Geologic controls on spring discharge in the Miller Creek basin, New World Mining District, Montana
by Alexander Daniel Durst

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:
Miller Creek flows from an alpine drainage basin which contains near surface sulfide rich bedrock ore bodies. There has been concern regarding the potential impact of mining on spring discharge because the surface water in the upper Miller Creek basin forms a tributary which contributes water to Soda Butte Creek which flows into Yellowstone National Park.

Field mapping, spring water measurement, and data previously collected by other researchers allowed determination of whether springs derive water from the bedrock aquifer (fractured and faulted Precambrian crystalline rocks, Paleozoic sedimentary rocks, and Tertiary igneous rocks) or the surficial-deposit aquifer (rock glaciers, glacial deposits and colluvial deposits). Springs interpreted to derive water from the bedrock aquifer are located near faults, fracture traces, lithologic contacts, lineaments and mineralized veins and have high and variable specific electrical conductivity (SC) values. Surficial-deposit springs are located near the downhill contacts between surficial deposits and underlying bedrock outcrops and have low and more constant SC values. SC data collected by other researchers from wells corroborates the division of springs.

Discharge volumes collected with portable measuring devices allowed calculation of the contribution of the spring groups. The group of springs interpreted to derive water from the bedrock aquifer discharged more than half of the measured and estimated spring discharge during mid July, 1997. During the remainder of the field season (August through October) the group of springs interpreted to be bedrock persisted with cumulative discharges between 40-50% of the basin's total measured and estimated discharge. The cumulative discharge of the bedrock springs during mid-July is 6 times greater than the cumulative discharge of the bedrock springs in early October. If a mine were to intersect bedrock groundwater, volumetric impacts are expected to be larger in the early summer than in the fall.

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APPROVAL
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Alexander Daniel Durst

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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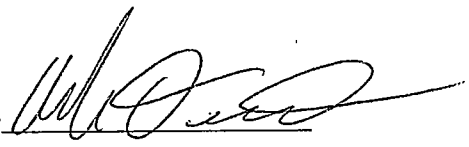
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ABSTRACT

Miller Creek flows from an alpine drainage basin which contains near surface sulfide rich bedrock ore bodies. There has been concern regarding the potential impact of mining on spring discharge because the surface water in the upper Miller Creek basin forms a tributary which contributes water to Soda Butte Creek which flows into Yellowstone National Park.

Field mapping, spring water measurement, and data previously collected by other researchers allowed determination of whether springs derive water from the bedrock aquifer (fractured and faulted Precambrian crystalline rocks, Paleozoic sedimentary rocks, and Tertiary igneous rocks) or the surficial-deposit aquifer (rock glaciers, glacial deposits and colluvial deposits). Springs interpreted to derive water from the bedrock aquifer are located near faults, fracture traces, lithologic contacts, lineaments and mineralized veins and have high and variable specific electrical conductivity (SC) values. Surficial-deposit springs are located near the downhill contacts between surficial deposits and underlying bedrock outcrops and have low and more constant SC values. SC data collected by other researchers from wells corroborates the division of springs.

Discharge volumes collected with portable measuring devices allowed calculation of the contribution of the spring groups. The group of springs interpreted to derive water from the bedrock aquifer discharged more than half of the measured and estimated spring discharge during mid July, 1997. During the remainder of the field season (August through October) the group of springs interpreted to be bedrock persisted with cumulative discharges between 40-50% of the basin's total measured and estimated discharge. The cumulative discharge of the bedrock springs during mid-July is 6 times greater than the cumulative discharge of the bedrock springs in early October. If a mine were to intersect bedrock groundwater, volumetric impacts are expected to be larger in the early summer than in the fall.

INTRODUCTION

The objective of this study was to determine whether spring discharge in the upper Miller Creek basin (Fig. 1 and Plate 1) derives a greater quantity of water from the bedrock aquifer or the surficial-deposit aquifer. Determining the origin of spring discharge has implications regarding the potential affect of mining near-surface bedrock ore bodies in the upper Miller Creek basin. If the springs in the upper Miller Creek basin derive a greater quantity of water from the bedrock aquifer then mining near-surface bedrock ore bodies in the upper Miller Creek basin would be more likely to disrupt spring discharge and possibly other forms of groundwater discharge, such as seeps or baseflow. On the other hand, if springs derive a greater quantity of water from the surficial-deposit aquifer, then mining near surface bedrock ore bodies would be less likely to disrupt spring discharge and other forms of groundwater discharge.

Whether mining the Miller Creek ore bodies would disrupt groundwater discharge to Miller Creek has been the subject of much controversy and could continue to be so in the future. The most recent proposal to mine the ore bodies (Crown Butte Mines (CBM), 1992) caused enough concern about environmental impact to prevent the inception of full scale mining operations. The U.S. government bought the land above and near the ore bodies and the Secretary of the Interior placed a 20 year mineral withdrawal in the area in August of 1997. The mineral withdrawal must be reviewed and re-approved every 20 years by the Secretary of the Interior. If the mineral withdrawal is not re-approved, another plan to mine these ore bodies could be proposed and the controversies and concerns surrounding the mining of these ore bodies could begin anew.

A principal concern regarding the underground mining of the ore bodies was whether or not underground mining could disrupt the quantity and/or quality of surface water in the upper

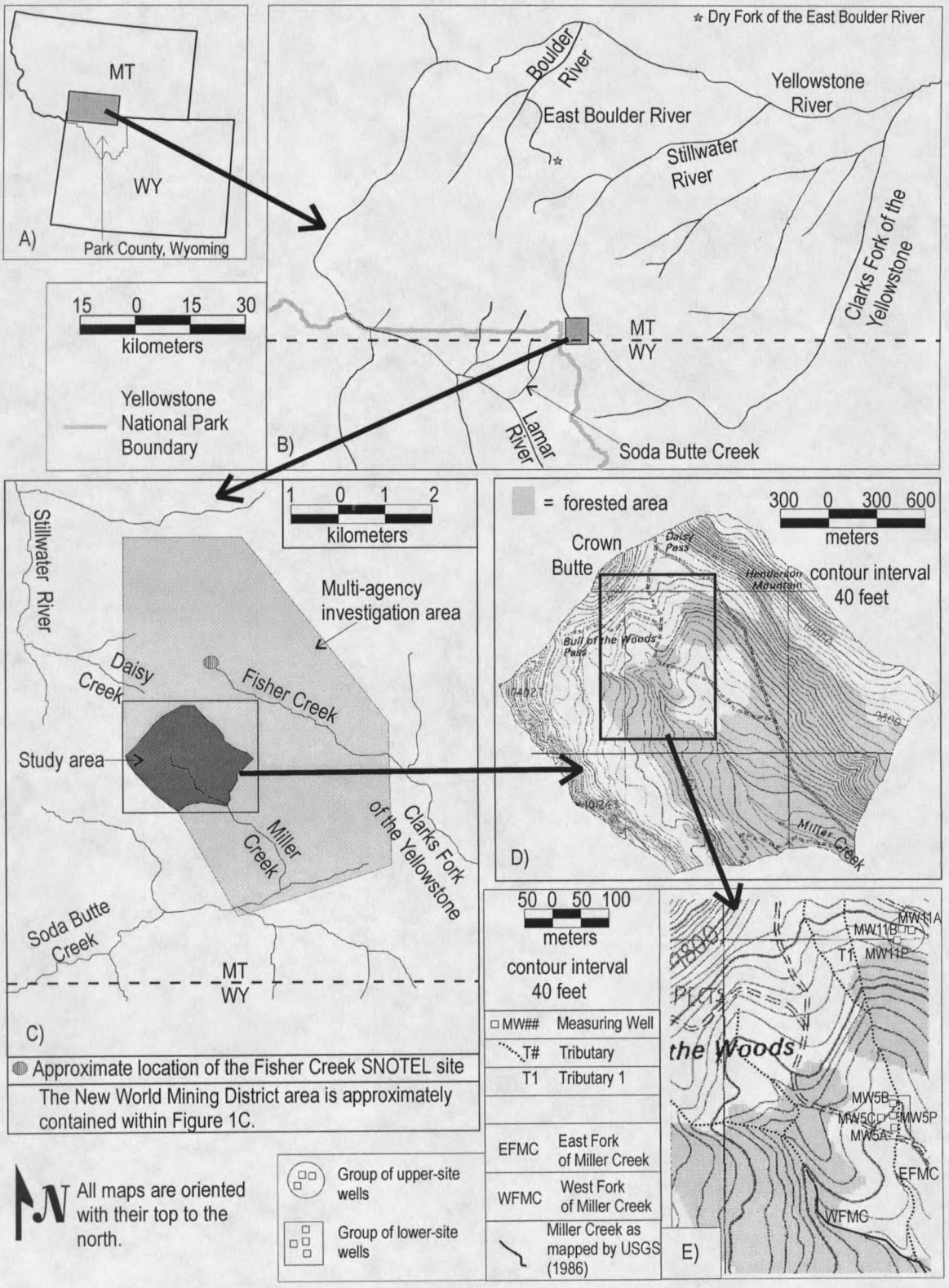


Figure 1. Study area. A) Location in Montana and Wyoming. B) Regional area. C) Study area and multi-agency investigation area. D) Study area. E) Wells and some tributaries.

Miller Creek basin. Quantity is an especially important issue because Miller Creek flows into Soda Butte Creek which joins the Lamar River in Yellowstone National Park (Fig. 1B). Given the design of historically proposed mining operations, (CBM, 1992) mine adits could intercept groundwater flow destined for Miller Creek and divert or delay the water away from surface flows in the Miller Creek basin. A compact between Yellowstone National Park and the state of Montana would require the replacement of any water diverted from Miller Creek. The water replacement must occur at the exact rate, timing and volume that water is removed from the upper Miller Creek basin (United States Department of the Interior and the State of Montana, 1994).

Determining the exact rate, timing and volume of water diverted from Miller Creek by underground mining could be very difficult. The difficulty stems from the poor understanding of groundwater flow systems in alpine basins. The groundwater flow system is important because underground mining would have to disrupt the groundwater flow system in order to be able to disrupt surface flows. Alpine groundwater flow systems are poorly understood because there is a general lack of wells in alpine basins (Schwartz and Domenico, 1997), and the interpolation of data gathered in other alpine basins is difficult because of the diverse geology of alpine basins throughout the world.

Despite the difficulty in determining the relative contributions of groundwater in alpine basins, some researchers have been able to determine that groundwater contributions in alpine basins can be significant either volumetrically or temporally. Modeling studies in the Reynolds Creek experimental watershed near Boise, Idaho indicate that a significant portion of streamflow is derived from shallow (<25 m) aquifers (Flerchinger et al., 1993). In the Dischma basin, Italy, 60% of the basin's total stream discharge was determined to be groundwater discharge during

snowmelt periods (Martinec et al., 1982). At a headwater basin of the Kaweah river in the Sierra Nevada, California, the percentage of streamflow which consists of groundwater during snowmelt periods is low, but subsurface flow is the primary input to streamflow for the 8-9 months of the year which are non-snowmelt periods thereby controlling stream chemistry for more than two-thirds of the year (Kattleman, 1989).

Groundwater can discharge to streams in alpine basins via flow from the groundwater system into the bed of the stream, as well as via seeps and springs. This study focuses on the determination of spring discharge origin in the upper Miller Creek basin because the mapping of springs and the measurement of specific electrical conductance (SC) and temperature of springs provides a fairly simple means of determining whether springs derive water from the bedrock aquifer or the surficial-deposit aquifer. If spring discharge derives a majority of water from the surficial-deposit aquifer, then underground mining of the near-surface bedrock ore bodies would be less likely to disrupt spring discharge. If spring discharge derives a majority of water from the bedrock aquifer then mining would be more likely to disrupt groundwater discharge. The possibility exists that there is extensive mixing between the bedrock and surficial-deposit aquifer in the Miller Creek basin. If a mixing scenario exists then distinguishing water from the two aquifers would be difficult.

Bedrock and Surficial-Deposit Aquifers

Bedrock and surficial-deposit aquifers must be defined in order to be able to distinguish bedrock-aquifer spring discharge from surficial-deposit aquifer spring discharge. A bedrock aquifer is defined as a body of bedrock that contains sufficient saturated permeable material or cavities to

conduct groundwater and yield water to springs and wells. Surficial-deposit aquifers are comprised of materials which lay above the bedrock surface and contain sufficient saturated permeable material to conduct ground water and yield significant quantities of water to wells and springs (definitions in part from Jackson, 1997, p. 32). Most materials that make up surficial-deposit aquifers are unconsolidated.

Relative Contribution of the Bedrock and Surficial-Deposit Aquifer to Groundwater Discharge

Flow from the bedrock aquifer may dominate baseflow in alpine basins. At a headwater valley in northwestern Nevada, SC measurements, demonstrated that bedrock-derived baseflow contributed 84-90% of total stream discharge (Hill, 1990). In the Reynolds Creek experimental watershed near Boise, Idaho a mathematical model demonstrated that subsurface flow through high permeability bedrock, (e.g. faulted bedrock) can be the sole source of streamflow (Stephenson and Freeze, 1974); other modeling studies in the same watershed provided additional evidence that the bedrock aquifer plays a significant role in delivering discharge to the stream (Flerchinger et al., 1993).

Conversely, surficial-deposit aquifer dominance of groundwater discharge is also possible. Specific electrical conductance (SC) and pH measurements indicated that a spring near Mt. Rushmore derived water largely from surficial-deposit materials (Rahn, 1990). At a headwater basin of the Kaweah river in the Sierra Nevada, California the available groundwater storage of the bedrock aquifer was determined to be much less than the available groundwater storage of the surficial-deposit materials (Kattleman, 1989).

Springs

A spring is a place where groundwater flows naturally from the ground onto the land surface (Jackson, 1997). The occurrence of springs depends on the nature and relationship of rocks, on the position of the water table and on topography. Knowledge regarding the types of geologic features where a spring may occur helps to determine whether a spring derives water from the bedrock or surficial-deposit aquifers. Features studied in this thesis which produce springs are herein termed potential spring-producing geologic features (Table 1). Though there are other factors which can control the location and origin of springs which are not listed in Table 1, such as topography, changes in hydraulic gradient and joint frequency, only the geologic factors which are most likely to occur in the Miller Creek basin and are best suited for discovery using the methods outlined in this thesis are discussed in this section.

Table 1. Potential spring-producing geologic features.

Bedrock features		Surficial-deposit features
Faults	Lineaments	The downhill contact between a surficial deposit and underlying bedrock.
Lithologic Contacts	Fracture Traces	
Mineralized Veins		

In the Miller Creek basin there are several bedrock features and one dominant surficial-deposit feature which can produce springs. Faults can be potential groundwater conduits (Huntoon and Lundy, 1979; Huntoon, 1986; Rahn, 1990) which may discharge groundwater in the form of springs. Lithologic contacts between bedrock units are potential groundwater conduits which may discharge "contact springs" at the surface expression of the contact (Fetter, 1994).

Faults and lithologic contacts can also be barriers to groundwater flow, and springs may form at the surface expression of these features (Huntoon, 1985; Fetter, 1994). Lineaments and fracture traces are also known to be sources of groundwater (Lattman and Parizek, 1964), and a line of springs may form on these features if they discharge groundwater (Fetter, 1994). The downhill contact between a surficial deposit and underlying bedrock is where a surficial-deposit spring is most likely to form. Such a spring is called a gravity contact spring (Taylor, 1964). Thus, there are several features which may form springs; and the determination of whether a spring is associated with a certain type of feature can help to segregate springs as either deriving water from the bedrock aquifer or from the surficial-deposit aquifer.

Study Area

The Miller Creek basin study area lies in the Beartooth mountains approximately 2 km north of Cooke City, Montana, in the New World Mining District (Fig. 1C). The entire Miller Creek basin has a drainage area of 6.0 km^2 (2.3 mi^2). However, only the upper 3.6 km^2 (1.4 mi^2) of the basin encompasses the study area. Only the upper portion was studied because this area is where the ore bodies are located and is the most relevant area to the evaluation of the potential effects of mining on Miller Creek basin springs. The study area lies between 2450-3170 m (8040-10402 ft) altitude (Fig. 1D and Plate 1). An east and west fork join to form Miller Creek (Fig. 1E). These forks each have two main tributaries. The easternmost tributary to the east fork is named Tributary One (T1). Tributary One becomes important in a test discussed in Appendix A. Miller Creek is a tributary to Soda Butte Creek which joins the Lamar River in Yellowstone National Park.

Climate

A Natural Resources Conservation Service snow telemetry (SNOTEL) station in the Fisher Creek Drainage (Fig. 1C) provides an excellent approximation of weather conditions in the Miller Creek basin because the Fisher Creek basin has the same aspect as the Miller Creek basin and the altitude of the SNOTEL site (2775 m (9100 ft)) is near the mean altitude of the study area.

The Fisher Creek SNOTEL indicates that there is great variance in ambient air temperatures. The great variance in ambient air temperatures of the study area helps to distinguish surficial-aquifer-spring water from deeper-aquifer-spring water because an area with great fluctuations of ambient air temperature will cause shallow-surficial-aquifer-water temperature to vary, whereas deeper-aquifer water temperature will not vary (Taniguchi, 1993). The Fisher Creek SNOTEL indicates that the average annual minimum temperature is -32° C (-26° F) and the average annual maximum temperature is 26° C (79° F) (water years 1983-97). Minimum air temperature at ground surface may be moderated due to snow cover and not likely to be lower than 0° C (32° F) because the stored heat in the ground from summer warming and geothermal heat combine to warm the temperature at the base of most heavy snowpacks to 0° C (or close to 0° C (32° F)) (McClung and Schaerer, 1993, p. 45). Temperatures as low as -43° C (-45° F) and as high as 30° C (86° F) have been recorded. The average annual temperature is -1° C (30° F).

The large annual snowpack in the study area provides ample snowmelt recharge for the bedrock and surficial-deposit aquifers. The Fisher Creek SNOTEL indicates that the average maximum annual snow pack is 103 cm (40.9 in) in snow water equivalent units occurring on or about May 1 (water years 1967-97). The greatest recorded annual maximum snow water equivalent is 153 cm (60.2 in) and the smallest recorded maximum snow water equivalent is 52 cm

(20.4 in). Up to 450 cm (15 ft) of snow depth have been observed at elevations above 2774 m (9100 ft) elevation (United States Environmental Protection Agency (EPA), 1996). Because such large quantities of snowmelt recharge are available, the properties of snowmelt recharge must be taken into account because snowmelt recharge will affect the SC and temperature of bedrock-aquifer or surficial-deposit-aquifer-spring discharge.

Rainfall may also be an important source of recharge for aquifers. However, in the study area, the rainfall quantities are much smaller than snowfall quantities. During the time when precipitation is expected to fall as rain (approximately June 1-Oct. 31), the amount of precipitation recorded at the Fisher Creek SNOTEL is 27 cm and 46 cm for the 1996 and 1997 seasons respectively, whereas the maximum snowpack recorded at the Fisher Creek SNOTEL during the same years (130 cm and 150 cm, respectively) in snow water equivalent units is greater by a factor of three to four.

Springs

Spring discharge is an important aspect of groundwater discharge in the upper Miller Creek basin. Researchers have mapped in excess of 35 springs in the upper Miller Creek basin (Hydrometrics, 1989, 1990) and several agencies agree that groundwater discharges to the surface in the form of springs (Kirk, 1995; Maxim Technologies, 1995; BLM, 1997).

Wells

Though wells can be scarce in alpine basins, they can be very important in providing information which could lead to the determination of spring origin. Fortuitously, Miller Creek basin contains several wells. Previous researchers (Huntingdon Engineering and Environmental, 1995),

have divided wells into two groups: the group of upper-site wells (n=3) and lower-site wells (n=4) (Fig. 1E). The upper-site wells (MW11A, MW11B and MW11P) fit the definition of a "bedrock well". A "bedrock well" is completed and/or screened in lithologies interpreted by previous researchers to be bedrock, grouted where surficial-deposit materials exist and has a packer at the base of the grouting material. The bedrock lithologies will be discussed in the section titled Bedrock Hydrogeology. Based on well log interpretations, the group of upper site wells do not intercept fracture zones. The lower-site contains three bedrock wells (MW5C, MW5B and MW5P) that intercept fracture zones, and one "surficial-deposit well" (MW5A). A "surficial-deposit well" is defined as a well which is capped at the base and screened only where the surficial deposit exists. The surficial-deposit materials will be discussed in the section titled Hydrogeology of Surficial Deposits.

In addition to the wells in the Miller Creek basin there are several other bedrock and surficial-deposit wells in the multi-agency investigation area (Fig. 1C). The pH, SC, temperature and depth-to-water have been measured at the two groups of wells in the Miller Creek basin and the various other wells in the multi-agency investigation area. Additionally, pump tests have been performed by other researchers at the Miller Creek basin wells which provide hydraulic conductivity and surface-water connectivity information. The information collected at the two groups of wells in the Miller Creek basin and the other wells in the Multi-agency investigation area provides some of the criteria used to determine whether a spring derives water from the bedrock aquifer or the surficial-deposit aquifer.

Bedrock Hydrogeology

The bedrock hydrogeology of the Miller Creek basin is of great importance in determining

the origin of spring discharge in the upper Miller Creek basin. The various types of lithologies and their geologic properties control the hydrologic properties of the bedrock aquifer and the potential location of springs. The existence of faults and their behavior as fault barriers or conduits can also control the location of spring discharge.

If the bedrock lithologies of the Miller Creek basin yield water, then they likely yield water from secondary permeability. The bedrock lithologies of the Miller Creek basin include Pre-Cambrian crystalline rocks, Paleozoic sandstone, limestone, dolomite, and shale and Tertiary intrusive and extrusive igneous rocks. In nearby Park County, Wyoming (Fig. 1A), the equivalent units of bedrock lithologies which exist in the Miller Creek basin have low water yields because primary permeability is low (Table 2; Plate 2) (Lowry et al., 1993). The only bedrock lithologies which have notable yields are the Flathead Sandstone and the Bighorn Dolomite. The Bighorn Dolomite has notable yields only because this unit contains secondary permeability (Lowry et al., 1993). In fact, other units throughout the Bighorn basin may contain water if fracturing, weathering and solution of carbonates has allowed the creation of secondary permeability through which groundwater can flow (Lowry et al., 1993). If the units in the Miller Creek basin have similar hydrogeologic properties to equivalent units in the Bighorn Basin, then most lithologies are more likely to have groundwater flowing through secondary permeability rather than primary permeability.

The only unit in the upper Miller Creek basin that may yield water from primary permeability in the upper Miller Creek basin is the Flathead Sandstone, but since there are no wells in the Flathead Sandstone in the upper Miller Creek basin or in the Multi-Agency investigation area, only speculations about the Flathead Sandstone's ability to yield water in the

Table 2. Hydrogeologic properties of surficial deposits and materials in Park County, Wyoming after Lowry et al., 1993. Equivalent Miller Creek basin lithologic units written in [brackets].

Quaternary	Glacial materials	Springs are common and yields of 100 gallons per minute are possible.	
	Landslide deposits	Springs are a source of water in some areas but wells generally do not yield much water because the deposits are from fine grained material, and deposition by mass movement increases heterogeneity.	
	Undivided surficial deposits (mostly alluvium, colluvium, and glacial and landslide deposits)	Availability [of groundwater] depends on type of deposit as already described.	
Tertiary	Intrusive igneous rocks	Availability of water should be similar to that of Precambrian rocks.	Secondary permeability as a result of fracturing, weathering, and/or carbonate solution or dolomitization may be present.
Ordovician	Bighorn Dolomite	Yield to wells differs greatly because the permeability is secondary.	
Cambrian	Snowy Range Formation	Not considered an aquifer.	
	Pilgrim Limestone	Not considered an aquifer.	
	Gros Ventre Formation [Park Shale] [Meagher Limestone] [Woisey Shale]	Not considered an aquifer.	
	Flathead Sandstone	Yields sufficient quantities of water for irrigation in parts of the Bighorn Basin.	
Precambrian	Granitic Rocks	Will yield water from fractures or weathered zones in adequate quantities for stock or domestic use. Obtaining a supply at shallow depth is uncertain and drilling to depths more than 200 feet often does not result in increased yield in this geologic unit.	

study area can be made. Despite the fact that there is evidence in Park County that the Flathead Sandstone may yield water from primary permeability (Lowry et al., 1993), the hydrogeologic properties of the Flathead Sandstone are variable and may not yield water in the upper Miller Creek basin. In parts of Montana such as Meagher County, the Flathead Sandstone is considered an aquifer which yields water only from fractures (Groff, 1965, p.18). In the upper Miller Creek basin, a metamorphic effect from the Tertiary intrusives may have caused the Flathead Sandstone's permeability to decrease. Therefore, all lithologies including the Flathead Sandstone may have low primary permeability in the upper Miller Creek basin.

Evidence from within the Miller Creek basin indicates that some of the bedrock lithologies have low primary porosities and permeabilities. Pump tests of the upper-site wells completed in Meagher Limestone indicate unfractured bedrock hydraulic conductivities range from $1.4x10^{-6}$ to $3.9x10^{-6}$ cm/sec (0.004-0.011 ft/day) (Maxim Technologies, 1995). The low primary porosity and permeability of the bedrock enhance the formation of surficial-deposit springs because the interstitial surficial-deposit water at the contact of the bedrock and the surficial deposit will flow along the bedrock surface rather than infiltrating into the bedrock.

Despite the low primary porosities and permeabilities of the lithologies in the upper Miller Creek basin, the structural geologic setting of the region allows for ample faults and fractures which can provide secondary permeability for the bedrock aquifer. The Miller Creek basin is in the Cooke City Structural Zone, a northwest-trending lineament and area of crustal weakness in the Beartooth uplift. This lineament is an area of extensive faulting (Foose et al., 1961). Miller Creek basin exists in a region classified as an area whose fractures have the greatest potential effect on fracture permeability in the northern Great Plains and the Rocky Mountains region (Cooley, 1986).

An example of how faults may affect the groundwater flow system and produce large springs exists in the nearby Dry Fork-East Boulder River (Fig. 1B) where springs likely related to the Dry Fork Thrust Fault discharge up to 7600 l/min (2000 gpm) from Paleozoic units (Feltis, 1986).

The regional trend of faults and fractures with pronounced affects on groundwater flow appears to also occur in the Miller Creek basin. Pump tests indicate that fractures have a pronounced affect on groundwater flow and several researchers conclude that subsurface water moves primarily through fractures and faults (Maxim Technologies, 1995; BLM, 1997). Pump tests in the group of lower-site wells indicate hydraulic conductivities of fractured bedrock range from $1.5x10^{-2}$ to $2.1x10^{-2}$ cm/sec (42-60 ft/day) (Maxim Technologies, 1995) which is four orders of magnitude greater than the unfractured bedrock aquifer conductivities mentioned previously. Because faults and fractures control groundwater flow through bedrock, bedrock-aquifer springs are expected to occur along the surface expression of fault locations in the Miller Creek basin.

A regional scale sub-horizontal detachment may produce spring discharge in the upper Miller Creek basin. The Heart Mountain Detachment is a sub-horizontal fault surface which extended over a large (1800 mi^2) portion of northwestern Wyoming and parts of southern Montana (Pierce, 1957). The fault surface is presently dissected, and a portion of the detachment fault is located in the Miller Creek basin (Elliot, 1979). Fluids migrated along this feature during the genesis of the feature in the Eocene, (Templeton et al., 1995; Beutner and Craven, 1996). If groundwater does flow through the Heart Mountain Detachment, springs may form at the surface expression of this feature. Admittedly however, there is no information which indicates groundwater presently flows from the surface of the Heart Mountain Detachment.

The elevation of the water table in the study area's bedrock aquifer fluctuates (Fig. 2).

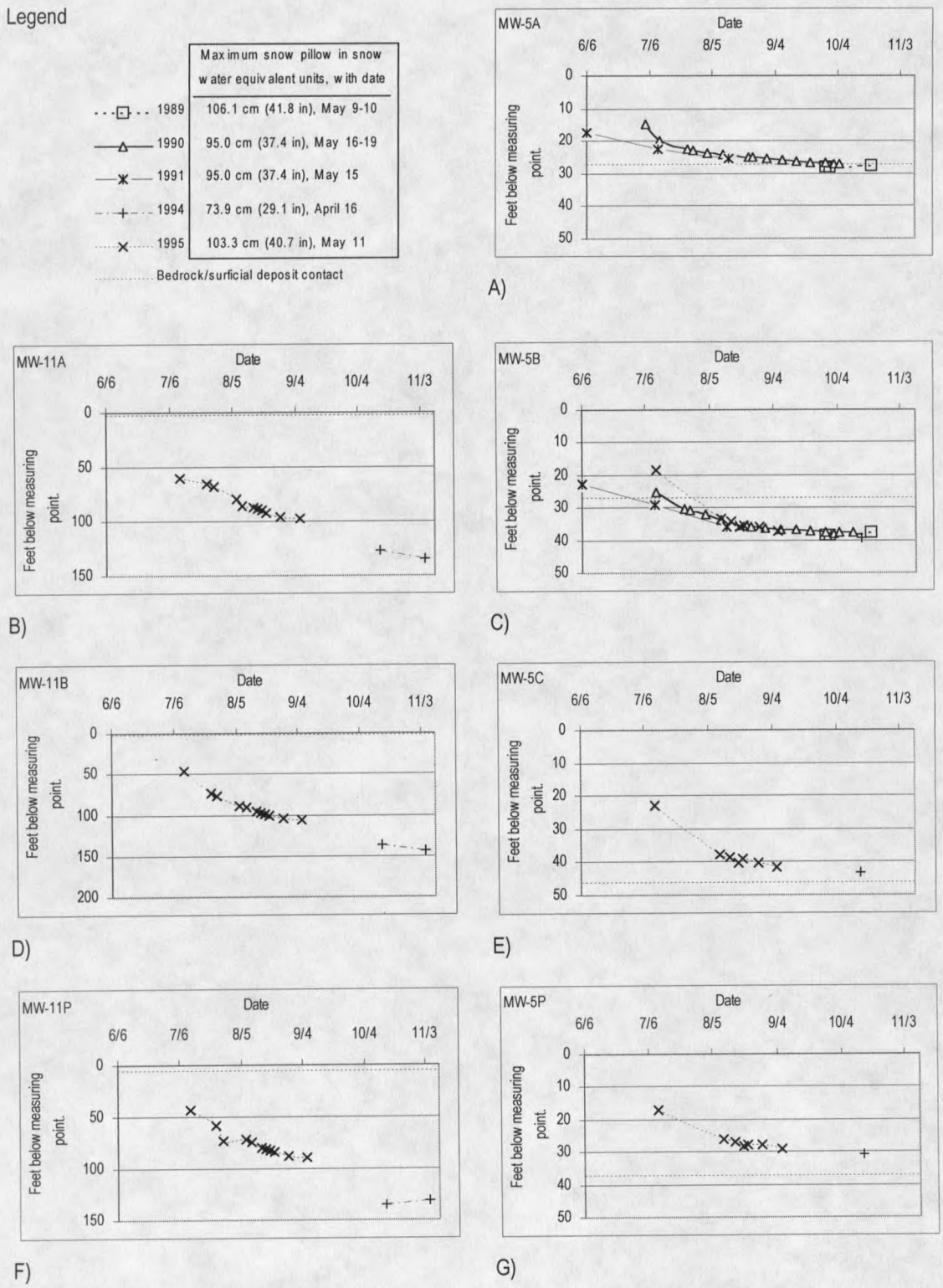


Figure 2. Time vs. depth-to-water of Miller Creek basin wells. The MW-5 series is the group of lower-site wells and the MW-11 series is the group of upper-site wells (Fig. 1E).

