. 9) were collected in two 500 mL high-density polyethylene bottles with no head space, sealed with electrical tape, and shipped to the University of Waterloo–Environmental Isotope Laboratory in Waterloo, Ontario, Canada. Tritium analysis was performed by liquid scintillation counting.

RESULTS

This section presents the data, analyses, and interpretation of the groundwater systems in the Big Sky area. Sections focus on the hydrogeologic units, their characteristics within each of the major developments, and water quality. Data from other parts of the hydrologic system, including precipitation records and measurements from the stream network, are also presented.

Snowmelt and Rainfall

Total annual precipitation averages, shown in table 1, include rainfall and snowmelt. Snowmelt is the primary source of stream flows and groundwater recharge within the study area. In typical years, the snowpack accumulates for 5 mo in the winter and melts over a 3-mo period in the spring. Groundwater levels peak during snowmelt, indicating that infiltrating meltwater is a primary component of annual groundwater recharge. Like other western Montana watersheds, large increases in river discharge at Big Sky in the spring suggest much of the snowmelt flows into streams and is subsequently conveyed out of the watersheds.

Snowpack accumulation increases with elevation in the mountainous terrain at Big Sky. As shown in figure 10, during water years 2015 and 2016 snow began accumulating in early November. In both years, low-elevation snowmelt began mid-March or early April and melted off by mid-April. From 1980 to 2010, the median peak SWE at low-elevation SNOTEL 924 site was 10.2 in. High-elevation snowmelt began mid-April, continuing into early June. Over a similar period, median-annual peak SWE at high-elevation site SNOTEL 590 was 18.9 in. A comparison of the SNOTEL SWE charts shows that snow at low elevations may completely melt before the high-elevation snow pack undergoes much melting (fig. 10). This difference in timing of melt events and the amount of accumulated snow with elevation extends the surface-water runoff period and related groundwater recharge from snowmelt to nearly 4 mo. These differences in the location, magnitude, and timing of snowmelt affect the magnitude and timing of local response in groundwater levels and stream discharge. Long-term records at West Yellowstone SNOTEL 924 from 1988 to present show that snowpack accumulates and melts at about the same time each year.

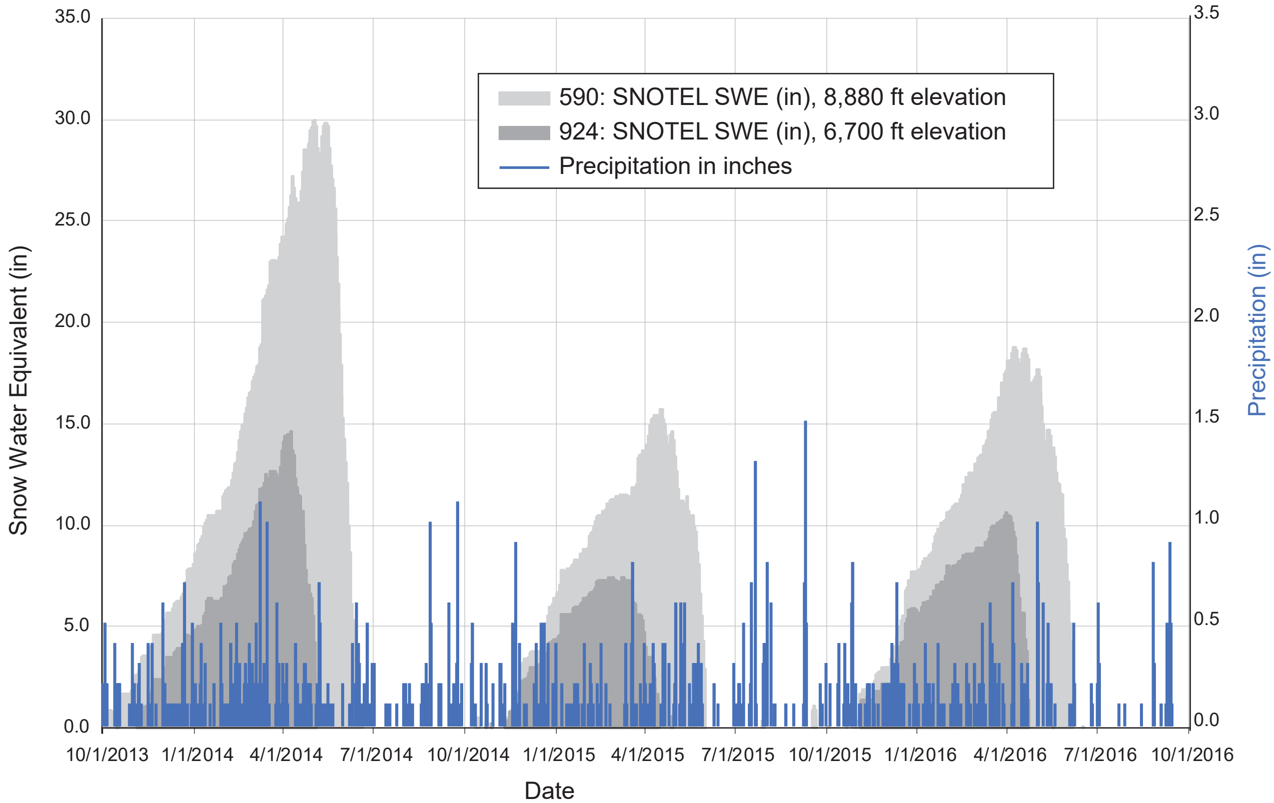


Figure 10. Snow water equivalent of snowpack, 2013 through 2016, at Lone Mountain SNOTEL site 590 and West Yellowstone SNOTEL site 924 in the Madison Mountain range. Daily precipitation records are from the SNOTEL 590 site.

Summer precipitation occurs mostly as rainfall. Precipitation recorded at low-elevation weather station Big Sky 2WNW (1967–2016) and at the high-elevation SNOTEL 590 site (1981–2014) shows that rainfall occurs from April through October, often as short-duration, low-accumulation events (less than 0.5 in). Occasional large storms and multiday rainfall can accumulate 1 to 2 in of water over 5 days or less. Precipitation records from both stations show that large storms occur about four times per season (fig. 10). As shown in the following portions of this report, stream stage hydrographs show that large rainfall events cause brief rises in river stage. Groundwater levels in only a few bedrock wells appear to rise in response to large rainfall events (>0.5 in).

Surface Water

Synoptic stream gaging measurements on September 24, 2014 and September 24, 2015 under base-flow conditions were compared to estimate the total contribution to West Fork discharge from the Middle Fork (including the North Fork) and South Fork. The Middle Fork flows through Mountain Village and Meadow Village, and the South Fork flows through Yellowstone Club and Spanish Peaks Mountain Club. Gage locations are shown in figure 6. On September 24, 2014, combined discharge on the Middle and North Forks (site 274333, below the golf course) was 8.5 cfs. A discharge of 21.5 cfs was measured on the South Fork above the confluence with the Middle Fork (site 274334). These measurements indicate that the Middle Fork and South Fork contribute about 28 percent and 72 percent, respectively, of the total discharge to the West Fork. On September 24, 2015, site 274333 contributed 12.6 cfs below the golf course, and site 274332, located on the West Fork, contributed 33.2 cfs. These measurements provided similar results, with the West Fork receiving 28 and 72 percent of flow from the Middle and South Forks, respectively. This relationship was consistent with measurements by Baldwin (1997).

Contribution of the West Fork watershed to the Gallatin River was estimated by comparing discharges of both rivers. RESPEC, LLC. reported 893 cfs of discharge on the West Fork (site 274332) on May 24, 2014 (K. Gardner, Gallatin River Task Force, written commun., 2018). The mean daily discharge of the Gallatin River on that date was 5,860 cfs (USGS, Gallatin River near Gallatin Gateway; 06043500). The

West Fork contributed 15 percent to the discharge of the Gallatin River.

Jack Creek

Mean monthly flows measured in Jack Creek (fig. 3) at the USGS gage 06040300 from 1976 to 1985 ranged from a low of 13 cfs at baseflow in February to a high of 163 cfs during snowmelt runoff in June. The mean annual discharge was 47 cfs.

Middle Fork in the Meadow Village Focus Area

Middle Fork stage measurements at site 274333, downstream of the MVA, rose sharply with snowmelt. Discharge measurements in April, June, and July of 2014–2016 at sites 275231, 274333, and 275238 (fig. 6), sites downstream of the golf course, ranged from 21.3 cfs to 38.4 cfs. Discharge dropped sharply after snowmelt to 12.6–15.2 cfs by the third week of July. Discharge continued to decline through late summer, fall, and winter, dropping to 3.6–10.3 cfs by late March and early April of the following year (appendix D, table D1).

Near-peak flow of the Middle Fork was measured on May 24, 2014 at 317 cfs (site 275230; GRTF, 2018). This is about 30 times greater than measured baseflow. Stream stage measured by the MBMG during this study (2014–2016) was comparable to historic gaging records for this site measured by the GRTF (K. Gardner, Gallatin River Task Force, oral commun., 2013).

We characterized groundwater/surface-water interaction between the MVA aquifer and the Middle Fork for construction of the MVA groundwater model (Waren and others, 2021). Stream discharge measurements at selected stations on the Middle Fork were compared to identify stretches where the river lost water to the aquifer and stretches where the aquifer discharged to the river.

Discharge data from the Middle Fork between sites 275228 and 274333, located above and below the MVA, show there are both gaining and losing reaches of the river where it flows across the aquifer (appendix D, table D1). Although Baldwin (1997) and Van Voast (1972) both reported a 12 cfs gain overall in Middle Fork discharge where it crosses through the MVA, stream gaging conducted during this study did not reproduce their results. Between September 2013 and July 2016, we conducted nine synoptic stream gaging events between these two sites. Each of the synoptic runs showed a net gain of 3 cfs or less (appendix D, table D1). The measured gains are small but repeatable; however, they are also close to the instrument measurement error.

The MVA groundwater flow model simulates groundwater and surface-water exchange between the Middle Fork and the aquifer (Waren and others, 2021). Incorporating the stream gaging data, the model supports the conclusion that the stream generally loses flow to groundwater in the upstream part of this reach and that groundwater discharges to the stream in the downstream segment.

A third approach to determining stream gain was analysis of specific conductance (SC) measurements at each Meadow Village gaging station. SC increased downstream on the Middle Fork from 27 to 70 µS/cm. Groundwater from the Frontier Formation that underlies the MVA is about 700 µS/cm. Assuming SC is conservative, simple mixing calculations show that the West Fork may be gaining 3 cfs or less from bedrock groundwater along this reach. Increased SC could also be derived from mineralized alluvial water. Possible sources of groundwater into the MVA include discharge from the permeable sandstone layers of the underlying Frontier Formation or from adjacent till and outwash deposits around the margins of the aquifer. Precipitation infiltrates from the land surface to the water table in surrounding till and outwash deposits and may discharge into the MVA. These sources of recharge to the MVA lead to discharge from the aquifer to the river.

The differences in stream gains near Meadow Village reported by Baldwin (1997) and Van Voast (1972) compared to this investigation reflect decades of land-use change in the area. The 1972 study occurred prior to construction of the Meadow Village development and golf course. At the time of that study, the Meadow Village area was grass pasture with extensive flood irrigation. By 1995, Meadow Village had been constructed, the treated effluent retention ponds were in use, and the application of effluent as golf course irrigation was unrestricted. Also in 1995, local officials discovered that sewage effluent retention ponds were leaking treated effluent to the groundwater (Ron Edwards, Big Sky Water and Sewer District, oral commun., 2016). The sewage effluent ponds were lined and sealed following this discovery. In 2010, personnel from the golf course and BSWSD began monitoring golf course irrigation rates and limiting water application to just meet the evapotranspiration demand of the grass, reducing irrigation recharge to groundwater (Ron Edwards, Big Sky Water and Sewer District, oral commun., 2014). Results from our study indicate that flood irrigation practices and golf course irrigation rates prior to recent water conservation efforts likely increased groundwater recharge compared to current conditions, which would explain higher rates of groundwater discharge to the river observed in past studies.

Hydrogeologic Framework

In the study area wells draw groundwater from seven different aquifers. Two of these aquifers consist of unconsolidated sediments, the MVA alluvium and outwash and the Mountain Village till and alluvial fan deposits. Bedrock aquifers are present in four shale-dominated bedrock formations: the Cretaceous Frontier, Muddy, and Kootenai (which for the purposes of this report includes the lower Thermopolis Sandstone), and the Jurassic Morrison Formation. The Cretaceous–Jurassic section averages about 2,000 ft in thickness (Tysdal, 1991; Vuke, 2013a; plate 1). The seventh aquifer consists of heavily fractured Cretaceous dacite sills of the Lone Mountain laccolith (fig. 4, plate 1). Plate 1 shows the stratigraphic relationship between the formations and includes the stratigraphy, geologic descriptions, hydrostratigraphy, and hydrogeologic summaries.

Wells within the study area completed in the Frontier, Muddy, Kootenai, and Morrison Formations draw groundwater from discrete, permeable sandstone beds within the shales. The sandstones contain both matrix porosity and fractures from faulting and folding. Vuke (2013a) suggested that these formations contain multiple sandstone beds ranging in thickness from about 1 to 10 ft. The sandstone beds make up about one-third of the total bedrock section (Vuke, 2013a; plate 1). Individual sandstone beds are difficult to trace between wells. Because the sandstones are thin, drillers often screen through multiple beds. In this report the sandstone layers within a single formation are referred to collectively as one aquifer and are named for the formation in which they are located (e.g., Frontier Formation and Frontier aquifer).

Geologic Controls

The pattern of tectonic structures and the intrusion of the laccoliths have segmented the bedrock in the area into discrete blocks with inconsistent geologic and aquifer characteristics. Aquifers in the extensive Cretaceous sedimentary units are typically in sandstone lenses that thin and pinch out laterally. Landslides have disrupted the continuity of aquifers. Therefore, aquifer characteristics such as groundwater availability, productivity, storage capacity, and rate of discharge vary from location to location.

Groundwater infiltration and movement may be enhanced or inhibited depending on local geology. Faults and folds can impede groundwater movement by creating clay-barrier zones along faults, displacing layering and breaking the continuity of the beds. Alternately, faults and folds can enhance groundwater movement by opening tension fractures in the bedrock. Erosion and landslides can expose permeable bedrock layers to surface recharge and rapid drainage, or bury the layers in debris.

The bedrock aquifers are less productive than the MVA, Mountain Village aquifer, and the fractured dacite aquifer at Mountain Village, because the permeable layers in the bedrock aquifers are generally confined, thin, and composed of lithified, fine-grained sandstone. The Kootenai and Frontier Formations contain more and/or thicker sandstone beds compared to the Muddy and Morrison Formations and therefore tend to be more productive. Groundwater in bedrock aquifers has higher mineral content than groundwater from the MVA and Mountain Village aquifer.

Wells and Public Water Systems

To meet water demand in these less productive settings, PWS systems consist of multiple water wells rather than relying on a single production well. As of 2019, the MBMG GWIC database had records for 76 PWS wells within the Big Sky study area (GWIC, 2020). PWS wells are operated by facility managers from the various developments and typically supply multiple households or businesses. GWIC also contains records of 395 domestic wells throughout the study area; most of these serve individual homes.

Aquifers and Aquitards

Meadow Village Aquifer

The MVA lies beneath the Meadow Village Golf Course (fig. 7). The aquifer is composed of unconsolidated alluvial sand and gravel on top of glacial outwash. The outwash, which includes cobbles, boulders, sand, and silt, lies on the eroded and irregular surface of the Frontier Formation (plate 1). Nine aquifer tests in this unit reported a range in transmissivity from 3,057 ft^2/d to 27,400 ft^2/d (appendix B, table B1).

Groundwater in the MVA generally flows from the west to the east (fig. 11). The thickest part of the sand and gravel aquifer is along a trough in the top of the Frontier Formation. The trough extends northeast–southwest (fig. 11). In the trough segment north of the Middle Fork, the sand and gravel range up to 67 ft deep with a saturated thickness of about 40 ft (Waren and others, 2021). The trough may be an ancestral river channel eroded into the shale. The shale surface rises in elevation to the south, and the sand and gravel thins to about 20 ft in thickness south of the Middle Fork. In the thinned sand and gravel the saturated aquifer thickness is less than 10 ft and, during late summer conditions, may be less than 1 ft.

Mountain Village Aquifer

The Mountain Village Aquifer is composed of glacial till, colluvium, and alluvial fan deposits that fill the bottom of a small basin on the north side of Lone Mountain beneath Mountain Village (fig. 2). Well logs show the aquifer is composed of 15 to 40 ft of gravel in clay and silty-sandy till. Up to 30 ft of alluvial fan deposits, composed of sand and gravel, overlie the till. The till and alluvium are hydrologically connected. Three of the seven BSWSD PWS wells at Mountain Village are completed at depths of 60 to 80 ft into the combined till and fan sediments. Transmissivities reported from three aquifer tests are 2,410 ft^2/d,

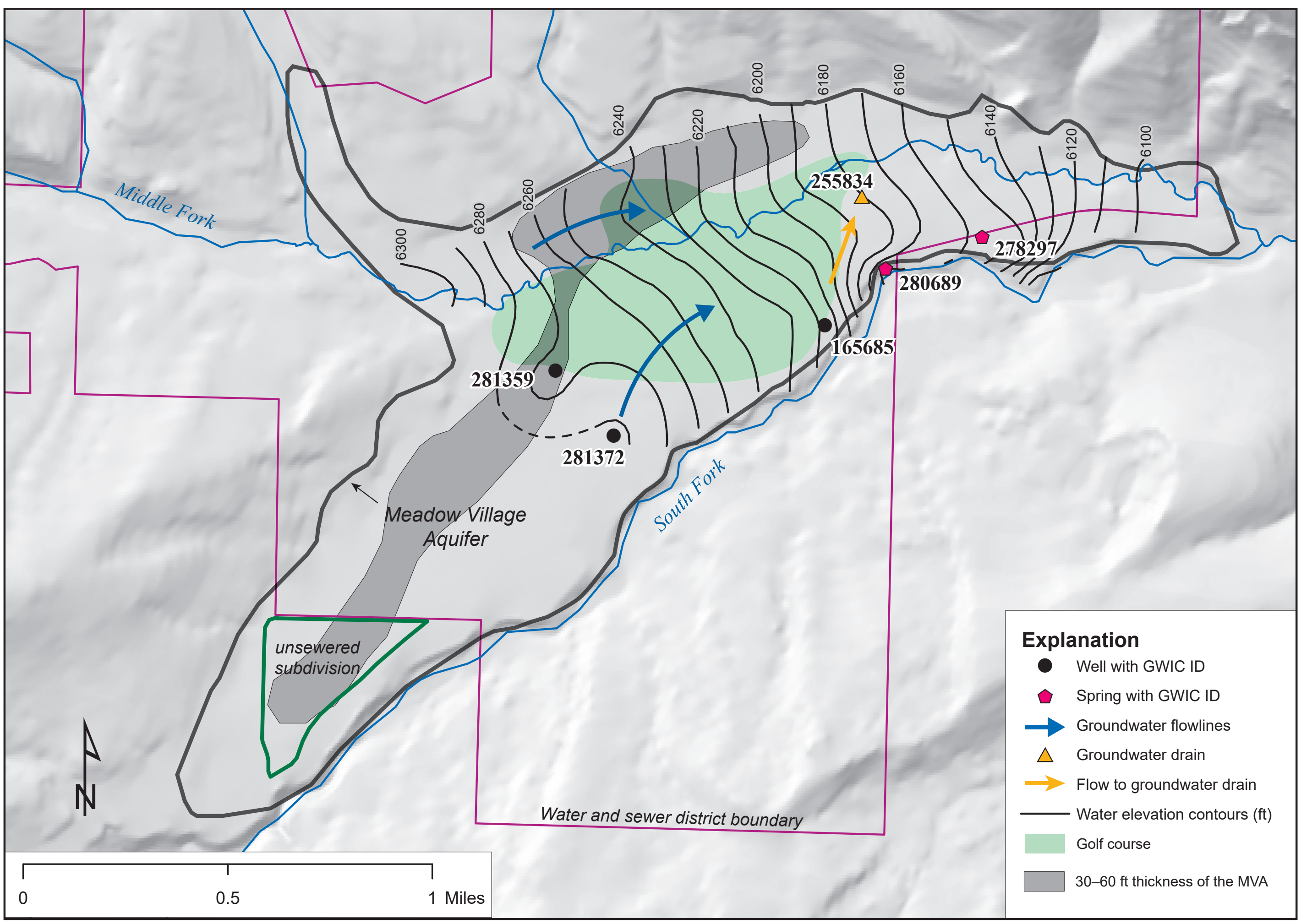


Figure 11. Potentiometric surface of the MVA groundwater generally flows west to east. The shaded area approximates a trough in the surface of the shale bedrock that forms the thickest part of the alluvial aquifer. Groundwater elevation contours are presented from Waren and others (2021).

2,950 ft^2/d, and 7,060 ft^2/d (wells 108811, 108810 and 108809, respectively; appendix B, table B1). Well 108809, which had the highest transmissivity, is completed primarily in sand and gravel associated with the alluvial fan.

Lone Mountain Dacite Aquifer

Dacite outcrops form the steep upper cliffs and local low-relief ridges and knobs on the lower slopes of Lone Mountain. Dacite sills crop out in many locations within the study area, most notably on the west slope of Lone Mountain in Moonlight Basin and on Andesite Mountain at Yellowstone Club (fig. 3). The fractured character of weathered sills is evident in the outcrops that appear as rubble piles on the land surface. The sills are irregular and unpredictable in shape and extent. The dacite has virtually no primary porosity, but fractures formed from rapid cooling of the intrusion and from weathering created secondary porosity voids for water storage. We characterized the degree of fracturing of the dacite based on drillers' descriptions recorded on well logs. Many of these logs report that dacite sills do not appear to be fractured and do not produce water. Based on drillers' descriptions, the dacite appears more fractured around the margin of the Lone Mountain intrusion (fig. 7, well 103496).

Stream gaging data collected for this study indicate that the Middle Fork is hydrologically connected to the MVA. In contrast, the South Fork lies beyond the southern extent of the alluvium and is underlain by shale of the Frontier Formation. The South Fork is at lower elevation than the golf course and is hydrologically isolated from the MVA.

Based on records from 19 wells, the depth to sills ranges from 250 to 880 ft with an average of 467 ft (appendix B, table B1, dacite aquifer wells). The sill thickness ranges from 42 to 464 ft with an average of 176 ft (appendix B, table B1). In many of these wells, the sill contacts are not perpendicular to the borehole, resulting in an apparent, rather than a true, thickness. In about half of the wells, the reported thickness is distributed over multiple sills, usually two or three in a single well. The geologic cross section (see fig. 12 for location) illustrates that the depth to dacite in each well is a factor of the surface topography and the trend of the sill (fig. 13).

Few wells are completed exclusively in dacite sills; most are completed and screened through the sill and adjacent sandstone beds in the Cretaceous formations. We compiled aquifer test records from the 19 wells completed at least partially in dacite sills (appendix B, table B1). Thirteen of the aquifer tests yielded transmissivities ranging from 40 to 1,589 ft^2/d (appendix B, table B1). Five of the aquifer tests indicated the presence of boundary conditions and one test showed fracture flow behavior.

Groundwater in the sills is confined, and water levels in some wells rise above ground level. Fractures in dacite outcrops capture snowmelt and recharge the aquifer. It is difficult to predict where a well will intercept a sill and whether a specific sill has enough interconnected fractures to provide flow. Fractured sill segments that are intercepted by water wells have relatively low storage capacity. However, where fractured sill segments are interconnected to other permeable bedrock layers, overall storage is increased.

Frontier Aquifer

The Frontier Formation is at relatively shallow depths and extends throughout most of the study area. The Frontier aquifer is accessible for well drilling in most areas (fig. 3). The formation ranges from 490 to 655 ft in thickness and is composed mostly of black shale with some gray, yellow, or tan sandstone layers that range up to 10 ft in thickness (plate 1; Vuke, 2013a). Two-thirds of the formation consists of shale (Vuke, 2013a) that hydrologically separates interbedded sandstones. The formation contains a few bentonite and porcellanite (a hard, silica-rich rock) layers, particularly near the base. Wells completed in these bentonitic layers produce water with suspended clay particles and require filtration for use (Aspen Groves wells 159764, 160152, and 169477). Most of the bentonite layers are inches thick, but one bed near the base is 16 ft thick.

At Meadow Village, on the south limb of the Big Sky syncline, the Frontier Formation is tilted about 10° north. The formation dips more steeply off the Andesite Mountain anticline and off Lone Mountain (fig. 3). Dipping beds make the formation vulnerable to landslides, often caused when precipitation infiltrates into and lubricates bentonitic beds within the formation (Vuke, 2013b).

The depths of 37 monitored and aquifer-tested wells completed in the Frontier aquifer range from 37 to 706 ft with an average depth of 356 ft (appendices

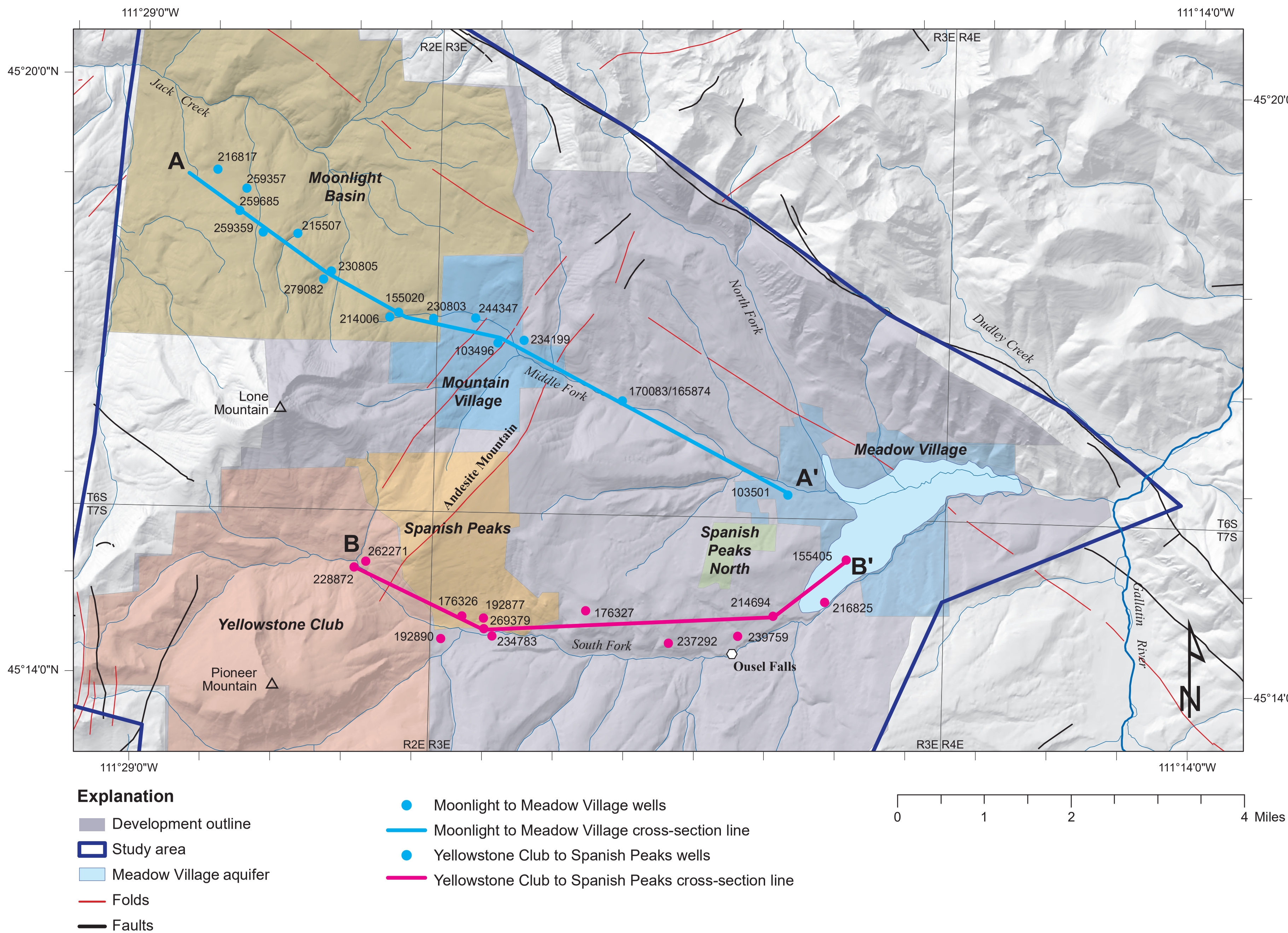


Figure 12. Well locations and geologic cross section locations. Cross section A–A' extends from Moonlight Basin to Meadow Village. Cross section B–B' extends from Yellowstone Club to Meadow Village.

