Driller specific capacity as a measure of aquifer transmissivity and a test of the hydrogeologic units in the Gallatin Local Water Quality District, Gallatin County, Montana
by Stewart Alan Dixon

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University

Abstract:
Increased development in the rural areas of Gallatin County, Montana has raised concerns about groundwater resources. Hydraulic properties of geologic units are needed to address groundwater quality and quantity issues. This study uses abundant driller specific capacity data to test whether eleven geologic units commonly thought to be different have statistically different hydraulic character. Aquifer transmissivity was estimated from driller specific capacity using an empirical equation developed from fifty data pairs of transmissivity and specific capacity calculated from single well tests at unscreened or non-perforated wells pumped for one hour. Unscreened or non-perforated wells represent 73% of the wells in the district. Seventy percent of the driller-tested wells in the district were pumped for one hour. Recovery transmissivity and specific capacity are log-linearly related. The best-fit regression is Log T = 1.3562(Log Q/s) + 3.5209, where T = transmissivity expressed in m2/day and Q/s (specific capacity) is in (m3/min)/m with a coefficient of determination, R2, of 0.749. The wells within the district had to be located to be allowed in the database. A test of pumped, airlift, and bailed driller tests showed that bailed tests could not be used. Although there are 7253 wells in the Gallatin Local Water Quality District only 16% (1136) could be located, were unscreened, were tested for one hour, had specific capacity data, and were not bail tested. The data only allowed statistical analysis of the Quaternary - Tertiary hydrogeologic units within the Gallatin Valley. The older units had few located wells or missing or inappropriate data such as short pumping times. A Mann-Whitney statistical analysis of the estimated transmissivity values among identified hydrogeologic units indicates significant difference between neighboring units. The eleven initial Quaternary - Tertiary Hydrogeologic units were recombined into three distinct hydrogeologic units to reflect the results of the statistical analysis. The units are the Quaternary West Gallatin alluvium aquifer, Quaternary small stream and fan aquifer, and the Quaternary-Tertiary basin fill aquifer. The calculated transmissivity values for the distinct Hydrogeologic units utilizing driller reported specific capacity data agree well with published values from aquifer tests in the region, except for the high transmissivity West Gallatin alluvium aquifer. This study demonstrates that driller reported specific capacity data can be used to estimate hydraulic parameters and that the values obtained are in good agreement with hydraulic parameters determined by traditional aquifer pump tests. Driller reported specific capacity is a rich but underused database, which can help characterize aquifers in an area.

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APPROVAL

of a thesis submitted by

Stewart Alan Dixon

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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Approved for the Department of Earth Sciences

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Approved for the College of Graduate Studies

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ABSTRACT

Increased development in the rural areas of Gallatin County, Montana has raised concerns about groundwater resources. Hydraulic properties of geologic units are needed to address groundwater quality and quantity issues. This study uses abundant driller specific capacity data to test whether eleven geologic units commonly thought to be different have statistically different hydraulic character. Aquifer transmissivity was estimated from driller specific capacity using an empirical equation developed from fifty data pairs of transmissivity and specific capacity calculated from single well tests at unscreened or non-perforated wells pumped for one hour. Unscreened or non-perforated wells represent 73% of the wells in the district. Seventy percent of the driller-tested wells in the district were pumped for one hour. Recovery transmissivity and specific capacity are log-linearly related. The best-fit regression is Log T = 1.3562(Log $^{Q}/_{S}$) + 3.5209, where T = transmissivity expressed in m^2/day and $^{Q}/_{S}$ (specific capacity) is in (m^3/min)/m with a coefficient of determination, R^2, of 0.749. The wells within the district had to be located to be allowed in the database. A test of pumped, airlift, and bailed driller tests showed that bailed tests could not be used. Although there are 7253 wells in the Gallatin Local Water Quality District only 16% (1136) could be located, were unscreened, were tested for one hour, had specific capacity data, and were not bail tested. The data only allowed statistical analysis of the Quaternary – Tertiary hydrogeologic units within the Gallatin Valley. The older units had few located wells or missing or inappropriate data such as short pumping times. A Mann-Whitney statistical analysis of the estimated transmissivity values among identified hydrogeologic units indicates significant difference between neighboring units. The eleven initial Quaternary – Tertiary Hydrogeologic units were recombined into three distinct hydrogeologic units to reflect the results of the statistical analysis. The units are the Quaternary West Gallatin alluvium aquifer, Quaternary small stream and fan aquifer, and the Quaternary-Tertiary basin fill aquifer. The calculated transmissivity values for the distinct Hydrogeologic units utilizing driller reported specific capacity data agree well with published values from aquifer tests in the region, except for the high transmissivity West Gallatin alluvium aquifer. This study demonstrates that driller reported specific capacity data can be used to estimate hydraulic parameters and that the values obtained are in good agreement with hydraulic parameters determined by traditional aquifer pump tests. Driller reported specific capacity is a rich but underused database, which can help characterize aquifers in an area.

CHAPTER 1

INTRODUCTION

In Gallatin County, Montana, ground water is the major water source for light industrial, agricultural, and domestic water supply in rural areas. Increased development in the rural areas of Gallatin County has raised concerns about potential problems affecting the groundwater resources of the region. Identification and characterization of the hydraulic parameters of the aquifers within the region is needed to help address water quality and quantity issues. For example, the aquifer parameters are needed for septic assessments (Bauman Shafer method (Bauman and Shafer, 1984)) and assessment of aquifer yield potential. There is a need for statistical analysis of hydraulic data to provide perspective regarding central tendency and variation in aquifer parameters. Some of the variation may rise from differences between geologic units. If hydraulic data can be stratified to account for differences then more meaningful characterization will be possible. Expected aquifer units were tested using existing driller reported data. This statistical testing allowed identification of hydraulically distinct geologic units based on the hydraulic properties of the units in the Gallatin Local Water Quality District (GLWQD) (Figure 1).

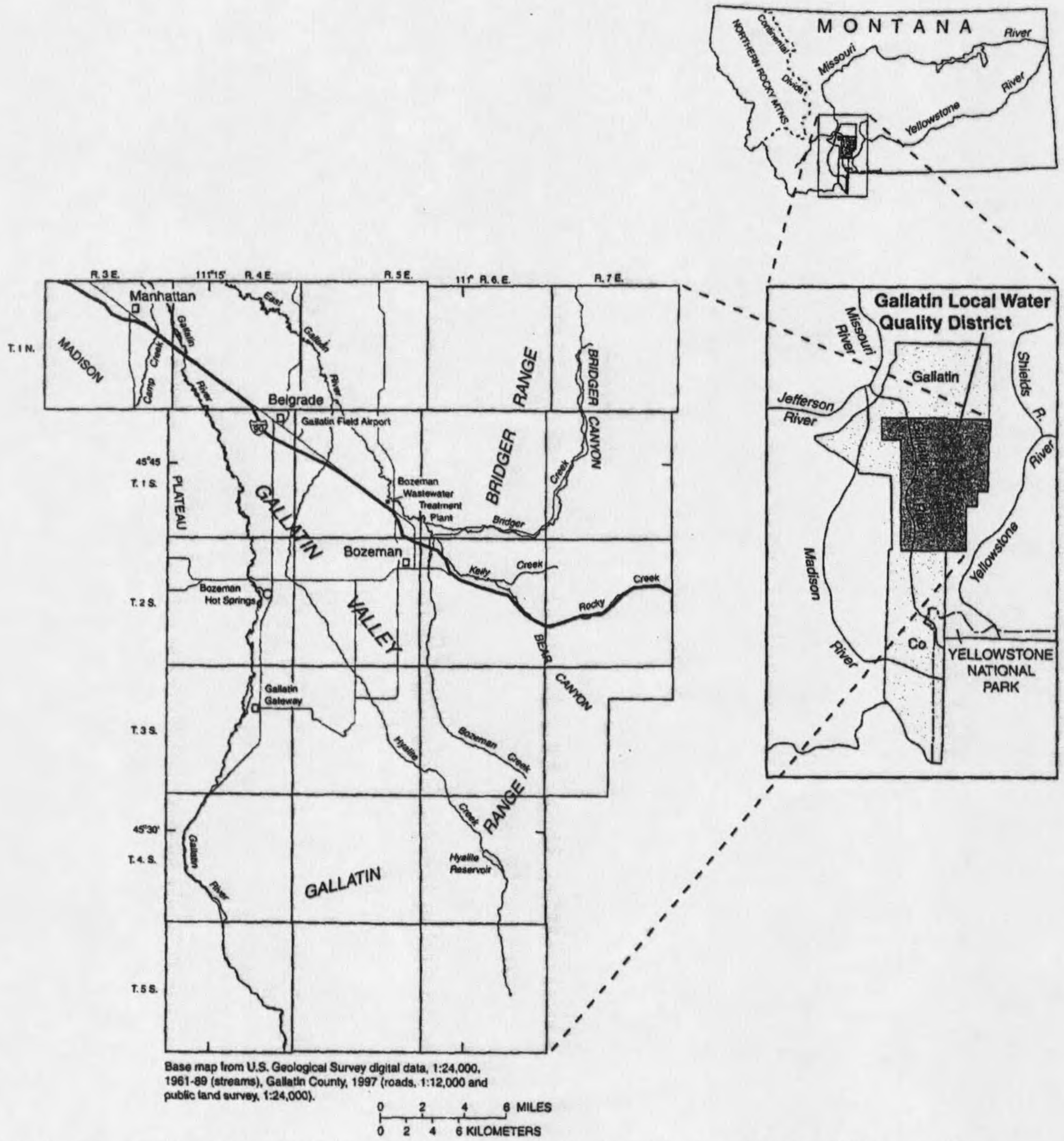

Figure 1: Location of the Gallatin Local Water Quality District, Montana (Kendy, 2001, page 3).

Common aquifer parameters defined during aquifer characterization studies include hydraulic conductivity (K) and transmissivity (T). The hydraulic conductivity of an aquifer is defined as the velocity of water moving through a unit area of a porous medium per unit time. This assumes a unit hydraulic gradient perpendicular to the direction of flow. Hydraulic conductivity is given in units of length divided by time [L/T]; for example in International System of Units (SI) as meters per day (m/day) or in American Practical Units (APU) as gallons per day per square foot (gpd/ft^2) (Driscoll, 1986, Fetter, 1994, Kruseman and de Ridder, 1994). Likewise, transmissivity is defined as the rate of flow through a cross-section of unit width; again, under a unit hydraulic gradient over the saturated thickness of the aquifer (Driscoll, 1986; Fetter, 1994; Kruseman and de Ridder, 1994). Transmissivity is expressed in units of L^2/T, for example in SI units as meters squared per day (m^2/day) or in APU as gallons per day per foot (gpd/ft) (Driscoll, 1986; Fetter, 1994; Kruseman and de Ridder, 1994). Hydraulic conductivity (K) and transmissivity (T) are related by thickness (b): T=Kb.

Hydraulic conductivity and transmissivity are ideally calculated from aquifer test data conducted with a pumping well and one or more observation wells in the geologic formation of interest (Driscoll, 1986; Fetter, 1994; Kruseman and de Ridder, 1994). However, there are disadvantages to pumping tests such as nonuniqueness and expense (Freeze and Cherry, 1979). The similarity in drawdown response from a variety of different aquifer types makes prediction of a unique solution of the effects of pumping difficult (Freeze and Cherry, 1979). Also, the expense of installation of test wells and observation piezometers is typically not justified except in those cases where the test wells will eventually serve as water supply production wells (Freeze and Cherry, 1979). Therefore, because of the prohibitive costs of conducting multiple well tests and the abundance of point tests that can provide adequate data, hydrogeologists often use point tests to evaluate hydraulic properties. Specific capacity data is an example of point test data that is frequently used to estimate hydraulic parameters of aquifers.

Specific capacity is chiefly related to the transmissivity of the aquifer with the aquifer storage coefficient, well efficiency, pumping time, and discharge having important influences (Driscoll, 1986; Newcome, 1993; Fetter, 1994). Specific capacity is expressed in units of flow rate (discharge) per length, (Q/L), for example cubic meters per minute per meter of drawdown (m^3/min/m), cubic meters per second per meter (m^3/s/m), or gallons per minute per foot of drawdown (gpm/ft). Specific capacity is determined by dividing the discharge from the well (m^3/minute; m^3/second; gallons/minute) by the amount of water level decline in the well (meters; feet) after a specified pumping time (Driscoll, 1986; Fetter, 1994).

Specific capacity has several advantages for aquifer hydraulic property estimation. Theoretical and empirical relationships between transmissivity and specific capacity have been used to estimate transmissivity from specific capacity data when available (for example; Thomasson et al., 1960; Custer et al., 1991; Razack and Huntley, 1991; Huntley et al., 1992; Mace, 1997). The use of specific capacity data to estimate transmissivity values has become more widespread because of the abundance of specific capacity data from water well logs and the paucity of aquifer pump test data for many areas.

Specific capacity is reported by drillers on the well logs for 52% of the reported wells within the Gallatin Local Water Quality District. However, the specific capacity data are rarely used for aquifer analysis in the GLWQD. The abundance and availability of the specific capacity data of the GLWQD provides an opportunity to examine hydraulic properties of the area aquifers statistically.

Study Objectives

The project was undertaken to test whether geologic units within the GLWQD that are commonly believed to be different are statistically different based on the hydraulic properties of the units. This will result in the identification and characterization of hydraulically distinct units. Specific capacity will be used to provide information on expected hydraulic characteristics and the variations in these characteristics for the various geologic stratigraphic units. Although a great deal of information exists in the form of static water levels, pumping rates, pumping water levels, pumping times, lithologic logs, and some aquifer test data, the data is not in a format that allows quick assessment of hydraulic properties for a particular area or aquifer. To test whether or not the geologic units of the GLWQD are similar, the following procedure was used:

1. identify expected distinct hydrogeologic units;
2. verify location of wells within the GLWQD;
3. derive an empirical equation that relates specific capacity to transmissivity using field tested specific capacity-transmissivity data pairs;
4. use derived equation to calculate transmissivity for the test hydrogeologic units using existing available specific capacity data;
5. statistically test units to determine whether transmissivity values are different;
6. combine units that fail to be statistically different; and
7. develop both a hydrogeologic map and hydrogeologic column for the GLWQD that reflects the results of the statistical analysis.

Study Area

The Gallatin Local Water Quality District (GLWQD) covers most of northern Gallatin County (Figure 1). The area encompasses roughly 2100 square kilometers (800 square miles). The study area is bounded on the east by the Gallatin County-Park County line; the northern boundary is Township 1 North, Ranges 3 East to 7 East; the western boundary is Townships 1 South to 5 South, Range 4 East, except near Manhattan where the western boundary extends into Township 1 North, Range 3 East (Figure 1). The southern boundary of the study area is along Township 5 South Ranges 4 East to 6 East.

General Geology

Precambrian through Mesozoic bedrock underlies Cenozoic alluvial deposits and borders the majority of the Gallatin Valley (Hackett et al., 1960; Kendy and Tresch, 1996). Although the rock units found in the surrounding mountains make up the majority of the lithostratigraphic units within the GLWQD, the Cenozoic basin-fill and alluvial deposits found in the Gallatin Valley cover a large part of the GLWQD and underlie the area of the GLWQD where most people live. The most prolific aquifers in the GLWQD are Cenozoic deposits. Cenozoic basin-fill ranges in thickness from 0 to 2000 m. (0 to 6000 ft.) (Hackett et al., 1960; Davis et al., 1965; Noble et al., 1982; Vuke et al., 1995). The Gallatin Valley basin-fill includes Tertiary Bozeman Group, Older alluvium (Quaternary-Tertiary?), Quaternary alluvial fan deposits, Quaternary glacial outwash (?) deposits, and alluvium deposited by rivers and streams during the Quaternary (Hackett et al., 1960; Robinson, 1963; Glancy, 1964; Hughes, 1980; Custer et al., 1991; Hay, 1997) (Figure 2). The majority of the domestic wells in the GLWQD are completed in sediments that have been interpreted either as Tertiary Sixmile Creek, Madison Valley Formation, or overlying Quaternary Units (Hackett et al., 1960; Kuenzi and Fields, 1971; Hughes, 1980;. Custer et al., 1991; Vuke et al., 1995).

The Gallatin Valley is a north-trending intermontane basin near the edge of the Northern Rocky Mountains (Hackett et al., 1960; Kendy and Tresch, 1996) (Figure 2). The valley is the eastern extension of the Three Forks structural basin (Robinson, 1963) and covers approximately 1330 square kilometers (520 square miles) (Hackett et al., 1960; Kendy and Tresch, 1996). The Gallatin Valley was formed as the compressional tectonic regime of the region was replaced by an extensional tectonic regime "around 46 Ma to 15 Ma" (Lageson, 1989).

Mountainous areas such as the Bridger Range, Gallatin Range and Madison Range cover the remaining half of the land area within GLWQD. The southern part of the GLWQD includes Madison and Gallatin Ranges (Figure 2). The Madison and Gallatin Ranges consist of complexly deformed Archean metamorphic rock (3 billon years before present); amphibolite, schist, gneiss, and basic dikes) (Mogk, 1992), Paleozoic and Mesozoic sedimentary rocks that are overlain locally by Eocene volcanic flows, and volcaniclastic debris (McMannis and Chadwick, 1964; Chadwick, 1969; Hiza, 1994) of the Absaroka Volcanic Supergroup (Smedes and Prostka, 1972).

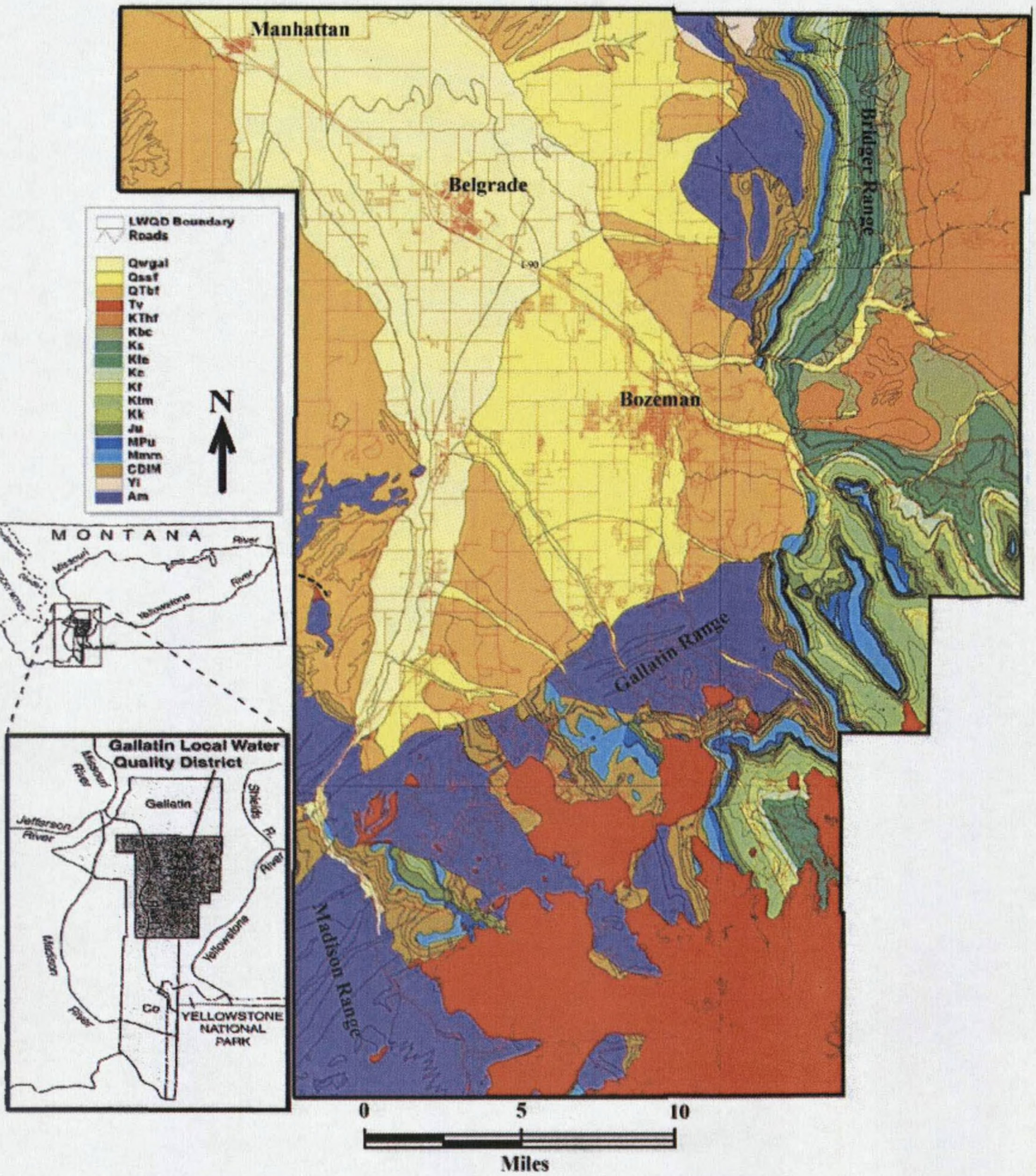

Figure 2: Generalized Geologic Map of the GLWQD. Qwgal = West Gallatin alluvial deposits; Qssf = Small Stream alluvium and alluvial Fan deposits; QTbf = Basin Fill deposits; Tv = Tertiary Volcanic Rocks; KThf = Ft. Union - Hoppers Formation; Kbc = Billman Creek Formation; Ks = Sedan Formation; Kte = Telegraph Creek-Eagle Sandstone; Kc = Cody Shale; Kf = Frontier Formation; Ktm = Thermopolis Shale; Kk = Kootenai Formation; Ju = Jurassic Formations; MPu = Upper Mississippian-Pennsylvanian-Permian Formations; Mmm = Mission Canyon Formation; CDlM = Cambrian-Lower Mississippian Formations; Yl = LaHood Formation; Am = Archean Gneiss (modified from Roberts, 1972; Vuke et al., 1995; Kellogg and Williams, 1998; Skipp et al., 1999; Custer et al., 2000; and Kendy, 2001).

