EVALUATION OF POTENTIAL HIGH-YIELD GROUNDWATER DEVELOPMENT IN THE GALLATIN VALLEY, GALLATIN COUNTY, MONTANA

Alan R. English

Montana Bureau of Mines and Geology

Montana Bureau of Mines and Geology Open-File Report 698

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Cover photo: Aerial photograph looking north along the West Gallatin River from Amsterdam Road (bottom of view). Stagecoach Trail Road runs north and northwest from Amsterdam Road in the lower left quarter of the view. The GWIP Stagecoach Trail Road aquifer test site is located in the trees along the west side of the river, in the center-left of the photograph. Photo by Alan English, MBMG.

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MBMG
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INTRODUCTION

Background

The city of Bozeman obtains its municipal water supply from three sources: Lyman Spring, Bozeman Creek, and Hyalite Reservoir. In early 2013, Bozeman began a planning process to project future water demand, increase water conservation, and expand the water supply over the next 50 years (2013 to 2062). The planning effort culminated with adoption of an Integrated Water Resources Plan (IRWP) in August 2013 (AE2S, 2013a). The IWRP projects that Bozeman will need to expand its water supply by 6,842–17,752 acre-feet per year (acre-ft/yr) by 2062. In December 2013, the city of Bozeman adopted an Implementation Plan to begin addressing the recommendations in the IWRP (AE2S, 2013b). The Implementation Plan includes evaluating the potential to develop up to 5,810 acre-ft/yr of groundwater to increase Bozeman's water supply. Developing 5,810 acre-ft/yr of groundwater will require constructing one or more well fields with several high-yield wells capable of producing a total of 3,600 gallons per minute (gpm) on a continuous basis. Other municipalities in the Gallatin Valley may also seek new groundwater supplies in the next 50 years as the population of the valley increases. The city of Belgrade, town of Manhattan, and community of Four Corners all rely solely on groundwater for their public water supplies. Like Bozeman, these municipalities may consider constructing high-yield wells to increase their water supply.

Previous Work

Hackett and others (1960) completed the first comprehensive hydrogeologic investigation of the Gallatin Valley. Recently, the Montana Bureau of Mines and Geology (MBMG) Ground Water Assessment Program (GWAP), Ground Water Investigations Program (GWIP), and geologic mapping program have all completed investigations of the hydrogeology and geology of the Gallatin Valley. GWAP recently collected data on wells, springs, and streams in the Gallatin Valley (Carstarphen and others, 2015), maintains a network of long-term monitoring wells in the Gallatin Valley, and maintains the Ground Water Information Center (GWIC) database. GWIP recently completed an investigation of the hydrogeology of the Four Corners area (Sutherland and others, 2014), and is currently assessing the hydrogeology of the Belgrade and Manhattan areas. The MBMG geologic mapping program has completed mapping of the bedrock and surficial geology of the Gallatin Valley and surrounding areas (Lonn and English, 2002; Vuke and others, 2002, 2014; Vuke, 2003). Collectively, the information provided by Hackett (1960) and the MBMG investigation provide a significant amount of information to evaluate the potential for groundwater development in the Gallatin Valley.

Purpose

This report evaluates the hydrogeology of the Gallatin Valley (fig. 1) to determine which areas have the greatest potential for developing high-yield wells (yield ≥ 950 gpm). Groundwater development potential is evaluated within a 350 mi^2 area surrounding the shallow (0–400 ft) unconsolidated Quaternary and Tertiary alluvial aquifer system underlying the Gallatin Valley. Groundwater "Scoping Areas" are delineated to identify areas where aquifer properties and existing land uses are most favorable for testing and potentially developing high-yield wells. Groundwater "Prospecting Areas" are delineated, where undeveloped groundwater resources may be present, but information is limited and the areas are unlikely to produce the 5,810 acre-ft/yr yield Bozeman is considering. The prospecting areas include the upper Bozeman Creek drainage, where the Madison Limestone crops out (fig. 1). Several "Potential Conflict Areas" are also delineated, where aquifer properties may be suitable for development of high-yield wells, but existing development and infrastructure pose potential conflicts.

Limitations

Information provided in this report is intended to assist Bozeman and other municipalities in the Gallatin Valley that may be interested in developing new groundwater supplies using high-yield wells. This work identified areas where groundwater may be physically available at the volume and flow rate required to construct one or more high-yield wells. Legal availability of groundwater, which includes assessing impacts to existing water rights, stream depletion, and mitigation requirements, was not considered. The evaluation also did not consider engineering constraints, financial considerations, and political issues. The municipalities will need to consider these issues when selecting specific locations for more detailed analysis.

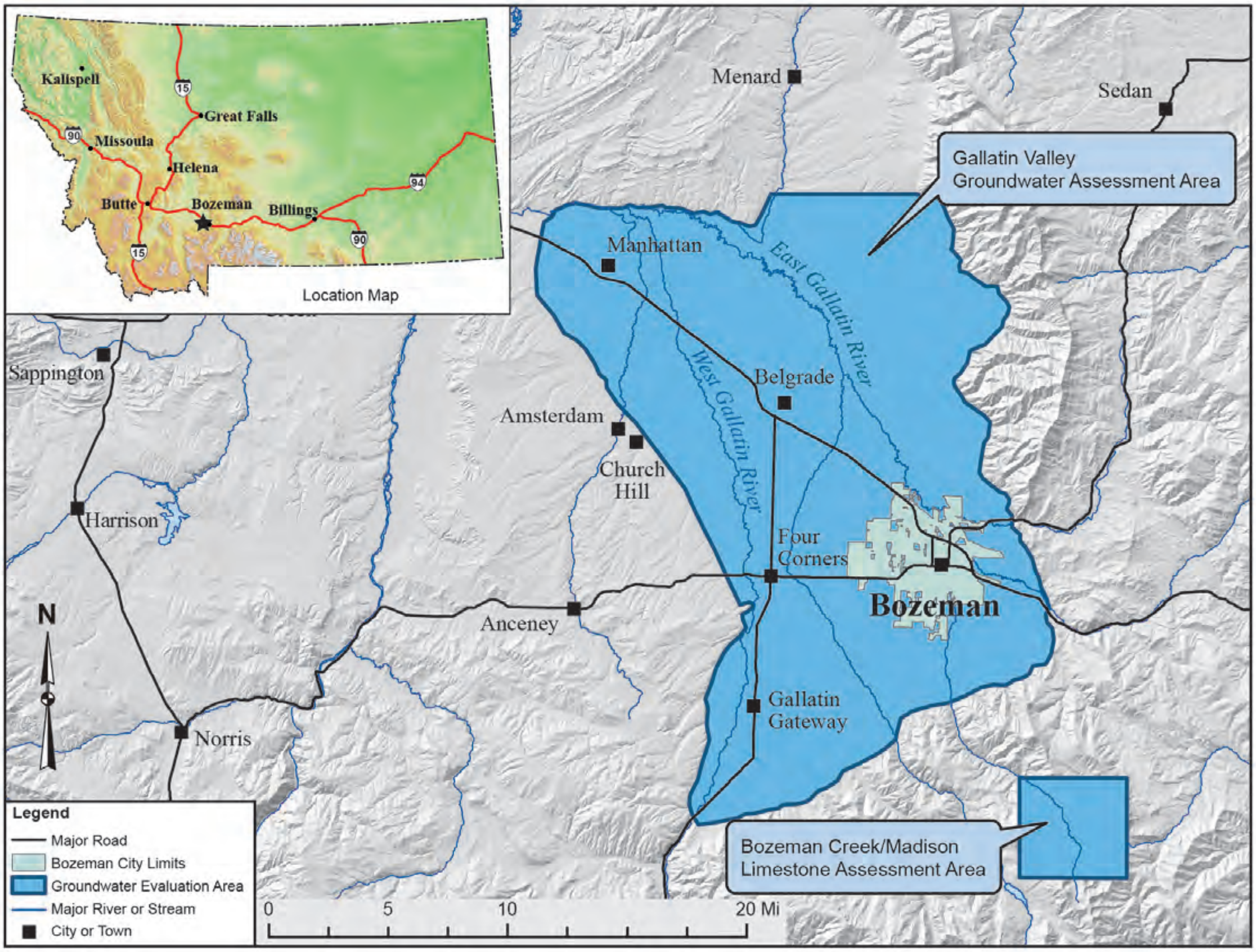

Figure 1. The Gallatin Valley is in southwest Montana and includes the Cities of Bozeman, Belgrade, and Manhattan. Evaluation of potential for high-yield groundwater development focused on the Gallatin Valley but also considered an area in the upper Bozeman Creek drainage where the Madison Limestone crops out.