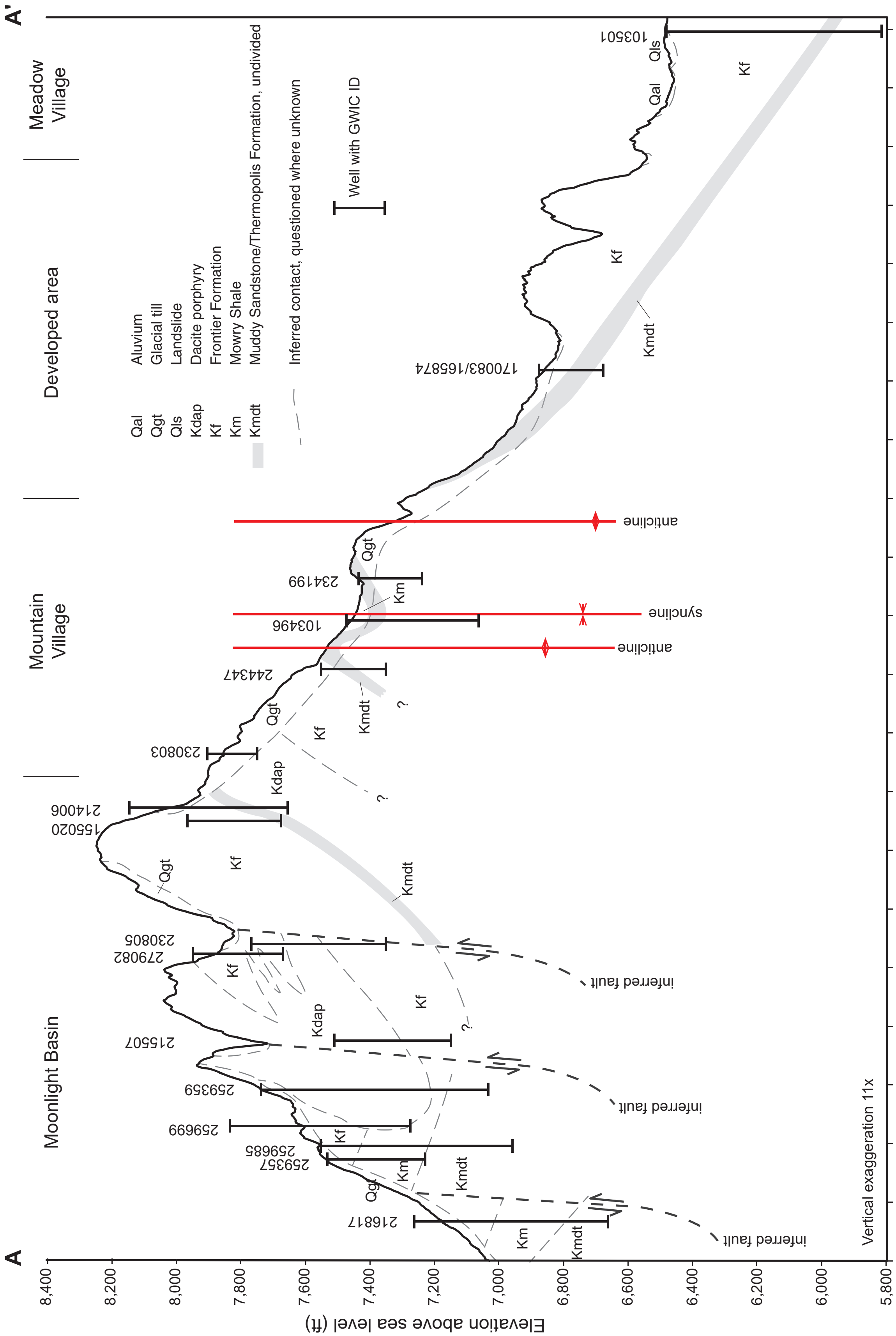


Figure 13. Generalized geologic cross-section from Moonlight Basin through Mountain Village to Meadow Village. The Muddy Formation is shaded to illustrate geologic complexity.

A and B, tables A2, B1). The aquifer is confined and water levels in wells rise into overlying interbedded shale layers that confine individual sandstone beds. Transmissivities in the aquifer range from 36 to 831 ft^2/d (appendix B, table B1). Analyses of 5 of 27 reported aquifer tests suggest a fracture-dominated flow system. No pattern to the spatial distribution of the transmissivities is apparent. The number and variable thickness of the sandstone layers likely play a role in productivity and explain the observed variability.

Mowry Aquitard

The Mowry aquitard consists of the entire Mowry Formation. It includes multicolored mudstones, siltstones, bentonite-rich clay, and some thin sandstone beds, within gray and black shales. The Mowry ranges in thickness from 295 ft to 590 ft (plate 1). None of the inventoried wells were screened exclusively in the Mowry, suggesting that the shale-rich formation is an aquitard with limited water-bearing capacity. Wells are typically drilled through the Mowry to reach underlying aquifers.

Muddy Aquifer

As its name implies, the Muddy aquifer is composed of thin- to medium-bedded, poorly sorted sandstones (salt and pepper sandstone) that contain abundant clay and mud chips, and as a result is typically not a productive aquifer. Sandstone beds separated by shales are present in the upper and lower parts of the Muddy Formation (plate 1). Thirteen of the monitored wells in Moonlight Basin, Mountain Village, and areas around Meadow Village are completed in, or partially in, the Muddy, usually in a sand interval containing minimal clay. These wells are not productive enough for use as a PWS. Aquifer test results from wells completed in the Muddy Formation vary widely, primarily because the same wells are also often screened into the overlying Frontier Formation (above the Mowry) or into the Thermopolis Formation below. Transmissivities from 16 reported aquifer tests from the Muddy range between 40 ft^2/d and 2,730 ft^2/d (appendix B, table B1).

Kootenai Aquifer, Including Portions of the Thermopolis Formation

The Kootenai aquifer is a productive and accessible source for high-quality groundwater at Big Sky. Outcrops of the Kootenai Formation are visible in the South Fork Valley between Ousel Falls and Yellowstone Club (figs. 2, 3).

In well logs the Thermopolis Formation can rarely be distinguished from the overlying Muddy or the underlying Kootenai. The Upper Thermopolis Formation consists of fissile shale with thin-bedded sandstones. It is not considered an aquifer at Big Sky due to its low productivity. The Lower Thermopolis aquifer is a resistant basal quartzose sandstone bed that directly overlies the Kootenai. For the purposes of this report, we lump the Lower Thermopolis with the Kootenai due to the difficulty of distinguishing the two in drill cuttings and well reports. In well log interpretations the Lower Thermopolis sandstone is likely included as part of the upper Kootenai Formation. Sandstone of the Lower Thermopolis is visible in outcrop (for example, it is exposed at Ousel Falls, fig. 2). It is composed of white to tan quartz–arenite sandstone (basal sandstone) with thin interbeds of fissile shale. The sandstone is used locally as an aquifer, as it yields water to wells where present. Only two inventoried wells are interpreted as completed in the lower Thermopolis Sandstone.

The Upper Kootenai Formation is composed of fossil-bearing limestone, variegated red, purple, yellow, and gray shales, mudstones, siltstone, and limestone. The lower Kootenai includes a salt-and-pepper sandstone identifiable in cuttings that grades downward into a coarse-grained sandstone underlain by chert–pebble conglomerate up to 3 ft thick (Vuke, 2013a). The lower sandstones are the most productive beds of the formation. At the land surface much of the Kootenai Formation is stained red from erosion of red mudstones in the upper portions of the unit, making it easier to locate in outcrop. The staining is not evident in drill cuttings due to the lack of oxidation.

Twenty of the wells monitored for this investigation were completed in the Kootenai aquifer. Well records were available for six additional wells. Well depths in these 26 wells ranged from 118 to 1,250 ft (appendices A and B, tables A1, B1, respectively). The Kootenai Formation is brittle and highly fractured at many locations, enhancing groundwater movement and storage. Transmissivities reported from five Kootenai aquifer wells located near the Meadow Village, Mountain Village, and Spanish Peaks Mountain Club developments range widely, from 3 to 1,522 ft^2/d (appendix B, table B1). The range in reported transmissivities reflects the variability in thickness of the basal sandstones and the degree of interconnecting and open fractures through the Kootenai and adjacent formations.

Morrison Aquifer

The Morrison Formation is composed primarily of mudstone with thin beds of clay-rich sandstone. These fine-grained layers limit groundwater movement and storage capacity (plate 1). Water chemistry data show the water in the Morrison aquifer is more mineralized than in the other aquifers. Poor connection to recharge and slow water movement through these low-permeability layers create long contact times between groundwater and formation sediments producing mineralized water.

Transmissivities from aquifer tests at Yellowstone Club wells 228880 and 228872 are 88 and 121 ft^2/d, respectively (appendix B, table B1). These wells are completed at depths of 527 and 468 ft, respectively. Groundwater from Yellowstone Club well 253676 is not potable, due to its high mineral content and a strong hydrogen sulfide odor. Slow recharge apparent in hydrographs (discussed below in local hydrogeology at the Yellowstone Club development) also affects the potential for long-term, high-volume pumping from this unit. The Morrison Formation aquifer is not suitable for large-scale water supply development due to the relatively great drilling depth, poor groundwater quality, and low transmissivity at most locations in the study area.

Madison Group Aquifer

The Mississippian Madison Group is an important, productive aquifer in some areas of Montana (Van Voast, 1972). In the study area, the Madison Group is composed of the Mission Canyon and Lodgepole limestones. On the south limb of the Big Sky syncline (fig. 3), the Madison Group rises gently to the south at about 10° (dipping north). On the north limb of the syncline the Madison Group crops out in the Gallatin River Canyon and dips 80–90° south. The limestone forms the peak of the ridge along the north boundary of the study area (fig. 3).

The dominant hydrogeologic characteristics of groundwater flow in the Madison include karst features, such as solution cavities and fracture flow. Although considered one of the principal aquifers in Montana (Meinzer, 1927), it is not widely used at Big Sky due to its depth. The elevation of the Madison Group is highly variable across the study area (fig. 4). At depths on the order of 3,000-4,000 ft below the land surface near the Meadow Village development, the Madison Group aquifer is beyond the reach of conventional water well drills in much of the study area. In contrast, the Madison Group crops out at the land surface along steeply dipping cliff faces in the Gallatin River canyon due to structural folds related to movement on the Spanish Peaks Fault (fig. 3). Springs emanate from fractures in Madison Group outcrops along both sides of the canyon and across the canyon floor, discharging into the river. This large spring system is thought to be the fourth largest in Montana (Meinzer, 1927).

Only two wells near Big Sky are known to be completed in the Madison Group, providing limited data about the aquifer within the study area. Well 103575 is 40 ft deep and is located near Madison Group outcrops in the Gallatin River Canyon at an elevation of about 6,000 ft amsl (figs. 2, 7). The well intercepts the Madison Group at 11 ft below ground surface. This well provides good quality water and has a reported yield of 40 gallons per minute (gpm; GWIC, 2020). The depth to water was 10 ft below ground surface (bgs) at the time of drilling. Well 296215, drilled south of Yellowstone Club at an elevation of 7,740 on the south flank of the Big Sky syncline (figs. 2, 3) intercepted the Madison Group at 1,280 ft bgs. The well, completed to a total depth of 1,783 ft, had a well yield of 7 gpm and produced highly mineralized groundwater. The depth to water was 1,450 ft at the time of drilling.

Several characteristics of the Madison Group limestone in the study area affect its potential to supply groundwater for the Big Sky community. The Madison Group aquifer is likely folded and disrupted by faulting, much like the Cretaceous formations mapped at the land surface. While the folding and faulting may have fractured the limestone and formed secondary porosity voids, the folds and faults may disrupt the continuity of the formation and impede groundwater flow. The two wells drilled into the Madison at Big Sky, completed to depths of 40 and 1,783 ft, have substantial differences in productivity and water quality. These differences likely reflect local controls on hydraulic conductivity and storage (such as the degree of interconnected fractures), and the difference between the length of groundwater flowpaths from recharge areas to each well.

Local Hydrogeologic Conditions at Major Developments

This section discusses aquifer characteristics locally, at each of the major developments: Moonlight Basin, Mountain Village, Meadow Village, Spanish Peaks Mountain Club, Spanish Peaks North, and Yellowstone Club (fig. 2).

We relied on groundwater hydrographs as the primary data source to assess local conditions. We compared hydrographs by aquifer and by location to assess variability within and between aquifers; this approach was adopted due to the varied geologic settings. In the following sections, we present examples of hydrographs from each available aquifer at each development. The datasets typically include water levels measured at hourly intervals from late 2014 through 2016.

Some general observations apply to most of these hydrographs and serve as an introduction to the hydrogeology within each development. Most wells showed seasonal fluctuations in response to local climatic and hydrologic conditions, with groundwater levels rising in the spring as snowmelt recharged aquifers and falling following the end of snowmelt. Water levels continued to decline through the fall and winter. The hydrographs differ somewhat in the timing, rate, and magnitude of water-level rise. These differences likely reflect the local hydrogeologic conditions at each well. Groundwater response is affected by several factors that vary from development to development within the Big Sky study area. These include the amount of snowmelt available for local recharge, the geometry and continuity of each aquifer, a well's location relative to local recharge areas, aquifer properties such as storage and transmissivity, and the timing and magnitude of nearby pumping from the aquifer.

Groundwater recharge across the study area depends on the volume and timing of snowmelt and subsequent infiltration. Snowmelt and surface-water runoff begin in late March and end by mid-June, and the hydrographs show related recharge as a rise in groundwater levels. Lower elevations receive less snowfall than higher elevations, and this may influence the amount of groundwater recharge locally available to each well. For comparison, each hydrograph shows the SWE recorded at high (Lone Mountain SNOTEL 590; USDA, 2018a) and low (West Yellowstone SNOTEL 924; USDA, 2018b) elevations. Precipitation (rainfall and snowfall) is also displayed using records from weather station BS-STA01at Meadow Village for low-elevation wells and records from the Lone Mountain SNOTEL 590 station for high-elevation wells.

Moonlight Basin

Most wells in Moonlight Basin are completed in the Frontier and Muddy aquifers. Here, dacite sills intrude these sandstones. Less productive wells are completed in the Lone Mountain dacite and the Muddy aquifers.

Frontier Aquifer

In Moonlight Basin, the Frontier Formation is overlain by glacial till and landslide debris (Vuke, 2013a). Uplift related to the Lone Mountain laccolith raised and steeply tilted the Frontier Formation to the west where it is exposed at higher elevations on the mountain (Vuke, 2013a). The uplift resulted in faults and landslides that have displaced the bedrock into blocky segments (figs. 12, 13). The dip on the formation lessens with decreasing elevation farther from the intrusion. Displacement of the bedrock along these geologic structures affects aquifer continuity, which can limit groundwater availability.

Water levels in wells 241699 and 279062, at elevations over 8,000 ft, are representative of groundwater response at higher elevations, where the formation is steeply dipping (figs. 8, 14A, 14B). In addition to snowmelt, seasonal patterns in these two wells are influenced by large precipitation events. Two such storms occurred in July (0.96 in) and September (1.16 in) 2015 and are visible on the hydrographs (figs. 14A, 14B). Well 230804 is located at a lower elevation (about 7,400 ft) in the less-developed north Moonlight Basin where the Frontier Formation is closer to flat-lying. This hydrograph shows similar timing but a smaller variation in head change in seasonal response to snowmelt (fig. 14C).

PWS well 241699 (fig. 14A) shows drawdown in response to pumping during peak tourist seasons (July–August and November–December). Groundwater levels generally recover during the subsequent spring recharge period. Although these data are limited to the 2-yr study period, the water levels indicated that

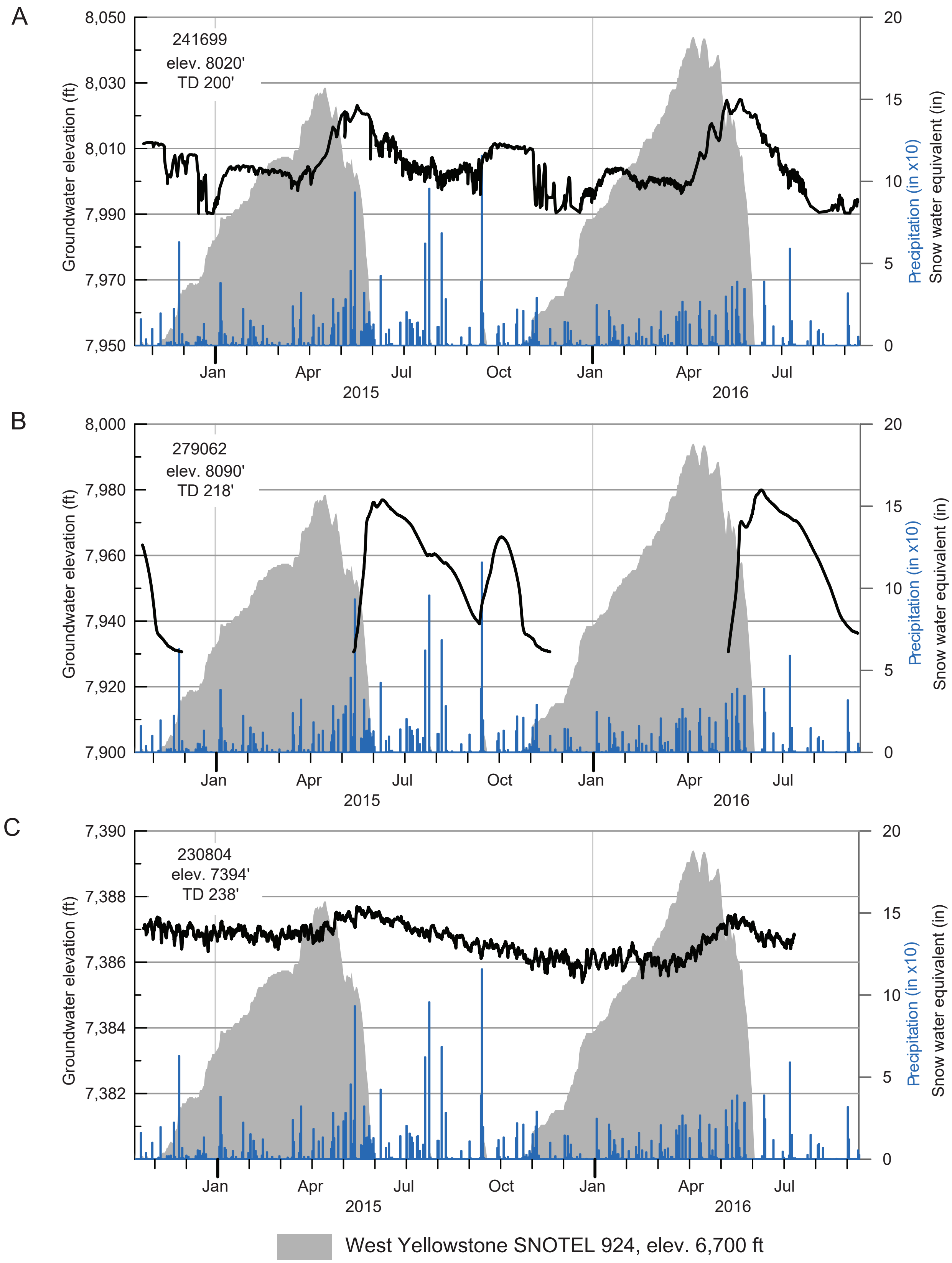


Figure 14. Hydrographs for wells completed in the Frontier aquifer in Moonlight Basin. (A and B) The precipitation record from the Lone Mountain SNOTEL 590 station; (C) the record from station BS-STA01 at Meadow Village (fig. 2). The partial record shown in B reflects times when the water level dropped below the transducer. Note scale change for C.

pumping rates did not deplete aquifer storage. Well 279062, an unused well located on the opposite side of the divide in the Jack Creek drainage, responds similarly to well 241699, in that water levels rise during snowmelt recharge and decline following that period. Water levels in both wells show a large response to infiltration of snowmelt, rising on the order of 20 to 40 ft in the spring of 2015 and 2016. This suggests fracture filling and low storage capacity of the bedrock. Well 279062 does not show a response to pumping from well 241699, which we attribute to the distance between the two wells (0.7 mi), the topographic ridge that separates them, and the opposing dip angles apparent on either side of the ridge.

Lower elevation well 230804 has a muted groundwater response to snowmelt recharge compared to wells 241699 and 279062 (figs. 14A, 14B, 14C). Groundwater levels vary less than 2 ft seasonally. This likely reflects greater permeability of the interbedded sandstone at this well compared to the other wells. Less snowmelt recharge at lower elevations could also contribute to the subdued response.

Muddy Aquifer

Like the Frontier Formation, the orientation of the Muddy Formation ranges from steeply dipping at higher elevations on Lone Mountain to relatively flat at lower elevations (figs. 12, 13). Aquifer continuity is affected by low-permeability zones within the formation and by multi-directional folds and faults that can create preferential flow paths or form barriers within the aquifer.

Wells 259685 and 259706 (fig. 8), located about ¾ mi apart, are completed in sandstones of the Muddy Formation at elevations of 7,580 and 7,020 ft, respectively. Groundwater in well 259685 fluctuated 20 to 25 ft during the study period, and shows a steep rise in response to spring snowmelt (fig. 15A). Water levels show a small but distinct response to large precipitation events in the summer of 2015. This response suggests a relatively direct connection to recharge at the land surface, perhaps through a well-connected fracture network. In contrast, the hydrograph from well 259706 (fig. 15B) is muted, without a clear response to seasonal snowmelt. This likely results from hydraulic isolation from local recharge, due to a lack of fractures, clay-filled fault structures, or more confining properties of the shale layers that overlie the aquifer.

The large difference in hydrograph response between the two wells supports the conclusion that the Muddy aquifer is highly heterogeneous within Moonlight Basin. This may result from the varied nature of the aquifer sediments or the distribution of fractures near each well. The discontinuous nature of the aquifer due to structural folds and faults could also result in differences in groundwater response to recharge.

Lone Mountain Dacite Aquifer

Fractured dacite sills locally crop out as dark, lichen-covered and rubbly ridges on the mountain slope (figs. 3, 4). In surface outcrops, the sills intrude along bedding in the Frontier Formation and Muddy Formation. Some fractures within the dacite sills at Moonlight Basin are water-bearing, but the fractured segments appear to be limited in extent, which limits storage capacity. Four aquifer tests were conducted in Moonlight Basin at wells that are completed in both a dacite sill and Frontier or Muddy aquifers (table B1; wells 259359, 259361, 259699, and 279080). Aquifer boundaries were encountered in all four aquifer tests, demonstrating the limited extent of the aquifer in Moonlight Basin (appendix B, table B1).

Kootenai Aquifer

Exploratory well 221627 (fig. 3) was drilled to the salt-and-pepper sandstone of the Kootenai Formation but did not produce water. This is attributed to confining properties of the overlying shale layers, fault separation of layers within the Kootenai Formation, and the lack of nearby outcrops of the Kootenai that would otherwise provide recharge to the aquifer.

Mountain Village

The Mountain Village development lies in a shallow basin along the Middle Fork at 7,500 ft elevation. The basin is bounded by Lone Mountain on the south, the Andesite Mountain Anticline to the east, and upturned bedrock of the north ridge along the Spanish Peaks Fault to the north (fig. 3). Basin bedrock consists of Frontier, Muddy, and Kootenai Formations and the Lone Mountain dacite intrusion. Bedrock is partly buried by glacial till and alluvial fan sediments.

The BSWSD Mountain Village PWS includes seven wells (fig. 7). Three of these are completed in the Mountain Village aquifer (wells 108809, 108810, 108811) and two are completed in the Muddy aquifer (wells 244347 and 248989). Two wells draw from the

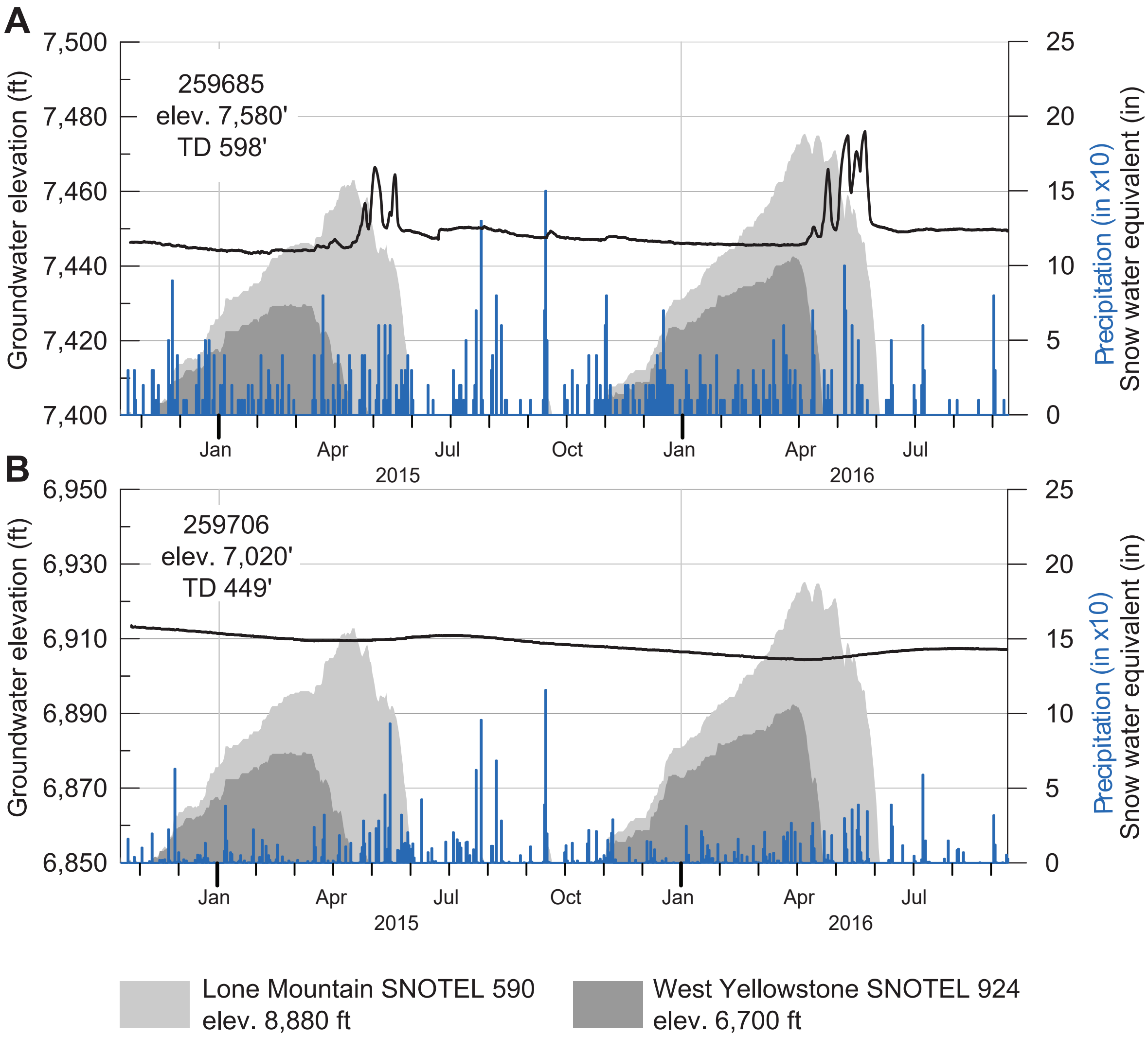


Figure 15. Hydrographs for wells completed in the Muddy aquifer in Moonlight Basin. Well 259685 responds to limited aquifer storage and a shorter recharge period (A) while well 259706 (B) suggests less snowmelt recharge, which we attribute to overlying low-permeability layers. (A) The precipitation record from the Lone Mountain SNOTEL 590 station; (B) precipitation record from station BS-STA01 at Meadow Village (fig. 2).

Lone Mountain dacite aquifer, at the margin of the Lone Mountain intrusion (wells 103496, 205931). Domestic wells that supply individual homes around the edges of Mountain Village are completed in the Frontier, Muddy, and Kootenai aquifers.

Mountain Village Aquifer

The Mountain Village aquifer consists of valley-fill till overlain by hydraulically connected alluvial fan sediments off Lone Mountain. Wells 108810 and 108811, and inactive well 108809, are completed in this aquifer at depths up to 80 ft. These wells produce between 80 and 240 gpm, with reported transmissivity ranging from 2,410 to 2,950 ft^2/d (appendix B, table B1).

Muddy Aquifer

Wells 244347 and 248989, inactive at the time of this report, are completed in the clay-rich sandstone and shale layers of the Muddy Formation and reportedly produce 95–110 gpm (WGS, 2018). However, an east–west fault mapped by Vuke (2013a) may act as a barrier within the aquifer, limiting productivity of these wells (appendix B, table B1, fig. B1). Water quality at these wells is degraded by notable hydrogen sulfide odors (i.e., the smell of rotten eggs).

Lone Mountain Dacite Aquifer and Kootenai Aquifer

Wells 103496 and 205931 draw water from fractured dacite sills and the Kootenai aquifer. These wells are the most productive in Mountain Village, yielding between 100 and 300 gpm (Ron Edwards, Big Sky Water and Sewer District, oral commun., 2016). Reported transmissivity at these wells is on the order of 1,500 ft^2/d (appendix B, table B1).

