A preliminary investigation of the Madison aquifer for a drinking water supply in Bozeman, Montana
by Karin Bohacek Kirk

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University
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Abstract:
The purpose of this study was to perform a preliminary assessment of the potential of the Madison aquifer in Sourdough Canyon for use as a supplement to the municipal water supply of Bozeman, Montana. The Paleozoic rock units in the upper Sourdough Creek drainage basin were mapped and a geologic cross section was constructed. The Mississippian Madison Group is comprised of the lower Lodgepole Limestone and the upper Mission Canyon Formation, and is 430 meters (1420 feet) in total thickness. Karst features and fractures were common in the Mission Canyon Formation and enhance the permeability of the formation. Recharge to the aquifer was estimated by measuring stream losses where streams flowed across the Madison Group rocks. Each of the streams in the Sourdough Creek watershed was found to be losing water and the estimated stream loss is 3,200,000 m^3/year (2,600 acre-feet/year). One spring was found that was discharging from the Lodgepole Limestone. The spring stage was measured by a data logger within a stilling well from October 2000 to October 2001. During this period, the annual spring discharge was 1,100,000 m^3/year (900 acre-feet/year). Correlation of a peak in the spring discharge with an isolated precipitation event revealed a response time of 5 days, suggesting a rapid connection between the surface water and the spring discharge. The water temperature, ion chemistry and tritium concentration all indicate the spring has a shallow circulation pattern , and a short residence time. Hence the spring is not representative of a deep, regional aquifer system within the Madison aquifer, and the depth to the regional saturated zone is unknown. The City should not drill a production well without further investigation of the depth to the saturated zone. By drilling a test well, the depth to saturation, well yield and subsurface geology could be determined. This is recommended if the City chooses to pursue the development of groundwater resources in the Sourdough Creek drainage. Other options for water development include the prevention of stream losses in order to provide a net gain to Sourdough Creek, and an assessment of the Madison aquifer in the Hyalite Creek drainage.

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Master of Science

in

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APPROVAL

of a thesis submitted by

Karin Bohacek Kirk

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date 4-18-02

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ABSTRACT

The purpose of this study was to perform a preliminary assessment of the potential of the Madison aquifer in Sourdough Canyon for use as a supplement to the municipal water supply of Bozeman, Montana. The Paleozoic rock units in the upper Sourdough Creek drainage basin were mapped and a geologic cross section was constructed. The Mississippian Madison Group is comprised of the lower Lodgepole Limestone and the upper Mission Canyon Formation, and is 430 meters (1420 feet) in total thickness. Karst features and fractures were common in the Mission Canyon Formation and enhance the permeability of the formation. Recharge to the aquifer was estimated by measuring stream losses where streams flowed across the Madison Group rocks. Each of the streams in the Sourdough Creek watershed was found to be losing water and the estimated stream loss is 3,200,000 m^3/year (2,600 acre-feet/year). One spring was found that was discharging from the Lodgepole Limestone. The spring stage was measured by a data logger within a stilling well from October 2000 to October 2001. During this period, the annual spring discharge was 1,100,000 m^3/year (900 acre-feet/year). Correlation of a peak in the spring discharge with an isolated precipitation event revealed a response time of 5 days, suggesting a rapid connection between the surface water and the spring discharge. The water temperature, ion chemistry and tritium concentration all indicate the spring has a shallow circulation pattern and a short residence time. Hence the spring is not representative of a deep, regional aquifer system within the Madison aquifer, and the depth to the regional saturated zone is unknown. The City should not drill a production well without further investigation of the depth to the saturated zone. By drilling a test well, the depth to saturation, well yield and subsurface geology could be determined. This is recommended if the City chooses to pursue the development of groundwater resources in the Sourdough Creek drainage. Other options for water development include the prevention of stream losses in order to provide a net gain to Sourdough Creek, and an assessment of the Madison aquifer in the Hyalite Creek drainage.

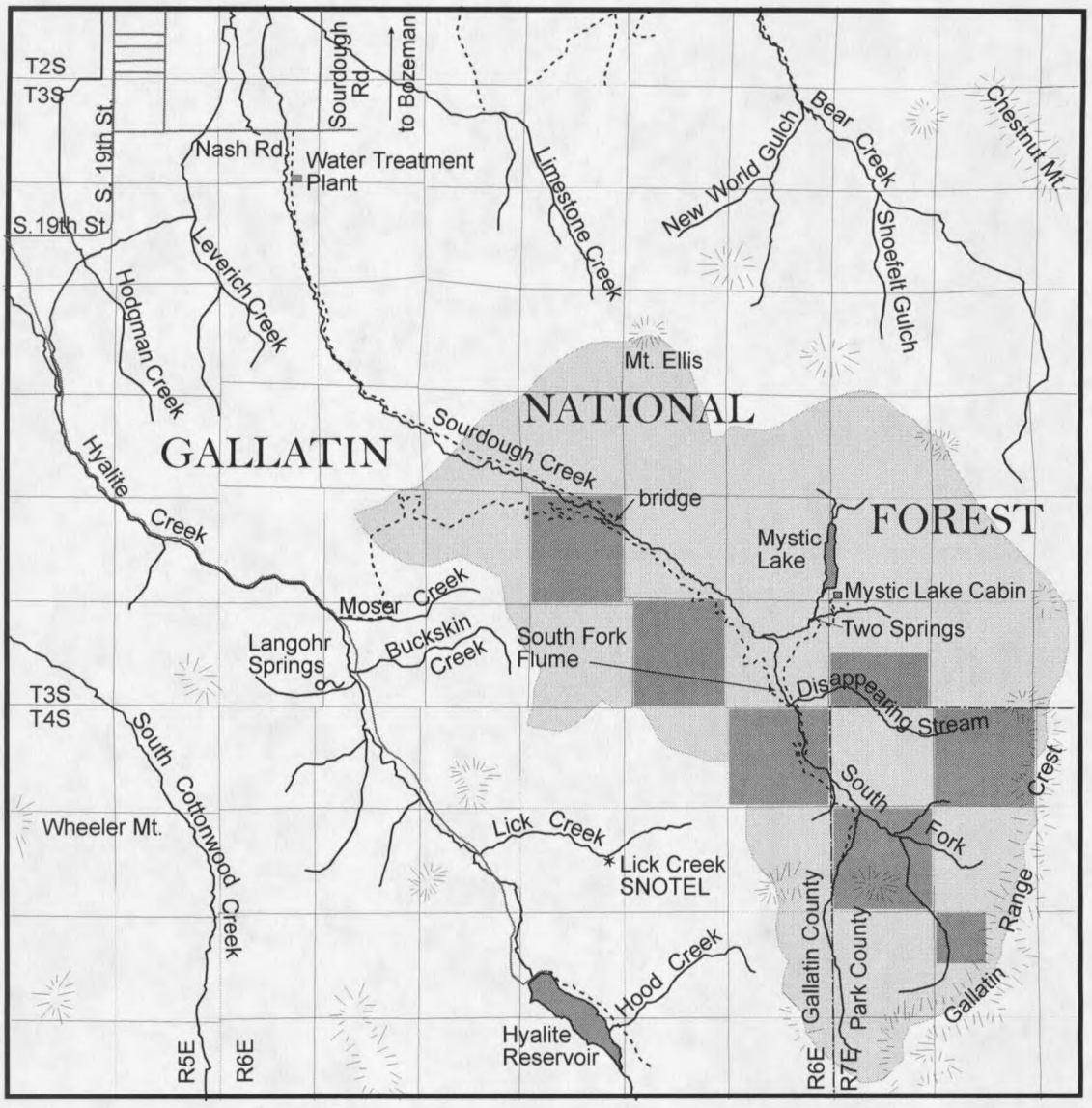
INTRODUCTION

Problem

The City of Bozeman, Montana is seeking an additional source of municipal drinking water to meet the needs of its growing population. Water supply wells in the Madison aquifer in the northern Gallatin Range near Sourdough Creek may provide a viable groundwater source of drinking water for the City, but the aquifer potential has not yet been studied.

Bozeman receives its drinking water from three sources: Sourdough Creek, Hyalite Creek and Lyman Creek. Until the early 1980s water from Sourdough Creek had been stored behind the Mystic Lake Dam (Fig. 1-1). In 1984 – 1985 the Mystic Lake Dam was intentionally breached due to concerns over the dam's integrity. With the loss of the Mystic Lake Dam, the City lost the ability to store approximately 7,400,000 cubic meters (6,000 acre-feet) of water (URS Greiner Woodward Clyde, 1999).

The estimated safe yield of the City's current water supplies is 13,3000,000 cubic meters per year (10,795 acre-feet per year), not including Mystic Lake (URS Greiner Woodward Clyde, 1999). Based on an estimated water use of 200 gallons per day per capita, Bozeman's current water supply can meet the needs of 48,000 people (URS Greiner Woodward Clyde, 1999). Depending on the rate of population growth in Bozeman, it is predicted that the City will need to expand its water supply in as little as 20 years.



Map Source:
USGS 7.5 minute series
Wheeler Mt. Quadrangle, 1987
Mt. Ellis Quadrangle, 1987
Mt. Blackmore Quadrangle, 1988
Fridley Peak Quadrangle, 1988

Figure 1. The study area.

Although it may be 20 years before Bozeman needs an additional source of water, it is prudent that a thorough search for the best alternative begin well in advance of the need. Most water development projects take 20 years or more from conception to completion. By allowing ample time for planning, there will be time to investigate all of the available options, make a well-informed decision, acquire land and water rights, and construct the infrastructure necessary for an expansion of the public water supply. This proactive planning should save money for the city and will avoid the need for crisis management should the problem be left unanswered. This research on the Madison aquifer potential is a preliminary step in the important process of assessing Bozeman's water supply options.

Background

In June 1999 the Bozeman Broad Spectrum Task Force issued recommendations to the Bozeman City Commission regarding Bozeman's future water needs. The task force recommended that the potential use of groundwater as a water supply "warrants immediate investigation and action" (Bozeman Broad Spectrum Task Force, 1999). Specifically, the Task Force recommended the following specific goals regarding the Madison aquifer.

- Determine water yield potential of the Madison aquifer.
- Determine water storage potential of the Madison aquifer (Bozeman Broad Spectrum Task Force, 1999).

A report submitted to the City by URS Greiner Woodward Clyde in January 1999 investigated the feasibility of building another dam in Sourdough Canyon. However, there are several concerns associated with the construction of a new dam. According to the URS

Greiner Woodward Clyde report, there are seven threatened or endangered animal species that may be present in the area. These species are the bald eagle, American peregrine falcon, grizzly bear, gray wolf, lynx, fluvial Montana arctic grayling, and the western toad (URS Greiner Woodward Clyde, 1999). There are also 35 species that may occur in the area that are listed as Montana threatened, endangered or of special concern (URS Greiner Woodward Clyde, 1999). Another concern regarding the construction of a reservoir is the loss of recreational areas for hiking, horseback riding, fishing, biking, ski touring and hunting. Due to these environmental and recreational concerns, other options for a water supply should be investigated before plans for a new dam are pursued.