METHODS

Geology and Hydrogeology of the Gallatin Valley

Published and unpublished geologic and hydrogeologic maps were reviewed to evaluate the bedrock structure of the Gallatin Valley and the stratigraphy of the sedimentary deposits that fill the valley. For discussion purposes, the shallow (0–400 ft) sedimentary deposits in the valley were divided into hydrogeologic subareas with similar aquifer properties (aquifer thickness, stratigraphy, and sediment grain size). The hydrogeologic subareas follow those described by Hackett and others (1960), but the boundaries were modified to better match more recent geologic mapping by the MBMG. The hydrogeology and groundwater development potential of the subareas were summarized based on ongoing work in the valley by the MBMG Groundwater Assessment Program and Ground Water Investigations Program, data in the GWIC database, data from Hackett and others (1960), and other reports as referenced. Aquifer test (pump test) data from previous investigations were also compiled and summarized by hydrogeologic subarea.

High-Yield Wells

The GWIC database contains information on wells, springs, and streams in Montana, is routinely updated, and is available to the public at http://mbmggwic.mtech.edu. The database was queried (December 8, 2015) to obtain information on existing wells in the Gallatin Valley. Records for monitoring wells, abandoned wells, dry holes, deepened wells, and wells without township, range, and section information were excluded. Remaining well records were sorted by reported yield to identify three high-yield well classes: wells with yields over 950 gpm, 500–950 gpm, and 200–499 gpm. A yield of 950 gpm was selected as the cutoff for the highest-yield wells because GWIC only contained one well record with a yield between 900 and 1,000 gpm (970 gpm) in Gallatin County. Most yield values in GWIC are based on a short duration (1 h) pumping test conducted by the driller when the well is completed. While these reported well yields likely over-estimate actual sustained yields, they are still useful for comparing potential well yields in the hydrogeologic subareas. The high-yield wells were also classified based on the “Well Use” data obtained from GWIC.

Identification of Groundwater Development Areas

Geologic maps (Vuke and others, 2014; Vuke, 2003; Lonn and English, 2002), hydrogeologic subareas (modified from Hackett and others, 1960), high-yield wells (GWIC), and aerial imagery (USDA-NAIP, 2015) were combined using ArcGIS. The aerial imagery was used to compare areas with existing high-density land development (residential, commercial, and industrial) with areas that have high-yield groundwater development potential. The data are summarized on two plates attached to this report. Plate 1 shows data on a geologic base map, while plate 2 shows data on an aerial imagery base map. Three types of groundwater development areas were delineated to help guide future groundwater development planning:

Scoping Areas:

Where aquifer properties are most favorable for high-yield groundwater development, there are existing high-yield wells, and significant areas of open land exist for a potential well field.

Prospecting Areas:

Where geologic and hydrogeologic data indicate undeveloped groundwater supplies may be present, but information is currently limited. More work would be required to determine the potential yield and/or water quality of these areas, but they are of interest for future groundwater development.

Potential Conflict Areas:

Where aquifer properties may be favorable for construction of high-yield wells, but existing municipalities, high-density developments, high-yield wells, water supply infrastructure, public water supplies, public wastewater treatment systems, or known geothermal resources are present. The MBMG delineates these areas to highlight potential conflicts, but these areas could still be explored for groundwater development if the potential conflicts are considered.

GEOLOGY OF THE GALLATIN VALLEY

Regional Tectonic Setting

Bedrock surrounding and underlying the Gallatin Valley records geologic events dating back to the Archean (2.7 billion years ago). However, the valley did not begin forming until about 17 million years ago. While the valley is geologically young, past tectonic events have influenced the current geologic structure. The Tertiary sediments that fill the valley were being deposited at the same time the valley was forming. There is also evidence that the valley was tectonically active during the Quaternary (0–2.6 million years ago).

Southwest Montana Transverse Zone

The geologic structure of the northern Gallatin Valley has been strongly influenced by the Southwest Montana Transverse Zone (SMTZ), a regional east–west-trending zone of crustal weakness that extends from the Tobacco Root Mountains southeast of Butte to the Bridger Range (fig. 2, plate 1). This zone of crustal weakness has existed since the Proterozoic (1.7 billion years ago) and has accommodated different types of fault movement through time, as tectonic stresses changed (Schmidt and O’Neill, 1982; Vuke and others, 2014).

Laramide Orogeny

The Laramide Orogeny caused east-directed compression of the earth’s crust, forming the Rocky Mountains between 75 and 35 million years ago. The tectonic forces folded and faulted the bedrock in the Gallatin Valley area. The SMTZ accommodated differential compression of the crust to the north and south, and had a profound impact on the style of bedrock folding and faulting on either side. North of the SMTZ, Paleozoic and Mesozoic sedimentary rocks were tightly folded and thrust faulted by thin-skinned Sevier-style tectonics that did not significantly offset the underlying Archean basement rocks (e.g., Horseshoe Hills). South of the SMTZ, the Archean basement rocks, along with the Paleozoic and Mesozoic