Water levels in well 234199 (fig. 8), monitored since 2008 by the MBMG, provides a long-term record of groundwater response in the Kootenai aquifer (fig. 16A). Recharge to the Kootenai depends on snowmelt and precipitation, with water levels rising generally from April through June during snowmelt (figs. 16A, 16B). The hydrograph shows annual declines during peak summer and winter tourist seasons (July–August and November–December). These are attributed to pumping from PWS wells 103496 and 205931, located about 1,000 ft south of well 234199. Water levels in well 234199 recover in the fall, be-

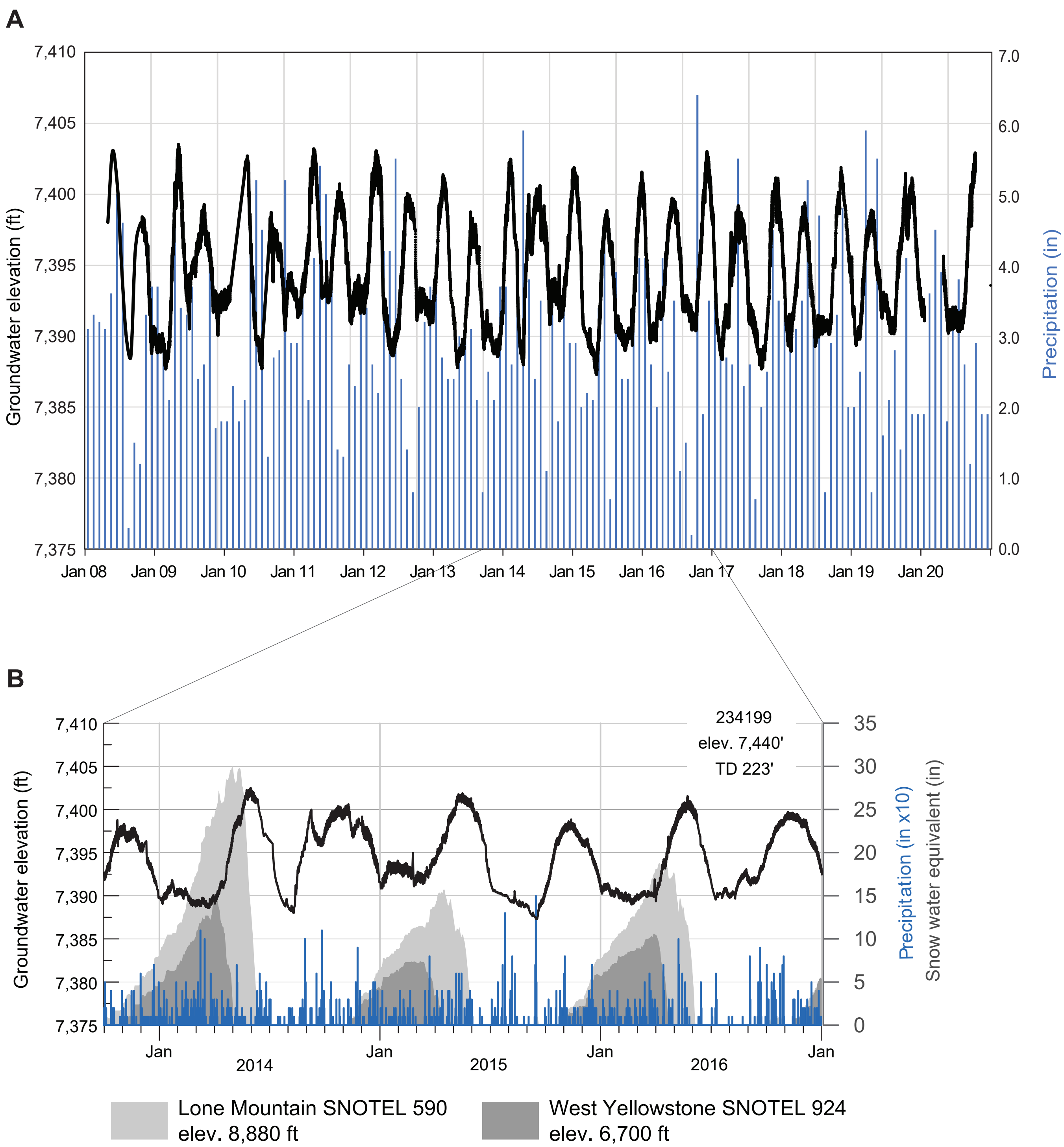


Figure 16. Long-term monitoring well 234199, completed in the Kootenai aquifer in Mountain Village, responds to snowmelt recharge and pumping (A). (B) Water levels during this study, 2014–2016. Both parts show the Lone Mountain SNOTEL 590 station precipitation record.

tween tourist seasons. The magnitude of seasonal water-level change during this project period was generally consistent with prior years (fig. 16A).

Fracturing of the Kootenai Formation provides storage of snowmelt recharge and sustains groundwater levels over time. Fracturing connects the dacite with the Kootenai in this area, enhancing aquifer productivity.

Meadow Village

Meadow Village Aquifer

Five BSWSD PWS wells (103505, 103507, 166989, 236777, and 236778) completed in the MVA provide water to Meadow Village and surrounding developments (fig. 8). The wells are located at the north end of the aquifer, where the aquifer has a greater saturated thickness. Each well produces about 100 to 250 gpm (Ron Edwards, Big Sky Water and Sewer District, oral commun., 2016) and reported transmissivity ranges from 3,057 to 27,400 ft^2/d (appendix B, table B1).

Groundwater response to snowmelt, precipitation, and pumping are illustrated in hydrographs for monitoring wells 165689 and 257677 (figs. 8, 17A, 17B, respectively). Groundwater levels in both wells rise during spring snowmelt, although the magnitude of the rise is greater in well 257677 (about 2 to 5 ft) compared to well 165689 (about 1 ft). Snowmelt response was larger during 2014, which had a greater SWE than 2015 and 2016.

Although the timing of seasonal groundwater response is similar, the wells respond differently to pumping due to their locations. Well 257677 (46 ft deep) is located 20 ft from PWS well 236777, in an area where the aquifer saturated thickness is about 46 ft (fig. 8). Well 165689 (20 ft deep) is located across the river from the PWS wells (fig. 8), where the saturated thickness thins to about 10 ft. Water levels in well 257677 recover soon after peak pumping ends in early September, while water levels in well 165689 recover more gradually. The MVA groundwater model (Waren and others, 2021) indicated the area of the aquifer near well 257667 receives recharge and water levels rise with spring runoff. Water levels in wells south of the river (i.e., 165689) do not change as much with spring runoff, suggesting this part of the aquifer is less connected to the recharge source compared to groundwater near well 257677.

The difference in response between the two wells indicates the river is a hydrologic boundary that buffers groundwater levels in well 165689 from the effects of pumping. Groundwater modeling suggests groundwater pumped from the PWS wells is supplied in part from the Middle Fork and any future increases in pumping from the MVA are likely to induce an equal volume of surface-water capture (Waren and others, 2021).

Hydrographs for wells 165689 and 257677 (fig. 7, inset) and surface-water stage on the Middle Fork, at site 274333 (figs. 17A–17C, fig. 6, inset), located about ½ mi downriver, show groundwater and river stage respond similarly to precipitation. River stage and groundwater respond to precipitation events >0.5 in (fig. 17). Heavy rainfall does contribute to groundwater recharge. In addition, heavy rain could reduce pumping for outdoor watering, which would also result in water-level increases. The response to rainfall, as well as the unconfined, shallow nature of the aquifer, indicate its vulnerability to contamination from the land surface.

We measured modest net streamflow gains or losses from the Middle Fork to the aquifer (appendix D, table D1); these data demonstrate that the groundwater and surface-water systems are directly connected. Groundwater modeling of the MVA by Waren and others (2021) showed that the Middle Fork can gain or lose water to the aquifer depending on relative elevations of the water table and river stage. This suggests that stream water quality can be affected by groundwater quality, and the stream is vulnerable to contamination from the groundwater.

Spanish Peaks Mountain Club

Cretaceous bedrock in the Spanish Peaks Mountain Club is tilted 10–15° northeast along the south limb of the Big Sky syncline (figs. 12, 18). At the southwest side of the development the formations are tightly folded and more steeply dipping off the southeast limb of the Andesite Mountain Anticline. A large landslide block covers most of the central and northwestern part of the development. Most homes in Spanish Peaks Mountain Club are connected to a PWS. Wells in this development are completed in three water-bearing units: the Frontier, Muddy, and Kootenai Formations.

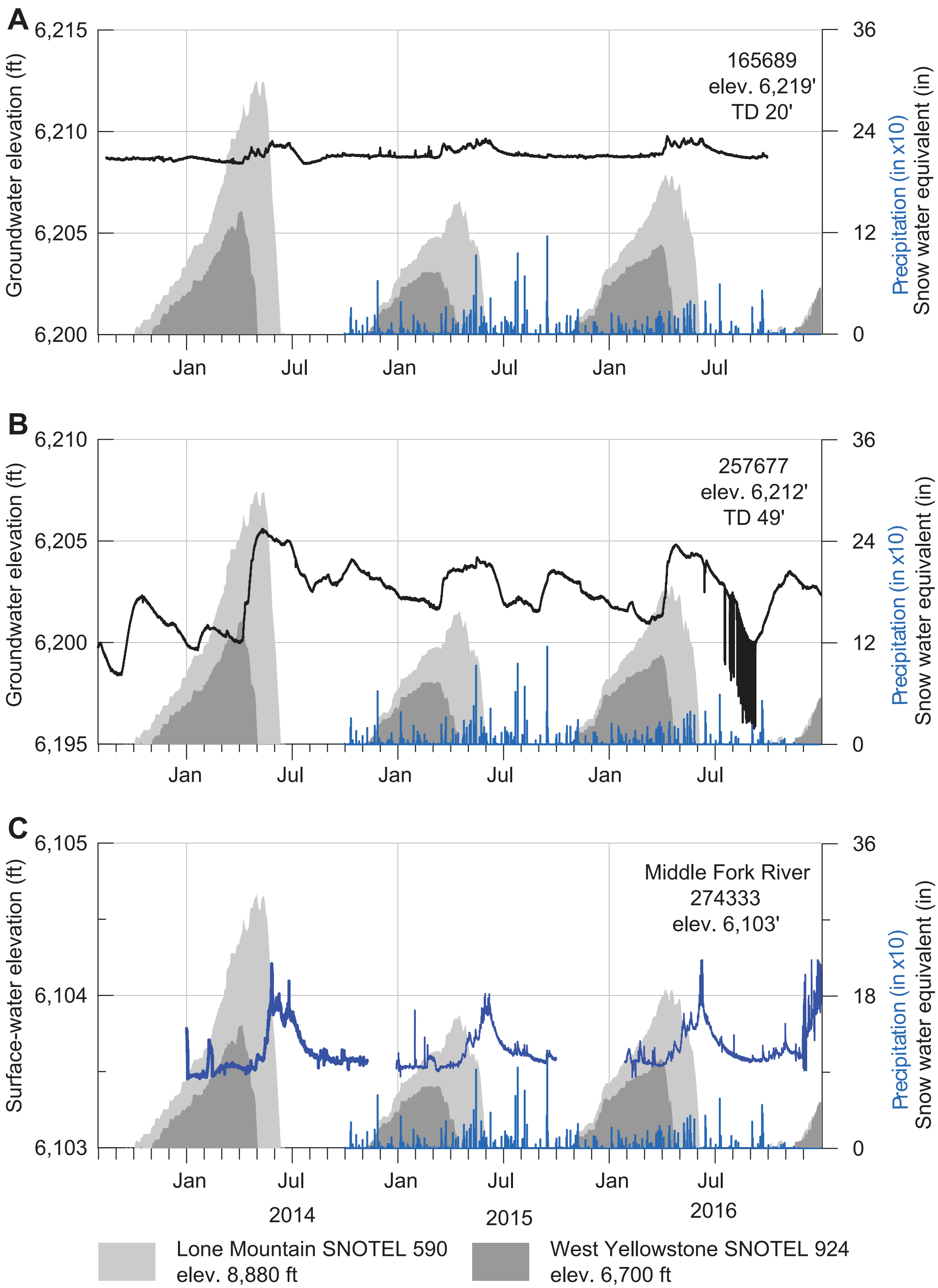


Figure 17. Groundwater in two wells completed in the Meadow Village aquifer respond to recharge from snowmelt and precipitation and nearby pumping (A, B). Changes in groundwater levels correlate to changes in river stage (C). Graphs show the precipitation record from station BS-STA01 at Meadow Village (fig. 2).

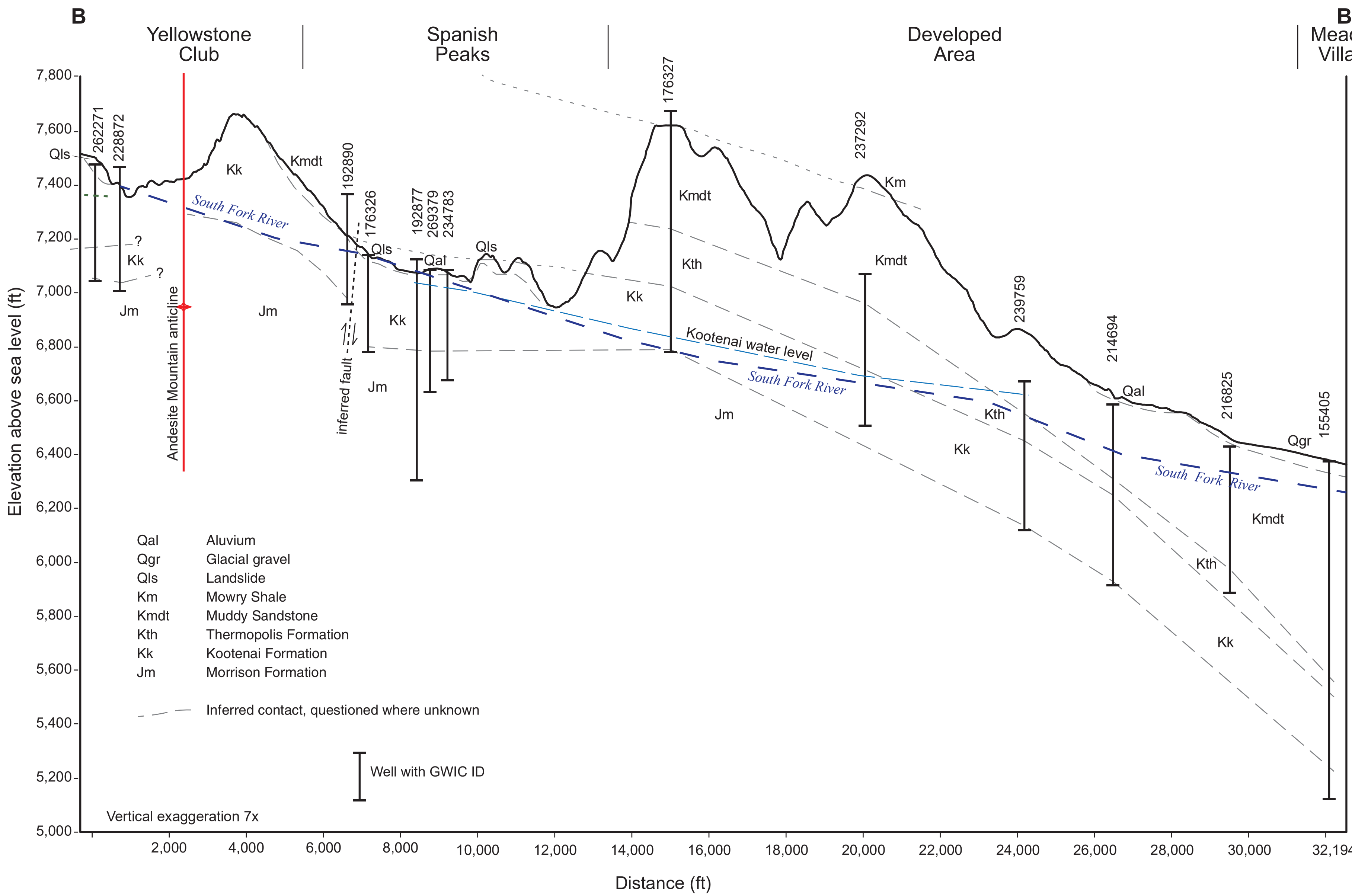


Figure 18. Generalized geologic cross-section through the South Fork River canyon from Yellowstone Club to Meadow Village.

Frontier Aquifer

Most of the Frontier Formation within Spanish Peaks has been thinned or removed by erosion or displaced by landslides (Vuke, 2013b). Here, the Frontier Formation is steeply tilted and segmented, and some wells drilled solely into this formation did not yield water.

Muddy Aquifer

Like the Frontier Formation, the Muddy Formation has steeply dipping bedding. The steep dip along with the silty sand of the formation promotes drainage of the aquifer, limiting water availability and storage potential of the Muddy aquifer.

Kootenai Aquifer

The Spanish Peaks PWS draws groundwater from four wells completed in the Kootenai aquifer. The wells are located southeast of the development along a ¼-mi stretch of the South Fork canyon near Ousel Falls (wells 208655, 214694, 239759, and 239761; figs. 7, 18). These four wells range from 470 to 630 ft deep and each can produce about 210 gpm (HKM and Gallagher, 2005). Reported transmissivity ranges from 162 to 364 ft^2/d (appendix B, table B1). The salt-and-pepper sandstone of the lower Kootenai Formation is the most productive aquifer in the Spanish Peaks area. This is attributed to outcrops in the South Fork Canyon and the Andesite Mountain Anticline, along the South Fork River, that provide bedrock exposure and may facilitate recharge to the local aquifer. These wells are completed along a syncline and folding of these rocks may enhance secondary porosity through fracturing (HKM and Gallagher, 2005).

Domestic wells at Spanish Peaks are primarily completed in the Kootenai and Muddy aquifers. Although the data are sparse, water levels in well 219966 (screened depth 325 ft to 525 ft), at the Spanish Peaks Mountain Club Main entrance gate, show a seasonal rise in response to snowmelt and a subsequent water-level decline from June to August (fig. 19A).

Spanish Peaks North

Domestic wells in the relatively small Spanish Peaks North development (fig. 2) are completed in the thin sandstones of the Frontier aquifer or in the deeper Muddy aquifer. Steep dips of the formations and the thin sandstone beds limit water availability and storage potential of both aquifers. The silty nature of the Muddy sandstone limits permeability through this aquifer. Most wells are completed in the Frontier aquifer and some are screened through multiple thin sandstone beds to provide adequate yield.

Hydrographs for well 210824, completed in the Frontier aquifer (fig. 19B), and for well 187230, completed in the Muddy aquifer (fig. 19C), show seasonal water-level rise during snowmelt.

Yellowstone Club

The Yellowstone Club relies on groundwater from 10 PWS wells. One well is completed in the Frontier aquifer, five in the Kootenai, two in the Kootenai and Morrison, and two in the Morrison Formation. The Frontier and Kootenai Formations are exposed in outcrop along the South Fork canyon (Kellogg and Williams, 2006). The Morrison Formation, which underlies the Kootenai, is not exposed on the land surface in the Yellowstone Club area.

Throughout the Yellowstone Club, dacite sills from Pioneer Mountain and Lone Mountain extend outward along bedding surfaces in the Cretaceous formations. Landslide debris and colluvium obscure much of the bedrock geology on the canyon slopes.

The geologic setting in the Yellowstone Club area limits groundwater flow and aquifer connectivity. Based on observations made from this area, the Frontier and Kootenai Formations dip in various directions, primarily dipping off Lone Mountain, Pioneer Mountain, and Andesite Mountain toward the central part of Yellowstone Club. Due to the multiple structural folds, orientations of the formations can differ from one side of the canyon to the other (fig. 3), and there may be unmapped faults through the area. This geologic complexity causes various orientations of segmented blocks of aquifers that are constrained by faults and folds. Hydrographs from wells in this setting show different responses based on their location within the Yellowstone Club, and the productivity of any one segment of the aquifer can vary greatly from others.

Kootenai Aquifer

The Kootenai Formation is the primary aquifer for the Yellowstone Club in the eastern part of the development. However, to the west the formation appears to be displaced by an unmapped fault that may affect aquifer properties. The fault drops the Kootenai For-

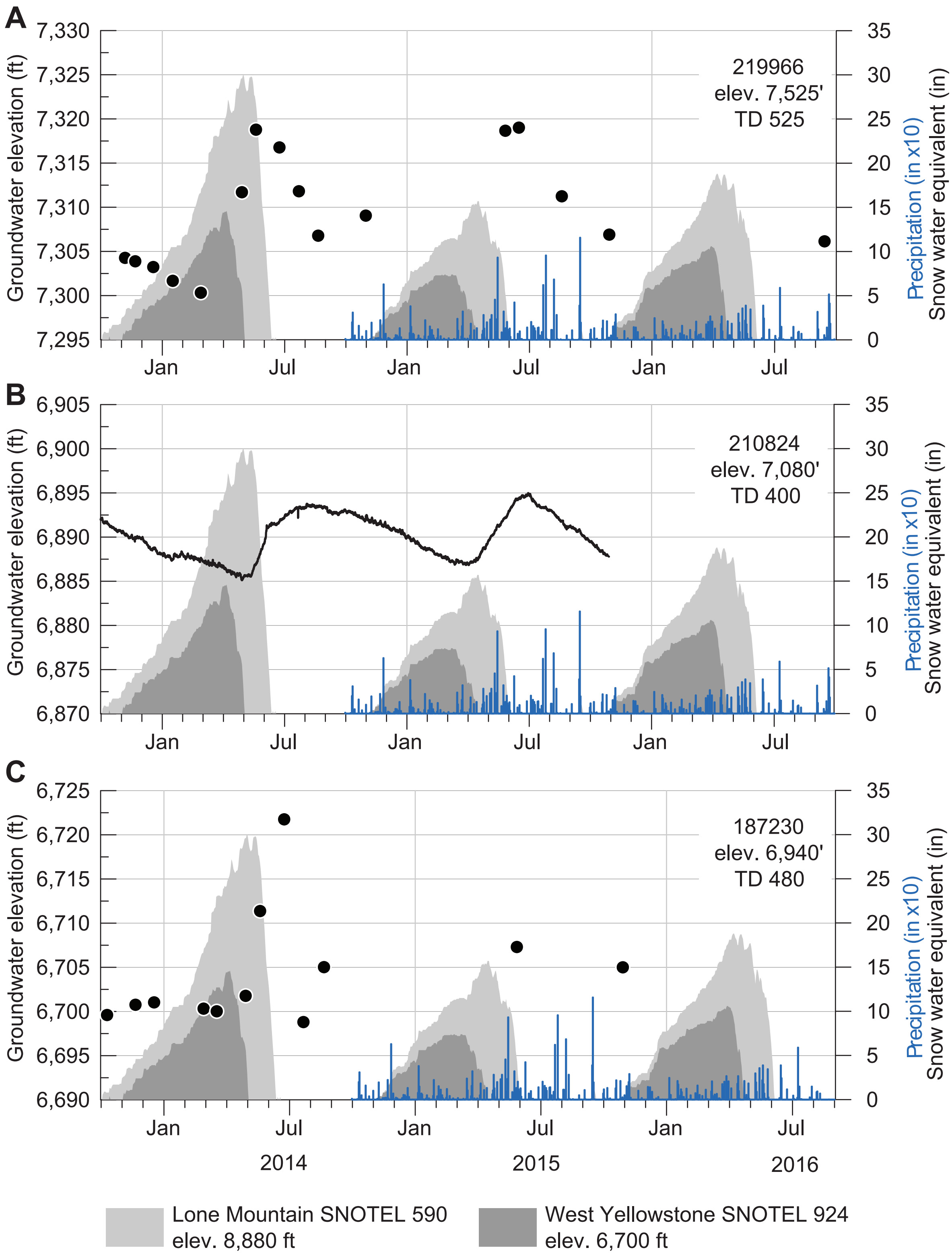


Figure 19. (A) The hydrograph for well 219966, completed in the Kootenai aquifer at the Spanish Peaks Mountain Club. At Spanish Peaks North, well 210824 is completed in the Frontier Formation (B) and well 187230 is completed in the Muddy sandstone (C). The precipitation record from station BS-STA01 at Meadow Village is also shown (fig. 2).

mation below the level of the South Fork River (fig. 18). Wells drilled into the Kootenai aquifer west of the fault are less productive and produce poorer quality water compared to wells east of the fault.

One Kootenai aquifer well (192897) located in the valley bottom (figs. 7, 8), responds to pumping in nearby PWS wells. The hydrograph from well 192897, an exploratory water well, shows a steep decline in water levels in November and December, presumably due to groundwater pumping for snowmaking and high visitation rates during holidays (figs. 7, 20A). We attribute the water-level rise in late December through spring snowmelt to recovery following a decline in pumping after early season snowmaking. Water levels show response to periodic intervals of nearby pumping during the late winter and early spring. Summertime pumping results in cyclic drawdown and recovery that continues until the November drawdown occurs again. The hydrograph also shows water-level increases in response to occasional large precipitation events, suggesting that precipitation recharges the aquifer, likely through bedrock exposures along the South Fork canyon. South Fork River stage (274334, fig. 8) and groundwater elevations follow somewhat similar seasonal trends (figs. 20A, 20B).

A treated effluent storage pond is located on a mountain top near the Yellowstone Club Golf Course at the south side of the development (fig. 12, south of well 192890, not shown in figure). On March 3, 2016, part of the impoundment dam failed and 30 million gallons of treated effluent water was released into the South Fork over a 4-d period (Gardner, 2016). The sudden release of water raised the river stage in the South Fork 0.9 ft (fig. 20B). This rise in stage may have led to stream loss to the groundwater, because 6 d later, water levels in well 192897 rose and fell about 1.3 ft. The well is located about 1.5 mi from the pond, between the pond and the river.

Properties of the Kootenai aquifer vary spatially within the Yellowstone Club area. Well 192856, located 1,000 ft above the canyon floor on the north limb of the Andesite Mountain Anticline, shows relatively little seasonal water table response (figs. 20C, 7) compared to well 192897 (fig. 20A). Water levels increase several feet at well 192856 in the spring, suggesting some aquifer recharge from snowmelt in this area. However, complex folding and faulting near this well, or limited connectivity to recharge areas, likely somewhat restrict recharge to the Kootenai aquifer in this area.

Morrison Aquifer

Folding of the Andesite Mountain Anticline, fault displacement, and erosion of overlying bedrock have brought the Morrison Formation closer to the surface in the Yellowstone Club than in other development areas. PWS well 262271 (fig. 7), completed at a depth of 444 ft in mudstones of the Morrison Formation, was in use during this project period. The hydrograph is dominated by frequent pumping cycles during the winter months, which generally obscure seasonal fluctuations (fig. 21). The gradual rise in water levels throughout 2016 suggests that the well is responding to an overall decrease in pumping rather than a seasonal signal from snowmelt or precipitation.

WATER CHEMISTRY

Water-quality information was compiled from previous studies and from water samples collected during this project. We examined water quality in the various aquifers in the study area because it has important implications for development of potable water supplies. Water-quality characteristics (for example, total dissolved solids, major ion composition, and concentrations of trace elements) also support interpretations of groundwater flowpaths from recharge areas to wells.

Selected wells and surface-water sites were sampled for analysis of oxygen and hydrogen isotopes and tritium. Comparing the isotopic composition of precipitation, surface water, and groundwater sheds light on the contribution of rainfall, snowmelt, and surface water to groundwater. Tritium concentrations in groundwater provide an indication of groundwater age. "Young" or "modern" groundwater has recharged since 1952. Groundwater recharged prior to this date will not have detectable levels of tritium.