The mountain ranges in the southern portion of the GLWQD are basement cored, Laramide-style, uplifts with Paleozoic and Mesozoic rock overlying the metamorphic rocks (Lageson, 1989). The pre-Tertiary rocks to the south are bounded on the north by a large normal fault (Davis et al., 1965). Based on gravity data, approximately 2000 m (6000 ft) of sedimentary basin fill material is estimated to be present north of the Gallatin Range (Davis et al., 1965; Noble et al., 1982). The estimated maximum throw of the Gallatin Range front normal fault is on the order of 3600 m (11,000 ft) (Custer et al., 1995).

The Bridger Range bounds the Gallatin Valley on the northeastern edge of the GLWQD. The Southern Bridger Range is similar to the rocks in the southern part of the GLWQD but has no volcanic deposits overlying the Paleozoic and Mesozoic strata, although there are Tertiary dikes and sills there. More than 1,500 m (> 4,900 ft.) of Proterozoic LaHood Formation metasedimentary rocks are present at the northern margin of the GLWQD, where the LaHood is in fault contact with Archean crystalline metamorphic rocks (McMannis, 1963; Schmitt, 1988; Lageson, 1989). The Bridger Range is bounded on the west by a listric normal fault, which drops the Gallatin Valley to the east (McMannis, 1955; Robinson, 1963; Lageson, 1989). The Bridger listric normal fault developed in response to the extensional tectonic forces. The extensional forces caused the crest and western limb of the ancestral "Bridger Anticline" to be faulted and dropped below the Gallatin Valley, while the east limb rose into the Bridger Range (Lageson, 1989). The Bridger Range shows evidence of four major tectonic provinces and displays a stratigraphic and structural record of major tectonic events from the last 1.4 billion years (Lageson, 1989). The tectonic provinces that the Bridger Range overlaps are 1) Middle Proterozoic Belt Basin, 2) the thin-skinned Sevier fold and thrust belt, 3) Laramide basement-involved province, and 4) the Basin-and-Range extensional province, which is responsible for the graben which forms the Gallatin Valley (Lageson, 1989).

CHAPTER 2

LOCAL STRATIGRAPHY AND HYDROGEOLOGIC UNITS

Hydrogeologic units

Geologic maps of the GLWQD were compiled to identify hypothesized hydrogeologic units in the GLWQD. A hydrogeologic unit is a unit with distinct hydraulic characteristics that may be composed of multiple geologic units or portions of geologic units. The presence or absence of fluid within a unit is not the ultimate determining factor in the delineation of the hydrogeologic units, but the potential of the unit to yield water is the determining factor (Seaber, 1988; Shirely, 1995).

The test-hydrogeologic units are based on data in the literature regarding the local and regional stratigraphy and groundwater resources. This information was compiled into a test-hydrogeologic column and test-hydrogeologic map that reflects the local stratigraphy and potential aquifer hydraulic properties within the GLWQD (Table 1, Table 2, and Figure 3). Most of the units are classified as aquifers or aquitards on the basis of published reports or unpublished theses, while a few were based on the lithologic character of that formation / group, when no unit groundwater data was available (for example; Archean metamorphic rocks, Proterozoic LaHood Formation, and Eocene Volcanic rocks). In the remaining sections of this chapter, the general expected water-yielding characteristics of each test-hydrogeologic unit are discussed. The units are discussed in order of oldest rock units to the youngest.

Lithostratigraphic units are split or combined into test-hydrogeologic units that reflect similar hydraulic properties at a scale consistent with the spatial distribution of the local geologic map data. The hydrogeologic units are based on previous studies and detailed analysis of reported or observed hydraulic properties such as hydraulic conductivity, transmissivity, specific capacity, and well yield (Hackett et al., 1960; Feltis, 1971; Moore, 1984; Clarke, 1991; Custer et al., 1991; Slagle, 1995; Kendy and Tresch, 1996; Hay, 1997; and Baldwin, 1997).

Local Stratigraphy and Hydrogeologic Units

The stratigraphic columns of Hackett and others (1960), Roberts (1964a-d), Skipp and McMannis (1971), Montagne (1976), Balster (1980), Hughes (1980), Levings and others (1981), Vuke and others (1995), Kellogg and Williams (1998), and Skipp and others (1999) were used as the basis of the initial hydrogeologic column. Precambrian through recent rocks are found in the GLWQD, with the exception of Ordovician, Silurian, and Triassic rocks as shown in Table 1 and Figure 3. Some modifications of the original stratigraphic columns in the upper Mesozoic and Cenozoic sections were necessary to represent the local stratigraphy in consistent units.

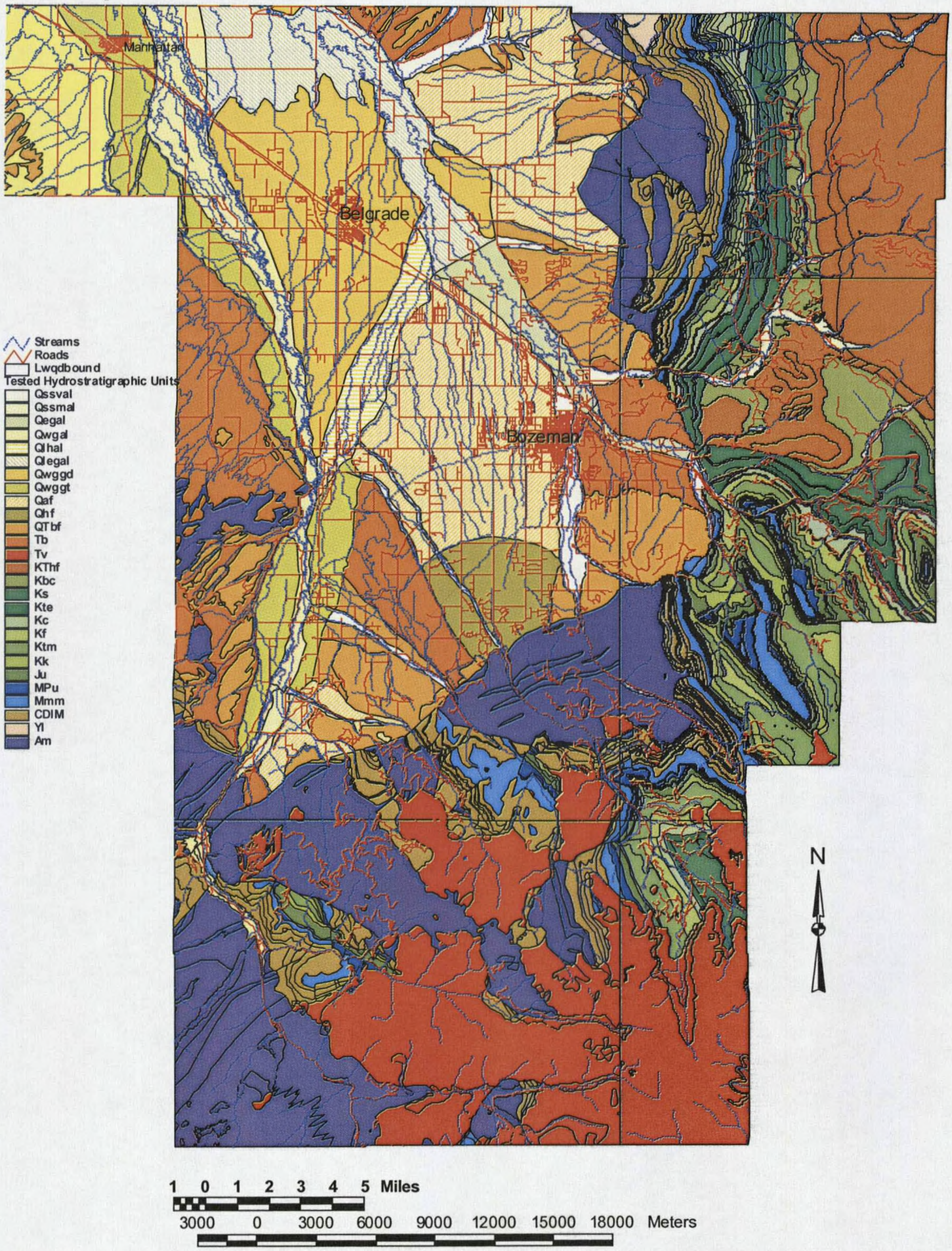

Figure 3: Map of Test-hydrogeologic units of the GLWQD (modified from Custer et al., 2000). See Tables 1 and 2 for acronym definitions as given in this figure.

Table 1: Tested Hydrogeologic units of the GLWQD (After, Hackett et al., 1960; Roberts, 1963; McMannis and Chadwick, 1964; Groff, 1965; Balster, 1971; Kuenzi and Fields, 1971; Skipp and McMannis, 1971; Roberts, 1972; Montagne, 1976, Skipp and McGrew, 1977; Aram 1979; Bonnet, 1979; Balster, 1980, Hughes, 1980; Levings et al., 1981; Chadwick, 1982; Smith and Welker, 1982; Smith, 1983; Moore, 1984; Lambing et al., 1987; Custer et al., 1991; Hiza, 1995; Dyman et al., 1995; Vuke et al., 1995; Kendy and Tresch, 1996; Skipp et al., 1999.)

Erathem	System	Series	Lithostratigraphic Unit				Hydrogeologic unit
CENOZOIC	Quaternary		Alluvium (See Table 2 for details)				
			Old Alluvium (Fan, pediment, and stream deposits)				Old Alluvium aquifer- QTal
	Tertiary	Pliocene	Bozeman Group (includes Sixmile Creek Formation, Madison Valley Formation, and Renova Formation)				Bozeman Group aquifer - Tb
		Miocene					
		Oligocene					
		Eocene	Gallatin-Absaroka Volcanics				Volcanic aquitard- Tv
			Unnamed gravels, sands, and siltstone				
		Paleocene	Fort Union Formation				Fort Union – Hoppers aquifer - KThf
MESOZOIC	Cretaceous	Upper	Montana Group	Livingston Group	Hoppers Formation		
					Billman Creek Formation		Billman Creek aquitard- Kbc
					Sedan Formation	Miner Creek Formation	Sedan aquifer- Ks
						Cokedale Formation	
				Eagle Sandstone Telegraph Creek Formation			Eagle-Telegraph Creek aquifer- Kte
			Colorado Group	Cody Shale	Upper Shale Member		Cody aquitard - Kc
					Eldridge Creek Member		
					Lower Shale Member		
				Frontier Formation			Frontier aquifer - Kf
		Lower		Mowry Shale			Mowry-Thermopolis aquitard (basal water) - Ktm
				Thermopolis Shale	Muddy Sandstone Member		
					Shale Member		
					Lower Sandstone Member		
			Kootenai Formation				Kootenai aquifer - Kk
	Jurassic	Upper	Morrison Formation				Jurassic aquitard - Ju
		Lower	Ellis Group	Swift Formation			
				Rierdon Formation			
				Piper Formation			

Table 1 (Continued): Tested Hydrogeologic units of the GLWQD.

Erathem	System	Series	Lithostratigraphic Unit		Hydrogeologic unit
PALEOZOIC	**Permian**		Phosphoria Formation		Permian – upper Mississippian aquitard - MPu
	Pennsylvanian		Quadrant Formation Amsden Group		
	Mississippian		Big Snowy Group		
			Madison Group	Mission Canyon Limestone	Mission Canyon aquifer - Mmm
				Lodgepole Limestone	Lower Mississippian, Devonian, and Cambrian aquitard - CDlM
	Devonian		Three Forks Formation Jefferson Dolomite Maywood Formation		
	Cambrian	**Upper**	Snowy Range Formation	Sage Pebble Conglomerate Mbr.	
				Dry Creek Shale Mbr.	
			Pilgrim Limestone		
		Lower	Park Shale Meagher Limestone Wolsey Shale Flathead Sandstone		
Precambrian	Proterozoic		LaHood Formation (Belt Super Group)		LaHood aquitard - Yl
	Archean		Archean Crystalline Metamorphic Rocks		Archean Crystalline aquitard - Am

Precambrian Hydrogeologic Units. The Precambrian system was divided into two units, Archean Crystalline aquitard (Am) and the Proterozoic LaHood aquitard, Yl (Table 1 and Figure 3). The Archean Crystalline aquitard includes all of the metamorphic rocks within the district (e.g. gneiss, schist, and amphibolite) (Mogk, 1992; Vuke et al., 1995; Kellogg and Williams, 1998). Archean crystalline rocks only have the potential to be aquifers if they are fractured and the fractures are interconnected. However, fracture density generally decreases with depth; therefore excessively deep wells in this unit should be avoided (Davis and Turk, 1964). Weathering of crystalline rock has been shown to produce porosities as high as 40% to 50% and specific yield values of up to

15% to 30% (Fetter, 1994). Median and mean well yields in weathered crystalline rock have been reported to be two to three times higher than fresh crystalline rock (Landers and Turk, 1973; Trainer, 1987).

The LaHood Formation is a poorly bedded arkose and conglomeratic arkose, with local beds of argillite and siliceous limestone beds (McMannis, 1963; Bonnet, 1979; Schmitt, 1988). The LaHood aquitard, Yl, also has the potential to yield water if it is fractured and the fractures are interconnected.

Paleozoic Hydrogeologic Units

Cambrian, Devonian, and Lower Mississippian Hydrogeologic Units. Rocks that are Cambrian, Devonian, and Lower Mississippian in age within the GLWQD were grouped into one hydrogeologic unit, the Cambrian, Devonian, and Lower Mississippian aquitard, CDlM, as shown in Table 1. The grouping of these units as one was primarily based on the lithology, indeterminate water-bearing characteristics, and the presence of hydrocarbon residue in the formations. These formations are generally not considered to be significant water producers in other areas; likewise, the presence of hydrocarbon residue in the dolostones of this group of formations suggests a low potential for potable water.

The Cambrian, Devonian, and Lower Mississippian aquitard (CDlM) consists of a silica cemented sandstone (Flathead Sandstone) and all of the marine shales, limestones, and dolostones in the Cambrian and Devonian systems (Wolsey Shale, Meagher Limestone, Park Shale, Pilgrim Limestone, Snowy Range Formation, Maywood

Formation, Jefferson Dolomite, and Three Forks Formation, respectively in ascending order), plus the Lower Mississippian Lodgepole Limestone. The Cambrian-Devonian units based on the lithology of the various units will likely act as an aquitard rather than an aquifer (Groff, 1965). The Jefferson Dolostone has dolomitic porosity in many areas, but because of high hydrocarbon residuum, will likely produce poor quality water (S. Custer, personal communication). The Lodgepole Limestone was included in the Cambrian, Devonian, and Lower Mississippian aquitard (CDlM) because the unit is a thinly bedded, argillaceous limestone (Balster, 1971; Aram, 1979). In addition, results from Feltis (1977) and Lambing and others (1987) support this classification noting the lack of aquifer like properties in the Judith Basin of Montana. Also, the absence of karst development in the Lodgepole Limestone as noted by Aram (1979) near Three Forks suggests lack of groundwater flow potential. The Lodgepole Limestone lacks the features that would allow the development of solution channels such as collapse breccia and evaporite zones (Feltis, 1977; Lambing et al., 1987). For these reasons, the Lodgepole Formation was lumped with Cambrian, Devonian, and Lower Mississippian aquitard (CDlM), rather than with the Mission Canyon Formation.

Mississippian Hydrogeologic Units. The Mississippian Madison Group includes the Lodgepole Limestone and Mission Canyon Limestone in ascending order (Table 1). The Madison Group as a whole is considered a regional aquifer in many parts of Montana, Wyoming, South Dakota, and North Dakota (Miller, 1976; Head and Merkel, 1977; Krothe and Bergerson, 1981; Whitehead, 1996). However, in this study the Madison Group was split into two hydrogeologic units because of the distinct lithologic and hydrogeologic differences between the formations within the Madison Group. The Lodgepole Limestone was included in the Cambrian, Devonian, and Lower Mississippian aquitard (CDlM), while the Mission Canyon was classified as the Mission Canyon aquifer, Mmm (Table 1 and Figure 3). The Mission Canyon Limestone is a potential aquifer particularly because of extensive karst deposits and solution breccias that exist within the upper part of the formation (Roberts, 1966; Miller, 1976; Feltis, 1977; Wilke, 1983; Lambing et al., 1987; Kurisoo, 1991). Commonly, the water-bearing zone within the Mission Canyon aquifer is found in the upper part of the Mission Canyon Limestone, where the solution channels are extensive and abundant (Miller, 1976; Wilke, 1983; Kurisoo, 1991). The solution channels and breccia zones with the Mission Canyon aquifer (Mmm) are expected to yield good quantities of water if recharge is sufficient (Miller, 1976; Wilke, 1983; Kurisoo, 1991).

Upper Mississippian, Pennsylvanian, and Permian Hydrogeologic Units. Rocks of the Upper Mississippian, Pennsylvanian, and Permian systems are considered as one hydrogeologic unit. The Mississippian Big Snowy Group, Pennsylvanian Amsden Group, Pennsylvanian Quadrant Formation, and the Permian Phosphoria Formation are included in the Permian-upper Mississippian aquitard, MPu (Table 1 and Figure 3). The Big Snowy Group and the Amsden Group are not considered aquifers because of the abundant fine grained lithologies of the units within these groups (Balster, 1971; Feltis, 1977; Lambing et al., 1987). Also, the lower dolostones of the Big Snowy Group are petroliferous. Therefore if water is present, the water would likely be of poor quality (Balster, 1971). The Quadrant Formation is composed of a lower cream-colored dolostone and an upper thick-bedded, light-colored, medium-grained, and rounded quartz sandstone. The upper portion may yield water especially where it is not completely cemented (Balster, 1971; Smith, 1983). The Shedhorn Sandstone Member of the Phosphoria Formation is the only portion of the Phosphoria known to exist in the GLWQD. The Shedhorn Sandstone Member is a silica-cemented medium-to-fine-grained angular chert and quartz bearing sandstone (Balster, 1971, Smith, 1983; Smith and Welker, 1982). The Shedhorn sandstones are typically silica (chert) cemented. Chert cement reduces the porosity and eliminates most of the permeability of the Shedhorn; therefore, water yield potential is significantly limited.

Mesozoic Hydrogeologic Units

Jurassic Hydrogeologic Units. The Jurassic Ellis Group and the Morrison Formation are grouped together as the Jurassic aquitard, Ju, overlying the Permian-upper Mississippian aquitard (MPu) (Table 1 and Figure 3). The Ellis Group includes in ascending order the Sawtooth-Piper Formations, Rierdon Formation, and the Swift Formation. The upper part of the Ellis Group contains the Swift Formation, a calcareous, glauconitic chert-bearing sandstone in Southern Montana (Balster, 1971). The lithology of the Swift Formation suggests that locally the formation may contain water (Feltis, 1977; Lambing et al., 1987); however, the Swift Formation is too thin to be usefully mapped in the study area at the 1:100,000 scale of the maps used to assess the Hydrogeologic Units. A study conducted in the Judith Basin Area of Montana reported that some wells drilled in the Swift Formation yielded 1.6 to 6 liters/second (l/s) (25 to

100 gallons/minute (gpm)) (Feltis, 1977; Lambing et al., 1987). However, the rest of the formations in the Ellis Group are dominantly dense oolitic or micritic limestones, siltstones, and shales and are not likely to yield water even for domestic purposes (Balster, 1971; Feltis, 1977; Lambing et al., 1987). The Jurassic Morrison Formation overlies the Ellis Group. The Morrison Formation is classified as an aquitard based on the lithology of the formation. The shales of the Morrison are expected to inhibit the movement of water; the well-cemented sandstone and siltstone beds of the formation are not expected to function as a reliable aquifer (Feltis, 1977; Lambing et al., 1987). Collectively, the rocks of the Jurassic system are not considered aquifers in the GLWQD.

Cretaceous Hydrogeologic Units. The first hydrogeologic unit of the Cretaceous system in the GLWQD is the Kootenai Formation. The Kootenai Formation is classified as the Kootenai aquifer, Kk, based on the lithology of the majority of the formation (Table 1 and Figure 3). Sandstones and the basal Pryor conglomerate are known to yield water in some areas of Montana (Feltis, 1977; Lambing et al., 1987; Nelson, 1993). In the Judith Basin area of Central Montana, the coarse-grained beds from the lower units of the Kootenai Formation are used for stock and domestic water supplies that range from 0.06 to 4 l/s (1 to 65 gpm) (Feltis, 1977; Lambing et al., 1987). In the Big Sky area, Baldwin (1997) reports that three (3) wells completed in the Kootenai Formation average 1.6 l/s (26 gpm). However, there was no evidence of water being produced from the upper units of the Kootenai Formation in the Judith Basin (Feltis, 1977; Lambing et al., 1987). The water bearing potential of the lower Kootenai sandstone and conglomerate remains to be tested in the GLWQD. The upper portion of the Kootenai Formation consists of thick-bedded shales and a massive low porosity fossiliferous limestone at the top of the formation; therefore, water production is expected to be minimal to non-existent (Smith, 1983, Smith and Welker, 1982). The shales and micritic limestones of the upper portion of the Kootenai Formation are not considered aquifers. Although there are distinct differences between the upper and lower portions of the Kootenai Formation, these units are not distinguished on geologic maps in Montana and are not effectively mappable on 1:100,000 scale maps of the GLWQD.

Colorado Group Hydrogeologic Units. The Colorado Group, which overlies the Kootenai Formation, is divided into three hydrogeologic units based on a combination of the formation lithologies within the Colorado Group, a hydrogeologic study done in the Judith Basin area of Central Montana, and a hydrogeologic study conducted in the Big Sky area (Feltis, 1977; Lambing et al., 1987; Baldwin, 1997). The two lower formations of the Colorado Group are the Thermopolis Shale (which includes the Muddy Sandstone Member) and the Mowry Shale. The Thermopolis Shale and the Mowry Shale are grouped together to form the Thermopolis-Mowry aquitard, Ktm (Table 1 and Figure 3). The Thermopolis and Mowry Shales are shales and siltstones that limit the movement of water through these formations (Balster, 1971). Contrary to the findings of Balster (1971), water yields from wells identified to be producing from the Mowry Formation in the Big Sky area are unexpectedly high (Baldwin, 1997). Well yields reported from the Mowry in the Big Sky area by Baldwin (1997) range from 0.4 to 7.3 l/s (7 to 116 gpm). Water flow in the Mowry is likely controlled by the connectivity of fractures and joints within this unit. In addition, the Muddy Sandstone Member of the Thermopolis Shale may yield water as may the local sand beds of the Mowry (Balster, 1971; Smith, 1983; Smith and Welker, 1982; Feltis, 1977; Lambing et al., 1987; Baldwin, 1997). Well yields reported from the Muddy Sandstone in the Big Sky area by Baldwin (1997) range from 0.8 to 3.2 l/s (12 to 50 gpm) with an average of 1.8 l/s (29 gpm). The unit is dominated by siltstones and shales, although there is some water yielding units within the Thermopolis-Mowry aquitard (Ktm).