Static water levels in wells have fluctuated 28 m (91 ft) at the upper-site and 7 m (21 ft) at the lower site. The highest static water levels occur during late spring or early summer (Maxim Technologies, 1995; EPA, unpublished). The high static water levels during spring imply the system is recharged by snowmelt. Maxim Technologies (1995) inferred from these fluctuations that a large portion of recharge water is initially held in bedrock fracture openings as storage, followed by depletion of water via discharge to springs, seeps and baseflow to streams. This implies that a bedrock spring may attain maximal discharge during spring, slowly decrease in discharge as summer progresses to fall and possibly stop discharging water before the bedrock aquifer is recharged again by snowmelt.

Lineaments and Fracture Traces

Lineaments greater than 30 km with trends ranging between NNW and NE have been mapped in the regional area (Cooley, 1983; Cooley, 1986).

Hydrogeology of Surficial Deposits

The constituents of the surficial-deposit aquifer include rock glaciers, glacial materials, colluvial deposits and other types of deposits (Plate 3).

Rock Glaciers. Rock glaciers exist on the western side of the Miller Creek basin (Bean and Carson, 1995) (Plate 3). The rock glaciers are located approximately where Elliot (1979) maps Quaternary undifferentiated materials in the western portion of the basin (Plate 2). The rock glaciers have complex surface morphology including conical pits, and both longitudinal and transverse ridges and furrows (Bean and Carson, 1995). The rock glaciers contain several important hydrologic features (Bean, 1995): 1) they are up to 26 m thick, indicating ample

thickness for storage of groundwater, 2) interstitial ice exists at depths as shallow as 80 cm indicating ground ice is available for melting and subsequent discharge as groundwater, 3) springs which apparently discharge from the rock glaciers have a water temperature of ~1° C, indicating a potential temperature signature for the rock glacier groundwater and 4) water heard running beneath the surface of rock glaciers indicates the existence of groundwater.

Glacial Deposits. Undifferentiated till and fluvioglacial deposits are present in the center of the Miller Creek basin (Elliot, 1979; Plates 2 and 3). The group of lower-site wells penetrate these materials. Drillers encountered 8-14 m (27-46ft) of unconsolidated material before encountering lithologies interpreted by the on-site geologist to be bedrock in the group of lower-site wells (CBM, 1992). In the one well interpreted as a surficial-deposit well (MW5A) measurable and fluctuating static water levels exist (Fig. 2). The thickness of the glacial deposits, combined with the presence of fluctuating groundwater levels suggests groundwater storage and transmission in the glacial deposits.

The water in the glacial deposits is hydraulically connected to the bedrock aquifer. In the three lower-site bedrock wells, static water levels fluctuate above the surficial-bedrock contact, indicating water either comes through the glacial deposits and drains to the bedrock or the water in the bedrock aquifer is under enough hydrostatic pressure to rise above the bedrock-surficial deposit contact (Fig. 2). Further evidence that there is a hydraulic connection between the glacial deposits and bedrock is indicated by dropping water levels in the surficial-deposit well (MW5A) which occurred during the pumping of the bedrock well MW5P (Maxim Technologies, 1995).

Portions of the glacial deposits become dry during fall. In two out of four lower-site wells, static water levels fell below the bedrock/surficial-deposit contact during this season, and in the

remaining wells, static water levels were near the bedrock/surficial-deposit contact in the other two wells during this season (Fig. 2). This indicates the springs from glacial deposits should become dry or nearly dry in the fall, and the glacial deposits should be devoid of water until recharged again in the spring by snowmelt.

Other Deposits. Several other types of deposits exist that may function as units which store or transmit groundwater (Plate 3). Talus, landslide deposits and soils developed from *in situ* weathering of crystalline bedrock (Shovic, 1984) may contain groundwater. (Ferricrete also exists in the Miller Creek basin (Furniss, 1996), but is not expected to function as an aquifer). Perhaps the only information about the thickness or groundwater characteristics of the colluvial deposits comes from information obtained at the group of upper-site wells (Fig. 1E). These upper site wells drilled through 0.6-1.6 m (2-5 ft) of colluvial materials before intercepting bedrock (CBM, 1992). This thickness suggests some potential for groundwater storage. Analysis of depth-to-water data from the upper site wells indicates that the bedrock aquifer water levels never reach the thin colluvial deposits in the vicinity of the group of upper site wells (Fig. 2).

Hydrology

There are few measurements of Miller Creek's total stream discharge. The USGS has made 3 measurements of Miller Creek's total discharge (Table 3). Despite the very few discharge measurements in the Miller Creek basin, daily discharge measurements taken during the late 1970's and early 80's exist for the upper portions of Daisy Creek and Fisher Creek (Montana Department of State Lands, unpublished data). The hydrographs in these two basins indicate peak water discharge volumes occur during late spring and/or early summer months.

Table 3. Miller Creek discharge measurements as measured by the USGS.

Date	Discharge measurement in cubic feet/second
7/23/69	40.6
9/11/96	0.3
10/23/96	0.2

Characterization of Springs from Bedrock and Surficial-Deposit Aquifers

The origin of spring discharge can be determined through mapping of springs and geology, and comparison of spring-water SC and temperature with well-water SC and temperature. Additionally, there are theoretical expectations regarding the relative values for the bedrock-aquifer-water and surficial-deposit-aquifer-water SC and temperature.

Also, certain pieces of field evidence can help to reveal a spring's origin; e.g., if a spring discharges from bedrock, the spring may derive water from the bedrock aquifer, or if several springs that are aligned in a linear fashion have iron-stained substrate, they may derive groundwater from a mineralized fault, vein or stratigraphic contact. Alternatively, springs with iron-stained substrate could discharge from tailings or pyrite-rich till or colluvium.

Analysis of Pre-existing data

Key to the determination of the contribution of the bedrock and surficial-deposit aquifers to spring discharge in the Miller Creek basin are the number of previous hydrologic studies that have occurred in the vicinity of the Miller Creek basin (CBM, 1992; Huntingdon Engineering and Environmental, 1995; Maxim Technologies, 1995; EPA, 1996; Hydrometrics, Unpublished, EPA unpublished). The area where these studies have occurred is referred to as the multi-agency

investigation area (Fig. 1C). This area is where researchers collected a substantial amount of publicly available hydrologic data in preparation for the Crown Butte Project. This data provides pH, SC, change of SC (ΔSC), and change of temperature (ΔT) values for bedrock-well water and surficial-deposit well-water which may serve as signatures for the bedrock aquifer and the surficial-deposit aquifer.

pH

In the Miller Creek basin, there are no readily apparent factors which would allow one to use pH to distinguish bedrock-spring discharge from surficial-deposit-spring discharge. However, pH was measured in this study because such data may be useful to those who need to base remediation efforts on the location and distribution of acid and alkaline waters in the Miller Creek basin. There are a number of factors in the Miller Creek basin which can effect the pH of spring discharge. Those factors that may make the spring discharge water acidic include the original pH of the recharge, existence of sulfides and wetland processes. Snowmelt recharge in the upper Miller Creek basin should be slightly acidic because the average pH for snowmelt in the Rocky Mountain west is slightly acidic ~6.8 (Feth et al., 1968). The existence of sulfides in the study area may cause the water to become acidic because oxygenated water will oxidize sulfides and release hydrogen ions, thereby increasing pH. Wetland areas in the Miller Creek basin may also decrease the pH of spring water samples. In general pH values in wetland areas tend to be acidic. Wetland areas generally have low pH values (3.7-7.2) (National wetlands working group, 1988). Fisher Creek wetland soils range in pH from 1.7 to 5.5 (Amacher, 1998).

Spring discharge water may also be alkaline because a significant portion of the study area's bedrock is limestone. If water is in contact with limestone then the water may dissolve the

limestone and carry away calcium and bicarbonate ions. Subsequently, the bicarbonate ions dissociate to carbon dioxide and hydroxyl ions. The addition of hydroxyl ions buffers the water and raises the pH (Faure, 1991).

Specific Electrical Conductance

SC values. In the Miller Creek basin there are three factors which control the SC of water in the bedrock and surficial-deposit aquifer: 1) the SC of snowmelt, 2) the contact time of aquifer water, and 3) type of material with which the water is in contact. SC of snowmelt is a controlling factor because of the great quantities of snowmelt which recharge the aquifer annually. The SC of snowmelt is low. Feth et al., (1964) measured the SC of 79 snow samples at varying locations in the western U.S.. Only six of the samples had SC values above 40 $\mu S\ cm^{-1}$ and none were above 100 $\mu S\ cm^{-1}$.

The contact time of water is a controlling factor because the degree of aquifer water mineralization (and therefore SC) is a function of contact time with the aquifer (Back and Hanshaw, 1970). The difference between the bedrock aquifer and the surficial-deposit aquifer is that portions of the surficial-deposit aquifer become dry or nearly so during fall; therefore, low SC snowmelt which is in contact with water only during summer months does not have the opportunity to achieve the higher SC values of perennial bedrock-aquifer water.

Other surficial-deposit aquifers and materials have been found to have low and invariable SC values when contact time is short. In a lab setting, distilled water equilibrated at 170 $\mu S\ cm^{-1}$ after only four days in contact with surficial materials from a basin whose bedrock was rhyolite and surficial materials were composed of the rhyolite (Hill, 1990). A low SC spring exists at the base of

Mt. Rushmore. This spring which derives water from a surficial-deposit aquifer composed predominantly of mica schist and granitic rock detritus has an average SC of 90 μS cm^{-1} and a maximum measured SC of 125 μS cm^{-1} (Rahn, 1990).

Additional evidence which indicates that surficial-deposit-aquifer water has lower SC values than bedrock-aquifers water comes from nearby Park County, Wyoming. There is an approximate linear relation between SC and total dissolved solids (Fetter, 1994). The total dissolved solids of bedrock aquifer water is higher than the total dissolved solids of water from surficial-deposit aquifers in Park County. The average value (± one standard error) of total dissolved solids in bedrock wells (1702 ± 204 milligrams per liter) is higher than the average of surficial deposit well water (551 ± 46 milligrams per liter) (values calculated from data in Lowry et al., 1993).

Change of SC. The change of SC (ΔSC) (maximum recorded SC value minus minimum recorded SC value) should be higher for bedrock-aquifer water than surficial-deposit-aquifer water. The bedrock aquifer receives an input of low SC snowmelt each year as evidenced by the depth-to-water hydrographs (Fig. 2). This low SC snowmelt may mix with higher SC perennial bedrock groundwater. Specific electrical conductance will vary as the proportions of older and higher SC water vs. younger and lower SC snowmelt change. The surficial-deposit aquifer should have a more constant SC because the primary source of water is low SC snowmelt which has little time to reach higher SC levels before being discharged. The surficial-deposit-spring water at Mt. Rushmore has a ΔSC of only 55 μS cm^{-1} (Rahn, 1990).

Temperature

Comparison of Spring-Water Temperature to Spring Elevation. There should be a correlation between surficial-deposit spring-water temperature and spring elevation because ambient air temperature decreases with increased altitude. Spring-water temperatures, if sustained by shallow surficial aquifers, should mimic ambient air temperatures (Whittingham, 1996). A strong correlation coefficient should exist when a linear regression of spring elevation vs. spring-water temperature is calculated. Correlation coefficients of 0.459 and 0.759 supported the interpretation that the Maynard Creek catchment's spring discharge is dominated by the surficial-deposit aquifer (Whittingham, 1996).

Comparison of Bedrock and Surficial-Deposit Water Temperature. Bedrock and surficial-deposit-aquifer-water temperatures may have different temperature signatures. Once springs are divided into bedrock-aquifer springs and surficial-deposit-aquifer springs, the temperatures of the two groups can be averaged and compared to determine if a difference exists.

Comparison of Spring Temperature with Mean Annual Air Temperature. The comparison of spring-water temperature with mean annual air temperatures may reveal information regarding depth of groundwater circulation. A 1°- 2° C increase of groundwater temperature above the mean annual air temperature can be expected for water 100 m below ground surface (Freeze and Cherry, 1979). Groundwater temperature close to the local average annual air temperature circulates within 100 m or (rarely) 200 m of the ground surface; groundwater temperatures 6° C above mean annual air temperatures originate from deeper (>200 m) sources, and groundwater temperatures below the local average ambient air temperature indicate the system is recharged by

snowmelt (Mazor, 1991).

While the comparison of groundwater sampled from a well is adequate for the aforementioned constraints, comparison of groundwater sampled from springs must be considered in the perspective of Miller Creek basin's hydrologic and climatic system. First, spring temperatures can not exist below the mean annual ambient air temperature (-1° C). If the mean annual ambient air temperature was higher and spring temperatures were below this value, this would indicate the system is recharged by snowmelt (Mazor, 1991). Second, the residence time of these springs is unknown. Possibly, the spring water exists in the aquifers only during the summer months. Water may enter the groundwater system during spring or early summer and discharge by early fall; thus, only warmer summer ambient air temperatures may affect the temperature of a portion of water in the groundwater system.

Alternatively, water may exist perennially in the bedrock aquifer. Perennial bedrock aquifer water may be more reflective of circulation depth when the spring-water temperature is compared with mean annual ambient air temperature. However, the fact that average annual ambient temperature is not reflective of ground temperatures beneath snowpack and the addition of low temperature snowmelt recharge may complicate matters. Because of the number of potential complications, this test is only for the springs determined to derive water from the bedrock-aquifer. If a bedrock spring consistently discharges spring water 6° C above mean annual ambient air temperature, then that spring likely derives water from a source greater than 200 m deep in the bedrock aquifer.

Change of Temperature. The change of temperature (ΔT) of spring water can be an excellent way to distinguish bedrock springs from surficial-deposit springs. Temperature of shallow

aquifers is affected by ambient air temperature (Freeze and Cherry, 1979; Mazor, 1991; Taniguchi, 1993) while deeper water in bedrock aquifers is less prone to such influences; therefore, surficial deposit springs should have a larger ΔT than bedrock springs. Shallow surficial-deposit-aquifer-water temperature is expected to fluctuate in response to ambient air temperatures, and deeper bedrock-aquifer-water temperature is expected to have more constant temperatures through time, regardless of air temperature fluctuations. Miller Creek basin experiences great fluctuations in temperature which enables the study of the effects of air temperature on spring temperatures.

METHODS

Determining the quantities of water discharged by the bedrock and surficial-deposit aquifers to springs involved several different steps (Fig. 3). Geologic maps were compiled, field checked and prepared for digitization. In a step termed the geographic analysis springs could be grouped as geology-based bedrock springs or geology-based surficial-deposit springs based on the proximity of the spring to potential spring-producing geologic features (Table 1). A third group, the "initial-group-of-springs-of-unknown-origin" could not have their origin determined at this step because they were either proximal to several types of potential spring producing features or they were not near any. Some evidence regarding the origin of the "initial-group-of-springs-of-unknown-origin" could be gained by further subdividing this group based on whether or not these springs were proximal to a fault and/or lineament.

An analysis of pre-existing well data enabled evaluation of signatures of pH, SC and maximum change of SC (ΔSC) for the bedrock and surficial-deposit well water in the multi-agency investigation area. Springs from the initial-group-of-springs-of-unknown-origin were tested to determine if they shared pH, SC and ΔSC signatures with groundwater sampled from bedrock or surficial-deposit well water in the multi-agency investigation area. Specific electrical conductance was a good parameter with which to distinguish springs allowing two new groups to be formed: the SC-based bedrock springs and SC-based surficial-deposit springs. The geology-based bedrock springs group and the SC-based bedrock springs group were combined to form the geology/SC based bedrock springs group and the geology-based surficial-deposit springs group and the SC-based surficial-deposit springs group were combined to form the geology/SC-based springs group.

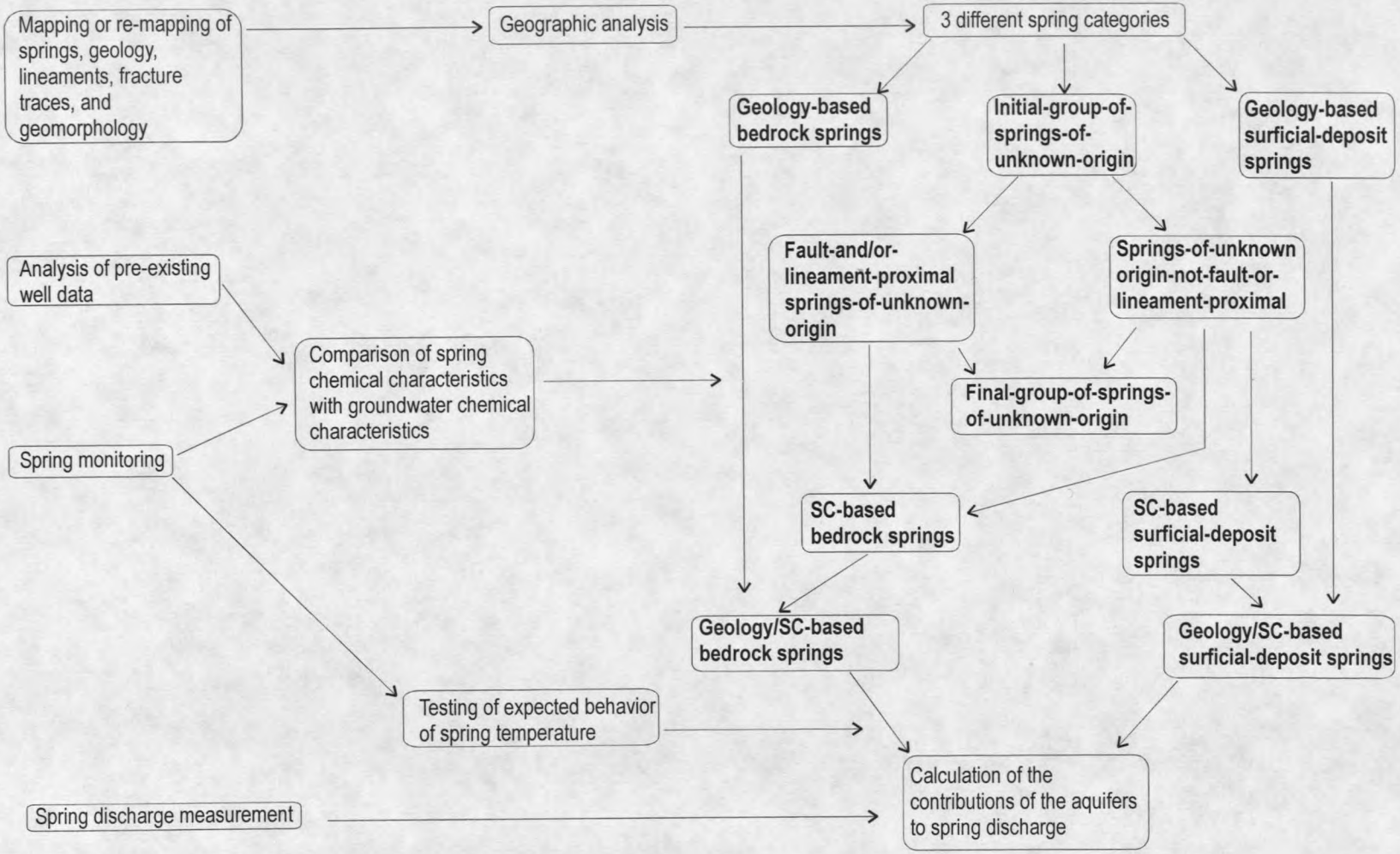


Figure 3. Methods flow chart. Key words used throughout text are **bold**.

The geology/SC-based bedrock and geology/SC-based surficial-deposit springs were then tested to determine whether these groups reflect expected bedrock and surficial-deposit-aquifer temperatures, respectively. Finally, the discharges from the two geology/SC-based spring groups were calculated.

Mapping

Mapping allowed the assessment of the spatial correlation of springs with geologic features. Three different maps were compiled: 1) spring locations, 2) lineament and fracture trace and 3) surficial geologic. Standard geologic mapping techniques and equipment (Brunton compass and a Casio ATC-1200 altimeter) were employed. The base map used for mapping was the 1:24,000 USGS Cooke City Quadrangle with 40 foot contour intervals published in 1986.

Mapping was performed using altimetry, triangulation and topographic referencing. Topographic referencing refers to the technique where the location of a spring or other point is found by determining whether the point is located on a ridge or gully or other suitable landmark and then finding the ridge or gully on the map. Altimetry could then be used to determine where along the ridge or gully the point is located, and finally triangulation allowed fine tuning or checking of the point's location. Using the combined techniques of altimetry, triangulation and topographic referencing the uncertainty for mapping is approximated at 30 m (100 ft).

Springs

Springs were mapped if their measurable discharge was greater than 0.1 l/min. This study attempted to map the location of every spring which had a discharge of at least 0.1 l/min. When a spring was discovered, the location was marked on a map and flagging was placed next to the

spring to enable sampling measurements to be taken at a consistent location. Additionally, information was recorded regarding whether the spring discharges from bedrock, surficial deposits or an adit and whether the spring channel has iron-stained substrate.

Lineaments and Fracture Traces

Lineaments and fracture traces were identified on aerial photographs using stereoscopic photograph pairs and a Bausch and Lomb 10X stereoscope. Lineaments are defined as natural linear features which are longer than 1500 m and fracture traces are linear features which are 300-1500 m long (Fetter, 1994). Linear features shorter than 1500 m defined by vegetation which trended perpendicular to ridge length were not considered to be fracture traces because these were likely caused by snow avalanches (Lovering, 1929) and not bedrock features. Linear features in Miller Creek's river bed and tributary river beds were considered fracture traces. Linear features in bedrock were also considered to be fracture traces if they were not at stratigraphic contacts.

Because lineaments and fracture traces could reach into the upper Miller Creek basin from outside the study area, the fracture trace and lineament analysis was not constrained to the boundary of the upper Miller Creek basin study area. The lineament and fracture trace analysis extended at least 1.5 km from the upper Miller Creek basin study area boundary.

Surficial Geology

A surficial geologic map was constructed for comparison with spring locations. Aerial photographs were used to help delineate the extent of surficial deposits and bedrock outcrops. Locations of the deposits were mapped in the field and surficial deposits were characterized in

terms of soil description, deposit morphology, clast lithology, clast size and where possible thickness. Clast lithologies and sizes were determined by visually inspecting numerous soil pits, road cuts and prospects in the upper Miller Creek basin.

Geographic Analysis

Understanding the spatial correlation between spring locations and potential spring-producing geologic features requires comparing information gained from different mapping techniques. Digitizing maps permitted position and scale rectification which allowed accurate overlaying of maps and subsequent determination of rectification uncertainty. The measuring point locations map, the surficial geologic map, the faults from maps by Elliot (1979) and CBM (unpublished), and the lineament and fracture trace maps were digitized using ARC/Info software. Elliot's (1979) geologic map was scanned to avoid prohibitively time consuming digitization of a complex map (Plate 2). Overlaying maps enabled determination of which springs were proximal to faults, lithologic contacts, lineaments and fracture traces and indicated which springs emanated from surficial deposits near the bedrock contact.

Assessment of spatial correlation between springs and the various geologic maps, required rectification of the geologic maps in digital format. The maps were rectified in position and scale with known geographic points present or transferred to all maps. Four section corners associated with the US public land survey system served as the known geographic points.

The rectification points and procedure could not be directly applied to lineament maps made from aerial photos or on unpublished CBM geologic maps which did not show section corners or UTM coordinates. The rectification process for CBM's unpublished map and the map of

lineaments and fracture traces required location of the section corners on CBM's map and the aerial photographs. Landmarks found on the base topographic map, the aerial photographs and the CBM map allowed location of the section corners on the aerial photographs and CBM's unpublished map. The process by which points can be transferred from map to photograph or map to map is outlined in Compton (1962, p. 85-87). Four landmarks were used to find each of the section corners.

Rectification and rectification uncertainty measurement were performed using Corel Draw™ 7. Rectification was possible because Corel Draw™ 7 can overlay images, proportionally resize images and measure the distance between two points. The first step of overlaying images entailed digitally placing a geologic map underneath the measuring point locations map. The scale of the underlain geologic map was proportionally resized and moved until the section corners of the geologic map were as close as possible to being perfectly beneath the section corners of the measuring points locations map. No measurable error existed on any map except Elliot's (1979) geologic map (Plates 2 and 4). Perfect rectification was not possible for the geologic map because of the difficulty of scanning maps without a small amount of distortion. The rectification uncertainty was determined by measuring the distance between the same section corners on Elliot's (1979) map and the spring location map set. For example, when the spring map was overlain on top of Elliot's (1979) map, the distance between the southeast section corner on the geologic map and the southeast section corner on the measuring point locations map was measured. This step was repeated for each corner and 14 m was the greatest discrepancy found.

The final portion of the geographic analysis was to determine which springs were spatially correlated with potential spring-producing geologic features. Using a ruler and laser printed hard

copies of the geologic maps with spring locations overlain, distances were measured from springs to potential spring-producing geologic features (Table 1). Interpretations based on whether the spring is proximal to bedrock or surficial-deposit spring-producing geologic features could then be made regarding whether a spring derived water from the bedrock or surficial-deposit aquifer.

Analysis of Pre-Existing Well Data

The purpose of the pre-existing data analysis was to determine if the bedrock aquifer or the surficial-deposit aquifer had distinguishable pH, SC, ΔSC, T or ΔT signatures. The first step in determining signatures was to determine if wells in the multi-agency investigation area derive water from the bedrock aquifer or the surficial-deposit aquifer. To do this, the lithologic well logs of the following wells were examined (**bold** if located within the study area boundary): MW-1, MW-2, MW-3, MW-4, **MW-5A, MW-5B, MW-5C, MW-5P, (lower-site)** MW-6, MW-8, MW-9, MW-10, MW-11, **MW-11A, MW-11B, MW-11P (upper-site)** and MW-13 (wells which are in bold face type can be found in Figure 1E and Plate 1). All wells are located within the multi-agency investigation area (Fig. 1C) (CBM, 1992). Wells were deemed "bedrock wells" if they are completed in lithologies interpreted to be bedrock by the well site geologist, screened only in bedrock and the outside of the well casing is grouted where surficial-deposit materials exists. Wells are deemed "surficial-deposit wells" if they are screened or completed in materials interpreted by the on site geologist to be surficial-deposit materials and capped at the bottom if they are drilled to bedrock.

Once the wells were divided into bedrock wells and surficial-deposit wells, pH and SC data could be analyzed to determine if certain consistent signatures existed in the bedrock wells or the surficial-deposit wells. A considerable amount of pH and SC data was collected from these wells

by other researchers as part of a baseline study in preparation for the mine proposed by CBM. Both field measured and lab measured data existed in the baseline study, but only the the data noted as field sampled was used to determine signatures. Field sampling of wells requires pumping of wells prior to sampling and rinsing of sampling devices with the water to be sampled. Correct sampling procedure by those who collected data for the baseline study is assumed. All pH and SC measurements taken from wells that are used in this study were noted by the original investigators as values which were taken in the field. Pumping of the correct volume of well water prior to sampling is assumed.

Spring Sampling

Springs were sampled for pH, SC and temperature to characterize geology-based springs and to divide springs in the initial-group-of-springs-of-unknown-origin into bedrock or surficial-deposit origin. Sampling of spring water using various instruments followed a standard procedure. A probe was first rinsed with the water to be sampled. The probe was then inserted as deep as possible into the spring discharge at the head of the spring. At some springs, the spring head would move down the spring channel away from the originally marked measuring point as summer progressed to fall. Field measurements were always taken within two meters of the originally marked measuring point and right at the originally marked measuring point if possible. If the spring flow was too low to allow the probe to be inserted, then a 500-ml bottle was rinsed and filled with spring water. The bottle was kept shaded while the instrument's probe was inserted and while the instrument adjusted to the pH, SC or temperature of the spring water. Measurements were recorded if two consecutive readings at a measuring point were the same. Time to equilibration

was typically less than five minutes.

A different instrument and calibration method was used for each measurement variable. The pH was measured using a Beckman 12 pH/ISE meter with a Beckman Thermocompensator electrode. The pH meter was calibrated using two different buffer solutions each time the instrument was turned on, and the probe was kept in 2 molar Potassium Chloride (KCl) solution in between measurements. Specific electrical conductance was measured using a Cole-Parmer 4070 conductivity meter. The SC meter was calibrated by Cole Parmer prior to sampling. All SC values reported in this study are adjusted to 25° C. Equation 1 was used to correct spring-water SC measurements to 25° C rather than a self correcting SC meter because self correcting SC meters generally do not correctly calculate SC for cold temperatures (Collins, 1977). For temperatures between 3° and 8° C, Equation 1

$$(25° \text{ C corrected SC}) = (\text{measured SC}) \times 0.95 / (1 + 0.091(T - 25)) \quad (1)$$

closely approximates the table of correction factors found in Golterman (1969). Most temperatures recorded in this study are between 3° and 8° C. Temperature was measured using a VWR 500 scientific digital thermometer. The thermometer was calibrated to ice water prior to each field season.

Discharge

Discharge was measured using a V-neck cut throat flume or a portable V-notch weir. If these devices did not fit a spring's irregular channel or if the discharge was diffuse or too large, then the discharge of the spring was visually estimated. Regardless of technique, discharges were measured or estimated in the same measuring location every time. If the spring was dry or

immeasurably small, this was noted and the discharge was recorded as 0.0 l/min. If the spring was flooded with water discharging from above, this was noted and no discharge measurement was recorded.

V-Neck Cut Throat Flume

The V-neck cut throat flume is a standard instrument which can easily be placed into channels to accurately measure discharge (Driscoll, 1986). To measure discharge, the flume was placed plumb and level in the spring channel as close as possible to the spring head while capturing as much water as possible. Hand levels helped assure that the flume was held plumb and level. Stage of the spring flow was measured using a thin (~1mm) plastic ruler. To minimize disturbance of the water, the width of the ruler was inserted parallel to spring-water flow direction. Stage was measured on the plastic ruler and then converted into discharge using Equation 2 which was determined by the flume manufacturers and based on the design of the flume.

$$Q=2.57\ h_a^{2.53} \qquad (2)$$

Q is the discharge in cubic feet per second (cfs), and h_a is the stage measured in feet (ft).