Total Dissolved Solids and Specific Conductance

Total dissolved solids (TDS) is the sum of all the dissolved constituents in a water sample. TDS in groundwater typically exceeds that in surface water because groundwater accumulates dissolved minerals from soil and aquifer solids as it infiltrates the vadose zone and flows through the saturated zone. Specific conductance is typically measured in the field and provides an indirect measure of TDS. TDS and SC of surface water can assist in determining the primary

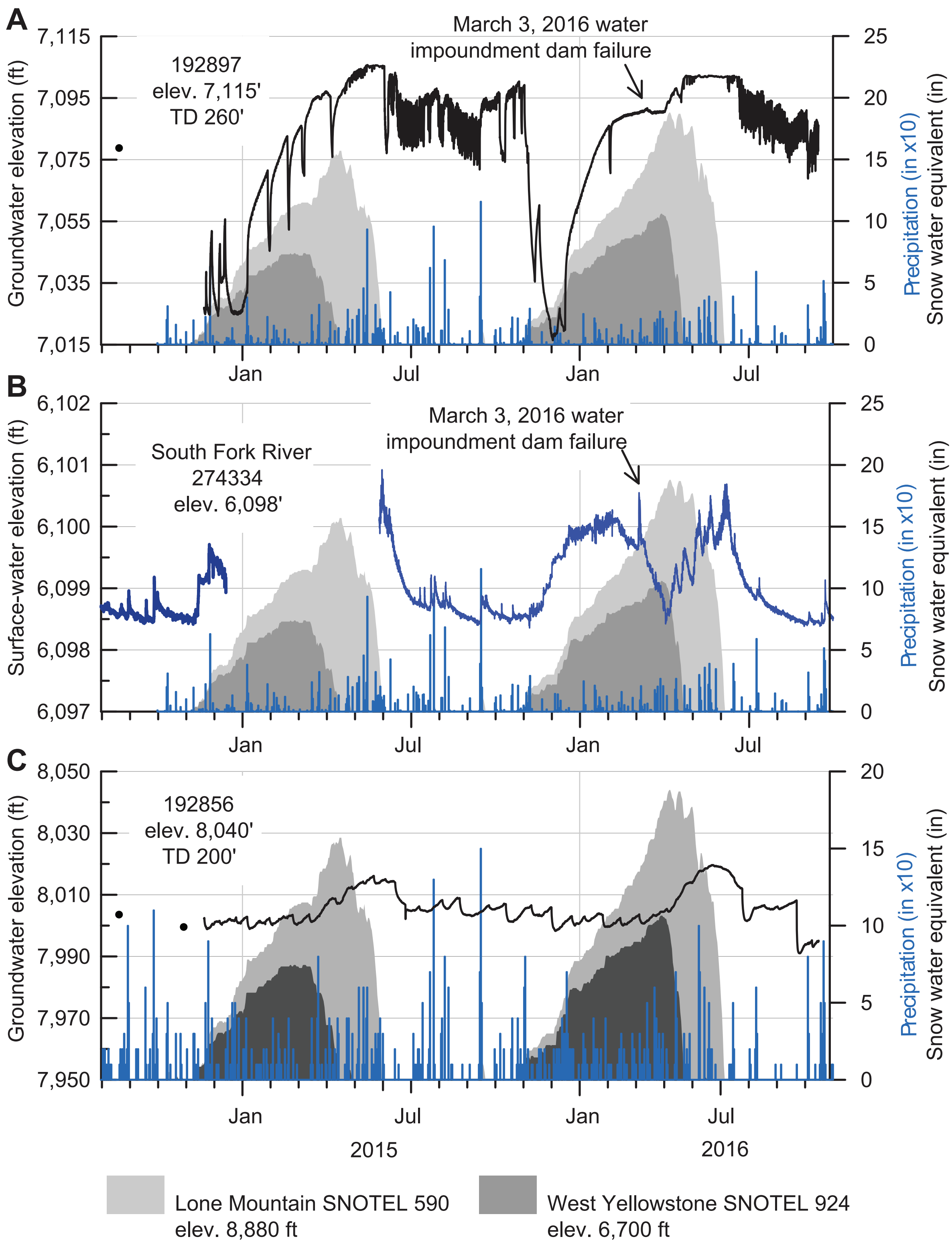


Figure 20. Hydrographs of well 192287, completed in the Kootenai aquifer (A) and the South Fork River stage (B; site 274334; K. Gardner, oral commun., 2019). The hydrograph from well 1928566 (C), also completed in the Kootenai aquifer, is muted compared to A, suggesting the aquifer has limited connectivity to the surface near this well. Precipitation records from stations BS-STA01 (A, B) and Lone Mountain SNOTEL 590 (C) are also shown.

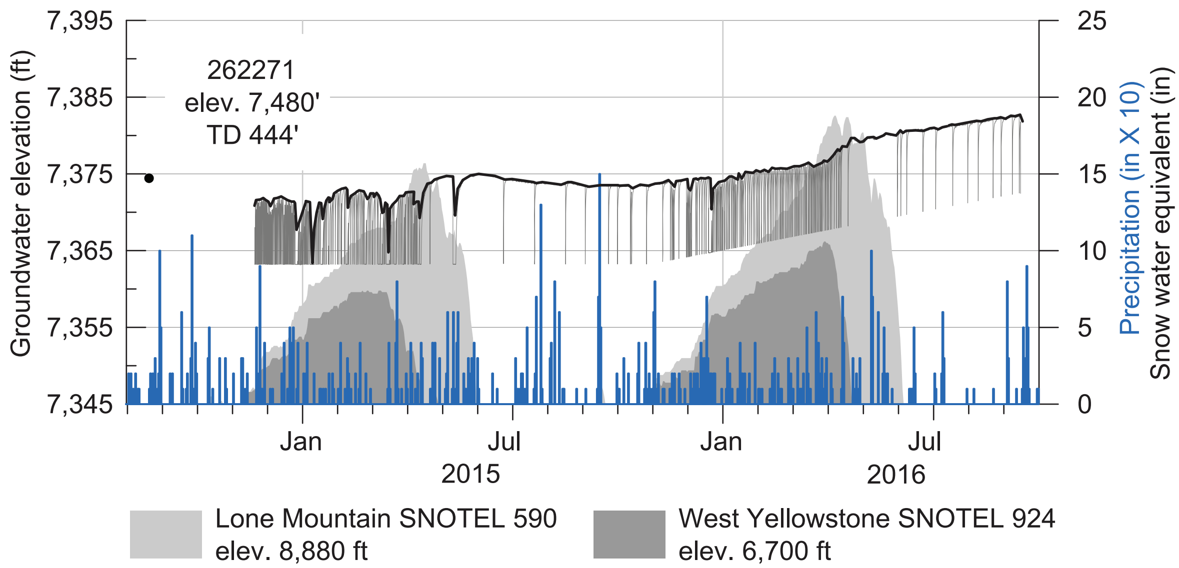


Figure 21. Hydrograph from well 262271. Frequent pumping cycles are seen in the water-level record, but groundwater levels rose overall through the study period. Precipitation from SNOTEL 590 station is also shown.

source of water (precipitation and snowmelt or baseflow from groundwater) to streams.

Surface water and groundwater at Big Sky originate mainly from snowmelt. The water chemistry of snow at 8,080 ft elevation is relatively pristine with low TDS (2 mg/L) and low SC (2 µmhos/cm; 276604, appendix C, table C2). As illustrated in figure 22, this is much lower TDS than in groundwater and surface water in the study area. Surface-water samples from 16 sites within the project area range from 40 mg/L to 135 mg/L with a median value of 66 mg/L (fig. 22). The median TDS for groundwater ranges from 117 mg/L in dacite to 353 mg/L in the Morrison. These values reflect mineral and geologic composition of the bedrock and residence times of groundwater. Overall, TDS at Big Sky is consistently lower in surface water compared to groundwater, reflecting that the primary source of surface water is precipitation and snowmelt.

Two samples collected from the Madison Group aquifer include shallow well 103575, with 393 mg/L TDS, and a nearby spring that emanates from the Madison Group, site number 255289, at 291 mg/L. These samples are an order of magnitude lower TDS than the deeply buried Madison Group well 296215 (outside the study boundary), which measured 2,431 mg/L (not shown on fig. 22). Locations are shown on figure 2.

Surface water that originates from snowmelt is low in dissolved mineral content. At times of the year when streamflow consists primarily of baseflow from groundwater, river water becomes more mineralized. TDS and SC measured over time in surface water show the change in the dominant source of streamflow, from snowmelt to groundwater baseflow. This change is evident in SC and stream discharge measurements from the West Fork near Meadow Village (site 275231, fig. 6). During snowmelt runoff in June 2016, stream discharge was 38.4 cfs with an SC of 138 µmhos/cm. During baseflow conditions in March 2014, stream discharge was 3.6 cfs with an SC of 347 µmhos/cm (appendix D, table D1). Measurements conducted through the winter of 2013 indicate the SC increased with decreasing discharge, suggesting groundwater discharge to the stream accounted for a larger proportion of streamflow.

Major Ions

Piper (trilinear) diagrams show the relative concentrations of major cations and anions (figs. 23, 24). Slow rates of groundwater flow increase the residence time of groundwater and lead to an increased amount of rock–water interactions.

Synoptic discharge measurements indicate the MVA receives some recharge from the Middle Fork (appendix D, table D1). As previously stated, the Middle Fork derives its source from snowmelt during spring runoff and relies on groundwater discharge from bedrock during the late summer through the winter. Groundwater in the MVA has higher TDS than surface water, likely reflecting the dilution of baseflow

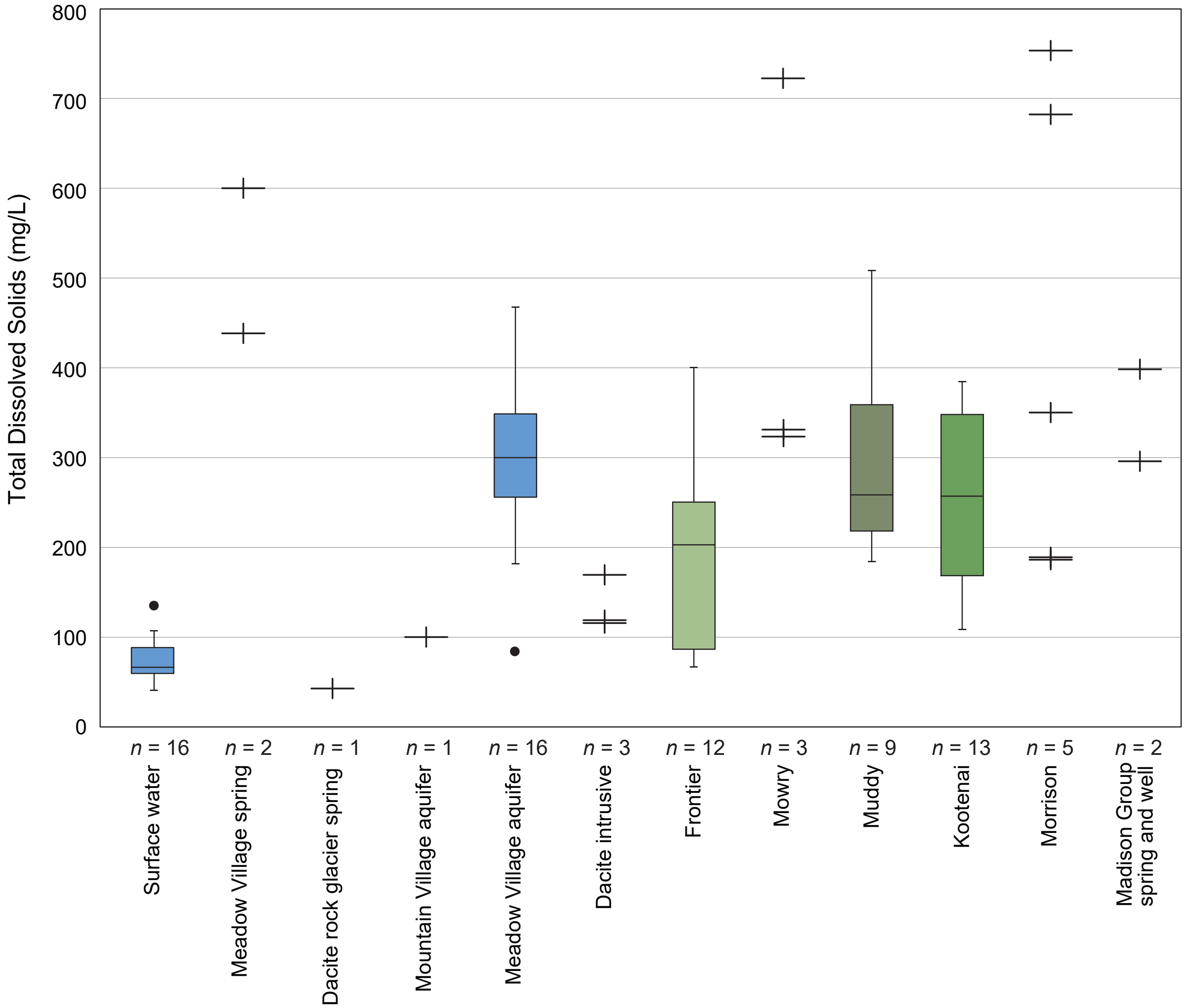


Figure 22. Box and whisker plots of total dissolved solids (mg/L) in groundwater and surface-water samples. Boxes represent the 25th to 75th percentile, lines within the box are the median, whiskers represent the 10th to 90th percentile, and dots represent outliers. Crosses show individual samples in groups with low sample size.

in streams (fig. 22). The MVA and the Middle Fork are similarly calcium–bicarbonate type water (fig. 23).

Although based on a single sample, snowmelt is a calcium–bicarbonate–chloride type water (276604, appendix C, table C2). This signature, with elevated calcium and bicarbonate, may be used to distinguish groundwater chemistry that is dominated by snowmelt recharge. If the source water is precipitation (calcium–bicarbonate water), then groundwater from the Frontier, Muddy, Kootenai, and Morrison aquifers evolves from a calcium–bicarbonate water to sodium–bicarbonate type as groundwater flows through the bedrock.

Groundwater in the study area is generally higher in relative concentrations of sodium and bicarbonate from sulfate reduction and ion exchange with the bedrock (Brinck and others, 2008; fig. 24; appendix C, table C1). The presence of a sulfur odor at well 253676 suggests that sulfate-reducing bacteria are present and active in the Morrison Formation at this location. The fine-grained, clay-bearing nature of the Morrison Formation may contribute to conditions that support sulfate reduction.

A sample collected from well 103575 in the Madison Group aquifer is uniquely recognizable by its major ion composition (fig. 24). Brown (2014) showed that springs and wells completed in the Madison Group in the Big Sky area are a calcium–magnesium sulfate–bicarbonate water type.

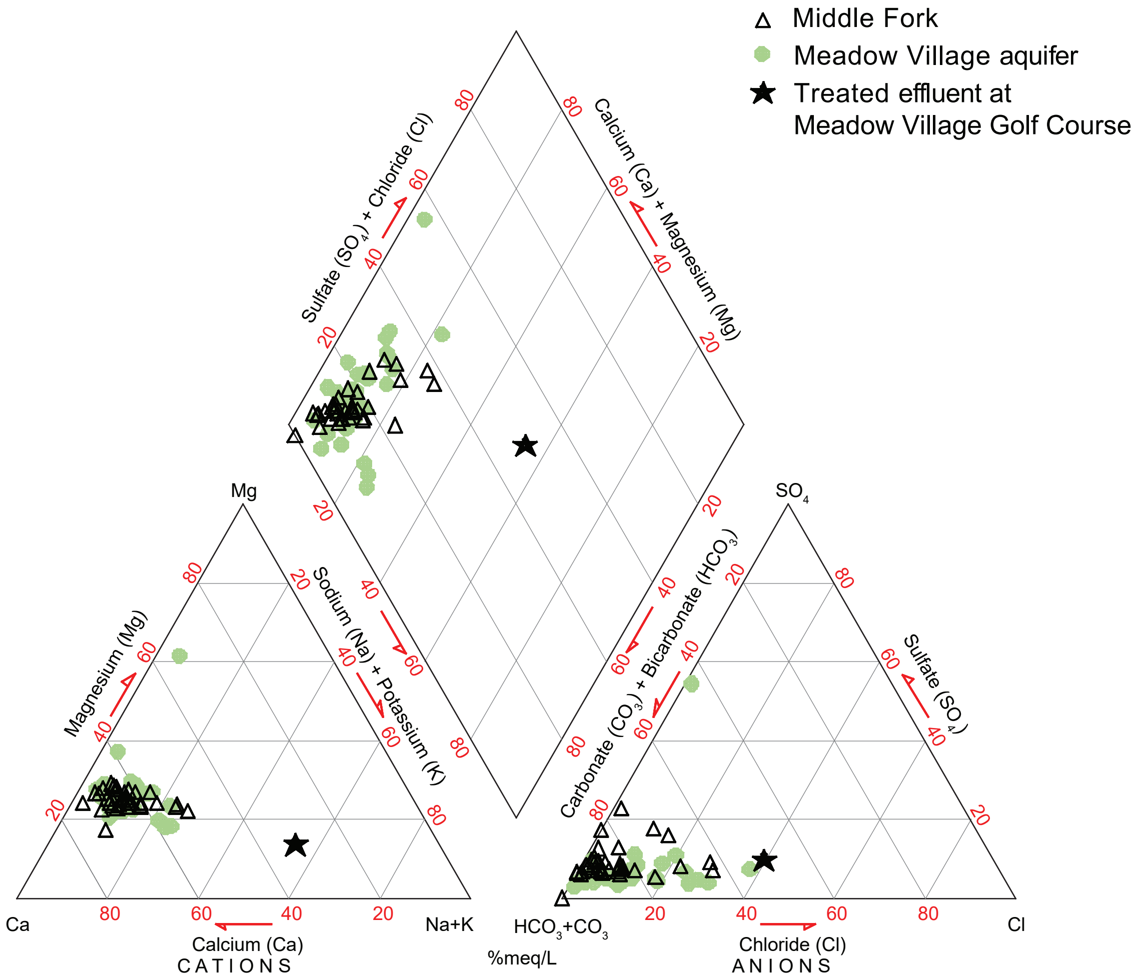


Figure 23. A Piper diagram of major ions (meq/L) in groundwater from the MVA and surface water from the Middle Fork. Most samples are calcium-bicarbonate; however, some groundwater samples have higher chloride. The sample of treated sewage effluent used for golf course irrigation is also shown.

Trace Elements

Analytical results for trace metals can be accessed through the GWIC database (2020). All trace elements detected in water samples from this project meet federal standards for drinking water. However, three bedrock wells sampled during a previous study (Carstarphen, 2015) in 2012 exceeded the standard of 10 µg/L for arsenic (U.S. EPA, 2019): 12 µg/L (well 103501), 15 µg/L (well 237639), and 19 µg/L (well 244347; fig. 9; appendix C, table C2). Two of the wells were completed in the Muddy Formation and one in the Lower Thermopolis sandstone. All three wells were over 200 ft deep. Earlier work by Baldwin (1997) also noted elevated arsenic in several wells, with concentrations ranging from 20 µg/L to 29 µg/L. Arsenic in surface water and spring samples collected for the study reported here ranged from below detection to 1 µg/L.

Arsenic is commonly found in measurable quantities in deposits of volcanic ash. Bentonitic beds, derived from volcanic ash, are mapped in the Cretaceous formations, most notably in the lower Frontier and the Vaughn Member of the Mowry Formation (Tysdal, 1991; Kellogg and Williams, 2006; Vuke, 2013a) and layers of the clay are reported in well logs (plate 1). The bentonitic mudstones may be the source of arsenic to wells completed in bedrock formations.

Wastewater Influences

Nitrate and chloride are both byproducts of sewage treatment systems. Where they occur above natural background levels in groundwater and surface water, nitrate and chloride may indicate the presence of sewage treatment effluent. Other potential sources of nitrogen and chloride are also discussed in this section.

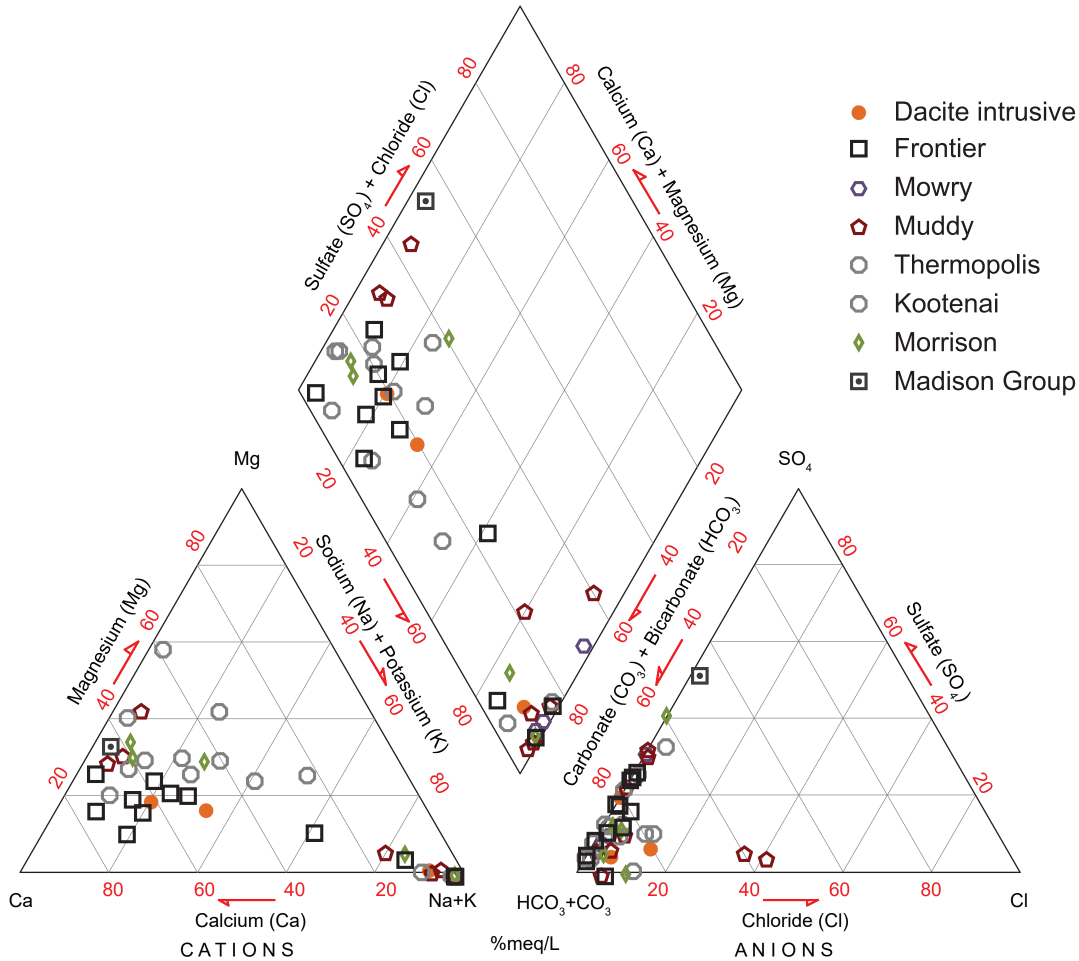


Figure 24. Bedrock aquifers illustrate a calcium-bicarbonate water type in recharge areas evolving to a sodium-bicarbonate chemistry as ground exchanges ions with bedrock minerals along its flowpath.

Nitrate and Nitrite

Nitrate and nitrite in drinking water present health concerns and are regulated at a concentration of 10 mg/L [United States Environmental Protection Agency (U.S. EPA, 2019)]. The Aquatic Life standard for total nitrate in Montana streams is 0.275 mg/L; higher concentrations are harmful to aquatic life (MT DEQ, 2014). Maintaining aquatic life habitat in streams is important to preserving fishery health. Naturally occurring concentrations of nitrate in groundwater tend to be less than 2 mg/L (MT DEQ, 2002). Potential anthropogenic sources of nitrate in groundwater include septic systems, agricultural and landscaping fertilizers, and livestock manure.

Many homes and facilities at Big Sky are on individual septic systems. Without large areas of agricultural land in the study area, intensive use of fertilizers is limited to golf courses. There are seasonal-use horse corrals at the North Fork (on the west side of Meadow Village), Spanish Peaks Mountain Club, Moonlight Basin, and Yellowstone Club. The contribution of nitrogen from bedrock weathering in the Big Sky area is thought to be low, with background concentrations <2.0 mg/L (Montross and others, 2013). Therefore, we consider septic systems, lawn and golf course fertilizers, and horse corrals to be potential sources of groundwater nitrate concentrations that exceed 2.0 mg/L.

Nitrate loading from septic systems depends on soil characteristics, septic system design and efficiency, and housing density. For livestock, the length of confinement, the number of animals, and surface drainage influence nitrate loading.

For this project 48 water samples from 45 wells (three wells were sampled twice, table 2) were analyzed for nitrate and all were below the drinking water standard of 10 mg/L. Concentrations ranged from less than detection (<0.010) to 6.3 mg/L with a median

Table 2. Nitrate and chloride concentrations in groundwater.

GWIC No.	Aquifer	Well Depth (ft)	Sample	NO^3 (mg/L)	Cl (mg/L)
103496	Dacite aquifer	400	8/4/2015	0.06	4.62
103575	Madison Group aquifer	40	4/20/2017	0.29	6.27
104510	Frontier aquifer	71.5	6/25/2015	0.10	12.00
165685	Meadow Village Aquifer	17.7	4/18/2012	3.45	56.33
176326	Morrison aquifer	362	6/24/2015	0.01	1.62
176327	Kootenai aquifer	898	6/26/2015	0.47	14.40
187230	Muddy aquifer	480	5/24/2018	0.37	7.95
192856	Kootenai aquifer	200	6/26/2015	0.01	3.93
192865	Kootenai aquifer	340	6/24/2015	0.56	17.59
192966	Kootenai aquifer	370	6/18/2015	0.01	0.68
205931	Dacite aquifer	312	8/4/2015	0.27	9.44
209445	Muddy aquifer	85	6/23/2015	0.20	69.48
215507	Frontier aquifer	396	6/23/2015	0.18	0.58
215510	Muddy aquifer	56	6/17/2015	0.01	1.70
219966	Muddy aquifer	525	6/16/2015	0.43	110.20
230689	Frontier aquifer	185	6/23/2015	0.01	0.59
230803	Frontier aquifer	176	6/19/2015	0.37	1.88
230804	Frontier aquifer	237.5	6/23/2015	0.01	0.55
231031	Muddy aquifer	160	6/17/2015	0.01	0.99
231745	Frontier aquifer	160	6/23/2015	0.01	0.63
234199	Kootenai aquifer	223	7/23/2018	0.60	1.49
234783	Morrison aquifer	402	6/24/2015	0.29	6.41
237292	Kootenai aquifer	565	6/5/2015	0.47	3.37
239759	Kootenai aquifer	553	8/5/2015	0.01	0.91
244347	Muddy aquifer	200	8/4/2015	0.11	4.12
253676	Morrison aquifer	800	6/24/2015	0.01	16.83
257677	Meadow Village Aquifer	49	4/20/2017	1.18	18.63
257678	Meadow Village Aquifer	58	4/18/2012	1.64	16.33
257678	Meadow Village Aquifer	58	4/20/2017	3.85	19.10
259357	Frontier aquifer	307	6/17/2015	<0.010	0.70
259685	Muddy aquifer	598	6/22/2015	<0.010	10.51
259706	Muddy aquifer	449	6/17/2015	<0.010	1.08
262271	Morrison aquifer	444	6/24/2015	<0.010	26.37
275582	Muddy aquifer	880	6/25/2015	<0.010	2.77
279062	Frontier aquifer	217.5	6/19/2015	0.40	0.46
279080	Dacite aquifer	198	6/23/2015	0.25	0.51
281359	Meadow Village Aquifer	45	10/27/2018	5.98	16.27
281359	Meadow Village Aquifer	45	6/2/2015	4.91	95.07
281360	Meadow Village Aquifer	45	6/3/2015	0.84	12.51
281362	Meadow Village Aquifer	15	6/3/2015	0.08	1.84
281363	Meadow Village Aquifer	25	9/30/2016	0.38	22.14
281363	Meadow Village Aquifer	25	6/2/2015	0.42	23.16
281366	Meadow Village Aquifer	25	6/3/2015	1.67	23.72
281367	Meadow Village Aquifer	35	6/3/2015	1.86	17.61
281368	Meadow Village Aquifer	15	6/3/2015	1.48	24.96
281371	Meadow Village Aquifer	55	6/4/2015	1.30	19.40
281372	Meadow Village Aquifer	20	6/4/2015	6.27	21.24
281373	Meadow Village Aquifer	20	6/4/2015	2.08	21.00

of 0.4 mg/L. Forty-two of the samples contained less than 2.0 mg/L, and the 6 samples that exceeded 2.0 mg/L were found in the Meadow Village area (table 2, fig. 25).

Nitrate in groundwater from five wells (165685, 257678, 281359, 281372, and 281373) completed in the MVA ranged from 2.1 mg/L to 6.3 mg/L (fig. 25, inset). A sample collected from the golf course sprinkler system (this system irrigates the course with treated effluent, site 246755) had a concentration of 0.82 mg/L nitrate (table 3). While nitrate in groundwater may be derived from fertilizer and effluent applied at the golf course, wells with the highest nitrate concentrations in the MVA (281359 and 281372) are upgradient of the golf course; well 165685 is within the southern boundary of the golf course (table 2, figs. 11, 25). This suggests that fertilizer and effluent applied to the golf course may not be the only source of nitrate to these wells.

Samples from two springs (280689 and 278297) located southeast of the MVA, the golf course, and one groundwater drain within the golf course (255834) contained nitrate concentrations of 3.0 mg/L (280689), 4.9 mg/L (278297), and 6.6 mg/L (255834; table 2, figs. 11 and 25, inset). The limited extent of the wells and springs in the MVA affected by elevated nitrate (>2.0 mg/L) suggests that the source of nitrate is not shale, which underlies the entire aquifer. Most of the affected area is natural grass and sagebrush vegetation with some grass lawns. In this setting, the likely source of the nitrates is from the south side of the golf course, upgradient septic effluent, or landscaping fertilizer from lawns. Rainfall events exceeding 0.5 in/d induce recharge in the study area (Waren and others, 2021); these events may leach nitrate from fertilizers to the water table.

Middle Fork site 274333 is located downgradient from the MVA (fig. 6, inset). Four water samples were collected in April, May, and June 2014 and September 2016. The samples collected on April 2014 and September 2016 both exceeded the aquatic life standard for total nitrate in Montana streams of 0.275 mg/L (table 3).

Meadow Village is the oldest development at Big Sky, and homes and businesses within the BSWSD boundaries are connected to the Big Sky Water and Sewer District sewer system and wastewater treatment plant. However, homes and developments on individual or community septic systems are located outside the BSWSD boundaries. The DEQ reports an unsewered development at the far south end of the MVA has a failing community septic system with reported nitrate discharge exceedances for years 2016–2020 (Eric Sivers, Montana DEQ, written commun., 2019; fig. 11).