The Frontier Formation of the Colorado Group is classified as the Frontier aquifer, Kf (Table 1 and Figure 3). The Frontier Formation is thin-to-medium-bedded, fine-to-coarse, arkosic sandstone, which may be locally silty (Balster, 1971; Smith and Welker, 1982, Baldwin, 1997). The sandstones of the Frontier Formation may yield water; therefore, this formation is considered a possible aquifer based on lithology. In the Judith Basin, there are wells that produce from sandstones of the Colorado (Frontier?) with yields of 0.03 to 1.6 l/s (0.5 to 25 gpm) (Feltis, 1977; Lambing, 1987). In the Big Sky area, a study conducted by Baldwin (1997) identified 29 wells producing from the Frontier Formation with yields ranging from 0.06 to 2.2 l/s (1.0 to 35 gpm). Fracture density and connectivity have been suggested as the cause of the wide range in yield from the Frontier Formation (Baldwin, 1997).

The upper-most formation of the Colorado Group in the GLWQD is the Cody Shale. The Cody Shale is classified as the Cody aquitard, Kc (Table 1 and Figure 3). Cody Shale is thin-bedded and contains siltstones and sandstones in the middle portion of the unit (Balster, 1971; Smith and Welker, 1982). The Eldridge Creek Member of the Cody Shale may have limited water bearing potential; but, to date it has not been reported. The shales of the Cody make the formation nearly impermeable; therefore, this unit is considered as an aquitard. However, Baldwin (1997) reported that four wells in the Big Sky area average 1.6 l/s (25.7 gpm). Baldwin (1997) suggests fractures and joints play a major role in the groundwater flow within the Cody Shale in the Big Sky area.

Montana Group Hydrogeologic Units. The Montana Group is the next group of formations above the Colorado Group. The part of the Montana Group that can be found in the GLWQD includes the Telegraph Creek Formation, Eagle Formation, and units within the Livingston Group (Table 1 and Figure 3) (Smith, 1983). Based on lithology and previous studies (for example, Feltis (1977), Moore (1984), Lambing and others (1987)), the Montana Group was divided into three aquifers and one aquitard.

The Telegraph Creek Formation and the Eagle Sandstone are the two lower units of the Montana Group of the GLWQD. These formations were combined as one hydrogeologic unit. The Telegraph Creek Formation and the Eagle Sandstone are classified as the Telegraph Creek-Eagle aquifer, Kte (Table 1 and Figure 3). These formations are grouped together based on previous work by Feltis (1977), Moore (1984), and Lambing et al., (1987) that suggests the siltstones and sandstones of the Telegraph Creek Formation may yield limited amounts of water. The Eagle Sandstone has more aquifer potential than the siltstones of the Telegraph Creek Formation. The Eagle Sandstone is expected to yield good quantities of water where the sandstone is the thickest (Moore, 1984). In the Judith Basin area, the Eagle Sandstone produces water for stock and domestic use at yields of 0.06 to 3 l/s (1 to 50 gpm) and as much as 4 l/s (70 gpm) (Feltis, 1977; Lambing et al., 1987). Although both the Telegraph Creek Formation and the Eagle Sandstone make up the Telegraph Creek-Eagle aquifer, the Eagle

Sandstone is expected be the dominant water producer (Feltis, 1977; Moore, 1984; Lambing et al., 1987).

The Livingston Group lies above the Eagle Sandstone in the GLWQD. The Livingston Group based on lithology and previous work done by Moore (1984) is divided into three hydrogeologic units. There are two aquifers and one aquitard within the Livingston Group.

The Cokedale Formation, Miner Creek Formation, and the Sedan Formation are grouped together to form the Sedan aquifer, Ks (Table 1 and Figure 3) The Cokedale Formation and the Miner Creek Formation are equivalent to the Sedan Formation (Skipp and McGrew, 1977; Skipp and McMannis, 1971; Skipp et al., 1999). Conglomerates, sandstones, siltstones, mudstones, ash flow tuffs, and bentonite beds are present in these three formations, collectively (Roberts, 1963, 1972; Skip and McGrew; 1977; Skipp and McMannis, 1971; Skipp et al., 1999). The composition of the Cokedale Formation varies from siltstone, sandstone, claystone, minor coal, and minor conglomerates (Roberts, 1963; Roberts, 1972; Moore, 1984). Water yield in the Cokedale is expected to be variable from poor to good (Moore, 1984). The siltstone units are poor water zones, while the sandstone units are expected to be potentially better water yielding zones (Moore, 1984). The Miner Creek consists of siltstones, sandstones, some bentonite, and a lower massive sandstone named the Sulphur Flats Sandstone Member (Roberts, 1963, 1972; Moore, 1984). The water yield in the Miner Creek varies from poor to good in the upper portion of the formation; but, usually good in the Sulphur Flats Sandstone Member (Moore, 1984). The Sedan Formation is composed of sandstones, mudstones, and ash-flow tuff units (Skipp and McGrew, 1977; Skipp and McMannis, 1971 Skipp et al., 1999). The water yield of the Sedan Formation like the Cokedale Formation is expected to vary from poor to good. The sandstone units have the greatest potential for good water yield, while the mudstone and ash-flow tuff members have the poorest water yield potential except where fractured. The water yielding characteristics of the Sedan Formation were based solely on the lithology of the formation.

The next unit in the Livingston Group is the Billman Creek Formation. The Billman Creek Formation consists of thick shales, claystones, and very minor sandstones (Roberts, 1963, 1972; Moore, 1984). The majority of the formation is tightly compacted silt or clay (Moore, 1984). The Billman Creek Formation is classified as the Billman Creek aquitard, Kbc, based on lithology and the previous work of Moore (1984) (Table 1 and Figure 3). However, some residents of the Bridger Canyon area depend on water from the Billman Creek Formation for domestic water supply. The water yielding potential of the Billman Creek Formation is typically very poor because of the silts and shales in the formation (Moore, 1984). In addition, the water quality of the Billman Creek Formation is very poor. Hydrogen sulfide odor and iron stained fixtures are common problems for those homeowners whose wells tap the Billman Creek Formation. The specific capacity of the Billman Creek Formation reported by Moore (1984) ranges from 3.5×10^{-5} to 1.2×10^{-3} $m^3/s/m$ (0.17 to 5.88 gpm/ft). Although sand and gravel lenses exist in the lower part of the Billman Creek Formation and may contain water, these sand and gravel bodies are isolated and likely do not receive reliable recharge (Moore, 1984).

The uppermost unit within the Livingston Group is the Hoppers Formation. Overlying the Hoppers is the upper Cretaceous-Tertiary Fort Union Formation. The Hoppers Formation and Fort Union Formation were grouped together as a single hydrogeologic unit named the Fort Union-Hoppers aquifer, KThf (Table 1 and Figure 3). Lithologic similarities and the juxtaposition of the two units (Hoppers and Fort Union) was the basis for combining them. The Hoppers Formation is a sandstone, claystone, and siltstone with conglomerate beds throughout the formation (Roberts, 1963; Roberts, 1972; Moore, 1984). The water yielding characteristics of the Hoppers Formation based on lithology is expected to be good, especially where the sandstones are the thickest (Moore, 1984).

The Fort Union Formation contains a basal conglomerate that is Upper Cretaceous in age (Roberts, 1963; Roberts, 1972). The Fort Union Formation consists of sandstones, conglomerates, and siltstones (Roberts, 1963; Roberts, 1972; Smith and Welker, 1982). Based on the lithology, the Fort Union Formation is a potential aquifer and water yielding characteristics, while variable, are generally good (Moore, 1984).

Cenozoic Hydrogeologic Units

The Cenozoic section of the test-hydrogeologic column contains both consolidated rocks and semi- to unconsolidated sediments. The Cenozoic lithostratigraphic units of the GLWQD include an Eocene volcanic complex; all of the Tertiary basin-fill material, and all of the Quaternary alluvial deposits.

Eocene Volcanic Rocks. Volcanic rocks of the Eocene Gallatin-Absaroka Volcanic Field are composed of many rock types, such as andesite and basalt, that are generalized as Volcanic Rocks, Tv, in the hydrogeologic column (Table 1). The Volcanic Rocks unit includes debris flows, pyroclastic flows, flow breccias, and lava flow deposits (Chadwick, 1969, 1982; Hiza, 1994). In addition, numerous Tertiary intrusive rocks are included within the Volcanic Rock hydrogeologic unit. The water yielding potential varies depending on the type of volcanic rock unit. The volcanic flows are expected to yield water only where jointed or fractured (Feltis, 1977; Lambing et al., 1987). The volcaniclastic deposits, consisting of breccias, autobrecciated flows, and breccia conglomerates, have the potential to produce higher water yields (Chadwick, 1982; Driscoll, 1986; Fetter, 1994; Hiza, 1994); however, recharge to these deposits may be limited. Most of these rocks are in the mountains under U.S. Forest Service jurisdiction so few aquifer tests exist. Because of limited data, it is difficult to determine the aquifer characteristics of the volcanic rocks in the GLWQD.

Tertiary Basin-Fill. Oligocene to Middle Pliocene consolidated rocks and unconsolidated sediments of the GLWQD are part of the Bozeman Group (Robinson, 1963). The Bozeman Group was originally divided into two lithologically distinct depositional sequences (Robinson, 1961, 1963; Glancy, 1964; Kuenzi and Fields, 1971; Hughes, 1980). Early interpretations of these Tertiary deposits suggest extensive lacustrine deposits (Peale, 1896); however, they are now regarded as deposited under fluvial, eolian conditions, and by some ponds and lakes of very limited extent (Mathew, 1899; Robinson, 1961, 1963; Kuenzi and Fields, 1971; Hughes, 1980). Robinson (1963) described the Tertiary deposits as being partly derived from the erosion of pre-Tertiary rocks and partly from penecontemporaneous pyroclastic debris. The Bozeman Group has been interpreted to include the fine-grained Renova Formation (Kuenzi and Fields, 1971; Hughes, 1980) and the coarse grained conglomerate Sixmile Creek Formation (Robinson, 1963), which is correlative with the Madison Valley Formation (Douglas, 1907).

Presently, there is great debate in the literature on the continued use of the lithostratigraphic nomenclature of the Bozeman Group. Hanneman and Wideman (1991) advocate the use of sequence stratigraphy to identify distinct units within the Cenozoic basins of Southwest Montana. The present lithostratigraphy of the Bozeman Group is problematic because of the abrupt lateral lithologic changes, vertical repetition of lithologies, and the lithologic variability within each of the units (Figure 4). There are significant fine- and coarse-grained deposits in both the Renova and Sixmile Creek Formations that make these two formations difficult to distinguish (Hanneman and Wideman, 1991). In the Jefferson Valley, the sequence stratigraphy approach suggests five sequences separated by basin-wide unconformities. In this instance, paleosols were identified as the basin-wide sequence boundaries (Hanneman and Wideman, 1991).

While there have been many attempts to differentiate distinct units within the Tertiary (Bozeman Group), all of the Tertiary (Bozeman Group) rocks and sediments herein will be treated as one hydrogeologic unit named the Bozeman Group aquifer, Tb (Table 1 and Figure 3). There are two principle reasons why consolidation of the Bozeman Group aquifer is appropriate. First, because seismic stratigraphy has not been conducted in the Gallatin Valley; the use of the Hanneman and Wideman (1991) sequences has not been tested in the study area. In the future, the division among the lithostratigraphic units of Bozeman Group aquifer may be possible; but at present, the data is not sufficient for sequence stratigraphic separations of the units. Second, the identification of the sequence boundaries, formation contacts (Renova and Sixmile Creek), and the differentiation of Tertiary and Quaternary sediments from lithologic descriptions in well logs (or during on-site during drilling) is nearly impossible because the cuttings and drilling properties of these units are similar (Glancy, 1964; Custer et al., 1991). Since there is no consensus regarding stratigraphic nomenclature and no recognized hydrogeologic pattern within the GLWQD, the most general and widely accepted Bozeman Group (Tb) is adopted for this study.

Water yielding characteristics of Bozeman Group aquifer (Tb) vary but are generally good, especially in channel gravels and sandstones. Water yielding characteristics of the Bozeman Group aquifer (Tb) is expected to be poorer in silty and muddy units than in the gravels and sandstones. Reported transmissivity values of Tertiary sediments from Hackett and others (1960), range from 4 to 320 m^2/day (300 to 26,000 gpd/ft). Specific capacity values reported by Slagle (1995) range from 4.1×10^{-5} to 9.8×10^{-3} m^2/s/m (0.2 to 47.6 gpm/ft). High capacity irrigation wells (32 to 126 l/s; 500 to 2000 gpm) have been reported in Tertiary sediments along the Madison Bluffs area near Manhattan, Amsterdam, and Churchill, Montana (Kendy and Tresch, 1996). Well logs obtained from the Montana Bureau of Mines and Geology (MBMG) Ground Water Information Center (GWIC) support the reported high capacity yields, though wells drilled east of the Madison Plateau tend have lower water yields.

Quaternary-Tertiary Alluvium. Alluvial fan deposits, pediment, and stream deposits of questionable Tertiary or Quaternary age overlie Bozeman Group aquifer (Tb) (Hackett et al., 1960; Vuke et al., 1995, Slagle, 1995) (Table 1). Hackett et al., (1960) mapped these deposits as older alluvium. The term "old alluvium" is used here to refer to the unconsolidated clays, silts, sand, and gravel deposits stratigraphically above the Bozeman Group sediments (Hackett et al., 1960, page 41) (Figure 5). Old alluvium aquifer, QTal, was used as the aquifer name for these deposits. The water yielding characteristics of old alluvium aquifer (QTal) varies but is considered good and is currently used for domestic and stock purposes. Because this deposit occurs close the mountain range front, depth to water and sufficient recharge (?) may be problematic (Custer et al., 1991; Hay, 1997).

Figure 4. Close up view of Tertiary Bozeman Group sediments along Church Street near Peets Hill in Bozeman, view to the East. Camera Lens cap for scale. Note the wide range of particle size (gravels, sands, and silts) found within the same deposit.

Figure 5. Close up of QTal, SE corner or the SW 1/4, NE 1/4, section 18, T3S, R5E (Same location as Hackett et al., 1960, Figure 8A). View to the Northwest. Note the wide range in size of the clasts. The field of view is approximately ten feet wide.

Quaternary Alluvium

Quaternary deposits of the GLWQD mapped by Hackett and others (1960), Custer and others (1991), Slagle (1995), and Vuke and others (1995) are divided into several different hydrogeologic units based on reported and expected well yields (Table 2). The Quaternary deposits consist of terrace gravels, glacial deposits, alluvial-fan deposits, and alluvial-stream deposits (Hackett, et al. 1960; Custer et al., 1991; Slagle, 1995; Vuke, et al., 1995). Lithologically the units of the Quaternary consist of varying amounts of gravel, sand, silt, and clays. The amount of gravel, sand, silt, and clay will affect the amount of production expected from a unit, along with the thickness and recharge potential of the unit.

Table 2. Tested Quaternary Hydrogeologic units of the GLWQD (After, Hackett et al., 1960; Roberts, 1963; McMannis and Chadwick, 1964; Groff, 1965; Balster, 1971; Kuenzi and Fields, 1971; Skipp and McMannis, 1971; Roberts, 1972; Montagne, 1976; Skipp and McGrew, 1977; Aram 1979; Bonnet, 1979; Balster, 1980, Hughes, 1980; Levings et al., 1981; Chadwick, 1982; Smith and Welker, 1982; Smith, 1983; Moore, 1984; Lambing et al., 1987; Custer et al., 1991; Hiza, 1995; Dyman et al., 1995; Vuke et al., 1995; Kendy and Tresch, 1996; and Skipp et al., 1999.

Erathem	System	Unit Name	Unit Symbol	Hydrogeologic unit Names
CENOZOIC	Quaternary	Alluvium	Qssmal	small mountain stream alluvium aquifer
			Qssval	small valley stream alluvium aquifer
			Qaf	Quaternary basin-fan aquifer
			Qhf	Hyalite alluvial fan aquifer
			Qwggt	West Gallatin gravel terrace aquifer
			Qegal	East Gallatin alluvium aquifer
			Qlegal	Lower East Gallatin alluvium aquifer
			Qlhal	Lower Hyalite Creek alluvium aquifer
			Qwgal	West Gallatin alluvium aquifer
			Qwggd	West Gallatin gravel deposit aquifer

Previously reported transmissivity values of the Quaternary alluvial material by Hackett and others (1960) and Custer and others (1991) range from 1 to 8300 m^2/day (80 to 670,000 gpd/ft). The Quaternary is split into smaller units to test the hypothesis that the differences in deposition and source terrain for various Quaternary alluvial units also leads to differences in hydraulic properties. The descriptions of the individual Quaternary hydrogeologic units follows in the remainder of this chapter. The units are discussed in ascending order of expected water yield.

Small Stream Alluvium-Mountain and Valley Streams. Alluvial deposits of small streams (Sourdough Creek, Middle Cottonwood Creek, South Cottonwood Creek, Hyalite Creek, Rocky Creek, and Bridger Creek) were separated as distinct hydrogeologic units depending on location within the GLWQD. Small stream alluvium is subdivided into mountain streams (Bridger Creek, upper Hyalite Creek, upper South Cottonwood Creek, and Rocky Creek) or valley streams (lower Sourdough Creek, lower Hyalite Creek (from range front to Four Corners), lower South Cottonwood Creek, and lower Middle Cottonwood Creek). Mountain stream alluvium is classified as the small mountain stream alluvial aquifer, Qssmal. Small valley stream alluvium is classified as the small valley stream alluvial aquifer, Qssval. An exception to small valley stream alluvium aquifer is the lower stretch of Hyalite Creek from Four Corners northeast to the East Gallatin River floodplain which was designated as the lower Hyalite Creek alluvium aquifer, Qlhal (Table 2).

Mountain and valley stream alluvia are distinguished from each other and from other basin-fill deposits, because they are likely to yield higher quantities of water than the

Tertiary aged materials (valley streams) or pre-Tertiary bedrock (mountain streams) on which they are deposited. The particle size of the deposits of the mountain and valley stream alluvial deposits are expected to be greater than the underlying Tertiary or pre-Tertiary bedrock units. Separating mountain stream alluvium from valley stream alluvium is done to aid in the testing the potential differences of the hydraulic characteristics of the small stream (mountain or valley) alluvium with the neighboring and potentially underlying deposits. The lower Hyalite Creek alluvium aquifer is separated from the small stream deposits to determine if the lower portion of Hyalite Creek actually flows on a cut surface of the West Gallatin gravel deposit (Qwggd) and if wells in this region are producing from gravelly deposits of West Gallatin gravel deposit, instead of the lower Hyalite Creek alluvium aquifer (Qlhal). The small-stream alluvium aquifers are expected to be the lowest yielding Quaternary alluvium units; because the competence of a small stream is lower, therefore finer grained alluvium deposits are expected. Furthermore, alluvial deposits in small streams may be thin; as a result, wells located in this type of deposit may penetrate through the alluvium and produce water from either the Tertiary sediments or pre-Tertiary rocks below. Quaternary alluvium can not generally be distinguished from Tertiary basin fill either in drill cuttings or from driller logs. Whether a significant difference exists in the hydraulic characteristics of the small valley stream alluvium aquifer (Qssval), small mountain stream alluvium (Qssmal), lower Hyalite Creek alluvium aquifer (Qlhal), and neighboring units will be tested later and discussed in detail in Chapter 5.

Alluvial Fan Deposits. Alluvial fan deposits mapped on the west side of the Bridger Range and emanating from the Gallatin Range were divided into two hydrogeologic units. The alluvial fan deposits on the west flank of Bridger Range are referred to as basin-fan aquifer, Qaf, after Hackett and others (1960) and alluvial fan deposits at Hyalite Creek are referred to as Hyalite alluvial fan aquifer, Qhf, after Nichols (1989) and Custer and others (1991). These deposits are mapped as separate hydrogeologic units (Table 2), because the origins of the fans are thought to be distinctly different. Hyalite alluvial fan (Qhf) is thought to be a glacial outwash fan from the Hyalite Creek drainage basin and the origin of basin-fan aquifer (Qaf) is unclear. Alluvial fan deposits are heterogeneous deposits (Neton et al., 1994). Alluvial fan deposits in the GLWQD were identified from existing geologic maps (Hackett et al., 1960; Custer et al., 1991; Vuke et al., 1995) and the morphology of the deposit.

The 'Bozeman Fan' of Hackett and others (1960) is mapped as the area bounded by Hyalite Creek to the west and northwest, Sourdough Creek to the east, and the East Gallatin River to the northeast (Figure 6). Recent work done by Nichols (1989) and Custer and others (1991) restricts the 'Bozeman Fan' to an area that encompasses about 148 square kilometers (km^2) (57 square miles (mi^2) from where Hyalite Creek exits the Gallatin Range to Patterson road at the 1548 m (5080 ft) topographic contour line. The hydrogeologic unit Hyalite alluvial fan aquifer (Qhf) is restricted only to the area of the Hyalite fan defined by Custer and others (1991) and Nichols (1989). The remaining portion of the 'Bozeman Fan' of Hackett and others (1960) is included in basin-fan aquifer (Qaf) (Figure 6).

Transmissivity values reported by Hackett and others (1960) and Custer and others (1991) for the two alluvial-fan aquifers range from 1 to 800 m^2/day (80 to 64,000 gpd/ft). Water yielding characteristics of the alluvial-fan deposits are expected to be highly variable, but different than fluvial deposits depending on the amount of debris flow channels, over-bank, and/or loess deposits present. Gravel deposits (channel and sieve deposits) are expected to have higher water yields than the silts and clays of the levee and over-bank deposits. Few exposures of these materials exist and the heterogeneity of the deposits makes generalization difficult. Tests of hydraulic property difference will be discussed later in Chapter 5.