Portable V-Notch Weir

Because of irregular spring channel shape, not all spring discharges could be measured using the V-neck cut throat flume. A portable V-notch weir was designed and constructed by the author from a closed-bottom plastic cylinder. The cylinder could capture water and send the water to a 90° V-notch cut out of the cylinder's bottom (Fig. 4). When taking measurements, the V-notch was held in a vertical position perpendicular to the spring flow direction.

The measurements taken by the portable V-notch weir can be demonstrated to be

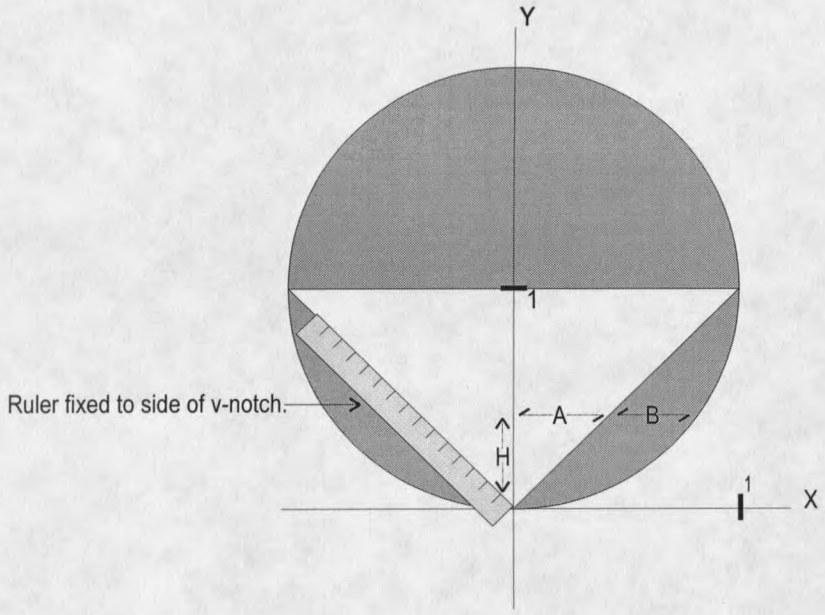


Figure 4. Portable V-notch weir, end view.

mathematically valid. The length *B* in Figure 4 must be greater than or equal to 150% the length, *A* (Eq. 3) (Driscoll, 1986, p. 1018).

$$B \geq 1.5A \tag{3}$$

Where *A* is the distance from the vertical bisector of the V-notch to the V-notch's edge, and B is the distance from the V-notch's edge to the edge of the barrel. If the bottom of the cylinder is imagined in Cartesian space, such that the bottom of the cylinder rests on the origin and the radius of the cylinder is the unit length $r=1$, then *A* is equal to *x* or *y* (Eq. 4);

$$A=x=y \tag{4}$$

and *B* can be solved for *y* using the equation of a circle (Eq. 5):

$$B=(r-(y-r)^2)^{1/2}-y \tag{5}$$

Substituting the values of *A* and *B* listed in Equations 4 and 5 into Equation 3 results in Equation 6:

$$r-(y-r)^2)^{1/2}-y \geq 3/2y \tag{6}$$

Equation 6 can be algebraically reduced to Equation 7:

$$0.276r \geq y \quad (7)$$

Equation 7 indicates that *B* is greater than or equal to 150% the length of *A* for values of *y* less than or equal to 0.276*r* meaning that discharges calculated for stages less than or equal to 27.6% of the cylinder radius are valid. Stages greater than 27.6% of the radius overestimate the discharge. The radius of the cylinder used in this study was 15.0 cm (0.5 ft), thus only discharges calculated from stages less than 4.1 cm (0.13 ft) are valid for the device used in this study.

Equation 8 was used to convert stage into discharge:

$$Q=2.4381H^{5/2} \text{ (Driscoll, 1986, p. 1018)} \quad (8)$$

Where *Q* is discharge in cfs and *H* is the stage in feet. Substituting the maximum stage (1.3×10^{-1} ft) for *H* indicates discharges of more than 28.2 l/min (16.5×10^{-2} cfs) are not valid. Testing the accuracy of the portable V-notch weir required comparing all discharge measurements less than 28.2 l/min taken by the portable V-notch weir with corresponding measurements taken at the same spring by the V-neck cut throat flume. Since the portable V-notch weir is largely experimental, the discharge values calculated from this device were not used in the summation of spring discharges. However, the discharge values calculated from this device proved to be useful when determining the accuracy of the V-neck cut throat flume.

RESULTS

Mapping

Springs

A total of 66 springs were mapped and measured. The springs locations are shown on Plate 1, and the spring locations are overlain on top of geologic maps in Plates 3, 4 and 5. Springs that discharge from bedrock or adits and springs that have iron-stained substrates are listed in Table 4. All springs not listed as discharging from bedrock or adits, discharge from surficial deposits.

Table 4. Field observations.

Springs that discharge from bedrock	*n*=4	M-1	M-29	M-54	M-67			
Springs that produce or have produced iron staining on the substrate below their discharge points	*n*=13	M-1	M-4	M-5	M-11B	M-30	M-31	M-44
		M-45	M-46	M-52	M-62	M-64	M-65	
Springs that discharge from adits or collapsed adits	*n*=4	M-1	M-4	M-24	M-24B			

Lineaments and Fracture Traces

Lineaments and fracture traces are marked by dotted lines on Plate 5. There is one lineament that trends northeast and there are several fracture traces of varying orientation. The one lineament extends outside of the study area. The lineament was identified on aerial photographs. The southwestern end of this lineament in the Miller Creek basin is distinguished in aerial photographs by a sharp color contrast between grey cliffs and rocks on the western side of the lineament and brown grass and meadows on the eastern side of the lineament in the Miller Creek basin. In the Fisher Creek basin the lineament is identified by a slight discoloration in the

aerial photograph. Further to the northeast the lineament follows drainage patterns of small tributaries. Field reconnaissance indicates that the portion of the lineament in the Miller Creek basin is defined by cliffs of Pilgrim Limestone and the linear terminus of coalescing talus cones. Fracture traces in the Miller Creek basin were distinguished in aerial photographs by troughs in bedrock outcrops and by straight reaches of Miller Creek and some tributaries.

Surficial Geology

The surficial geologic map and descriptions of surficial materials of upper Miller Creek basin are shown in Plate 3. The unit descriptions in Plate 3 describe the surficial materials of the Miller Creek basin. The only material that needs further discussion are alluvial materials. Uncosolidated alluvial material exists along the banks of Miller Creek in the form of channel bars consisting of silt, sand, gravel and cobbles. The deposits of alluvium do not exist on the surficial geologic map (Plate 3) because these deposits do not cover enough surface area to be mapped.

Geographic Analysis

The purpose of the geographic analysis was to determine which springs were proximal to potential spring-producing geologic features. Plates 3, 4 and 5 show spring locations overlain on top of the surficial geologic map, the geologic map and the lineament and fracture trace map. These were the maps used to determine whether springs were proximal to potential spring-producing geologic features.

Pre-Existing Well Data and Spring Sampling Data

The pH, SC, ΔSC and ΔT data for wells sampled in the multi-agency investigation area and for springs sampled during this study are presented in Figures 5, 6, 7 and 8. Additionally, the data collected from springs sampled during this study are presented in Appendix B.

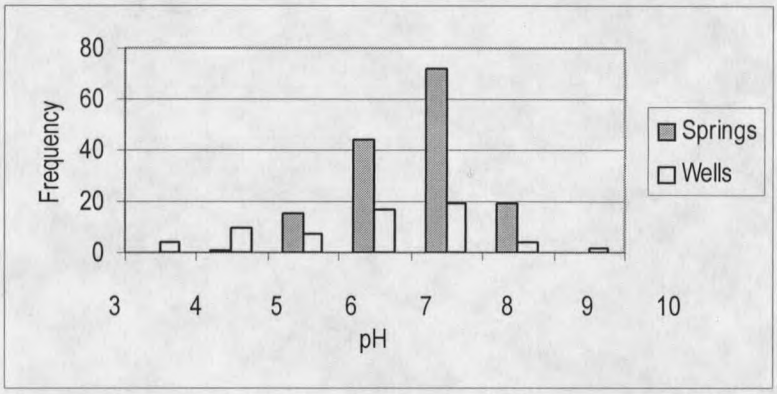


Figure 5. Histogram of pH data of water from springs (data collected during this study) and wells (data collected by other researchers at wells within the multi-agency investigation area).

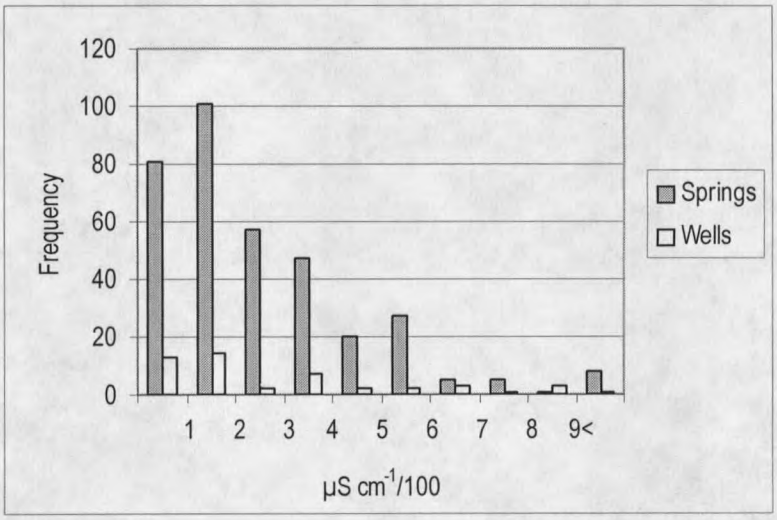


Figure 6. Histogram of specific electrical conductance values of water from springs (data collected during this study) and wells (data collected by other researchers at wells within the multi-agency investigation area).

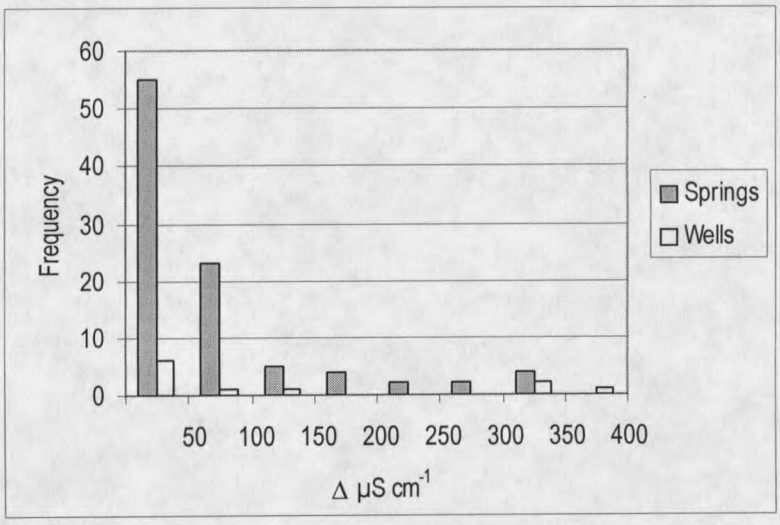


Figure 7. Histogram of maximum change of specific electrical conductance (ΔSC) of water from springs (data collected during this study) and wells (data collected by other researchers at wells within the multi-agency investigation area).

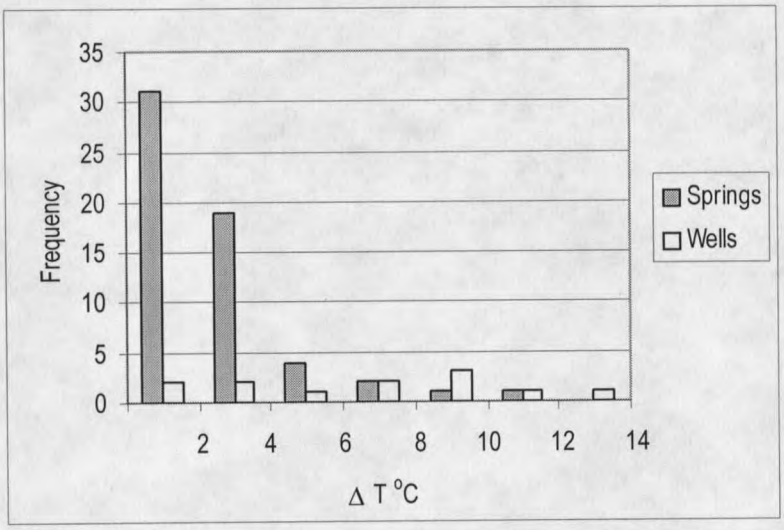


Figure 8. Histogram of maximum change of temperature (ΔT) data of water from springs (data collected during this study) and wells (data collected by other researchers at wells within the multi-agency investigation area).

Uncertainty of Spring Sampling Measurements.

The uncertainty associated with pH and temperature measurements is assumed to be

within the measurement uncertainty reported by the manufacturers of the instruments because the pH meter was calibrated frequently (every time the meter was turned on) and the thermometer was also calibrated sufficiently. For the pH meter the uncertainty was 0.01 and for the thermometer the uncertainty was 0.1° C.

Determining uncertainty is more difficult for SC measurements. Cole Parmer reports that the SC meter used in this study has a measurement uncertainty of 1.5%. Cole Parmer calibrated the machine prior to the 1996 season. Ideally, this calibration should have provided accurate results within ± 1.5% during the 1996 season. To check a probe's accuracy, one should calibrate the probe in a solution of KCl of known concentration before and after field work, (before and after each day of measurements is most preferable). At the end of the 1997 field season, the SC meter irreparably failed so the meter could not be checked for accuracy.

Measurements taken in 1996 were compared with measurements taken in 1997 to determine if time dependent drift existed in the SC meter (Fig. 9). The equation determined by the linear regression (Eq. 10):

$$y=0.94x \tag{10}$$

where y represents 1997 SC values and x represents the 1996 SC values, indicates that 1997 measurements are 6% lower than 1996 measurements. This 6% year to year variance could have been caused naturally or by drift of the SC meter.

If the SC meter did not drift, the meter could have begun to function more erratically during the 1997 season. To determine how erratic 1997 measurements could have been, the year to year variability was determined assuming that 1996 values were true. Ideally, if there was no year to year natural variability and there was no drift of the SC meter, the 1997 values would be within

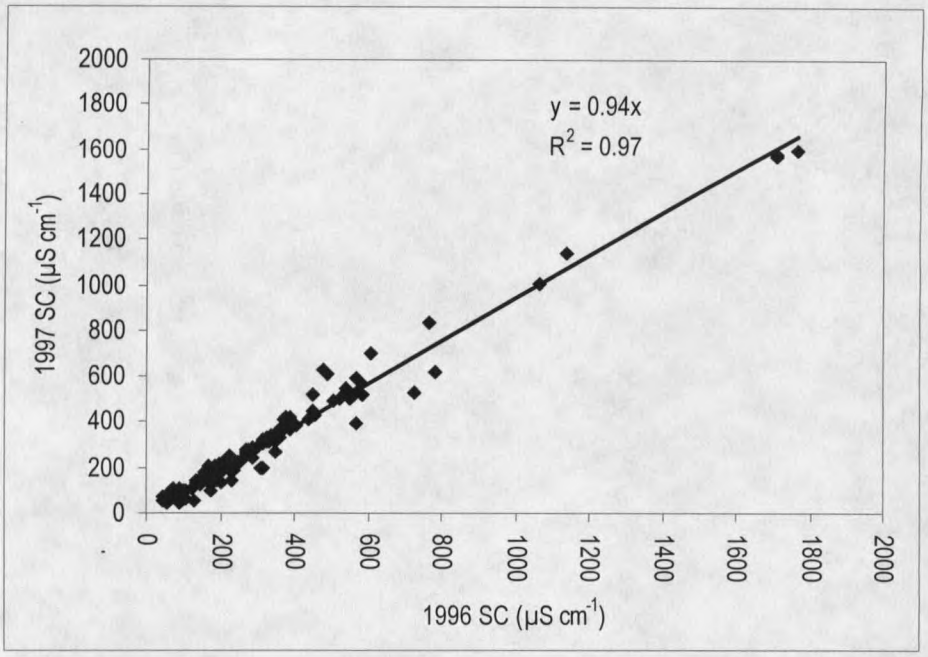


Figure 9. Correlation of specific electrical conductance values taken at springs in 1996 vs. specific electrical conductance values taken exactly one year later at the same springs.

1.5% of 1996 values. Absolute inter-year variability from 1996 to 1997 averages 11%. If a 6% decreasing drift is accounted for in 1997 measurements then inter-year variability is 12%. This 11-12% variability from one year to the next is the result of either natural inter-year variabilty or because of uncertainty associated with the SC meter. Twelve percent is interpreted to be the maximum uncertainty associated with the SC meter.

Discharge

Uncertainty

Discharge measurements are reported in Appendix B. There are three likely sources of discharge measurement uncertainty in this study. 1) If the flume or weir were not plumb and level when stage was recorded this would have propagated a false discharge calculation. Because

great care was taken to ensure that the measuring devices were plumb and level, this is a small source of error. 2) Error could have occurred at those springs that necessitated discharge estimation because of the qualitative nature of this method of discharge measurement. 3) Water which escaped measurement by flowing beneath or around the measuring devices could have caused measurements to be inaccurately small. Though every effort was made to create a tight contact between the spring channel bed and the flume or weir, water flowing underneath the discharge measuring devices was noted on several occasions.

An estimation for the discharge measurement precision uncertainty associated with misreading stage measurements (due to non-plumb and/or non level measuring devices) and improper discharge estimation is possible. The V-neck cut throat flume stage measurements were recorded in English units, and one-eighth of an inch is the maximum estimated amount that a stage measurement could have been misread. The portable V-notch weir measurements were measured in metric units, and 0.5 cm is the maximum estimated amount that a stage measurement could have been misread. The discharge uncertainty for a 1/8 inch or 0.5 cm misreading was calculated for the range of measurements recorded in this study. For smaller discharge measurements (0.1 l/min) the amount of uncertainty could be great (up to 90%). For larger measurements (566 l/min) the percentage of uncertainty was smaller (as low as 6%). For estimated discharges, a similar scale was used where smaller estimates had a large potential uncertainty (up to 100%) and larger estimates had smaller uncertainty (as low as 5%). When summing cumulative discharges for spring groups, the potential error for each cumulative discharge was determined by squaring each individual measurement's error, and then determining the square root of the mean of the squared errors values (known as RMS or root mean squared

error) (Anderson and Woessner, 1992, p. 241). This value represents the measurement precision. Thus, when a cumulative discharge value is reported, the value is always followed by a "±" and a value which is the measurement precision value.

An estimation of how much water escaped underneath the V-neck cut throat flume is important because the V-neck cut throat flume measurements were used in summing the cumulative discharge of spring groups. An estimation of this source of error is possible by comparing the discharges as measured by the portable V-notch weir with the discharges as measured by the V-neck cut throat flume (Fig. 10). Each data point in Figure 10 represents two discharge measurements taken at the same spring. The amount of time between a spring measurement pair was not more than a minute. The great scatter in Figure 10 is likely caused by the differing abilities of the two measuring devices to capture water. For example, the data point in the lower right hand corner (26, 4) indicates that at least 22 l/min escaped underneath or around the V-neck cut throat flume; i.e. the actual discharge of the spring may have been 650% or more greater than the V-neck cut throat flume indicated.

While some individual spring discharges could be greater than the V-neck flume discharge measurements by 650% or more, most measurements do not display such large error. Figure 11 is a histogram of the ratio of portable V-notch weir discharge measurements vs. V-neck cut throat flume measurements using the same discharge pairs that were used in Figure 10. The histogram in Figure 11 shows that more than three-quarters (168 out of 213) of the ratio values are less than one. This indicates the V-neck cut throat flume was able to capture more water than the portable V-notch weir more frequently. Because the V-neck cut throat flume appeared to be better at capturing spring discharge and since the portable V-notch weir was largely experimental, only the

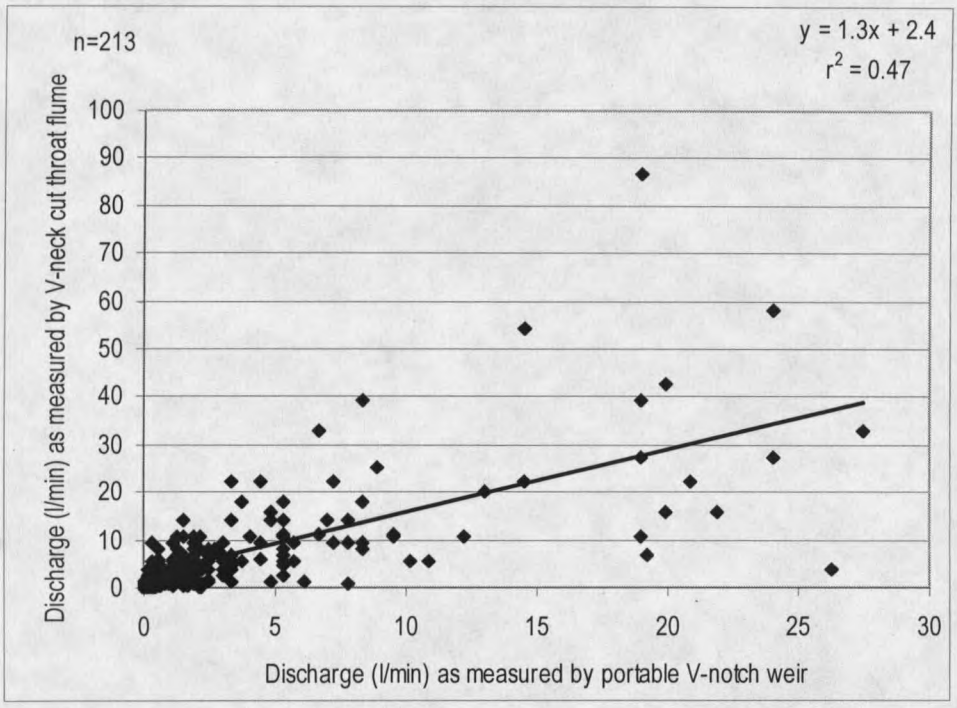


Figure 10. Correlation of discharge as measured by portable V-notch weir vs. discharge as measured by V-neck cutthroat flume.

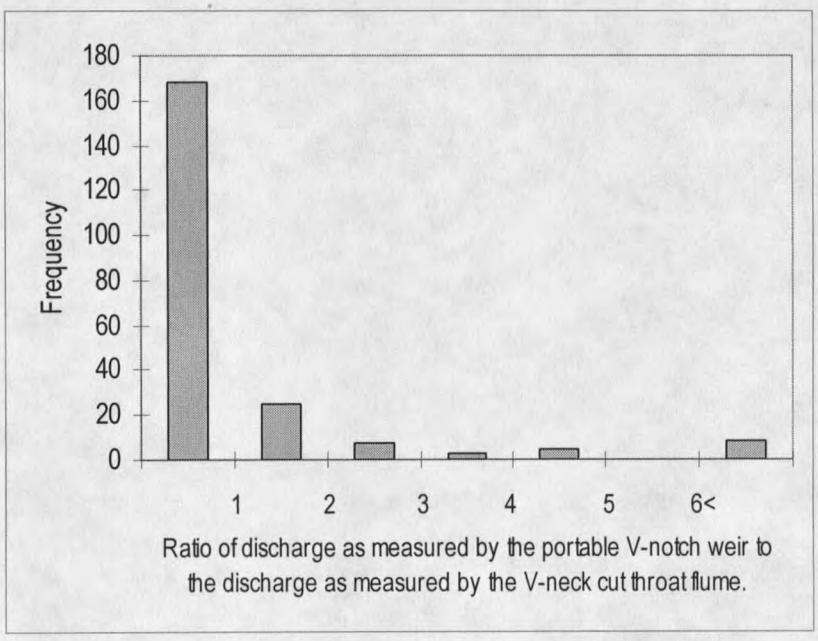


Figure 11: Histogram of the ratios of portable V-notch weir discharge measurements vs. V-neck cut throat flume discharge measurements.

flume data were used in summing cumulative discharges for spring groups.

Though the V-neck cut throat flume was able to catch more water more frequently, 45 of the 213 ratio values are greater than one (Fig. 11). In these 45 cases, the portable V-notch weir was able to capture more water than the V-neck cut throat flume.

Field notes indicate that there are four factors which could have contributed to unmeasured spring discharge. 1) In some cases, rocky substrates in spring channels prevented good flume/weir contact with the spring channel bed and water flowed underneath the discharge measuring devices. 2) Some springs were multi-headed with many small spring heads whose measurement would have been unproductively time intensive. 3) There were many other small springs which were unnoticed during the original spring mapping effort. The discharge of these originally unmapped springs were not recorded during the 1997 field season (some of these originally unnoticed springs are mapped on plate 1 with a question mark next to their location). 4) During the earlier parts of the field season, especially mid-July many springs could not be measured because they were snow covered. The uncertainty attributable to the accuracy of measurements is estimated to be as much as +100%. Thus, to correctly convey both precision and accuracy of measurements requires that each cumulative discharge is followed by a "±" sign and a value which represents the measurement precision as determined by the root mean square error method mentioned earlier and that each cumulative discharge value has a caveat which always appears in the text or table heading stating that because of unmeasurable spring discharge, the actual discharge values may be 100% larger than reported. The total measured spring discharges for 1997 are reported in Table 5.

Table 5. Cumulative discharge of all measured and estimated spring discharges. Because of unmeasurable spring discharge, the actual discharge values may be 100% larger than reported.

Date	Discharge (l/min)
7/17/97 & 7/23/97	3200 ± 130
7/31-8/2/97	1800 ± 90
8/20-21/97	1500 ± 75
9/14/97	1100 ± 66
10/7/97	700 ± 49

INTERPRETATIONS AND DISCUSSION

Geographic Analysis

The purpose of the geographic analysis was to determine which springs were proximal to potential spring-producing geologic features (Table 1). For the purposes of this study, if a spring is mapped within 50 m of a potential spring-producing geologic feature then the spring is defined as proximal to that feature. The distance of 50 m is meant to incorporate the uncertainty associated with rectification (14 m), and the mapping uncertainty (30 m).

Placement of all springs into the geology-based bedrock and surficial-deposit spring groups was not possible. Springs proximal to both bedrock and surficial-deposit spring-producing features and springs not proximal to any type of potential spring-producing geologic feature necessitated placement in a group titled the initial-group-of-springs-of-unknown-origin (Table 6). The initial-group-of-springs-of-unknown-origin could be further divided into those that are proximal to faults and/or lineaments and those that are not proximal to faults and/or lineaments. Fault and/or lineament proximity is important because bedrock subsurface water moves primarily as fracture flow in the study area (Maxim Technologies, 1995; BLM, 1997).

The results of the geographic analysis (Table 7) and the discharge measurements (Appendix B) allowed determination and comparison of the contributions of the bedrock and surficial-deposit aquifers (albeit based on geologic and hydrologic mapping) and the discharge of the initial-group-of-springs-of-unknown-origin (Table 8 and Fig. 12). Because of unmeasurable spring discharge, all of the following discharges may be 100% greater than reported. The initial-group-of-springs-of-unknown-origin appears to discharge much more than the geology-based

Table 6. Geology-based spring categories.

Geology-based bedrock springs		Springs located within 50 meters of a fault, fracture trace, lithologic contact, lineament or mineralized vein, or any combination of the aforementioned, but **not** within 50 meters of a downhill contact between a surficial deposit and underlying bedrock.
Geology-based surficial-deposit springs		Springs located within 50 meters of a contact between a surficial deposit and underlying bedrock, but **not** within 50 meters of a potential bedrock spring-producing feature.
Initial-group-of-springs-of-unknown-origin	Fault-and/or-lineament-proximal-springs-of-unknown-origin	Springs within 50 meters of a fault and/or lineament **and** within 50 meters of a downhill contact between a surficial deposit and underlying bedrock.
	Springs-of-unknown-origin-not-fault-or-lineament-proximal	Springs within 50 meters of a potential bedrock spring-producing feature **and** within 50 meters of a downhill contact between a surficial deposit and underlying bedrock, **but not within** 50 meters of a fault or lineament. Or, Springs **not** within 50 meters of a potential spring-producing geologic feature

Table 7. Geographic analysis results.

Geology-based bedrock springs	*n*=22	M-2	M-3	M-4	M-5	M-6	M-11B	M-13	M-15A	M-18	M-34A	M-34L
		M-34R	M-36	M-45	M-50	M-53	M-57	M-58	M-65	M-66	M-69	M-70
Geology-based surficial-deposit springs	*n*=10	M-19	M-20	M-23	M-24	M-24B	M-26A	M-31	M-39	M-40	M-41	
Fault-and/or-lineament-proximal-springs-of-unknown-origin	*n*=7	M-12	M-30	M-47	M-48	M-55	M-67	M-68A				
Springs-of-unknown-origin-not-fault-or-lineament-proximal	*n*=27	M-1	M-14	M-16A	M-16B	M-21	M-22	M-25A	M-25B	M-27	M-28	M-29
		M-35	M-37	M-42	M-43	M-44	M-46	M-49	M-51	M-52	M-54	M-56
		M-59	M-60	M-61	M-62	M-63						

spring groups. During the 1997 summer field measuring season the initial-group-of-springs-of-unknown-origin began with a discharge of 1900 ± 100 l/min in mid July and slowly decreased to a discharge of 400 ± 30 l/min, whereas the combined discharges of the geology-based spring groups was no more than 1300 ± 70 l/min in mid July subsequently decreasing to only 240 ± 70 l/min as summer progresses to fall.

Table 8. Calculated spring discharges of the initial-group-of-springs-of-unknown-origin and the geology-based bedrock and surficial-deposit springs groups. Because of unmeasurable discharge, all of the following values may be 100% greater than reported. The ± values represent discharge uncertainty due to reading error which may have occurred when stage measurements were recorded.