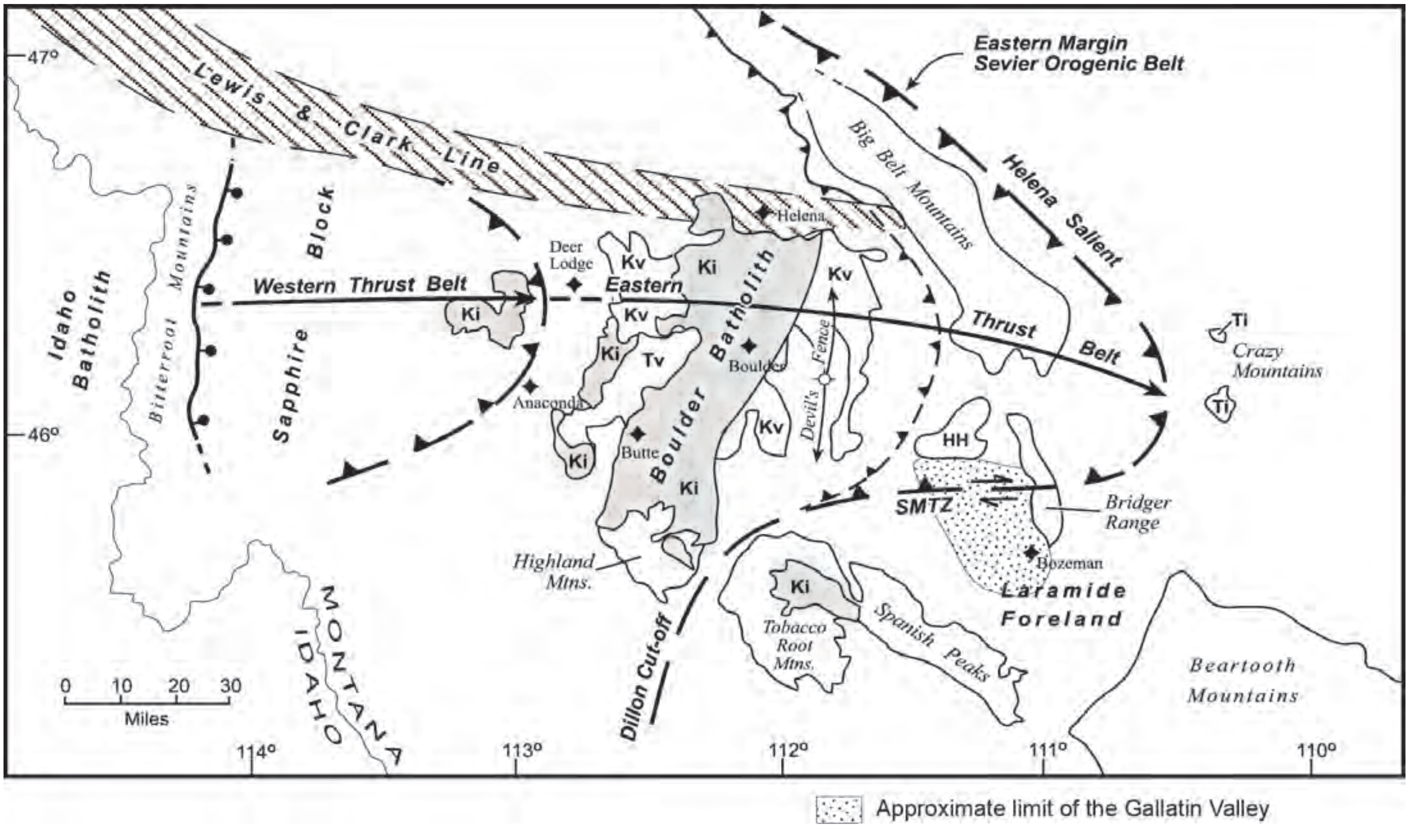

Figure 2. The Southwest Montana Transverse Zone (SMTZ) bisects the northern Gallatin Valley and forms the southern boundary of the Helena Salient of the Montana fold and thrust belt. North of the SMTZ, tectonic deformation consists of thin-skinned (Sevier-style) folds and thrusts, while to the south, deformation consists of thick-skinned (Laramide style) basement-cored folds and faults in the Laramide Foreland. Figure modified from Burton and others (1993).

sedimentary rocks, were more gently folded and block faulted by basement-cored, thick-skinned Laramide-style tectonics (e.g., southern Bridger Range, Madison Range, and Gallatin Range).

Basin and Range Extension

The Gallatin Valley began forming about 17 million years ago, when tectonic forces began pulling the crust apart. This tectonic event formed the Basin and Range province, with large basins separated by fault-bounded mountain blocks. The Gallatin Valley occupies the east half of one of these basins, known as the Three Forks Basin (Robinson, 1961), and the uplifted mountain blocks include the Bridger Range, Gallatin Range, Madison Range, and Tobacco Root Mountains.

Structural Geology

The Three Forks Basin encompasses the Gallatin, Madison, and Jefferson River Valleys. The western boundary of the Gallatin Valley is defined by the Madison Bluffs, which extend southward from the Horseshoe Hills at Logan, Montana, to the northern edge of the Madison Range (plate 1). The north–south trend of the Madison Bluffs may follow the axis of a large asymmetric anticline (Vuke and others, 2014). It is also possible that a basement-cored extensional or reverse fault underlies the Madison Bluffs at depth and the bedrock is draped over the fault.

Numerous faults offset the bedrock surrounding and underlying the Gallatin Valley (plate 1). The faults can be grouped into three types: northwest-trending faults, northeast-trending faults, and range-front faults. Range-front fault zones, formed during Basin and Range extension, bound the Gallatin Valley along the west flank of the Bridger Range and the north–northwest flank of the Gallatin Range. The range-front fault zones consist of numerous individual faults that are concealed in most places by alluvial fans emanating from the mountains. The west side of the Gallatin Valley is underlain by middle to late Tertiary basin-fill deposits that dip gently (<5°) towards the east–northeast, along the eastern limb of the anticline that follows the trend of the Madison Bluffs (Vuke, 2003). The Tertiary basin-fill deposits underlie the Camp Creek Hills and Madison Plateau, and crop out along the Madison Bluffs south of Logan (plate 1).

Bedrock structure on the north side of the Gallatin Valley is more complex due to repeated fault movement along the SMTZ. Faults likely bound the north edge of the Gallatin Valley and the east and west sides of the Dry Creek Valley, but their presence is concealed by basin-fill deposits. The Central Park fault zone may define the southern limit of the SMTZ (plate 1). Multiple lines of evidence support the existence of the Central Park fault zone, but it has been mapped in slightly different positions by different researchers. Geologic and geophysical data indicate the Central Park fault zone was active during deposition of the Tertiary and possibly Quaternary sediments in the Gallatin Valley (Hackett and others, 1960; Davis and others, 1965; Vuke and others, 2014). Gravity data (Davis and others, 1965) suggest scissor-like down-to-south offset along the Central Park fault zone, with offset of less than 200 ft in the Camp Creek Hills on the west side, and thousands of feet on the east side, near the Bridger Range.

Gravity data (Davis and others, 1965) also indicate a bedrock depression formed in the area where the Central Park fault zone and the Bridger range-front fault zone intersect. This bedrock depression may contain up to 4,000 ft of Tertiary basin-fill sediments (plate 1, East Belgrade Deep). The gravity data also indicate a northeast–southwest-trending fault-bounded trough (graben) along the base of the Gallatin Range, which may also contain up to 4,000 ft of Tertiary basin-fill deposits (plate 1, Gallatin Range Front Deep). Multiple lines of evidence, including gravity data, indicate an east-trending ridge of bedrock that forms a subsurface bedrock high in the southern Gallatin Valley (plate 1).

HYDROGEOLOGY

Overview of the Gallatin Valley Aquifer System

The Gallatin Valley covers about 350 mi^2 and is underlain by a complex mixture of Tertiary and Quaternary basin-fill sediments that range from less than 100 ft thick to several thousand feet thick. Because of the valley's size and the complexity of the basin-fill deposits, the aquifer formed in the basin-fill deposits is better described as an aquifer system rather than a single aquifer. The aquifer system primarily contains shallow unconfined groundwater, but also contains groundwater that is semi-confined, confined, and possibly even perched. A 250-ft-deep test well (259073) drilled by GWIP, about 3 mi northeast of Four Corners, encountered confined groundwater at a depth of 240–250 ft, in Tertiary sediments. Drillers' logs commonly report confining cemented gravel layers in the Quaternary gravels in the Belgrade area. There are likely other confined aquifer zones deeper in the Tertiary basin-fill sediments within the valley that have yet to be discovered.

The shallow aquifer system is hosted in the upper few hundred feet of Quaternary and Tertiary sediments in the valley, and interacts with rivers, streams, irrigation ditches, and other surface-water bodies. Generally, groundwater and surface water flows from southeast to northwest across the valley. The elevation and slope of the shallow aquifer water table, represented by potentiometric surface contours mapped by Hackett and others (1960), is shown on plate 1. Along the valley margins groundwater flow generally follows the topography, with northeast flow from the Camp Creek Hills, southwest flow from the Dry Creek Valley, westerly flow from the Bridger Range, and northwest flow from the Gallatin Range (plate 2). Groundwater flow also generally parallels the flow of the West Gallatin River, East Gallatin River, and creeks flowing from the valley margins. However, groundwater is locally modified where the rivers and creeks are gaining or losing water. Recent potentiometric surface mapping by GWIP in the Four Corners and Belgrade–Manhattan project areas shows that groundwater levels (elevations) have not significantly changed since the mapping by Hackett and others (1960). Almost all groundwater and surface water exits the valley through a narrow gorge cut into bedrock at Logan, in the northwest corner of the valley (plate 2).

Hydrogeologic Subareas

Hackett and others (1960) divided the Gallatin Valley into 12 "hydrogeologic subareas" that provide a useful framework for summarizing the hydrogeology (fig. 3). Geologic mapping (Lonn and English, 2002; Vuke, 2003; Vuke and others, 2014) provides more detail on the surficial geology in the Gallatin Valley (plate 1). Table 1 summarizes aquifer properties from aquifer tests (transmissivity, hydraulic conductivity, and storativity) in the hydrogeologic subareas shown in figure 3. For discussion purposes, the hydrogeologic subareas of Hackett are grouped as: (1) Quaternary fluvial deposits on the valley floor; (2) Quaternary–Late Tertiary alluvial fan complexes; and (3) Middle-Late Tertiary basin-fill deposits.