Chloride

Chloride occurs naturally in groundwater from the dissolution of salts in bedrock, especially from marine sediments. Anthropogenic sources of chloride include road salt and sewage effluent. Chloride is conservative (it persists and generally remains unchanged in the environment) and rarely reacts with other minerals. In settings where naturally occurring chloride concentrations are low, elevated concentrations in surface water and groundwater may indicate contamination by sewage effluent or road salt.

Chloride concentrations in 48 groundwater samples ranged from 0.5 mg/L to 110 mg/L with a median value of 8.7 mg/L (table 2). No samples exceeded the EPA (1996) secondary (aesthetic) drinking water standard of 250 mg/L chloride.

Four samples had relatively higher chloride, with concentrations ranging from 56.3 mg/L to 110.2 mg/L (table 2, fig. 26). Well 281359 is completed in the MVA upgradient from the Meadow Village Golf Course (fig. 11). Well 165685 is located along the southern edge of the golf course. Although groundwater samples from the MVA were elevated in nitrate and chloride concentrations, and they are both indicators of septic leaching, there is not a correlation between nitrate and chloride concentrations in individual wells. Well 219966 at Moonlight Basin is located at the headwater divide between Middle Fork and Jack Creek, and is completed to 85 ft in the Muddy aquifer at a road maintenance shop. The chloride here could be derived from road de-icer or nearby septic systems and subsequently transported through preferential flowpaths (fractures) in the aquifer. The source for chloride in well 209445 at Spanish Peaks Mountain Club, screened from 325 ft to 525 ft, is undetermined (fig. 26). Groundwater samples from 10 wells completed in the Frontier, Muddy, or Kootenai aquifers had chloride concentrations <1.0 mg/L, suggesting bedrock is not generally a source of chloride to groundwater in this setting (table 2).

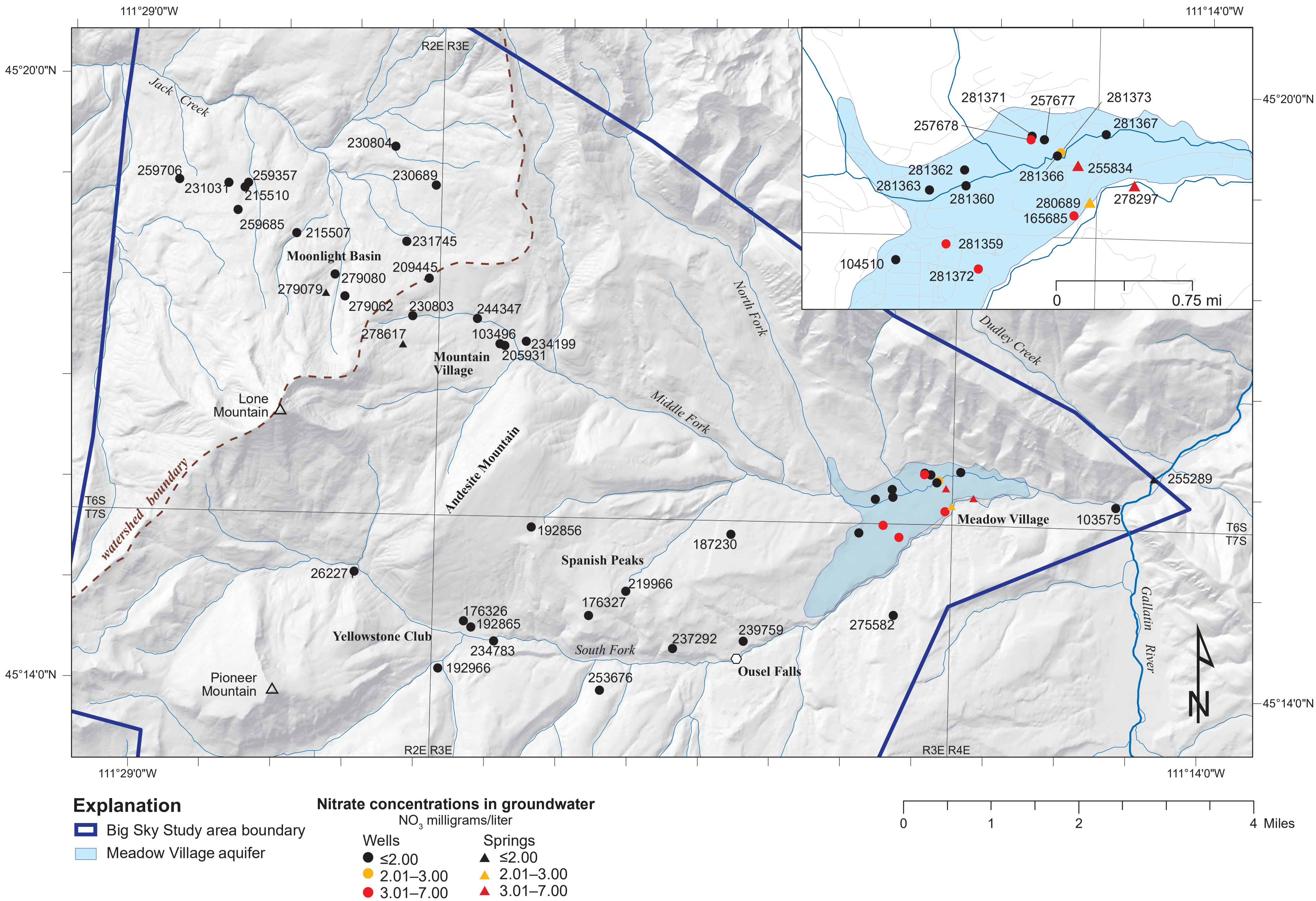


Figure 25. Groundwater sampling locations and distribution of nitrate in groundwater. Elevated nitrate concentrations (shown in orange and red) are limited to groundwater in the Meadow Village Aquifer. Site 255834 is a groundwater drain.

Table 3. Nitrate and chloride concentrations in surface water.

GWIC No.	Site Location	Sample	NO^3 (mg/L)	Cl (mg/L)
246755	Treated Effluent—Meadow Village Golf Course	8/19/2015	0.82	95.82
255289	Madison Aquifer spring at Gallatin River	8/5/2014	0.11	1.62
255289	Madison Aquifer spring at Gallatin River	7/31/2017	0.14	1.80
255289	Madison Aquifer spring at Gallatin River	8/6/2018	0.15	1.79
255289	Madison Aquifer spring at Gallatin River	7/25/2016	0.15	1.82
255289	Madison Aquifer spring at Gallatin River	8/12/2015	0.16	1.92
278617	Dacite aquifer at Mountain Village	6/19/2015	0.25	0.54
279079	Moonlight Basin Lone Creek spring	6/23/2015	0.31	0.47
280689	MVA spring	6/18/2015	2.98	151.10
278297	MVA spring	6/18/2015	4.94	69.86
255834	MVA golf course drain	10/27/2018	6.55	53.11
276593	Beehive Basin Creek	11/12/2014	0.03	0.46
276593	Beehive Basin Creek	6/4/2014	0.09	0.39
276593	Beehive Basin Creek	5/21/2014	0.1	0.50
278618	Lone Creek	6/23/2015	0.19	0.50
274333	Middle Fork	6/4/2014	0.13	2.30
274333	Middle Fork	5/22/2014	0.15	4.78
274333	Middle Fork	9/30/2016	0.32	10.94
274333	Middle Fork	4/17/2014	0.52	29.91
276156	Middle Fork	6/4/2014	0.23	0.79
276156	Middle Fork	5/21/2014	0.25	1.21
276156	Middle Fork	6/19/2015	0.26	0.68
276156	Middle Fork	11/12/2014	0.28	0.96
276425	Middle Fork	6/4/2014	0.13	2.40
276425	Middle Fork	5/22/2014	0.13	5.02
277302	Middle Fork	6/4/2014	0.14	2.20
277302	Middle Fork	4/17/2014	0.14	29.34
277302	Middle Fork	5/22/2014	0.15	4.47
277303	Middle Fork	5/21/2014	0.13	6.06
280685	Muddy Creek	6/18/2015	0.05	0.49
274335	North Fork	6/4/2014	0.07	0.48
274335	North Fork	4/17/2014	0.09	1.93
274335	North Fork	5/22/2014	0.11	0.61
274335	North Fork	11/13/2014	0.12	1.28
274334	South Fork	6/4/2014	0.09	1.10
274334	South Fork	6/4/2014	0.11	1.04
274334	South Fork	5/22/2014	0.14	2.08
274334	South Fork	4/17/2014	0.22	14.34
280686	South Fork	6/18/2015	0.12	0.99
278927	Unnamed tributary of Moonlight Basin Creek	6/23/2015	0.01	0.63
274332	West Fork	6/4/2014	0.12	1.41
274332	West Fork	5/22/2014	0.14	2.99
274332	West Fork	11/13/2014	0.38	10.16
274332	West Fork	4/17/2014	0.41	21.23
275228	West Fork	8/19/2015	0.05	4.96
275228	West Fork	11/13/2014	0.06	9.76
275228	West Fork	6/4/2014	0.09	1.67
275228	West Fork	5/22/2014	0.11	4.01
275228	West Fork	4/17/2014	0.16	31.14
275238	West Fork	8/19/2015	0.14	8.39

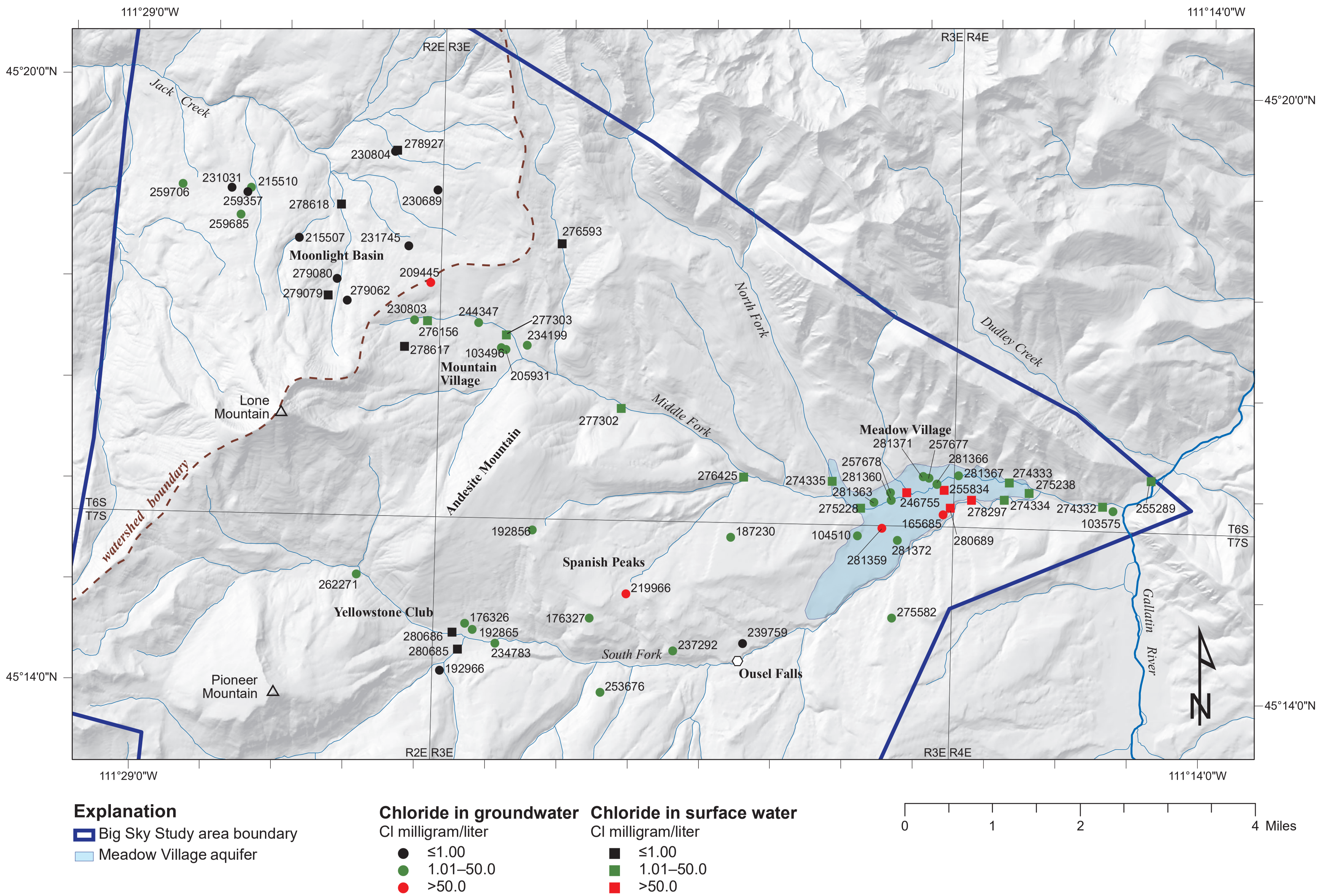


Figure 26. Groundwater and surface-water sampling locations and the distribution of chloride. Most of the elevated chloride concentrations (shown in red) were in groundwater from the Meadow Village Aquifer and adjacent surface water. Site 255834 is a groundwater drain.

Chloride concentrations in 50 surface-water samples from 22 sites ranged from 0.4 mg/L to 151.1 mg/L, with a median value of 12.1 mg/L (table 3). Fourteen of these samples had chloride concentrations <1.0 mg/L (table 3, fig. 26). Chloride ranged from 53.1 mg/L to 151.1 mg/L at four sites in the Meadow Village area (255834, groundwater drain; 278297 and 280689, springs; and 246755, the golf course sprinkler system/treated effluent; fig. 26, table 3). The springs are located southeast of the golf course (fig. 11). The spring sites are also near State Road 64 and could be affected by road salt (fig. 9). The drain (255834) collects groundwater from the southeast end of the golf course.

Surface-water samples in the creeks/rivers ranged from 0.4 mg/L to 31. 2 mg/L. Montana does not have an aquatic life standard for chloride. The U.S. EPA recommends an acute standard of 860 mg/L and a chronic standard of 230 mg/L (MDEQ, 2002).

Samples collected over time from specific locations showed that chloride concentrations changed seasonally. Sampling on the Middle Fork downstream of Meadow Village (sites 275228, 274332, 274333, and 274334) shows that during 1 yr, chloride concentrations varied by an order of magnitude (table 3). The samples, collected during 2014 and 2015, ranged from 1.0 mg/L to 31.1 mg/L chloride (table 3) and negatively correlate to stream discharge (appendix D, table D1). During high discharge at spring snowmelt, concentrations of chloride are low. As discharge declined from late summer through winter, under baseflow conditions, chloride concentrations rose.

Tritium

Detectable tritium in groundwater indicates some recent (post-1951) groundwater recharge (Nikolov and others, 2019). Results of tritium sampling from this study are presented in appendix F and figure 27. Concentrations are divided into three groups based on definitions established by Nikolov and others (2019):

- Old water: contains no detectable tritium (<0.8 TU), suggesting the groundwater was recharged more than 70 years ago. These aquifers do not receive appreciable amounts of modern recharge.
- Mixed old/modern water: contains detectable tritium between 0.8 and 5.0 TU, indicating a mix of old groundwater and younger, post-1950, groundwater. These aquifers receive some modern recharge.
- Modern water: tritium exceeds 5 TU, indicating predominantly young groundwater that has recharged the aquifer within the past 70 yr.

Groundwater samples from 21 wells were analyzed for tritium. Three samples showed no detectable tritium, 6 samples contained tritium above detection (0.8 TU) and <5.0 TU, and 12 samples contained tritium concentrations of 5 TU and greater (appendix F). Figure 27 illustrates the distribution of tritium in wells across the study area. Groundwater of various ages (old, mixed, and modern) are encountered within the various developments. Except for the MVA, there is no apparent spatial trend in groundwater age across the study area. Both wells sampled from the MVA have relatively high tritium concentrations, consistent with shallow, unconfined sand and gravel aquifers that produce young, recently recharged groundwater.

Relationships among groundwater age (expressed as tritium concentration), well depth, and aquifer are illustrated in figure 28. In general, one would expect that groundwater from shallow wells would be younger in age than groundwater pumped from greater depths. This conceptual model holds true for the MVA, but figure 28 shows that both wells that produce old water and wells that produce modern water span a large range of well depths. This is attributed to the nature of fracture networks (or other preferential flow pathways), which provide deep and relatively rapid infiltration of modern recharge near some wells. Ten of the 12 samples with 5.0 TU or more were from wells that exceed 175 ft deep, and six of these wells exceed 300 ft in depth. While it is not surprising that the MVA contains modern recharge, the distribution of relatively young groundwater at depth suggests that hydraulically well-connected fracture networks convey infiltration to some wells.

Figure 28 illustrates that wells completed entirely in bedrock formations show a range of groundwater age. Bedrock aquifer wells that produce old groundwater span a range in depth from about 200 to 800 ft; this can be explained by little to no hydraulic connection to modern recharge at these locations. However, most bedrock aquifer wells, ranging in depth from about 190 to 900 ft, have tritium concentrations reflecting mixed to modern groundwater ages. Fracture

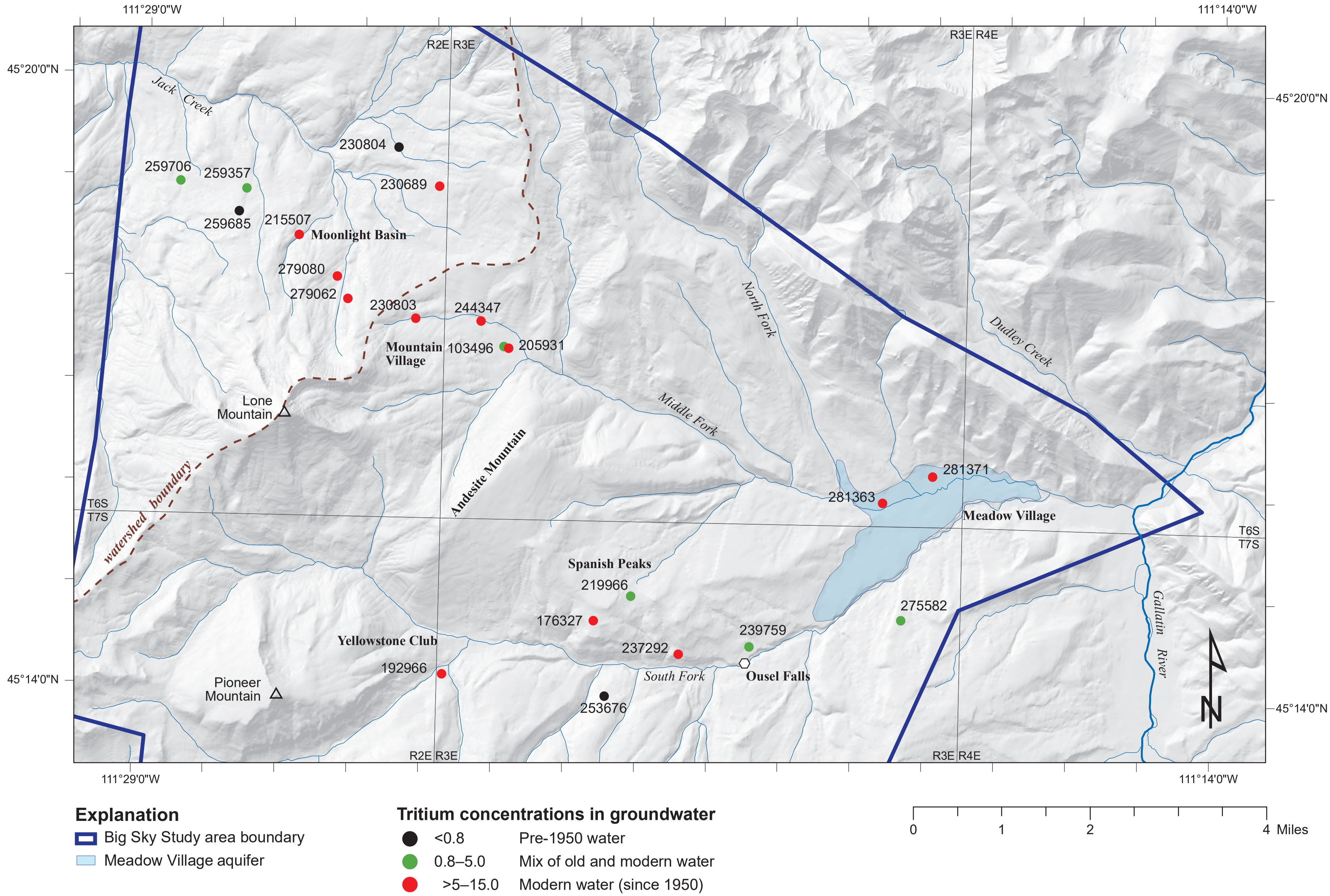


Figure 27. Map showing concentrations of tritium in groundwater.

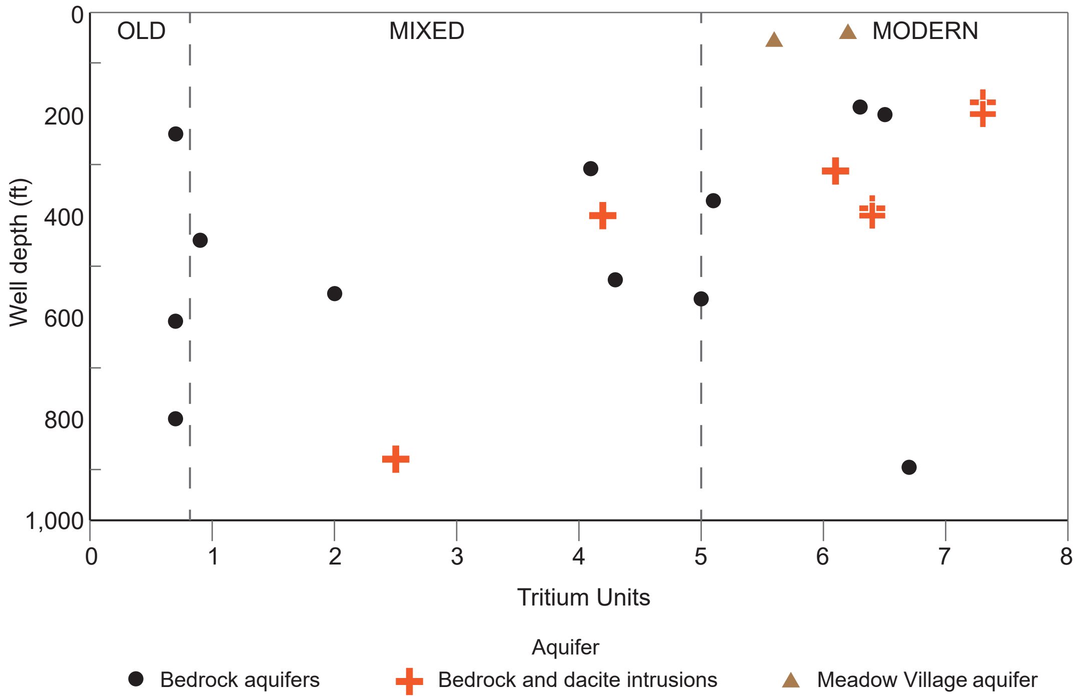


Figure 28. Tritium concentrations in groundwater versus well depth.

networks or other high-permeability pathways provide relatively large volumes of recent recharge to these wells.

Figure 28 also illustrates the distribution of groundwater age in wells that are open to both a bedrock aquifer and the dacite intrusion. Tritium in five of the seven wells exceeds 5 TU. This indicates that most wells completed in dacite are located in heavily fractured areas that provide a hydraulic connection between the wells and modern recharge.

Groundwater recharge in the study area typically occurs at high elevations where aquifer-bearing formations are exposed at the land surface, or where fractures in the bedrock connect the land surface to underlying aquifers. At locations where the aquifer is hydraulically connected to the land surface, groundwater levels rise in response to snowmelt (i.e., well 279062; fig. 14B) and the groundwater age is mixed to modern. Conversely, where groundwater response in wells shows slow and small rises in water levels, the aquifer has low to non-detectable concentrations of tritium. For example, the hydrograph from well 230804 (fig. 14C) shows no response to snowmelt recharge and tritium is less than detection in groundwater from this well (fig. 27; appendix F). At Yellowstone Club, well 253676 (fig. 9) was drilled through shales into the Morrison aquifer and is completed at 800 ft below the land surface. Tritium is below the detection limit in groundwater from this well, indicating old groundwater age.

Groundwater pumped from wells 176327 and 237292 is of modern age, but these wells are completed at depths of 525 and 565 ft, respectively, in the Kootenai aquifer, which is overlain by shale. Although there are limited water-level measurements from well 237292, the data show a rising groundwater response to snowmelt recharge followed by a decline in fall and winter. Both wells are located near the South Fork canyon, and groundwater might be recharged where the South Fork flows across the surface exposure of the fractured Kootenai Formation between Yellowstone Club and Spanish Peaks Mountain Club at Ousel Falls. Groundwater flow along well-developed fracture networks may also explain in part the flow of relatively recent recharge to these wells.

DISCUSSION

Typical concerns related to use of groundwater for water supply include (1) the effects of pumping from groundwater systems on nearby surface-water features, and (2) the potential for pumping to reduce the volume of groundwater that is in storage and available for future use. Data collected during this study and related modeling (Waren and others, 2021) demonstrate that groundwater in the MVA is well connected to surface water, and increases in pumping from the system will reduce baseflow to the Middle Fork. In other areas studied within Big Sky, hydrographs from wells completed in bedrock aquifers showed that groundwater pumping caused seasonal declines in groundwater levels that generally recovered following springtime recharge or a cessation in pumping. Depending on site-specific hydrogeologic conditions, effects of groundwater withdrawals may be largely offset in areas with adequate groundwater recharge. Water resources at Big Sky benefit from abundant snowfall that provides a large amount of water on a seasonal basis. However, due to overall low aquifer permeability and little storage capacity in the bedrock formations, a small portion of snowmelt recharges the groundwater system while a large portion of snowmelt leaves the basin through the surface-water network. In this section, we discuss the study results in the context of specific water resource issues and concerns in the Big Sky community.

The MVA is one of the most heavily used aquifers at Big Sky. Model simulations of water use and hypothetical growth scenarios (Waren and others, 2021) indicate that high-intensity pumping (up to 75% over 2016 pumping rates) from the aquifer over short time periods will reduce groundwater discharge from the MVA to the Middle Fork. High-intensity pumping can decrease groundwater levels across a large portion of the aquifer because the aquifer is of limited aerial extent. The groundwater flow model quantifies these effects; it is a tool that can be used to test various management and water-use scenarios associated with changes in pumping and climatic conditions. Model simulations can inform efforts of PWS operators to avoid overstressing this system.

Bedrock aquifers within Big Sky consist primarily of thin sandstone layers within shale-dominated formations. Geologic structures and processes (faults, folds, areas of uplift and erosion) cause the aquifer configurations to be highly variable across Big Sky. Formations and the aquifers they contain are close to the land surface in some areas and deeply buried at other locations. Importantly, as a result of tectonism, these bedrock formations are discontinuous; the aquifers differ locally, from development to development within the study area. Differences in permeability and transmissivity of the aquifers across this mountainous region contribute to the heterogeneity observed in the aquifers and result in differences in aquifer productivity within the study area.

Dacite sills add to the variation in bedrock well productivity across the study area. Where the dacite is both present and heavily fractured, it increases the productivity of the bedrock aquifers. Bedrock aquifers in the Frontier and Thermopolis/Kootenai Formations are generally more productive than those of the Muddy and Morrison Formations. Most sandstone layers within these shale formations are thin, and this limits the area of the aquifer that contributes water to each well. Limited hydraulic connectivity between recharge areas and some bedrock aquifers negatively affects the yield of high-capacity pumping wells. The geologic faults and folds described above, along with thick sequences of shale, create no-flow boundaries within the aquifers. These boundaries restrict recharge and limit the area from which a single well can draw water. Although aquifer tests can identify these boundary conditions, well yields in the bedrock aquifers vary greatly across the study area, and this complicates predicting where new wells will yield adequate groundwater supply. Alluvial deposits at Meadow Village and Mountain Village form productive aquifers, but they are of limited aerial extent.

Most groundwater recharge occurs during 3 to 4 mo of spring snowmelt. Well hydrographs show this recharge period as increasing groundwater levels in spring and early summer. During peak pumping periods in the winter and summer months, hydrographs show groundwater drawdown. Water-level records collected for this project indicate recovery of groundwater levels during spring recharge and in the fall, following cessation of summer pumping.

Despite the seasonal recharge and periods of high pumping, snowmelt infiltration during the investigation provided adequate recharge to offset drawdown from pumping. This indicates that given typical amounts of snowfall, snowmelt recharge is adequate to meet the groundwater demand experienced during this study. Most hydrographs show rapid water-level rise in response to recharge, followed by declining (or periodically stabilizing) water levels throughout the remainder of the year. These findings indicate the amount of recharge adequately supported pumping during winter and summer periods of high demand. The bedrock aquifers recovered to levels of previous years during off-season, low-demand periods. Several other hydrographs from wells in bedrock aquifers showed different patterns, including a delayed and subdued groundwater-level response to snowmelt.

We attribute this response to less hydraulic connection between infiltration at the land surface and the aquifer. The groundwater system at these locations is unlikely to provide much additional groundwater.