Measuring Period (1997)	Initial-group-of-springs-of-unknown-origin	Geology-based bedrock springs	Geology-based surficial-deposit springs
7/17&7/23	1900 ± 100 l/min	1300 ± 70 l/min	19 ± 4 l/min
7/31-8/2	1300 ± 70 l/min	460 ± 50 l/min	44 ± 8 l/min
8/20-21	1000 ± 60 l/min	430 ± 30 l/min	36 ± 7 l/min
9/14	740 ± 50 l/min	300 ± 20 l/min	29 ± 6 l/min
10/7	400 ± 30 l/min	240 ± 20 l/min	22 ± 4 l/min

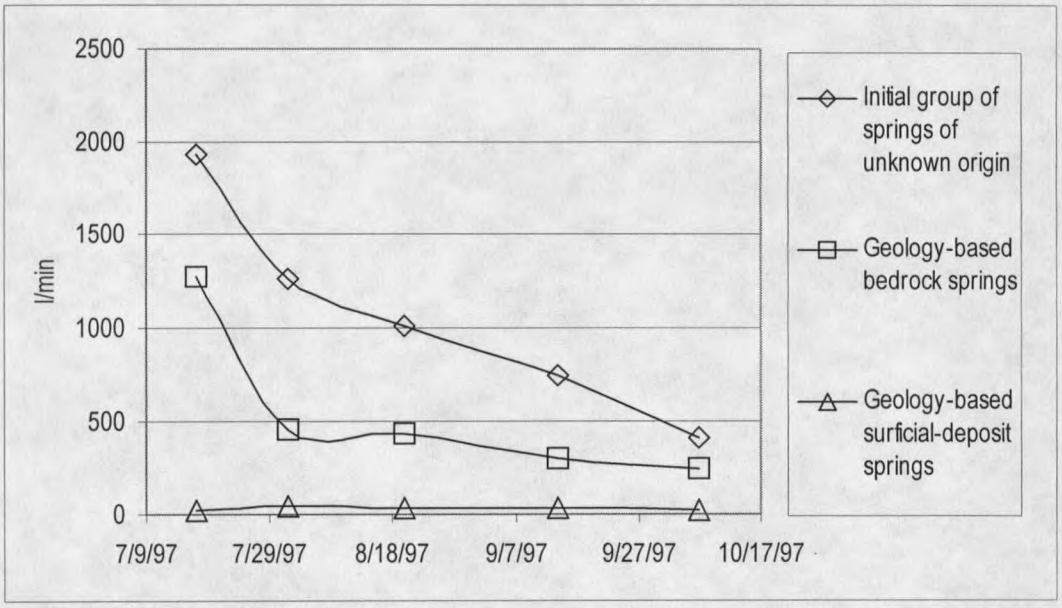


Figure 12. Summed discharges of the geology-based spring groups and the initial-group-of-springs-of-unknown-origin. Because of unmeasurable discharges, all of the cumulative discharge values used in the above graph may be 100% greater than reported.

Because the discharge of the initial-group-of-springs-of-unknown-origin is comparatively large the division of that group of springs is important. If the discharge of the initial-group-of-springs-of-unknown-origin belonged solely to the surficial-deposit aquifer, then the surficial-deposit aquifer would discharge a greater amount of water to springs than the bedrock aquifer. On the

other hand, if most of the discharge from the initial-group-of-springs-of-unknown-origin belonged to the bedrock aquifer then the bedrock aquifer would clearly dominate spring discharge.

Pre-Existing Well Water Data and Spring Sampling Data

Dividing the initial-group-of-springs-of-unknown-origin required the analysis of pre-existing well water data and spring sampling data. Analyzing pre-existing well water pH, SC and temperature allowed determination of whether distinguishable signatures exist which can be used to separate springs which derive water from the bedrock aquifer and springs which derive water from the surficial-deposit aquifer. The spring sampling and pre-existing well water data are presented together in this section to facilitate comparison between the well water and spring sampling data. The data are presented using standard box and whisker plots (Iman, 1994). The data collected from springs can be found in Appendix B.

Wells

The first step in analysis of well-water data was to interpret which wells derive water from the bedrock aquifer and which wells derive water from the surficial-deposit aquifer based on the materials and lithologies in which the wells are completed and/or screened. Analysis of well logs in the multi-agency study area (CBM, 1992) allowed division of wells presented in Table 9.

Table 9. Subdivision of wells based on well log data.

Bedrock wells *n*=11		Surficial-deposit wells *n*=6
MW-1, MW-2, MW-3, MW-5B, MW-5C, MW-5P, MW-6, MW-8, MW-11A, MW-11B, MW-11P		MW-4, MW-5A, MW-9, MW-10, MW-11, MW-13

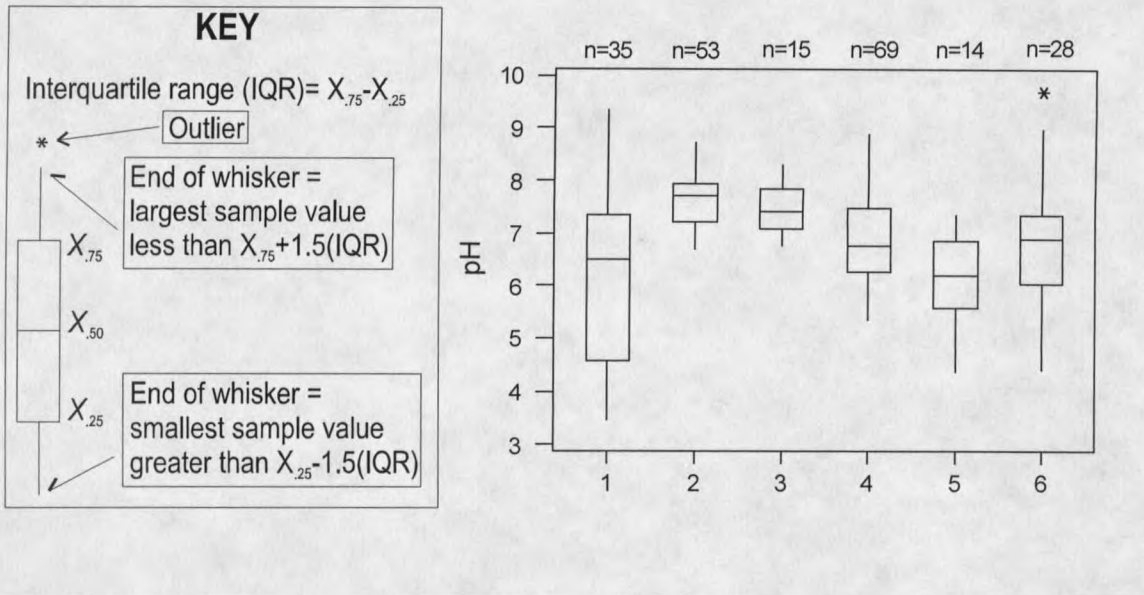
pH

Values of pH were not expected to be able to distinguish surficial-deposit-aquifer water from bedrock-aquifer water. The reason for measuring the pH of springs was to provide data for future work because the location of low pH sources is of interest in the Miller Creek basin. The pH values of measuring points are listed in Appendix B and the locations of the springs are indicated on Plate 1. There are only a few measuring point locations where the water appears to be acidic. Measuring point locations M-21, M-23, M-26A, M-59 and M-60 are the only measuring points which discharge water with pH values below 6.00.

Despite, the lack of an expectation which would distinguish surficial-deposit-aquifer water and bedrock-aquifer-water, the various spring groups were compared to determine if differences in pH values did exist. Comparison of pH values did not distinguish bedrock-aquifer water from surficial-deposit-aquifer water because the interquartile range of bedrock well-water pH (4.57-7.34) overlaps the interquartile range of surficial-deposit well water pH (6.04-7.37) (Fig. 13).

There is not a clear distinction between the fault-and/or-lineament-proximal-springs-of-unknown-origin and springs-of-unknown-origin-not-fault-or-lineament proximal. The interquartile range of spring water from fault-and/or-lineament-proximal-springs-of-unknown-origin (pH 7.08-7.83) overlaps the interquartile range of spring water from the springs-of-unknown-origin-not-fault-or-lineament-proximal (pH 6.26-7.49) (Fig. 13).

Despite overlapping pH values for the well groups and the two groups of springs of unknown origin, the interquartile ranges of the two geology-based spring groups do not overlap (Fig. 13). The interquartile range of the geology-based bedrock springs (pH 7.24-7.96) is higher



1= bedrock wells 2=geology-based bedrock springs 3=fault-and/or-lineament-proximal-springs-of-unknown-origin	4=springs-of-unknown-origin-not-fault-or-lineament-proximal 5=geology-based surficial-deposit springs 6=surficial-deposit wells

Figure 13. Box and whisker plots of pH values. Classified by spring group and unit in which well was completed.

than the interquartile range of the geology-based surficial-deposit springs (pH 5.59-6.85). The difference in interquartile ranges of the two geology-based groups indicates that a difference in pH may exist for geology-based bedrock springs and geology-based surficial-deposit springs in the upper Miller Creek basin.

Origin of pH Patterns. This study indicates that geology-based bedrock springs may have an alkaline pH and geology-based surficial-deposit springs may have an acidic pH in the upper Miller Creek basin (Fig. 13). However, this distinction between pH values was not noted between the bedrock and surficial-deposit aquifer in the well water data from the multi-agency investigation area. The higher pH values of Miller Creek basin's geology-based bedrock springs could be due to the location of many of these bedrock springs near limestone bedrock.

Specific Electrical Conductance

SC Values. Specific electrical conductance values are expected to be higher for the bedrock aquifer than the surficial-deposit aquifer because groundwater in the bedrock aquifer is postulated to have a longer residence time than groundwater in the surficial-deposit aquifer. This expectation was supported in that the interquartile ranges of SC values for bedrock-aquifer components are all higher than the interquartile ranges of SC values for surficial-deposit-aquifer components, and the SC values of geology-based-bedrock-spring water and geology-based-surficial-deposit-spring water are similar to the SC values of bedrock and surficial-deposit-well water, respectively (Fig. 14). The interquartile range of bedrock-well water (293-656 $\mu S\ cm^{-1}$) is higher than the interquartile range of surficial-deposit-well water (68-125 $\mu S\ cm^{-1}$). The interquartile range of geology-based bedrock-spring water SC (233-474 $\mu S\ cm^{-1}$) is higher than the interquartile range of geology-based surficial-deposit-spring water (69-182 $\mu S\ cm^{-1}$). The interquartile range of SC values from fault-and/or-lineament-proximal-springs-of-unknown-origin (178-467 $\mu S\ cm^{-1}$) is greater than the interquartile range of the SC values from springs of unknown origin which are not fault or lineament proximal (80-198 $\mu S\ cm^{-1}$). However, the latter group contains outliers which are 306 $\mu S\ cm^{-1}$ and higher. The expectation that bedrock-aquifer water has higher SC values than surficial-deposit-aquifer water is supported.

Change of SC. Analysis of the values determined by subtracting the maximum SC value minus the minimum SC value (ΔSC) indicate differences exist between bedrock and surficial-deposit-aquifer components. Bedrock-aquifer water is expected to have higher ΔSC values than the surficial-deposit-aquifer water because bedrock-aquifer water receives an annual input of low

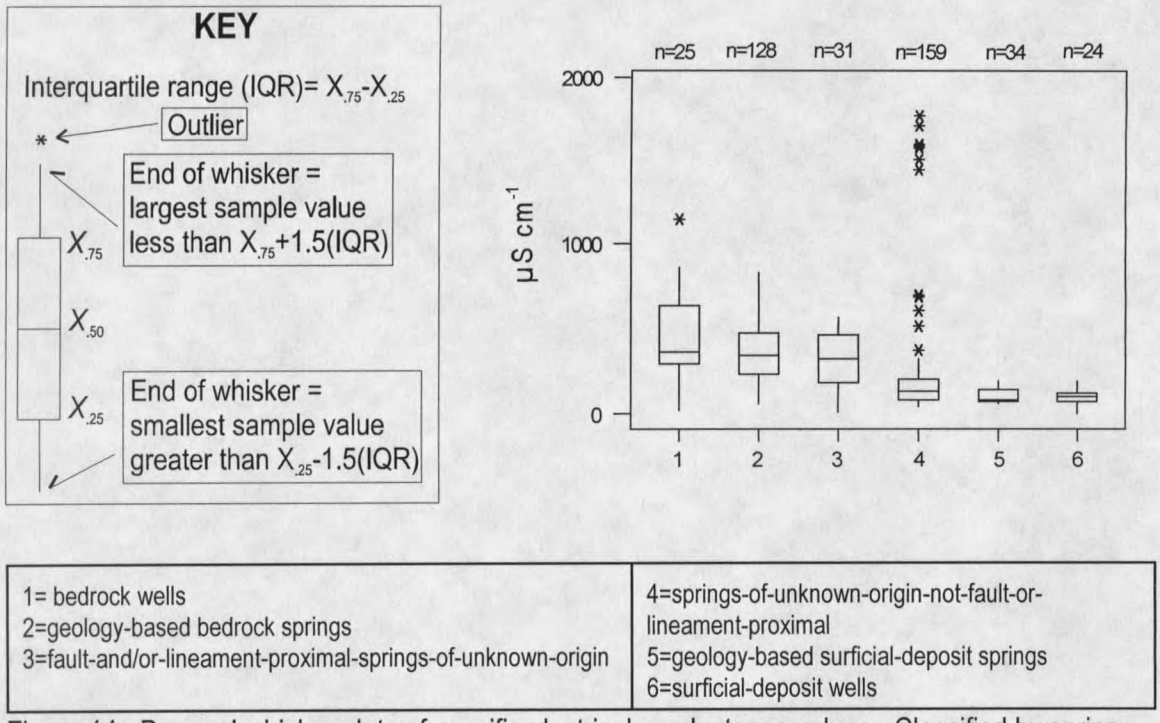
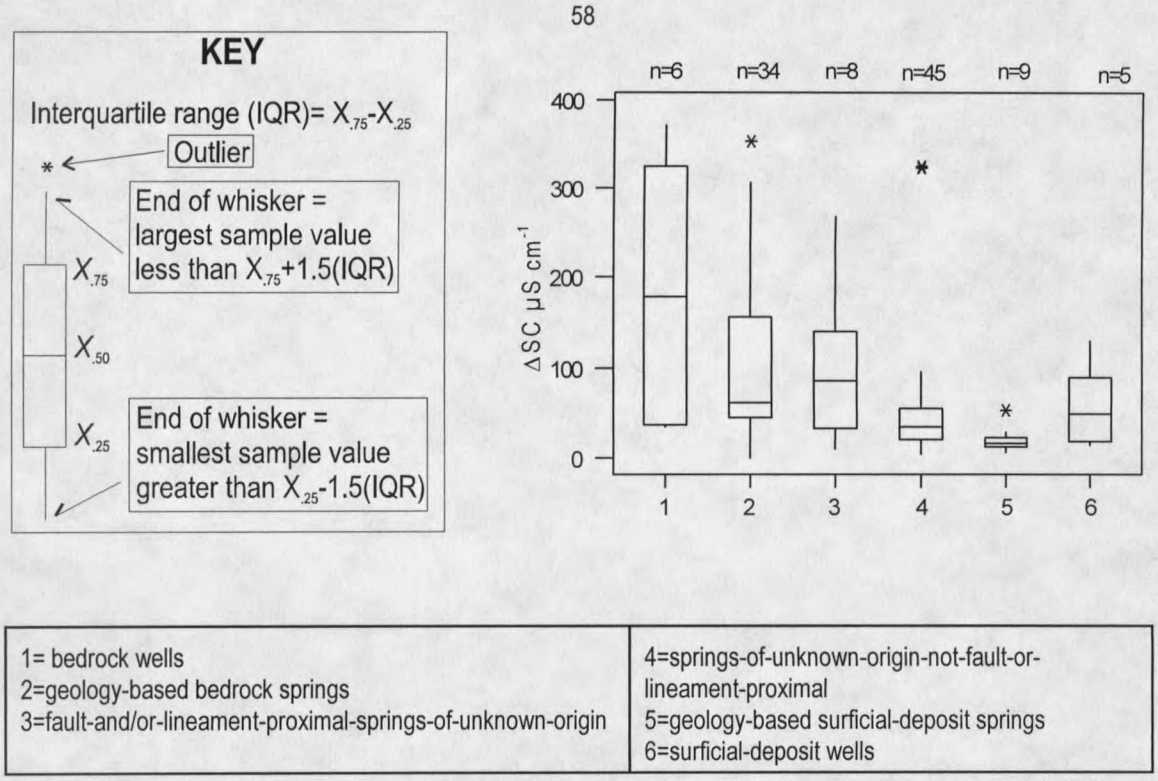


Figure 14. Box and whisker plots of specific electrical conductance values. Classified by spring group and unit in which well was completed.

SC snowmelt which mixes with higher SC perennial groundwater, whereas the surficial-deposit aquifer is annually depleted of most groundwater thereby not allowing mixing or variability of SC to occur. The bedrock-aquifer components have higher ΔSC values (Fig. 15). The interquartile range of bedrock-well water ΔSC (37-326 µS cm^{-1}), is greater than the interquartile range of surficial-deposit-well water ΔSC (19-89 µS cm^{-1}). The interquartile range of geology-based bedrock-spring water ΔSC (44-157 µS cm^{-1}) is greater than the interquartile range of geology-based surficial-deposit-spring water ΔSC (12-23 µS cm^{-1}). The interquartile range of ΔSC values from fault-and/or-lineament-proximal-springs-of-unknown-origin (33-139 µS cm^{-1}) is greater than the interquartile range of springs-of unknown-origin-not-fault-or-lineament-proximal (20-56 µS cm^{-1}). The expectation that bedrock aquifer water has a higher ΔSC is supported in



1= bedrock wells 2=geology-based bedrock springs 3=fault-and/or-lineament-proximal-springs-of-unknown-origin	4=springs-of-unknown-origin-not-fault-or-lineament-proximal 5=geology-based surficial-deposit springs 6=surficial-deposit wells

Figure 15. Box and whisker plots of maximum change of specific electrical conductance (ΔSC) values. Classified by spring group and unit in which well was completed.

that there are bedrock aquifer components which have high ΔSC values, but the overlap in interquartile ranges of the bedrock and surficial-deposit aquifer components (Fig. 15) indicates that ΔSC is not a good criterion for determining whether a spring originates from the bedrock or surficial-deposit aquifer when ΔSC is low.

Origin of SC Values and Change of SC Patterns. The results and interpretations of this study indicate that bedrock-aquifer water has a higher and more variable SC than the surficial-deposit aquifer. The following hypothesis is proposed to explain the higher and more variable SC of the bedrock aquifer. Water remains in contact with the bedrock aquifer perennially, whereas water in the surficial-deposit aquifer remains in contact only seasonally (as interpreted by depth-to-water hydrographs (Fig. 2)). The longer contact time of the bedrock-aquifer water allows the water

to achieve higher SC values because the degree of mineralization (and therefore SC) is a function of groundwater residence time (Back and Hanshaw, 1970).

The more variable SC of the bedrock aquifer is hypothesized to be a result of annual snowmelt recharge mixing with perennial bedrock groundwater. Each year snowmelt recharges both the bedrock aquifer and the surficial-deposit aquifer. When the bedrock aquifer is recharged with snowmelt during spring and early summer, the low SC snowmelt mixes with higher SC perennial groundwater and causes the SC of the bedrock aquifer water to vary depending on the amount of mixing that occurs. This variability does not occur in the surficial-deposit aquifer because little if any perennial groundwater exists in the surficial-deposit aquifer.

There are two measuring points which have noticeably elevated (>1000 $\mu S\ cm^{-1}$) average SC values. The two measuring points are M-1 and M-64. M-1 discharges from an adit (Table 4) and M-64 is a well which has groundwater discharging from the base of the portion of casing which sticks up above the ground. Both of the channels formed by these groundwater discharge points have iron-stained substrate (Table 4). The high SC values and iron-stained substrate of these features may be related to the oxidation of sulfides by the spring water. Interestingly, both M-1 (adit spring) and M-64 (leaking well) are associated with manmade features.

Dividing the Initial-Group-of-Springs-of-Unknown-Origin

SC was used to divide the initial-group-of-springs-of-unknown-origin, because the interquartile range of bedrock-well water SC is higher than the interquartile range of surficial-deposit-well water SC (Fig. 14). To separate the initial-group-of-springs-of-unknown-origin into the bedrock and surficial-deposit aquifer components, the averages of individual well SC values were

used. The lowest individual bedrock-well average (± one standard deviation) SC was 185 ± 16 µS cm^{-1}, and the highest individual surficial-deposit-well average was 138 ± 22 µS cm^{-1}.

The division of springs in the initial-group-of-springs-of-unknown-origin was based on the following reasoning. Spring water with an average SC higher than the lowest-bedrock-well-water average SC is likely bedrock derived and spring-water with an average SC lower than the highest surficial-deposit-well-water average SC is likely surficial deposit derived. Applying this reasoning resulted in the final division of springs (Table 10 and Fig. 16). Those springs with average SC values above 185 µS cm^{-1} were deemed SC-based bedrock springs (*n*=9). Those springs with average SC values below 138 µS cm^{-1} were deemed SC-based surficial-deposit springs (*n*=15). Springs with values between 138 and 185 µS cm^{-1} were placed in the final-group-of-springs-of-unknown-origin (*n*=7). Three other springs, M-55, M-67 and M-68A were also placed in the final-group-of-springs-of-unknown-origin because these springs had insufficient SC data (n<2).

Table 10. Division of the initial-group-of-springs-of-unknown-origin.

SC-based bedrock springs	*n*=9	M-1	M-14	M-16A	M-30	M-37	M-47	M-48	M-49	M-54
SC-based surficial-deposit springs	*n*=15	M-21	M-22	M-25A	M-28	M-35	M-42	M-43	M-44	M-46
		M-51	M-52	M-59	M-60	M-61	M-62			
Final-group-of-springs-of-unknown-origin	*n*=10	M-12	M-16B	M-25B	M-27	M-29	M-55	M-56	M-63	M-67
		M-68A								

The resulting SC-based-bedrock springs were pooled with the geology-based-bedrock springs group to form the geology/SC-based bedrock springs group and the SC-based-surficial-

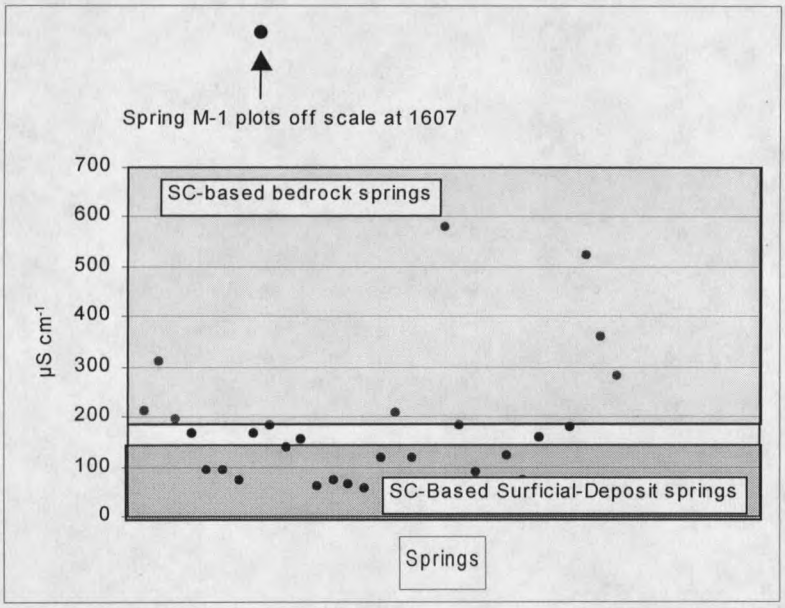


Figure 16. Average specific electrical conductance values from springs in the initial-group-of-springs-of-unknown-origin.

deposit springs were pooled with the geology-based-surficial-deposit-springs to form the geology/SC-based surficial-deposit springs group (Fig. 3). The discharges of the springs in each of the two groups could then be summed and graphed (Table 11 and Fig. 17).

Table 11. Calculated spring discharges of the geology/SC-based bedrock and surficial-deposit springs. Because of unmeasurable discharge all of the following discharges may be 100% greater than reported. The ± values represent discharge uncertainty due to reading error which may have occurred when stage measurements were recorded.

Measuring Period (1997)	Final-group-of-springs-of-unknown-origin	Geology/SC-based bedrock springs	Geology/SC-based surficial-deposit springs
7/17&7/23	570 ± 30 l/min	2000 ± 100 l/min	660 ± 40 l/min
7/31-8/2	600 ± 40 l/min	690 ± 40 l/min	480 ± 30 l/min
8/20-21	520 ± 30 l/min	610 ± 40 l/min	330 ± 20 l/min
9/14	360 ± 30 l/min	410 ± 30 l/min	290 ± 20 l/min
10/7	160 ± 20 l/min	320 ± 20 l/min	180 ± 20 l/min

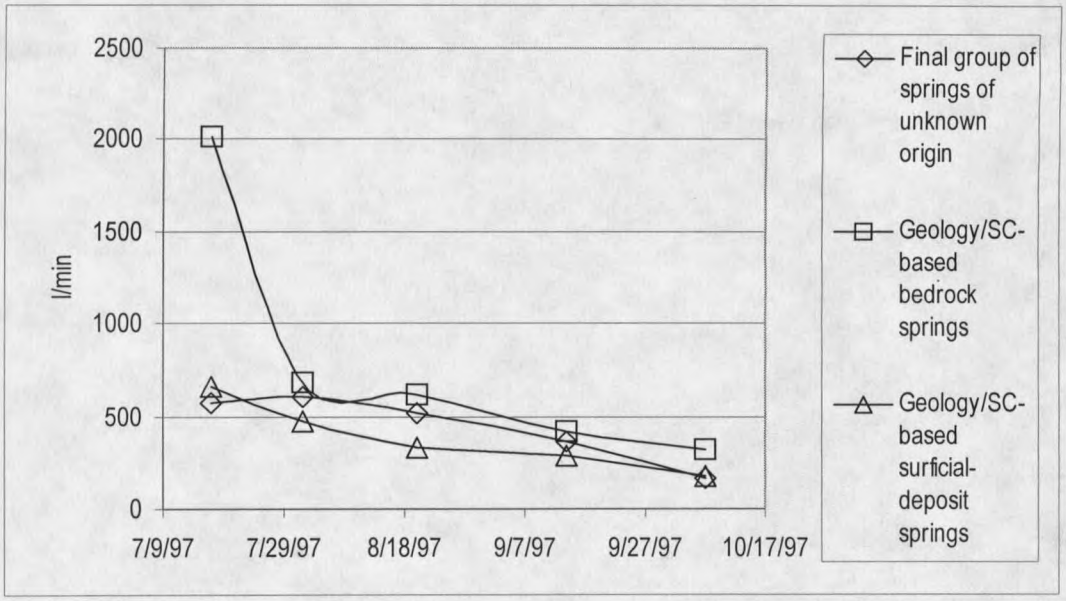


Figure 17. Summed discharge of geology/SC-based spring groups and the final-group-of-springs-of-unknown-origin. Because of unmeasurable discharges, all of the cumulative discharge values used in the above graph may be 100% greater than reported.

Bedrock and Surficial-Deposit Aquifer Behavior and Contribution to Spring Discharge

The geology/SC-based bedrock springs group dominates spring discharge during the early part (mid-July) of the 1997 field season. The geology/SC-based bedrock springs' discharge during mid-July, 1997 was 2000 ± 100 l/min (over half of the total measured and estimated spring discharge). Because of unmeasurable discharge, the 2000 l/min value may be 100% larger. During the remainder of the 1997 field season, determining which aquifer dominates spring discharge is not possible because all three spring groups discharge nearly equal amounts of water (Fig. 17).

Although determining which aquifer dominates spring discharge during the latter part of the 1997 sampling period is difficult, very important information regarding bedrock and surficial-

deposit aquifer behavior is gained from the spring discharge hydrographs. After snowmelt recharge occurred in 1997, the geology/SC-based bedrock springs responded with a large discharge of 2000 ± 100 l/min. This large discharge then rapidly declined to just 690 ± 40 l/min in approximately 2 weeks and slowly declined to a discharge of at least 320 ± 20 l/min by early October. Because of unmeasurable discharge the aforementioned and the following cumulative discharge values may be 100% greater than reported. Of great importance is the fact that geology/SC-based bedrock-spring discharge is 6 times greater in mid July than in early October. Interestingly, the geology-based bedrock springs display a similar behavior. The discharge from geology-based bedrock springs started with a mid-July discharge of 1300 ± 70 l/min and then declined rapidly within two weeks to a discharge of only 460 ± 50 l/min in early August. Subsequently, the discharge of the geology-based bedrock springs slowly declined to 240 ± 20 l/min in early October (Table 8 and Fig. 12) (note the mid-July discharge value is approximately six times greater than the early October discharge value).

In contrast to the geology-based bedrock springs and the geology/SC-based bedrock springs, the geology/SC-based surficial-deposit springs do not display a large drop in discharge after the 1997 snowmelt period, and the spring discharge of this group appears to decrease slowly throughout the measuring period. The discharge of the geology/SC-based surficial-deposit springs group begins at 660 ± 40 l/min in mid-July and declines steadily to 180 ± 20 l/min in early October (Fig. 17). Because of unmeasurable discharge, the aforementioned values could be 100% larger than reported.

Aquifer Behavior Beyond the Sampling Period

Spring-water sampling is difficult from October through June due to snow cover and inclement weather. However, some interpretations can be made regarding the behavior of the aquifers beyond the sampling season. Spring data collected on November 9-10, 1996 indicates that the bedrock aquifer continues to discharge during late fall. On November 9-10, 1996, the overlying snowpack was removed from above 14 springs (Table 12). Springs lay beneath approximately one meter of snow in the upper Miller Creek basin. Fisher Creek SNOTEL data from these dates indicate that a snowpack of 9.4 cm (3.7 in) in snow water equivalent units existed and that a measurable snowpack had existed since October 16, 1996. Thirteen of the 14 springs uncovered from snow had flows strong enough to allow the measurement of their SC values. With the exception of M-12, the SC values of all springs were above 193 $\mu S\ cm^{-1}$ which is the highest SC value measured in a surficial-deposit well or geology-based surficial-deposit spring. When the springs were dug out from the snow they had not yet been classified as bedrock or surficial-deposit springs. The springs were chosen based on the author's judgement about which springs would be easy to find and which springs were likely to still be flowing. Interestingly, 11 out of the 13 flowing springs uncovered from the snow are grouped as bedrock springs. The elevated SC values and grouping of these springs as bedrock springs is evidence which indicates that the bedrock aquifer continued to discharge to springs during mid fall 1996 after a snowpack had accumulated in the upper Miller Creek basin.

While the bedrock aquifer appears to continue discharging to springs during mid fall, portions of the surficial-deposit aquifer appear to become depleted of groundwater. Based on depth-to-water well data measured during late fall months from several different years, portions of

Table 12. Springs measured on November 9-10, 1996.