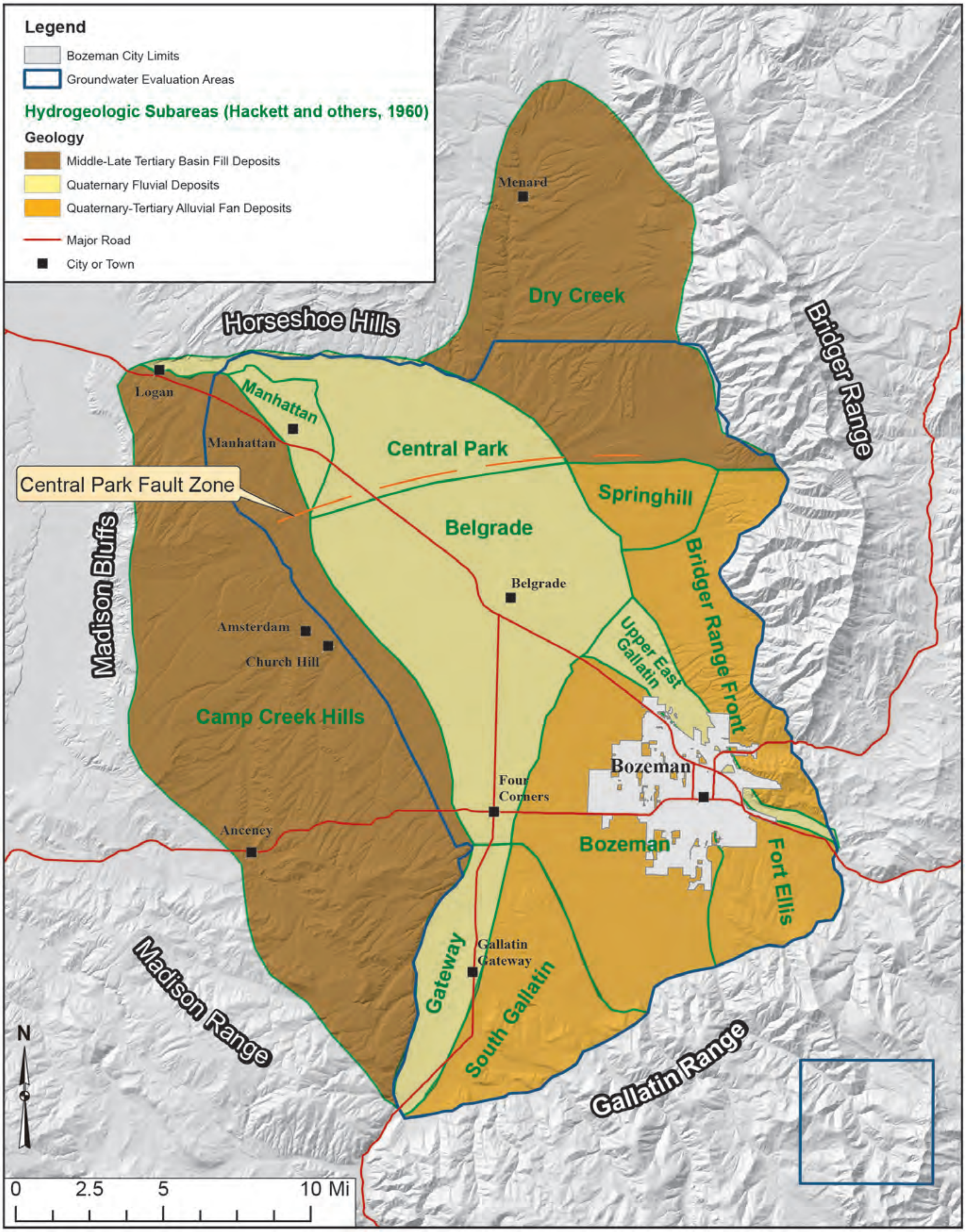

Figure 3. Hackett and others (1960) divided the Gallatin Valley into 12 “hydrogeologic subareas” that provide a useful framework for describing the hydrogeology of the valley. The subareas are herein grouped based on the predominant geologic age and depositional environment of the surficial deposits. The northern boundary of the Belgrade subarea is modified by moving it north to parallel the trend of the Central Park Fault zone, with a 2,000-ft offset to the south.

Table 1. Summary of reported aquifer properties by hydrogeologic subarea [Hydrogeologic subareas modified from Hackett and others (1960)].

Hydrogeologic Subarea	Source	Unit	Transmissivity (T) (gpd/ft)	Hydraulic Conductivity (K) (gpd/ft^2)	Storativity (S) [Specific Yield]
Gateway	Hackett & others (1960)	Q	170,000–380,000	2,000	NR
	GWIP Four Corners Proj.	Q/T?	120,000–137,000	1,700–2,000	0.0003
Belgrade	Hackett & others (1960)	Q	50,000–670,000	4,500	NR**
	Hackett & others (1960)	T	17,000	230	
	GWIP Belgrade–Man. Proj.	Q		670–1120	0.01–0.001
	GWIP Belgrade–Man. Proj.	T		82–546	0.0008–0.00001
Central Park	Hackett & others (1960)	Q	38,000–110,000	1,500–4,000	0.006
	Hackett & others (1960)	T	3,700		
	GWIP Belgrade–Man. Proj.	T	Not Reported	546	0.0008
Manhattan	Hackett & others (1960)	Q	120,000–140,000	7,800	0.001
	Carstensen (2008)	T	14,625–19,300	157–224!	
Upper East Gallatin	No Data				
Dry Creek	No Data				
Spring Hill	Hackett & others (1960)	Q	7,000–30,000	Not Reported	Not Reported
Bridger Range Front	Breuninger & Mendes (1993)	Q/T	5,690–12,720		0.00003–0.00017
	Kaczmarek (2003)	Q/T	1,360–1,530		0.00005–0.00025
	Gaston (1996)	Q/T	1,900		0.00023
	Hay (1997)	Q/T	4,550		0.00066 {0.16}
Fort Ellis	No Data				
Bozeman (Bozeman Fan)	Hackett & others (1960)	Q	4,500–65,000	600	0.06
	Hackett & others (1960)	T	300–2,700		
	Custer & others (1991)	Q/T	1,600–80,000		
South Gallatin	GWIP Four Corners Proj.	Q/T	120,000–137,000	1,700–2.000	0.0003
Camp Creek Hills	Hackett (1960)	T	1,200–26,000	10–70	Not Reported

Quaternary Fluvial Deposits on the Valley Floor

Cobbles, gravel, sand, silt, and clay deposited by rivers and streams are herein referred to as Quaternary fluvial deposits. These deposits underlie the Gateway, Belgrade, Central Park, Upper East Gallatin, and Manhattan subareas (fig. 3, plate 1). The Quaternary fluvial deposits overlie Late Tertiary fluvial deposits that can be hard to distinguish from the Quaternary deposits on well logs, or from drill cuttings, especially in the Central Park and Upper East Gallatin subareas. The Quaternary deposits are typically less than 100 ft thick, except in the Belgrade subarea and the western Upper East Gallatin subarea. The Quaternary fluvial deposits contain the coarsest sediments and form the most productive aquifer areas in the valley.

Gateway Subarea

Quaternary fluvial deposits in the Gateway subarea are uniformly coarse grained, consisting mainly of cobbles, gravel, and sand. They are distinct from the underlying Late Tertiary fluvial deposits, which consist mainly of fine gravel, sand, silt, and clay. The Quaternary deposits have a relatively uniform thickness of 50 to 80 ft (Hackett and others, 1960; Sutherland and others, 2014), and host a shallow unconfined aquifer with a water table that is typically within 10 to 15 ft of the surface. The areal extent of the Quaternary fluvial deposits in the Gateway subarea is limited to a 1.5- to 2-mi-wide area along the West Gallatin River, extending northward from the mouth of Gallatin Canyon to about 1 mi south of Four Corners (fig. 3, plate 1).