URS Greiner Woodward Clyde (1999) found that the development of the Madison aquifer as a water supply "merits future evaluation due to its use in other areas as a groundwater resource and [its] proximity to the Sourdough Creek drainage" (URS Greiner Woodward Clyde, 1999). Several recommendations for further investigation were put forth in the report, including, "detailed geologic field characterization and mapping of outcrops of the Madison Formation should be performed in the Mystic Lake area to provide further information on structural, stratigraphic, and secondary porosity characteristics of the formation" (URS Greiner Woodward Clyde, 1999).

This study assesses the groundwater potential of the Madison aquifer in the Sourdough Creek watershed (Figure 1-1). This drainage area was selected because it contains large exposures of the Madison Group which may serve as recharge areas for the aquifer, because Bozeman's water treatment facility is at the base of Sourdough Canyon, and because the ideal water source would be located proximal to and uphill from the water

treatment plant to minimize conveyance losses and to avoid the need to pump the water uphill to the city.

Goals and Objectives

This research addresses several questions that are listed below.

1. Is the karst porosity and permeability that has been documented in the Mission Canyon Formation near Livingston present in the Sourdough Creek watershed?
2. Is there dolomite porosity and permeability in the Madison Group rocks in the Sourdough Creek watershed?
3. Do streams recharge the Madison aquifer in the study area? If so, at what rate? Are the springs ephemeral or perennial?
4. Does the Madison aquifer discharge into springs and streams in Sourdough Canyon? If so, at what rate?
5. Do fold-axis fractures or faults affect recharge potential, direct or control the groundwater flow, or control the locations of springs?
6. Is the water quality from the Madison aquifer suitable as a raw drinking water source?
7. Can suitable locations for drilling a test well be determined?
8. Are there known water rights issues pertaining to large-scale use of Madison aquifer water in Montana?

Anticipated Outcomes

There are several anticipated outcomes that arise from the questions above.

1. Karst features are present and do allow rapid transmission and storage of groundwater.
2. Dolomite porosity is present in the Mission Canyon Formation of the Madison Group and represents storage capacity.
3. Streams recharge the Madison aquifer.
4. Springs discharge the Madison aquifer, especially along faults and at the contact between the Madison Group rocks and underlying formations.
5. Additional recharge and discharge areas exist along fracture zones at the crest of anticlines.
6. Water from springs discharging the Madison aquifer may be high in hardness and sulfate, but the water quality will be acceptable for a raw water source for a public drinking water supply.
7. There are suitable locations for drilling a test well in the Madison aquifer in Sourdough Canyon.
8. Water rights issues have been encountered for other large-scale users of Madison aquifer water, and water rights must be considered before Bozeman pursues groundwater development in Sourdough Canyon.

Previous Work

Regional Stratigraphy of the Madison Group

The Mississippian Madison Group rocks are cyclically deposited, fine to medium grained limestones and dolomites with evaporite units. The Madison Group is made up of three formations, the basal Lodgepole Limestone, the Mission Canyon Formation, and the Charles Formation. The Lodgepole Limestone is further subdivided into the Paine Shale and the Woodhurst Limestone. The Mission Canyon Formation has been divided into an upper and lower member. The Charles Formation consists largely of evaporite rocks and is often not present at the surface, presumably due to dissolution of the evaporites. The Charles Formation is present in the subsurface of the Williston Basin (Aram, 1981).

The thickness of the Madison Group rocks ranges from 210 meters (700 feet) in the Bighorn Mountains, to 610 meters (2000 feet) in the Williston Basin (Miller, 1976). The depth of the formation ranges from surface outcrops in mountainous regions, to 3000 meters (10,000 feet) along the Montana – Wyoming border (Miller, 1976). Madison Group rocks lie conformably over the upper Devonian to lower Mississippian Sappington Formation. The uppermost unit of the Sappington Formation is the Bakken shale, which is an organically rich, black shale and is a confining layer below the Madison aquifer. The Bakken Shale also is the source of much of the petroleum and natural gas found within the Madison aquifer (Downey, 1984). Within the study area, the Sappington Formation was not recognized by Roberts (1964) and the Madison Group directly overlies the Three Forks Formation, which is comprised of shale and fine-grained limestone and also acts as a confining layer. The rocks of the Madison Group are overlain uncomformably by the upper Mississippian Big Snowy Group or the lower Pennsylvanian Amsden Formation, both of

which are confining layers. Where present, the uppermost member of the Madison Group, the Charles Formation, can act as a confining layer as well.

Local Stratigraphy of the Madison Group

The rocks in the Madison Group near Livingston, Montana were studied by Roberts (1966). The unit was measured to be 346 meters (1,136 feet) thick and is divided into two formations, the Lodgepole Limestone and the Mission Canyon Limestone (Figure 1-2; Roberts, 1966). The Lodgepole Limestone consists of the Paine Shale Member and the Woodhurst Limestone Member. The Paine Shale is 102 meters (334 feet) thick and is generally limestone and dolomite but contains some silty units. The Woodhurst Limestone is 45 meters (146 feet) thick and is comprised of thin-bedded limestone and dolomite (Roberts, 1966). The Mission Canyon Limestone is further subdivided into a lower and upper member. The lower member is 100 meters (330 feet) thick and consists of massive, medium to fine grained limestone and dolomite. The upper member of the Mission Canyon Limestone is 99 meters (326 feet) thick and is comprised of finely crystalline limestone and dolomite interbedded with dolomitic solution-breccia (Roberts, 1966). The Charles Formation is comprised primarily of evaporite deposits and is typically absent at the surface. In some localities, a solution breccia is present in the same stratigraphic position as the Charles Formation.

The limestone units of the Madison Group were described as massive or thickly bedded with some fossils and fossil debris. Oolites and pelletal material are minor constituents and a small percentage of the rock is comprised of clastic material. The dolomite units are either fine-grained or medium-grained and are a product of recrystallization of limestone. Roberts (1966) observed that the limestone units are resistant

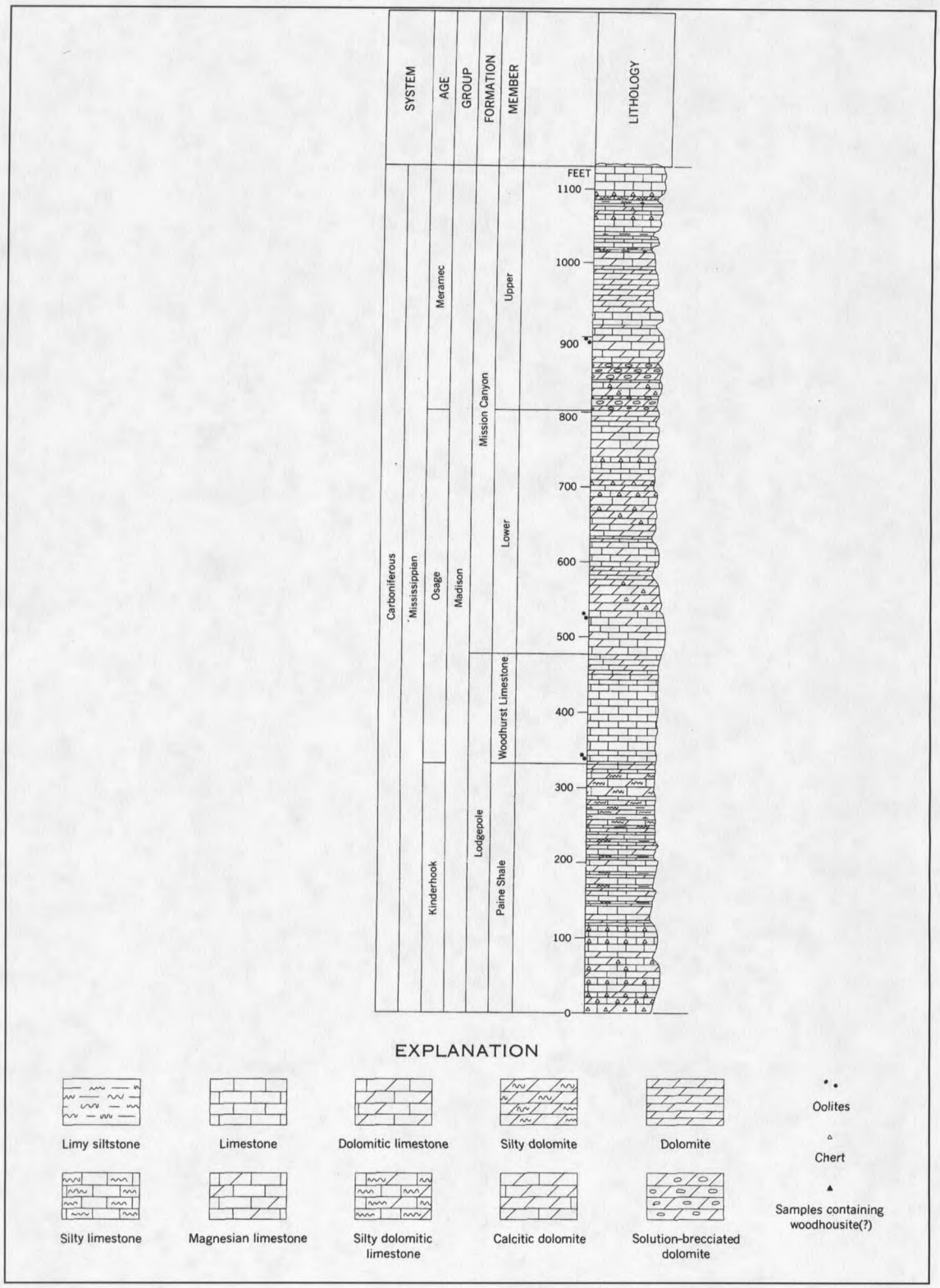


Figure 1-2. Stratigraphic column of the Madison Group, from Roberts (1966).

to erosion and form cliffs and ridges while the dolomites weather more rapidly and create indentations in the profile of the outcrop.

Tectonic Setting for the Deposition of the Madison Group

During the Antler Orogeny in late Devonian and early Mississippian time, a volcanic arc was converging with western North America (Reid and Dorobek, 1989). This created a foreland basin east of the orogenic zone. The foredeep was located in east-central Idaho, and an extension of the foredeep extended into western and central Montana. On the eastern margin of the foredeep, a broad shallow platform developed. The North American continent was positioned so the paleoequator was 5 to 10 degrees south of Montana, thus the area experienced a warm climate. This combination of shallow water and warm climate set the stage for carbonate deposition of the Madison Group rocks (Reid and Dorobek, 1989).