Spring #	SC	Temperature	Type of spring
M-1	1439	2.2	SC-based bedrock
M-2	346	0.7	Geology-based bedrock
M-3	415	3.3	Geology-based bedrock
M-4	524	1.4	Geology-based bedrock
M-12	178	0.6	Fault and/or lineament proximal spring of unknown origin
M-13	279	2.9	Geology-based bedrock
M-14	211	2.6	SC-based bedrock
M-30	530	2.5	SC-based bedrock
M-36	Dry	Dry	Geology-based bedrock
M-45	539	3.1	Geology-based bedrock
M-47	467	1.0	SC-based bedrock
M-57	377	3.0	Geology-based bedrock
M-63	217	2.4	Spring of unknown origin not fault or lineament proximal
M-65	430	2.5	Geology-based bedrock
M-64	1118	2.1	Leaking Well
M-11*	Dry	Dry	*Spring surface-flow measuring point. For discussion of spring surface-flow measuring points see Appendix A, p. 98.
M-15*	186	1.3	

the surficial-deposit aquifer become dry during mid fall (Fig. 2). On the other hand, the bedrock aquifer appears to continue discharging to springs during mid-fall.

Temperature

The purpose of collecting temperature was to allow the field measured SC values to be corrected to 25° C. The temperature could also be used to test whether geology/SC-based

bedrock springs and the geology/SC-based surficial-deposit springs reflect expected temperature tendencies for bedrock and surficial-deposit aquifers, respectively.

Comparison of Spring-Water Temperature to Spring Elevation. Surficial-deposit spring temperatures were expected to exhibit strong correlations with spring elevation and bedrock spring temperatures were expected to exhibit weak correlations with spring elevation. The comparison of spring-water temperature to spring elevation provides some evidence to indicate the bedrock and surficial-deposit springs were grouped correctly. The bedrock spring groups show generally poor correlations between spring water temperature and elevation as expected. However, the surficial-deposit spring groups also generally exhibit poor correlations. On most days where at least 10% of the springs were sampled, correlation coefficients are generally poor (r^2 <0.45) with minor exception (Figs. 18, 19, 20 and 21).

Despite the overall poor correlations for the surficial-deposit spring groups, there is some evidence which indicates a relation exists between surficial-deposit spring-water temperature and ambient air temperature. On October 7, 1997 the correlation coefficient for geology/SC-based surficial-deposit springs is 0.46 Fig. (21I), and on the same date geology-based surficial-deposit spring temperatures have a 0.61 correlation coefficient (Fig. 19E). The equations in Figures 19E and 21I indicate that the spring-water temperatures decrease at a rate of 0.4° and 0.6° C per 100 m of elevation gain, respectively. This is close to the rate of atmospheric cooling cited for the world (0.65° C per 100 m elevation gain) (Battan, 1979). Additionally, there are overall negative slopes for the linear regressions for all geology-based surficial-deposit springs and all geology/SC-based surficial-deposit springs (Figs. 19 and 21) indicating that for these groups there is a relationship whereby spring-water temperature decreases with increased elevation.

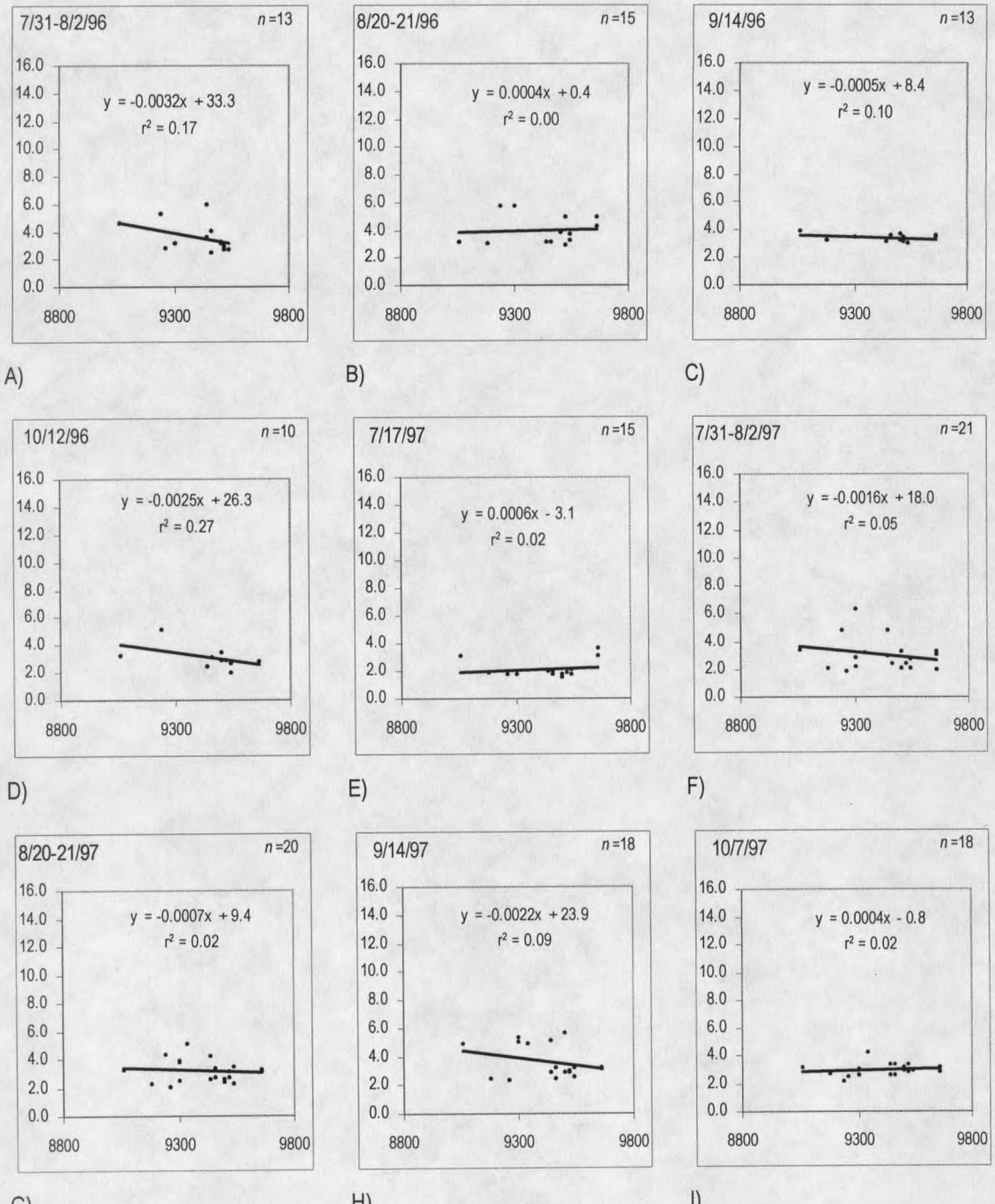


Figure 18. Geology-based bedrock spring water-temperature vs. spring elevation. Elevation in feet on X-axis and spring water temperature in degrees Celsius on Y-axis.

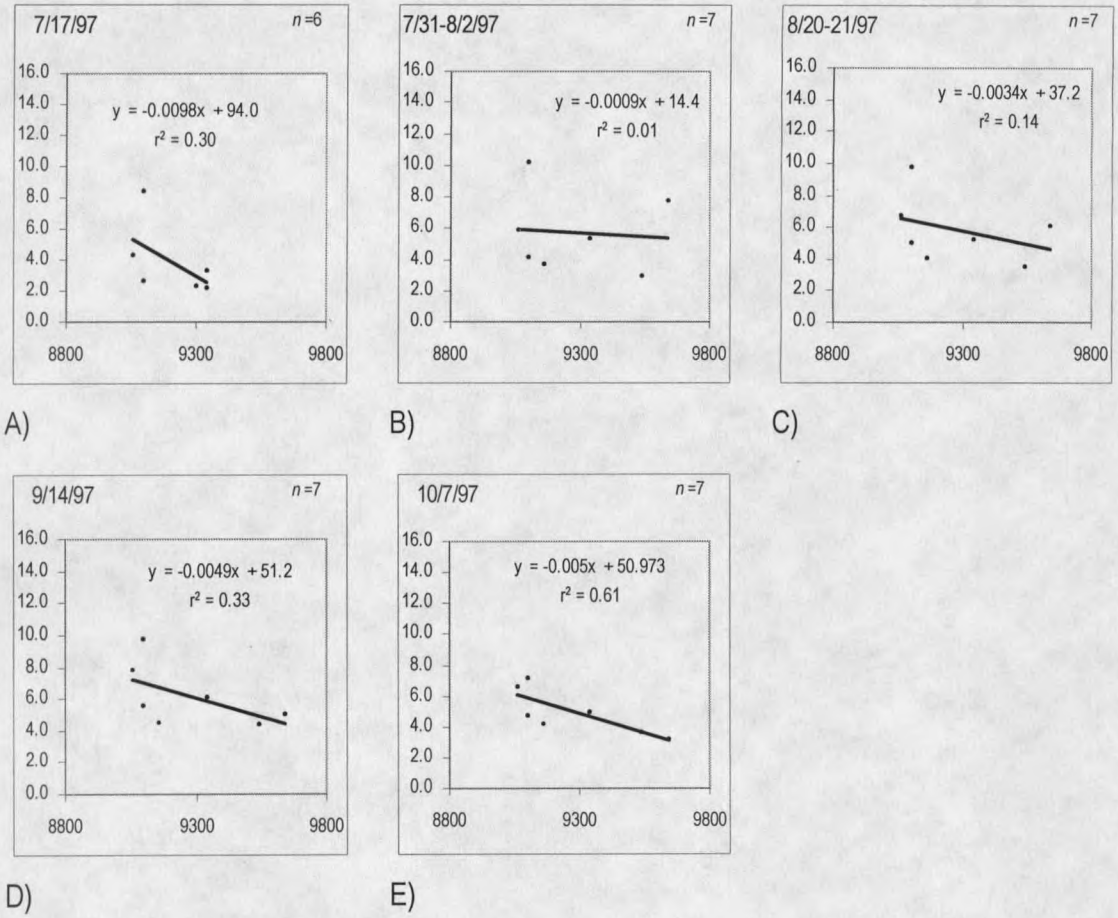


Figure 19. Geology-based surficial-deposit spring-water temperature vs. spring elevation. Elevation in feet on X-axis and spring water temperature in degrees Celsius on Y-axis.

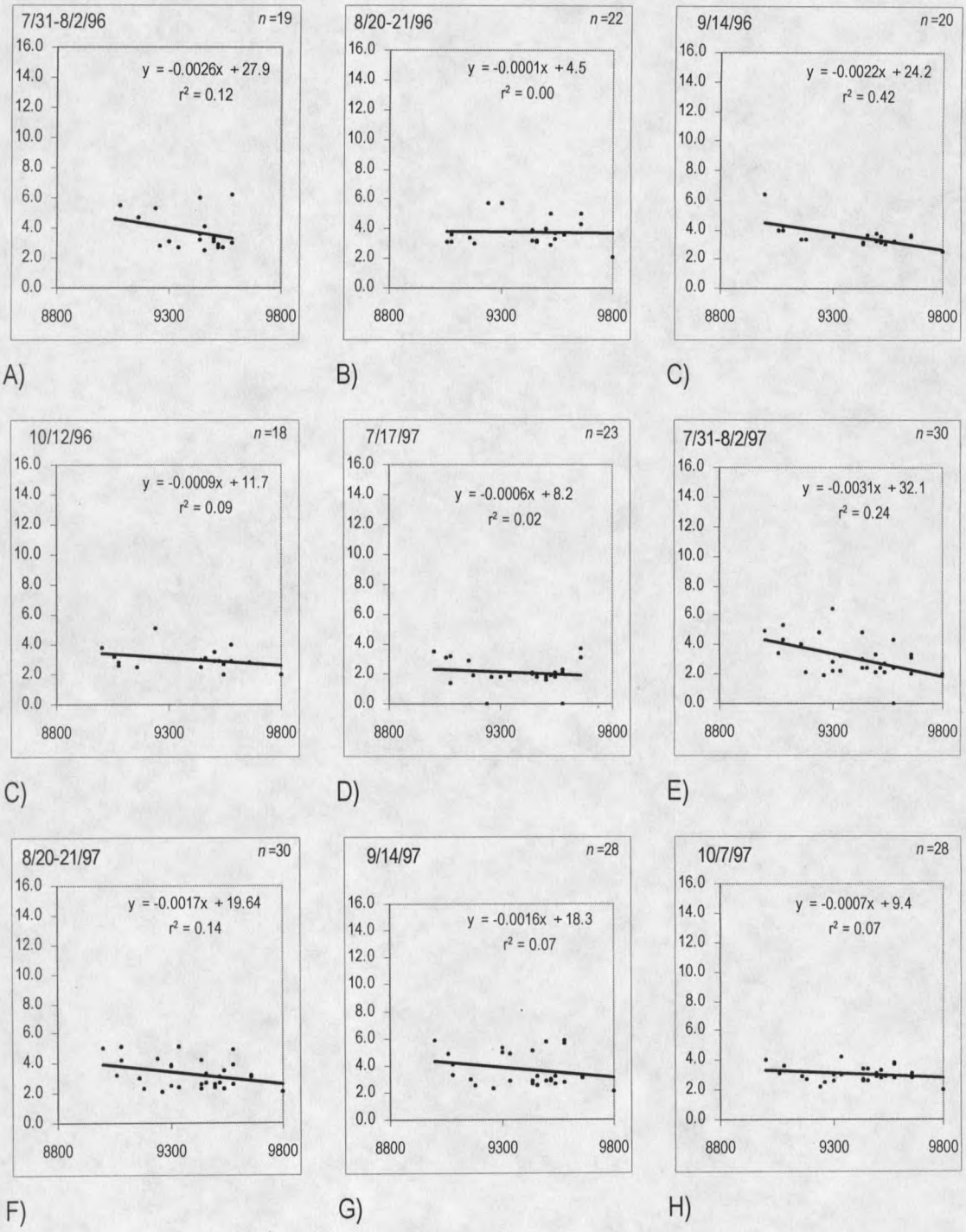


Figure 20. Geology/SC-based bedrock spring-water temperature vs. spring elevation. Elevation in feet on X-axis and spring water temperature in degrees Celsius on Y-axis.

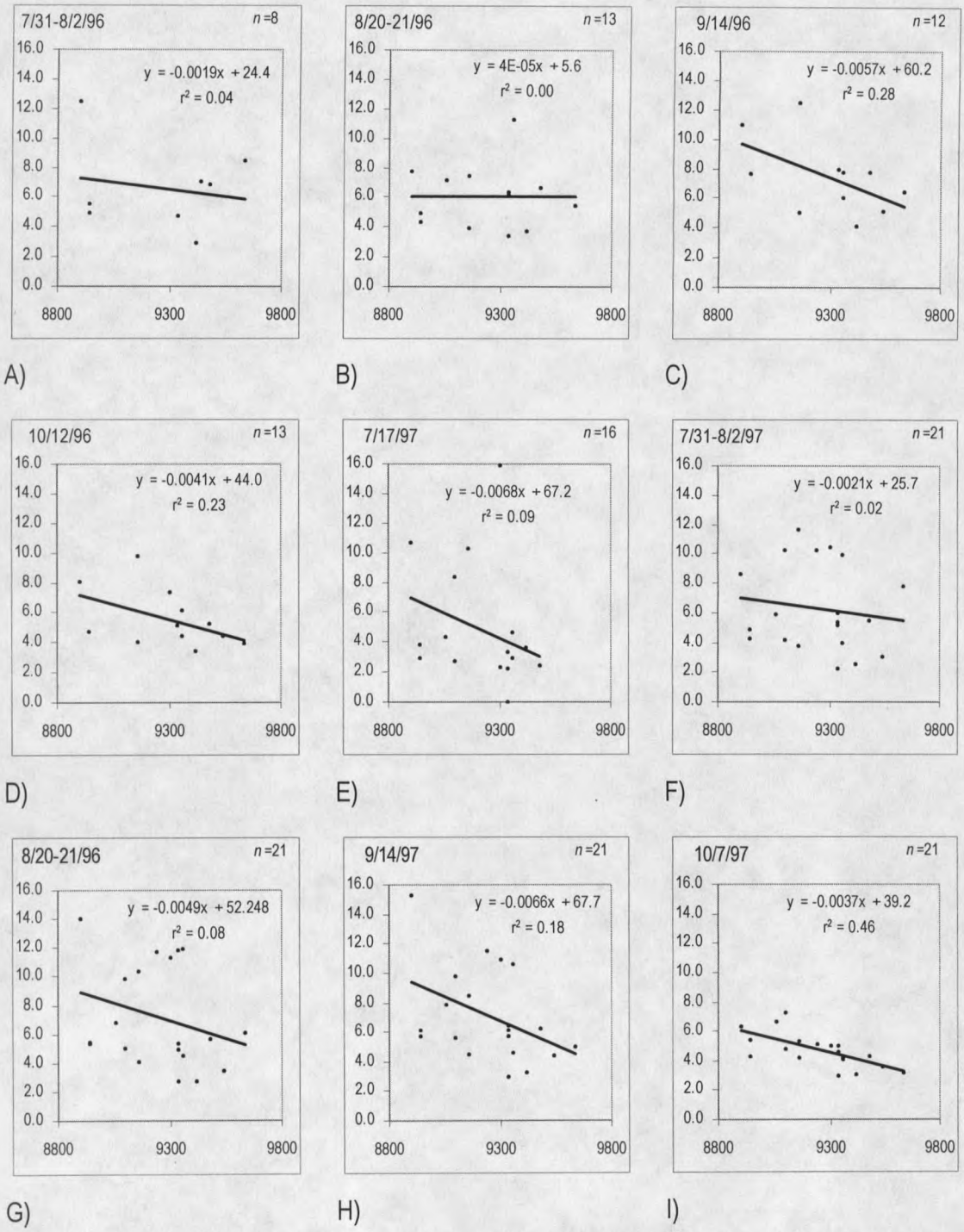


Figure 21. Geology/SC-based surficial-deposit spring-water temperature vs. spring elevation. Elevation in feet on X-axis and spring water temperature in degrees Celsius on Y-axis. Spring M-28 removed from this group because M-28's low temperature is controlled by melting rock glacier ice and not ambient air temperature.

Comparison of Bedrock and Surficial-Deposit Spring-Water Temperatures. Bedrock and surficial-deposit spring water temperatures were expected to be different. The averages of the two spring groups' temperatures are different (Table 13). The average (± one standard error) temperatures are 3.0 ± 0.1° C and 3.3 ± 0.3° C for geology-based bedrock springs and geology/SC-based bedrock springs, respectively. The average temperatures are 5.4 ± 0.1° C and 5.8 ± 0.5° C for geology-based surficial-deposit springs and geology/SC-based surficial-deposit springs, respectively.

Table 13. Average temperature (± one standard error) of spring groups.

Geology-based bedrock springs	3.0° ± 0.1° C	Geology-based surficial-deposit springs	5.4° ± 0.1° C
Geology/SC-based bedrock springs	3.3° ± 0.3° C	Geology/SC-based surficial-deposit springs	5.8° ± 0.5° C

Comparison of Spring-Water Temperature with Mean Annual Air Temperature. The comparison of spring-water temperature with mean annual air temperature did not confirm that the bedrock spring groups are from deep (> 200 m) bedrock sources. If bedrock springs had derived water from deep bedrock sources then the average temperature of bedrock springs would be 6.0° warmer than the mean annual air temperature (-1° C) (Mazor, 1991). The average temperature of geology/SC-based spring groups (3.2° ± 1.0° C) is below the 5° C mark necessary for confirmation as a deep bedrock source. In fact, there is not a single spring (of bedrock or surficial-deposit origin) with an average temperature over 5° C. While the comparison of average spring temperature with mean annual air temperature does not confirm springs as bedrock, the comparison does not negate those springs as bedrock springs. Circulation of groundwater within 200 m of the surface and in bedrock is possible without raising the spring water temperature

significantly (Mazor, 1991).

Change of Temperature. Bedrock water ΔT values were expected to be lower than surficial-deposit water ΔT values. However, the opposite of this expectation appears to be true given the data collected by other researchers in the multi-agency investigation area. The interquartile range of bedrock-well water ΔT (7.4°-10.9° C) is higher than the interquartile range of the surficial-deposit-well water ΔT (2.0°-7.4° C) (Fig. 22). The hypothesis that water in the bedrock aquifer is shielded from ambient air temperature fluctuations and the surficial-deposit aquifer is not shielded is not supported.

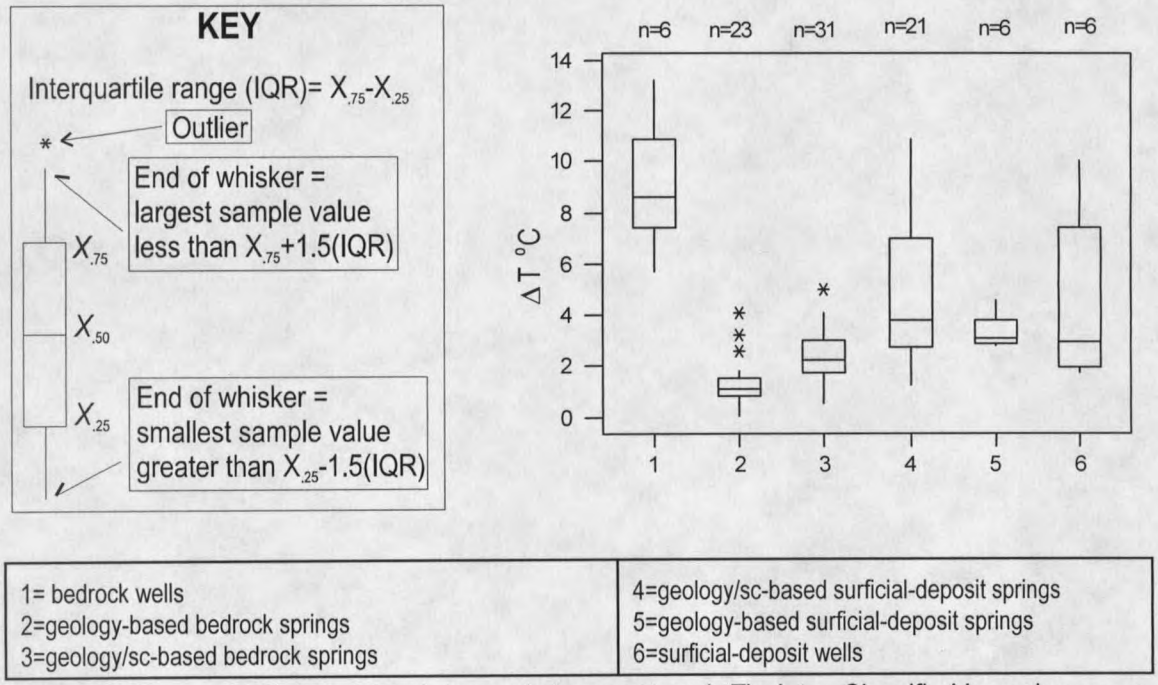


Figure 22. Box and whisker plots of change in temperature (ΔT) data. Classified by spring group and unit in which well was completed.

Origin of Temperature Patterns. The analyses of water temperatures suggest that the surficial-deposit-aquifer-spring water has higher and more variable temperatures than the bedrock

aquifer. The fact that the average temperature (± one standard error) of geology/SC-based surficial-deposit-spring water (5.8° ± 0.5° C) is higher than the average temperature of geology/SC-based bedrock-spring water (3.3° ± 0.3° C) (Table 13) suggests the bedrock spring water has lower temperatures than the surficial-deposit aquifer. Despite conflicting well water data, the fact that the interquartile range of geology-based surficial-deposit spring-water ΔT (2.9°-3.8° C) is higher and larger than the interquartile range of geology-based bedrock spring-water ΔT (0.8°-1.5° C) suggests that surficial-deposit-spring water has higher temperature variability than the bedrock aquifer.

To explain the higher temperatures and greater temperature variability of the surficial-deposit-spring water, the following hypothesis is suggested. Surficial-deposit-aquifer water is stored at shallow depths where warm summer temperatures and/or insolation raises the temperature of the aquifer. The bedrock aquifer on the other hand stores water at depth sheltering water from insolation and excessive summer warming.

If insolation controls surficial-deposit-spring water temperatures, this may explain why correlations between surficial-deposit spring-water temperatures and spring elevation are generally poor and geology/SC-based-surficial-deposit-spring temperatures are elevated. If a spring's temperature is controlled by insolation then the spring's temperature would be a function of the amount of sun the surface received during the day. Upper Miller Creek basin's variable aspects, shading and weather would make surficial-deposit spring temperatures vary greatly and be more variable than bedrock-aquifer-spring-water temperatures.

The comparison of spring elevation and temperature also suggests ambient air temperature or insolation may control surficial-deposit aquifer temperature. The only day

reasonable correlations between spring temperature and elevation exist (October 7, 1997, Fig. 19E and 21I) the weather was cold and cloudy. On October 7, 1997 the mean temperature was 0° C, and cloudy, snowy weather was noted in field notes and photographs. In contrast, on all other sampling days where at least three geology/SC-based surficial deposit springs were sampled and no snowpack existed, the average daily temperature ranged from 7°-13° C, and sunny weather with occasional rain showers was noted. Possibly, the cold temperatures and cloudy weather could have prevented insolation from affecting the temperatures of surficial-deposit-spring water on October 7, 1997.

Origin of Lineaments and Fracture Traces

The geologic origin of these lineaments and fracture traces is unknown, note that only some of the fracture traces occur near mapped faults such as the fracture trace on the western side of the basin which is near and parallel to a small fault mapped by Elliot (1979). There are also two fracture traces which may be related to the Crown Butte Fault. One of the fracture traces is located at the southern end of the Crown Butte fault as mapped by CBM and the other is located at the southeastern corner of the field area. The proximity and subparallel nature of the fracture traces indicates a possible relation to the Crown Butte Fault.

Hydrogeology of Surficial Deposits

Simplicity is the reason for the treatment of the surficial-deposit aquifer as a single unit. In actuality, the surficial-deposit aquifer is divided into four separate components each of which have different hydrogeologic behaviors. The components of Miller Creek basin's surficial-deposit

system are rock glaciers, glacial deposits, thin colluvial deposits and iron-oxide deposits (Plate 3). To emphasize the differences of these deposits the hydrogeology of each of these four components is discussed.

Rock Glaciers

Based on water temperature and position with respect to the rock glaciers, springs M-28 and M-29 likely discharge the rock glaciers' groundwater. The two springs are located near the termini of the rock glaciers, where a rock glacier's groundwater discharge would be expected. Temperature measurements of springs M-28 and M-29 average 0.7° C and 0.8° C, respectively. The rock glaciers' groundwater discharge is likely cold (less than 1° C) because the groundwater discharge is melted interstitial ice and/or infiltrated precipitation that was in contact with interstitial ice. The temperatures of these springs is lower than the average temperature of any other spring in the Miller Creek basin.

While springs M-28 and M-29 are excellent candidates for rock glacier springs, there are a few characteristics of M-29 which suggest bedrock interaction with M-29's discharge. Spring M-29 discharges from bedrock (Table 4). The SC of M-29 is consistently 3-35 $\mu S\ cm^{-1}$ higher than M-28's SC, yet the average SC of M-29 is not high enough to place this spring in the SC-based group of bedrock springs or low enough to place M-29 in the group of SC-based surficial-deposit springs given the parameters defined in this study. Spring M-29 could not be grouped as a bedrock spring or a surficial-deposit spring.

Large volumes of water can be heard flowing underneath the ground surface in two places to the northeast of M-29: 1) underneath the surface of one of the rock glaciers about 100 meters to the northeast and 2) in an adit about 10 meters to the northeast. Perhaps, sub-permafrost flow

(Ritter et al., 1995, p. 384) is guided into a fault or area of jointing and then into an intersecting adit before discharging to M-29. If sub-permafrost groundwater exists, the groundwater could be under enough hydrostatic pressure to induce sliding of the rock glaciers, and rock glacier movement.

Both springs M-28 and M-29 constitute a large portion of spring discharge for the entire upper Miller Creek basin and of the surficial-deposit aquifer. During the 1997 field season, springs M-28 and M-29 contributed 30-50% of the upper Miller Creek basin's measured and estimated spring discharge. Spring M-28's contribution to the surficial-deposit aquifer's total 1997 discharge varied 40-90%, and spring M-28's contribution to the basin's total discharge varied 10-20%. Spring M-29's contribution to the 1997 discharge of the final-group-of-springs-of-unknown-origin varied 60-90%, and spring M-29's contribution to the basin's total 1997 discharge varied 10-30%.

If deeming springs M-28 and M-29 as discharging the majority of rock glacier discharge (albeit some possible addition of bedrock groundwater via M-29) then the overall hydrology of Miller Creek basin's rock glaciers is similar to that of rock glaciers studied by other researchers. The flow volume of a medium length (1000 m) rock glacier can vary between 120-3000 l/min (Gardner and Bajewski, 1987). The spring discharge from the rock glaciers varied between 230 ± 20 l/min and 900 ± 50 l/min during the 1997 field season as determined by the estimates of springs M-28 and M-29. Because of unmeasurable discharge, the aforementioned discharge values could be 100% greater than reported. Highest discharge of most rock glaciers occurs during spring snowmelt and discharge can decline to zero during winter (Gardner and Bajewski, 1987). The discharges of M-28 and M-29 are highest shortly after snowmelt periods, and decline as summer progresses to fall.

Glacial Deposits

Based on the material discussed in the Glacial Deposits subsection of the Introduction chapter and on the occurrence of geology/SC-based surficial-deposit springs (M-31, M-35 and M-44) in the glacial deposits, the glacial deposits appear to be able to store and transmit water.

Colluvial Deposits

Colluvial deposits appear to be thinner than the rock glaciers and the glacial deposits. Interestingly, well over half of the geology/SC-based surficial-deposit and geology-based surficial deposit springs (M-19, M-20, M-21, M-23, M-24, M-24B, M-25A, M-26A, M-39, M-40, M-41, M-59, M-60 and M-61 (Plate 3)) discharge from co2 deposits. The great number of springs which discharge from the co2 deposits is an indication that type two colluvium is able to store and transmit water. All of these springs have relatively small discharges, but many of them discharge consistently throughout the season. The number and persistence of springs in the co2 deposit indicate the deposits may function as an aquifer despite a small thickness, although the bedrock aquifer may contribute the majority of water to this thin aquifer.

Iron oxide cemented deposits

No springs were found discharging from ferricrete deposits. Groundwater processes may have contributed to the formation of the ferricrete deposits, but the relation is not clear. Conversely, there are many springs which discharge from the "iron oxide and organic deposits" (e.g., M-22, M-42, M-43, M-44, M-62 and M-59 (Plate 3)), indicating that there may be a relation between spring discharge and the formation of the "iron oxide and organic deposits".