Hackett reported aquifer transmissivity values of 170,000 to 380,000 gpd/ft, and a hydraulic conductivity value of 2,000 gpd/ft^2 for the Gateway subarea (table 1). GWIP completed an aquifer test on well 259053, which is 80 ft deep and located just east of the Gateway subarea (plates 1 and 2). The GWIP aquifer test results show an aquifer transmissivity of 120,000–137,000 gpd/ft and a hydraulic conductivity of 1,700–2,000 gpd/ft^2. However, it is not clear if this aquifer test evaluated Quaternary deposits or Tertiary deposits. Including the GWIP test well, GWIC shows three wells within the Gateway subarea that have reported yields ≥950 gpm (plates 1 and 2). Existing high-yield wells, the coarse grain size of the aquifer materials, and the reported transmissivity values all indicate the Gateway subarea may be able to provide sustainable yields in the range of 950 gpm.

Belgrade Subarea

In the Belgrade subarea, the thickness of the fluvial deposits increases from about 70 ft at Four Corners to over 400 ft north of Belgrade, and areal extent increases from about 2 mi wide near Four Corners to about 8 mi wide north of Belgrade (fig. 3, plate 1). Like the Gateway subarea, the fluvial deposits in the Belgrade area are primarily coarse grained. Reported aquifer transmissivity values range from 50,000 to 670,000 gpd/ft, and reported hydraulic conductivity values range from 670 to 4,500 gpd/ft^2 (table 1). Most of the wells in the GWIC database with reported yields >950 gpm are located in the Belgrade subarea (plates 1 and 2). The thickness and coarse nature of the fluvial deposits in the Belgrade subarea, along with the reported transmissivity and hydraulic conductivity values, indicate this subarea could provide sustainable well yields >950 gpm.

Hackett and others (1960) arbitrarily defined the northern boundary of the Belgrade subarea using an east–west road (Walker Road). However, the nature of the Quaternary fluvial deposits does not change across Walker Road, but instead changes farther north, across the approximate trend of the Central Park fault zone (plate 1). Hackett and others (1960) drilled test wells across the fault zone and found that the thickness of the Quaternary fluvial deposits was over 300 ft just south of the fault zone, about 200 ft in the area of the fault zone, and only 30 ft a few miles north of the fault zone. Based on these observations, the northern boundary of the Belgrade subarea has been modified to parallel the trend of the Central Park fault zone, with an offset of about 2,000 ft to the south (fig. 3, plate 1).

Central Park Subarea

Along with the decrease in thickness of the Quaternary fluvial deposits north of the Central Park fault zone, the deposits also become finer grained, with more sand, silt, and clay. The Central Park subarea is also characterized by a shallow water table (<15 ft deep), extensive wetland and riparian areas, and numerous spring creeks. Hackett and others (1960) report aquifer transmissivity values of 38,000 to 110,000 gpd/ft. The decrease in aquifer thickness, decrease in grain size of the aquifer materials, and the reported aquifer transmissivity values all suggest it is unlikely that wells in this subarea can provide sustainable yields over 500 gpm.

Upper East Gallatin Subarea

The Upper East Gallatin subarea is limited to the floodplain of the East Gallatin River east and north of Bozeman (fig. 3, plate 1). The fluvial deposits are composed of fine gravel, sand, silt, and clay. Test wells indicate the alluvium is only about 30 ft thick north of Bozeman, and increases to about 160 ft at the northwest end of the subarea (Hackett and others, 1960). No known aquifer tests have been completed in this subarea. Because the Quaternary fluvial sediments are generally thin and fine grained, the Upper East Gallatin subarea is not likely to provide sustainable well yields much above 250 to 500 gpm.

Manhattan Subarea

The Manhattan subarea consists of a terrace above the modern floodplain of the Gallatin River. The terrace is underlain by fluvial deposits that are about 30 to 55 ft thick and highly permeable. Hackett and others (1960) reported aquifer transmissivity values of 120,000 to 140,000 gpd/ft, and a hydraulic conductivity value of 7,800 gpd/ft^2 (table 1). The fluvial deposits on the terrace are above the modern floodplain of the Gallatin River and are hydrologically disconnected from the river. The fluvial deposits overlie Middle-Late Tertiary basin-fill deposits. Recharge to the Manhattan subarea is limited to groundwater flow from the Camp Creek Hills, irrigation canal leakage, and excess irrigation water applied within the subarea.

The GWIC database does not contain any records for wells with reported yields ≥950 gpm within the subarea, but there are wells with reported yields between 500 and 800 gpm, including public water supply wells for the town of Manhattan (wells 193168, 223575, and 9366). However, these public water supply wells are all producing from the Middle–Late Tertiary basin-fill deposits under the Quaternary fluvial deposits. A 450-ft-deep test well drilled by Hackett and others (1960) (well A2-2-33da) showed 55 ft of Quaternary fluvial deposits resting on Middle–Late Tertiary basin-fill deposits. Two distinct water-bearing zones were reported: a shallow zone from 32 to 73 ft bgs, and a deeper zone from 215 to 300 ft bgs. Static water levels reported for these zones indicate the deeper water-bearing zone is confined and separated from the shallow groundwater.

Quaternary–Late Tertiary Alluvial Fan Complexes

The Springhill, Bridger Range Front, Fort Ellis, Bozeman Fan, and South Gallatin subareas consist of coalescing alluvial fans deposited from the surrounding mountains (fig. 3, plate 1). The alluvial fan deposits are Quaternary to late Tertiary (Pliocene) age, but older Tertiary (Oligocene–Miocene?) basin-fill deposits are partially exposed in the southern portion of the Bridger Range Front subarea, much of the Fort Ellis subarea, and portions of the Bozeman and South Gallatin subareas (plate 1). The older Tertiary basin-fill deposits probably correlate with the Middle to Late Tertiary basin-fill deposits in the Camp Creek Hills and Dry Creek subareas (Lonn and English, 2002). Middle to Late Tertiary basin-fill deposits may also underlie the Quaternary–Tertiary alluvial fan deposits at depth in the Springhill and Bozeman subareas.

Range-front faults bound the alluvial fan deposits along the base of the Bridger and Gallatin ranges. The alluvial fan deposits pinch out or interfinger with Quaternary fluvial deposits on the valley floor. The thickness of the alluvial fan deposits is poorly known, but they are probably over 500 ft thick near the Bridger and Gallatin Range fronts. Overall, the alluvial fan deposits consist of interbedded, discontinuous layers of gravel, sand, silt, and clay. Some layers are well sorted, but many of the layers consist of poorly sorted sediments. The deposits tend to be coarser grained and poorly sorted near the mountains, and become finer grained and better sorted away from the mountain front. No wells with reported yields <950 gpm are reported in the alluvial fan complexes, with the exception of one well along the west edge of the South Gallatin Subarea. Only a few wells with reported yields of 500 to 950 gpm are reported in the alluvial fan complexes, mainly in the Bozeman Subarea.

Springhill Subarea

Information on the hydrogeology of the Springhill subarea is limited. The subarea consists of a single alluvial fan that is younger than other fan deposits along the Bridger Range (Hackett and others, 1960). The only known aquifer test data for the subarea are two short-term (30-min) pump tests completed by Hackett and others (1960) (table 1). The alluvial fan deposits are probably similar to those further south in the Bridger Range Front subarea, which have been better studied. Generally, the alluvial fan deposits are complexly stratified, moderately to poorly sorted, and contain lenses and layers of silt and clay. These properties, along with aquifer test data from the alluvial fan deposits to the south, make it unlikely that this subarea could provide sustained well yields much over 100 to 200 gpm.

Bridger Range Front Subarea

Several hydrogeologic investigations have been completed in the Bridger Range Front subarea, in the Sypes Canyon and North Cottonwood Canyon areas (Breuninger and Mendes, 1993; Gaston, 1996; Erickson, 1995; Hay, 1997; Kaczmarek, 2001; Levens, 2007). Erickson (1995) and Hay (1997) concluded that the alluvial fan deposits consisted of discontinuous water-bearing zones that were interconnected, forming a single, unconfined aquifer system. Kaczmerek (2001) concluded that the water-bearing zones were best described as leaky-confined strip aquifers. He conducted several aquifer tests near Sypes Canyon, including a test using a well over 500 ft deep (table 1), and was unable to obtain a sustained yield above 100 gpm. Based on this information, it is unlikely sustainable well yields greater than 100 to 200 gpm can be expected in this subarea.