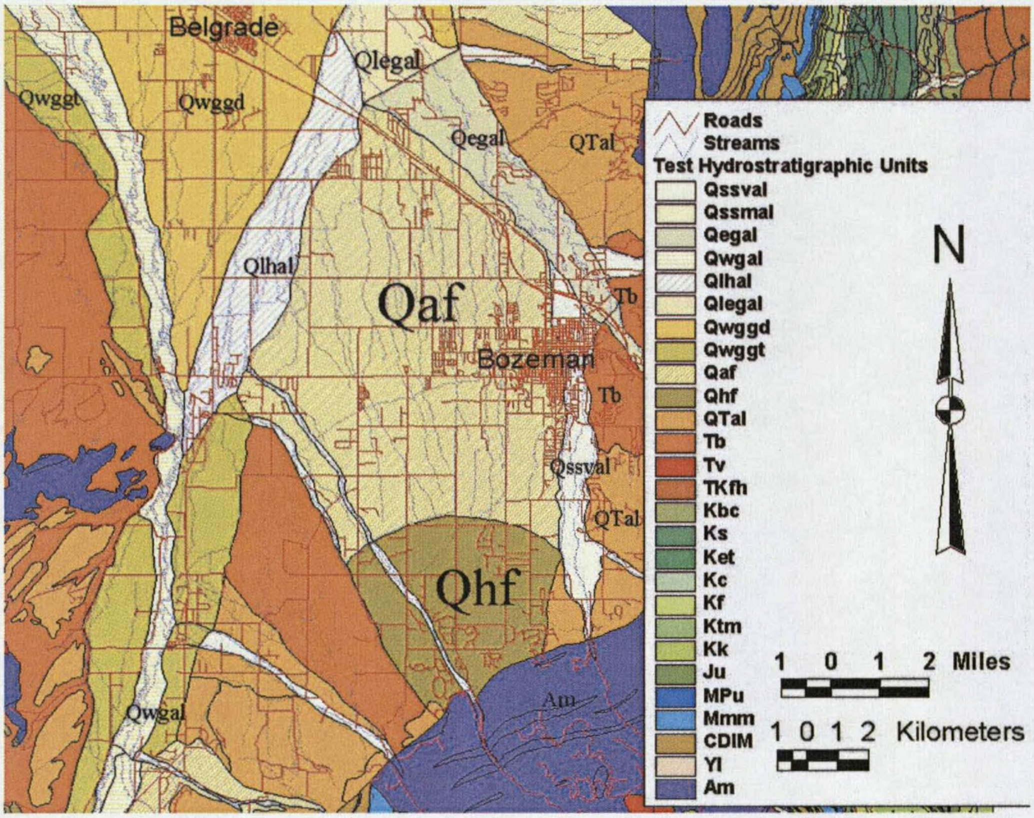

Figure 6: A portion of the Test Hydrogeologic Map (Figure 3) showing the division of the Hackett and others (1960) Bozeman Fan Sub-area into two separate hydrogeologic units, Hyalite alluvial fan aquifer (Qhf) and basin-fan aquifer (Qaf), updated by the work of Custer and others (1991) (Modified from Custer et al., 2000).

<u>West Gallatin Gravel Terrace Deposits</u>. Gravel terraces along the West Gallatin River are identified as a distinct hydrogeologic unit named the Quaternary West Gallatin gravel terrace aquifer, Qwggt (Table 2 and Figure 3). The terrace deposits are separated from the West Gallatin River alluvium because the subsurface geometry of these deposits is unknown. Also, recharge of these deposits is likely different than the alluvium adjacent to the river, however only the transmissivity of the deposit was tested for this study. The problem is whether the terrace deposits are thin or thick. If the terrace deposits are thin, then the real aquifer is the material below the terrace deposit, which would likely be Tertiary sediments and the transmissivity values in these deposits would be similar to the Bozeman Group aquifer (Tb). Conversely, if the terrace deposits are thick then the transmissivity values of the terrace deposits would be similar to the West Gallatin alluvium aquifer (Qwgal). Figure 7 represents three possible interpretations of the subsurface geometry of the West Gallatin terraces. Figure 7A shows the deposits as fill-terraces. Figure 7B and 7C show them to be cut terraces; however, Figure 7B is hydraulically connected to the river alluvium, while cut terraces depicted in 7C are above the river level.

Wells drilled in the West Gallatin gravel terrace area (Hackett et al., 1960) indicate at least 22 m (70 ft) of gravelly material was encountered before reaching Tertiary sediments below terrace materials. Water yield is expected to be good if the gravel is thick and recharge is supplied by the West Gallatin River. Water yield in West Gallatin gravel terrace aquifer (Qwggt) is expected to be much lower if the terraces are cut-terraces, the gravel cap is thin, and the recharge is limited.

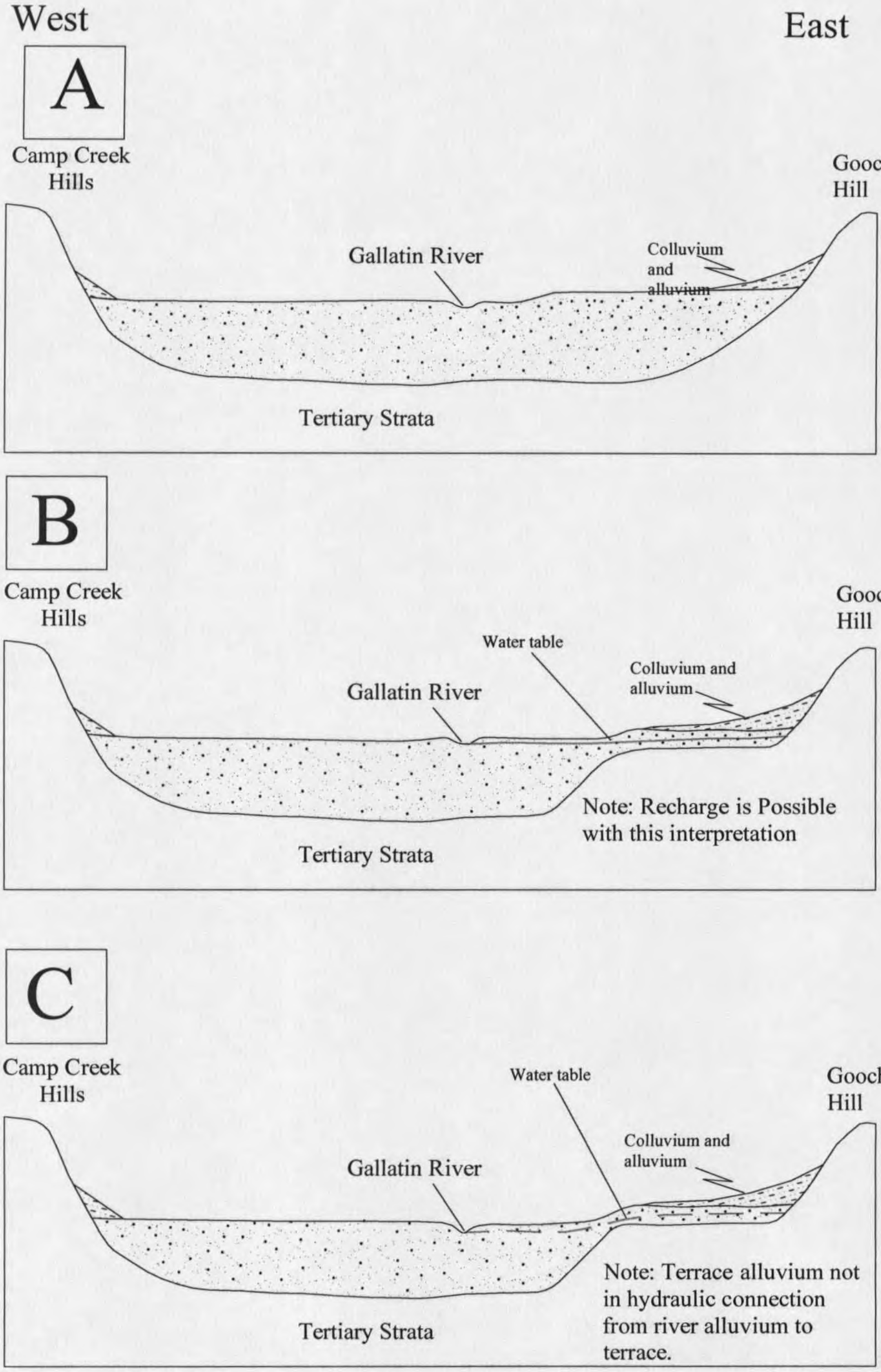

Figure 7. Three possible interpretations of West Gallatin terrace deposits near Gallatin Gateway. Interpretation A represents fill terraces, Interpretation B represents cut terraces in hydraulic connection with the Gallatin River, and Interpretation C represents cut terraces not in hydraulic connection with the Gallatin River (modified from Hackett et al., 1960).

Large Stream (River) Alluvium-East and West Gallatin Rivers. East and West Gallatin River alluvium was divided into three distinct hydrogeologic units. The division of this alluvium was based on the mapped pattern of alluvial deposits, aquifer tests conducted by Hackett and others (1960), and the geology of the drainage basins. Alluvial deposits of the East Gallatin River are divided into two aquifers, the East Gallatin alluvium aquifer, Qegal, and lower East Gallatin alluvium aquifer, Qlegal (Table 2 and Figure 3). Alluvial deposits of the modern West Gallatin River are classified as the West Gallatin alluvium aquifer, Qwgal (Table 2 and Figure 3).

Alluvium of the East Gallatin River (Qegal) is expected be a low yielding Quaternary alluvial aquifer because of the expected fine grained nature of the deposits. East Gallatin alluvium is thought to be finer-grained than West Gallatin alluvium. East Gallatin River tributaries Bridger, Kelly, and Rocky Creeks all drain areas that are underlain by Paleozoic and Mesozoic limestones, siltstones, and shales (Hackett et al., 1960; Roberts, 1964a-d). These rock units are easily eroded, especially the Cretaceous units, which result in a deposit of fine-grained alluvium (Hackett et al., 1960). Also, the drainage basin of East Gallatin River is smaller than the West Gallatin River which would affect the average discharge of the river. The lower discharge does not allow for large-grained clasts to be transported and deposited (USGS, 2002). Water yields expected to be good but lower than the alluvium of the West Gallatin. Test holes drilled by Hackett et al., (1960) into East Gallatin River alluvium encountered probable Tertiary materials around 10 m (30 ft) in one test hole, while in another test hole drilled to a depth of 54 m (162 ft) and did not encounter Tertiary material. Though aquifer tests were conducted in East Gallatin River alluvium by Hackett and others (1960), transmissivity values could not be calculated from the data. Wells in the area are usually around 10 m (30 ft) in depth, and the water level is approximately 3 meters (10 ft) below land surface (Hackett et al., 1960; Slagle, 1995).

The lower East Gallatin alluvium aquifer (Qlegal) is mapped as a separate aquifer unit from East Gallatin alluvium aquifer (Qegal) because of the map pattern of surrounding alluvial deposits in the vicinity of Belgrade (Figure 8). The hydraulic characteristics of the lower East Gallatin alluvium aquifer (Qlegal) are expected to be similar to that of West Gallatin gravel deposit aquifer instead of East Gallatin alluvium aquifer (Qegal). Notice the lower East Gallatin alluvium aquifer (Qlegal) is bound on both sides near Belgrade by West Gallatin gravel deposit aquifer (Qwggd). The alluvium of lower East Gallatin alluvium aquifer (Qlegal) is hypothesized to be the edge of the West Gallatin gravel deposit aquifer (Qwggd) which has been interpreted as glacial (?) outwash deposits with a veneer of fine-grained material deposited by the modern East Gallatin River.

West Gallatin alluvium (Qwgal) is hypothesized to have the second highest water yielding capability of the Cenozoic alluvial aquifers. The West Gallatin alluvium aquifer (Qwgal) consists of all of the modern floodplain alluvium of the West Gallatin River, which has the highest peak discharge of all GLWQD rivers and has the highest competence to carry large clasts (USGS, 2002). The alluvium consists of cobbles, and coarse gravel, intermixed with varying amounts of sand, silt, and clay. Transmissivity values reported by Hackett and others (1960) based on aquifer tests at 13 sites in the 'Belgrade Subarea' ranged from 1,200 to 3,600 m^2/day (94,000 to 290,000 gpd/ft) for nine of the test sites, while two had transmissivity values of less than 870 m^2/day (70,000

Gallatin alluvium aquifer (Qwgal) has high yield capabilities because of the coarse-grained nature of the alluvial materials and the thickness of the deposit. The coarse-grained materials reflect the higher competence of the West Gallatin River and also likely reflect glacial outwash deposits from when glacial ice was present near the headwaters of the Gallatin River.

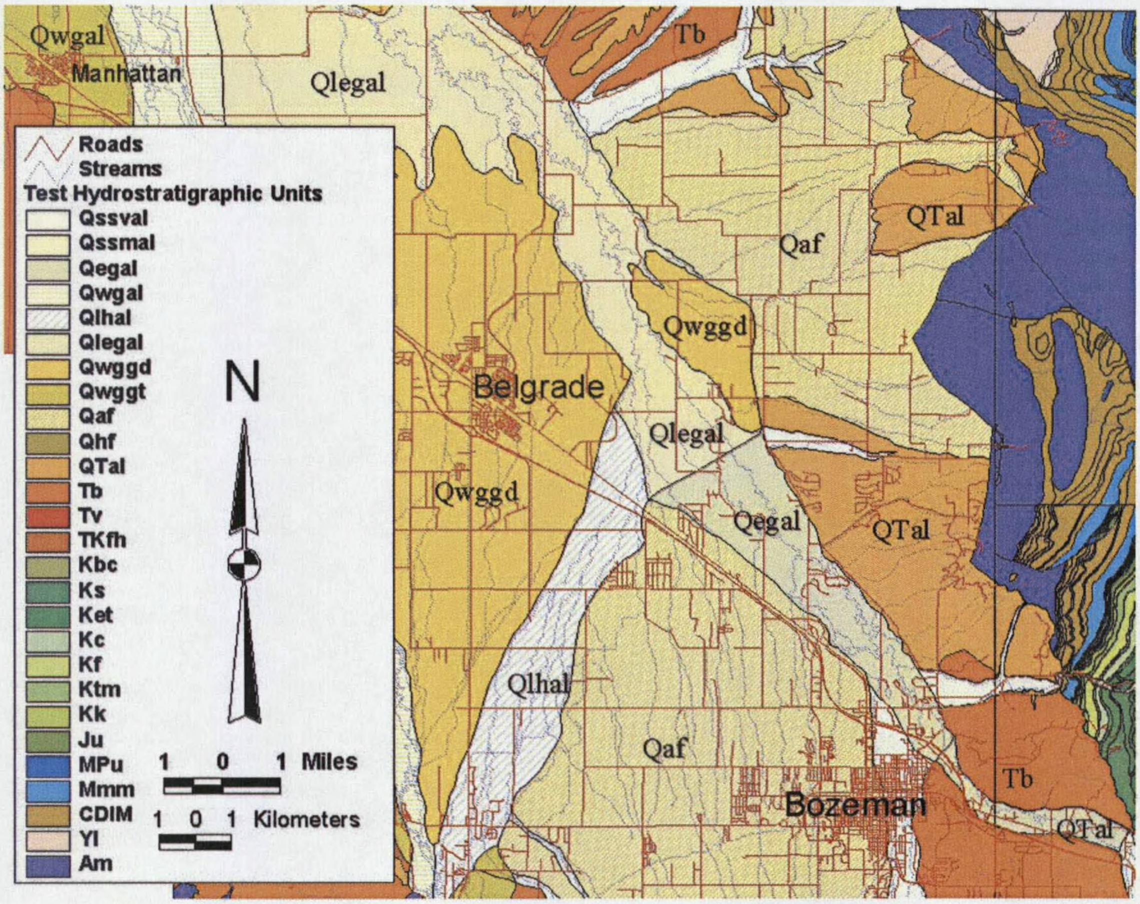

Figure 8: A portion of the Test Hydrogeologic map showing the separate test-hydrogeologic units of the East Gallatin River deposits (Qegal and Qlegal) and surrounding units. (Modified from Custer et al., 2000).

<u>West Gallatin Gravel Deposit Aquifer (Belgrade Subarea).</u> The massive gravel deposit exposed by excavations along Interstate 90 near Belgrade is part of a diamond shaped unit mapped by Slagle (1995) and Vuke et al., (1995) as Qal (predominantly

fluvial deposits – Quaternary) and Qg (gravel deposit of alluvial terraces and dissected valley fill), respectively. West Gallatin gravel deposit aquifer (Qwggd) is expected to be the highest yielding unit in the GLWQD. The gravel deposit consists of imbricated cobbles and coarse gravel in a silt-and-sand matrix as shown in Figure 9. A well was drilled in the area to a depth of 132 m (400 ft) without penetrating Tertiary sediments (Hackett et al., 1960). The city of Belgrade obtains its municipal water supply from four wells drilled in this gravel deposit. The yield of the four City of Belgrade wells ranges from approximately 50 to 95 l/s (800 to 1500 gpm).

Figure 9: View of gravels and sands of the West Gallatin gravel deposit from the JTL Quarry, Belgrade, Montana. The small yellow field book is approximately 19.05 centimeters (7.5 inches) long and 12 centimeters (4.7 inches) wide.

Summary

The test-hydrogeologic unit designations are based on local and region geologic and hydrologic information. The lithostratigraphic units of the GLWQD are divided into 27 test-hydrogeologic units. Statistical testing of the test-hydrogeologic units will help determine if the initial units are statistically valid or if revision of the grouping of units is warranted.

CHAPTER 3

METHODS

Hydrogeologic Map

The hydrogeologic map of the GLWQD was created from the compilation of several published geologic maps for the area and later tested by statistical comparisons of the test-hydrogeologic units. Eight geologic maps covering the GLWQD were compiled to build a hydrogeologic map for the district (Roberts, 1964a-d; Chadwick, 1982; Vuke et al., 1995; Kellogg and Williams, 1998; Skipp et al., 1999; Custer et al., 2000); Table 3. The digital maps were joined and edged-matched using ArcEdit. The digital maps were reprojected to UTM NAD83. The paper maps were digitized, projected in UTM NAD83, joined, edge matched, and merged with the digital maps. Each source map used different geologic units, therefore interpretation and simplification was required to draw together the hydrogeologic units. Original map-unit designations were preserved as one attribute in the ArcView coverage (Custer et al., 2000). In addition, the boundaries between the maps were preserved to close polygons that do not extend across map boundaries; however each polygon was assigned attributes appropriate to a level of generalization that allowed continuous geologic coverage across map boundaries.

Table 3. Geologic Base Maps Used for the Hydrogeologic Map (After Custer et al., 2000)

Name of Map	Scale	Format	Publication	Reference
Geologic Map of the Bozeman 30'x60' quadrangle, Montana	1:100 000	Digital	MBMG Open File 334	Vuke et al., 1995
Geologic Map of the Ennis 30'x60' quadrangle, Montana	1:100 000	Digital	USGS Open File 97-851	Kellogg and Williams, 1998
Igneous Geology of the Fridley Peak Quadrangle, Montana	1:62 500	Paper	MBMG Geologic Map 31	Chadwick, 1982
Geologic Map of the Sedan quadrangle, Gallatin and Park Counties, Montana	1:48 000	Digital	USGS I-2634	Skipp et al., 1999
Geologic Map of the Maxey Ridge Quadrangle, Montana	1:24 000	Paper	USGS I-396	Roberts, 1964a
Geologic Map of the Fort Ellis quadrangle, Montana	1:24 000	Paper	USGS I-397	Roberts, 1964b
Geologic Map of the Mystic Lake Quadrangle, Montana	1:24 000	Paper	USGS I-398	Roberts, 1964c
Geologic Map of the Bozeman Pass Quadrangle, Montana	1:24 000	Paper	USGS I-399	Roberts, 1964d

The geologic unit boundaries were relocated only where necessary to match geologic unit contacts across map boundaries. At times it was necessary to subdivide the geologic units further to incorporate the hypothesized hydrogeologic units (Table 1). An example of this addition of contacts occurs in the area mapped by Roberts (1964a-d). Roberts (1963a-b) mapped the Madison Group as one unit, while McMannis and Chadwick (1964) separated the Lodgepole and Mission Canyon Formations. Because the hydraulic properties of the Lodgepole Limestone and the Mission Canyon Limestone within the Madison Group are expected to be different, the Madison Group was split into two different hydrogeologic units where the group was mapped as undivided (Table 1). Because no field mapping was done for this project, the Madison group map width was proportionally divided into the Lodgepole Limestone and Mission Canyon Limestone based on the regional thickness of each unit, and each unit's thickness on adjacent maps

(Smith and Welker, 1982; Custer et al., 2000). Figure 10 demonstrates an example of the division between Cambrian, Devonian, and Lower Mississippian aquitard and Mission Canyon aquifer.