Implications for Surface Water

A comparison of spring discharge and total surface-water discharge helps place the volume of spring discharge in perspective. The USGS has made three measurements of Miller Creek's surface water discharge. These measurements occurred just upstream from the Creek's mouth, approximately 3 kilometers downstream from the study area boundary in 1969 and 1996. Fortuitously, two of the three surface water discharge measurements occurred at nearly the same time as spring discharge measurements were made (Table 14). Figure 23 illustrates that the measured and estimated Miller Creek spring discharge during fall of 1996 is equal to well over half of Miller Creek's surface water discharge. This supports the possibility that spring discharge could be a significant contributor to stream discharge during mid fall.

Table 14. Surface water and spring discharge measurements.

Miller Creek surface water discharge (USGS).		Upper Miller Creek basin spring discharge. Because of unmeasurable spring discharge the following values may be 100% greater than reported.	
Date	Measurement	Date	Measurement
9/11/96	560 l/min	9/14/96	300 ± 20 l/min
10/23/96	340 l/min	10/12/96	300 ± 20 l/min

Perhaps the most important implication of this study is that the behavior of the bedrock aquifer groundwater discharge may be represented by the behavior of the geology/SC-based bedrock-spring discharge. If bedrock-spring discharge is representative of the behavior of the bedrock aquifer, then bedrock-aquifer-groundwater discharge could behave in a similar manner. This study indicates geology/SC-based bedrock spring discharge was at least six times greater in mid July, 1997 than geology/SC-based bedrock spring discharge in early October 1997 (Table 11

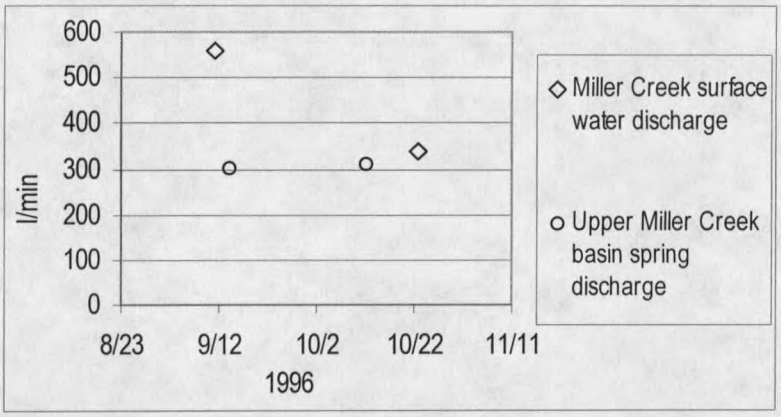


Figure 23. Discharge of Miller Creek as measured by the USGS and discharge of springs in the upper Miller Creek basin.

and Fig. 17). Bedrock groundwater discharge to Miller Creek may also be six times greater in early summer than bedrock groundwater discharge in early fall. Further work is needed to test this hypothesis.

A bedrock aquifer which contributes significantly more during early summer than late fall can be explained by three different scenarios: 1) snowmelt could recharge the bedrock aquifer and displace older groundwater via a hydrologic pressure transmission pulse 2) snowmelt can rapidly infiltrate and discharge from faults and fractures in bedrock or 3) snowmelt can recharge the bedrock aquifer, mix with older bedrock groundwater causing an older/younger water mixture to subsequently discharge.

Further Research

A hydrologic pressure transmission pulse is a plausible mechanism for groundwater flow in the Miller Creek basin. Several authors have previously found that multi-year water is released shortly after snowmelt or rainfall events and suggested pressure transmission as a mechanism for

this phenomenom (Dinçer, et al., 1970; Sklash and Farvolden 1979; Martinec et al., 1982). Tritium and O^{18} isotope analysis indicated that about two-thirds of snowmelt infiltrated and displaced water recharged during previous years (mean residence time was 2.5 years) toward stream channels in a Northern Czechoslovakian mountain basin (Dinçer et al., 1970). Deuterium, O^{18} and tritium isotope analysis indicated that for all except the most intense rainstorms and prolific meltwater days, groundwater dominates the runoff hydrographs in several different hydrogeologically diverse watersheds (Sklash and Farvolden, 1979). Basin lithology and deep groundwater storage was hypothesized to be responsible for the 11-month lag time between bromide tracer application to the ground surface and detection of maximum tracer levels in stream flow of a central Sierra Nevada California watershed (MacDonald, 1987). Tritium isotope analysis indicated a pressure transmission system allows the release of 4-5 year old groundwater shortly after snowmelt recharge occurs in the Dischma basin, Italy (Martinec et al., 1982). In alpine basins with thin surficial deposits such residence times are only possible if a rapid pressure transmission is induced in the bedrock aquifer.

A study using tritium, O^{18}, or deuterium isotopes could determine if a pulse type system occurs in the Miller Creek basin. Determination of isotopic signatures for snowmelt and perennial bedrock aquifer water would be necessary. Because variable SC data indicates that the bedrock-aquifer may mix with snowmelt periodic isotopic sampling of bedrock well water for an extended period of time would be required. If temporally differentiable signatures for snowmelt and the bedrock aquifer can be determined the relative contributions of snowmelt and the bedrock aquifer to stream water can be determined. Further methodology can be found in several research articles (Martinec et al., 1982; Sklash and Farvolden, 1979; Dinçer, et al., 1970).

Determination of the SC of distilled water in contact with surficial deposits for a short period of time in a lab setting may help to further constrain SC values of surficial-deposit aquifer water and better quantify the input of the surficial deposit to stream flow (Pilgrim et al., 1979).

If further study of the Miller Creek basin springs is deemed important by other researchers, photographs of all springs are on file with the department of Earth Sciences, Montana State University. Spring location and identification using these photographs is highly recommended. There may still exist at least a few springs that were not discovered during this study.

The design of the portable V-notch weir can be improved. This device which can be made from any round cylinder with a bottom, would have a much greater measurement range if a 60° V-notch rather than a 90° V-notch was used. The 60° notch would increase the ratio of B to A (Fig. 4) allowing a higher stage to be measured. The problem of water escaping beneath spring-measuring devices is problematic and needs work.

CONCLUSIONS

The objective of this study was to determine whether the bedrock aquifer or the surficial-deposit aquifer dominated spring discharge in the upper Miller Creek basin. This objective is important because of environmental concerns regarding the mining of near surface bedrock ore bodies in the upper Miller Creek basin. If the bedrock aquifer dominates spring discharge then underground mining of Miller Creek basin's near surface bedrock ore bodies would be more likely to disrupt spring discharge and possibly other forms of groundwater discharge. If the surficial-deposit aquifer dominates spring discharge then mining would be less likely to disrupt spring discharge and possibly other forms of groundwater discharge.

Bedrock springs are distinguished from surficial-deposit springs based on their SC and proximity to potential spring-producing geologic features. Bedrock springs have high and variable SC values and are located near faults, lithologic contacts, lineaments and fracture traces. The group of springs interpreted to derive water from the bedrock aquifer are named geology/SC-based bedrock springs. The surficial-deposit springs have lower and less variable SC values and are located near the downhill contact between a surficial deposit and underlying bedrock. The group of springs interpreted to derive water from the surficial-deposit aquifer are named the geology/SC-based surficial-deposit springs.

Springs were measured using flume discharge measuring devices and the summation of the spring group discharges allowed determination of whether a spring group dominated spring discharge. Because of unmeasurable spring discharge the total summed values for spring group discharges could be +100% greater than reported. Geology/SC-based bedrock springs dominated spring discharge during mid-summer of the 1997 field season. During mid-July of 1997, the

geology/SC-based bedrock springs discharged approximately 60% of the upper Miller Creek basin's total measured and estimated spring discharge. Geology/SC-based bedrock springs continued to discharge water during the remainder of the field season contributing between one-third and one-half of Miller Creek basin's total measured and estimated spring discharge between August and September of 1997. Measured and estimated geology/SC-based bedrock spring discharge is 6 times greater in mid-July than in early October. The great difference in discharge between early summer and early fall implies that spring snowmelt recharge of the bedrock aquifer causes a rapid discharge of groundwater to springs followed by a gradual decrease for the remainder of the sampling season.

The bedrock aquifer appears to continue to discharge water to springs during mid-fall. On November 9-10, 1996 13 of 14 spring heads uncovered from beneath the snowpack had estimable discharges. Eleven out of 13 of these springs are classified as bedrock springs. The remaining two are of unknown origin. With one exception, all of the uncovered meausurable springs had SC values above the highest SC measured in a surficial-deposit well or geology-based surficial-deposit spring (193 $\mu S\ cm^{-1}$). The fact that 11 out of 13 springs are classified as bedrock springs and had SC values above 193 $\mu S\ cm^{-1}$ suggests that the bedrock aquifer continues to discharge during late fall and may continue to discharge in the winter.

The surficial-deposit aquifer is also a significant contributor to spring discharge. After early August the geology/SC-based surficial-deposit springs' measured and estimated discharge is approximately equal to the measured and estimated discharge of the geology/SC-based bedrock springs. The discharge of the geology/SC-based surficial-deposit springs encompassed approximately one fourth of the basin's total measured and estimated spring discharge, thereby

indicating that the geology/SC-based surficial-deposit springs are an important factor when considering the basin's total measured and estimated spring discharge.

There are four components of the surficial-deposit aquifer: 1) rock glaciers, 2) glacial materials, 3) colluvial deposits and 4) iron-oxide deposits (including ferricrete). The rock glaciers discharge a significant portion of the geology/SC-based surficial-deposit spring discharge and of the upper basin's entire spring discharge. Spring M-28 discharges from the rock glaciers and accounts for between 40-90% of the geology/SC-based surficial-deposit spring discharge, and for approximately 10-20% of the basin's total measured and estimated spring discharge. The glacial materials and colluvial (especially type two colluvium) deposits are also potentially significant aquifers and much of the remaining surficial-deposit spring discharge is attributed to these deposits. There are many small springs which discharge from the unlithified "iron oxide and organic deposits", but the lithified ferricrete deposits contribute little water to basin-wide spring flow from a volumetric perspective.

Springs which could not be divided into bedrock or surficial-deposit spring groups were deemed the "final-group-of-springs-of-unknown-origin". This group of springs could not be distinguished based on their proximity to potential spring-producing geologic features or based on their SC. This group of springs also discharges a significant portion of the upper Miller Creek basin's total discharge. The discharge from the final-group-of-springs-of-unknown-origin accounts for 20-30% of the basin's total measured and estimated 1997 spring discharge. Because the discharge from this group was so large, determining which aquifer dominated spring discharge during the latter part of the 1997 field season is not possible.

Perhaps the most enigmatic and important spring in the final-group-of-springs-of-unknown-

origin is spring M-29. Spring M-29 has a low temperature and discharges near the termini of the rock glaciers; therefore, M-29 likely derives most water from the rock glaciers, yet M-29 discharges from bedrock indicating that the bedrock aquifer plays a role in M-29's discharge. Appropriately, M-29's moderate SC value would not allow this spring to be classified as a bedrock or surficial-deposit spring. Spring M-29 accounts for 60-90% of the final-group-of-springs-of-unknown-origin's total measured and estimated 1997 spring discharge, and accounts for between 10-30% of the basin's total measured and estimated 1997 spring discharge.

Because spring discharge is a form of groundwater discharge, other forms of groundwater discharge are likely to behave in a similar manner. Both the geology/SC-based bedrock springs and the geology/SC-based surficial-deposit springs are significant contributors to spring discharge. However, the relative contributions change during the year, and during mid-July of 1997, over half of the total measured and estimated spring discharge was from the geology/SC-based bedrock springs indicating that the bedrock aquifer likely dominated spring discharge during early 1997 summer months. Additionally, the discharge from the geology/SC-based bedrock springs discharge was 6 times greater in mid-July 1997 than in early October, 1997. The behavior of the geology/SC-based bedrock springs indicates that the bedrock aquifer contributes more water to springs during early summer snowmelt periods, than in late fall. If mining were to intersect groundwater conduits such as faults which discharge water to springs, early summer is when mining is expected to have the greatest impacts on spring discharge, and possibly other forms of groundwater discharge because springs interpreted to derive water from the bedrock aquifer discharge the greatest amounts of water during early summer snowmelt periods.

APPENDIX A

A series of tests were devised to help facilitate understanding of Miller Creek basin's spring water, surface water and groundwater systems. Although these tests are not specific to the question of whether the bedrock aquifer or surficial-deposit aquifer dominates spring discharge, these tests are included in this report because they could provide the basis for future work in the Miller Creek basin and adjacent basins.

The temperature, pH, SC and discharge of spring water and/or surface water were measured in some of the following tests. The following brief reports do not reiterate the protocol or instrumentation used to measure the aforementioned parameters because this information is already described in the Methods chapter. Only pertinent nuances in measurement technique and site selection are described in the following methods subsections.

Further Geologic Mapping

The objective of further geologic mapping was to resolve discrepancies of fault locations discovered when geologic maps were overlain on top of each other. When Elliot (1979) was overlain on top of CBM (unpublished) (Plate 5), differences in fault locations were discovered. Subtle differences in geologic mapping can be expected when an area is mapped by different researchers. However, the differences discovered when these two geologic maps were overlain, have implications with regard to mining impacts. Most noticeable and important, is the southern end of the Daisy Pass Fault. CBM (unpublished) show the fault within 14 m of the group of lower-site wells, and Elliot (1979) does not map the fault passing as closely.

That Elliot (1979) and CBM (unpublished) mapped these faults differently, does not

necessarily indicate that either investigator is incorrect; rather, the Daisy Pass Fault could splay into two faults. The lack of bedrock exposure and drill core data at the southern mapped end of the Daisy Pass Fault makes determination of the location of this portion of the fault difficult.

Despite the difficulty in determining the location of the Daisy Pass Fault, further efforts should be made regarding the location of this fault and other faults because they are important with regard to mining's potential impact on Miller Creek basin's hydrology. Groundwater movement in bedrock is predominantly controlled by bedrock fractures and faults (BLM, 1997). In fact, based on pump tests in the Miller Creek basin, Huntingdon Engineering and Environmental (1995) concluded that if any major fault or fracture systems are intercepted by mining activities, high rates of groundwater flow could be encountered.

When considering mining impacts in the Miller Creek basin, there are three faults of great importance whose location should be researched thoroughly: the Crown Butte Fault, the Daisy Pass Fault and the Little Daisy Pass Fault (Plate 2). These faults are important because they may be hydraulically connected to fractures intercepted by the group of lower site wells. The group of lower-site wells intersected fractures which have high hydraulic conductivities and pumping of one of the lower site wells induced a 56.7% flow reduction in the east fork of Miller Creek (Maxim Technologies, 1995).

An assertion regarding which fault is associated with the fractures in the group of lower site wells has previously been made, yet the basis for this assertion is unclear. Maxim Technologies (1995, p. 24) contends, "Wells at the lower-site are completed in Wolsey Shale to depths of approximately 100 ft [30.5 m] in a major fracture/fault zone associated with the Crown Butte Fault." Certainly, the fractures in the group of lower site wells could be genetically related to

the Crown Butte Fault (e.g., the Crown Butte Fault and the fractures intercepted by the group of lower site wells could have formed contemporaneously as a result of the same tectonic forces), but a genetic relation does not necessarily imply a hydraulic connection.

An indicator of a hydraulic connection between the wells and the Crown Butte Fault could be determined by simple trigonometric calculations using fault location, fault dip and well locations. At the closest, the Crown Butte Fault is mapped 230 m (750 ft) to the southwest of the group of lower-site wells (CBM, unpublished maps and Plate 5). Though the Crown Butte Fault has an easterly dip of 60°-90° (Stanley, 1995) the dip is too steep to intersect any of the wells. The closest well would have to be at least 400 m deep to intersect the Crown Butte Fault, and the deepest well in the group of lower-site wells is only 34 m deep (CBM, 1992).

Only further investigation will reveal which fault (if any) is hydraulically connected to the fractures intersected by the group of lower site wells. Because of the sub-vertical nature of faults in the Miller Creek basin (Stanley, 1995) a fault that is hydraulically connected to the group of lower site wells is expected to occur within a few meters of the group of lower site wells. In an attempt to better constrain the location of faults at the headwaters of the upper Miller Creek basin and determine which fault is closest to the group of lower site wells this study collected additional strikes and dips not reported by Elliot (1979) or CBM (unpublished) and searched for any bedrock outcrops not previously mapped in the upper Miller Creek basin.

In addition to potentially determining which fault is nearest the group of lower-site wells, geologic mapping may also reveal information about fault location down-gradient of the group of lower-site wells. This area is important because faults may cross or trend near Miller Creek or near some of Miller Creek's tributaries. Possibly, faults discharge water directly to Miller Creek,

and knowing the exact location of faults would be beneficial to determining where impacts may occur to Miller Creek or her tributaries.

Methods

The geology was confirmed and where necessary re-mapped to determine if any additional information regarding fault locations could be found. The methods of geologic mapping utilized standard procedures outlined in McClay (1987). Aerial photographs were used to locate and map bedrock outcrops. Strikes and dips were collected using a Brunton compass. A carpenter's protractor was used for dips less than 6°.

Results

Collected strikes and dips are displayed on Plate 2. Additionally, one small bedrock outcrop of Cambrian Snowy Range on the western side of the basin not previously reported and a few small igneous intrusions not previously reported are displayed on Plate 2. Stratigraphic descriptions specific to the Miller Creek basin are listed on the page following Plate 2. Outcrop location and attitude are consistent with previous studies. Kirk (1995) described most bedding in the project area as dipping 4°-7° to the southwest. In this study, most dips were found to be between 0° and 16° to the southwest, although dips as high as 65° exist. There is not enough outcrop exposure in the Miller Creek basin to constrain the locations of faults better than previously mapped using field mapping techniques.

Discussion

The objective of this test was to determine whether faults could be better constrained with additional geologic mapping. Additional geologic mapping did not better constrain the locations of

faults in the upper Miller Creek basin. There is not enough bedrock outcrop exposure in the Miller Creek basin to further constrain fault location through geologic field mapping exercises.

Despite not being able to further constrain fault locations further, the hydraulic connection of faults to the fractures intercepted by the group of lower site wells should be considered. Based on proximity and the sub-vertical nature of faults, the Little Daisy Pass Fault or the Daisy Pass Fault are much more likely to be hydraulically connected to the fractures in the group of lower site wells than any other fault in the basin (Plate 5).

The fact that the Little Daisy Pass Fault may be hydraulically connected to surface flows is of great consequence because the Little Daisy Pass Fault crosscuts two shallow sulfide rich ore bodies (Stanley, 1995; CBM, unpublished maps). If this fault is a groundwater conduit, groundwater may be affected by mining because the average depths to the tops of the ore bodies (67 m (220 ft) and 125 m (410 ft)(CBM, 1992)) are below recorded static water levels and the top surface of the southern ore body is as close as 24 m (80 ft) to the ground surface (Stanley, personal communication) which is a level which static water levels have fluctuated above and below. Average ore body depths were below static water levels measurements during the summer and fall of 1994 and 1995, but the static water levels fluctuated above (e.g. depth-to-water on July 7, 1995 was 45.70 ft in well MW11B) and below (e.g depth-to-water on September 6, 1995 was 105.55 ft in well MW11B) (Fig. 2) the southern ore body's approximate minimum depth (24 m (80 ft)).

A conclusion that indicates that mining ore bodies in the Miller Creek basin would not disrupt Miller Creek's flow quantity, can not yet be reached because: 1) the fault (if any) that is in hydraulic connection with the fractures intercepted by the group of lower site wells has not yet

been determined and 2) the Little Daisy Pass Fault is a likely candidate for being connected to those fractures. The possibility that a fault with high rates of groundwater flow could be encountered by mining activities contradicts Maxim Technologies (1995, pg. 26).

> "...there is no indication the New World Ore Bodies are in direct connection with the primary fault/fracture zone located in the center of upper Miller Creek [basin]. This structural zone appears to be associated with the Crown Butte Fault that extends north of the New World Ore bodies. As a result, the proposed new World Mine is not expected to have a significant effect on flow quantity in the Miller Creek drainage."

While the assertion that there is no indication that the Miller Creek ore bodies are in direct connection with the Crown Butte Fault is true, this does not imply that mining will not have significant effect on Miller Creek's flow quantity or quality. There is no evidence to indicate that the Crown Butte Fault is the only fault in the upper Miller Creek basin through which groundwater flows or to indicate that the Crown Butte Fault contributes the majority of bedrock groundwater discharge to Miller Creek. In fact, there are no wells and few (if any) drill cores in the upper Miller Creek basin which have been drilled through the Crown Butte Fault. Additionally, groundwater is more likely to flow through normal faults with smaller offset (e.g. the Little Daisy Pass Fault) than through reverse faults with larger offset (e.g. the Crown Butte Fault). Smaller extensional faults are more likely to allow groundwater flow because surface irregularities in the fracture planes are not ground off thereby the facing surfaces are forced to separate, and gouge development is minimized (Huntoon, 1986).

Prior to mining, if and when mining occurs, the hydrologic properties of the Little Daisy

Pass Fault need to be determined. The examination of spring locations provides only a small piece of evidence with regard to the hydrologic properties of the Little Daisy Pass Fault and other faults in the basin. There are springs located near all of the three major faults (Crown Butte Fault, Daisy Pass Fault and Little Daisy Pass Fault) at the headwaters of Miller Creek, and no fault appears to have more springs located along its trace than any other fault. However, springs M-48, M-31, M-47, M-30 and M-45 appear to form a sub-linear extension of either or both the Little Daisy Pass Fault or the Daisy Pass Fault (Plate 5), and most of these springs along with several other springs located on or near the Little Daisy Pass Fault have iron-stained substrates (e.g., M-1, M-64, M-65, Table 4).

To ascertain whether the Little Daisy Pass Fault has high hydraulic conductivities, the author suggests placing wells in the Little Daisy Pass Fault in the ore bodies and then conducting pump tests on those wells. (Though the group of upper site wells are located near the Little Daisy Pass fault, they do not intercept the fault or any fractures, and therefore do not provide much information about the Little Daisy Pass Fault's hydrogeologic properties). Drilling a well through the Little Daisy Pass Fault is possible because the location of this fault in the ore body is well constrained by drill cores (Stanley, 1995). (Not analyzing oriented drill core logs collected by CBM prior to drilling wells would be a mistake because their analysis could guarantee the interception of fractures in the ore body). Since the fault is sub-vertical, drilling an angled well may be necessary. The well casing would have to be screened at intervals open to any fractures encountered in the ore body while drilling. If pump tests demonstrated that the Little Daisy Pass Fault (or other fractures in the ore body) conducted large amounts of water and is (are) hydraulically connected to surface flows during spring, summer or fall, then mining the Miller Creek ore bodies would likely

have an effect on surface flows in the Miller Creek basin.

This report concludes by agreeing with Huntingdon Engineering and Environmental's (1995) original conclusion that if any major fault or fracture systems are intercepted by mining activities, high rates of groundwater flow could be encountered. If and when mining of the Miller Creek ore bodies occurs, then the mining activities would intercept the Little Daisy Pass Fault. Since there is a likelihood that the Little Daisy Pass Fault is hydraulically connected to the fractures in the group of lower site wells, and those fractures have high hydraulic conductivities, then the possibility exists that mining Miller Creek's ore bodies would have a significant effect on flow quantity in the Miller Creek drainage.

Surface and Spring Water Temperature Measurements During Snowmelt Periods

Studying spring discharge and surface water flow during snowmelt periods is important because the possibility exists that the bedrock aquifer may dominate groundwater discharge during this time period (Stephenson and Freeze, 1974; Martinec et al., 1982; Flerchinger et al., 1993). Certainly, the results of this study indicate the possibility exists that Miller Creek basin's bedrock aquifer may dominate groundwater discharge during periods of snowmelt because during the spring discharge measuring period closest to snowmelt (mid-July, 1997) the bedrock aquifer dominated spring discharge (over half of the total measured and estimated spring discharge). If the bedrock aquifer dominates spring and/or groundwater discharge during earlier snowmelt periods, then the greatest volumes of groundwater discharge could be affected by mining during these earlier snowmelt periods.

Though snowmelt periods are extremely important, an extensive snowpack makes the

study of spring discharge and surface water during snowmelt periods difficult. July 17, 1997 is the earliest calendar date that spring discharge has been measured. This date was the earliest part of 1997 where enough snow had cleared from the upper Miller Creek basin to allow measurement of spring discharge. Note that during other years of lesser snowpack, access to spring heads earlier in the year may be possible.

What is unknown and what this test attempted to find, is evidence that the bedrock aquifer discharges to the surface during snowmelt periods when a considerable snowpack still exists in the upper Miller Creek basin. If the bedrock aquifer discharges to the surface, then this discharge should be reflected in the temperature of springs and surface water in the Miller Creek basin because the bedrock discharge should be warmer than pure snowmelt runoff and recharge. This theory is similar to a test designed by Cartwright (1974) who indicated that during winter, groundwater discharge areas can be identified by measuring soil temperatures. Cold soil temperatures indicate recharge areas, whereas warm soil water temperatures indicate discharge areas.

In the Miller Creek basin, Cartwright's (1974) test can be adapted to snowmelt periods when the basin is nearly entirely snow-covered. Recharge water temperature should be 0° C because virtually all of the recharge is snowmelt. Even in the subsurface, recharge water may maintain a 0° C temperature if the water is in contact with ground ice. Ground ice has been demonstrated to exist in the Beartooth Mountains (Pierce, 1961). Only if the snowmelt recharge mixes with warmer groundwater or causes a pressure transmission release of warm multi-year water, will the discharge water be warmer than 0° C. Underneath a dense thick snowpack subnival surface water cannot be warmed by ambient air temperatures because during early snowmelt

periods, snowmelt flowing over the ground surface in an alpine basin is insulated from warming by insolation or ambient air temperatures by an extensive and deep snowpack.

If the bedrock aquifer discharges to springs, tributaries and small rivulets, the water discharging from these features should be elevated above what is expected from pure snowmelt (0° C). Measuring the temperature of water discharging from these features should indicate whether the bedrock aquifer may be providing water to these features.

Methods

Choosing a date when an extensive snowpack existed, yet after snowmelt had begun was an important part of this test. The Fisher Creek SNOTEL indicates that maximum 1997 snowpack occurred on May 3 (150 cm (60 in) in snow water equivalent units). The snowpack steadily decreased after this date and on June 13, 1997 extensive snow cover still existed in the Miller Creek basin. The Fisher Creek SNOTEL recorded a snowpack of 96.0 cm (37.8 in) on June 13, 1997. The upper Miller Creek basin was visited on June 13, 1997 to determine if spring water and surface-water measurements could be taken.

To determine the location of flowing water or spring discharge required either: A) hearing flowing water under the snowpack and digging this area out until a temperature of the flowing water could be measured or B) finding small holes (~30 cm) created by the melting of overlying snow by spring or surface water. In these areas where water could be found the temperature was measured and recorded.

Results

Water temperatures collected from springs varied from 0.2°-2.3° C (Appendix B). Most

spring water temperatures were above 1.2° C. Only M-30's temperature was below 1.2° C, and interestingly, M-30's temperature changed erratically from 0.2°-2.2° C while measuring. The average (± one standard deviation) temperature (excluding M-30) of spring water on this date was 1.6 ± 0.4° C.

Surface water temperatures taken from where small holes in snowpack existed ranged from 0.1°-2.3° C. Table 15 indicates the location and temperature of the water exposed by the small holes. Table 16 indicates the temperature measurements taken from Miller Creek and the channel that is formed by the rock glacier spring M-29. The average temperature of these surface-water measurements was 1.2 ± 0.7° C.

Table 15. Temperature of visible flowing water on June 13, 1997.

Location Description	Water temperature (°C)
20 meters SE of M-62	0.1
100 meters N and 100 meters lower than M-25B	2.0
20 meters NW of M-22	1.2
20 meters WNW of M-22	1.0
4 meters above M-58	1.8
0.5 meters N of M-14	0.1
30 meters WNW of M-36	1.3
200 meters NE of M-37	1.3
10 meters below M-47	0.9
200 meters SSE of M-29	0.7
200 meters SSE of M-49	0.5
20 meters W of M-43	2.1
20 meters NNE of M-43	1.9
Average ± one standard deviation (n=13)	1.2 ± 0.7
Average spring water temperature (from Appendix B, M-30 excluded) n=7	1.6 ± 0.4

Table 16. Temperature of water in tributary and stream channels on June 13, 1997.

Location Description	Water temperature (°C)
200 meters SSE of M-29	0.7
E of M-49 in Miller Creek	1.2

Discussion

Temperature measurements collected on June 13, 1997 in the study area suggest that there may be interaction with warmer groundwater. Temperatures of 2.3° C are higher than expected for pure snowmelt in contact with snow (Table 15).

Ground Probe Temperature Measurements

To determine whether insolation and/or ambient air temperature affects spring-water temperature, the soil water temperature beneath springs was measured. If spring water is warmed by surface processes then the soil temperature beneath the spring should decrease with depth.

Methods

At select springs, temperatures were measured beneath the ground surface. To facilitate measurement at depth, a long hollow metal shaft with a handle was used. A thermal probe was placed snugly at the end of the metal shaft with the instrument's wire running inside and up the metal shaft to a hand-held display console. The metal shaft was plunged into the ground surface beneath a spring. Incremental markings on the shaft allowed temperature measurements at incremental depths. Time at each incremental depth was allowed for the probe to adjust to the temperature of the ground soil. Springs were selected for sub-surface temperature measurements based on the ability of the substrate to be penetrated by the shaft and temperature of the spring water in comparison with other spring water temperatures in the rest of the basin.

Results

The temperatures in the soil below springs M-43 and M-44 were measured. These

springs were chosen because they had easily penetrable soil, and these springs had higher temperatures than springs in the rest of the basin. The average temperature of all measuring points including springs, pools and spring surface flow measuring points was 4.4° C whereas average temperature measurements of M-43 and M-44 were 5.4° C and 10.2° C respectively. While the temperatures below M-44 decrease, temperatures below M-43 are variable (Table 17).

Table 17. Subsurface ground temperature measured by ground probe below select springs (September 14, 1997).

Depth (cm) below ground surface	Temperature (°C) below M-43	Temperature (°C) below M-44
0	6.1	15.3
15	5.9	
45	6.4	
60	6.2	14.6
75		
90		9.8

Discussion

Decreasing temperatures below M-44 indicate that insolation and/or ambient air temperature may be the cause of elevated spring-water temperatures. Warming by insolation and/or ambient air temperature may cause the temperature of water in the surficial deposits to be raised to greater temperatures than that of the bedrock aquifer.

Spring Surface-Flow and Spring Areas

A significant problem with a spring study in an alpine basin is that a spring may discharge reemerging surface water. Reemerging surface water is surface water which has emerged from one spring, then infiltrated back into the ground and then reemerged from another down-gradient spring. If the discharge of this reemerging surface water is measured then this could cause

spurious data to have been tallied when the bedrock and surficial-deposit aquifer contributions to spring discharge were summed.