Fort Ellis Subarea

Information on the hydrogeology of the Fort Ellis subarea is very limited. Hackett and others (1960) did not report any aquifer tests in the subarea, but they did note that the area was similar to the Dry Creek subarea (fig. 3, plate 1), which is underlain by Middle–Late

Tertiary basin-fill deposits. No wells with reported yields >950 gpm are reported in the subarea.

Bozeman Subarea

The Bozeman subarea extends from the Gallatin Range northward to Interstate 90 on the north side of Bozeman (fig. 3, plate 1). A hydrogeologic investigation by Custer and others (1991), and geologic mapping by Lonn and English (2001), show this subarea can be further subdivided into three distinct hydrogeologic areas (plate 1). The southern portion of the subarea consists of a relatively young, wedge-shaped Quaternary alluvial fan deposit that emanates mainly from Hyalite Canyon and overlays older alluvial deposits. In the middle portion of the subarea older Quaternary alluvial deposits crop out. These deposits are less than 50 ft thick, sheet-like, and have been partially dissected by erosion. The northern portion of the Bozeman subarea consists of Middle to Late Tertiary basin-fill deposits that have been dissected by erosion. These deposits tend to be more compacted and finer grained than the Quaternary alluvial fan deposits. The GWIC database contains records for two wells in this subarea with yields >950 gpm, both located along the northwest boundary of the subarea. Hackett and others (1960) concluded that it was unlikely that wells completed in the Bozeman subarea could produce yields more than 500 gpm, based on aquifer tests within the subarea. Custer and others (1991) similarly concluded that sustained yields of over 400 gpm were unlikely in the Bozeman subarea.

South Gallatin Subarea

Information on the South Gallatin Subarea is limited. Hackett and others (1960) did not report any aquifer testing in this subarea. The area consists of thin Quaternary alluvial fan deposits that overlie Middle–Late Tertiary basin-fill deposits. The basin-fill deposits are mapped at the surface in much of the subarea (plate 1). The driller's log for a GWIP test well (259053), located along the western edge of the subarea, had a reported yield of 1,500 gpm. However, this yield is incorrect, and an aquifer test completed by GWIP using this well as a pumping well shows a sustained yield of about 50 gpm.

Middle to Late Tertiary Basin-Fill Deposits

Middle to Late Tertiary (Oligocene to Pliocene) basin-fill deposits underlie the Camp Creek Hills and Dry Creek subareas (fig. 3, plate 1). As previously noted, they also crop out in portions of the Bridger Range front, Fort Ellis, Bozeman, and South Gallatin subareas. The Middle to Late Tertiary deposits are well exposed along the Madison Bluffs south of Logan and underlie the Madison Plateau and Camp Creek Hills area (plate 1). The Tertiary basin-fill deposits are locally capped by Quaternary–Tertiary deposits. Vuke (2003) mapped the Tertiary basin-fill deposits as the Madison Plateau map unit, Madison Valley Formation, and Renova Formation, in descending order (plate 1). The Tertiary basin-fill deposits are composed primarily of sand, silt, and volcanic ash, but they also contain lenses and layers of gravel that can produce significant quantities of groundwater.

Camp Creek Hills Subarea

This subarea is mostly outside the high-yield groundwater assessment area in the Gallatin Valley, but it supports numerous high-yield irrigation wells located between 1.5 and 5.5 mi south of Manhattan (fig. 3). The Tertiary deposits dip gently to the northeast at 2° to 35° (Vuke, 2003), and have been folded along the trend of the Central Park fault zone (fig. 3, plate 1). The deposits are thickest in the northern portion of the Camp Creek Hills subarea and thin towards the south, due to differential erosion of the tilted layers. West of Gallatin Gateway the deposits have been completely removed by erosion, exposing Archean metamorphic basement rocks. The same Tertiary deposits are also believed to underlie the Quaternary alluvium on the floor of the Gallatin Valley and may extend underneath the valley floor to the Bridger Range front (Vuke, 2003). However, the depth and structure of the deposits under the Gallatin Valley are poorly understood.

Hackett concluded that the Tertiary deposits in the Camp Creek Hills subarea were "incapable of yielding more than enough water for domestic and stock supply." However, since they conducted their investigation, numerous high-yield irrigation wells have been successfully completed in the northern Camp Creek Hills, at depths of 202 to 710 ft (fig. 3). The Montana Department of Natural Resources and Conservation (1992) evaluated the stratigraphy of the Tertiary deposits underlying the Madison Plateau, measured water levels in wells, and estimated aquifer recharge. They concluded that confined and unconfined aquifer conditions existed within the Tertiary deposits, and the high-yield irrigation wells were producing from areally extensive interconnected gravel deposits, interbedded with claystone, silt, and sand layers. They also concluded that the highly productive gravel deposits probably continue eastward under the valley floor and are connected to the shallow gravel deposits along the West Gallatin River. At least in the north half, the Central Park subarea is clearly capable of producing sustained yields of more than 950 gpm. However, groundwater recharge to the subarea is primarily from irrigation canal leakage and excess irrigation water (Hackett and others, 1960; Waren, 1992). Changes in land use and irrigation practices could significantly reduce recharge to the Central Park subarea in the future.

Dry Creek Subarea

Much of the Dry Creek subarea is outside the high-yield groundwater evaluation area (fig. 3). Information on this subarea is limited, and unlike the Camp Creek Hills subarea, the Dry Creek subarea does not contain any reported wells with yields ≥950 gpm. Hackett and others (1960) noted that most wells in the area were producing from shallow wells completed in Quaternary alluvium along streams in the subarea, or Quaternary alluvial fans. They concluded that the area probably could not sustain high-yield wells.

The Madison Limestone in Bozeman Creek

The Madison Group, commonly referred to as the Madison Limestone, crops out in the upper Bozeman Creek drainage basin (plate 1), where it is exposed along an anticline. The Madison Limestone in this area includes the Lodgepole and Mission Canyon Formations, and is known to produce significant quantities of water in Montana. Production is mainly from the Mission Canyon Formation. Bozeman has long considered the potential for developing groundwater from the Madison Limestone in the Bozeman Creek drainage basin because it is close to the city's water treatment plant, the water could be gravity fed to the plant, and the water quality is generally good.

Kirk (2002) conducted a preliminary assessment of the groundwater development potential of the Madison Limestone in the Bozeman Creek drainage. She reported that Bozeman Creek and other streams in the canyon all lost water as they flowed across the Madison Limestone. Recharge to Madison Limestone from the streams was found to be highest in the fall and spring, and estimated to be 2,600 acre-ft/yr (Kirk, 2002). Drilling of a test well and further evaluation of the groundwater development potential was recommended, but no additional evaluation of this potential water source has been completed.

SUMMARY OF WELLS AND WELL YIELDS IN THE GALLATIN VALLEY

The GWIC database contained 17,065 well records for Gallatin County when queried (December 8, 2015). After excluding records for monitoring wells and wells that were abandoned, destroyed, deepened, dry, or had poor location information, 16,628 well records remained, of which 10,628 (65%) were within the Gallatin Valley high-yield groundwater assessment area. Most wells (85%) are used for domestic purposes and agriculture. Agricultural use is primarily irrigation, but includes some livestock use. Less than 2% (224) of the wells in the Gallatin Valley high-yield groundwater assessment area are public water supplies.

Wells with Reported Yields >950 gpm

The locations of wells with reported yields >950 gpm are shown in figure 4, in relation to the hydrogeologic subareas in the Gallatin Valley. The locations and primary well use for these wells are shown in plates 1 and 2. GWIC records for all of Gallatin County contain only 53 wells in this yield category, and 43 (81%) of those are in the Gallatin Valley, including the Camp Creek Hills and Madison Plateau (fig. 4).