Depositional History

The rocks within the Madison Group were deposited in the Madison Sea during the late Mississippian period (Reid and Dorobek, 1989). Cyclical beds of limestone, dolomite and evaporites represent alternating environments of deep marine and shallow marine, restricted circulation environments. The Antler foreland basin filled with thick deposits of siliciclastic sediments eroding from the Antler highlands, but the western part of the basin was dominated by carbonate deposition. The Lodgepole Limestone was deposited in a subtidal environment on the carbonate ramp (Reid and Dorobek, 1989). This produced thin-bedded, fine to coarse grained, fossiliferous limestones with occasional silty horizons.

The Mission Canyon Formation was deposited conformably above the Lodgepole Limestone in a shallow subtidal to peritidal environment. This setting allowed for subaerial exposure and the precipitation of evaporite minerals (Reid and Dorobek, 1989). Many of the parasequences show a shallowing-upward trend and there is evidence for subaerial exposure during deposition, such as desiccation features, pseudomorphs after evaporite minerals, vadose diagenetic fabrics and crytpalgal laminae. The subaerial exposure was caused by aggradation of the platform deposits and relative drops in sea level (Reid and Dorobek, 1989). These parasequences are regionally correlated. The top of the Mission Canyon Formation represents a regional unconformity that spanned 9 to 14 million years of subaerial exposure (Reid and Dorobek, 1989).

The depositional setting of the Mission Canyon Formation was a gradual inundation of the Wyoming shelf to create a broad and shallow sea (Vice and Utgaard, 1989). Individual microfacies in the Mission Canyon Formation were examined in the northern Bighorn Basin region of Montana and Wyoming, and evidence of subaerial exposure was recognized. Evidence of desiccation and a hypersaline environment include sparse biota with low diversity, bird's eye limestone structures, pseudomorphs after evaporite minerals and cryptalgal laminae. These features were characteristic of supratidal and upper intertidal zones. The hypersaline environment in the supratidal zones on the edge of the platform allowed for precipitation of evaporite facies such as gypsum and anhydrite. These units may become dissolved, leaving large secondary pore spaces. If the voids are large enough, collapse breccias may form (Vice and Utgaard, 1989).

Development of Solution Breccias and Karst Features

The Madison Group is often characterized by the presence of solution breccias and karst features (Sando, 1988). The majority of these features are near the top of the Mission Canyon Formation and its stratigraphic equivalents. The development of these secondary pore spaces has created large voids within the rock, and has increased the permeability of the formation in some cases. There have been at least two episodes of karst development in the Mission Canyon Formation (Sando, 1988). The depositional and post-depositional history of the Mission Canyon Formation has contributed to the formation of karst features and solution breccias and will be discussed below.

Paleokarst. Deposition of Madison sediments ceased during early Meramecian time in the mid-Mississippian (about 345 m.y. BP). The craton was uplifted and sea level fell (Gutschick et al., 1980). The Madison shelf became exposed and was subject to subaerial weathering and the development of karst (Sando, 1988, Roberts, 1966). Many of these caves subsequently collapsed or filled with sediments as the overlying formations were being deposited. Beginning in late Meramecian time the Amsden-Big Snowy transgression began and the Darwin Sandstone member of the Amsden Formation was deposited from west to east in Wyoming. In southwestern Montana the Kibbey Formation of the Big Snowy Group was deposited instead of the Darwin Sandstone. The Kibbey Formation consists of red shale, siltstone, fine sand and small amounts of evaporites. The transgression proceeded from west to east, thus the western portions of the Madison shelf were exposed for a shorter length of time than the areas to the east. It has been estimated that the Madison shelf was exposed for between 9 and 34 million years (Reid and Dorobeck, 1989, Sando, 1988). Sando

(1988) concluded that the karst developed before the deposition of the Amsden Formation because many of the karst features are filled with deposits from the Amsden Formation. These karst fillings appeared to have been deposited as unconsolidated sediments rather than fragments of the overlying formations that collapsed after deposition. The maximum depth of this paleokarst is 60 to 105 meters (200 to 350 feet) below the top of the Mission Canyon Formation (Aram, 1981, Sando, 1988).

Four types of paleokarst features that have been described by Sando (1988) in north-central Wyoming. These are enlarged joints, sinkholes, caves and evaporite solution zones. The enlarged joints are either perpendicular or parallel to the bedding planes and can be up to one foot wide. Enlarged joints are most common in the uppermost 28 meters (93 feet) of the Mission Canyon (or Bull Ridge Member). The enlarged joints were formed by meteoric water passing through fractures in the rock when the Madison was exposed above sea level. Sediments from the Darwin Sandstone member of the Amsden Formation fill the enlarged joints (Sando, 1974).

Sinkholes have been observed in the upper Bull Ridge Member (Mission Canyon equivalent) in Wyoming and may be as much as 15 meters (50 feet) wide and 27 meters (90 feet) deep. The sinkholes have steep sides with nearly parallel walls. The sinkholes formed from solution by meteoric water along fractures. The primary filling of the sinkholes is sand that was deposited during deposition of the overlying Darwin Sandstone. Some of the filling is carbonate and chert breccia from the walls of the sinkholes (Sando, 1974).

Caves are described by Sando (1974) as irregularly shaped solution cavities and were most commonly observed in the Bull Ridge Member to a depth of 60 to 105 meters (200 to 350 feet) below the top of the Madison Group. Many of the caves are tubular and their

shape is strongly controlled by the bedding planes. The cave filling is similar to that found within the sinkholes. There are no flowstones or dripstones within the caves, which suggests that the caves were formed below the vadose zone (Sando, 1988). Some of these paleocaves may have been re-excavated during Tertiary and Holocene time (Sando, 1988).

Two prominent zones of leached evaporites occur in the Mission Canyon Formation in northern Wyoming and Southern Montana. The lithology is brecciated carbonate rock within a matrix of poorly bedded siltstone and shale (Sando, 1974). The origin of the solution zones has been debated in the literature. They have been interpreted as unconformities within the Madison Group (Strickland, 1960), collapse of karst (McCaleb and Wayhan, 1969), or as leaching and collapse of evaporite deposits (Roberts, 1966). The breccias may have formed during the post-Madison, pre-Amsden karst episode or during late Cretaceous or early Tertiary uplift (Sando, 1974).

Miller (1976) describes "lost circulation zones" recorded on drilling logs in the southern and central parts of Montana, indicating areas of high porosity which may be attributed to collapse or solution breccia or karst porosity. Solution breccia features are generally laterally continuous within the rocks and have a clearly defined lower surface and a poorly defined upper surface (Miller, 1976). A laterally continuous solution breccia marks the base of the upper member of the Mission Canyon Formation. Roberts (1966) describes this unit as containing "many cavities ranging from a few inches to several feet wide." This basal unit of solution breccia is observed in several localities where the rocks are exposed at the surface. Below the surface, a unit of anhydrite is present at the same stratigraphic position. Thus it is proposed that the solution breccia was formed by the dissolution of the anhydrite when the unit was exposed at the surface. In addition to the prominent solution

breccia at the base of the upper member of the Mission Canyon Formation, several other solution breccia units were reported by Roberts. Typically the units are from 5 to 6 feet thick (Roberts 1966).

In contrast to the solution zones discussed above, Roberts (1966) described the karst features as laterally discontinuous, with both the upper and lower surfaces poorly defined. Karst topography is present on the upper surfaces of the Mission Canyon Formation. Solution channels and collapsed cavities are filled with material from the overlying Amsden Formation as well as with reworked Mission Canyon Limestone (Roberts, 1966).

Clay mineralogy has also been used to attempt to determine the origins of collapse or solution breccias in the Madison Group. Roberts found that kaolinite was present in some breccias and illite was associated with others. The kaolinite was thought to be attributable to the formation of paleosol during the paleokarst episode, prior to the deposition of the Amsden Formation. Illite has marine origins and may have been derived from the overlying Amsden Formation. Thus the kaolinite-bearing deposits are thought to be representative of paleokarst features while the illite deposits are associated with the dissolution of evaporites (Roberts, 1966; Sando, 1974, Sando, 1988).

While the paleokarst features described in the Madison Group rocks have increased the formation's permeability somewhat, the post-Laramide karst and the Laramide or post-Laramide fracturing impart substantially greater permeability to the aquifer (Huntoon, 1985). This conclusion is based on observations that the paleokarst features are poorly interconnected and that the fillings of the paleokarst cavities are either fine-grained or well cemented. Moreover, springs discharging from paleokarst features have not been documented (Huntoon, 1985).

Post-Laramide Karst. Tectonic stresses during the Laramide Orogeny created faults, fractures and folds in the Madison Group rocks in western Montana and Wyoming. The secondary porosity created by the Laramide deformation of the rocks has allowed for infiltration of groundwater and channeling of water through the formation, thus increasing the permeability of the aquifer and promoting dissolution of the carbonates and the development of more recent karst features in the Madison aquifer. Huntoon (1993) attributes the largest permeabilities in the Madison aquifer to be associated with modern karst that has developed on the flanks of mountain ranges or with the extensional fractures along the crests of anticlines.

Lewis and Clark Caverns is an outstanding example of the development of post-Laramide karst within the Madison Group. Some of the large rooms in Lewis and Clark Caverns formed along the axis of an anticline, where fracturing was most prominent (Figure 1-3; Aram, 1981). The fractures allowed for high permeability and dissolution of the limestone along the hinge line. Fractures also weakened the ceilings of the rooms, causing boulders to fall from the ceiling. Faulting too, contributed to the development of the karst. Many of the cave passages have developed along intersections of bedding planes and faults (Aram, 1981).

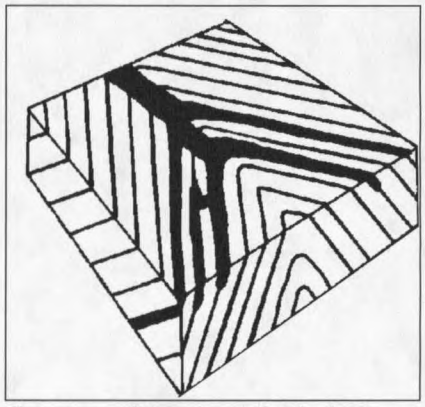


Figure 1-3. Schematic diagram of Lewis and Clark Caverns (from Aram, 1981).

Lewis and Clark Caverns developed within the Mission Canyon Formation, as is the case with most caves in Montana. The Mission Canyon Formation contains only 1 to 6% insoluble material, compared to up to 25% insoluble material in the Lodgepole Limestone (Aram, 1981). The thick beds of the Mission Canyon Formation also help to concentrate groundwater along the bedding planes, creating large conduits in thick beds where the limestone was removed by dissolution.

Regional Hydrology of the Madison Aquifer

Some authors consider the Madison aquifer to be comprised of the Mississippian Madison Group, the Ordovician Bighorn Dolomite and the Devonian Jefferson Dolomite, which are interconnected by fractures that cross-cut the formations (Huntoon, 1976). However, in this research, the Madison aquifer is considered only to be the Madison Group rocks with particular focus on the Mission Canyon Limestone because that is where the post-Laramide karst is most prevalent.