Geologic structures and bedrock orientations mapped at the land surface likely extend through the Madison Group limestone. Like overlying units, the Madison Group was affected by tectonism and intrusive events that presumably caused fracturing, offset, folding, and possibly enhanced karst development. The variability of the water chemistry and productivity of the two wells completed in the Madison aquifer near Big Sky indicates that portions of it are locally disconnected. However, springs emanating from some outcrops of the Madison Group have consistent water chemistry and only small, seasonal changes from a relatively steady discharge rate. This indicates that the springs are fed by long and generally contiguous regional flowpaths.

Although the pumping rates that were used during this study do not appear to cause long-term aquifer depletion, extending the winter and summer pumping seasons or increasing the magnitude of pumping will place additional stress on the limited water resources available in Big Sky. Increases in pumping rates or extending periods of withdrawal can negatively affect water levels and the associated volume of groundwater in storage. Drilling and pumping from new wells may exacerbate drawdown at existing wells, depending on their proximity to each other and the local aquifer transmissivity.

Groundwater quality at Big Sky is generally good. Previous studies in this area found arsenic at concentrations of concern in several wells. The source of this arsenic is likely clay minerals derived from volcanic ash deposits in the Frontier and possibly Muddy Formations. Nitrate and chloride concentrations in groundwater are elevated in the Meadow Village development. Based on the location of the wells with high concentrations and the one sample we collected of treated sewage effluent that is applied to the land surface, we speculate that septic system effluent (rather than fertilizer or treated effluent) is a likely source of this contamination. Due to shallow water table and unconfined conditions in the MVA, large precipitation events and any irrigation that exceeds evapotranspiration can transport nitrate to the water table. The permeable sands and gravels of the Meadow Village and Mountain Village aquifers, the shallow depth to groundwater, and the density of residential/commercial development make this groundwater especially vulnerable to surface activities.

RECOMMENDATIONS

The following recommendations address methods to augment the Big Sky community water supply. We focus on adding additional public supply wells, managing the groundwater system, protecting groundwater quality to ensure its usability, and considering additional conservation to constrain anticipated growth in water use.

Development of additional groundwater supplies:

- In some locations, particularly at higher elevations, wells completed in the bedrock aquifers show a dynamic response to snowmelt. Under current conditions, these aquifers supply groundwater for seasonal, high-volume pumping, and water levels recover during seasonal decreases in pumping in the late spring and fall. Aquifers in these areas may be able to sustain flow to additional wells. However, new wells could cause interference (exacerbate drawdown) in nearby existing wells. A program to monitor groundwater levels in PWS wells can alert system managers to pumping rates that exceed the aquifer’s capacity to recharge and to issues related to well interference.

- Consider installation of several low-capacity production wells in place of single large-capacity wells for public water supply systems. High-volume production wells are difficult to site across much of the study area due to the low transmissivity and limited storage capacity of the bedrock aquifers. The discontinuous nature of the bedrock aquifers imparted by the geologic setting results in conditions that better support low pumping rates.

- Consider the locations of geologic features (folds, faults, etc.) that bound the extent of local aquifers when siting new wells. This will increase the likelihood of siting new wells at locations that can support additional groundwater withdrawal. Monitoring groundwater levels in nearby wells during aquifer tests helps to delineate aquifer boundaries.

- Continue investigation of developing the Madison Group aquifer. Springs emanating from the Madison Group in the Gallatin River Canyon could be a source of supply, but impediments to use of spring water include acquisition of water rights and the engineering and infrastructure required to pump water to the developments at Big Sky. Although the chances for success may be small, additional characterization of recharge areas and groundwater flow paths associated with the Madison Group aquifer may suggest locations where wells completed in the formation could yield potable water. In the south of the study area, geologic folds and faults associated with the Spanish Peaks Fault, the Hilgard Fault, and the Lone Mountain Intrusion likely impose local boundaries to groundwater flow in this aquifer.

Management of public water supply wells:

- Encourage connection to public water supply systems at new residential and commercial developments. These systems enhance the capacity for professional management of the limited water resources available to the Big Sky community. PWS systems can monitor, evaluate, and improve operations to optimize well field management and avoid negative consequences of over pumping.

- Additional water storage capacity (e.g., tanks or impoundments) could provide flexibility with respect to daily pumping rates. Water storage is typically required for firefighting but additional storage capacity would allow extended periods of pumping at lower rates from wells, and allow longer aquifer recovery periods when pumps are inactive. For example, pumps could be operated at night to fill storage, providing additional supply during hours of peak demand.

- Although not common practice in Montana, hydraulic fracturing of bedrock formations is used in the United States and abroad to enhance the productivity of bedrock aquifers (Hart, 2016; Cobbing and Dochartaigh, 2007; Less and Andersen, 1994). The process involves injecting water into a borehole under high pressure to increase fracture apertures and connectivity. This increases aquifer storage through development of the fracture networks that store and convey groundwater to wells.

Develop a groundwater quality protection plan to support long-term availability of groundwater for potable supply:

- Establish and/or expand a water-quality monitoring program for surface and shallow groundwater. In addition to nitrate and chloride, sample for other constituents common to septic waste (pharmaceuticals and personal care products), fuel storage, fertilizers, and pesticides.

- Consider expanding sewer systems to serve more developed areas in Big Sky. Ensure that existing septic systems are operated and maintained to protect groundwater quality. Similarly, ensure that fuel, road salt, and other potentially harmful materials are properly contained and monitored to reduce risk of groundwater contamination.

Reduce water use/increase water reuse:

- Consider alternatives to groundwater for snowmaking. Snowmaking is a seasonally intensive water use that stresses the groundwater system in late fall and early winter, coinciding with periods of little to no groundwater recharge.

- Increasing water conservation and water reuse strategies will reduce groundwater demand. Examples include expanding water-conservation landscape techniques, water-efficient plumbing fixtures and appliances, and exporting water-intensive services such as hotel laundry.

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APPENDIX A

LIST OF SURFACE-WATER MONITORING SITES

Table A1. Surface-water monitoring sites and type of monitoring.

GWIC ID	Latitude	Longitude	Elevation (ft)	Sample Source	Monitored
276604	45.308380	-111.381760	8080	Precipitation	Sampled[1]
277295	45.285520	-111.368720	7240	Precipitation	Sampled
277296	45.266170	-111.306340	6260	Precipitation	Sampled
246755	45.268590	-111.290260	6255	Sewage effluent/irrigation water	Sampled
255834	45.267971	-111.294234	6195	Groundwater drain	Stream gaging/sampled
278297	45.266434	-111.287800	6160	Spring	Sampled/water parameters[2]
278617	45.292142	-111.420814	8060	Spring	Sampled
279079	45.297977	-111.440187	7990	Spring	Sampled
280689	45.265088	-111.292806	6165	Spring	Sampled
280691	45.264520	-111.292575	6160	Spring	Sampled
280693	45.265711	-111.291682	6155	Spring	Sampled
280694	45.262996	-111.293985	6170	Spring	Water parameters
275232	45.268800	-111.292710	6180	Pond	Stream gaging
274332	45.265770	-111.257050	6000	West Fork	Sampled
274333	45.269470	-111.278980	6118	West Fork	Stream gaging/water parameters
274334	45.266616	-111.280147	6078	South Fork	Stream gaging/water parameters
274335	45.269162	-111.320707	6420	North Fork	Water parameters
275228	45.264680	-111.313820	6310	West Fork	Stream gaging/sampled
275230	45.266040	-111.306230	6260	West Fork	Stream gaging/sampled
275231	45.269690	-111.293570	6180	West Fork	Streamgaging
275238	45.267800	-111.274300	6060	West Fork	Stream gaging/water parameters
275806	45.266510	-111.303360	6235	West Fork	Stream gaging
275863	45.270150	-111.291080	6165	West Fork	Water parameters
276153	45.291580	-111.397110	7435	Middle Fork	Water parameters
276154	45.293280	-111.402000	7500	Middle Fork	Water parameters
276155	45.294010	-111.405280	7560	Middle Fork	Water parameters
276156	45.294070	-111.416620	7800	Middle Fork	Water parameters
276405	45.261880	-111.294780	6160	South Fork	Water parameters
276406	45.250160	-111.315360	6300	South Fork	Water parameters
276425	45.269400	-111.341440	6520	Middle Fork	Water parameters
276591	45.267140	-111.344200	6580	Middle Fork	Water parameters
276593	45.307420	-111.385400	7915	Beehive Basin Creek	Sampled
277070	45.267310	-111.298550	6210	West Fork	Water parameters
277071	45.270368	-111.288356	6150	West Fork	Water parameters
277302	45.280310	-111.370610	6870	Middle Fork	Water parameters
277303	45.292060	-111.398090	7450	Middle Fork	Water parameters
277304	45.254480	-111.304980	6320	South Fork	Sampled
278616	45.236677	-111.344830	6620	South Fork	Sampled
278618	45.313071	-111.437626	7120	Lone Creek	Water parameters

Table A1—*Continued*.

GWIC ID	Latitude	Longitude	Elevation (ft)	Sample Source	Monitored
278924	45.307404	-111.447269	7560	Unnamed west tributary of Lone Creek	Water parameters
278925	45.293554	-111.423628	7990	Unnamed tributary of Middle Fork	Water parameters
278927	45.322258	-111.424667	7370	Unnamed tributary of Moonlight Basin Creek	Water parameters
279077	45.297040	-111.438113	8040	Lone Creek	Water parameters
279109	45.296710	-111.436400	8055	Lone Creek	Water parameters
280685	45.239720	-111.407740	7095	Muddy Creek	Sampled
280686	45.242540	-111.409078	7115	South Fork	Sampled
282927	45.264659	-111.310353	6280	West Fork	Stream gaging/sampled
282928	45.268836	-111.295622	6187	West Fork	Stream gaging/sampled

[1]Sampled: chemical lab analysis (major ions and trace metals), including water parameters.
[2]Water parameters: field measurement of pH, SC, temperature.

Table A2 . Monitoring wells and frequency of water-level measurements.

GWIC ID	Location	Latitude	Longitude	Land Surface Elevation (ft-amsl)	Total Well Depth (ft)	Aquifer	Water-Level Monitored Interval[1]
103500	Meadow Village	45.265288	-111.330119	6488	350	Mowry	Monthly
103508	Meadow Village	45.266790	-111.291960	6200	27	Meadow Village aquifer	Monthly
103556	Meadow Village	45.269147	-111.273056	6180	95	Alluvium/colluvium	Monthly
103557	Meadow Village	45.265520	-111.284100	6150	103	Frontier	Monthly
103560	Meadow Village	45.268750	-111.286220	6159	29	Meadow Village aquifer	Monthly
103561	Meadow Village	45.269620	-111.287560	6151	17	Meadow Village aquifer	Monthly
103575	Meadow Village	45.265090	-111.254512	5998	40	Madison Group	Hourly
104510	Meadow Village	45.260051	-111.314322	6375	72	Frontier	Monthly
153399	Meadow Village	45.254210	-111.324476	6574	178	Frontier/Mowry	Monthly
155052	Meadow Village	45.268630	-111.283080	6145	58	Meadow Village aquifer	Hourly
165681	Meadow Village	45.255075	-111.315532	6382	160	Mowry	Monthly
165685	Meadow Village	45.263925	-111.294399	6227	18	Meadow Village aquifer	Hourly
165686	Meadow Village	45.263920	-111.300560	6250	20	Meadow Village aquifer	Hourly
165687	Meadow Village	45.269480	-111.305100	6263	37	Meadow Village aquifer	Hourly
165688	Meadow Village	45.267630	-111.300630	6230	21	Meadow Village aquifer	Hourly
165689	Meadow Village	45.267170	-111.298450	6218	20	Meadow Village aquifer	Hourly
165690	Meadow Village	45.268680	-111.294100	6188	17	Meadow Village aquifer	Hourly
170548	Meadow Village	45.290210	-111.336060	7090	415	Kootenai	Monthly
185435	Meadow Village	45.249880	-111.315210	6312	27	Alluvium	Monthly
185437	Meadow Village	45.250970	-111.313800	6307	24	Alluvium	Monthly
192607	Meadow Village	45.268894	-111.273114	6181	203	Kootenai	Monthly
220659	Meadow Village	45.266770	-111.284970	6155	42	Frontier	Monthly
257677	Meadow Village	45.269927	-111.297913	6212	49	Meadow Village aquifer	Hourly
257678	Meadow Village	45.267398	-111.306787	6261	58	Meadow Village aquifer	Hourly
275582	Meadow Village	45.246633	-111.305897	6750	880	Mowry/Muddy/dacite	Hourly
281359	Meadow Village	45.261487	-111.308795	6310	45	Meadow Village aquifer	Hourly
281360	Meadow Village	45.266167	-111.306649	6260	45	Meadow Village aquifer	Hourly
281362	Meadow Village	45.266176	-111.306628	6260	15	Meadow Village aquifer	Hourly
281363	Meadow Village	45.265743	-111.310774	6280	25	Meadow Village aquifer	Hourly
281364	Meadow Village	45.265128	-111.312057	6295	11	Meadow Village aquifer	Hourly
281365	Meadow Village	45.264770	-111.310406	6280	12	Meadow Village aquifer	Hourly
281366	Meadow Village	45.268988	-111.295999	6183	25	Meadow Village aquifer	Hourly
281367	Meadow Village	45.270497	-111.290896	6160	35	Meadow Village aquifer	Hourly
281368	Meadow Village	45.269019	-111.296006	6183	15	Meadow Village aquifer	Hourly
281369	Meadow Village	45.266718	-111.288556	6170	21	Meadow Village aquifer	Monthly
281370	Meadow Village	45.264761	-111.301461	6245	21	Meadow Village aquifer	Hourly
281371	Meadow Village	45.270191	-111.299282	6230	55	Meadow Village aquifer	Hourly
281372	Meadow Village	45.259556	-111.305059	6285	20	Meadow Village aquifer	Hourly
281373	Meadow Village	45.270164	-111.299266	6230	20	Meadow Village aquifer	Hourly
281374	Meadow Village	45.261161	-111.304130	6275	18	Meadow Village aquifer	Hourly
155020	Moonlight Basin	45.294657	-111.422978	7980	296	Frontier	Monthly
209445	Moonlight Basin	45.300446	-111.416116	7830	85	Mowry	Monthly
215510	Moonlight Basin	45.315496	-111.458842	7230	56	Muddy	Monthly
216817	Moonlight Basin	45.317871	-111.466630	7280	600	Frontier	Hourly
216820	Moonlight Basin	45.301112	-111.465291	8020	540	Muddy	Monthly
230689	Moonlight Basin	45.315841	-111.414965	7750	185	Frontier	Hourly
230803	Moonlight Basin	45.294177	-111.419724	7900	176	Frontier/dacite intrusive	Monthly
230804	Moonlight Basin	45.322074	-111.424647	7394	238	Frontier	Hourly

Table A2—*Continued*.

GWIC ID	Location	Latitude	Longitude	Land Surface Elevation (ft-amsl)	Total Well Depth (ft)	Aquifer	Water-Level Monitored Interval[1]
231031	Moonlight Basin	45.315460	-111.463421	7275	160	Muddy	Monthly
241699	Moonlight Basin	45.293855	-111.423832	8020	200	Frontier	Hourly
259357	Moonlight Basin	45.314774	-111.459675	7260	307	Frontier/Mowry	Monthly
259361	Moonlight Basin	45.316345	-111.474759	7020	426	Frontier/Muddy	Monthly
259554	Moonlight Basin	45.312930	-111.432888	7285	463	Muddy	Monthly
259685	Moonlight Basin	45.311006	-111.461167	7580	598	Muddy/Mowry	Hourly
259699	Moonlight Basin	45.305711	-111.463127	7850	565	Frontier/dacite intrusive	Monthly
259706	Moonlight Basin	45.315836	-111.474947	7020	449	Muddy	Hourly
268986	Moonlight Basin	45.315864	-111.417365	7650	308	Mowry	Monthly
279062	Moonlight Basin	45.297165	-111.435670	8090	218	Frontier/dacite intrusive	Hourly
103496	Mountain Village	45.289910	-111.399190	7475	400	Muddy/dacite intrusive	Monthly
166316	Mountain Village	45.290730	-111.422630	8110	279	Frontier	Monthly
170083	Mountain Village	45.280700	-111.369450	6880	200	Kootenai	Monthly
180301	Mountain Village	45.310110	-111.383970	8200	226	Kootenai	Monthly
213758	Mountain Village	45.290750	-111.423110	8125	160	Frontier	Monthly
234199	Mountain Village	45.290440	-111.393070	7440	223	Kootenai	Hourly
245287	Mountain Village	45.290440	-111.393070	7440	200	Kootenai	Hourly
245287	Mountain Village	45.290440	-111.393070	7440	200	Kootenai	Monthly
159764	Spanish Peaks	45.262450	-111.342120	6810	180	Frontier	Monthly
160152	Spanish Peaks	45.262340	-111.341580	6800	340	Frontier/Mowry	Monthly
167350	Spanish Peaks	45.261830	-111.341320	6800	100	Frontier	Monthly
180287	Spanish Peaks	45.252887	-111.359476	7350	550	Muddy	Monthly
180289	Spanish Peaks	45.260402	-111.355882	6930	65	Frontier	Monthly
180290	Spanish Peaks	45.260563	-111.356151	6930	85	Mowry	Monthly
187230	Spanish Peaks	45.259390	-111.344240	6940	480	Muddy	Monthly
205918	Spanish Peaks	45.256454	-111.367751	7355	500	Frontier	Hourly
205921	Spanish Peaks	45.260321	-111.371142	7400	195	Frontier	Monthly
210824	Spanish Peaks	45.256210	-111.343850	7080	400	Frontier	Hourly
219966	Spanish Peaks	45.249582	-111.368455	7525	525	Muddy/Thermopolis/Kootenai	Monthly
237292	Spanish Peaks	45.240337	-111.357176	7075	565	Kootenai	Monthly
239759	Spanish Peaks	45.241774	-111.340806	6675	553	Kootenai	Hourly
239761	Spanish Peaks	45.243567	-111.342322	6725	630	Kootenai	Monthly
240514	Spanish Peaks	45.260868	-111.353058	6840	56	Mowry	Monthly
167329	Yellowstone Club	45.241431	-111.408387	7100	95	Kootenai	Monthly
176326	Yellowstone Club	45.244084	-111.406254	7135	362	Kootenai/Morrison	Hourly
192856	Yellowstone Club	45.259782	-111.390854	8040	200	Kootenai	Hourly
192865	Yellowstone Club	45.243070	-111.404410	7100	340	Kootenai/landslide	Monthly
192897	Yellowstone Club	45.239685	-111.406463	7115	260	Muddy/Thermopolis/Kootenai	Hourly
192966	Yellowstone Club	45.236197	-111.411863	7200	370	Kootenai/Morrison	Hourly
195189	Yellowstone Club	45.243341	-111.405470	7118	106	Kootenai	Monthly
227908	Yellowstone Club	45.263389	-111.426810	8140	668	Frontier	Monthly
234273	Yellowstone Club	45.263887	-111.432145	8325	412	Frontier	Hourly
234783	Yellowstone Club	45.240847	-111.398991	7075	402	Morrison	Monthly
246177	Yellowstone Club	45.226102	-111.396462	7920	405	Kootenai	Hourly
253676	Yellowstone Club	45.233180	-111.374080	6675	553	Morrison	Monthly
262271	Yellowstone Club	45.251835	-111.431980	7480	444	Kootenai/Morrison	Hourly

[1]Wells were monitored hourly with a pressure transducer.

APPENDIX B

AQUIFER TEST RESULTS

Table B1. Aquifer test results compiled from other publications.

GWIC ID	Location	Site Name	Aquifer	Aquifer Type	Total Well Depth (ft)	Saturated Thickness (ft)	Transmissivity (ft^2/d)	Storativity	Specific Capacity (gpm/ft)	Hydraulic Conductivity (ft/d)	Boundary Conditions	Authors Comments	Publication Source
103495	Meadow Village	Lone Mountain Ranch #1	Frontier aquifer	Confined	400				0.1				WGS (2002)
103496	Mountain Village	Mountain Village #4	Muddy/dacite aquifers	Confined	400	82.0	1,450		0.5	18.0			HKM (2005)
103496	Mountain Village	Mountain Village #4	Muddy/dacite aquifers	Confined	400		1,589	5.00E-04	2.4				WGS (2008)
103499	Meadow Village	Hidden Village #1	Frontier/alluvium aquifers	Unconfined	45	10.0	1,170		1.9	120.0			HKM (2005)
103501	Meadow Village	Hidden Village #2	Muddy/dacite aquifers	Confined	665	141.0	40		0.2	0.3			HKM (2005)
103505	Meadow Village	Meadow Village #1	Meadow Village Aquifer	Unconfined	50	26.0	27,400		32.5	1050.0			HKM (2005)
103505	Meadow Village	Meadow Village #1	Meadow Village Aquifer	Unconfined	50	39.0	5,903	8.16E-05	15.8				WGS (2008)
103507	Meadow Village	Meadow Village #2	Meadow Village Aquifer	Unconfined	59	21.0	13,500		35.3	640.0			HKM (2005)
103507	Meadow Village	Meadow Village #2	Meadow Village Aquifer	Unconfined	59	45.0	5,000	1.00E-04					WGS (2008)
108809	Mountain Village	Mountain Village #1	Mountain Village aquifer	Unconfined	80	15.0	7,060		6.6	470.0			HKM (2005)
108809	Mountain Village	Mountain Village #1	Mountain Village aquifer	Unconfined	80				16.9				WGS (2008)
108810	Mountain Village	Mountain Village #2	Mountain Village aquifer	Unconfined	60	15.0	2,950		2.9	200.0			HKM (2005)
108810	Mountain Village	Mountain Village #2	Mountain Village aquifer	Unconfined	60				14.9				WGS (2008)
108811	Mountain Village	Mountain Village #3	Mountain Village aquifer	Unconfined	67	15.0	2,410		5.0	160.0			HKM (2005)
108811	Mountain Village	Mountain Village #3	Mountain Village aquifer	Unconfined	78				12.3				WGS (2008)
155024	Meadow Village	Lone Mountain Ranch #2	Glacial till aquifer	Unconfined	40	28.0	(5,700) est		2.1	(200) est			WGS (2002)
155405	Meadow Village	West Fork Meadows #1	Kootenai/Morrison aquifers	Confined	1250	14.0	3		<0.1	12.0			HKM (2005)
155405	Meadow Village	West Fork Meadows #1	Kootenai/Morrison aquifers	Confined	1250				<0.1				WGS (2008)
155405	Meadow Village	West Fork Meadows #1	Kootenai/Morrison aquifers	Confined	1250								WGS (2010)
159764	Meadow Village	Aspen Grove #1	Frontier aquifer	Confined	180	30.0	415		1.2	14.0			HKM (2005)
166989	Meadow Village	Meadow Village #3	Meadow Village Aquifer	Unconfined	78	33.0	8,800		18.3	270.0			HKM (2005)
166989	Meadow Village	Meadow Village #3	Meadow Village Aquifer	Unconfined	67	34.0	5,000	1.00E-04					WGS (2008)
166989	Meadow Village	Meadow Village #3	Meadow Village Aquifer	Unconfined	67	33.0	4,500	1.00E-07	13.5				WGS (2010)
169476	Meadow Village	Aspen Grove #2	Frontier/Mowry aquifer	Confined	640	100.0	45		0.2	0.5			HKM (2005)
169476	Meadow Village	Aspen Grove #2	Frontier/Mowry aquifer	Confined	340 (rpt)		101	1.49E-05				Well was later deepened	WGS (2008)
169477	Meadow Village	Aspen Grove #3	Mowry/Muddy aquifers	Confined	529	118.0	1,645		1.1	14.0			HKM (2005)
170083	Meadow Village	Lone Moose #1	Kootenai aquifer	Confined	200		1,440		4.7		Yes	T= 346 ft^2/d with boundary	HKM (2005)

Table B1—*Continued.*

GWIC ID	Location	Site Name	Aquifer	Aquifer Type	Total Well Depth (ft)	Saturated Thickness (ft)	Transmissivity (ft^2/d)	Storativity	Specific Capacity (gpm/ft)	Hydraulic Conductivity (ft/d)	Boundary Conditions	Authors Comments	Publication Source
170083	Meadow Village	Lone Moose #1	Kootenai aquifer	Confined	200		252	8.00E-02	4.7				WGS (2008
187212	Meadow Village	Lone Moose #2	Muddy aquifer	Confined	100		302		5.6				HKM (2005
187212	Meadow Village	Lone Moose #2	Muddy aquifer	Confined	100		266	1.20E-01	5.4				WGS (2008
192865	Yellowstone Club	Fishing Village–Yellowstone Club	Kootenai/landslide aquifer	Confined	118				50.0			Drilled to 340 ft, backfilled to 118 ft.	HKM (2005
192877	Yellowstone Club	North Spring Well - Yellowstone Club	Ellis Group (Swift Fm)/dacite aquifers	Confined	830				150.0				HKM (2005
192890	Yellowstone Club	Lake Well	Kootenai aquifer	Confined	410				400.0			Flowing well	HKM (2005
192897	Yellowstone Club	Log Deck #2–Yellowstone Club	Muddy (Thermopolis)/Kootenai aquifers	Confined	260				150.0			Flowing well	HKM (2005
192900	Yellowstone Club	Log Deck #1–Yellowstone Club	Kootenai aquifer	Confined	385				500.0				HKM (2005
192966	Yellowstone Club	3rd Muddy–Yellowstone Club	Kootenai/Morrison aquifers	Confined	370				50.0				HKM (2005
205931	Mountain Village	Mountain Village #7	Kootenai/dacite aquifers	Confined	312	27.0			1.7				HKM (2005
205931	Mountain Village	Mountain Village #7	Kootenai/dacite aquifers	Confined	312		1,522	5.41E-04	1.7				WGS (2008
208655	Spanish Peaks	Spanish Peaks PWS #1	Kootenai aquifer	Leaky-Confined	675		162	2.75E-04	1.0			Flowing well	HKM (2005
214006	Moonlight Basin	Moonlight Basin Well #3 Lodge well	Muddy (Thermopolis) aquifer	Confined	490	100.0	943						DNRC database[2]
214694	Spanish Peaks	Spanish Peaks PWS #2	Kootenai aquifer	Confined	675						Yes	Unusual water-level response, no aquifer parameters determined	HKM (2005
215507	Moonlight Basin	Moonlight Basin Well #6	Frontier/dacite aquifers	Confined	305 (rpt)	100.0	158						DNRC database[2]
215981	Yellowstone Club	Yellowstone Club 3A-1test	Frontier aquifer	Confined	660	276.0	155	1.50E-03		1.0			DNRC database[2]
228872	Yellowstone Club	Yellowstone Club 3A-7	Morrison aquifer	Confined	468	283.0	121	4.50E-05		3.1			DNRC database[2]
228880	Yellowstone Club	Yellowstone Club 3A-8	Morrison aquifer	Confined	527	261.0	88	4.00E-05		0.5			DNRC database[2]
230805	Moonlight Basin	Moonlight Basin Well #5	Frontier/dacite aquifers	Confined	453	100.0	195	2.00E-05		2.4			DNRC database[2]
230807	Moonlight Basin	Moonlight Basin Well #4	Frontier/dacite aquifers	Confined	483	100.0	179	1.00E-05		1.1			DNRC database[2]
234271	Yellowstone Club	Yellowstone Club 3A-1	Frontier aquifer	Confined	470	142.0	86	9.80E-03					DNRC database[2]
234273	Yellowstone Club	Yellowstone Club 3A-3	Frontier aquifer	Confined	412	126.0	232			2.1			DNRC database[2]
234278	Yellowstone Club	Yellowstone Club 3A-4	Frontier aquifer	Confined	620	146.0	44			1.1			DNRC database[2]

Table B1—*Continued*.