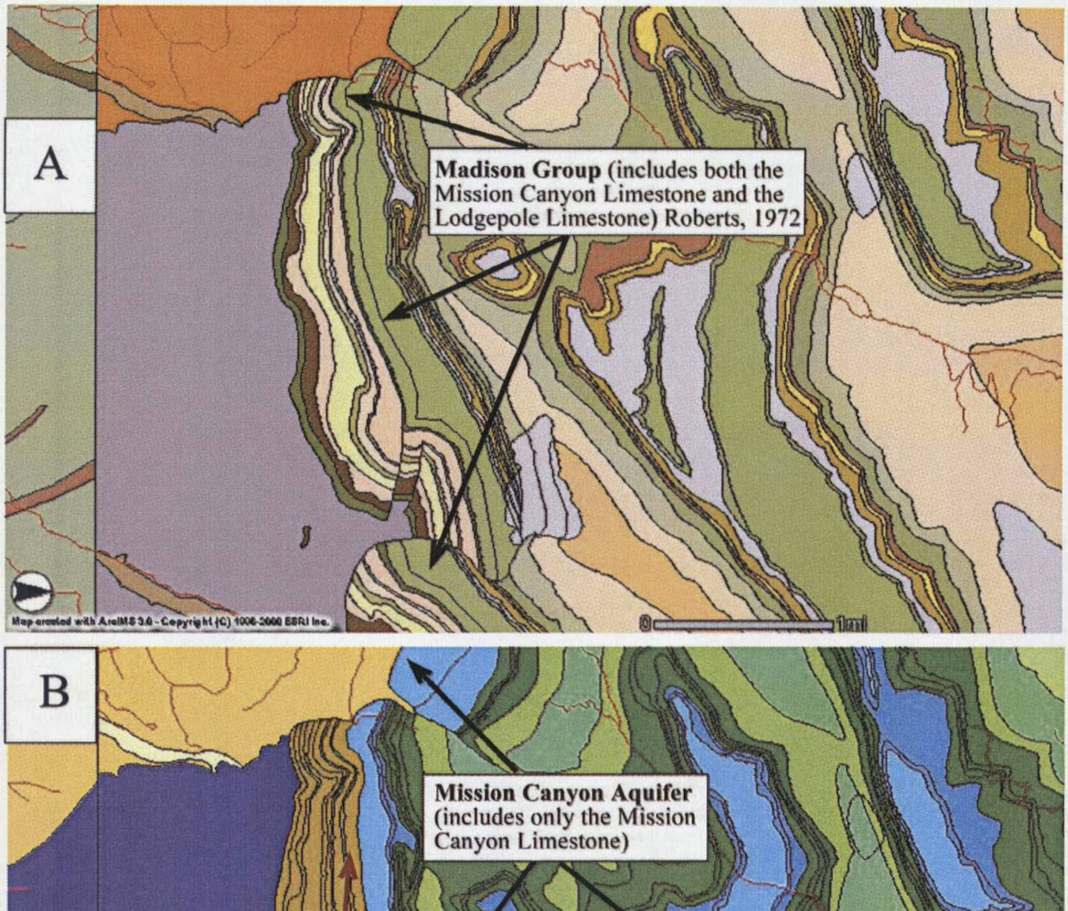

Figure 10: Map **A** shows the original geologic units as mapped by Roberts, 1972; and Map **B** shows an example of the adding geologic contacts (Scale and north arrow on Map B serves for both maps) (after Custer et al., 2000).

The Fridley Peak (1:62:500) geologic map by Chadwick (1982) was used to complete the geologic coverage of the southeastern most portion of the GLWQD. Chadwick's (1982) mapping focused on the igneous geology of the area, thus he did not differentiate between the Paleozoic and Mesozoic units in his map area. The Paleozoic and Mesozoic strata were added to the Fridley (1:62:500) map by interpolating the rock units from the adjacent maps as demonstrated in Figure 11 (Custer et al., 2000). However, considerable uncertainty still exists regarding exact contact positions within the Paleozoic and Mesozoic units as estimated on the Fridley Peak Map, and the contacts need to be field verified.

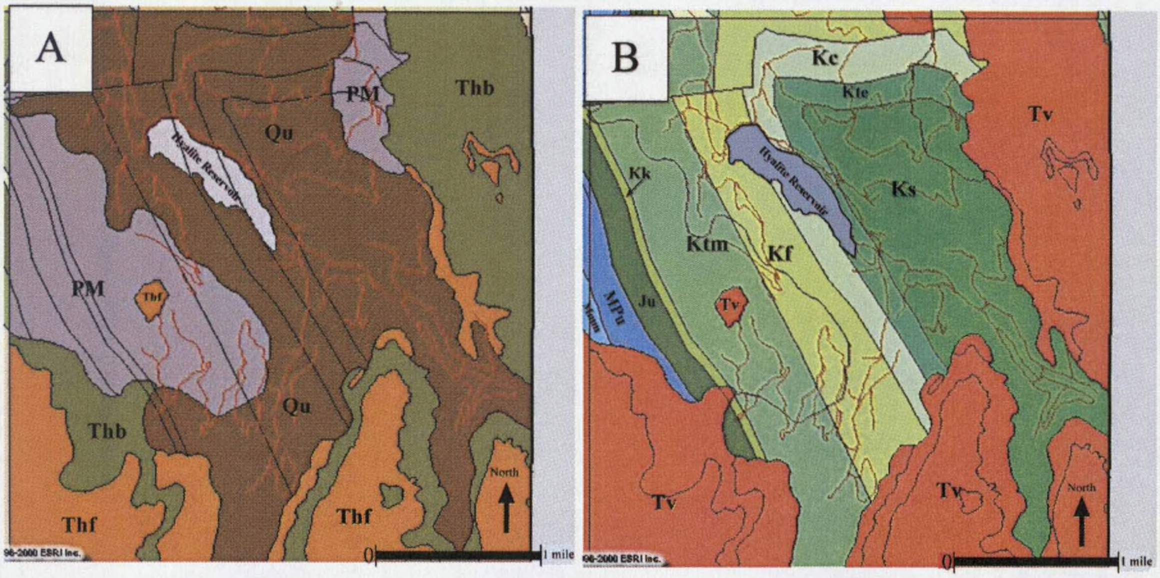

Figure 11. Map **A** - Original map units of the Fridley Peak Quadrangle by Chadwick (1982). Map **B** – the Fridley Peak Quadrangle portion of the Hydrogeologic Map of the GLWQD (Custer et al., 2000). Map units of Chadwick (1982) which includes the following: PM – Sedimentary rocks, undifferentiated; Thf – Hyalite Peak Volcanics (pyroxene andesite, autobrecciated flows); Thb - Hyalite Peak Volcanics (epiclastic breccia); Qu – Undifferentiated deposits. Hydrogeologic units of Custer and others (2000) include the following: Mmm – Mission Canyon Aquifer; MPu – Upper Mississippian-Permian Aquitard; Ju – Jurassic Aquitard; Kk – Kootenai Aquifer; Ktm – Thermopolis-Mowry Aquitard; Kf – Frontier Aquifer; Kc – Cody Aquitard; Kte – Telegraph Creek-Eagle Aquifer; and Ks-Sedan Aquifer.

Although new polygons were created during the map editing process, the original map unit designations were preserved as a separate attribute to retain the integrity of the original map. Additionally, in each polygon, separate attributes were defined to preserve both the surficial and the hydrogeologic units. In this manner, disagreements regarding unit designation are easily resolved by comparing original and reassigned unit names. The outcome of these consistent unit designations and attribute preservation lead to the creation of a hydrogeologic map for the GLWQD with consistent well defined units.

Location of Wells in the GLWQD

Well location data for the study area were obtained from the Ground Water Information Center (GWIC) at the Montana Bureau of Mines and Geology (MBMG) in Butte, Montana. The last data retrieval from the GWIC database used for this project was conducted in August 1998. The location data obtained from GWIC was used to locate wells in the GLWQD. At times however, the location information for a particular well was incorrect because of several factors including; 1) the wrong Township, Range, and/or section may be recorded on the well log, 2) a transfer error from the log to the database for township, range and section may have occurred, 3) or there may be incorrect or incomplete address information given for a well. Incomplete and/or incorrect addresses are particularly problematic because well addresses are often different than the well owner's address. Many wells are drilled for domestic water supply. The well is often drilled before the house is built. Commonly, the given owner address reflects the owner's previous address prior to the drilling of the well. For example, an address within the city limits of Bozeman, Montana or even a Denver, Colorado address may given for a well drilled north of Bozeman outside of the city limits. Not all addresses are wrong however, some wells are drilled for the property after the owner moves to the property in which case the address is correct. As a result, the owner address was only used for corroborating a wells location.

Several existing databases were used to cross-reference and verify well locations within the GLWQD. These databases include the GWIC well database, Gallatin County septic permit records, Gallatin County land-ownership records, and the U.S. West Bozeman area (1996/1997) telephone directory. These databases were used to mark well locations on the 1995 Gallatin County Road Book (GCRB). The 1995 GCRB was used because it shows all street addresses, subdivisions, lots and blocks in unincorporated Gallatin County, some addresses and streets in the city limits of Belgrade, Manhattan, and Bozeman. Once the correct location of the well was determined, the unique MBMG identifier M-number was noted adjacent to the dot in the 1995 GCRB that represents a structure at the correct piece of property (Figure 12). If no structure marker was shown for the piece of property that all of the well location information pointed to as the correct location for the well in question, then a dot and well number was added in the near front of the piece of property near the road in the road book. In addition to downloading a well's M-number from the GWIC database, well location information was collected which includes township, range, section, quarter sections, owner name, addition (subdivision name), block, lot, and owner address. The criteria used to determine well locations in the GLWQD are discussed next.

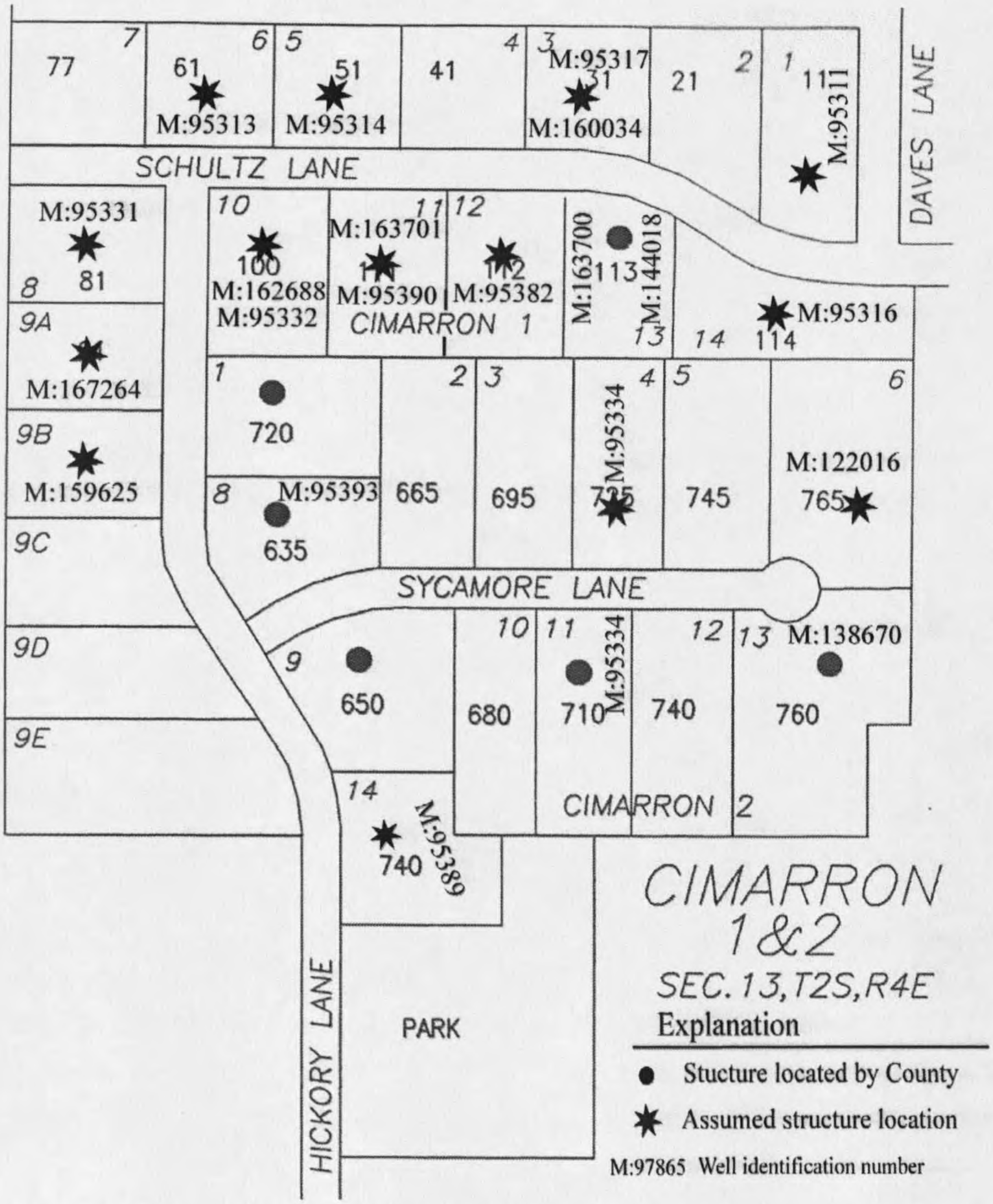

Figure 12: Example of the 1995 Gallatin County Road Book with located wells.

Starting with a known township, range and section, the subdivision name, block and lot were first checked. If all of these pieces of information existed for a particular M-number, then the well was marked at the dot in the appropriate lot shown on the 1995

Gallatin County Road Book maps and given a high confidence level of accuracy (Figure 10). The placement of the dot for the well is assumed to be within 30 m (100 ft) of the correct location of the well because lots are commonly one acre in size (70 m (200 ft) on a side). The markers are placed closer to the front of the lot because homes tend to be closer to the road and the well is usually close to the house. The location of a marker placed in the middle of the lot but closer to the road is not likely to be inaccurate by more than half a lot or about 30 m (100 ft).

If any portion of the subdivision information was missing or non-existent, then Gallatin County septic permit records were searched by well owner's name. The assumption for this method is that a well owner is highly likely to also have a septic system. It the septic permit search produced a subdivision name, block, lot, and/or street address in general agreement with the location data provided by the GWIC well log, the this information was used to locate the well at the appropriate address in the 1995 GCRB. Wells located with septic permit data are assumed implicitly correct because each septic system requires a county health inspector site visit. However, if the septic permit search did not provided the necessary well location information either for a particular owner's name, or there were too many septic permits to the same owner to distinctly determine which septic permit corresponded to the well record, the well site was determined from a combination of the address in the GWIC records, the township, range, and section designation along with the U.S. West Bozeman Area (1997-1998) telephone directory, and county property records.

The telephone directory and county property records were used most often to complete township, range, and section data. Township, range, and section data designations are extremely important to properly locate wells within the GLWQD. This is because many well records did not have an owner's address, lot, block, and/or subdivision information. In such cases, township range, and section data were used to estimate well locations in the 1995 GCRB. If it was possible to determine the distinct well site from the township, range, and section information, the well was marked on the 1995 GCRB and included in the database. However, if there were too many undifferentiated structures in a particular area, the well or wells were not mapped and not included in the database.

The data was digitized from the 1995 GCRB by coordinating to the section corners of each road book page. Later, information from the GWIC system was added to the coverage by linking on the M:number. The located wells are assumed to be approximately within 30 meters (100 feet) of the correct location, based on the average lot size (1 acre). Where more than one well existed at a site, additional wells were "spawned" 10 m from the original well so each well was unique. The first well was spawned to the east, the second to the south, the third to the west, the fourth to the north, and the fifth (if present) to the northeast (B. Snyder, S. Custer, and A. Wright, personal communication).

Selection of Test Wells

Five single well pump tests were conducted as part of this research project. The pump tests were conducted to obtain information on the aquifer properties of various geologic formations in the study area. In addition, the pump tests provided data with which to develop a mathematical relationship between specific capacity and transmissivity for the

GLWQD. The aquifer tests conducted as part of this study focus on unscreened or non-perforated wells because these well types represent the 73% of the wells in the GLWQD. Unscreened or non-perforated wells are preferred over perforated wells because they reduce the variability in well yields and specific capacity caused by different well construction techniques in the database. However, transmissivity values calculated from unscreened or non-perforated wells should be viewed as low estimates of aquifer parameters because of lower well efficiency (Driscoll, 1986, page 245).

Also, existing well test data was assembled into a database, which was then reviewed to determine which test results were appropriate for inclusion in the analysis. This database includes data from 45 aquifer tests conducted by Custer and others (1991) and 41 aquifer tests conducted by Hackett and others (1960). These aquifer test results will be combined with the aquifer test results conducted during this study and filtered to develop the mathematical relationship between specific capacity and transmissivity for the GLWQD. As discussed later, only aquifer test results from unscreened or non-perforated wells pumped for one hour will be used to develop the mathematical relationship between specific capacity and transmissivity for the GLWQD.

Testing of Wells

Five single well pump tests were conducted as part of this study. The tests were conducted within four different hydrogeologic units. Two of the wells (M:91730 and M:128350) were located within the lower Hyalite Creek alluvial aquifer. Well M:92206 is located within the Billman Creek aquitard. Wells M:9858 and M:96581 are located within the basin-fan aquifer and Bozeman Group aquifer, respectively. As previously stated all five tested wells were unscreened or nonperforated and pumped for one hour, with the exception of M:92206. M:92206 was pumped for only 15 minutes, because the water level in the well dropped below the pump intake level prior to reaching one hour of pumping.

The pump tests followed a consistent procedure. Once permission from the land/home owner was granted, an appointment time was set for well testing. The field tests involved only the pumping well. To begin the aquifer test 3 to 4 spigots were turned on, however the pump does not turn on immediately after the spigots are opened. The delay of the pump initiation is related to water delivery from the pressure tank. The pressure must drop in the pressure tank to a predetermined level before the pump is signaled to turn on. Time was started when the pump was heard to start. Water level measurements were taken every 30 seconds for the first 5 minutes, then once a minute between five to ten minutes, then every five minutes between ten and fifty minutes, and lastly a final measurement at sixty minutes (Driscoll, 1986; Custer et al., 1991). Recovery measurements began after the pump became inaudible (signaling the pump was shut off). Measurements of well recovery followed a similar schedule to those during drawdown. Drawdown and recovery were measured with a Slope Indicator® electric light-and-sounder probe because the probe allowed rapid measurement of the drawdown and recovery of the water level (Driscoll, 1986).

All of the wells tested were domestic wells. Domestic well pumps are controlled by a pressure tank in the home, which controls when the pump turns on and off (Figure 13). A constant discharge rate is important for these well tests, therefore it was important that the pump ran continuously. This was checked by listening for the well pump motor during the duration of each test.

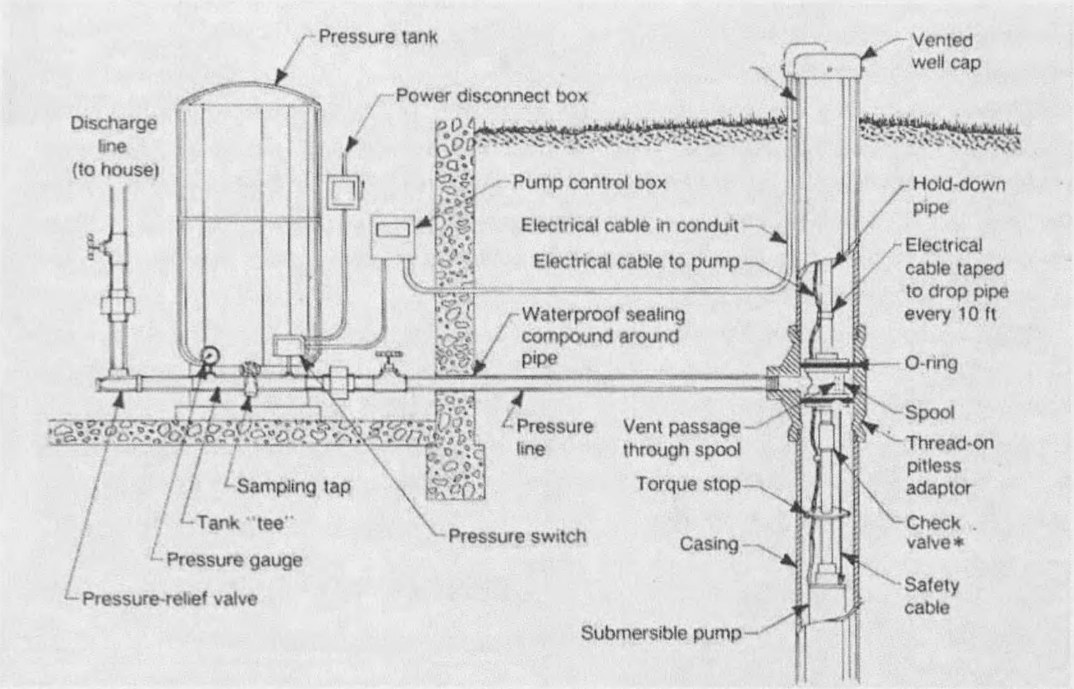

Figure 13: Sketch of typical domestic well and components showing water line running directly from the submersible pump in the well to the pressure tank (Driscoll, 1986, page 626).

Discharge was determined by measuring the amount of time to fill a five-gallon bucket at each spigot and summing the measurements at all spigots to arrive at a discharge for a specific time during the pump test (Driscoll, 1986). The discharge value used in the transmissivity and specific capacity calculation was determined by averaging the discharge measurements made throughout the test. Discharge from the spigots is approximately the discharge from the pump, as long as the pressure tank was not full and the pump remained on, according to local well pump installers at OwenHouse Hardware and Mountain Supply, both in Bozeman, Montana. The well was pumped at a constant rate during the entire drawdown portion of the test. Average discharge rates of between 0.9 - 1.1 l/s (15 - 17 gpm) were measured during the aquifer tests.

The pump tests were conducted for one hour, since this is the pump time usually reported by area drillers, and the majority of specific capacity tests were conducted for one hour, it provides for direct comparison with driller data and eliminates a source of variance (Figure 14).