The Madison aquifer is part of the Northern Great Plains regional aquifer system (Figure 1-4). The U.S. Geological Survey has recognized five major subdivisions of the aquifer system. They are the Cambrian-Ordovician, the Madison, Pennsylvanian, Lower Cretaceous and Upper Cretaceous aquifers (Downey, 1984). Collectively, these aquifers make up one of the largest confined aquifer systems in the United States. Regional flow is generally from west to east, with recharge areas in the mountainous areas of Montana, Wyoming and western South Dakota, and discharge areas in the eastern Dakotas and Manitoba, Canada. The aerial extent of this aquifer system is 300,000 square miles (Downey, 1984).

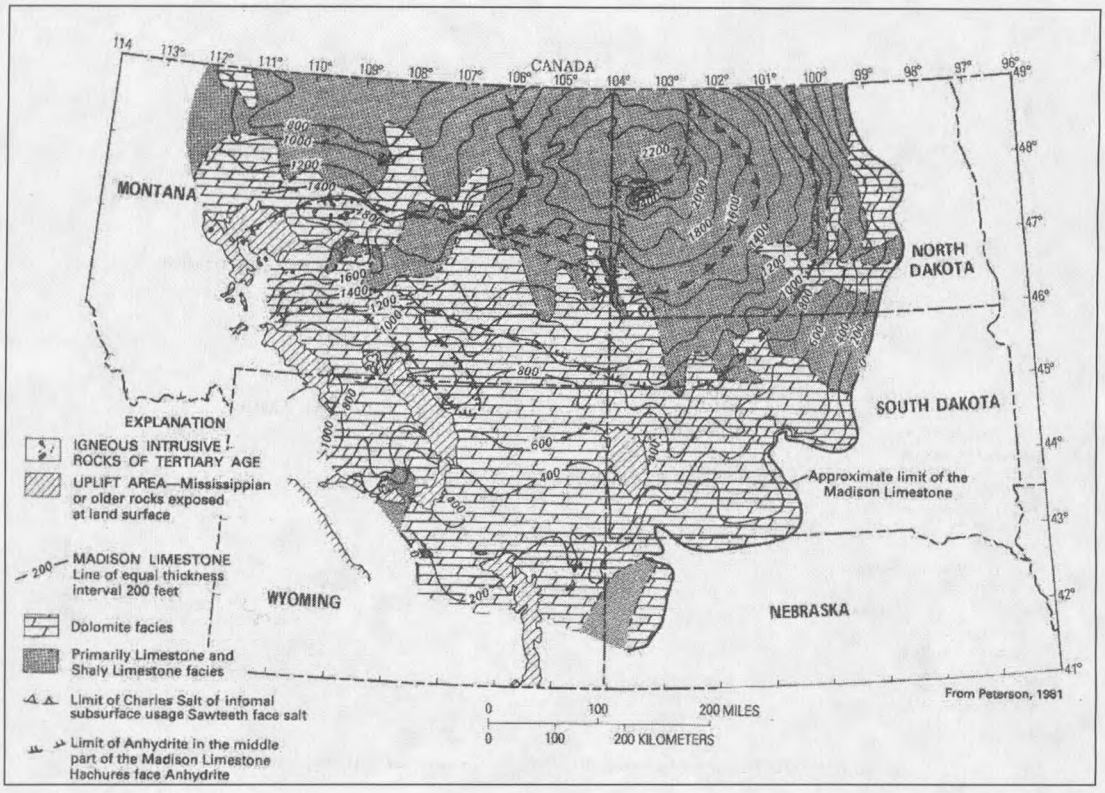


Figure 1-3. Thickness and lithology of the Madison aquifer in the Northern Great Plains (from Downey, 1984).

The hydrologic properties of the Madison Group rocks in southeastern Montana were studied by Miller in 1976. The purpose of this study was to assess the potential for using the Madison aquifer as a water supply for the processing of coal from the Fort Union coal beds in southeastern Montana. Miller reported four types of voids that create high porosity within Madison Group rocks.

1) Primary pores between individual grains.
2) Dolomite porosity caused by the diagenesis of limestone to dolomite, which decreases the rock volume and thus increases the pore volume.
3) Fracturing induced by folding or faulting.
4) Dissolution of carbonate or evaporite rocks.

Similarly, Huntoon (1985) lists the two important types of secondary porosities as (1) the enlargement of pore spaces through solution and (2) the fracturing along foreland basin perimeters associated with the uplift of the mountain ranges.

In most localities, water within the Madison aquifer was reported to be under artesian pressure, causing flowing wells in most areas of eastern Montana (Miller, 1976). The aquifer is unconfined in places where it outcrops on the surface. The potentiometric surface ranges from 300 meters (1,000 feet) above the land surface near the Yellowstone River, to 365 meters (1,200 feet) below the land surface in topographically high areas in southern Montana. Reported well yields range from 0.003 m^3/sec to 0.09 m^3/sec (50 gallons per minute to 1,400 gallons per minute) from a flowing artesian well on the flank of the Porcupine Dome. Transmissivities estimated from drill stem tests range from 500 m^2/day to 0.001 m^2/day (5,400 ft^3/day/ft to 0.01 ft^3/day/ft) (Miller, 1976).

Huntoon (1993) reports that the permeability of the Madison aquifer is not uniform throughout the uplifted mountain ranges and foreland basins of Wyoming. The greatest permeabilities were reported in the recharge areas near the flanks of mountain ranges. This permeability is due to the fracturing of the rocks associated with their uplift and to the development of post-Laramide karst in the exposed sections of Madison rock. Within the foreland basins, the permeability of the formation has been shown to decrease sharply due to recrystallization, cementation and compaction (Huntoon, 1985). Recharge water that enters the aquifer in the mountains has been observed to discharge from the aquifer at the toe of the range and does not enter the confined aquifer within the basin. Where the ranges are severed by faults at their margins, the faults do not allow for transmission of groundwater into the basin (Huntoon, 1993, Huntoon, 1985).

Groundwater circulation through karst is also discussed by Mills (1981). According to Mills, karst develops along fractures and bedding planes in foreland uplifts where the Madison aquifer outcrops and recharges. Groundwater flow is rapid and does not typically reach the basinal portion of the aquifer. Instead, most of the groundwater is discharged from springs that are commonly found at the lowest elevation of the Madison aquifer along the mountain front. Mills found that groundwater can travel more than 3 miles per day in these foreland karstic aquifers, with flow directions that are different from surface water drainage patterns. Discharge from karstic springs is continuous throughout the year but increases during the late spring and early summer as the snowpack melts. These flows can be large enough to sustain agricultural and municipal water users near the foreland ranges (Mills, 1981).

Recharge to the Madison Aquifer

Recharge for the Madison aquifer is provided by streams that cross the outcrop areas, and by infiltration within the interstream areas of the outcrops (Miller, 1976). Unknown amounts of recharge also occur from subsurface leakage from overlying and underlying formations or through fractures and faults. Discharge is via springs, gaining streams, leakage through adjacent formations, and pumping wells (Miller, 1976).

Feltis and Shields (1982) measured stream losses where selected streams cross the Madison Group rocks in the Little Belt and Big Snowy Mountains of Montana. They determined the amount of stream losses by establishing long-term gauging stations and also by doing instantaneous measurements during various times of the year. The study indicated that nearly every reach of stream that flowed across the Madison aquifer lost water. At several streams there was no flow at the downstream gauging station because all of the water

from the stream had drained into the Madison aquifer. Stream losses ranged from 0.22 m^3/sec (7.6 cfs) on the South Fork Judith River to as much as 1.8 m^3/sec (64 cfs) in Dry Wolf Creek. The stream losses were generally greatest in the spring (Feltis and Shields, 1982).

Stream loss was the major source of recharge to the Madison aquifer in the Black Hills of South Dakota (Greene, 1997). Stream losses were greatest in the spring, and there appeared to be a maximum, or 'cap' on the amount of stream loss that was associated with each of the streams measured. Even during times of peak stream discharge the stream losses did not exceed the maximum loss. Presumably this maximum loss is determined by the permeability of the aquifer. Isotopic analysis of hydrogen and oxygen was performed to trace the contributions from losing streams to discharge points such as wells and springs. This analysis indicated that there was significant lateral migration of groundwater beneath adjacent surface water drainage basins (Greene, 1997).

Sinking streams have also been documented by Huntoon (1985) along the eastern perimeter of the Bighorn Basin where streams flow from Precambrian highlands onto the Madison aquifer. This water discharges from the aquifer at the toe of the recharge area, via springs and gaining reaches of streams. Some of the water lost from the streams was found to migrate beneath topographic divides and discharge into streams in an adjacent drainage basin (Huntoon, 1985).

Study Area Description

General

The study area is the drainage basin of Sourdough Creek from the headwaters to a point approximately 8 km (5 miles) downstream from Mystic Lake (Figure 1-1). The study area covers approximately 40 square kilometers (25 square miles) and ranges in elevation from 1722 meters to 2664 meters (5650 feet to 8740 feet). The study area lies within the Gallatin National Forest, with 7 sections of land owned entirely or partially by the City of Bozeman (Figure 1-1). These are sections 27 and 35 in T3S, R6E; the southern half of section 31 in T3S, R7E; section 1 of T4S, R6E; sections 5, 7 and the NW ¼ of section 17 in T4S, R7E.

Hydrology

Three major streams flow within the study area. Sourdough Creek drains Mystic Lake near its headwaters and flows southwest for 1.6 km (1 mile) before bending to the northwest and flowing down Sourdough Canyon. Sourdough Creek is also called Bozeman Creek. The South Fork of Sourdough Creek drains the southern portion of the study area and joins Sourdough Creek 1.3 km (0.8 miles) downstream from Mystic Lake. The Disappearing Stream is a tributary to the South Fork of Sourdough Creek and generally flows only in its upstream portion; the downstream portion of the Disappearing Stream is dry.

A major spring is located in the study area, and has been named Two Springs (Figure 1-1). The springs are located on the southeast bank of Sourdough Creek, 0.6 km (0.35 miles)

downstream from Mystic Lake at an elevation of 1887 meters (6190 feet). Two Springs consists of two individual discharge points emanating from the Lodgepole Limestone. The two components of Two Springs have been named Upper Spring and Lower Spring.

Three minor springs were seen within the study area. There is a spring discharging from volcaniclastic landslide debris adjacent to Sourdough Creek approximately 130 meters (400 feet) upstream from Two Springs. There are two ephemeral springs along the South Fork, both of which appeared to be discharging from surficial deposits adjacent to the creek.

Geology

The geology of the study area consists primarily of folded Paleozoic and Mesozoic rocks (Roberts, 1964). The folds plunge gently to the southeast. A large anticline is located in the center of the study area, with the South Fork of Sourdough Creek flowing along its axis. Precambrian gneisses outcrop within the study area along Sourdough Creek approximately 1.6 km (1 mile) downstream from Mystic Lake. Eocene volcanic rocks overlie Mesozoic sedimentary rocks in the southeast portion of the study area, forming the high peaks of the Gallatin Range. Volcanic breccias and unconsolidated volcanic deposits overlie much of the area in the headwaters of the South Fork of Sourdough Creek. An extensive Quaternary landslide deposit forms the eastern edge of Mystic Lake. The original geologic mapping of the area was done by Roberts in 1958, and was published in 1964 as part of an 8-quadrangle study of the region.