The most likely area where reemerging surface-water measurements would occur is in an area of unmonitored springs (Plate 1). To determine if an area of unmonitored springs contains reemerging surface water, a test involving the monitoring of spring surface flow was devised. Spring surface flow is water which flows in the channel formed by a spring. Spring surface flow was measured in a spring channel at predetermined distances below the spring head. If springs have similar pH, temperature and SC behaviors as spring surface-flow measuring points, then those springs could be discharging reemerging surface water. The test is based on the assumption that surface flow down-gradient from a spring head would behave in a similar manner to reemerging surface water.

Methods

Springs in spring areas were chosen as representative of the spring area based on their location and discharge. If the spring area was large, an "up-gradient spring" at the head of the spring discharge area and "down-gradient spring" at the down gradient end of the discharge area were chosen; e.g., there is an area of unmonitored springs in the south central portion of the study area whose upgradient spring is M-27 and downgradient spring is M-49 (Plate 1).

A spring surface-flow measuring point is defined as a point in a spring channel which has water flowing for at least two meters above the measuring point. Select spring surface-flow measuring points down gradient from matching up-gradient springs were mapped and monitored.

Results

The names of the spring surface-flow measuring points appear in Table 18, and spring surface-flow measurements are reported in Appendix B. Table 19 indicates the average differences between up-gradient and down-gradient springs in spring areas and the average differences between spring surface-flow measuring points and their matching up-gradient spring.

Table 18. Spring surface-flow measuring points.

M-7	M-11	M-15	M-16C	M-17	M-25	M-26	M-34B	M-37B	M-68	M-71

Table 19. Spring surface flow and up-gradient spring comparisons. Note that all means are shown ± one standard deviation.

	Spring surface-flow measuring point minus the up-gradient spring				Down-gradient spring minus up-gradient spring in spring areas			
	n (# of pairs)	mean Δ	maximum Δ	minimum Δ	*n* (# of pairs)	mean Δ	maximum Δ	minimum Δ
Temperature (°C)	26	1.7°±2.0°	4.6	-2.4	10	3.0°±1.8°	6.4	0.7
SC (µS cm^{-1})	19	-6±27	63	-35	6	-2±17	12	-27
pH	9	-0.02±0.4	0.84	-0.39	2	0.66±0.37	0.92	0.39
Discharge (l/min)	22	8.5±14	30.7	-1.3	NA	NA	NA	NA

Discussion

This test can not conclude whether springs in areas of unmonitored springs are discharging reemerging surface water. The monitoring of spring surface flows did not establish significant signatures for differences between up-gradient and down-gradient surface-flow measuring points. The average differences between pH, SC and temperature for up-gradient and down-gradient surface-flow measuring points had large standard deviations.

Temperature Measurements of Tributary One's Surface Flow and Adjacent Springs

To determine if springs contribute significantly to surface flow, temperatures were collected from a nearby tributary both up and down gradient of a spring confluence. A change in tributary-water temperature which trends in the direction of the spring's temperature is evidence to indicate the spring contributed significantly to surface flow.

Methods

Tributary One (T1 in Figure 1E) was chosen because of the proximity of spring M-50. When sampling Tributary One's surface-flow temperature, temperature measurements were taken every ten meters, and time was allowed for the thermal probe to equilibrate to water temperature.

Results

Table 20 lists the temperature measurements taken at Tributary One. The temperature measurements are plotted in Figure 24. The temperature measurements from Tributary One's surface flow indicate that the temperature of Tributary One rises from 3.1° C to 9.2° C in 230 meters of downstream distance. Only 20 meters before the confluence of spring M-50 the temperature drops to 8.4° C, and then after the confluence the temperature drops to 5.9° C.

Discussion

The temperature of water discharged from spring M-50 is cold compared with the rest of the basin. The temperature of M-50 varied 1.8°-2.8° C during the field seasons, whereas the average temperature of all measuring points including springs, pools and spring surface-flow measuring points was 4.4° C. On July 23, 1997, M-50's temperature was 1.8° C.

Table 20. Tributary one surface-water and nearby spring-water temperature measurements.

Meters downstream	Temperature (°C) of surface water	Measuring feature and temperature (°C)	Meters downstream	Temperature (°C) of surface water	Meters downstream	Temperature (°C) of surface water	Measuring feature and temperature (°C)
0	3.1		120	5.8	240	9.0	
10	3.3		130	6.1	250	8.4	
20	3.6		140	6.1	260	8.7	
30	3.9	(M-67) 1.8	150	6.2	270	8.4	
40	4.2	(Seep) 3.0	160	6.9	280	8.6	
50	4.2	(Seep) 3.2	170	6.9	290	8.0	(M-50) 1.8
60	4.6		180	7.0	300	6.4	
70	4.8		190	7.9	310	5.9	
80	5.0		200	7.9	320	6.1	
90	5.4		210	8.1	330	6.3	
100	5.8		220	8.7	340	6.6	
110	5.8		230	9.2	350	6.9	
					360	6.9	

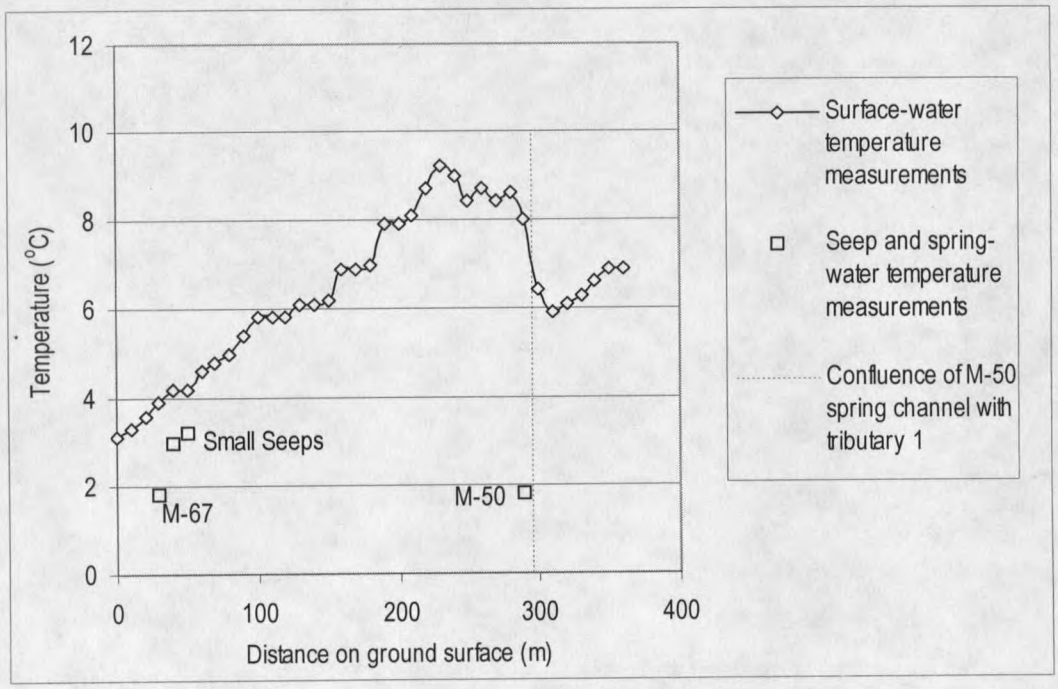


Figure 24. Distance downstream vs. temperature of surface water in tributary one and vs. temperature of water discharging from nearby springs and seeps. Spring names are labeled. Measured on July 23, 1997 between 13:04 and 14:51. Approximate location of sampled tributary is indicated in Figure 1E.

On July 23, 1997, the temperature of water in Tributary One started low (3.1° C), but climbed rapidly to 9.2° C in only 230 meters of downstream distance (Table 20 and Fig. 24). The rapid climb of temperature is hypothesized to be from the influx of warmer surficial-deposit-aquifer water, which has been warmed by ambient summer air temperatures and/or insolation.

Water in Tributary One appears to be affected by an influx of cold groundwater in the vicinity of M-50. Upstream of the confluence with M-50's spring channel, the surface water temperature drops steadily from 9.2° C to 8.4° C. The decreased temperature indicates that the contribution of cold groundwater is likely. This influx of cold groundwater is hypothesized to be from the bedrock aquifer because the average temperature of geology/SC-based bedrock spring water is lower than the geology/SC-based surficial-deposit spring water (Table 13).After the confluence, the effect of spring M-50's addition of lower temperature water is readily apparent as the temperature decreases dramatically.

The effect of M-50's water on Tributary One's water temperature indicates that groundwater discharge affects the temperature of surface water. A similar test can be executed on reaches of Miller Creek to determine if groundwater influxes affect stream water temperatures. Temperatures taken at incremental distances in Miller Creek may reveal a sudden drop or increase in temperature. If the temperatures are taken along the floor of the creek the temperature differences may be greater than if the temperatures are taken from the creek's surface. A sudden drop or increase in temperature may be the result of groundwater influx.

APPENDIX B

TEMPERATURE, SPECIFIC ELECTRICAL CONDUCTANCE, pH AND DISCHARGE MEASUREMENTS

AD	=	flow appears diminished compared to discharge observed during last visit
DA	=	flow does not appear diminished compared to discharge observed during last visit
DRY	=	no water discharging for six meters from within discharge point
FA	=	the spring is flooded by runoff from above
MD	=	the discharge measuring point has moved down
SC	=	the measuring point is covered in snow
SE	=	flow seeping
TL	=	the flow is too low to be measured
5.0,5.6		indicates that two measurements were taken in a single day
5.0-5.6		indicates that the measurements fluctuated between the two indicated values
71.7+0.7...		indicates discharge was measured from two spring heads less than one meter apart

Table 21. Temperature measurements (°C)

Measuring point	1	2	3	4	5	6	8	11	12	13	14	15	15A	16A	16B
7/31-8/2/96		3.1	2.5	3.6	4.1				8.9	3.3	3.2	7.3	2.7	3.0	3.5
8/20-21/96	2.1	3.8	3.2	3.2	3.1			10.3	6.3	4.0	3.9	7.9	5.0	3.6	3.4
8/31/96						3.4	7.2								
9/14/96	2.5	3.7	3.6	3.1		3.7	5.9	8.3	6.2	3.2	3.0	5.9	3.5	3.2	
10/12/96	2.0	3.5	3.1	2.5		3.0	3.7	4.0	4.8	2.9	3.0	5.5		2.9	
11/9-10/1996	2.2	0.7	3.3	1.4	SC	SC	SC	SC	0.6	2.9	2.6	1.3	SC	SC	SC

Measuring point	16C	17	18A	19	20	21	22	23	25A	25B	26A	28	29	30	34A
7/31-8/2/96	5.0			8.5		2.9		4.7		3.0				5.5	5.0,5.6
8/20-21/96	3.3			5.4		3.7		6.1	3.4	2.9	3.9			3.1	5.7
8/31/96		5.5	9.5				4.1					0.8	0.7		
9/14/96				6.4	5.1	4.1	6.0	7.9			5.0	1.2	0.9	3.9	
10/12/96	5.1		11.5	3.9	4.4	3.4	4.4	5.1			4.0	0.4	0.7	2.8	5.1
11/9-10/1996	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	2.5	SC

Measuring point	34B	34L	36	37	41	42	43	44	45	46	47	48	49	50	52
7/31-8/2/96		3.3,2.9	2.9	2.5,2.9		4.9	5.5	12.5	4.6			4.7		2.8	
8/20-21/96	5.0	5.7	2.9	3.7	7.1	4.3	4.9	7.7	3.1		3.6	3.4			11.3
8/31/96										7.8			5.3		
9/14/96	4.5	3.5	3.1				7.6	11.0	3.9		4.3	3.3	6.4		7.7
10/12/96			2.9				4.7	8.1	3.2	7.3	2.6	2.5	3.8		6.1
11/9-10/1996	SC	SC	SC	SC	SC	SC	SC	SC	3.1	SC	1.0	SC	SC	SC	SC

Measuring Point	53	54	56	57	58	59	60	61	62	63	64	65	66	71	
7/31-8/2/96	6.0		6.2	2.7			7.0	6.8		2.2					
8/20-21/96				3.3	5.0	6.3		6.6	7.4	2.3		4.3	3.0		
8/31/96		4.0												4.8	
9/14/96				3.0	3.6			7.7	12.5	3.7	3.9	3.5	3.3	7.1	
10/12/96		4.0		2.7				5.2	9.8	2.4	2.7	2.8			
11/9-10/1996	SC	SC	SC	3.0	SC	SC	SC	SC	SC	2.4	2.1	2.5	SC	SC	

Table 21 (cont.). Temperature measurements (°C).

Measuring point	1	2	3	4	5	6	7	8	11	11B	12	13	14	15	15A	16A
6/13/97	SC	1.3	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	2.3
7/17/97	SC	1.6	2.0	2.0	1.8	2.0		SC	SC		SC	1.8	2.1	5.0	1.9	2.3
7/23/97																
7/31-8/2/97	2.0	3.3	2.4	3.0	2.4	2.1	SC	6.2	6.0	2.0	5.0	2.1	2.4	8.1	2.4	2.4
8/20-21/97	2.1	2.6	2.7	2.6	3.3	2.7	10.0	1.6	16.3	TL	4.4	2.4	2.3	7.0	3.1	2.6
8/26/97																
9/14/97	2.1	5.7	3.2	2.9	2.5	3.5	15.4	11.5	2.6		7.6	2.9	2.6	4.7	2.9	2.8
10/7/97	2.0	2.9	3.4	2.6	2.6	3.2	2.3	4.1	1.4		3.3	3.1	2.7	2.1	2.8	2.8

Measuring point	16B	16C	17	18	18A	19	20	21	22	23	24	24B	25	25A	25B	26
6/13/97	SC	SC	SC	SC	SC			1.5		1.2	SC	SC	SC	SC	2.3	SC
7/17/97	2.4	FA			7.5	FA		3.6	2.9	3.3	2.2	2.3		SC	2.3	
7/23/97			3.6	2.2			2.2									
7/31-8/2/97	2.5	2.2	3.3	3.2	18.6	7.8	3.0	2.5	4.0	5.4			3.6	2.2	2.3	5.6
8/20-21/97	2.6	3.3	3.7	5.1	25.9	6.1	3.5	2.7	4.5	5.3			3.8	2.7	2.6	6.4
8/26/97																6.5
9/14/97	2.9	3.1	3.7	4.9	22.5	5.0	4.4	3.3	4.6	6.1			3.6	3.0	2.9	6.4
10/7/97	2.8	2.8	3.2	4.2	5.3	3.2	3.6	3.1	4.2	5.0			3.1	3.0	DRY	5.7

Measuring point	26A	27	28	29	30	34A	34B	34L	34R	35	36	37	37B	39	40	41
6/13/97	SC	SC	SC	SC	0.2-2.2	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC
7/17/97	FA		0.2	SC	3.2	SC		1.8			1.9	1.9	2.3	8.4	2.7	4.3
7/23/97		1.1	0.3								2.1					
7/31-8/2/97	3.7	1.6	0.6	0.7	5.3	4.8	3.7	2.2	2.8	10.2	2.4	2.2	3.4	10.2	4.2	5.9
8/20-21/97	4.1	2.2	0.6	0.7	4.2	4.3	3.3	2.5	3.8	11.7	2.7	2.4	5.0	9.8	5.0	6.8
8/26/97														11.0	5.2	7.4
9/14/97	4.5	2.6	2.8	0.8	4.1		3.5	5.0	5.3	11.5	3.0	2.9	6.8	9.8	5.6	7.8
10/7/97	4.2	2.7	0.6	0.8	3.6	2.2	3.0	3.0	2.6	5.1	3.3	3.0	3.0	7.2	4.8	6.6

Table 21 (cont.). Temperature measurements (°C)

Measuring point	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57
6/13/97	1.7	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	1.3	SC	SC
7/17/97	2.9	3.8	10.7	3.1	15.9	1.4	2.9	3.5	1.8	SC	4.6	6.0FA	SC		2.1	1.8
7/23/97								3.8	1.8					6.9	3.3	
7/31-8/2/97	4.3	4.9	8.6	3.4	10.4	4.3	4.0	4.9	1.9	6.0	9.9	4.8	SC	DRY	4.3	2.1
8/20-21/97	5.4	5.3	14.0	3.2	11.3	5.1	3.0	5.0	2.1	11.8	11.9	4.2	3.9	DRY	4.9	2.3
8/26/97	5.3	5.5	7.3													
9/14/97	5.7	6.1	15.3	4.9	10.9	3.3	3.0	5.9	2.3	6.4	10.6	5.1	5.8		5.6	2.6
10/7/97	4.3	5.4	6.3	3.1	5.0	3.6	2.9	4.0	2.5	4.5	4.1	3.4	3.7		3.8	2.9

Measuring point	58	59	60	61	62	63	64	65	66	67	68	68A	69	70	71
6/13/97	SC	SC	SC	SC	SC	1.5	SC	SC	SC	SC	SC	SC	SC	SC	SC
7/17/97	3.7			2.4	10.3	1.7	3.1	3.1	1.9						
7/23/97				3.7						1.8			2.1	4.0	
7/31-8/2/97	3.3	5.2		5.5	11.6	1.2	2.9	3.1	2.1	DRY	2.5	0.4	DRY	6.4	4.3
8/20-21/97	3.2	4.9		5.6	10.4	2.4	3.4	3.1	2.3	DRY	11.5	DRY	DRY	3.9	3.8
8/26/97					10.4										
9/14/97	3.2	5.7		6.2	8.5	2.8	4.6	3.1	2.5		5.2			DRY	4.9
10/7/97	2.8	4.6		4.3	5.3	3.2	2.9	3.1	2.7		2.0			DRY	TL

Table 22. Specific electrical conductance values equilibrated to 25° C (µS cm^{-1})

Measuring point	1	2	3	4	5	6	8	11	12	13	14	15	15A	16A	16B
7/31-8/2/96		232	360	350	332				129	235	203	175	210	193	139
8/20-21/96	1709	195	361	371	392			177	137	246	188	168	183	180	165
8/31/96						509	256							222	
9/14/96	1763	237	395	438		586	314	216	397	264	233	196	221		
10/12/96	1704	311	572	481		578	351	208	176	271	223	195	227	201	
11/9-10/96	1439	346	415	524	SC	SC	SC	SC	178	279	211	186	SC	SC	SC

Measuring point	16C	17	18A	19	20	21	22	23	25A	25B	26A	28	29	30	34A
7/31-8/2/96	169			139		92		78						550	246,266
8/20-21/96	174			176		99		74	87	181	88			567	269
8/31/96		159	142				92					127	135		
9/14/96				178	135	92	97	65			81	169	204	449	535
10/12/96	195		140	193	150	108	69	67			86	159	181	562	
11/9-10/96	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	530	SC

Measuring point	34B	34L	36	37	41	42	43	44	45	46	47	48	49	50	52
7/31-8/2/96		378,404	454	288,312		46	62	44	507			287		313	
8/20-21/96	372	379	529	316	84	93	80	89	539		337	285			55
8/31/96										123			196		
9/14/96	453	390	568				57	58	525		374	276	200		75
10/12/96			488				61	73	531	151	362	328	281		71
11/9-10/96	SC	SC	SC	SC	SC	SC	SC	SC	539	SC	467	SC	SC	SC	SC

Measuring point	53	54	56	57	58	59	60	61	62	63	64	65	66	71
7/31-8/2/96	180		170	328			83	105		145				
8/20-21/96				326	157	92		125	79	138		782	270	
8/31/96		692												226
9/14/96				387	194			122	62	186	1066	729	269	227
10/12/96		606		404	231			170	71	187	1139	769		
11/9-10/96	SC	SC	SC	377	SC	SC	SC	SC	SC	217	1118	430	SC	SC

Table 22 (cont.). Specific electrical conductance values equilibrated to 25° C (µS cm^{-1})

Measuring point	1	2	3	4	5	6	7	8	11	11B	12	13	14	15	15A	16A
7/31-8/2/97	1498	143	329	318	314	419	SC	74	78	56	132	218	194	154	189	181
8/20-21/97	1570	176	367	369	398	445	373	277	97		139	226	205	166		178
9/14/97	1594	193	378	409	411	519	429	200	229		142	247	224	199	217	191
10/7/97	1579	199	391	624	558	570	720	269				258	223	220	223	214

Measuring point	16B	16C	17	18	18A	19	20	21	22	23	25	25A	25B	26	26A	27
7/31-8/2/97	137	150	175	119	98	144	136	83	95	61	67	67	159	71	75	151
8/20-21/97	149	164	183	116	87	161	140	99	94	69	83	71	166	75	82	188
9/14/97	186	183	187	123	90	172	144	104	98	70	96	70	173	77	84	209
10/7/97	198	200				146	151	67	101	77	83	75		83	87	

Measuring point	28	29	30	34A	34B	34L	34R	35	36	37	37B	39	40	41	42	43
7/31-8/2/97	100	129	498	227	336	363	322	64	426	288	267	65	76	60	71	62
8/20-21/97	135	138	526	256	412	425	366	59	510	323	292	71	78	73	73	65
9/14/97	134	150	520		447	418	379	56	591	322	313	66	78	78	78	62
10/7/97									612			83	76	76		

Measuring point	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59
7/31-8/2/97	53	495	76	244	238	163	301	120	51	172		DRY	176	317	146	78
8/20-21/97	49	544	116	343	283	204	319	97	47	206	379	DRY	185	335	179	93
9/14/97	48	498	124	386	279	217	352	106		227	519		189	370	192	95
10/7/97							342	158	70	225	703		201	388	181	101

Measuring point	61	62	63	64	65	66	67	68	68A	69	70	71
7/31-8/2/97	103	61	127	949	722	248	DRY	23	9		283	146
8/20-21/97	110	66	134	977	621	273	DRY	41	DRY		404	171
9/14/97	111	76	147	1007	532	277		53				251
10/7/97	138	110	160	1138	835						MD	

Table 23. pH measurements

Measuring point	1	2	3	4	5	6	8	11	12	13	14	15	15A
7/31-8/2/1996		7.82	7.60	7.67	7.79				7.60	6.79	7.73	7.29	7.63
8/20-21/1996	6.60	8.29	8.74	8.22	7.75			6.90	6.80	7.36	7.75	7.31	7.70
8/31/96						7.00	7.30						
9/14/96	6.99	8.02	7.92	8.01		7.82	8.04	7.01	7.40	7.30	7.96	7.79	7.99
10/12/96	6.99	8.17	7.76	7.81		7.79	8.12	7.83	8.13	7.19	8.40	7.72	8.03

Measuring point	16A	16B	16C	17	18A	19	20	21	22	23	25A	25B	26A
7/31-8/2/1996	6.26	6.88	6.88			7.29		5.37		5.67		6.04	
8/20-21/1996	6.59	7.36	7.30			7.36		5.86		6.35	6.16	6.17	5.88
8/31/96				6.50	6.20				6.10				
9/14/96	6.68					7.06	6.71	5.90	5.99	5.62			5.49
10/12/96	6.75		7.22		7.05	6.78	6.10	5.81	6.52	5.23			4.39

Measuring point	28	29	30	34A	34B	34L	36	37	41	42	43	44	45
7/31-8/2/1996			7.48	6.88,7.31		7.63,7.92	7.24	7.68,7.30		6.64	6.25	6.41	7.42
8/20-21/1996			7.41	7.37	7.43	7.77	6.70	7.61	6.30	6.62	6.39	6.66	7.20
8/31/96	8.10	7.90											
9/14/96	6.90	8.29	7.77	8.07	8.30	8.08	8.10				6.11	6.47	7.72
10/12/96	8.90	7.99	7.21				8.03				6.43	6.75	7.23

Measuring point	46	47	48	49	50	52	53	54	56	57	58	59	60
7/31-8/2/1996			6.76		7.63		7.20		7.18	7.03			5.70
8/20-21/1996		7.20	7.00			6.70				7.47	7.19	5.91	
8/31/96	7.80			7.20				6.90				6.10	
9/14/96		8.29	7.85	7.87		6.87				7.06	7.62	5.99	
10/12/96	5.70	7.83	7.08	7.67		7.24		8.40		7.54	7.74		

Table 23 (cont.). pH measurements

Measuring point	61	62	63	64	65	66	71
7/31-8/2/1996	6.41		7.38				
8/20-21/1996	7.08	6.83	7.20		7.20	7.10	
8/31/96							7.90
9/14/96	6.76	6.38	7.56	7.94	8.05	7.71	8.39
10/12/96	6.79	5.94	7.47	7.75	7.92		

Table 24. Discharge (l/min) as measured by V-neck cutthroat flume

Measuring point	3	4	5	6	14	15	15A	16A	16B	18A	22	23	24	24B	25A	25B	30	31	34A	34B	34L	34R
7/31-8/2/1996	8.1	9.5			2.5	8.1	10.9	1.4	1.4			1.9	0.0	0.0		0.7	3.9	0.0	0.0	8.1,10.9	0.0,0.2	0.0
8/20-21/1996	1.9	1.9	0.0				0.1	2.5	0.2	0.0		0.2	0.0	0.0	AD	AD	DA	0.0		1.9		0.0
08/31/96																						
09/14/96	1.9	0.4		5.8									0.0	0.0	0.0	0.0	AD	0.0	0.2		0.0	0.0
10/12/96	1.4	2.5	0.0	10.9				SE		0.0	0.7	0.0	0.0	0.0				0.0		0.0		0.0

Measuring point	36	37	37B	42	43	44	45	47	48	49	57	58	60	61	62	64	65	66
7/31-8/2/1996	16.2	25.1,14.3	43.3,46.9	1.9	25.1	5.8	9.5		9.5		6.9			1.4				
8/20-21/1996	10.9	MD	3.9	0.2	25.1	1.4	10.9	5.8	5.8		0.2		0.0		2.5		0.0	33.5
08/31/96																		
09/14/96	1.4	0.0	0.0	0.0	1.9	1.4	14.3	1.9	0.0			0.0			2.5	3.1		0.2
10/12/96	AD	0.0			8.1	5.8	8.1	3.9	0.2	5.8	0.2			0.0	1.0	1.4	0.0	0.0

Measuring Point	1	3	4	5	6	11	11B	12	13	15	15A	16A	16B
7/17/97	SC	18.0	8.0	33.1	22.4	SC			27.4		54.1	5.7	0.7
7/31-8/2/97	3.9	14.1	22.4		14.1	6.8				10.8	6.8	4.8	5.7
8/20-21/97	0.0	6.8	10.8		20.1	4.8	TL	MD		10.8	MD	1.4	0.4
9/14/97	TL	10.8	10.8		14.1	MD	TL	MD		9.4	MD	1.0	1.4
10/7/97	TL	10.8	1.4		10.8	TL	TL	MD		9.4	MD	0.2	0.7

Table 24 (cont.). Discharge (l/min) as measured by V-neck cutthroat flume

Measuring Point	18	19	20	21	22	23	24	24B	25B	26	27	29	31	34A	34B	34L	34R	35	37
7/17/97				3.9	3.9	16.0		14.1	3.9	FA		SC	0.0	SC		0.7	0.0		103.9
7/23/97	9.4										62.5								
7/31-8/2/97	8.0	1.4	0.4		2.4	8.0	0.0	0.0			158.5		0.0	3.9	5.7	1.4	0.0		9.4
8/20-21/97	3.9	TL	3.9		3.9	1.0	0.0	0.0			71.7+0.7		0.0	2.4	2.4	TL	0.0		2.4
9/14/97	1.4		TL		1.9	1.4	0.0	0.0			6.8		0.0		2.4	Se	0.0	8.0	MD
10/7/97	0.0	0.1	0.2		3.9	1.9	0.0	0.0			1.4		0.0	0.0	3.9		0.0	6.8	MD

Measuring Point	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57
7/17/97	1.0	9.4		1.0	27.4	3.9	9.4	0.0	16.0	22.4		5.7	SC			SC			22.4
7/23/97																		0.7	
7/31-8/2/97	2.4	2.4		5.7	42.8	3.9	10.8	0.0	6.8	14.1	2.0		TL	TL	3.9	SC		0.2	6.8
8/20-21/97	0.0	1.9	TL	3.9	39.4	5.7	18.0	TL	6.8	14.1		39.4	TL	TL		9.4	DRY	1.4	8.0
9/14/97	0.1	1.0	TL	0.7	33.1	9.4	8.0	1.4	3.9	10.8		8.0	TL	TL	TL	5.7	DRY	0.7	8.0
10/7/97	0.4	1.4	TL	1.0	27.4	10.8	10.8	2.4	5.7	3.9		10.8	TL	TL	TL	0.2	DRY	SE	5.7

Measuring Point	58	59	60	61	62	63	64	65	66	67	68	68A	69	70
7/17/97		8.0		6.8	16.0	158.5	5.7	5.7	565.9	0.7				
7/23/97				8.0						0.7			6.8	2.4
7/31-8/2/97	10.8	3.9	46.4	3.9	22.4	27.4	1.4	5.7	136.4	DRY	18.0	39.4	0.0	
8/20-21/97	5.7	3.9	SE	2.4	18.0	86.9	5.7	5.7	98.0	DRY	0.0	DRY	DRY	MD
9/14/97	5.7	5.7	DRY	TL	4.8		3.9	1.9	58.2	SE		DRY	DRY	DRY
10/7/97	1.4	TL	DRY	3.9	1.4		4.8	5.7	81.6	DRY	SE	DRY	DRY	MD

Table 25. Discharge (l/min) as measured by portable V-notch weir

Measuring point	3	4	5	6	11	12	15	15A	16A	16B	17	20	22	23	26A	28	31	34A	34B
7/31-8/2/1996	2.4		0.9														0.0	0.2	0.3
8/20-21/1996	1.3	0.3	0.2				2.4	2.2	3.0	1.7				0.1	1.5		0.0	0.1	2.4
08/31/96				0.9							0.1		0.2			0.3			
09/14/96	0.9	0.3		1.9									0.1				0.0		0.0
10/12/96	1.9	0.3		5.3	MD	MD						0.3	0.2	0.1			0.0	0.0	0.0

Measuring point	34L	34R	36	37B	42	43	44	45	46	47	48	49	50	54	57	58	59	61	62
7/31-8/2/1996													18.9						
8/20-21/1996			6.7	1.1	0.1	8.9	4.9	9.5		2.4	1.1		0.0		0.1	4.9	0.0	0.3	5.3
08/31/96									0.1			0.1		0.0					
09/14/96	0.2	0.0	3.3	0.0	0.0			7.8		0.5	0.3		0.0	0.0		0.1	SE	0.0	1.3
10/12/96						5.3	0.5	5.3		3.0	0.2	4.4		0.9	0.5	0.3		0.1	1.1
11/9-10/1996			0.0								0.0								