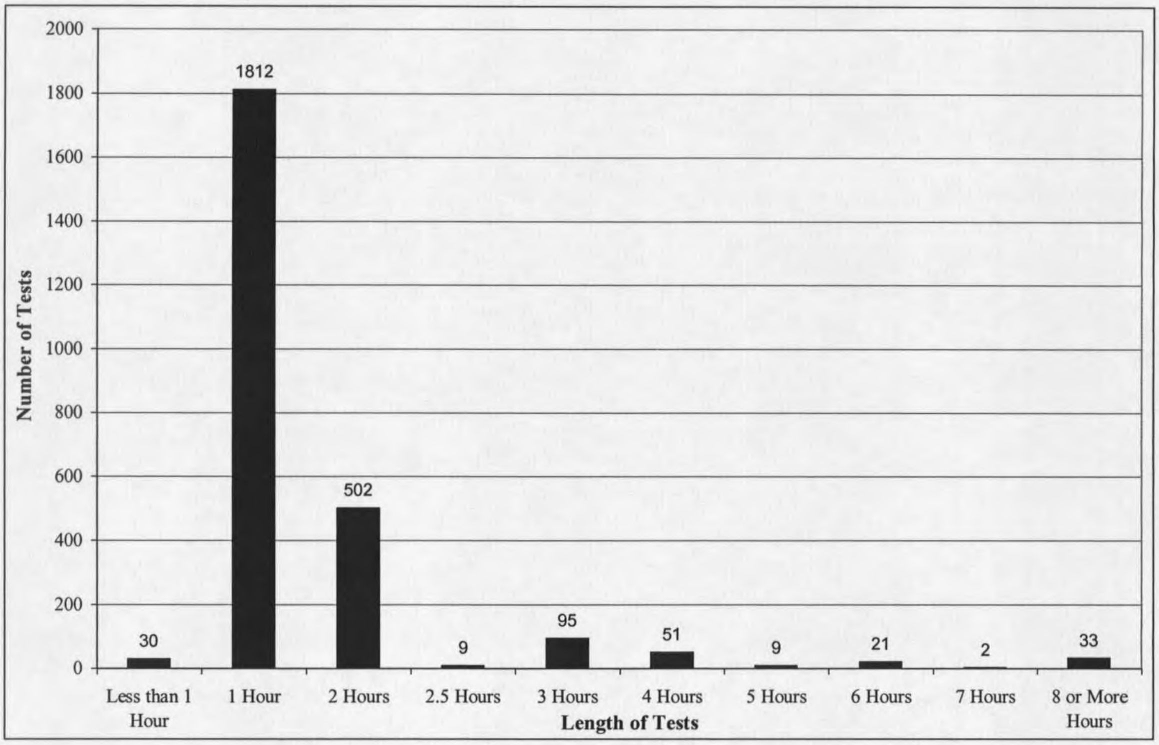

Figure 14. Duration of specific capacity tests performed by drillers for wells in the GLWQD.

Calculation of Transmissivity

Transmissivity can be calculated from both drawdown and recovery data collected from a single-well aquifer test (Driscoll, 1986; Fetter, 1994; Kasenow, 1996a-b). However, drawdown data are subject to inherent problems which often lead to erroneously calculated transmissivity values (Driscoll, 1986). Water-level measurements made during the drawdown phase of an aquifer test may be in error because of turbulence in the well caused by the well pump. Casing storage may also cause problems for transmissivity calculation. During the early part of an aquifer test, water withdrawn from the well may not come directly from the aquifer; but instead, may come from the water stored in the well casing (Driscoll, 1986). Once the pump has stopped and the water level is allowed to recover, the problems of casing storage and well turbulence cease to exist.

As a result, recovery data was collected and analyzed to calculate the transmissivity values for the aquifer. Ideally, the water level rise in the well should be a mirror image of the drawdown; however, this is rarely the case because drawdown measurements are subject physical processes that do not occur during the recovery phase (Driscoll, 1986). The recovery method assumes that once a well is pumped and then shut off, the residual drawdown can be measured and considered to be the result of a recharge to the well at a discharge equal to the pumping rate (Theis, 1935; Ferris et al., 1962; Fetter, 1994; Driscoll, 1986). Recovery analysis can only be used after an aquifer test in which the discharge remains relatively constant throughout the test period (Theis, 1935; Jacob, 1963; Driscoll, 1986; Kasenow, 1996a-b).

The recovery data is plotted as residual drawdown data versus the ratio of time since pumping started (t) and time since pumping stopped (t′) (Driscoll, 1986; Kasenow, 1996a) (Figure 15). Residual drawdown (s') is the measured water level in the well after the pump test has been concluded minus the initial static water level (Cooper and Jacob, 1946; Jacob, 1963; Driscoll, 1986; Kasenow, 1996a). Transmissivity was calculated from the residual drawdown graph by taking the slope of the line over one log cycle

(Figure 13) (Cooper and Jacob, 1946; Jacob, 1963; Driscoll, 1986; Kasenow, 1996a) and entering these values in to the following equation:

$$T = \frac{264Q}{\Delta s'} \tag{1}$$

where T = transmissivity (gpd/ft), where Q = discharge in gpm, and $\Delta s'$ = slope over one log cycle during recovery. Initial calculations of specific capacity and transmissivity were done in American Practical Units (APU), gpd/ft and were later converted to SI units, m^2/day.

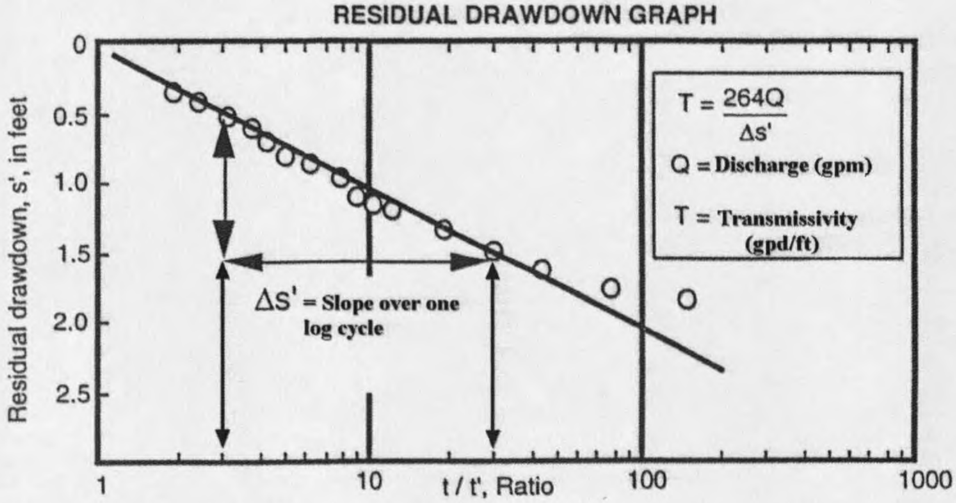

Figure 15: Example of the Cooper-Jacob method semi-log plot (after Kasenow, 1996a)

<u>Specific Capacity – Transmissivity Empirical Relationship</u>

Well specific capacity and recovery-transmissivity pairs were used to develop a numerical relationship between specific capacity and transmissivity. The empirical relationship between specific capacity and transmissivity was determined from a combination of the data collected from the field-tested wells and from similarly unscreened or non-perforated wells tested during previous studies. Following the methods of previous authors, log transformations were applied to both the observed specific capacity and transmissivity data (for example, Custer et al., 1991; Razack and Huntley, 1991; Huntley et al., 1992; Jalludina and Razack, 1994; Mace, 1997). This log transformed data was plotted as the log specific capacity (m^3/min/m) versus log transmissivity (m^2/day). Since each variable has been log transformed, the axes of the graph reflect the power of ten per increment. A best-fit linear trend line was derived for this data using a least-squares regression analysis. The resultant numerical relationship is the slope and intercept of the best-fit trend line based on 50 observations (N). This equation was used to then estimate transmissivity values at located unscreened or nonperforated well sites where only specific capacity data is available in the GLWQD.

Statistical Analysis of Driller Test Methods

Examination of well log data for the well sites properly located within the GLWQD reveal that the aquifer tests conducted by drillers often used significantly different testing methods. There are three primary water removal methods (air, bailer, and pump) used by the drillers who work in the GLWQD (Figure 16). The different water removal methods raised concerns about the comparability of the aquifer parameters calculated from the various methods. For this reason, it is necessary to determine if specific capacity values and therefore the derived transmissivity values are significantly different among the different driller test methods.

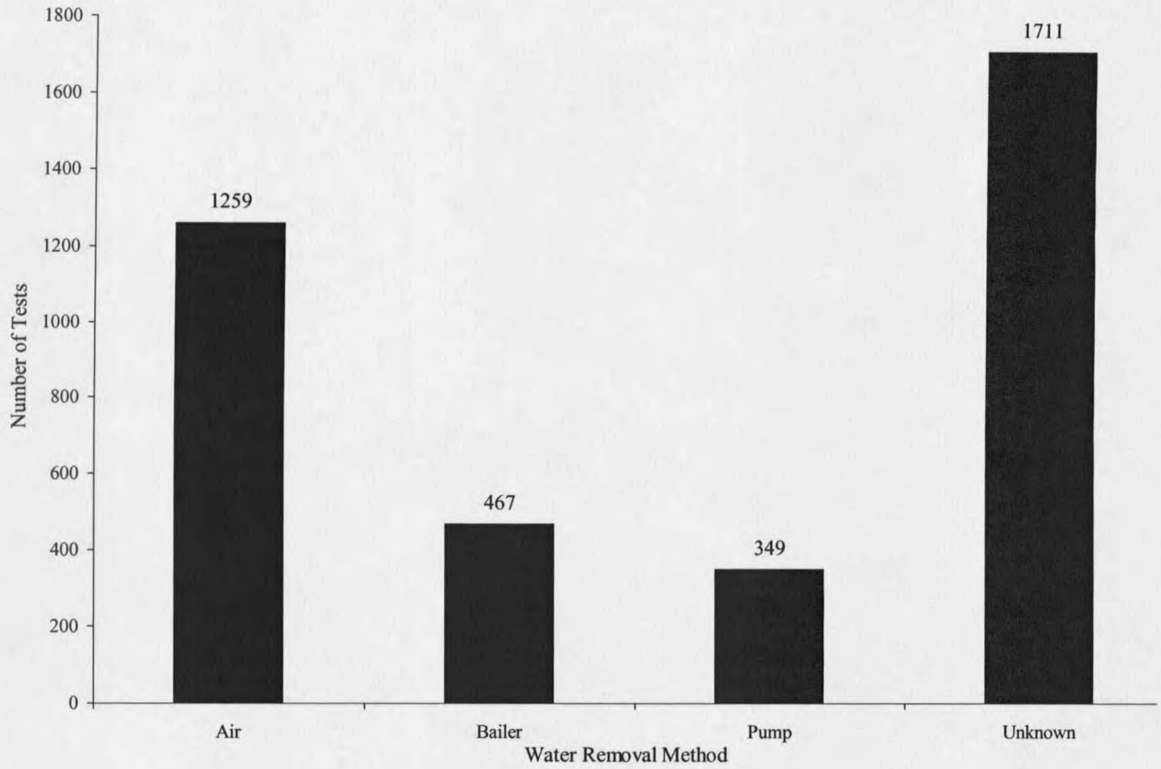

Figure 16. Number of tests per test method for all of the wells within the GLWQD with specific capacity data.

A one-way analysis of variance (ANOVA) was performed on the log transformed transmissivity values using MINITAB™, a statistical software package, to determine if there was a statistical difference between the pump, air, and bailer test methods. Based on the results of the one-way ANOVA, pump test and air test transmissivity data are not statistically different (Figure 17). However, bailer test data results are significantly different. Because the well can partially recover during bailer trips, water removal with a bailer is a poor method for aquifer testing. A Mann-Whitney test, a non-parametric two-sample rank test was then used as an error check on the statistical similarities between the pump and air test methods and the pump and bailer test methods.

```
Analysis of Variance
Source      DF        SS        MS        F        P
Factor       2    50.607    25.303    67.16    0.000
Error     2072   780.623     0.377
Total     2074   831.230
                                    Individual 95% CIs For Mean
                                    Based on Pooled StDev
Level        N      Mean     StDev  ------+---------+---------+---------+
log Air   1259    0.9957    0.5653  (-*--)
Log Pump   349    1.0782    0.6225      (---*---)
Log Bail   467    1.3806    0.7233                          (---*---)
                                    ------+---------+---------+---------+
Pooled StDev =    0.6138                1.05      1.20      1.35      1.50
```

Figure 17: One way Analysis of Variance graph of the pumping methods used in the GLWQD. Notice the overlap of the Air and Pump data and lack of overlap of the Bailer data.

The Mann-Whitney test (sometimes known as the two-sample Wilcoxon rank sum test) is a statistical test that is a type of paired t-test for non-normally distributed data. Though the Mann-Whitney test is intended for non-normally distributed data, it is 86% as efficient as the paired t-test for a normal distribution (Devore, 1995). Therefore, *a priori*, the Mann-Whitney test is applicable regardless of the underlying transmissivity distributions. It is expected, however, that because transmissivity data are highly variable and range over several orders of magnitude that they are not normally distributed (Viessman and Lewis, 1996).

The Mann-Whitney test was applied using the null hypothesis (H_o). In this case, the rejection of the H_o at the 0.05 significance level (within the 95% confidence limits) indicates that the tested pair is statistically different. All statistical tests were performed using MINITAB™, a statistical software package, using the log transformed data in the units of m^2/day, converted to gpd/ft after the statistical analysis.

Results of the Mann-Whitney test confirm that pump and air test transmissivity data are statistically similar (Table 4) and pump and bailer test transmissivity data are statistically different (Table 5). The Mann-Whitney test between air and pump is significant at 0.4443, which is greater than alpha = 0.05. Therefore, the null hypothesis can not be rejected indicating air and pump are statistically similar at a confidence interval of 95% (Table 4). All of the wells tested by the local drillers using the air method will remain in the well database.

Table 4. Mann-Whitney Test Results for log transformed air transmissivity values and pump transmissivity values.

Mann-Whitney Test: Log Air (m^2/day), Log Pump (m^2/day)			
Log Air	N = 1259	Median =	1.0124
Log Pump	N = 336	Median =	1.0365
Point estimate for ETA1-ETA2 is			-0.0231
95.0 Percent CI for ETA1-ETA2 is (-0.0788, 0.0340)			
W = 1006993.0			
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.4443			
The test is significant at 0.4442 (adjusted for ties)			
Cannot reject at alpha = 0.05, Statistically Similar			

However, the Mann-Whitney test between bailer and pump is significant at 0.0000, which is less than alpha = 0.05 (Table 5). Therefore, the null hypothesis can be rejected indicating bailer and pump are not statistically similar at a confidence interval of 95% and all of the wells tested by local drillers using the bailer method are removed from the well database.

Table 5. Mann-Whitney Test Results for log transformed bailer transmissivity values and pump transmissivity values.

Mann-Whitney Test: Log Bailer (m^2/day), Log Pump (m^2/day)			
Log Bailer	N = 467	Median =	1.3899
Log Pump	N = 349	Median =	1.0365
Point estimate for ETA1-ETA2 is			0.3410
95.0 Percent CI for ETA1-ETA2 is (0.2442, 0.4304)			
W = 214636.0			
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0000			
The test is significant at 0.0000 (adjusted for ties), Statistically Different			

The removal of bailer data from all the test-hydrogeologic units eliminated most if not all of the transmissivity data for some units. After the removal of bailer test well data from the Archean Crystalline aquitard, Mission Canyon aquifer, Kootenai aquifer, Thermopolis-Mowry aquitard, Frontier aquifer, Telegraph Creek-Eagle aquifer, Sedan aquifer, Billman Creek aquitard, and Hopper-Fort Union aquifer, none of these units contained ten or more data points; therefore statistical comparisons of these units were not conducted. Therefore, the elimination of the bailer test data only allowed for statistical comparisons among the basin fill aquifers. Also, well data points in which the water removal method was unknown were removed from the database. The revised well datasets of the individual test-hydrogeologic units were adjusted to reflect the removal of the bailer method and unknown water removal method data prior to statistical analysis of the test-hydrogeologic units.

In a similar manner, the one-way ANOVA and Mann-Whitney tests were used to determine if significant differences exist between the test-hydrogeologic units of the GLWQD (Table 1 and Table 2). Connell and Bailey (1989) used a one-way ANOVA and Mann-Whitney analysis techniques to assess hydraulic conductivity and to determine statistically significant differences between juxtaposed hydrogeologic units at the Oak Ridge Reservation, Tennessee. Rizzo (1993) similarly used a one-way ANOVA and Mann-Whitney tests to compare the specific capacity and transmissivity of juxtaposed hydrogeologic units in the River Styx basin of Medina and Wayne Counties, Ohio. The statistical analysis of this study closely followed the procedures and criteria used by Connell and Bailey (1989).

The statistical tests were performed to determine if the initial groupings of test-hydrogeologic units are statistically unique and warranting distinct hydrogeologic units. The statistical analyses of the calculated transmissivity data was done between adjacent test-hydrogeologic unit and vertically juxtaposed stratigraphic units (with assumed similar depositional histories) (Figure 3, Table 1, and Table 2). Table 6 presents the pairings of test-hydrogeologic units that were statistically tested. In addition, these results are used to further refine the hydrogeologic column and hydrogeologic map of the GLWQD. Statistical comparisons between hydrogeologic units were only performed with units containing ten or more transmissivity values because of the high variability of the transmissivity values (Connell and Bailey, 1989). A discussion of the statistical analysis will be presented in Chapter 5.

Table 6: Test Hydrogeologic unit Comparisons conducted using the Mann-Whitney statistical test are indicated by an X. The shaded regions indicate duplicate comparisons.

Test Unit	Tb	QTal	Qwggd	Qwgal	Qlhal	Qlegal	Qegal	Qwggt	Qhf	Qaf	Qssval
Tb											
QTal	X										
Qwggd											
Qwgal			X								
Qlhal			X	X							
Qlegal			X								
Qegal	X		X	X		X					
Qwggt	X			X							
Qhf	X										
Qaf	X								X		
Qssval	X						X		X	X	

CHAPTER 4

RESULTS

Summary of Located Wells

A summary of the number of wells within the GLWQD is given in Table 7. The number of wells that could be located and ultimately digitized into the database is less than half of the total number of wells retrieved from the GWIC data base in August 1998. The distribution of the wells located as part of this study is shown on Plate 1. Only 22.2% of the 7253 wells in the GLWQD were accepted into the database.

Table 7. Summary of the number of well data points in the GLWQD.

Data Category	Number data points	Percent of Total Wells in GLWQD
Total Number of Wells in the GWIC database in 1998	7253	100%
Number of Non-perforated / Un-screened Wells	5317	73.3%
Number of Wells with Specific Capacity Data	3786	52.2%
Number of Wells with Known Location	3368	46.4%
Number of Located unscreened wells with specific capacity data	2522	34.8%
Number of pump and air test located unscreened wells with specific capacity data	1136	16%

Summary of Aquifer Test Analysis

Five single well aquifer tests were completed for this study. All tested wells except M:92206, were pumped for the full hour during the drawdown portion of the aquifer. Specific capacity was calculated for all of the tested wells after one hour of pumping, except M:92206 (Table 8). However, transmissivity could only be calculated for three of the five tested wells. Early termination at 15 minutes after the aquifer test because of drawdown to the pump intake at M:92206 resulted in insufficient data to calculate specific capacity after one hour of pumping. Extremely rapid recovery and limited drawdown at M:91730 resulted in insufficient data to calculate transmissivity for this well. Aquifer test data, including water level measurements, discharge measurements, and residual drawdown semi-log plots are included in Appendix A.

Table 8. Summary of the single well aquifer test data from wells tested during this study.

Well Number	Average Discharge	Maximum Drawdown	Recovery (minutes)	Specific Capacity	Transmissivity
M:9858	0.064 m^3/min 17 gpm	2.47 m 8.11 ft	Full recovery 39 minutes	0.026 m^3/min/m 2.1 gpm/ft	80 m^2/day 6400 gpd/ft
M:96581	0.07 m^3/min 18.4 gpm	6.4 m 21.01 ft	Full recovery 92 minutes	0.011 m^3/min/m 0.88 gpm/ft	48 m^2/day 3900 gpd/ft
M:92206†	0.062 m^3/min 16.3 gpm	36 m 118.15 ft	Partial recovery 54 minutes*	0.0017 m^3/min/m† 0.14 gpm/ft†	0.3 m^2/day 22 gpd/ft
M:128350	0.07 m^3/min 18.4 gpm	6.4 m 21.01 ft	Full recovery 57 minutes	0.034 m^3/min/m 2.8 gpm/ft	1,600 m^2/day 130,000 gpd/ft
M:91730	0.064 m^3/min 17 gpm	1.3 m 4.38 ft	Full recovery 2.8 minutes	0.048 m^3/min/m 3.9 gpm/ft	Insufficient data

† Specific Capacity calculated after only 15 minutes of pumping.
* Did not fully recover, 21.6 meters (71 feet) remaining when test was terminated.

Specific Capacity-Transmissivity Empirical Relationship

Several aquifer tests conducted during this study and previous studies were not included in the regression analysis because data was collected from screened or perforated wells or pumping times were not consistent with the one hour criteria (Table 9). Data from previous studies were not used if the well tested was constructed with a screened or perforated interval, or if the pumping duration was less than one (1) hour.

Table 9. Aquifer Test Data Sources used in the Regression Analysis

Source of Data	Number of aquifer test data points	Number of aquifer test data points used in the regression analysis
Bozeman Fan Sub-area (Custer et al., 1991)	45	33
Gallatin Valley (Valley-wide) (Hackett et al., 1960)	41	14
This Study (District-wide)	5	3
Total	91	50

The empirical relationship between specific capacity and transmissivity was determined by using specific capacity and transmissivity data pairs from the same well from select data collected from the field-tested wells of this study and wells tested during previous studies (Hackett et al., 1960; Custer et al., 1991) (Table 10). Log transformations were applied to the observed specific capacity and transmissivity data (Custer et al., 1991, Razack and Huntley, 1991; Huntley et al., 1992; Jalludina and Razack, 1994; Mace, 1997). The log transformed transmissivity values were plotted as a function of log transformed specific capacity values using the X-Y scatter plot. The best-fit line to the 50 data points is:

$$\text{Log T} = 1.3562(\text{Log Q/s}) + 3.5209 \quad (2)$$

Where log T = transmissivity expressed in m^2/day and log Q/s (specific capacity) is in (m^2/min) (Figure 16). The coefficient of determination, R^2, is 0.749.