METHODS

Forest Service Permits

The field research was conducted within the Gallatin National Forest and was authorized under Special Use Permit # BOZ5556. The permit granted permission to collect water and rock samples, and allowed for motorized use of Bozeman Creek Road on weekdays, prior to 4:00 pm. Motor vehicle use was not permitted during rifle hunting season or when the road was wet.

Geologic Mapping

Geologic field mapping was carried out in selected locations within the field area. This was done in order to provide structural data for the construction of geologic cross sections. Rock formations from the Precambrian through the Jurassic Ellis Group were mapped in a 15.5 square kilometer (6 square mile) area centered on the South Fork drainage. This area was selected because it had the largest extent of Madison Group exposures within the study area. Mapping was performed by identifying rock formations, locating contacts between rock units and measuring strike and dip angles. The stratigraphy and formation names from Roberts' 1964 map were used on the new geologic map created in this study. During the course of the mapping, information from 224 individual sites was recorded and 160 strike and dip measurements were taken. Aerial photos, topographic maps and a global positioning system unit were used to identify field locations. This work took place in June and July of 2001.

Thin Sections

Thin sections of rock samples from the Madison Group were examined to determine their lithology and porosity. A sample from the Mission Canyon Formation at Bozeman Pass was included to compare the rocks in the study area to the highly karstic rocks observed at Bozeman Pass. Eight samples from the Madison Group (5, 90, 93, 94, 95F, 95 NF, 103, 103B) were selected to represent a vertical section of the Madison Group, from the Lodgepole Limestone to the top of the Mission Canyon Formation. Samples 95 F and 95 NF were taken from the same outcrop, but unit 95 F was highly fractured, while unit 95 NF had only minor fracturing. Samples 103 and 103B were both collected from the upper Mission Canyon Formation, but sample 103 was slightly brecciated while 103 B was highly brecciated. A sample from the Lodgepole Limestone at Two Springs was also included to determine the porosity and lithology at the springs. For sample locations, please refer to Appendix A.

Thin sections from 10 different rock samples were prepared by Wagner Petrographic in Salt Lake City, UT. Each thin section was impregnated with blue epoxy to show the pore spaces within the rock. A red calcite stain and a blue iron/magnesium stain were applied to each sample to aid in mineral identification. The mineral content and the percentage of porosity of each sample were determined visually with a petrographic microscope.

Stream Discharge Measurements

The stream discharge of Sourdough Creek and the South Fork of Sourdough Creek was measured three times during the study. Stream discharge measurements were performed according to the velocity-area method (Dingman, 1994). Measurements were

taken using a Marsh-McBirney Flo-Mate Model 2000 portable flow meter with a top-setting wading rod. The criteria for selection of stream discharge measurement sites were safe access to the stream, a relatively straight reach of the stream with little observable backflow, and stream banks that were not undercut. The flow meter measured velocity readings averaged over a 30 second interval. The water velocity was measured at 0.6 of the total water depth, measured from the top of the water surface. Readings of depth and velocity were taken at horizontal intervals between 0.03 and 0.12 meters (0.1 and 0.4 feet). Readings were taken closer together in areas where the flow was faster or the water was deeper. Typically 30 to 60 readings were taken for each stream discharge measurement.

In order to determine the repeatability of manual stream flow measurements, three successive measurements were made in the same location on the same day. This was performed on October 17, 2000 at the South Fork of Sourdough Creek. The results of the reproducibility measurements are in Table 2-1. The measurement error was determined by dividing the standard deviation by the average, and multiplying by 100, yielding +/- 6.4 %.

Table 2-1. Stream discharge reproducibility measurements.

	Discharge (m^3/sec)
1st Measurement	0.065
2nd Measurement	0.060
3rd Measurement	0.057
Average	0.061
Standard Deviation	0.0039
Measurement Error = +/- 6.4%	

Stream Gain/Loss Measurements

One method to estimate recharge into the Madison aquifer is to measure stream losses. A stream loss is the amount of water that is being drained from a stream into its stream bed over a given reach. Where the stream channel is bedrock or covered by only a thin layer of alluvium, it is likely that the water lost from the stream is recharging the aquifer below. Stream losses are a common occurrence on the Madison aquifer and have been used as an estimate of recharge to the Madison aquifer by Feltis and Shields (1982) and Greene (1997).

There are three locations within the study area where streams flow across the Madison Group rocks: at Sourdough Creek, the South Fork and the Disappearing Stream. Stream losses were measured at two locations outside the study area, at Hyalite Creek and at Bear Creek (Figure 1-1).

Stream loss measurements on Sourdough Creek and the South Fork were made in July 2000, October 2000 and May 2001 in order to identify seasonal changes. The location where the creek flowed across the upper Mission Canyon Formation was located and a suitable stream gauging location was selected within 20 meters (65 feet) downstream from the contact. The stream discharge was measured. Working in a downstream direction, the discharge of each tributary to the creek was measured in a location slightly upstream from where the tributary joined the main creek. On Sourdough Creek the only tributary was Two Springs. On the South Fork there were two flowing tributaries and one dry tributary. The dry tributary was observed to be losing all of its water into the Madison Group rocks prior to flowing into the South Fork. The stream losses in this tributary were estimated by recording the time it took to fill a one-liter bottle because the channel was too small to be

measured by the velocity-area method. Lastly, a downstream discharge measurement was taken at the lower Lodgepole Limestone contact. The discharge measurement was taken at a suitable location slightly upstream from the contact, thus all discharge measurements were taken within the Madison Group. The downstream discharge measurement was subtracted from the sum of the upstream measurement plus the tributaries. The resulting number was the stream loss or gain.

In the case of the Disappearing Stream (Figure 1-1), the creek lost all of its water. Hence the stream loss measurement consisted only of the stream discharge at the upper Madison Formation contact. There were no tributaries to the Disappearing Stream. The location where the stream flow ceased was noted on a topographic map. The Disappearing Stream was measured in July 2000, August 2000, May 2001 and July 2001.

Bear Creek and Hyalite Creek, which are outside the study area, were also gauged. At Bear Creek the stream was measured at the upstream and downstream contacts of the Madison Group, and there were no tributaries along this reach. At Hyalite Creek, the discharge was measured at the upstream Madison contact and at the contact of the Madison Group and a large alluvial deposit. The downstream Madison contact could not be located because it was covered by the alluvial deposit. There were no tributaries along this reach.

Stream loss measurements typically took an entire day for each stream, during which evapotranspiration was also occurring. Evapotranspirative losses were estimated from a flume on the South Fork (Figure 1-1). The stage of the water in the flume was manually read in the morning and in the afternoon of each day of field work. This provided for an average stream loss during the day, presumably due to evapotranspiration.

Spring Location

Each of the major drainages within the study area was visited to check for the presence of springs discharging from Madison Group rocks. Possible locations for springs were in areas where the Madison Group outcropped at low elevations, such as along stream channels. These areas were checked by hiking the length of each of the stream channels that cross Madison Group rocks. The areas around faults mapped by Roberts (1964) were also checked for the presence of springs.

Spring Temperature Measurements

The water temperature of Two Springs was measured several times throughout the study. A VWR Scientific Digital Thermometer 500 was used for all the measurements. The measurements were made at the orifices of both the upper spring and the lower spring.

Spring Discharge Measurements

Manual Measurements

Two Springs discharges from two orifices, the Upper Spring and the Lower Spring. Water flows away from each spring as a small creek. The two creeks join and flow together for approximately 2 meters (6 feet), then discharge into Sourdough Creek. Measurements of the spring discharge were made at the point where the two spring creeks join. Spring discharge measurements were made several times throughout the study to determine the seasonal fluctuations in flow. The discharge measurements were performed as described previously. The ground around Two Springs was saturated and water was also discharging

from the springs directly into Sourdough Creek via shallow groundwater flow. This flow could not be measured and was not accounted for in the discharge measurements. Thus, the actual spring discharge is likely greater than the discharge measurements.

Data Logger Measurements

A stilling well and data logger were used to provide continuous measurements of the stage of Two Springs. The stilling well was located at the confluence of the two small creeks flowing from Upper and Lower Springs. A small hole was dug at the edge of the creek, and the stilling well was anchored within this hole. The stilling well consisted of a 3.2 cm (1.25 inch) diameter, schedule 40 PVC vertical pipe with a 1.3 cm (0.5 inch) diameter horizontal pipe attached to it (Figure 2-1). The horizontal pipe was perforated with 0.95 cm (3/8 inch) diameter holes to allow water to enter the pipe.

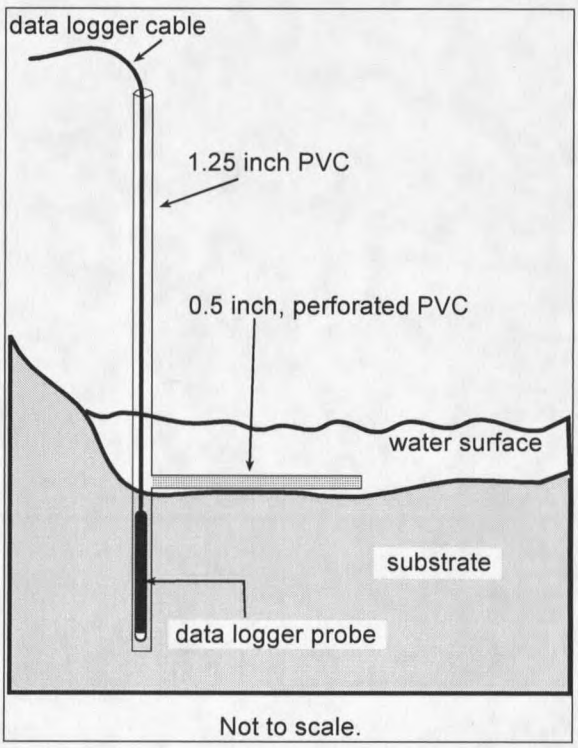


Figure 2-1. Stilling well schematic.

On July 27, 2000 the stilling well was installed at the confluence of the two discharge channels flowing from Two Springs. The horizontal pipe was positioned so that it lay on the bottom of the creek bed. A steel fencepost was driven into the ground adjacent to the stilling well and the stilling well was fixed to the fencepost with copper wire. A meter stick was attached to the stilling well to provide a means to read the stage of the creek manually.

On July 28, 2000 a Global Water WL-14 data logger was deployed inside the stilling well. The probe of the data logger was inserted into the stilling well so that it was below the bottom of the channel. The sampling interval was set so that the data logger took a water level reading every 15 minutes. Downloading the data logger proved to be problematic, so the data logger was removed for data retrieval on August 7, 2000. The data logger was reinstalled on August 21, 2000 and was set for a sampling interval of 20 minutes. The batteries failed on September 19, 2000 and a short circuit was suspected so the data logger was removed again and sent back to the manufacturer for service. On October 19, 2000 the data logger was reinstalled and was set for a one-hour sampling interval. The data logger remained in service for the duration of the project.