Measuring point	63	64	65	66	71
7/31-8/2/1996	107.1				
8/20-21/1996	2.2		0.2	18.9	
08/31/96					0.1
09/14/96		0.3	0.3	0.7	
10/12/96	AD	0.3	0.2	0.0	

Table 25 (cont.). Discharge (l/min) of springs as measured by portable v-notch weir

Measuring Point	1	3	4	5	6	11	11B	12	13	15	15A	16A	16B	17	18	18A
7/17/97	SC	8.3	8.3	39.4	14.6	SC		SC	71.4	52.2	14.6	10.2	7.8			0.1
7/23/97													0.2	0.2	4.4	
7/31-8/2/1997	1.9	5.3	7.2	1.1	1.5	2.4				12.2	5.3	5.3	0.3	0.4	2.2	0.0
8/20-21/1997	0.7	3.3	1.9	0.9	13.0	3.3	TL	MD		1.9	MD	0.8	1.5	0.9	0.8	0.0
9/14/97	0.3	1.3	1.9	0.3	5.3	MD	TL	MD		1.1		0.5	0.3	0.8	0.3	TL
10/7/97	1.9	1.9	1.1	0.3	5.3		TL	MD		1.9	MD	1.1	0.4	0.3		

Measuring Point	19	20	21	22	23	24	24B	25B	26	27	31	34A	34B	34L	35	37
7/17/97			26.3	0.9	19.9		7.0	2.2	FA			SC		2.2		
7/23/97		10.8								118.2						
7/31-8/2/1997	0.4	0.2		0.2	2.2	0.0	0.0			115.4	0.0	0.7	3.3	0.1	0.0	7.8
8/20-21/1997	0.3	1.3		0.1	1.9	0.0	0.0			48.8+0.8	0.0	0.3	1.9	0.0	1.9	1.9
9/14/97	0.1	0.3		1.5	0.3	0.0	0.0			18.9+0.3	0.0		0.9	Se	1.9	MD
10/7/97	0.0	0.4		0.5	0.5	0.0	0.0			0.4+5.7	0.0	0.0	0.5	0.9	1.9	MD

Measuring Point	37B	39	40	42	43	44	45	46	47	48	50	51	52	53	54	55
7/17/97		0.9	7.2	0.5	39.4	3.3	3.0	0.4	4.9	3.3	10.2	SC	0.0	10.8	SC	
7/23/97																7.8
7/31-8/2/1997	29.9	0.1	0.3	3.7	19.9	2.2	4.1	0.0	1.9	4.9	32.4			1.5	SC	DRY
8/20-21/1997	6.7	0.0	0.3	0.3	40.8	0.5	5.3	TL	1.5	3.3	18.9	TL	TL	0.5	8.3	DRY
9/14/97	0.5	0.0	0.3	0.0	27.4	5.7	2.7	0.0	0.9	1.5	1.9	TL	TL	0.0	3.0	DRY
10/7/97	0.9	0.0	0.3	0.3	18.9	9.5	2.2	0.3	1.9	2.4	1.9	TL	TL	TL	0.3	DRY

Measuring Point	56	57	58	59	61	62	63	64	65	66	67	68A	69	70
7/17/97	4.4FA	20.9		1.9	1.9	21.9	48.8	3.3	10.8	112.6				
7/23/97	1.1				1.3						0.8		5.3	
7/31-8/2/1997	0.2	3.0	18.9	3.0	0.9	4.4	24.0	2.4	1.5	126.9	DRY	8.3	0.0	
8/20-21/1997	0.0	1.9	5.3	1.1	0.3	3.7	18.9	1.3	2.4	61.3	DRY	DRY		MD
9/14/97	0.1	0.5	5.7	1.1	0.1	1.3	6.2	1.7	1.3	24.0				
10/7/97	SE	1.9	1.9	0.3	0.3	0.5	7.8	1.5	1.1	52.2				DRY

Table 26. Estimated discharge (gallons per minute)

Measuring Point	1	2	4	11	11B	12	13	14	15	15A	16A	16C	19	20	21	22	23	24	24B	25A
7/31-8/2/1996					SC	2	6	45							6			HD	HD	
8/20-21/1996	10	2										3	1		3			HD	HD	SE
08/31/96																		HD	NH	
09/14/96	5	1				3	5	10	10	5	5		2	1	2	0.1	4			0.0
10/12/96				4			5	10	10	10		SE		SE	2					
11/9-10/1996	2	0.5	0.5	Dry		1	0.5	2	0.5											

Measuring Point	25B	26A	28	29	30	41	46	47	51	53	56	57	60	63	65	69	71
7/31-8/2/1996										SE	2		0.5				
8/20-21/1996	0.5			60		0.5								6			
9/14/96		10	2	40		SE	AD		1			1					3
10/12/96		10	2	40													
11/9-10/96					2			1				1			1	2.1	

Measuring Point	2	7	11B	12	13	14	16C	21	24	24B	25	25A	25B	26	26A	28	29	30	36	49	71
7/17/97						70										150			125	80	
7/23/97																	90?			80	
7/31-8/2/1997	25	25	1	2	10	10	10	5	HD	HD	25	5	3	15	8	70	90	0.4	20	40	15
8/20-21/1997	25				10	10	8	4	HD	HD	25	4	2	15	8	50	90		20	30	20
9/14/97	20	30			5	5			HD	HD	15	2	0.5	8	7	50	90	1	20	20	20
10/7/97	8	2			4	2	MD	3	HD	NH	12	4	0	3	5	20	40	1	15	15	SE

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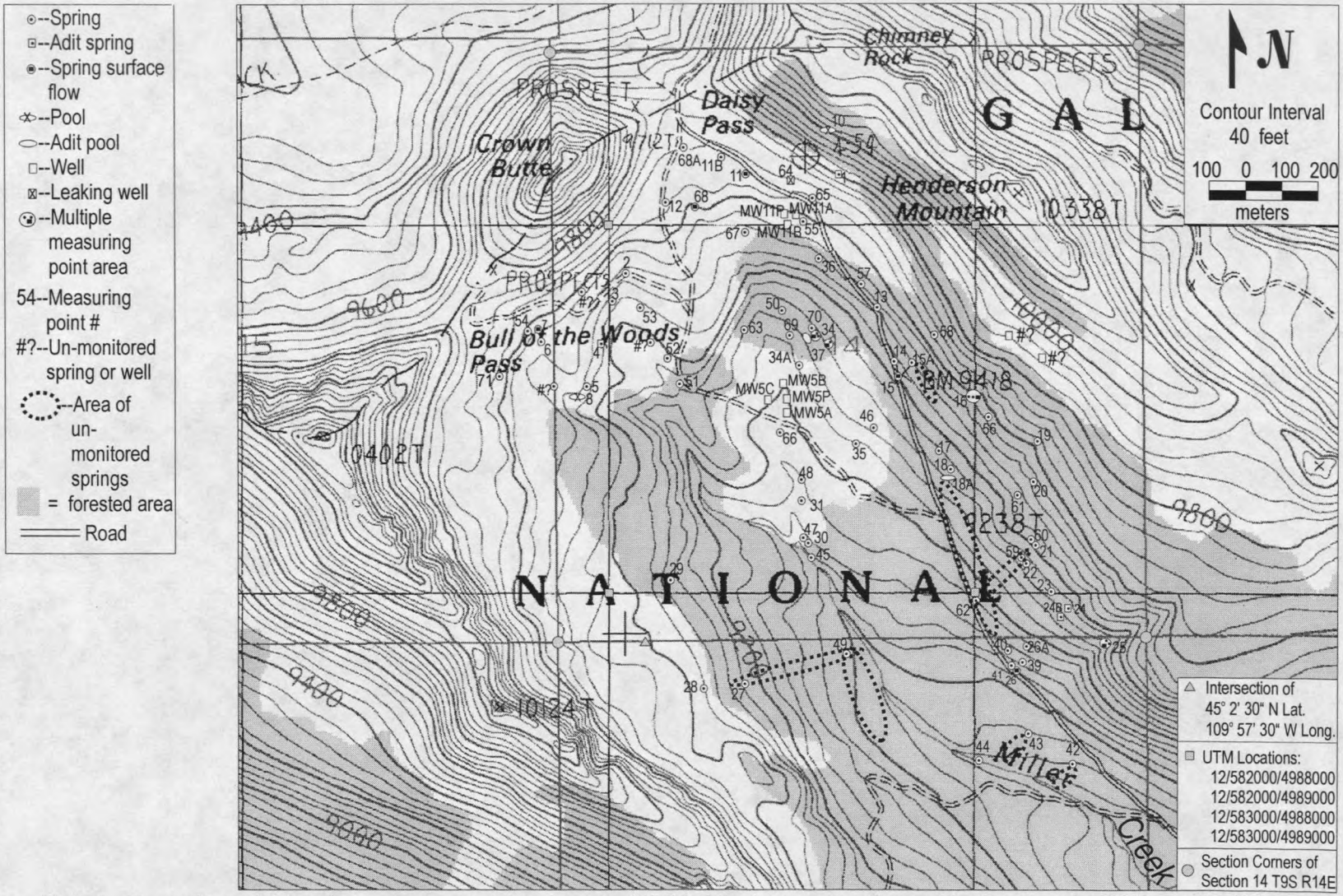


Plate 1. Measuring point locations. Base map taken from the USGS 7.5 minute series Cooke City Quadrangle, 1986, provisional edition.

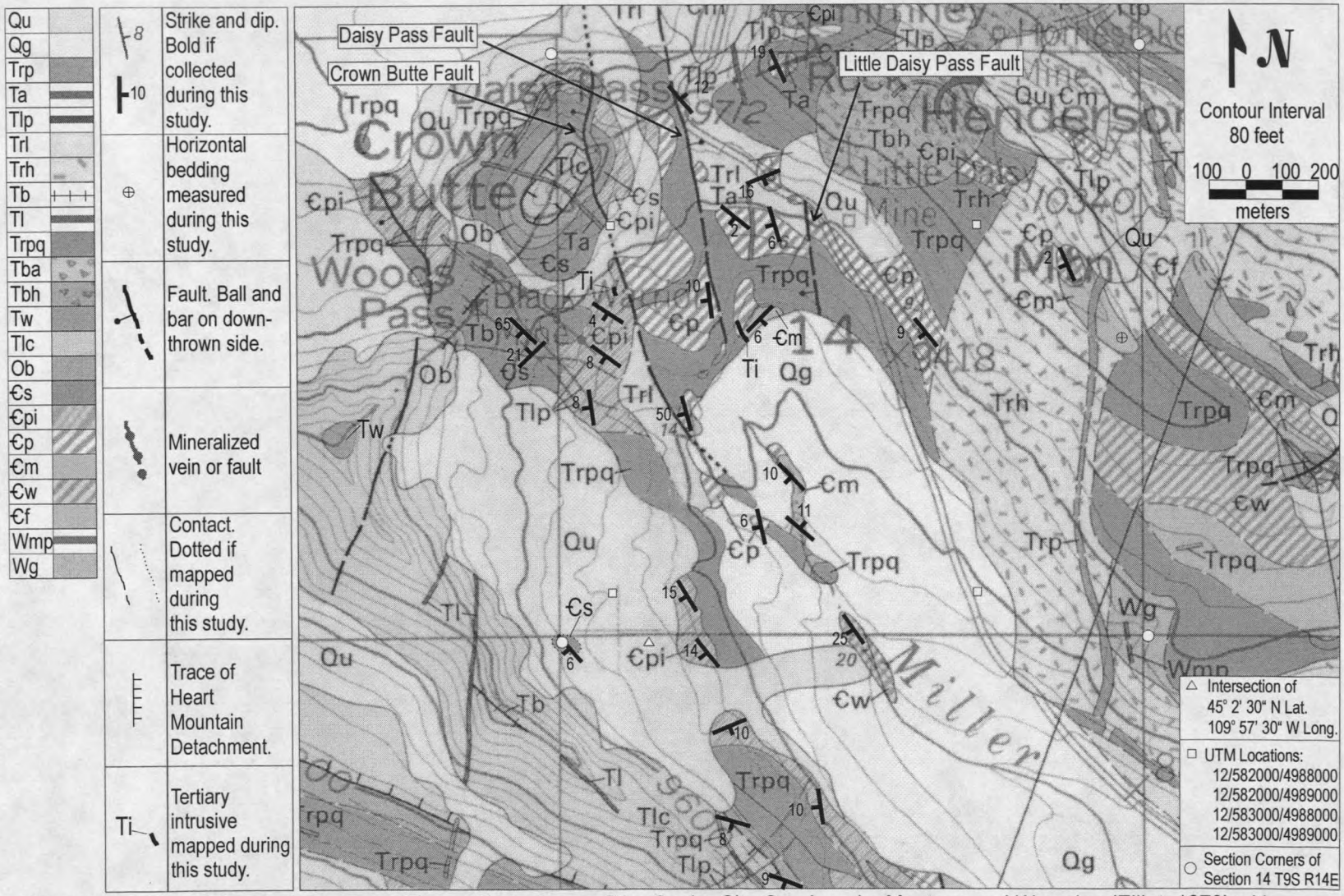


Plate 2. A portion of the geologic map of the southwest part of the Cooke City Quadrangle, Montana and Wyoming (Elliot, 1979) with additional information collected during this study. Description of bedrock units on following page.

Plate 2 continued. Description of units which appear on Elliot (1979) abbreviation of unit at left.

Quaternary Q:

Qu - Undifferentiated surficial deposits. Includes alluvium, talus, and colluvium.

Qg - Glacial deposits. Till and fluvioglacial deposits undifferentiated.

Tertiary T:

Trp, Ta, Tip, Trl, Trh, Tb, Tl, Trpq, Tba, Tbh, Ti - Tertiary intrusives. Includes porphyritic and aphanitic latites, rhyodacites, andesites, quartz latites, basalt and intrusion breccias. Color and mineral composition vary.

Tlc, Tw - Extrusive igneous rocks. (Lamar River, Cathedral Cliffs and Wapiti formations). Dark colored andesite. Aphanitic andesite and basalt commonly with plagioclase.

Ordovician O:

Ob - Bighorn Dolomite. Dark blue fossiliferous dolomite. Only the lower 8 m of the Bighorn Dolomite is observed in the study area.

Cambrian ϵ:

ϵ s - Snowy Range formation. Gray and tan limestones and shales. Approximately 70 m thick.

ϵ pi - Pilgrim Limestone. Upper portion, dark blue oolitic limestone; lower portion, gray alternating layers of thinly bedded flat pebble conglomeratic limestone. Approximately 75 m thick.

ϵ p - Park Shale. Shale and limestone. White, thinly bedded limestone layer is a cliff former. Locally altered to a yellow or white clay near intrusions. Approximately 75 m thick.

ϵ m - Meagher Limestone. Marbleized white to black with varying shades of light blue, green and gray limestone. Occasional pyrite crystals. Approximately 30 m thick.

ϵ w - Wolsey Shale. Black shale and sandstone. Approximately 55 m thick.

ϵ f - Flathead Sandstone. White and rust colored psammitic sandstone. Approximately 30 m thick.

Precambrian W:

Wmp - Metadolerite Porphyry. "Leopard rock" dikes, gray to black groundmass with plagioclase phenocrysts up to 4 cm in diameter.

Wg - Granitic Rocks. Predominantly white to gray granitic gneiss. Quartz and plagioclase feldspars are abundant.

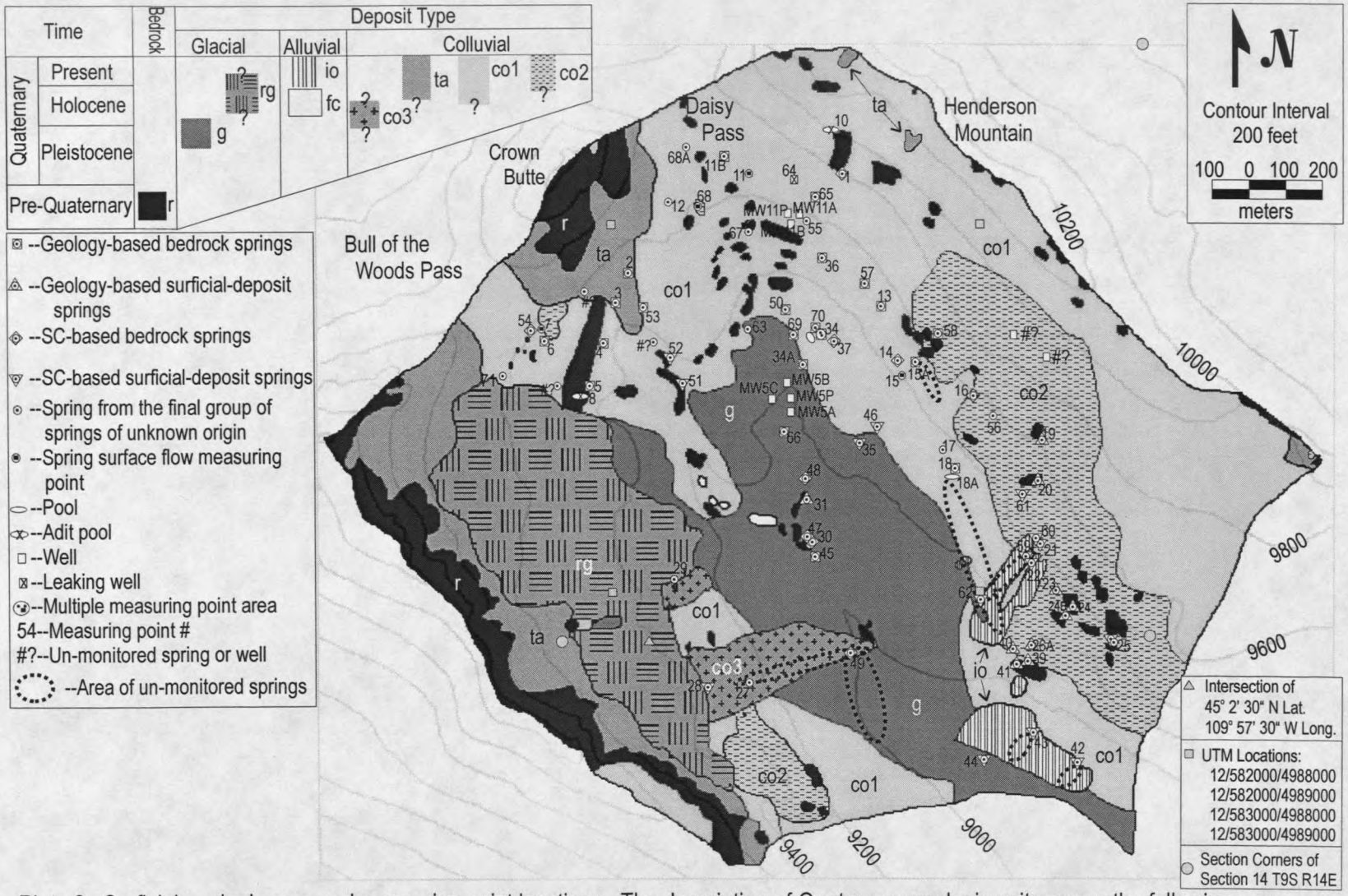


Plate 3. Surficial geologic map and measuring point locations. The description of Quaternary geologic units are on the following page.

Plate 3 continued. Description of Surficial geologic units. Abbreviation of unit at left.

io - Iron oxide and organic deposits. Poorly sorted with intermittent stratification. Sub-rounded to angular fines, granules, and pebbles. Predominantly composed of felsic angular granules and organic materials, including some woody debris. In places, the matrix is un-cemented iron oxide; in other places no matrix exists and clast-to-clast contact occurs between granule sized particles. Vegetation generally covers these deposits. Forms a thin covering on slopes and at slope toes; slump scarps up to 2 m wide and 1.5 m high exist. Thickness 0.2 to 2 m.

fc - Ferricrete. Similar to the iron oxide and organic deposits except these deposits are lithified and organic material is less prevalent. Exposed in cutbanks along stream channels. Thickness 0.5 to 2 m.

ta - Talus. Unsorted and unstratified. Angular clasts commonly greater than 15 cm in diameter. Fine matrix. Clast lithology is generally reflective of upslope rock types. Forms aprons and cones. Sparse vegetation occurs. Thickness 1 to 10 m.

co1 - Type 1 colluvium. Unsorted and unstratified. Subangular to angular pebble through boulder-sized clasts. Fine matrix. Clast lithology generally reflects nearby and upslope bedrock lithologies. The deposit forms on slopes and as toe-slope accumulations. Vegetation covers these deposits. Thickness 0.2 to 2 m.

co2 - Type 2 colluvium. Unsorted and unstratified. Predominantly angular, sand through granule size, and felsic (generally rhyodacite porphyry) in composition. Some sub-rounded cobble and boulder-sized clasts exist. Sub-rounded cobble and boulder lithologies are generally reflective of nearby and upslope bedrock lithologies. Slopes on which this deposit appears are generally steeper than the ones on which type one colluvium appear. Vegetation grows on approximately 50% of the deposit; bowed trees are common. Thickness 0.2 to 2 m. The main differences between this material and co1 are: 1) vegetation covers only approximately 50% of this deposit, whereas vegetation covers most of co1 and 2) the dominant composition of co2 is rhyodacite porphyry whereas co1 is composed of a variety of lithologies.

co3 - Type 3 colluvium. Unsorted and unstratified. Angular boulders up to 10 m in maximum dimension and generally greater than 2 m in dimension. Predominantly Lamar River and Cathedral Cliffs formations; some Bighorn Dolomite occurs. A matrix of angular cobbles and granules exists at the base of the deposit; matrix and boulder lithology are identical. The boulders are strewn down the hillside. Some boulders rest against one another whereas others are isolated. Vegetation grows on the matrix, but generally does not grow on the boulders. Thickness of the matrix is 0.5 to 1 m. The main differences between co3 and the other 2 colluvial deposits are 1) co3 is composed nearly entirely of large (>2m in dimension) boulders, whereas in the other two types of colluvial deposits boulders greater than 2 m in dimension are rare and 2) these deposits are composed predominantly of the Larmar River and Cathedral Cliffs formation whereas co1 is composed of a variety of lithologies and co2 is composed predominantly of rhyodacite porphyry.

rg - Rock glaciers. Unsorted and unstratified. Angular boulders of predominantly Lamar River and Cathedral Cliffs formations. The rock glaciers' matrices are composed of fines and ice. Some clasts of Bighorn Dolomite exist. The rock glaciers contain furrows, and several conical pits exist. Vegetation grows in few places. Thickness 2 to at least 26 m (Bean, 1995).

g - Glacial materials. Unsorted and unstratified. Cobble size and smaller rocks are generally sub-rounded whereas boulder sized clasts are sub-angular. The matrix consists of fine sands and clays. The lithologies of the clasts are the same lithologies of the bedrock in the Miller Creek basin; few if any erratics carried from other basins are observed. The till forms hummocks of low relief. Vegetation generally covers this deposit. Thickness 1 to ~14 m (Maxim Technologies, 1995).

r - Bedrock undifferentiated.

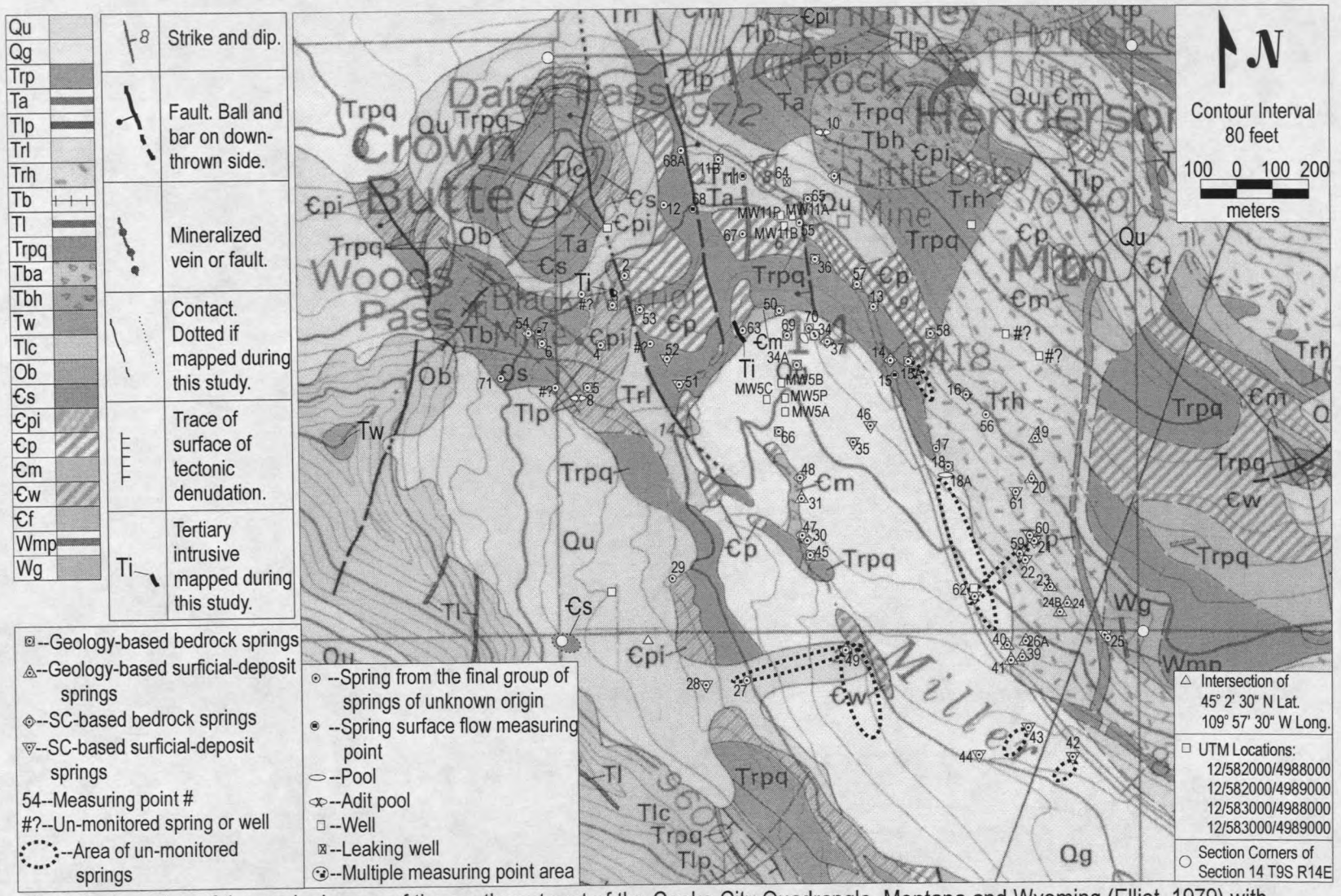


Plate 4. A portion of the geologic map of the southwest part of the Cooke City Quadrangle, Montana and Wyoming (Elliot, 1979) with measuring points. Description of geologic units on preceding page.

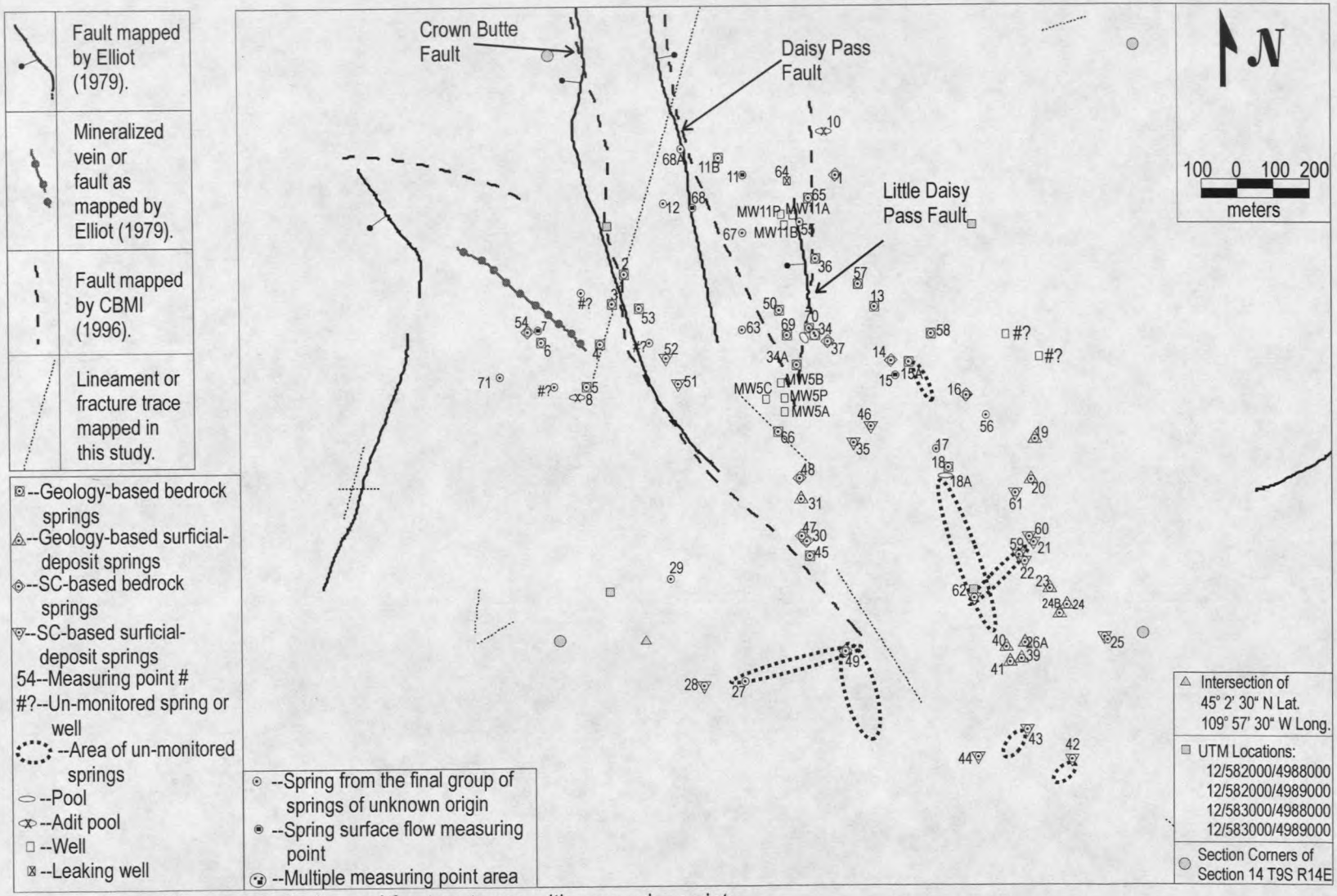


Plate 5. Map of lineaments, faults, and fracture traces with measuring points.

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