Twenty-eight wells with reported yields >950 gpm are within the Gallatin Valley high-yield groundwater assessment area (fig. 4, plates 1 and 2). Almost all of these wells are producing from the Quaternary fluvial deposits on the valley floor, and 17 (61%) are in the Belgrade subarea. Exceptions include a cluster of wells south of Manhattan in the Camp Creek Hills subarea, and an MBMG test well on the western edge of the South Gallatin subarea. Of the 28 wells within the high-yield groundwater evaluation area, 13 (46%) are irrigation wells and 7 (25%) are public water supply wells. The remaining 8 wells (29%) include MBMG research wells, fire protection wells, and a geothermal well. Total depths for the 28 wells with reported yields >950 gpm range from 60 to 387 ft and average 151 ft. The reported yields range from 970 to 2,000 gpm and average about 1,300 gpm.

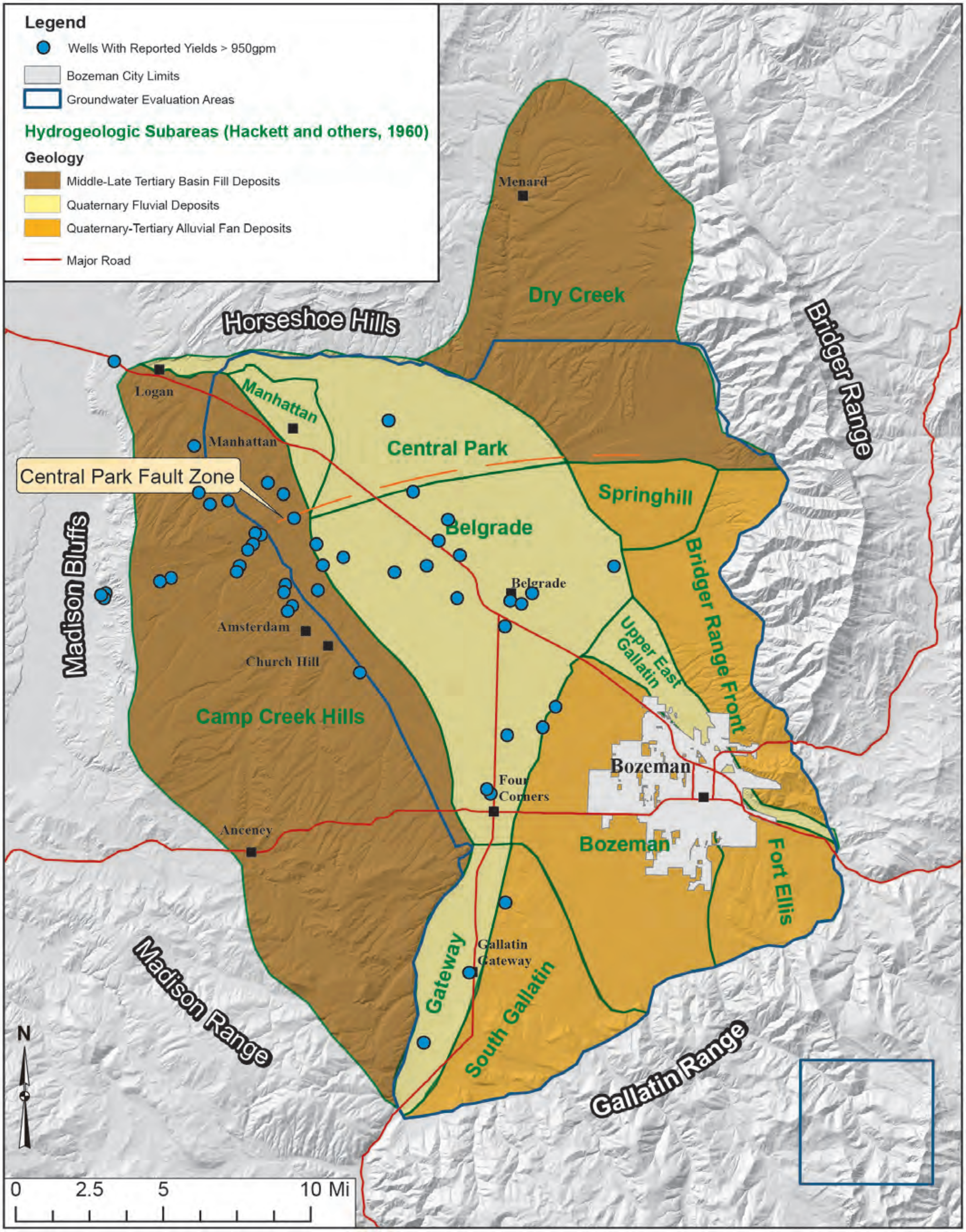

Figure 4. The GWIC database has records for 53 wells in Gallatin County with reported yields >950 gpm. Of those, 43 (81%) are in the Gallatin Valley, including the Camp Creek Hills and Madison Plateau. Twenty-eight (53%) are located within the Gallatin Valley high-yield groundwater evaluation area outlined in blue, and most of those are in the Belgrade subarea as modified from Hackett and others (1960).

Wells with Reported Yields of 500 to 950 gpm

The locations of wells with reported yields of 500 to 950 gpm are shown in figure 5, in relation to the hydrogeologic subareas in the Gallatin Valley. The locations and primary well use for these wells are shown in plates 1 and 2. The GWIC database contains records for 83 wells in Gallatin County with reported yields of 500 to 950 gpm; of these, 58 (70%) are in the Gallatin Valley, including the Camp Creek Hills and Madison Plateau.

Fifty-two wells with reported yields of 500 to 950 gpm are within the Gallatin Valley high-yield groundwater assessment area (fig. 5, plates 1 and 2). Similar to the highest-yield wells (>950 gpm), most wells in this yield category are located in the hydrogeologic subareas underlain by Quaternary fluvial deposits. However, there are 10 of these wells in Quaternary–Tertiary alluvial fan deposits within the Bozeman subarea. Most (89%) of the wells in this yield category within the Gallatin Valley high-yield groundwater assessment area are public water supply wells (35%), irrigation wells (29%), and fire protection wells (25%). The remainder (11%) are geothermal, industrial, or domestic wells. Total well depths range from 19 to 545 ft, but most wells depths are 300 ft or less (87%). Reported yields for these wells average 630 gpm, and only 8 (15%) have reported yields above 750 gpm.

Wells with Reported Yields of 200 to 499 gpm

There are 134 wells with reported yields of 200 to 499 gpm within the Gallatin Valley high-yield groundwater assessment area. Within the entire Gallatin Valley, extending to the Madison Bluffs and including the Dry Creek Valley, there are only 11 more wells in this yield category. Similar to the wells with yields of 500 to 950 gpm, most of the wells in this lower-yield category are located in areas underlain by Quaternary fluvial deposits and the Quaternary–Tertiary alluvial fan deposits.

Well use is more variable in this yield category, but most of the wells (77%) are used for domestic purposes (43%), public water supply (21%), and irrigation (18 wells, 13%). Total depth for these wells ranges from 11 to 525 ft, but almost all of them are completed at 300 ft or less (96%), and most are completed at less than 200 ft (88%). The reported yields for wells in this category range from 200 to 470 gpm and average 285 gpm. Most of the reported yields are 300 gpm or less (93 wells, 69%).

CONCLUSIONS AND RECOMMENDED GROUNDWATER EVALUATION AREAS

Aquifer Properties and Existing Wells

The Quaternary fluvial deposits that underlie the Gallatin Valley have the most favorable aquifer properties for developing high-yield wells, and most of the existing high-yield wells are completed in these deposits. The quaternary fluvial deposits underlie the Gateway, Belgrade, Central Park, Manhattan, and Upper East Gallatin subareas. There is also a cluster of high-yield wells south–southwest of Manhattan, which are completed in the Middle to Late Tertiary basin-fill deposits in the Camp Creek Hills subarea (fig. 4).