On October 10, 2001 the data logger was removed from the stilling well and the stilling well was dismantled. All components of the stilling well were removed so no visible impact remained at the spring.

Water Sampling

Major Ions

Samples were collected from Two Springs on April 29, 2001 and October 1, 2001 for analysis of calcium, magnesium, potassium, sodium, chloride, sulfate, bicarbonate, carbonate,

specific conductance, total dissolved solids and pH. A sample was taken from both the Upper Spring and the Lower Spring. The samples were collected in 500 ml polyethylene bottles with no filtering and no preservatives added, according to the protocol specified by Energy Laboratories, Inc. The samples were kept cold and shipped on ice to Energy Laboratories in Billings, MT within 24 hours of sample collection.

Tritium

Tritium is a radioactive isotope of hydrogen that decays at a known rate and thus can be used for dating water. Samples were collected from Two Springs on April 29, 2001 for analysis of tritium. One sample was obtained from the Upper Spring and one from the Lower Spring. Samples were collected in one-liter polyethylene bottles with no filtering and no preservatives added. The samples were obtained by holding the sample bottle directly under the spring discharge, as close to the orifice as possible. The sampler did not carry or wear a wristwatch or a compass with a luminescent dial, which can create artificially high tritium concentrations.

A sample of snow at Two Springs was also collected for tritium analysis, to provide a baseline tritium value for winter precipitation. A column of snow was cut from the wall of a snow pit to obtain a vertically integrated sample from the snow surface to the ground. The snow was placed in two one-gallon plastic bags for transportation. The following day, the melted snow was poured into a one-liter sample bottle. The transfer of snowmelt from the plastic bags to the bottle was done outdoors to prevent mixing with indoor air, which may have a higher tritium concentration due to the presence of luminescent dials. The sampling protocol was provided by the Tritium Laboratory at the University of Miami Rosenstiel

School. The samples were shipped via UPS within 24 hours of sample collection to the Tritium Laboratory at the University of Miami Rosenstiel School, where the analyses were performed on June 26, 2001.

Drinking Water Quality

Water samples for water quality analyses were collected from Two Springs on October 1, 2001. The sampling protocol recommended by Energy Laboratories, Inc. was followed and all sample bottles and preservatives were provided by the laboratory. All samples were collected from the lower spring of Two Springs.

One sample was collected in a 500 ml plastic bottle for analyses of potassium, sodium, calcium, magnesium, sulfate, chloride, total dissolved solids, alkalinity, conductivity, pH, nitrate plus nitrite, total iron, fluoride and turbidity. No preservatives were added to this sample. One sample was collected in a 250 ml plastic bottle for analysis of antimony, arsenic, barium, beryllium, cadmium, chromium, mercury, nickel, selenium, thallium, lead and copper. This sample was filtered with 0.45-micron filter paper and was preserved with nitric acid. One sample was collected for coliform bacteria analysis in a sterile container with powdered sodium thiosulfate that had been provided by the laboratory. All samples were packed in a cooler with ice and were shipped on October 1, 2001 via UPS to Energy Laboratories in Billings, Montana.

A water sample for cryptosporidia and giardia analysis was collected on October 10, 2001. The sample was collected from the upper spring of Two Springs in a 20-liter plastic jug. No preservatives were added. The water sample was delivered to Montana Microbiological Services in Bozeman, MT on the same day.

Water Rights

A survey of communities in Montana that use Madison aquifer water for their municipal water supplies was performed in April and May of 2001. Tom Patton, Director of the Groundwater Information Center of the Montana Bureau of Mines and Geology identified the known municipal users of Madison aquifer water within Montana. Telephone interviews were conducted with water system operators or City Clerks with knowledge of the community water system. The following issues were discussed with each person:

- Population served by the water supply
- Well depth
- Flow rate of well or spring
- Fluctuations in flow rate or water level
- General water quality and water treatment
- Water rights.

Water analysis reports were obtained from personnel at Giant Springs and Big Springs in order to provide a comparison of spring waters from the Madison aquifer.

Scott Compton, Regional Manager of the Montana Department of Natural Resources Conservation, was consulted regarding potential water rights conflicts if Madison aquifer water from the Sourdough drainage were used for the Bozeman public water supply.

RESULTS

Geologic Mapping

The geology of area around the Sourdough Creek anticline was mapped in order to observe the lithologic features of the Madison Group rocks, to gather structural data of the area, and to confirm or redraw the formation contacts on the existing geologic map by Roberts (1964). Plate 1 is a geologic map which integrates the results of the mapping. The primary area that was mapped was the drainage basin of the South Fork and the Disappearing Stream. This area was mapped because it contained the largest area of Madison Group bedrock on Roberts' map, because Roberts' map provided few strikes and dips, and because the contacts for the Madison Group were believed to potentially be inaccurate. A table of all data compiled during geologic mapping is presented in Appendix A.

Outcrop exposure in the study area was generally poor. There is extensive tree cover and colluvial cover over most of the study area, making it difficult to find outcrops. Near the headwaters of the South Fork, surficial deposits cover the bedrock. These factors made it difficult to trace the contacts over long distances. Thus, the contacts are dashed where their locations are uncertain.

Thin Sections

Thin sections of rock samples from the Madison Group were examined to determine their lithology and porosity. Rock samples were selected to represent a vertical section of the Madison Group. A sample from the Lodgepole Limestone at Two Springs was selected

to determine the porosity and lithology at the springs. One sample from the Mission Canyon Formation at Bozeman Pass was also included to provide a comparison to the rocks in the study area. For sample locations, please refer to Appendix A.

Two types of porosity were recorded for each sample (Table 3-1). Dolomite porosity was characterized by intercrystalline pore spaces with angular boundaries. Fractures were linear voids that cut across many grains. The small scale of the thin sections precluded the measurement of large-scale fracturing. Thus the thin sections were primarily used to measure dolomite porosity, while visual estimates of the fracture intensity were made on the outcrops.

Table 3-1. Comparison of lithology and porosity from thin sections.

Sample Location	Formation	% Calcite	% Dolomite	% Other	% Dolomite Porosity	% Fracture Porosity	% Total Porosity
Bozeman Pass	Mission Canyon	15	85	0	5	2	7
Two Springs	Lodgepole	39	60	1 (clay)	0	0	0
5	Lodgepole	50	50	0	0	0	0
90	Mission Canyon	5	94	1 (clay)	7	1	8
93	Mission Canyon	0	95	5 (quartz)	1	0	0
94	Mission Canyon	0	100	0	2	3	5
95 F (fractured)	Mission Canyon	0	100	0	2	15	17
95 NF (not fractured)	Mission Canyon	0	100	0	1	0	1
103	Mission Canyon	0	99	1 (quartz)	1	5	6
103 B (breccia)	Mission Canyon	0	75	25 (quartz)	0	1	1

Stream Gains and Losses

Stream discharges were measured where streams flow across the Madison Group in order to determine whether the streams were gaining water from the Madison aquifer or losing water to the Madison aquifer. This helped define areas where groundwater was recharging to or discharging from the aquifer. These measurements were performed on Sourdough Creek, the South Fork, the Disappearing Stream, Hyalite Creek and Bear Creek. Figure 3-1 shows the locations of the stream discharge measurements.

Sourdough Creek

Sourdough Creek was gauged at the upstream and downstream Madison contacts. Two Springs flows into Sourdough Creek between these measuring points, so the discharge of Two Springs was gauged as well. The results of the stream discharge measurements for Sourdough Creek are given in Table 3-2 below. Spreadsheet calculations for each stream discharge measurement are provided in Appendix B.

Table 3-2. Sourdough Creek stream losses.

Date	Upstream Madison Contact (m^3/sec)	Two Springs (m^3/sec)	Downstream Madison Contact (m^3/sec)	Stream Loss		
				(m^3/sec)	(cfs)	%
July 11, 2000	0.16	0.09	0.22	0.03	1.2	13.9
Oct. 10, 2000	0.14	0.02	0.09	0.07	2.3	40.3
May 23, 2001	0.37	0.10	0.43	0.04	1.5	9.0

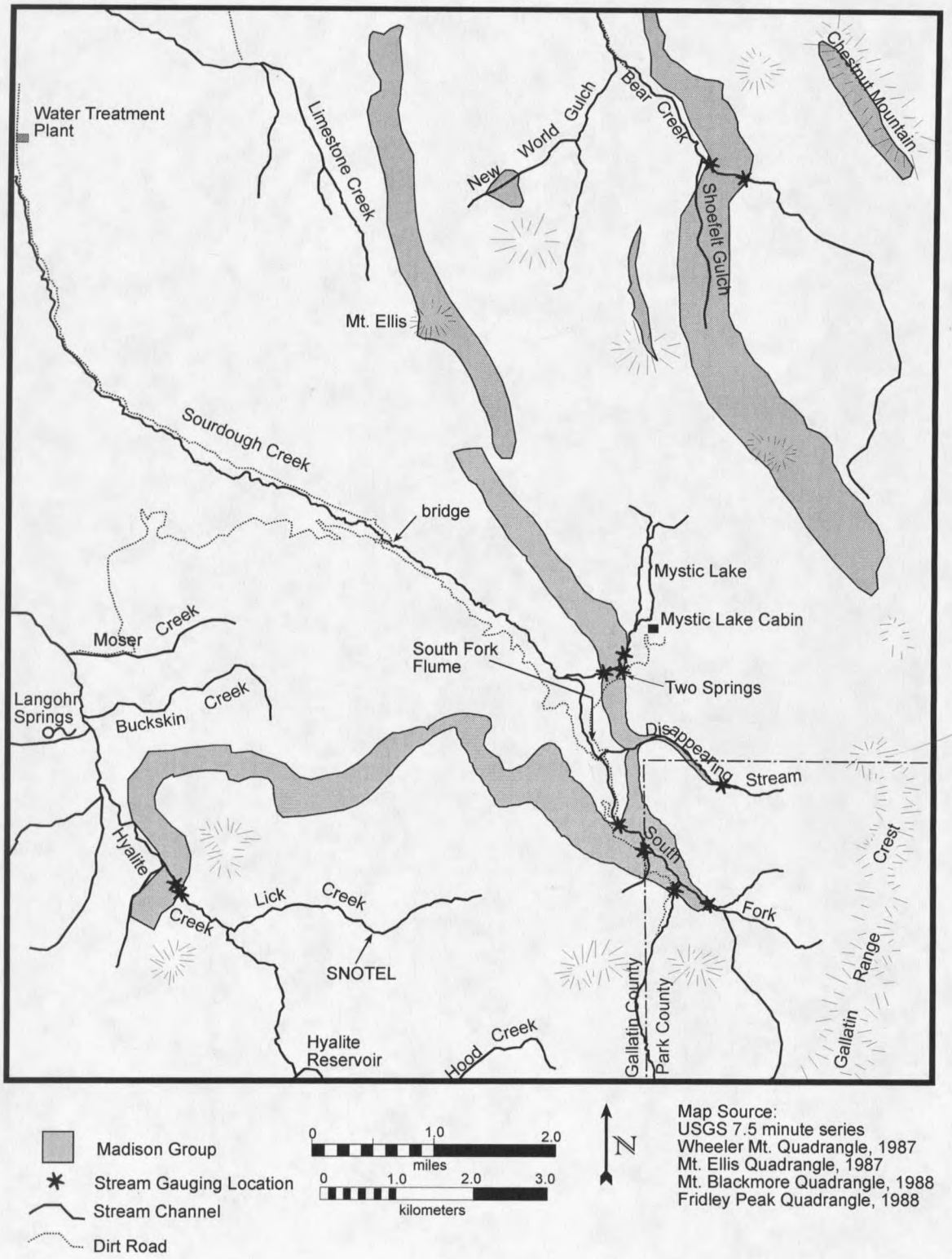


Figure 3-1. Locations of stream discharge measurements.