GWIC ID	Location	Site Name	Aquifer	Aquifer Type	Total Well Depth (ft)	Saturated Thickness (ft)	Transmissivity (ft^2/d)	Storativity	Specific Capacity (gpm/ft)	Hydraulic Conductivity (ft/d)	Boundary Conditions	Authors Comments	Publication Source
236777	Meadow Village	Meadow Village #4	Meadow Village Aquifer	Unconfined	56	45.5	3,057	1.31E-03	13.9				WGS (2008)
236778	Meadow Village	Meadow Village #5	Meadow Village Aquifer	Unconfined	57	40.7	4,124	1.26E-03	14.6				WGS (2008)
239759	Spanish Peaks	Spanish Peaks PWS #3	Kootenai aquifer	Confined	553		200			0.4			DNRC database[2]
239761	Spanish Peaks	Spanish Peaks PWS #4	Kootenai aquifer	Confined	630		364	2.40E-04					DNRC database[2]
244347	Mountain Village	Mountain Village #6 Cascade well	Muddy (Thermopolis) aquifer	Confined	200	40.0	2,730		10.2	70.0			HKM (2005)
244347	Mountain Village	Mountain Village #6 Cascade well	Muddy (Thermopolis) aquifer	Confined	200				10.2	17.3		Fracture flow	WGS (2008)
244347	Mountain Village	Mountain Village #6 Cascade well	Muddy (Thermopolis) aquifer	Confined	200		1,512						WGS (2018)
248989	Mountain Village	Mountain Village #5 Cascade well #1	Muddy (Thermopolis) aquifer	Confined	212	32.0	450		1.7	15.0			HKM (2005)
248989	Mountain Village	Mountain Village #5 Cascade well #1	Muddy (Thermopolis) aquifer	Confined	212		380	1.00E-04	1.7				WGS (2008)
248989	Mountain Village	Mountain Village #5 Cascade well #1	Muddy (Thermopolis) aquifer	Confined	212		955	1.19E-04			Yes		WGS (2018)
259357	Moonlight Basin	Moonlight Basin Well # 2010-4 (aka TH-09)	Frontier aquifer	Confined	307	290.0	183						DNRC database[2]
259357	Moonlight Basin	Moonlight Basin Well # 2010-4 (aka TH-09)	Frontier aquifer	Confined	307		53					Late-time data	Morrison Maierle (2016)
259359	Moonlight Basin	Moonlight Basin Well # 2010-3 (aka TH-10)	Frontier/Mowry/dacite aquifers	Confined	706	462.0	200			0.4			DNRC database2
259359	Moonlight Basin	Moonlight Basin Well # 2010-3 (aka TH-10)	Frontier/Mowry/dacite aquifers	Confined	706		194				Yes		Morrison Maierle (2016)
259361	Moonlight Basin	Moonlight Basin Well # 2010-7 (aka TH-13)	Frontier/Muddy aquifers	Confined	426	325.0	364	2.40E-04					DNRC database2
259361	Moonlight Basin	Moonlight Basin Well # 2010-7 (aka TH-13)	Frontier/Muddy aquifers	Confined	426		316	5.89E-04			Yes		Morrison Maierle (2016)
259699	Moonlight Basin	Moonlight Basin Well # 2010-5 (aka TH-08)	Frontier/dacite aquifers	Confined	565	220.0	307						DNRC database[2]
259699	Moonlight Basin	Moonlight Basin Well # 2010-5 (aka TH-08)	Frontier/dacite aquifers	Confined	565	220.0	147				Yes	Late-time data	Morrison Maierle (2016)
275582	Meadow Village	Uplands #1	Mowry/Muddy/dacite aquifers	Confined	430		890		2.5		Yes	Test performed at original well depth of 430 ft	HKM (2005)

Table B1—*Continued*.

GWIC ID	Location	Site Name	Aquifer	Aquifer Type	Total Well Depth (ft)	Saturated Thickness (ft)	Transmissivity (ft^2/d)	Storativity	Specific Capacity (gpm/ft)	Hydraulic Conductivity (ft/d)	Boundary Conditions	Authors Comments	Publication Source
275582	Meadow Village	Uplands #1	Mowry/Muddy/dacite aquifers	Confined	880		480				Yes	Test performed after well was deepened to 800 ft, 430–800 ft open hole. Low-flow boundary conditions in test.	HKM (2005)
279080	Moonlight Basin	Moonlight Basin Well # 2007-4	Frontier/dacite aquifers	Confined	400	400.0	831	8.20E-05					DNRC database[2]
279080	Moonlight Basin	Moonlight Basin Well # 2007-4	Frontier/dacite aquifers	Confined	400	400.0	151	8.20E-05			Yes	Flowing well, fracture flow, late time data	Morrison Maierle (2016)
288206	Moonlight Basin	Moonlight Basin Well # 2008-6	Frontier/dacite aquifers	Confined	250	77.0	56					No well log	DNRC database[2]
288206	Moonlight Basin	Moonlight Basin Well # 2008-6	Frontier/dacite aquifers	Confined	250							Fracture flow, non-uniform response	Morrison Maierle (2016)
n/a[1]	Moonlight Basin	Moonlight Basin Well MW-07-1	Lower Cretaceous undifferentiated-w/dacite aquifers	Confined	400	100.0	477	2.00E-03		6.0		No well log	DNRC database[2]
n/a	Meadow Village	Big Sky 1970 consultants well 1	Meadow Village Aquifer	Unconfined	45	37.0			5.0				Wayne Van Voast (1972)
n/a	Meadow Village	Big Sky 1970 consultants well 2	Meadow Village Aquifer	Unconfined	36	27.8			9.0				Wayne Van Voast (1972)
n/a	Meadow Village	Big Sky 1970 consultants well 3	Meadow Village Aquifer	Unconfined	27	10.8			14.0				Wayne Van Voast (1972)
n/a	Meadow Village	Big Sky 1970 consultants well 4	Meadow Village Aquifer	Unconfined	45	36.5			3.0				Wayne Van Voast (1972)
n/a	Meadow Village	Big Sky 1970 consultants well 5	Meadow Village Aquifer	Unconfined	50	39.0			40.0				Wayne Van Voast (1972)
n/a	Meadow Village	Big Sky 1970 consultants well 6	Meadow Village Aquifer	Unconfined	42	23.0			5.8				Wayne Van Voast (1972)
n/a	Meadow Village	Big Sky 1970 consultants well 7	Meadow Village Aquifer	Unconfined	81	58.0			8.0				Wayne Van Voast (1972)
	Yellowstone Club	Yellowstone Club 3A-4test	Frontier aquifer	Confined	600	149.0	36			0.9			DNRC database[2]

Note. Data are not evaluated and are presented as reported.
[1]n/a, well could not be associated with any existing GWIC well number.
[2]Montana DNRC database accessed in 2014.

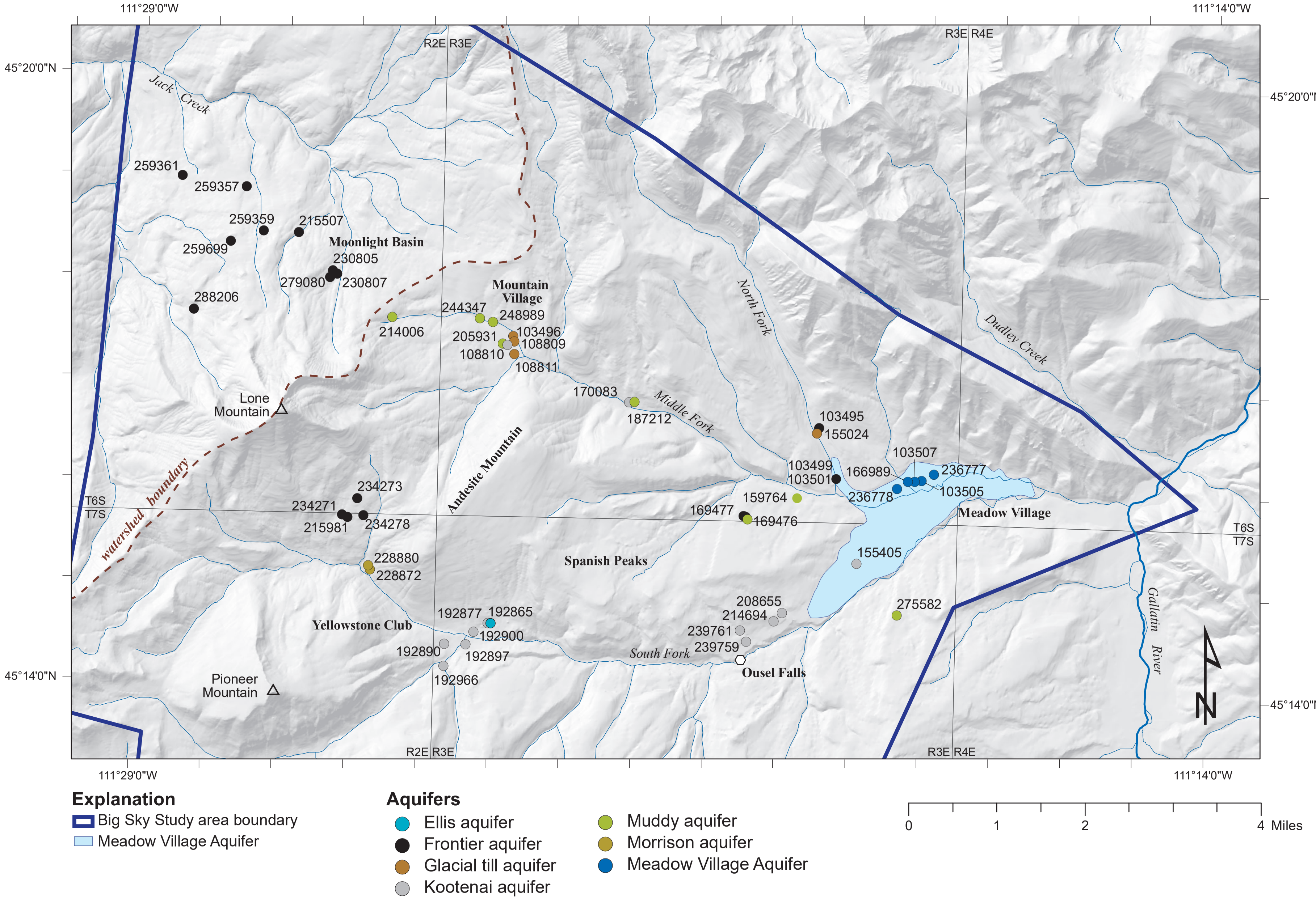

Figure B1. Aquifer test locations. Thirteen wells in table B1 had no location information and are not presented on the map.

APPENDIX C

CHEMISTRY

Table C1. Locations for sampled constituents.

GWIC ID	Location	Latitude	Longitude	Total Well Depth (ft)	Aquifer	Source Type	Major Ions	Tritium	Stable Isotopes
103556	Meadow Village	45.269147	-111.273056	37	Alluvium/colluvium	Well			X
103557	Meadow Village	45.265459	-111.284086	103	Frontier	Well			X
103575	Meadow Village	45.265090	-111.254512	40	Madison Group	Well			X
104510	Meadow Village	45.260051	-111.314322	72	Frontier	Well	X		X
153399	Meadow Village	45.254210	-111.324476	178	Frontier/Mowry	Well			X
165687	Meadow Village	45.269451	-111.305081	37	Meadow Village aquifer	Well			X
192607	Meadow Village	45.268894	-111.273114	203	Kootenai	Well			X
246755	Meadow Village	45.268590	-111.290260	n/a[1]	Surface water	Effluent	X		X
257677	Meadow Village	45.269927	-111.297914	49	Meadow Village aquifer	Well			X
275228	Meadow Village	45.264680	-111.313820	n/a	Surface water	Stream	X		
275238	Meadow Village	45.267800	-111.274300	n/a	Surface water	Stream	X		
275582	Meadow Village	45.246633	-111.305897	880	Mowry/Muddy/dacite intrusive	Well	X	X	X
277296	Meadow Village	45.26617	-111.30634	n/a	precipitation	Snow			X
278297	Meadow Village	45.266434	-111.287800	0	Meadow Village aquifer	Spring	X		
280689	Meadow Village	45.265088	-111.292806	0	Meadow Village aquifer	Spring	X		
281359	Meadow Village	45.261487	-111.308795	45	Meadow Village aquifer	Well	X		X
281360	Meadow Village	45.266167	-111.306649	45	Meadow Village aquifer	Well	X		X
281362	Meadow Village	45.266176	-111.306628	15	Meadow Village aquifer	Well	X		X
281363	Meadow Village	45.265743	-111.310774	25	Meadow Village aquifer	Well	X	X	X
281366	Meadow Village	45.268988	-111.295999	25	Meadow Village aquifer	Well	X		X
281367	Meadow Village	45.270497	-111.290896	35	Meadow Village aquifer	Well	X		X
281368	Meadow Village	45.269019	-111.296006	15	Meadow Village aquifer	Well	X		X
281371	Meadow Village	45.270191	-111.299282	55	Meadow Village aquifer	Well	X	X	X
281372	Meadow Village	45.259556	-111.305059	20	Meadow Village aquifer	Well	X		X
281373	Meadow Village	45.270164	-111.299266	20	Meadow Village aquifer	Well	X		X
283861	Meadow Village	45.244519	-111.253455	n/a	Precipitation	Rainwater			X
209445	Moonlight Basin	45.300446	-111.416116	85	Mowry	Well	X		X
215507	Moonlight Basin	45.307404	-111.447269	396	Frontier/dacite intrusive	Well	X	X	X
215510	Moonlight Basin	45.315496	-111.458842	56	Muddy	Well	X		X
230689	Moonlight Basin	45.315841	-111.414965	185	Frontier	Well	X	X	X
230803	Moonlight Basin	45.294177	-111.419724	176	Frontier/dacite intrusive	Well	X	X	X

Table C1—*Continued*.

GWIC ID	Location	Latitude	Longitude	Total Well Depth (ft)	Aquifer	Source Type	Major Ions	Tritium	Stable Isotopes
230804	Moonlight Basin	45.322074	-111.424647	237	Frontier	Well	X	X	X
231031	Moonlight Basin	45.315460	-111.463421	160	Muddy	Well	X		X
231745	Moonlight Basin	45.306402	-111.421550	160	Frontier	Well	X		X
259357	Moonlight Basin	45.314774	-111.459675	307	Frontier/Mowry	Well	X	X	X
259685	Moonlight Basin	45.311006	-111.461167	598	Mowry/Muddy	Well	X	X	X
259706	Moonlight Basin	45.315836	-111.474947	449	Muddy	Well	X	X	X
276156	Moonlight Basin	45.294070	-111.416620	n/a	Surface water	Stream	X		
278617	Moonlight Basin	45.289750	-111.421930	n/a	Surface water	Spring	X		
278927	Moonlight Basin	45.322258	-111.424667	n/a	Surface water	Stream	X		
279062	Moonlight Basin	45.297165	-111.435670	218	Frontier/dacite intrusive	Well	X	X	X
279079	Moonlight Basin	45.297977	-111.440187	n/a	surface water	Stream	X		
279080	Moonlight Basin	45.300744	-111.438171	198	Frontier/dacite intrusive	Well	X	X	X
279082	Moonlight Basin	45.297165	-111.435670	279	Frontier/dacite intrusive	Well			X
103496	Mountain Village	45.289910	-111.399190	400	Muddy/dacite intrusive	Well	X	X	X
205931	Mountain Village	45.289660	-111.398050	312	Kootenai/dacite intrusive	Well	X	X	X
234199	Mountain Village	45.290440	-111.393070	223	Kootenai	Well			X
244347	Mountain Village	45.293986	-111.404635	200	Muddy/Thermopolis	Well	X	X	X
276604	Mountain Village	45.30838	-111.38176	n/a	Precipitation	Snow			X
277295	Mountain Village	45.28552	-111.36872	n/a	Precipitation	Snow			X
283860	Mountain Village	45.293388	-111.401489	n/a	Precipitation	Rainfall			X
187230	Spanish Peaks	45.259390	-111.344240	480	Muddy	Well			X
219966	Spanish Peaks	45.249582	-111.368455	525	Muddy/Kootenai	Well	X	X	X
237292	Spanish Peaks	45.240337	-111.357176	565	Kootenai	Well	X	X	X
239759	Spanish Peaks	45.241774	-111.340806	553	Kootenai	Well	X	X	X
176326	Yellowstone Club	45.244084	-111.406254	362	Morrison	Well	X		X
176327	Yellowstone Club	45.245457	-111.376968	898	Kootenai/Morrison	Well	X	X	X
192856	Yellowstone Club	45.259782	-111.390854	200	Kootenai	Well	X		X
192865	Yellowstone Club	45.243070	-111.404410	340	Kootenai/landslide	Well	X		X
192966	Yellowstone Club	45.236197	-111.411863	370	Kootenai	Well	X	X	X
234783	Yellowstone Club	45.240847	-111.398991	402	Morrison	Well	X		X
253676	Yellowstone Club	45.233180	-111.374080	800	Morrison	Well	X	X	X
262271	Yellowstone Club	45.251835	-111.431980	444	Kootenai/Morrison	Well	X		X
280685	Yellowstone Club	45.239720	-111.407740	n/a	Surface water	Stream	X		
280686	Yellowstone Club	45.242540	-111.409078	n/a	Surface water	Stream	X		

[1]n/a, data not available.

Table C2. Analytical results for groundwater and surface-water samples.

GWIC ID	Aquifer/ Source	Well Depth (ft)	Sample Date	Water Temp (°C)	Field (pH)	Field SC (µmhos/ cm)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Fe (mg/L)	Mn (mg/L)	SiO_2 (mg/L)	HCO_3 (mg/L)	CO_3 (mg/ L)	SO_4 (mg/L)	Cl (mg/L)	NO_3-N (mg/L)	As (µg/L)	NO_2-N (mg/L)	NO_3+NO_2-N (mg/L)	Total N as N (mg/L)	TDS (mg/L)
103556	River alluvium	95	8/7/2008	8.0	8.04	374	27.10	30.30	3.20	2.60	<0.003	0.01	6.57	221.10	0.00	8.05	2.39	3.50 P	0.70				189.31
185435	River alluvium	26.5	10/10/2011	9.2	7.20	373	47.53	9.63	18.69	2.16	0.04	0.002 J	10.42	216.91	0.00	18.82	2.76	0.11	0.200 J	<0.010 U	<0.200 U	<1.000 U	217.08
155052	Meadow Village aquifer	58	7/1/2008	7.1	7.18	718	98.80	20.50	12.50	3.36	0.22	0.05	10.90	306.50	0.00	33.80	23.90	9.12 P	<0.1				355.54
165685	Meadow Village aquifer	17.7	4/18/2012	4.1	7.32	833	114.10	23.56	23.84	1.52	0.009 J	<0.002 U	11.05	341.69	0.00	42.06	56.33	3.45	0.270 J	<0.010 U	3.49	4.08	444.16
165686	Meadow Village aquifer	19.5	7/1/2008	6.4	7.49	641	85.80	22.70	6.71	1.17	0.27	<0.003	10.40	303.80	0.00	25.40	27.80	2.24 P	0.18				329.26
165687	Meadow Village aquifer	37.4	7/2/2008	9.6	7.97	400	54.20	9.75	7.29	3.14	0.20	0.02	10.10	228.90	0.00	5.32	1.81	0.113 P	0.52				203.76
257677	Meadow Village aquifer	49	4/20/2017	7.1	7.59	517	70.36	15.38	11.44	2.17	0.019 J	<0.002 U	10.62	278.41	0.00	11.84	18.63	1.18	0.210 J	<0.010 U	1.04		278.69
257678	Meadow Village aquifer	58	4/20/2017	6.5	7.80	476	63.54	14.55	9.56	2.17	0.037 J	<0.002 U	9.31	235.32	0.00	11.01	19.10	3.85	0.220 J	<0.010 U	3.16		248.85
281359	Meadow Village aquifer	45	6/2/2015	8.1	7.63	770	106.55	31.93	20.22	1.58	<0.015 U	0.009 J	15.73	355.56	0.00	16.40	95.07	4.91	0.340 J	<0.010 U	4.54	5.21	467.86
281360	Meadow Village aquifer	45	6/3/2015	5.6	7.75	289	42.75	9.30	9.26	1.34	<0.015 U	0.002 J	10.42	171.45	0.00	11.08	12.51	0.84	0.81	<0.010 U	0.94	<1.000 U	181.29
281362	Meadow Village aquifer	15	6/3/2015	6.5	7.78	127	18.16	4.10	4.10	0.97	0.022 J	<0.002 U	8.96	85.27	0.00	4.14	1.84	0.08	0.46	<0.010 U	<0.200 U	<1.000 U	84.17
281363	Meadow Village aquifer	25	6/2/2015	5.8	7.66	448	66.84	14.76	16.53	2.04	<0.015 U	0.020 J	14.39	271.07	0.00	17.78	23.16	0.42	0.290 J	<0.010 U	0.47	<1.000 U	289.12
281366	Meadow Village aquifer	25	6/3/2015	7.8	7.52	478	75.10	16.51	13.28	1.41	<0.015 U	0.004 J	11.50	288.65	0.00	19.16	23.72	1.67	0.340 J	<0.010 U	1.64	1.81	304.98
281367	Meadow Village aquifer	35	6/3/2015	7.3	7.31	472	75.24	17.55	10.00	2.31	<0.015 U	<0.002 U	12.92	299.46	0.00	13.14	17.61	1.86	0.360 J	<0.010 U	1.80	1.80	298.08
281368	Meadow Village aquifer	15	6/3/2015	6.8	7.41	485	77.09	16.87	13.08	1.42	0.017 J	<0.002 U	11.20	290.53	0.00	19.64	24.96	1.48	0.340 J	<0.010 U	1.46	1.71	308.31
281371	Meadow Village aquifer	55	6/4/2015	7.5	7.51	452	72.68	16.83	8.02	2.16	<0.015 U	0.005 J	12.66	283.93	0.00	12.40	19.40	1.30	0.290 J	<0.010 U	1.22	1.63	284.41
281372	Meadow Village aquifer	20	6/4/2015	5.3	7.60	603	100.27	24.53	5.78	1.06	0.024 J	0.003 J	13.00	377.97	0.00	16.70	21.24	6.27	<0.100 U	<0.010 U	5.45	5.81	375.01
281373	Meadow Village aquifer	20	6/4/2015	7.6	7.68	477	79.41	17.76	7.50	2.11	<0.015 U	<0.002 U	12.37	299.38	0.00	12.15	21.00	2.08	0.230 J	<0.010 U	1.90	2.27	301.46
108809	Mountain Village aquifer	80	7/18/2011	5.1	6.96	175	18.90	5.47	5.91	0.64	<0.004 U	<0.002 U	13.72	74.78	0.00	7.08	10.50	0.48	0.260 J	<0.050 U	0.41	<1.000 U	100.38
103496	Dacite intrusive	400	8/4/2015				3.09	0.56	58.02	0.98	<0.015 U	<0.002 U	20.26	113.25	20.69	5.19	4.62	0.06	0.80	<0.010 U	<0.200 U	<1.000 U	169.32
205931	Dacite intrusive	312	8/4/2015	5.2	8.04	214	21.51	4.71	17.16	0.88	<0.015 U	<0.002 U	11.79	90.15	0.00	6.62	9.44	0.27	4.20	<0.010 U	0.24	<1.000 U	116.56
279080	Dacite intrusive	198	6/23/2015	3.3	8.44	191	23.43	4.65	8.89	1.01	<0.015 U	0.003 J	5.73	102.73	0.00	21.24	0.51	0.25	0.72	<0.010 U	0.27	<1.000 U	116.82
103499	Frontier	45	7/13/2011	5.7	7.87	375	55.90	13.29	3.39	1.89	0.02	0.00	8.80	224.24	0.00	7.56	1.69	1.57	0.340 J	<0.050 U	1.57	1.74	205.56
103557	Frontier	103	8/7/2008	6.6	7.49	362	42.20	11.40	15.60	1.25	<0.003	0.01	9.09	203.30	0.00	21.40	3.07	<0.5 P	0.29				203.62
104510	Frontier	71.5	6/25/2015	8.6	8.81	765	0.89	0.14	148.81	<0.050 U	<0.015 U	0.005 J	13.84	333.71	18.79	41.36	12.00	0.10	0.49	<0.010 U	0.55	4.73	400.56
166316	Frontier	279	7/9/2009	4.5	8.81	122	16.50	1.60	5.13	0.45	0.01	0.00	16.60	53.20	0.00	15.89	<0.5	<0.5 P	6.49				82.21
215507	Frontier	396	6/23/2015	4.2	8.62	119	13.22	2.13	4.65	0.51	<0.015 U	<0.002 U	8.07	53.91	0.00	9.82	0.58	0.18	0.390 J	<0.010 U	<0.200 U	<1.000 U	66.99
220659	Frontier	42	8/7/2008	7.5	7.42	519	58.90	14.40	29.50	1.34	<0.003	0.01	11.00	275.20	0.00	<0.5	12.81	1.612 P	0.27				263.78
230689	Frontier	185	6/23/2015	6.1	7.94	377	35.54	9.02	22.72	0.62	0.18	0.30	13.44	177.10	0.00	32.84	0.59	<0.010 U	2.50	<0.010 U	<0.200 U	<1.000 U	202.75
230803	Frontier	176	6/19/2015	5.1	7.25	104	13.35	2.57	3.66	0.54	0.026 J	0.002 J	13.48	53.53	0.00	9.20	1.88	0.37	0.220 J	<0.010 U	0.30	<1.000 U	71.53

Table C2—*Continued.*

GWIC ID	Aquifer/ Source	Well Depth (ft)	Sample Date	Water Temp (°C)	Field (pH)	Field SC (µmhos/ cm)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Fe (mg/L)	Mn (mg/L)	SiO_2 (mg/L)	HCO_3 (mg/L)	CO_3 (mg/ L)	SO_4 (mg/L)	Cl (mg/L)	NO_3-N (mg/L)	As (µg/L)	NO_2-N (mg/L)	NO_3+NO_2-N (mg/L)	Total N as N (mg/L)	TDS (mg/L)
230804	Frontier	237.5	6/23/2015	6.5	10.14	547	0.54	0.020 J	111.40	0.110 J	<0.015 U	0.002 J	11.33	153.47	63.74	12.70	0.55	<0.010 U	<0.100 U	<0.010 U	<0.200 U	<1.000 U	276.91
231745	Frontier	160	6/23/2015	6.4	9.29	298	6.26	1.72	62.80	0.87	0.09	0.018 J	8.98	180.13	8.68	8.48	0.63	<0.010 U	<0.100 U	<0.010 U	<0.200 U	<1.000 U	187.65
259357	Frontier	307	6/17/2015	5.8	9.59	331	19.04	4.94	50.45	0.39	<0.015 U	0.05	10.17	149.35	11.97	39.88	0.70	<0.010 U	1.80	<0.010 U	<0.200 U	<1.000 U	210.38
279062	Frontier	217.5	6/19/2015	3.1	7.85	194	25.23	3.57	3.47	0.65	<0.015 U	<0.002 U	5.48	78.91	0.00	22.01	0.460 J	0.40	0.40	<0.010 U	0.40	<1.000 U	98.72
103500	Mowry	350	8/6/2009	7.0	9.19	610	1.17	0.21	144.00	0.24	0.01	0.01	9.35	248.50	40.70	<25.0	<5.0	<0.5 P	0.66				323.04
153399	Mowry	178	8/13/2008	7.5	9.14	634	1.73	0.23	142.00	0.16	<0.003	<0.001	7.77	323.60	17.40	<25.0	<5.0	<0.5 P	0.79				330.57
275582	Mowry	880	6/25/2015	6.0	8.44	1274	3.43	0.61	265.01	0.33	<0.038 U	0.046 J	12.05	498.01	3.84	188.60	2.77	<0.010 U	0.660 J	<0.010 U	0.29	2.19	723.36
103501	Muddy	665	7/13/2011	7.9	10.18	458	0.57	0.030 J	106.78	0.30	<0.002 U	<0.001 U	12.37	133.11	63.36	7.87	1.79	<0.050 U	11.46	<0.050 U	<0.250 U	<1.000 U	259.09
187230	Muddy	480	5/24/2018	7.3	9.13	381	0.91	0.22	89.27	0.41	0.20	0.023 J	16.56	177.21	19.89	18.67	7.95	0.37	8.97	<0.010 U	0.52		242.62
209445	Muddy	85	6/23/2015	5.2	7.96	444	43.22	22.81	5.92	1.44	<0.015 U	<0.002 U	13.75	154.77	0.00	10.80	69.48	0.20	0.380 J	<0.010 U	<0.200 U	<1.000 U	243.39
215510	Muddy	56	6/17/2015	5.3	7.96	336	46.02	12.90	4.20	1.32	0.052 J	0.26	9.21	139.11	0.00	51.26	1.70	<0.010 U	<0.100 U	<0.010 U	<0.200 U	<1.000 U	194.39
219966	Muddy	525	6/16/2015	6.3	7.76	945	9.72	1.30	195.27	0.70	<0.015 U	<0.002 U	14.46	306.75	0.00	25.84	110.20	0.43	1.49	<0.010 U	0.48	<1.000 U	509.27
231031	Muddy	160	6/17/2015	5.9	7.80	488	65.66	21.08	9.74	1.65	<0.015 U	0.046 J	12.67	229.02	0.00	90.41	0.99	<0.010 U	<0.100 U	<0.010 U	<0.200 U	<1.000 U	315.55
244347	Muddy	200	8/4/2015	6.0	9.74	302	1.77	0.75	66.86	0.87	<0.015 U	<0.002 U	13.86	118.73	28.50	7.49	4.12	0.11	18.62	<0.010 U	<0.200 U	<1.000 U	183.14
259685	Muddy	598	6/22/2015	7.8	9.48	700	1.16	0.100 J	148.12	0.34	<0.015 U	<0.002 U	7.13	265.27	28.17	1.110 J	10.51	<0.010 U	<0.100 U	<0.010 U	<0.200 U	<1.000 U	345.70
259706	Muddy	449	6/17/2015	9.2	8.80	663	16.68	4.91	115.82	0.90	0.021 J	0.05	9.64	290.51	7.36	70.86	1.08	<0.010 U	0.43	<0.010 U	<0.200 U	<1.000 U	371.96
237639	Thermopolis	458	7/18/2011	7.5	9.61	431	1.31	0.11	102.15	0.49	0.02	0.001 J	14.39	165.61	28.73	21.81	5.50	0.12	15.38	<0.050 U	<0.200 U	<1.000 U	257.22
155405	Kootenai	1250	1/19/1998			524	41.73	33.66	30.68	9.76	5.68	0.07	2.16	248.90	0.00	107.50	<10.	<.25	<1.	<0.25			356.07
170548	Kootenai	415	6/1/2010	7.1	7.47	331	14.50	11.20	40.60	2.70	1.09	0.36	0.31	178.90	0.00	<2.5	15.86	0.601 P[2]	<0.20				175.35
176327	Kootenai	898	6/26/2015	7.6	7.69	398	37.60	12.49	9.78	2.06	<0.015 U[3]	0.006 J	9.55	177.30	0.00	20.17	14.40	0.47	0.390 J	<0.010 U	0.44	1.25	193.31
180301	Kootenai	226	8/14/2008	6.3	8.64	287	4.06	0.40	55.70	0.07	<0.003	0.04	22.40	147.90	0.00	6.14	0.48	<0.5 P	0.35				161.37
192607	Kootenai	203	8/7/2008	8.1	7.33	680	55.20	53.60	3.00	5.81	<0.003	0.05	5.40	385.20	0.00	47.12	<5.0	<0.5 P	0.58				360.48
192856	Kootenai	200	6/26/2015	5.3	6.81	222	20.42	9.52	1.04	1.69	3.46	0.21	5.59	103.20	0.00	10.22	3.93	<0.010 U	<0.100 U	<0.010 U	<0.200 U	1.62	106.69
192865	Kootenai	340	6/24/2015	7.3	7.73	354	44.81	12.69	9.24	1.05	<0.015 U	<0.002 U	8.49	179.87	0.00	20.93	17.59	0.56	0.310 J	<0.010 U	0.49	<1.000 U	204.20
192966	Kootenai	370	6/18/2015	5.7	7.45	646	60.50	20.85	36.17	4.55	0.13	0.08	5.13	361.69	0.00	27.79	0.68	<0.010 U	0.360 J	<0.010 U	<0.200 U	<1.000 U	335.68
234199	Kootenai	223	7/23/2018	6.3	7.24	187	27.16	5.16	4.29	1.03	<0.015 U	<0.002 U	13.98	121.49	0.00	4.72	1.49	0.60	1.38	<0.010 U	0.54		117.93
237292	Kootenai	565	6/5/2015	9.7	7.66	498	47.17	22.48	39.81	6.68	0.08	0.007 J	7.16	271.18	0.00	79.44	3.37	0.47	<0.100 U	<0.010 U	0.43	1.08	340.15
239759	Kootenai	553	8/5/2015	11.1	7.61	530	56.62	22.72	27.62	5.36	0.11	0.16	6.73	284.11	0.00	65.72	0.91	<0.010 U	0.230 J	<0.010 U	<0.200 U	<1.000 U	327.28
259854	Kootenai	920	7/21/2011	11.4	7.43	651	49.03	22.22	67.54	4.13	<0.004 U	0.01	7.53	375.25	0.00	47.43	1.42	0.11	0.310 J	<0.050 U	<0.200 U	<1.000 U	385.06
176326	Morrison	362	6/24/2015	7.1	7.46	1084	110.15	47.50	77.35	9.59	0.125 J[1]	0.098 J	6.71	466.32	0.00	267.80	1.62	<0.010 U	0.840 J	<0.010 U	<0.200 U	<1.000 U	752.21
230944	Morrison	261.5	10/24/2011	4.4	7.80	311	37.61	12.23	7.25	1.66	0.009 J	<0.001 U	6.78	189.43	0.00	23.57	3.42	0.16	0.180 J	<0.010 U	<0.200 U	<1.000 U	185.95
234783	Morrison	402	6/24/2015	5.2	7.95	375	39.51	14.93	5.60	2.14	0.18	0.011 J	6.96	180.65	0.00	21.06	6.41	0.29	<0.100 U	<0.010 U	0.24	<1.000 U	185.66

Table C2—*Continued*.