The Belgrade subarea stands out as the area with the greatest potential for groundwater development capable of producing high yields. The Gateway subarea also has aquifer properties capable of supporting high-yield wells, but the Quaternary fluvial deposits are thinner and limited to a narrow zone along the Gallatin River. The Central Park and Upper East Gallatin subareas have thin fluvial deposits that are finer grained, and are less likely to support sustainable well yields above 250 to 400 gpm.

The Quaternary–Tertiary alluvial fan complexes along the Bridger and Gallatin Range fronts do not have aquifer properties favorable for completing wells with yields much over 200–400 gpm. These deposits underlie the Springhill, Bridger Range Front, Fort Ellis, and Bozeman subareas. The Bozeman subarea supports several wells with moderately high reported well yields, but has been well studied and does not appear to be capable of producing sustained yields over 400 gpm. Both Hackett and others (1960) and Custer and others (1991) support this conclusion.

Scoping Areas

The South Belgrade and North Belgrade scoping areas (plate 2) are recommended as the best areas to consider for construction of a well field with high-yield wells. These areas are recommended based on the hydrogeology, reported aquifer properties, existing high-yield well locations, and existing municipalities with developed water and wastewater infrastructure. The Gateway scoping area is a third option, but is not preferred because the productive aquifer materials are thin and limited in areal extent.

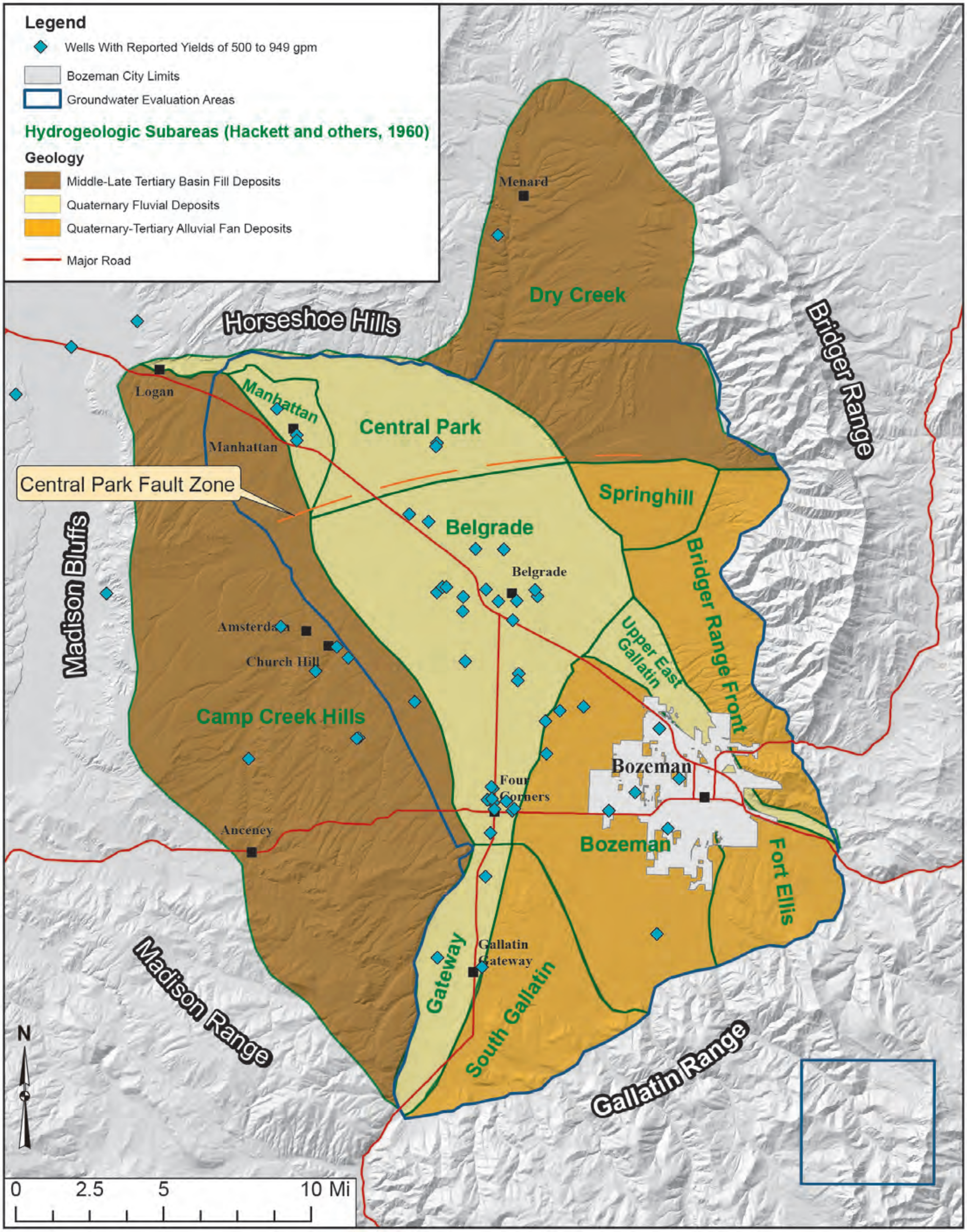

Figure 5. The GWIC database has records for 83 wells in Gallatin County with reported yields of 500 to 950 gpm. Of those, 52 (63%) are located within the Gallatin Valley high-yield groundwater evaluation area outlined in blue, and most of those are in the Belgrade subarea as modifi ed from Hackett and others (1960).

Prospecting Areas

Based on geologic mapping and gravity data, the East Belgrade Deep and Gallatin Range Front Deep areas (plate 2) may contain up to 4,000 ft of Tertiary sediments. These prospecting areas may contain significant groundwater resources, under confining conditions, and could be considered for future groundwater exploration. However, no deep wells have been drilled into these areas, exploratory drilling costs would be very high, and if significant groundwater resources are present, water quality may be poor.

The Stagecoach Trail prospecting area contains several wells with reported yields <950 gpm (plate 2). These wells appear to be producing from sand and gravel beds within the Middle–Late Tertiary basin-fill deposits underlying the Quaternary alluvium west of the West Gallatin River. More information is needed to determine the extent of these sand and gravel beds, the source(s) of recharge to them, and the possible connection between the sand and gravel beds and the shallow alluvium along the West Gallatin River.

The Madison Limestone in the upper Bozeman Creek drainage shows promise for groundwater development, and water quality would likely be good. Based on the preliminary assessment by Kirk (2002), this area could supplement Bozeman's water supply, but is probably only capable of providing 1,000 to 1,500 acre-ft/yr. This volume is a rough estimate, and further evaluation and testing would be required to determine the potential yield from the Madison Limestone.

Potential Conflict Areas

Exclusion areas are delineated around Manhattan, Belgrade, and Four Corners (plate 2). These areas are identified based on the level of land development visible on aerial imagery (USDA-NAIP, 2015), locations of existing high-yield wells, and existing water and wastewater treatment infrastructure. These areas overlie otherwise favorable areas for groundwater development and could be explored in cooperation with the municipalities if the potential conflicts are considered.

The Belgrade area includes Belgrade's public water supply wells, Belgrade's wastewater infrastructure (treatment lagoons, land application areas, and infiltration beds), the airport area, the high-density development west of Belgrade, and the River Rock Water and Sewer District. The Manhattan area includes Manhattan's public water supply wells and their public water supply spring. The Manhattan wastewater treatment plant discharges to the Gallatin River and does not impede groundwater development. The Four Corners area includes the high-density development surrounding Four Corners, the public water supply wells for the Four Corners Water and Sewer District, and the public water supply well and wastewater treatment lagoons for the Forest Park Trailer Court. The wastewater treatment plant located next to the Elk Grove subdivision is not included in the Four Corners potential conflict area, but the Gallatin Gateway is drawn to avoid the treatment plant area.

The Four Corners Geothermal Area is identified to avoid potentially drilling into geothermal groundwater resources. The geothermal waters that historically surfaced at Bozeman Hot Springs are thought to be associated with a northeast-trending fault. The exclusion area is drawn as a 500-ft buffer on either side of the fault, but is also extended southward to include several geothermal wells.

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