The South Fork

The stream discharge of the South Fork was measured at the upstream and downstream Madison contacts. The discharges of two tributary streams were also measured. The results from the stream discharge measurements are shown in Table 3-3. During the May 2001 stream discharge measurements, two ephemeral springs were found discharging near the banks of the South Fork. The combined discharge of these springs was estimated to be 0.02 m^3/sec. One of the tributaries to the South Fork was dry where the tributary flowed into the South Fork, but it was flowing at the upstream Madison contact. The estimated discharge of this tributary was 0.0003 m^3/sec (0.01 cfs). These numbers are not reflected in the stream losses in Table 3-3.

Table 3-3. South Fork stream losses.

Date	Upstream Madison Contact (m^3/sec)	First Tributary (m^3/sec)	Second Tributary (m^3/sec)	Downstream Madison Contact (m^3/sec)	Stream Loss		
					(m^3/sec)	(cfs)	%
July 14, 2000	0.06	0.07	0.01	0.13	0.01	0.4	7.8
Oct. 3, 2000	0.03	0.04	0.002	0.06	0.01	0.6	21.1
May 25, 2001	0.13	0.12	0.01	0.25	0.01	0.5	5.8

The Disappearing Stream

The results for the stream discharge measurements on the Disappearing Stream are shown in Table 3-4. The Disappearing Stream lost all of its water as it flowed across the Madison Group rocks, so the stream discharge at the upstream measuring point was equal to the stream loss.

Table 3-4. Disappearing Stream losses.

Date	Upstream Madison Contact (m^3/sec)	Downstream Madison Contact (m^3/sec)	Stream Loss		
			(m^3/sec)	(cfs)	%
July 25, 2000	0.03	0	0.03	1.0	100
Aug. 18, 2000	0.02	0	0.02	0.6	100
May 31, 2001	0.06	0	0.06	2.0	100
July 19, 2001	0.03	0	0.03	1.1	100

Bear Creek

The discharge of Bear Creek was measured at the upstream and downstream contacts of the Madison Group. In this location Bear Creek intersects the Madison Group at the crest of the Bear Creek anticline, so both of the Madison contacts are the upper Madison contact. The results of stream gauging are shown in Table 3-5 below.

Table 3-5. Bear Creek stream discharges.

Upstream Madison Contact (m^3/sec)	Downstream Madison Contact (m^3/sec)	Stream Loss		
		(m^3/sec)	(cfs)	%
0.044	0.037	0.007	0.24	15.3

Hyalite Creek

The discharge of Hyalite Creek was measured at the upper Madison contact, but the lower Madison contact was obscured by a large alluvial deposit. Therefore the downstream

gauging point was not the lower Madison contact, rather it was the point at which the Madison became covered by alluvium. Table 3-6 provides the stream discharge results for Hyalite Creek.

Table 3-6. Hyalite Creek stream discharges.

Upstream Madison Contact (m^3/sec)	Downstream Gauging Location (m^3/sec)	Stream Gain		
		(m^3/sec)	(cfs)	%
0.78	0.82	0.04	1.4	5.0

Spring Discharge

The discharge of Two Springs was determined by manual discharge measurements as well as by stage recordings with a data logger. The results yielded by each method are given separately.

Manual Measurement of Spring Discharge and Water Temperature

When Two Springs was visited during field work, the spring discharge was measured manually, the water temperature was measured and the stage was recorded. The stage was determined with a meter stick attached to the outside of the stilling well. The ruler was positioned so that the 14 cm mark was at the bottom of the channel. Thus a ruler stage of 14 cm would represent zero discharge. The results of these measurements are given in Table 3-7 below.

Table 3-7. Summary of measured discharge, stage and temperature at Two Springs.

Date	Discharge		Ruler Stage (cm)	Temp. (C)
	(m^3/sec)	(cfs)		
11-Jul-00	0.09	3.1	NM	NM
18-Jul-00	0.06	2.2	NM	NM
28-Jul-00	0.04	1.3	20	4.4
7-Aug-00	0.04	1.4	18.75	4.5
21-Aug-00	0.03	1.2	18.5	4.5
10-Oct-00	0.02	0.8	18	4.3
29-Apr-01	NM	NM	21.75	3.4
23-May-01	0.10	3.6	22.25	3.4
24-Jul-01	0.05	1.9	19.5	4.3
01-Oct. 01	0.02	0.8	17.5	4.4
10-Oct-01	NM	NM	17.2	4.3

NM – Not measured.

Data Logger Stage Measurements

A data logger was installed at Two Springs to provide a continuous record of the stage of the springs. The data logger record begins in July 2000 and goes through October 2001, with two gaps in the data due to equipment malfunctions. The stage measurements as recorded by the data logger are plotted in Figure 3-2. The average discharge from Two Springs between October 2000 and October 2001 was 0.035 m^3/sec (1.23 cfs), and the total discharge over that same period was 1,100,000 m^3/yr (900 acre-feet/yr). The complete data set is provided in Appendix C.

Comparison of Stage Measurements with Weather

Data from a SNOTEL site located near Lick Creek was used to provide daily precipitation and average daily temperature in the area (http://mt.nrcs.usda.gov/swcs/snow/table_mt.html). This allowed for the correlation of changes in the spring stage with local weather events. The Lick Creek SNOTEL site is approximately 5 km (3 miles) from Two Springs and is shown on Figure 3-1. The Lick Creek site is at an elevation of 2090 meters (6860 feet), while Two Springs is at an elevation of 1890 meters (6190 feet). Due to the proximity of the SNOTEL site to the springs, it is reasonable to assume that the temperature and precipitation of the SNOTEL site are similar to the conditions experienced at Two Springs. Temperature and precipitation at Lick Creek are plotted in Figure 3-3, and the complete data set is provided in Appendix D.

Spring Water Chemistry

Major Ions

Water from Two Springs was sampled for major ion analysis during the spring and fall of 2001. The results from these analyses are summarized in Table 3-8. Laboratory analytical reports can be found in Appendix E.

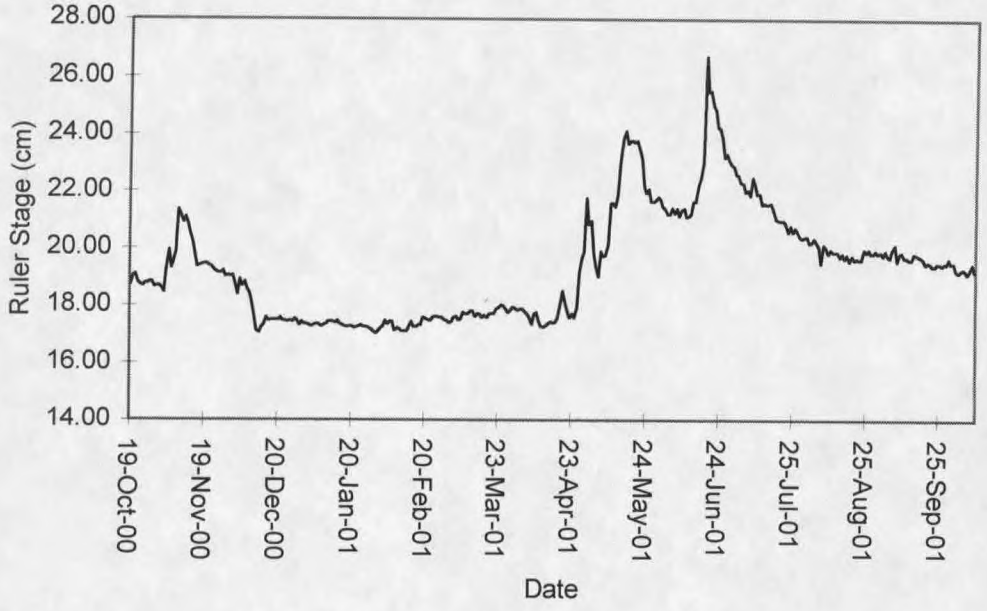


Figure 3-2. Stage of Two Springs as recorded by data logger.

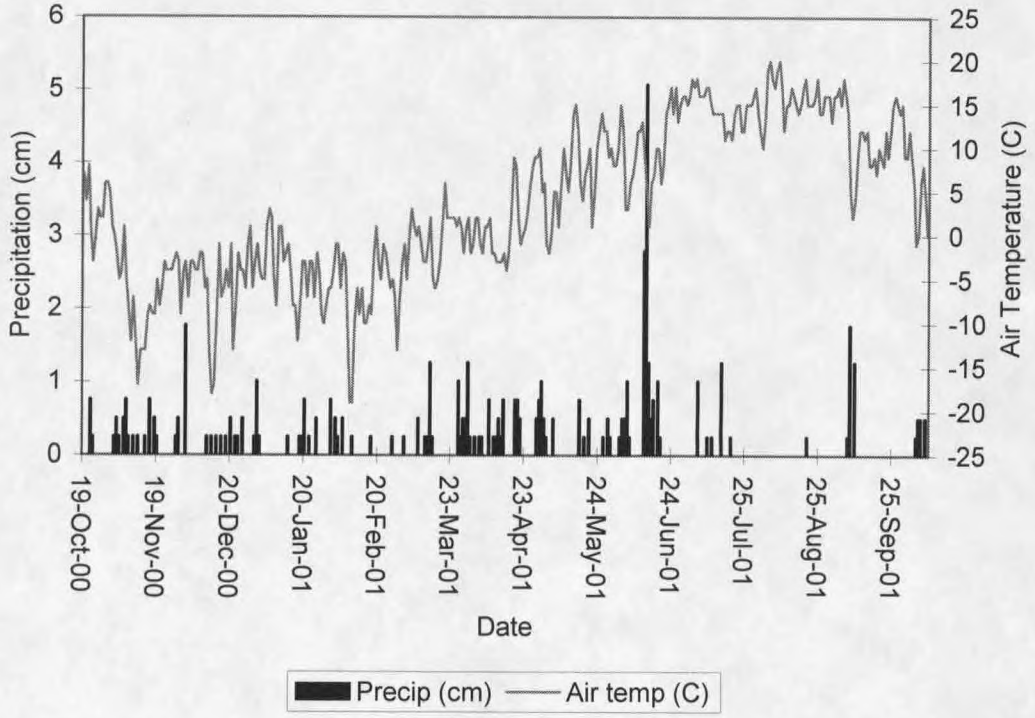


Figure 3-3. Precipitation and air temperature from the Lick Creek SNOTEL site.