GWIC ID	Aquifer/ Source	Well Depth (ft)	Sample Date	Water Temp (°C)	Field (pH)	Field SC (µmhos/ cm)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Fe (mg/L)	Mn (mg/L)	SiO_2 (mg/L)	HCO_3 (mg/L)	CO_3 (mg/ L)	SO_4 (mg/L)	Cl (mg/L)	NO_3-N (mg/L)	As (µg/L)	NO_2-N (mg/L)	NO_3+NO_2-N (mg/L)	Total N as N (mg/L)	TDS (mg/L)
253676	Morrison	800	6/24/2015	10.6	9.18	1332	1.25	0.74	288.89	1.12	<0.038 U	<0.005 U	10.06	614.85	35.57	31.48	16.83	<0.010 U	<0.250 U	<0.010 U	<0.200 U	<1.000 U	691.95
262271	Morrison	444	6/24/2015	7.8	8.63	592	12.13	4.81	128.59	3.54	0.13	0.009 J	6.83	336.71	0.00	2.280 J	26.37	<0.010 U	0.50	<0.010 U	<0.200 U	<1.000 U	352.95
103575	Madison Group	40	4/20/2017	12.4	7.80	635	80.09	26.88	6.00	1.51	<0.015 U	<0.002 U	9.66	185.16	0.00	170.2 0	6.27	0.29	1.25	<0.010 U	0.25		393.14

J[1], Estimated quantity above detection limit but below reporting limit.
P[2], Preserved sample.
U[3], Undetected, below detection limit.

APPENDIX D

MIDDLE FORK SYNOPTIC STREAMFLOW MEASUREMENTS

Table D1. Synoptic stream discharge measurements in the Middle Fork of the West Fork of the Gallatin River, Meadow Village area.

GWIC ID	Site Name	Date	Discharge (cfs)	Net Gain/Loss[1] (cfs)	Temperature (°C)	Specific Conductance (µmhos/cm)
275228	Below Two Moon Bridge	9/19/13	10.0			
275230	At Golf Course Shop Bridge		10.5	0.5		
275231	Above Lower Pond		12.4	1.9		
274333	At Middle Fork GRTF gage		13.5	1.1		
275238	At Highway 64 Culvert		12.8	-0.7		
275228	Below Two Moon Bridge	10/11/13	8.6		4.6	198
275230	At Golf Course Shop Bridge		8.7	0.1	4.8	200
275231	Above Lower Pond		9.6	0.9	5.6	245
274333	At Middle Fork GRTF gage		10.5	0.9	6.4	261
275238	At Highway 64 Culvert		10.0	-0.5	6.4	263
275228	Below Two Moon Bridge	11/19/13			0.0	223
275230	At Golf Course Shop Bridge				-0.1	225
275231	Above Lower Pond		8.1		1.2	255
274333	At Middle Fork GRTF gage		8.5	0.4	2.3	286
275238	At Highway 64 Culvert		8.7	0.2	2.3	288
275231	Above Lower Pond	3/20/14	3.6		1.2	347
275228	Below Two Moon Bridge	4/17/14	8.4			299
274333	At Middle Fork GRTF gage		10.3	1.9	3.1	
275228	Below Two Moon Bridge	4/30/14	20.1			238
275231	Above Lower Pond		21.3	1.1	8.3	280
275231	Above Lower Pond	7/24/14	29.2			
275228	Below Two Moon Bridge	9/24/14	7.3			203
275231	Above Lower Pond		9.1	1.8	9.3	263
274333	At Middle Fork GRTF gage		8.5	-0.6	12.2	273
274334	South Fork above Middle Fork		13.1	n/a	13.3	281
275228	Below Two Moon Bridge	8/6/15	16.7		9.0	
275231	Above Lower Pond		16.3	-0.5		
274333	At Middle Fork GRTF gage		17.4	1.2	13.9	
275238	At Highway 64 Culvert		19.0	1.6	12.2	
275228	Below Two Moon Bridge	8/18/15	13.5		7.0	
275231	Above Lower Pond		12.5	-1.0	8.1	
274333	At Middle Fork GRTF gage		14.4	1.9	9.7	
275238	At Highway 64 Culvert		14.3	-0.1	10.3	
275228	Below Two Moon Bridge	9/3/15	7.8			175
275231	Above Lower Pond		7.6	-0.2		
274333	At Middle Fork GRTF gage		9.2	1.6	14.0	233
275238	At Highway 64 Culvert		7.7	-1.5		
275228	Below Two Moon Bridge	9/24/15	11.0			153

Table D1—*Continued*.

GWIC ID	Site Name	Date	Discharge (cfs)	Net Gain/Loss[1] (cfs)	Temperature (°C)	Specific Conductance (µmhos/cm)
275231	Above Lower Pond		11.4	0.4		
274333	At Middle Fork GRTF gage		12.6	1.3		
275238	At Highway 64 Culvert		13.1	1.8		
275228	Below Two Moon Bridge	6/29/16	30.6			131
275231	Above Lower Pond		38.4	7.9	10.9	138
274333	At Middle Fork GRTF gage		35.4	-3.1	14.6	159
275238	At Highway 64 Culvert		37.2	1.8	16.4	158
275228	Below Two Moon Bridge	7/20/16	12.3		8.8	
275231	Above Lower Pond		12.6	0.3	11.4	
274333	At Middle Fork GRTF gage		14.1	1.6	16.7	
275238	At Highway 64 Culvert		15.2	1.1	17.3	

Note. Measurements are listed in downstream order.
[1]Net gain/loss: the increase (or decrease, if negative) in discharge compared to upstream measurement.

APPENDIX E

STABLE ISOTOPES

Table E1. Concentrations of $\delta^{18}O$ and $\delta^{2}H$ in groundwater.

GWIC ID	Site Type	Aquifer	Sample Date	$\delta^{18}O$	$\delta^{2}H$
103496	Well	Muddy/dacite intrusion	8/4/2015	-20.0	-151.0
103556	Well	Alluvium/colluvium	8/7/2008	-17.6	-143.2
103557	Well	Frontier	8/7/2008	-18.4	-147.1
103575	Well	Madison Group	8/14/2008	-19.3	-149.0
104510	Well	Frontier	6/25/2015	-20.4	-158.0
153399	Well	Frontier/Mowry	8/13/2008	-20.2	-160.9
165687	Well	Meadow Village aquifer	5/4/2009	-18.6	-149.2
176326	Well	Morrison	6/24/2015	-20.4	-158.0
176327	Well	Kootenai/Morrison	6/26/2015	-18.0	-140.0
187230	Well	Muddy	5/24/2018	-19.5	-151.0
192607	Well	Kootenai	8/7/2008	-19.0	-153.5
192856	Well	Kootenai	6/26/2015	-20.3	-156.0
192865	Well	Kootenai/landslide	6/24/2015	-18.7	-143.0
192966	Well	Kootenai/Morrison	6/18/2015	-19.7	-150.0
205931	Well	Kootenai/dacite intrusion	8/4/2015	-19.7	-148.0
209445	Well	Mowry	6/23/2015	-19.3	-147.0
215507	Well	Frontier/dacite intrusion	6/23/2015	-19.0	-142.0
215510	Well	Muddy	7/15/2014	-19.2	-144.0
219966	Well	Muddy/Thermopolis/Kootenai	6/16/2015	-19.2	-148.0
230689	Well	Frontier	6/23/2015	-19.7	-150.0
230803	Well	Frontier/dacite intrusion	6/19/2015	-19.5	-145.0
230804	Well	Frontier	6/23/2015	-20.6	-155.0
231031	Well	Muddy	6/17/2015	-19.0	-146.0
231745	Well	Frontier	6/23/2015	-20.4	-152.0
234199	Well	Kootenai	7/23/2018	-19.2	-147.0
234783	Well	Morrison	6/24/2015	-19.1	-144.0
237292	Well	Kootenai	6/5/2015	-19.7	-153.0
239759	Well	Kootenai	8/5/2015	-20.5	-154.0
244347	Well	Muddy/Thermopolis	7/18/2011	-20.5	-151.2
253676	Well	Morrison	6/24/2015	-20.7	-157.0
255289	Spring	Madison Group	8/5/2014	-19.7	-149.0
257677	Well	Meadow Village aquifer	4/20/2017	-18.8	-145.0
259357	Well	Frontier/Mowry	7/15/2014	-19.4	-145.0
259685	Well	Muddy/Mowry	6/22/2015	-20.3	-154.0
259706	Well	Muddy	6/17/2015	-19.7	-149.0
262271	Well	Kootenai/Morrison	6/24/2015	-20.6	-154.0
275582	Well	Mowry/Muddy/dacite intrusion	6/25/2015	-20.1	-157.0
279062	Well	Frontier/dacite intrusion	6/19/2015	-18.7	-139.0
279080	Well	Frontier/dacite intrusion	7/21/2014	-19.5	-145.0
279082	Well	Frontier/dacite intrusion	7/21/2014	-19.8	-147.0
281359	Well	Meadow Village aquifer	6/2/2015	-18.2	-144.0
281360	Well	Meadow Village aquifer	6/3/2015	-18.6	-145.0

Table E1—*Continued*.

GWIC ID	Site Type	Aquifer	Sample Date	$\delta^{18}O$	$\delta^{2}H$
281362	Well	Meadow Village aquifer	6/3/2015	-18.3	-140.0
281363	Well	Meadow Village aquifer	6/2/2015	-19.2	-149.0
281366	Well	Meadow Village aquifer	6/3/2015	-18.7	-145.0
281367	Well	Meadow Village aquifer	6/3/2015	-18.9	-148.0
281368	Well	Meadow Village aquifer	6/3/2015	-18.6	-145.0
281371	Well	Meadow Village aquifer	6/4/2015	-18.9	-148.0
281372	Well	Meadow Village aquifer	6/4/2015	-18.4	-146.0
281373	Well	Meadow Village aquifer	6/4/2015	-18.9	-148.0

Table E2. Concentrations of $\delta^{18}O$ and $\delta^{2}H$ in surface water, rain, and snow.

GWIC No.	Sample Date	$\delta^{18}O$	$\delta^{2}H$	Region	Median $\delta^{18}O$	Median $\delta^{2}H$
274333	10/10/2013	-18.1	-145	Meadow Village Mid Fk W FK Gallatin	-18.1	-144.0
275228	10/10/2013	-17.9	-144	Meadow Village Mid Fk W FK Gallatin		
275230	10/10/2013	-18.1	-144	Meadow Village Mid Fk W FK Gallatin		
275231	10/10/2013	-17.9	-144	Meadow Village Mid Fk W FK Gallatin		
275238	10/10/2013	-18.5	-145	Meadow Village Mid Fk W FK Gallatin		
274332	4/17/2014	-18.9	-145	West FK Gallatin	-20.4	-148.5
274333	4/17/2014	-20.9	-151	Meadow Village Mid Fk W FK Gallatin		
274334	4/17/2014	-19.4	-146	South Fk W FK Gallatin		
274335	4/17/2014	-20.1	-148	North Fk W FK Gallatin		
275228	4/17/2014	-20.9	-152	Meadow Village Mid Fk W FK Gallatin		
277302	4/17/2014	-20.6	-149	Upper Mid Fk W FK Gallatin		
274332	4/28/2014	-19	-147	West FK Gallatin	-20.1	-150.0
274333	4/28/2014	-20.1	-150	Meadow Village Mid Fk W FK Gallatin		
274334	4/28/2014	-20.6	-150	South Fk W FK Gallatin		
274335	4/28/2014	-19.7	-147	North Fk W FK Gallatin		
275228	4/28/2014	-20.5	-151	Meadow Village Mid Fk W FK Gallatin		
275231	4/28/2014	-19.8	-150	Meadow Village Mid Fk W FK Gallatin		
276155	4/30/2014	-20.4	-148	Upper Mid Fk W FK Gallatin		
277302	4/28/2014	-20.3	-150	Upper Mid Fk W FK Gallatin		
277303	4/30/2014	-18.7	-144	Upper Mid Fk W FK Gallatin		
274332	5/22/2014	-21.2	-153	West FK Gallatin	-21.5	-155.0
274333	5/22/2014	-21.5	-155	Meadow Village Mid Fk W FK Gallatin		
274334	5/22/2014	-21.3	-152	South Fk W FK Gallatin		
274335	5/22/2014	-21.9	-155	North Fk W FK Gallatin		
275228	5/22/2014	-21.5	-155	Meadow Village Mid Fk W FK Gallatin		
276156	5/21/2014	-21.1	-151	Upper Mid Fk W FK Gallatin		
276425	5/22/2014	-21.5	-155	Upper Mid Fk W FK Gallatin		
276593	5/21/2014	-21.8	-155	Upper Mid Fk W FK Gallatin		
277302	5/22/2014	-21.5	-155	Upper Mid Fk W FK Gallatin		
277303	5/21/2014	-21.2	-153	Upper Mid Fk W FK Gallatin		
274332	6/4/2014	-21.1	-153	West FK Gallatin	-21.2	-154.0
274333	6/4/2014	-21.5	-155	Meadow Village Mid Fk W FK Gallatin		
274334	6/4/2014	-21.2	-153	South Fk W FK Gallatin		
274334	6/4/2014	-21.2	-153	South Fk W FK Gallatin		
274335	6/4/2014	-21.2	-156	North Fk W FK Gallatin		
275228	6/4/2014	-21.3	-155	Meadow Village Mid Fk W FK Gallatin		
276156	6/4/2014	-21	-151	Upper Mid Fk W FK Gallatin		
276425	6/4/2014	-21.2	-154	Upper Mid Fk W FK Gallatin		
276593	6/4/2014	-21.7	-156	Upper Mid Fk W FK Gallatin		
277302	6/4/2014	-21.1	-154	Upper Mid Fk W FK Gallatin		
277303	6/4/2014	-20.8	-151	Upper Mid Fk W FK Gallatin		
274332	6/26/2014	-19.7	-148	West FK Gallatin	-19.3	-147.5
274333	6/26/2014	-19.4	-148	Meadow Village Mid Fk W FK Gallatin		

Table E2—*Continued*.

GWIC No.	Sample Date	$\delta^{18}O$	$\delta^{2}H$	Region	Median $\delta^{18}O$	Median $\delta^{2}H$
274334	6/26/2014	-19.1	-147	South Fk W FK Gallatin		
274335	6/26/2014	-19.6	-149	North Fk W FK Gallatin		
275228	6/26/2014	-19.5	-149	Meadow Village Mid Fk W FK Gallatin		
276156	6/25/2014	-19.1	-146	Upper Mid Fk W FK Gallatin		
278616	6/23/2014	-19.1	-146	South Fk W FK Gallatin		
278618	6/25/2014	-18.8	-144	Moonlight Basin		
274332	7/24/2014	-18.6	-144	West FK Gallatin	-18.9	-145.0
274333	7/24/2014	-19.3	-147	Meadow Village Mid Fk W FK Gallatin		
274334	7/24/2014	-18.8	-145	South Fk W FK Gallatin		
274335	7/23/2014	-19.4	-147	North Fk W FK Gallatin		
275228	7/23/2014	-19.1	-146	Meadow Village Mid Fk W FK Gallatin		
276156	7/23/2014	-19	-145	Upper Mid Fk W FK Gallatin		
276406	7/24/2014	-18.9	-145	South Fk W FK Gallatin		
276593	7/23/2014	-18.7	-144	Upper Mid Fk W FK Gallatin		
277302	7/23/2014	-19	-145	Upper Mid Fk W FK Gallatin		
277303	7/23/2014	-18.8	-144	Upper Mid Fk W FK Gallatin		
278616	7/23/2014	-18.8	-144	South Fk W FK Gallatin		
278924	7/15/2014	-18.4	-146	Moonlight Basin		
278925	7/15/2014	-18.7	-146	Upper Mid Fk W FK Gallatin		
278927	7/16/2014	-19	-148	Moonlight Basin		
279077	7/21/2014	-19.3	-145	Moonlight Basin		
274333	9/24/2014	-19.5	-146	Meadow Village Mid Fk W FK Gallatin	-19.4	-144.0
274334	9/24/2014	-19.3	-143	South Fk W FK Gallatin		
275228	9/24/2014	-19	-143	Meadow Village Mid Fk W FK Gallatin		
275231	9/24/2014	-19.4	-145	Meadow Village Mid Fk W FK Gallatin		
274332	11/13/2014	-16.8	-141	West FK Gallatin	-18.0	-141.0
274335	11/13/2014	-18	-144	North Fk W FK Gallatin		
275228	11/13/2014	-16.1	-141	Meadow Village Mid Fk W FK Gallatin		
276156	11/12/2014	-15.3	-135	Upper Mid Fk W FK Gallatin		
276593	11/12/2014	-19	-144	Upper Mid Fk W FK Gallatin		
280685	10/29/2014	-18.1	-138	South Fk W FK Gallatin		
280686	10/29/2014	-18.8	-142	South Fk W FK Gallatin		
276156	6/19/2015	-19.3	-144	Upper Mid Fk W FK Gallatin	-18.7	-140.0
278618	6/23/2015	-19	-140	Moonlight Basin		
278927	6/23/2015	-18.4	-140	Moonlight Basin		
280685	6/18/2015	-16.7	-131	South Fk W FK Gallatin		
280686	6/18/2015	-18.7	-141	South Fk W FK Gallatin		
274332	8/19/2015	-18.2	-140	West FK Gallatin	-18.4	-141.0
274333	8/19/2015	-18.4	-141	Meadow Village Mid Fk W FK Gallatin		
274334	8/19/2015	-18.2	-139	South Fk W FK Gallatin		
275228	8/19/2015	-18.4	-141	Meadow Village Mid Fk W FK Gallatin		
275230	8/19/2015	-18.4	-141	Meadow Village Mid Fk W FK Gallatin		
275230	8/19/2015	-18.4	-141	Meadow Village Mid Fk W FK Gallatin		

Table E2—*Continued*.

GWIC No.	Sample Date	$\delta^{18}O$	$\delta^{2}H$	Region	Median $\delta^{18}O$	Median $\delta^{2}H$
275231	8/19/2015	-18.4	-141	Meadow Village Mid Fk W FK Gallatin		
275238	8/19/2015	-18.4	-141	Meadow Village Mid Fk W FK Gallatin		
278618	8/20/2015	-18.5	-140	Moonlight Basin		
282928	8/19/2015	-18.3	-141	Meadow Village Mid Fk W FK Gallatin		
274333	9/3/2015	-18.3	-142	Meadow Village Mid Fk W FK Gallatin	-18.3	-141.0
284220	9/3/2015	-18.3	-142	West FK Gallatin		
284220	9/24/2015	-18.2	-140	West FK Gallatin		
285424	9/24/2015	-18.2	-139	West FK Gallatin		

Table E3. Groundwater concentrations of $\delta^{18}O$ and $\delta^{2}H$ averaged for each subarea.

GWIC No.	Aquifer	Depth (ft)	Sample Date	$\delta^{18}O$	$\delta^{2}H$	Region	Median $\delta^{18}O$	Median $\delta^{2}H$
255289	Madison Group		8/5/2014	-19.7	-149	Madison Group Spring		
255289	Madison Group		8/12/2015	-20	-149	Madison Group Spring		
255289	Madison Group		9/3/2015	-19.6	-150	Madison Group Spring		
255289	Madison Group		9/24/2015	-19.2	-148	Madison Group Spring		
255289	Madison Group		7/25/2016	-19.8	-149	Madison Group Spring		
255289	Madison Group		7/31/2017	-18.5	-148	Madison Group Spring		
255289	Madison Group		8/6/2018	-18.5	-149	Madison Group Spring		
						Madison Group Spring average	**-19.6**	**-149.0**
104510	Mowry	71.5	6/25/2015	-20.4	-158	Meadow Village		
281359	Alluvium	45	6/2/2015	-18.2	-144	Meadow Village		
281360	Alluvium	45	6/3/2015	-18.6	-145	Meadow Village		
281362	Alluvium	15	6/3/2015	-18.3	-140	Meadow Village		
281363	Alluvium	25	6/2/2015	-19.2	-149	Meadow Village		
281366	Alluvium	25	6/3/2015	-18.7	-145	Meadow Village		
281367	Alluvium	35	6/3/2015	-18.9	-148	Meadow Village		
281368	Alluvium	15	6/3/2015	-18.6	-145	Meadow Village		
281371	Alluvium	55	6/4/2015	-18.9	-148	Meadow Village		
281372	Alluvium	20	6/4/2015	-18.4	-146	Meadow Village		
281373	Alluvium	20	6/4/2015	-18.9	-148	Meadow Village		
						Meadow Village average	**-18.7**	**-146.0**
209445	Mowry	85	6/23/2015	-19.3	-147	Moonlight Basin		
215507	Frontier	396	6/23/2015	-19	-142	Moonlight Basin		
215510	Mowry	56	7/15/2014	-19.2	-144	Moonlight Basin		
215510	Mowry	56	6/17/2015	-18.9	-145	Moonlight Basin		
230689	Muddy	185	6/23/2015	-19.7	-150	Moonlight Basin		
230803	Muddy	176	6/19/2015	-19.5	-145	Moonlight Basin		
230804	Muddy	237.5	6/23/2015	-20.6	-155	Moonlight Basin		
231031	Mowry	160	6/17/2015	-19	-146	Moonlight Basin		
231745	Muddy	160	6/23/2015	-20.4	-152	Moonlight Basin		
259357	Muddy	307	7/15/2014	-19.4	-145	Moonlight Basin		
259357	Muddy	307	6/17/2015	-19.5	-150	Moonlight Basin		
259685	Muddy	598	6/22/2015	-20.3	-154	Moonlight Basin		
259706	Muddy	449	6/17/2015	-19.7	-149	Moonlight Basin		
279062	Frontier	217.5	6/19/2015	-18.7	-139	Moonlight Basin		
279080	Dacite Intrusion	198	7/21/2014	-19.5	-145	Moonlight Basin		
279080	Dacite Intrusion	198	6/23/2015	-19	-141	Moonlight Basin		
279082	Frontier/Dacite	279	7/21/2014	-19.8	-147	Moonlight Basin		
						Moonlight Basin average	**-19.5**	**-146.0**
103496	Dacite Intrusion	400	8/4/2015	-20	-151	Mountain Village		
205931	Kootenai/Dacite	312	8/4/2015	-19.7	-148	Mountain Village		
244347	Muddy	200	8/4/2015	-19.4	-146	Mountain Village		
						Mountain Village average	**-19.7**	**-148.0**
219966	Morrison	525	6/16/2015	-19.2	-148	Spanish Peaks		
237292	Kootenai	565	6/5/2015	-19.7	-153	Spanish Peaks		
239759	Kootenai	553	8/5/2015	-20.5	-154	Spanish Peaks		
						Spanish Peaks average	**-19.7**	**-153.0**
176326	Morrison	362	6/24/2015	-20.4	-158	Yellowstone Club		
176327	Morrison	898	6/26/2015	-18	-140	Yellowstone Club		
192856	Kootenai	200	6/26/2015	-20.3	-156	Yellowstone Club		
192865	Kootenai	340	6/24/2015	-18.7	-143	Yellowstone Club		
192966	Kootenai	370	6/18/2015	-19.7	-150	Yellowstone Club		
234783	Morrison	402	6/24/2015	-19.1	-144	Yellowstone Club		
253676	Morrison	800	6/24/2015	-20.7	-157	Yellowstone Club		
262271	Morrison	444	6/24/2015	-20.6	-154	Yellowstone Club		
						Yellowstone Club average	**-20.0**	**-152.0**

APPENDIX F

TRITIUM

Table F1. Tritium concentrations in groundwater.

GWIC ID	Tritium Units	Analytical Margin of Error (σ)	Tritium Units Replicate[1]	Analytical Margin of Error (σ)	Tritium Age Determination	Field SC (µmhos/cm)	TDS (mg/L)	Aquifer	Total Well Depth (ft)
103496	4.2	±0.5			Mix old/modern	256	169	Muddy/dacite intrusion	400
176327	6.7	±0.6	5.6	±0.6	Modern water	398	193	Kootenai/Morrison	898
192966	5.1	±0.5			Modern water	646	336	Kootenai/Morrison	370
205931	6.1	±0.6	4.9	±0.5	Modern water	214	117	Kootenai/dacite intrusion	312
215507	6.4	±0.6			Modern water	119	67	Frontier/dacite intrusion	396
219966	4.3	±0.5			Mix old/modern	945	509	Muddy/Thermopolis/Kootenai	525
230689	6.3	±0.6			Modern water	377	203	Frontier	185
230803	7.3	±0.6	6.1	±0.6	Modern water	104	72	Frontier/dacite intrusion	176
230804	<0.8	±0.3			Old water	547	277	Frontier	238
237292	5.0	±0.6			Modern water	498	340	Kootenai	565
239759	2.0	±0.4			Mix old/modern	530	327	Kootenai	553
244347	6.5	±0.6			Modern water	302	183	Muddy/Thermopolis	200
253676	<0.8	±0.3			Old water	1332	692	Morrison	800
259357	4.1	±0.5			Mix old/modern	331	210	Frontier/Mowry	307
259685	<0.8	±0.3			Old water	700	346	Mowry/Muddy	606
259706	0.9	±0.1			Old, or old/modern mix	663	372	Muddy	449
275582	2.5	±0.4			Mix old/modern	1274	723	Mowry/Muddy/dacite intrusion	880
279062	6.4	±0.6			Modern water	194	99	Frontier/dacite intrusion	400
279080	7.3	±0.7			Modern water	191	117	Frontier/dacite intrusion	198
281363	6.2	±0.6			Modern water	448	289	Meadow Village aquifer	40
281371	5.6	±0.6			Modern water	452	284	Meadow Village aquifer	55

[1]Laboratory replicate result for same sample.