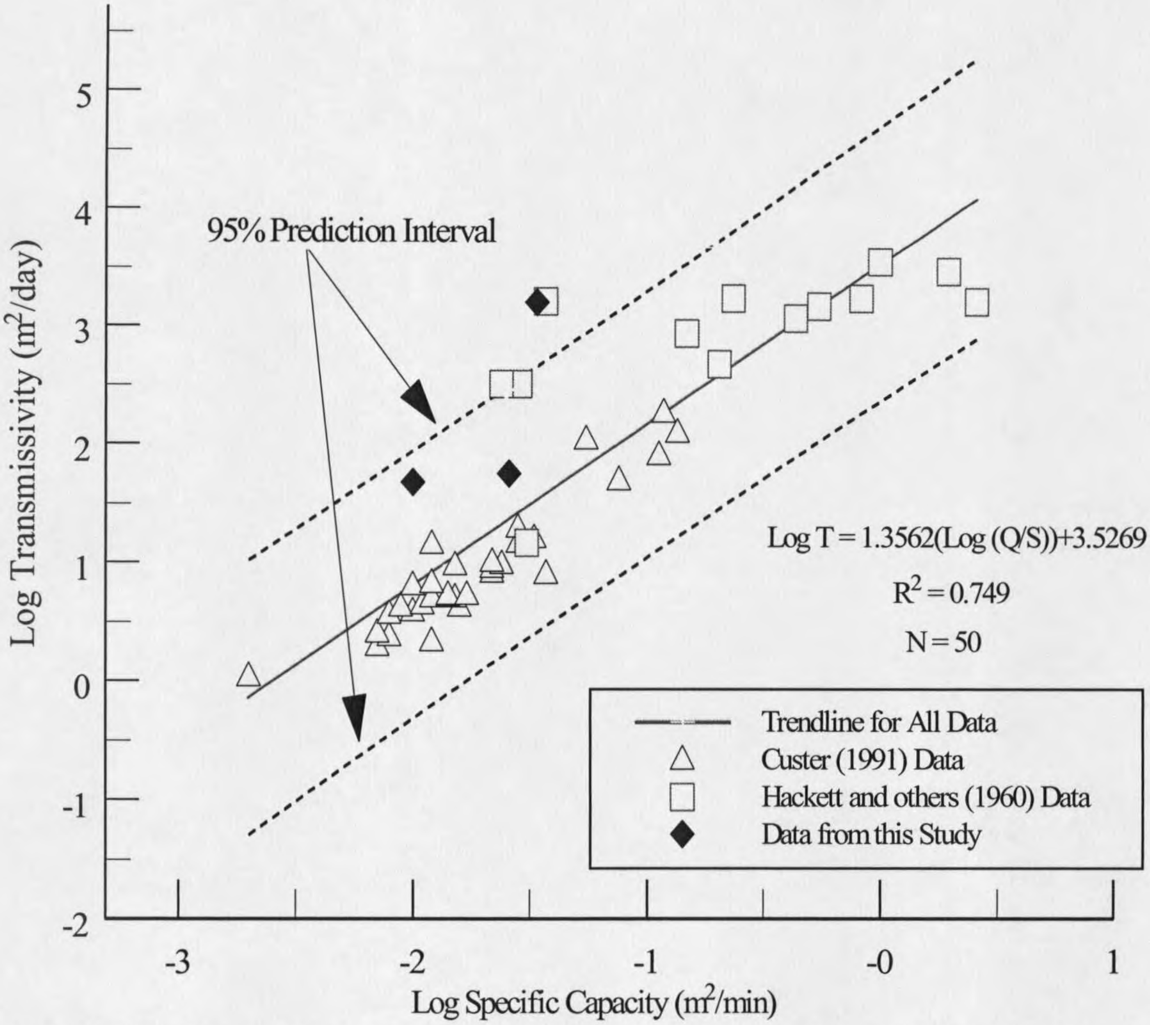

Figure 18. Plot of log transmissivity versus log specific capacity for the Gallatin Local Water Quality District with fitted regression lines (Drawdown taken at 1 hour after pumping began).

The coefficient of determination, R^2, is 0.749 indicating that the linear regression model explains approximately 75% of the variance in the data. The remaining unexplained variance is the result of several factors. The specific capacity data used in the regression analysis may not be an equilibrium specific capacity, since only a one hour pumping time was used. Well efficiency influences drawdown in a pumping well thereby influencing the resultant specific capacity value. Although, the efficiency of each well used in the regression analysis is expected to be low, well efficiency does vary from well to well thus introducing uncontrollable variance. Also, the pumping rates used to test the wells in the regression analysis are not all the same. Specific capacity is influenced by variations in pumping rate.

Table 10: Specific capacity-transmissivity data pairs used in regression analysis. Numeric well numbers from Custer and others (1991); alphanumeric well numbers from Hackett and others (1960), and M: numbers are from this study. Data ranked by transmissivity value within test-hydrogeologic unit.

Well Number	Specific Capacity		Transmissivity)		Test-hydrogeologic unit
	(m^3/min)/m)	(gpm/ft)	(m^2/day)	(gpd/ft)	
d2-4-26dc	0.20	16.04	4700	380,000	West Gallatin alluvium aquifer (Qwgal)
a1-3-22da2	0.55	44.12	1,500	120,000	West Gallatin gravel terrace aquifer (Qwggt)
a1-3-10bd	0.24	19.05	1,700	140,000	
d2-4-9bc	0.03	2.51	14.88	1,200	Bozeman Group aquifer (Tb)
M:96581	0.01	0.81	48	3,900	
M:128350	0.034	2.8	1,600	130,000	Lower Hyalite Creek alluvial aquifer (Qlhal)
332	0.002	0.16	1.1	89	Basin-fan aquifer (Qaf)
391.5	0.007	0.56	2.0	160	
433	0.012	0.97	2.2	180	
360	0.008	0.65	2.4	190	
282	0.007	0.56	2.6	210	
390	0.007	0.56	2.6	210	
283	0.008	0.65	3.7	300	
398	0.01	0.81	3.9	310	
366	0.009	0.73	4.3	350	
442	0.016	1.29	4.3	350	
543	0.011	0.89	4.5	360	
493	0.015	1.21	5.1	410	
238	0.014	1.13	5.3	430	
542	0.01	0.81	6.4	520	
547	0.022	1.77	8.4	680	
368	0.024	1.94	9.8	790	
544	0.012	0.97	14.4	1,200	
255	0.028	2.26	20	1,600	
509	0.076	6.13	50.5	4,100	
M:9858	0.03	2.10	56	4,500	
d2-5- 15aa1	0.02	1.94	322.4	26,000	
a1-5-26cd	0.03	2.31	322.4	30,000	
d1-5-26da	0.15	12.03	870	70,000	

Table 10 (Continued): Specific capacity-transmissivity data pairs used in regression analysis. Numeric well numbers from Custer and others (1991); alphanumeric well numbers from Hackett and others (1960), and M: numbers are from this study. Data ranked by transmissivity value within test-hydrogeologic unit.

Well Number	Specific Capacity (m^3/min)/m)	(gpm/ft)	Transmissivity) (m^2/day)	(gpd/ft)	Test-hydrogeologic unit
172	0.012	0.97	5.1	410	Hyalite alluvial fan aquifer (Qhf)
226	0.014	1.13	5.4	440	
231	0.017	1.37	5.4	440	
13	0.012	0.97	6.8	550	
186	0.037	2.98	8.2	660	
123	0.022	1.77	9.1	730	
219	0.015	1.21	9.6	770	
197	0.022	1.77	10.3	830	
170	0.03	2.26	14.7	1,200	
105	0.033	2.66	16.2	1,300	
165	0.11	9.11	80.7	6,500	
132	0.055	4.44	109.9	8,900	
77	0.14	10.89	126.3	10,000	
120	0.12	9.52	187	15,000	
d2-4-14bb	0.20	16.52	483.6	39,000	West Gallatin gravel deposit aquifer (Qwggd)
d1-4-15ab	0.44	35.58	1,200	94,000	
d1-5-5ad	0.04	3.01	1,600	130,000	
d1-4-2dd	2.57	207.24	1,600	130,000	
d1-4-9cb	0.84	67.75	1,700	140,000	
d1-4-1dc	1.96	158.01	3,000	240,000	
d1-5-30cb	1.01	81.48	3,600	290,000	

Calculation of Transmissivity for the hydrogeologic units

The individual values of transmissivity calculated for each located well within the test-hydrogeologic units of the GLWQD Equation (2) is presented in Appendix B. The mean, median, mode, standard deviation, and standard error of the mean computed from the log transformed transmissivity values of the test- hydrogeologic units are presented in Table 11. Table 11 presents the results for wells with data collected by pump test and air test methods only. The bailer test data and those data points in which water removal method could not be determined have been purged from the database.

Table 11. Descriptive statistics of the log transformed transmissivity values for the test-hydrogeologic units with only pump and air driller test data.

Hydrogeologic Unit	Number of observations		Geometric Mean	Geometric Median	Geometric Mode	Geometric Mean ± 1 Standard Deviation	Geometric Mean ± 1 Standard Error
QTal Old alluvium aquifer	65	m^2/day	3.4	4.0	12	0.72-16	2.7-4.1
		gpd/ft	270	320	970	58-1,300	220-330
Tb Bozeman Group aquifer	33	m^2/day	3.5	3.7	0.87	0.8-15	2.7-4.6
		gpd/ft	280	300	70	65-1200	220-370
Tv Volcanic aquitard	0	m^2/day	*	*	*	*	*
		gpd/ft	*	*	*	*	*
KThf Hoppers-Fort Union aquifer	8	m^2/day	0.94	0.88	19	0.07-13	0.37-2.4
		gpd/ft	75	71	1500	5.4-1100	30-190
Kbc Billman Creek aquitard	3	m^2/day	1.7	0.92	N/A	0.07-41	0.27-11
		gpd/ft	140	74	N/A	5.7-3300	22-860
Ks Sedan aquifer	4	m^2/day	4.7	1.8	N/A	0.27-81	1.1-20
		gpd/ft	380	150	N/A	22-6500	90-1600
Kte Telegraph Creek-Eagle aquifer*	0	m^2/day	*	*	*	*	*
		gpd/ft	*	*	*	*	*
Kc Cody aquitard*	0	m^2/day	*	*	*	*	*
		gpd/ft	*	*	*	*	*
Kf Frontier aquifer*	1	7.1 m^2/day					
		570 gpd/ft					
Ktm Thermopolis-Mowry aquitard	2	m^2/day	0.2	0.2	N/A	0.045-1	0.07-0.63
		gpd/ft	17	17	N/A	3.6-80	5.7-52
Kk Kootenai aquifer*	0	m^2/day	*	*	*	*	*
		gpd/ft	*	*	*	*	*
Ju Jurassic aquitard*	0	m^2/day	*	*	*	*	*
		gpd/ft	*	*	*	*	*
MPu Upper Mississippian-Permian Aquitard*	0	m^2/day	*	*	*	*	*
		gpd/ft	*	*	*	*	*
Mmm Mission Canyon aquifer*	0	m^2/day	*	*	*	*	*
		gpd/ft	*	*	*	*	*
CDlM Cambrian, Devonian, and Lower Mississippian aquitard*	0	m^2/day	*	*	*	*	*
		gpd/ft	*	*	*	*	*
Yl Lahood aquitard*	0	m^2/day	*	*	*	*	*
		gpd/ft	*	*	*	*	*
Am Crystalline aquitard	4	m^2/day	1.7	1.5	N/A	0.5-5.6	0.9-3.1
		gpd/ft	130	120	N/A	40-450	74-250

Table 11 (Continued). Descriptive statistics of the log transformed transmissivity values for the test-hydrogeologic units with only pump and air driller test data. Asterisk, *, indicates sample number insufficient for calculations.

Hydrogeologic Unit	Number of observations		Geometric Mean	Geometric Median	Geometric Mode	Geometric Mean ± 1 Standard Deviation	Geometric Mean ± 1 Standard Error
Qssval Small Valley Stream alluvium aquifer	29	m^2/day	9.4	8.0	3.1	3.6-24	7.9-11
		gpd/ft	760	640	250	290-1,900	630-900
Qaf Quaternary Basin-Fan aquifer	253	m^2/day	8.7	8.8	8.0	3.3-23	660-750
		gpd/ft	700	710	650	270-1,900	660-750
Qhf Hyalite alluvial fan aquifer	152	m^2/day	7.3	6.9	6.2	3.4-15	6.8-7.7
		gpd/ft	590	560	500	270-1,200	550-620
Qwggt West Gallatin Gravel Terrace aquifer	74	m^2/day	20	13	7.1	5.0-80	17-24
		gpd/ft	1,600	1,000	570	400-6,500	1,400-1,900
Qegal East Gallatin alluvium aquifer	79	m^2/day	10	11	11	3.7-29	9.1-11
		gpd/ft	810	890	890	300-2,300	730-890
Qlegal Lower East Gallatin alluvium aquifer	69	m^2/day	16	13	4.2	6.0-44	14-18
		gpd/ft	1,300	1,100	340	480-3,600	1,100-1,500
Qlhal Lower Hyalite Creek alluvium aquifer	48	m^2/day	22	21	28	9.7-50	20-25
		gpd/ft	1,800	1,700	2,300	780-4,000	1,600-2,000
Qwggd West Gallatin gravel deposit aquifer	278	m^2/day	16	14	8	5.3-46	15-17
		gpd/ft	1,300	1,100	650	430-3,700	1,200-1,400
Qwgal West Gallatin alluvial aquifer	55	m^2/day	20	19	6.3	5.9-68	16-25
		gpd/ft	1,600	1,500	500	470-5,400	1,300-2,000

CHAPTER 5

DISCUSSION

Aquifer Tests

Transmissivity was calculated from three of the five single well aquifer tests conducted during this study. Reasonable estimates of transmissivity were obtained from tests at wells M:9858, M:98581, and M:128350. The transmissivity values calculated from each of these unscreened or non-perforated wells are within the expected ranges of transmissivity values for the units in which they are completed. The ranges of transmissivity values presented for comparison are based on aquifer tests using screened and/or multiple wells (Table 12).

Table 12. Comparison of Transmissivity values calculated from aquifer tests conducted during this study and published ranges of transmissivity values.

Well Number	Transmissivity data (this study)	Test-hydrogeologic units	Range of transmissivity values (Hackett et al., 1960)	Subarea from (Hackett et al., 1960)
M:9858	80 m^2/day 6400 gpd/ft	Basin-fan aquifer	87 m^2/day to 372 m^2/day 7,000 gpd/ft to 30,000 gpd/ft	Springhill Subarea
M:96581	48 m^2/day 3900 gpd/ft	Bozeman Group aquifer	3.7 m^2/day to 33 m^2/day 300 gpd/ft to 2,700 gpd/ft	Bozeman Fan (Tertiary Strata)
M:128350	1,600 m^2/day 130,000 gpd/ft	Lower Hyalite Creek alluvial aquifer	621 m^2/day to 8,322 gpd/ft 50,000 gpd/ft to 670,000 gpd/ft	Belgrade Subarea

Transmissivity was not able to be calculated from the recovery data from M:91730 because of extremely rapid recovery of water level after the pump was shut off. Extremely rapid recovery caused problems in calculating transmissivity for M:91730, because the step-like shape of the residual drawdown curve made traditional analysis of the recovery data using the Cooper-Jacob method impossible. Determination of the slope of the data and to calculate transmissivity using the Cooper-Jacob method was impossible because the line drawn through the limited late time recovery data resulted in a horizontal line. This indicated that the transmissivity is extremely high in the lower Hyalite Creek alluvium aquifer, probably greater than 1250 m^2/day (100,000 gpd/ft).

Transmissivity was also calculated from an aquifer test that was conducted in the Billman Creek Formation using well M:92206. However, this test was terminated 15 minutes into the drawdown phase of the test because the water level had dropped to the level of the pump intake. The pump was allowed to shut off and recovery measurements were collected, although the recovery phase of the test was terminated early as well. The recover transmissivity value calculated from the limited recovery data is 0.3 m^2/day (22 gpd/ft). Specific capacity was also calculated for M:92206. However, since drawdown was not measured for one hour, the calculated specific capacity does not meet the criteria set earlier to use in the derivation of the specific capacity and transmissivity empirical relationship. The specific capacity was calculated to compare with specific capacity values calculated by Moore (1984) using drawdown data from 15 to 20 minutes after the pump started in Billman Creek Formation. The specific capacity calculated for M:92206 is 0.0017 m^3/s/m (0.14 gpm/ft) compared to 0.000035 to 0.0012 m^3/s/m (0.17 to 5.88 gpm/ft) as calculated by Moore (1984).

Comparison of the GLWQD Empirical Relationship

The empirical relationship developed for the GLWQD to relate transmissivity to specific capacity was compared with the empirical relationships of Razack and Huntley (1991), Huntley and others (1992), and Mace (1997) (Table 10). The comparison was done by plotting all of the empirical relationships of Razack and Huntley (1991), Huntley and others (1992), and Mace (1997) on the same graph as the empirical relationship derived for the GLWQD. All of the empirical equations have high coefficients of determination, R^2, above 0.60. The R^2 for the Mace (1997) and Huntley and others (1992) equations is 0.89, while the Razack and Huntley (1991) equation had an R^2 of 0.63. The empirical relationship derived for the GLWQD using unscreened wells differs slightly from other empirical equation presented in the literature (Figure 19).

The differences in the empirical equations of the various author(s) may be due to differences in well construction methods, pumping time, pumping rate, and type of aquifer. Wells used to develop the Mace (1997) and Huntley and others (1992) equations are typically open hole completions in karst and fractured granite aquifers, respectively. The differences between the Razack and Huntley (1991) and the GLWQD equation reflect differences in drilling and well installation, test practices between the two regions and pumping time of the tested wells. Screened wells pumped for 24 hours in a heterogeneous aquifer were used to develop the empirical relationship of Razack and Huntley (1991) for the Haouz Plain in Morocco. Screened wells increase well efficiency thereby increasing the specific capacity. Specific capacity-transmissivity relationships for different areas are expected to be different because of the variability introduced by the numerous drillers within a specific area. Since, specific capacity is controlled by well efficiency and the transmissivity of the aquifer, the variability in aquifer material will be reflected in the transmissivity value. If the test procedures are controlled, in the case of driller aquifer tests, the tests can be used to assess the aquifer.

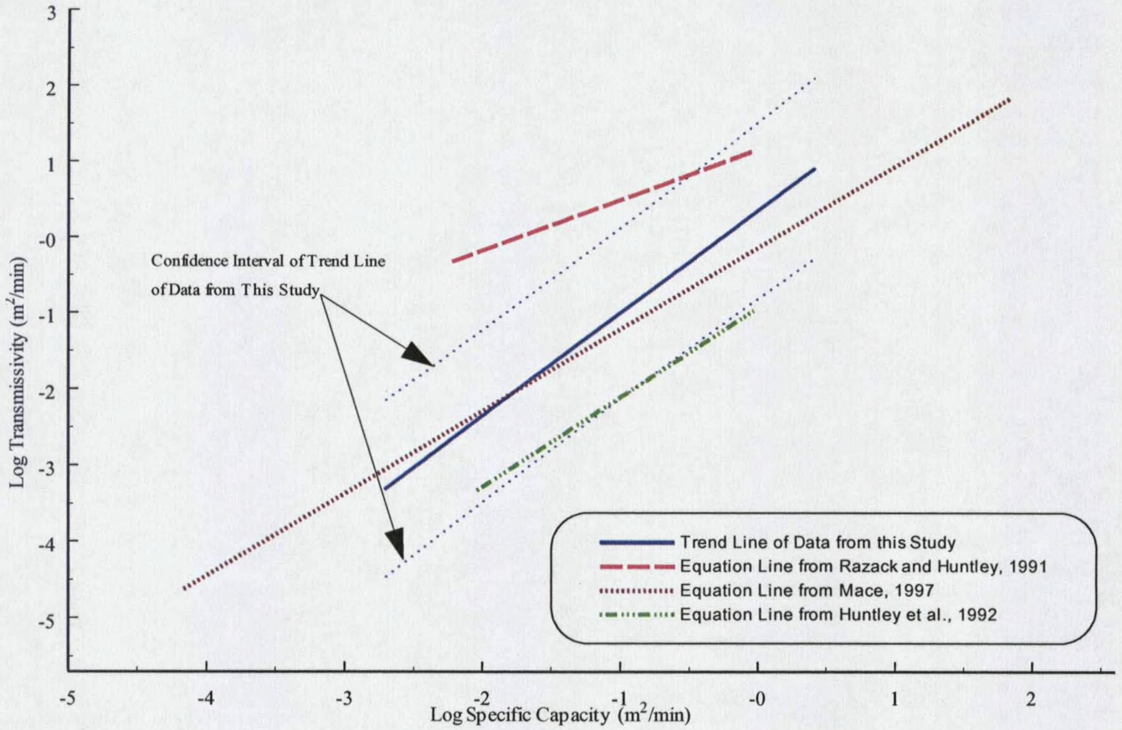

Figure 19. Comparison of empirical equations of Razack and Huntley (1991), Huntley and others (1992), Mace (1997), and this study. Note the similarity of the equations.

<u>Summary of statistical analysis of hydrogeologic units</u>

A one-way analysis of variance (ANOVA) was used to test if differences exist between the means of all of test-hydrogeologic units with 10 or more transmissivity values that did not contain bailer test data. The result of the one-way analysis of variance between all of the test-hydrogeologic units is summarized in Figure 20. The one way

ANOVA indicates three distinct groupings of test-hydrogeologic units with similar transmissivity populations.

```
Analysis of Variance
Source      DF        SS        MS         F        P
Factor      10    52.661     5.266     24.50    0.000
Error     1101   236.680     0.215
Total     1111   289.342
                                     Individual 95% CIs For Mean
                                     Based on Pooled StDev
Level        N      Mean     StDev   --------+---------+---------+--------
Qlhal       48    1.3415    0.3547                              (----*---)
Qwgal       32    1.3022    0.5283                             (----*-----)
Qwggd      278    1.1918    0.4673                             (-*-)
Qwggt       74    1.3031    0.6017                               (--*---)
Qlegal      69    1.2095    0.4378                            (--*---)
Qegal       79    1.0100    0.4475                      (---*--)
Qssval      29    0.9722    0.4115                   (----*-----)
Qaf        253    0.9401    0.4179                     (-*-)
Qhf        152    0.8615    0.3244                  (--*-)
QTal        65    0.5271    0.6718     (---*--)
Tb          33    0.5476    0.6382    (----*-----)
                                     --------+---------+---------+--------
Pooled StDev =    0.4636                  0.60      0.90      1.20
```

Figure 20. One Way Analysis of Variance test results for all of the test-hydrogeologic units. Transmissivity data for all of the units has been log transformed.

The one way ANOVA test indicated that there are at least three distinct groups of hydrogeologic units. Mann-Whitney statistical tests were performed on stratigraphically juxtaposed and spatially-located nearest neighbor hydrogeologic units to determine their statistical relationship (Table 6). This was done as an independent check of the one way ANOVA and to test the previously presented hypotheses about the various test-hydrogeologic units. The results of the Mann-Whitney tests on the test-hydrogeologic units are summarized in Table 13 and discussed in the remaining paragraphs of this section. The Mann-Whitney test significance values for the test-hydrogeologic units are presented in Table 13. Mann-Whitney test significance values greater than 0.05 indicate that the null hypothesis, which states that the two units are similar, is accepted. However, Mann-Whitney test significance values less than 0.05 indicate that the null hypothesis is rejected and the two units are to remain separate.