Table 3-8. Major ion analyses from Two Springs.

Parameter	April 29, 2001		Oct. 1, 2001	Analytical Method
	Upper Spring	Lower Spring	Lower Spring	
Calcium	20 mg/l	20 mg/l	25 mg/l	EPA 200.7
Magnesium	7 mg/l	7 mg/l	8 mg/l	EPA 200.7
Potassium	2 mg/l	2 mg/l	2 mg/l	EPA 200.7
Sodium	2 mg/l	2 mg/l	2 mg/l	EPA 200.7
Chloride	<1 mg/l	<1 mg/l	>1 mg/l	EPA 300.0
Sulfate	4 mg/l	4 mg/l	5 mg/l	EPA 300.0
Bicarbonate	87 mg/l	88 mg/l	117 mg/l	SM2320B
Carbonate	<1 mg/l	<1 mg/l	<1 mg/l	SM2320B
Specific Conductance at 25 C	147 µmohs/cm	142 µmohs/cm	178 µmohs/cm	SM2510B
Total Dissolved Solids	56 mg/l	65 mg/l	159 mg/l (calculated)	SM2540C
pH	7.7	7.7	8.0	EPA 150.1

Drinking Water Quality

Water from Two Springs was analyzed to determine if it met EPA drinking water standards. The results of these analyses are provided in Table 3-9. Complete laboratory reports are included in Appendix E.

Table 3-9. Drinking Water Quality Analyses of Two Springs.

Parameter		Two Springs (Lower Spring) Oct. 1, 2001	Analytical Method	EPA Standard
General Water Quality	Hardness, Total	95 mg/l	calculated	--
	Calcium	25 mg/l	EPA 200.7	--
	Magnesium	8 mg/l	EPA 200.7	--
	Sodium	2 mg/l	EPA 200.7	--
	Sulfate	5 mg/l	EPA 300.0	250 mg/l*
	Chloride	< 1 mg/l	EPA 300.0	250 mg/l*
	Alkalinity	96 mg/l	SM2320B	--
	Iron	< 0.03 mg/l	EPA 200.7	0.3 mg/l*
	Fluoride	0.10 mg/l	SM4500FC mod	4.0 mg/l
	Nitrate + Nitrite	0.06 mg/l	EPA 353.2	10 mg/l
	Total Dissolved Solids	159 mg/l	calculated	500 mg/l*
	Turbidity	0.33 NTU	EPA 180.1	1 NTU
	pH	8.0	EPA 150.1	6.5 – 8.5*
Microbiological	Total Coliform	Present	SM 9223	95% of samples must be negative
	E. Coli	Absent	SM 9223	0
	Giardia	< 0.05/1		99.9% removal
	Cryptosporidia	< 0.05/1		99.9% removal
Trace Metals	Lead	< 0.005 mg/l	EPA 200.8	0.015 mg/l**
	Copper	< 0.01 mg/l	EPA 200.7	1.3 mg/l**
	Antimony	< 0.003 mg/l	EPA 200.8	0.006 mg/l
	Arsenic	< 0.005 mg/l	EPA 200.8	0.05 mg/l
	Barium	<0.1 mg/l	EPA 200.7	2 mg/l
	Beryllium	<0.001 mg/l	EPA 200.7	0.004 mg/l
	Cadmium	< 0.001 mg/l	EPA 200.7	0.005 mg/l
	Chromium	< 0.01 mg/l	EPA 200.7	0.1 mg/l
	Mercury	< 0.0002	EPA 200.8	0.002 mg/l
	Nickel	< 0.01 mg/l	EPA 200.7	0.1 mg/l
	Selenium	< 0.005 mg/l	EPA 200.8	0.05 mg/l
	Thallium	< 0.001 mg/l	EPA 200.8	0.002 mg/l

Note: EPA standards are the National Primary Drinking Water Regulations (MCLs) except where otherwise noted.

* National Secondary Drinking Water Regulations ** EPA Action Level

Tritium

Tritium analyses were performed in order to provide an estimate of the residence time of groundwater discharging at Two Springs. Table 3-10 below contains the results of tritium analysis on the water from Two Springs and from the snowpack. The results are expressed in tritium units (TU), where 1 TU equals a tritium to hydrogen ratio of 10^{-18}. The tritium analytical reports are included in Appendix E.

Table 3-10. Tritium concentrations from Two Springs and snowpack.

Location	Tritium Concentration (TU)	Reported Error (TU)
Upper Spring	14.9	0.5
Lower Spring	13.8	0.5
Snowpack	10.7	0.4

Water Rights

In order to determine how water rights issues may affect Bozeman's potential use of the Madison aquifer, the major users of Madison aquifer water in Montana were identified. These entities were identified by the Montana Bureau of Mines and Geology Groundwater Information Center staff from their database and included four municipalities and two bottling companies. The locations of the municipalities and bottling companies that use the Madison aquifer are shown in Figure 3-4.

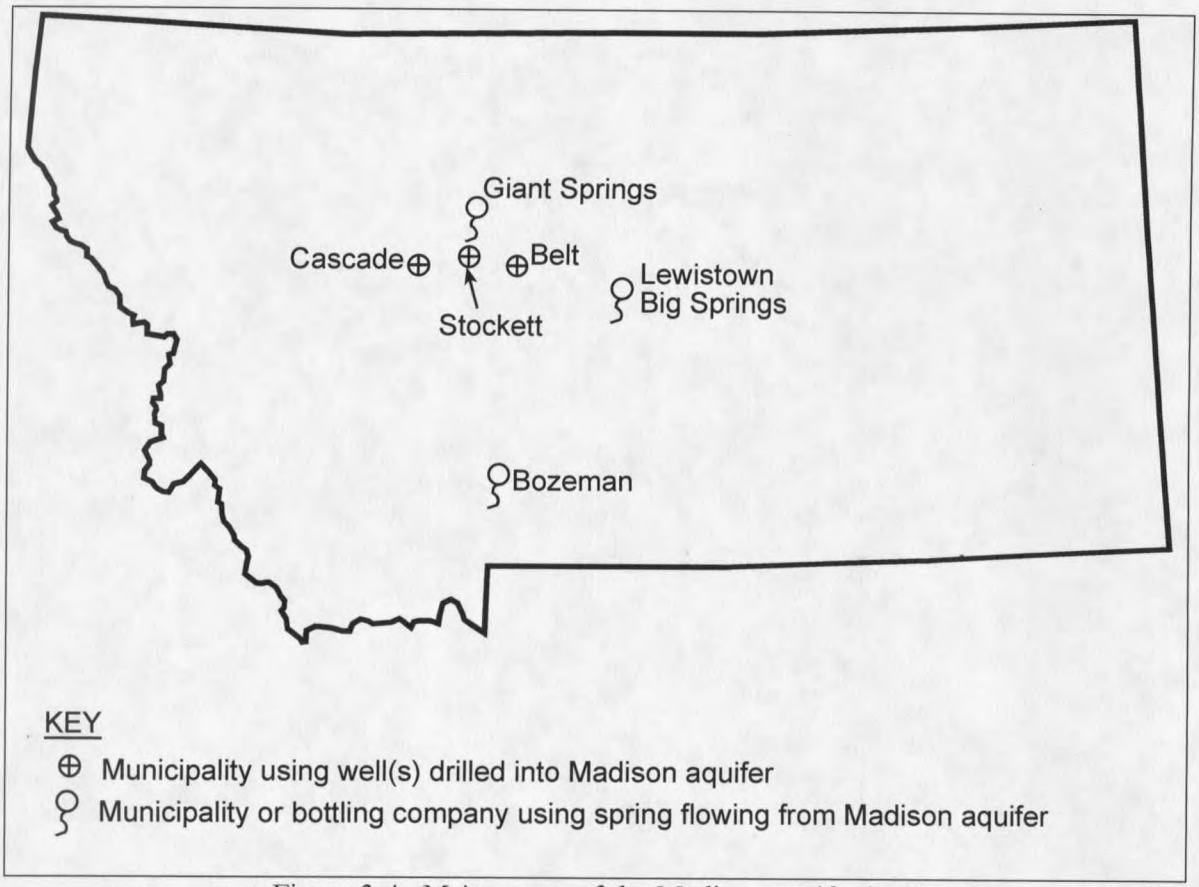


Figure 3-4. Major users of the Madison aquifer in Montana.

Officials from each of these municipalities and bottling companies were interviewed. The responses from telephone interviews with town officials in municipalities using Madison aquifer water are summarized below.

Town of Cascade

Contact: Karen Morrison, Clerk / Treasurer (406) 468-2808. The Town of Cascade has two wells drilled into the Madison aquifer, which serve a population of approximately 800 people. The wells are 730 meters and 670 meters (2400 and 2200 feet) deep. The first well was drilled in 1990 and yields 22 liters/sec (350 gpm). A second well was drilled

recently due to a bent pipe in the first well. The second well initially yielded 9.5 liters/sec (150 gpm) but was hydraulically fractured to increase yield. The well now yields over 17 liters/sec (267 gpm). The water level had been fairly constant in the wells, but began to decline during the spring of 2001. The water level had declined approximately 30 meters (100 feet) as of May 2001. The water is treated with chlorine. No water rights issues were reported.

Town of Stockett

Contact: Beverly Pepos, Water and Sewer Operator (406) 736-5351. Stockett has a population of 220 people, and a spring discharging from the Madison aquifer and a well drilled into the Madison aquifer provide the public water. The spring is the primary source of water for the town, has an average flow rate of approximately 6 liters/sec (100 gpm) and is distributed into the town by gravity flow. The discharge from the spring has declined over the last two years, leading to restrictions in water usage. The well is only used to supplement the water from the spring , and is 230 meters (750 feet) deep with a flow rate of 2 to 3 liters/sec (30 to 50 gpm). Typically the well is only used during the late spring and summer, but the well was used during this past winter due to low flows from the spring. The water from the spring is treated with chlorine and the well water is not treated. Both the well and the spring are on privately owned land and the water rights are held by the land owner. The Town of Stockett pays $300 per month to the land owner for use of the water.

Town of Belt

Contact: Jean Fontana, Clerk / Treasurer (406) 277-3621. The Town of Belt is served by two wells drilled into the Madison aquifer. The wells are less than 60 meters (200 feet) deep and supply water to 700 to 800 people. The groundwater meets drinking water