Table 13. Summary of the results of the Mann-Whitney statistical tests. The Mann-Whitney test statistic is given for each pair of tested hydrogeologic units. The Mann-Whitney test statistic for test-hydrogeologic units that are statistically similar (greater than 0.05) is colored red. An uncolored Mann-Whitney test statistic indicates that the two test-hydrogeologic units are not statistically similar.

Test Unit	Tb	QTal	Qwggd	Qwgal	Qlhal	Qlegal	Qegal	Qwggt	Qhf	Qaf	Qssval
Tb											
QTal	0.834										
Qwggd											
Qwgal			0.095								
Qlhal			0.003	0.825							
Qlegal			0.870								
Qegal	0.000		0.002	0.001		0.012					
Qwggt	0.000			0.535							
Qhf	0.000										
Qaf	0.000								0.013		
Qssval	0.001						0.282		0.243	0.899	

Shaded regions indicate duplicate comparisons

The Mann-Whitney test for East Gallatin alluvium aquifer and Bozeman Group aquifer is significant at 0.0000, which is less than alpha = 0.05. The null hypothesis which states that the two units are similar is rejected. This indicates that East Gallatin alluvium aquifer and the Bozeman Group aquifer are statistically different at a confidence interval of 95% and should remain as separate units (Table 14).

Hyalite alluvial fan aquifer and the Bozeman Group aquifer were compared to test the difference between the transmissivity values for the two units. Custer and others (1991) mapped and described the Hyalite alluvial fan as a northward thinning alluvial fan emanating from Hyalite Creek, overlying probable Tertiary aged sediments. The Mann-

Whitney test between the Hyalite alluvial fan aquifer and the Bozeman Group aquifer is significant at 0.0001, which is less than alpha = 0.05 (Table 15). Therefore, the null hypothesis is rejected and the separate grouping of Hyalite alluvial fan aquifer and Bozeman Group aquifer is valid at a 95% confidence interval.

Table 14. Mann-Whitney Test Results for log transformed Qegal and Tb.

Mann-Whitney Test: Log Qegal (m^2/day), Log Tb (m^2/day)
Log Tb N = 33 Median = 0.5730
Log Qegal N = 79 Median = 1.0370
Point estimate for ETA1-ETA2 is -0.5130
95.0 Percent CI for ETA1-ETA2 is (-0.7500, -0.3139)
W = 1191.5
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0000
The test is significant at 0.0000 (adjusted for ties)

Table 15. Mann-Whitney Test Results for log transformed Qhf and Tb transmissivity values.

Mann-Whitney Test: Log Qhf (m^2/day), Log Tb (m^2/day)
Log Tb N = 33 Median = 0.5730
Log Qhf N = 152 Median = 0.8400
Point estimate for ETA1-ETA2 is -0.3900
95.0 Percent CI for ETA1-ETA2 is (-0.5981,-0.1939)
W = 2008.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0001
The test is significant at 0.0001 (adjusted for ties)

The Bozeman Group aquifer was compared to the basin-fan aquifer to test whether the two units are statistically different based on their transmissivity populations. The basin-fan aquifer includes the lower portion of Hackett and others (1960) Bozeman Fan Subarea that was interpreted as possible Tertiary aged sediments by Nichols (1989) and Custer and others (1991) based on seismic refraction data. The Mann-Whitney test of the Bozeman Group aquifer and the basin-fan aquifer is significant at 0.0000, which is less than alpha = 0.05. Therefore, the null hypothesis that the Bozeman Group aquifer and the basin-fan aquifer were similar is rejected. The units are statistically different at a confidence interval of 95% (alpha = 0.05) (Table 16). Therefore, Bozeman Group and basin fan aquifer are to remain separate units.

Table 16. Mann-Whitney Test Results for log transformed Qaf and Tb.

Mann-Whitney Test: Log Qaf (m^2/day), Log Tb (m^2/day)
Log Tb N = 33 Median = 0.5730
Log Qaf N = 253 Median = 0.9450
Point estimate for ETA1-ETA2 is -0.4560
95.0 Percent CI for ETA1-ETA2 is (-0.6631,-0.2621)
W = 2781.5
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0000
The test is significant at 0.0000 (adjusted for ties)

The lack of similarity between the Bozeman Group aquifer and basin-fan aquifer, which includes the lower portion of the Bozeman Fan of Hackett and others (1960) was an unexpected outcome. The Bozeman Group aquifer and the basin-fan aquifer were originally expected to be similar based on seismic refraction data from the Bozeman Fan area presented by Nichols (1989) and Custer and others (1991). The seismic refraction data indicated that the seismic velocities measured from the lower portion of the Bozeman Fan were similar to that of Tertiary aged sediments. However, the two units are not similar based on statistical analysis of the calculated transmissivity values. The Bozeman Group aquifer has an overall lower range of transmissivity values than the basin-fan aquifer, which may be the result of more fine grained deposits within the Bozeman Group sediments.

The Mann-Whitney test between Bozeman Group aquifer and old alluvium aquifer is significant at 0.8362, which is greater than alpha = 0.05. Therefore, the null hypothesis cannot be rejected, thus indicating that the Bozeman Group aquifer and old alluvium aquifer are not statistically different units at a confidence interval of 95% (Table 17). Bozeman Group aquifer and old alluvium aquifer may therefore be combined into one hydrogeologic unit.

Table 17. Mann-Whitney Test Results for log transformed QTal and Tb.

Mann-Whitney Test: Log QTal (m^2/day), Log Tb (m^2/day)			
Log Tb	N = 33	Median =	0.5730
Log QTal	N = 65	Median =	0.6030
Point estimate for ETA1-ETA2 is			-0.0240
95.0 Percent CI for ETA1-ETA2 is (-0.3051, 0.2519)			
W = 1605.5			
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.8362			
The test is significant at 0.8362 (adjusted for ties)			
Cannot reject alpha = 0.05			

The Bozeman Group aquifer and the small valley stream alluvium aquifer were compared statistically to determine if significant differences exist between the transmissivity values for the two groups. The Mann-Whitney test for Bozeman Group aquifer and small valley stream alluvium aquifer is significant at 0.0016; which is less than alpha = 0.05, and therefore the null hypothesis that the two units are similar is rejected. This indicates that Bozeman Group aquifer and small valley stream alluvium aquifer are statistically different units at a confidence interval of 95% and should remain as separate units (Table 18).

Table 18. Mann-Whitney Test Results for log transformed Qssval and Tb.

Mann-Whitney Test: Log Qssval (m^2/day), Log Tb (m^2/day)
Log Tb N = 33 Median = 0.5730
Log Qssval N = 29 Median = 0.9050
Point estimate for ETA1-ETA2 is -0.4720
95.0 Percent CI for ETA1-ETA2 is (-0.7530, -0.1990)
W = 800.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0016
The test is significant at 0.0016 (adjusted for ties)

A Mann-Whitney statistical test was used to determine if there are significant differences in the transmissivity values between the West Gallatin gravel terrace aquifer and the Bozeman Group aquifer. One interpretation of the West Gallatin gravel terrace aquifer is that it is deposited on a cut surface with very thin gravelly deposits overlying sediments of the Bozeman Group. If this is the case, then wells drilled into the West Gallatin gravel terrace aquifer are actually producing from the underlying Bozeman Group sediments and the transmissivity values of the two units should be similar. However, the Mann-Whitney test of the Bozeman Group aquifer and West Gallatin gravel terrace aquifer is significant at 0.0000; and therefore, the two units are not similar with respect to calculated transmissivity values at a confidence interval of 95% and should remain as separate units (Table 19). The results of the statistical analysis indicate that the idea of wells in the West Gallatin gravel terrace aquifer producing from the underlying Bozeman Group is invalid.

The West Gallatin gravel terrace aquifer was also compared to the West Gallatin alluvium aquifer to test if differences exist between the two units, because the other interpretation of the West Gallatin gravel terrace deposits is that it represents a fill terrace (Figure 5A). The Mann-Whitney test of West Gallatin gravel terrace aquifer and West

Gallatin alluvium aquifer is significant at 0.537; which is greater than alpha = 0.05. Therefore, the null hypothesis cannot be rejected which indicates that the units are statistically similar at a confidence interval of 95% and can be combined into a single hydrogeologic unit (Table 20). The deposits of these two units should be similar in grain size and deposit architecture, because they are both products of the same fluvial system.

Table 19. Mann-Whitney Test Results for log transformed Qwggt and Tb.

Mann-Whitney Test: Log Qwggt (m^2/day), Log Tb (m^2/day)		
Log Tb	N = 33	Median = 0.5730
Log Qwggt	N = 74	Median = 1.1290
Point estimate for ETA1-ETA2 is -0.7885		
95.0 Percent CI for ETA1-ETA2 is (-1.0009,-0.5419)		
W = 982.0		
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0000		
The test is significant at 0.0000 (adjusted for ties)		

Table 20. Mann-Whitney Test Results for log transformed Qwggt and Qwgal.

Mann-Whitney Test: Log Qwggt (m^2/day), Log Qwgal (m^2/day)		
Log Qwggt	N = 32	Median = 1.2900
Log Qwgal	N = 74	Median = 1.1290
Point estimate for ETA1-ETA2 is 0.0765		
95.0 Percent CI for ETA1-ETA2 is (-0.1571, 0.2771)		
W = 1802.5		
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.5357		
The test is significant at 0.5356 (adjusted for ties)		
Cannot reject alpha = 0.05		

West Gallatin alluvium aquifer was also compared to several other hydrogeologic units, including the East Gallatin alluvium aquifer, West Gallatin gravel deposit aquifer, and the lower Hyalite Creek alluvium aquifer. Transmissivity values of the West Gallatin alluvium aquifer and the East Gallatin alluvium aquifer were statistically compared to test the hypothesis that the hydraulic properties of the deposits are not similar because of differences in drainage basin geology and size between the West Gallatin River and East Gallatin River. The Mann-Whitney test is significant at 0.0013, which is less than alpha = 0.05; therefore, West Gallatin alluvium aquifer and East Gallatin alluvium aquifer are statistically different at a confidence interval of 95% and should remain separate units (Table 21). The statistical analysis of the East Gallatin alluvium aquifer and the West Gallatin alluvium aquifer indicates that drainage basin size and geology may indeed affect the hydraulic properties of the deposits.

Table 21. Mann-Whitney Test Results for log transformed Qegal and Qwgal.

Mann-Whitney Test: Log Qegal (m^2/day), Log Qwgal (m^2/day)
Log Qegal N = 79 Median = 1.0370
Log Qwgal N = 32 Median = 1.2900
Point estimate for ETA1-ETA2 is -0.2990
95.0 Percent CI for ETA1-ETA2 is (-0.4790, -0.1151)
W = 3929.5
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0013
The test is significant at 0.0013 (adjusted for ties)

The Mann-Whitney test is significant at 0.0955 for the statistical analysis of West Gallatin gravel deposit aquifer and West Gallatin alluvium aquifer. This indicates that these two units are statistically similar at a confidence interval of 95% and are combined into a single hydrogeologic unit (Table 22). These deposits were deposited by the same fluvial system, however more than likely under different load and flow regimes. However, the deposits are similar and have statistically similar hydraulic properties. The West Gallatin gravel deposit aquifer is slightly topographically higher than the present day floodplain of the West Gallatin River. The West Gallatin gravel deposit has been suggested to be a glacial outwash deposit (S. Custer and W. Locke, personal communication). This interpretation is consistent with the findings of other regional studies in which glacial-outwash terraces stand higher than Holocene stream terraces and present day floodplains (Zelt et al., 1999).

Table 22. Mann-Whitney Test Results for log transformed Qwggd and Qwgal.

Mann-Whitney Test: Log Qwggd (m^2/day), Log Qwgal (m^2/day)
Log Qwgal N = 32 Median = 1.2900
Log Qwggd N = 278 Median = 1.1370
Point estimate for ETA1-ETA2 is 0.1450
95.0 Percent CI for ETA1-ETA2 is (-0.0240, 0.3020)
W = 5777.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0955
The test is significant at 0.0955 (adjusted for ties)
Can not reject at alpha = 0.05

The proximity of the lower Hyalite Creek alluvium aquifer and the West Gallatin alluvium aquifer was the reasoning behind statistical analysis of these units. The Mann-Whitney test for the lower Hyalite Creek alluvium aquifer and the West Gallatin alluvium aquifer is significant at 0.8251, which is greater than alpha = 0.05 indicating that the null hypothesis that the two units are similar cannot be rejected (Table 23). Therefore, these units are statistically indistinct at a confidence interval of 95% and are combined into one hydrogeologic unit.

The lower Hyalite Creek alluvium aquifer and the West Gallatin gravel deposit aquifer were statistically compared to test the hypothesis that the lower Hyalite Creek alluvium aquifer is a thin deposit and that wells completed in this unit are actually producing from gravelly deposits of the West Gallatin gravel deposit aquifer. The Mann-Whitney test for lower Hyalite Creek alluvium aquifer and West Gallatin alluvium aquifer is significant at

0.0039, which is less than alpha = 0.05 indicating that the null hypothesis can be rejected (Table 24). Although, the Mann-Whitney statistical test indicates that these two units are statistically different, the ANOVA analysis indicates some overlap in the transmissivity values of the units.

Table 23. Mann-Whitney Test Results for log transformed Qlhal and Qwgal.

Mann-Whitney Test: Log Qlhal (m^2/day), Log Qwgal (m^2/day)
Log Qlhal N = 48 Median = 1.3180
Log Qwgal N = 32 Median = 1.2900
Point estimate for ETA1-ETA2 is 0.0185
95.0 Percent CI for ETA1-ETA2 is (-0.1701, 0.2111)
W = 1967.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.8251
The test is significant at 0.8251 (adjusted for ties)
Cannot reject at alpha = 0.05

Table 24. Mann-Whitney Test Results for log transformed Qlhal and Qwggd.

Mann-Whitney Test: Log Qlhal (m^2/day), Log Qwggd (m^2/day)
Log Qlhal N = 48 Median = 1.3180
Log Qwggd N = 347 Median = 1.1370
Point estimate for ETA1-ETA2 is 0.1700
95.0 Percent CI for ETA1-ETA2 is (0.0550, 0.2740)
W = 11645.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0039
The test is significant at 0.0039 (adjusted for ties)

The two alluvial fan aquifers, basin-fan aquifer and Hyalite alluvial Fan aquifer, were also compared to small valley stream alluvium aquifer to test whether the transmissivity values of these deposits are similar. The hydraulic properties of these units are expected to be similar because the small valley stream alluvium is expected to be thin and or reworked alluvial fan deposits. The Mann-Whitney test of Hyalite alluvial fan aquifer and small valley stream alluvium aquifer is significant at 0.2436; therefore these units are statistically similar (at a 95% confidence interval) and can be combined into one hydrogeologic unit (Table 25). The Mann-Whitney test of basin fan aquifer and small valley stream aquifer is significant 0.5848; and likewise, these units are statistically similar (at a 95% confidence interval) and can be combined into on hydrogeologic unit (Table 26). The statistical analyses indicated that the Hyalite alluvial Fan aquifer and small valley stream alluvium aquifer are statistically indistinguishable from one another and that the basin-fan aquifer and small valley stream alluvium aquifer are also statistically indistinguishable from one another, thereby suggesting similarity in deposits of these units.

Table 25. Mann-Whitney Test Results for log transformed Qhf and Qssval.

Mann-Whitney Test: Log Qhf (m^2/day), Log Qssval (m^2/day)
Log Qhf N = 152 Median = 0.8400
Log Qssval N = 29 Median = 0.9050
Point estimate for ETA1-ETA2 is -0.0690
95.0 Percent CI for ETA1-ETA2 is (-0.1940, 0.0620)
W = 13530.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.2436
The test is significant at 0.2436 (adjusted for ties)
Cannot reject at alpha = 0.05

Table 26. Mann-Whitney Test Results for log transformed Qaf and Qssval.

Mann-Whitney Test: Log Qaf (m^2/day), Log Qssval (m^2/day)
Log Qaf N = 253 Median = 0.9450
Log Qssval N = 29 Median = 0.9050
Point estimate for ETA1-ETA2 is 0.0060
95.0 Percent CI for ETA1-ETA2 is (-0.1271,0.1401)
W = 35852.5
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.8996
The test is significant at 0.8996 (adjusted for ties)
Cannot reject at alpha = 0.05

The basin-fan aquifer was expected to be similar to the Bozeman Group aquifer; however the statistical comparison of the two units did not support this idea. The Hyalite alluvial fan aquifer and the basin-fan aquifer are thought to be separate units as well based on the work of Nichols (1989) and Custer and others (1991). Seismic refraction demonstrated that the Hyalite alluvial fan defined was distinguishable from the deposits north of the 5080 foot topographic line, which includes the basin-fan aquifer (Qaf) of this study (Nichols, 1989; Custer et al., 1991). Seismic velocities of the deposits north of Hyalite alluvial fan are similar to seismic velocities measured from Tertiary materials. The Mann-Whitney test of the basin-fan aquifer and the Hyalite alluvial fan aquifer is significant at 0.0136, which is less than alpha = 0.05, indicating that null hypothesis can be rejected (Table 27). The statistical analysis of the transmissivity values from two alluvial fan aquifers, Hyalite alluvial fan aquifer and basin-fan aquifer, indicates that these units are statistically different from one another at a confidence interval of 95%, and are thus hydraulically distinct units as suggested by Custer and others (1991).

Table 27. Mann-Whitney Test Results for log transformed Qhf and Qaf.

Mann-Whitney Test: Log Qhf (m^2/day), Log Qaf (m^2/day)		
Log Qhf	N = 152	Median = 0.8400
Log Qaf	N = 253	Median = 0.9450
Point estimate for ETA1-ETA2 is -0.0820		
95.0 Percent CI for ETA1-ETA2 is (-0.1450,-0.0170)		
W = 28040.5		
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0136		
The test is significant at 0.0136 (adjusted for ties)		

The results of the Hyalite alluvial fan aquifer and the basin-fan aquifer statistical analysis are paradoxical when viewed in conjunction with that of the previous statistical analyses of the small valley stream alluvium aquifer with the Hyalite alluvial fan aquifer and the basin-fan aquifer. (See ANOVA test results presented as Figure 18) The ANOVA test results show that the 95% confidence interval of the mean values of the Hyalite alluvial fan aquifer and the basin-fan aquifer overlap, therefore suggesting that similarity exists between the units. Also, both the Hyalite alluvial fan aquifer and the basin-fan aquifer are statistically indistinguishable at a 95% confidence interval from the small valley stream alluvium aquifer based on the Mann-Whitney test results. This suggests that the small valley stream alluvium aquifer, Hyalite alluvial fan aquifer, and small valley stream alluvium aquifer can be combined into a single hydrogeologic unit. Therefore, the basin-fan aquifer, the Hyalite alluvial fan aquifer, and the small valley stream alluvium aquifer are grouped as a single hydrogeologic unit based on (1) the overlap of the 95% confidence interval of the means of the basin-fan aquifer and the Hyalite alluvial fan aquifer, and (2) the results of the Mann-Whitney tests between both basin-fan aquifer and Hyalite alluvial fan aquifer and the small valley stream alluvium aquifer.

The lower East Gallatin alluvial aquifer and the West Gallatin gravel deposit aquifer were compared to test the idea that wells in lower East Gallatin alluvial aquifer are actually producing from deposits related to the West Gallatin gravel deposit aquifer. The alluvium of the lower East Gallatin alluvial aquifer is hypothesized to be the edge of the West Gallatin gravel deposit aquifer glacial (?) outwash deposits with a veneer of fine-grained material deposited by the modern East Gallatin River. The Mann-Whitney test for lower East Gallatin alluvium aquifer and West Gallatin gravel deposit aquifer is significant at 0.8706 indicating that the two units are statistically similar at the 95% confidence interval (Table 28). Based on the results of the statistical analysis, lower East Gallatin alluvium aquifer and West Gallatin gravel deposit aquifer are combined into a single hydrogeologic unit. The lack of statistical difference in the hydraulic properties of these two deposits helps support the idea that the deposits of the lower East Gallatin alluvium aquifer may be actually related to the West Gallatin gravel deposit.

Table 28. Mann-Whitney Test Results for log transformed Qlegal and Qwggd.

Mann-Whitney Test: Log Qlegal (m^2/day), Log Qwggd (m^2/day)
Log Qwggd N = 278 Median = 1.1370
Log Qlegal N = 69 Median = 1.1160
Point estimate for ETA1-ETA2 is -0.0070
95.0 Percent CI for ETA1-ETA2 is (-0.1080,0.0880)
W = 48250.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.8706
The test is significant at 0.8706 (adjusted for ties)
Cannot reject at alpha = 0.05

The transmissivity data of lower East Gallatin alluvium aquifer and East Gallatin alluvium aquifer were compared using the Mann-Whitney test. The comparison was done to evaluate the appropriateness of splitting the alluvial deposits of the East Gallatin River into two separate hydrogeologic units. The Mann-Whitney test for lower East Gallatin alluvium aquifer and East Gallatin alluvium aquifer is significant at 0.0112 (Table 29), which is less than the alpha of 0.05. As a result, the null hypothesis can be rejected at a 95% confidence interval. The sample population medians of lower East Gallatin alluvium aquifer and East Gallatin alluvium aquifer are statistically different and remain as individual hydrogeologic units.

Table 29. Mann-Whitney Test Results for log transformed Qlegal and Qwggd.

Mann-Whitney Test: Log Qlegal (m^2/day), Log Qwggd (m^2/day)
Log Qlegal N = 69 Median = 1.1160
Log Qegal N = 79 Median = 1.1160
Point estimate for ETA1-ETA2 is -0.1450
95.0 Percent CI for ETA1-ETA2 is (0.0310, 0.2720))
W = 5801.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0112
The test is significant at 0.01126 (adjusted for ties)

Summary of revision of hydrogeologic units

The collective results of the statistical analysis of the individual test-hydrogeologic units demonstrate that the original hydrogeologic unit designations (Table 1, Table 2, and Figure 3) need to be revised. West Gallatin alluvial aquifer (Qwgal), West Gallatin gravel terrace aquifer (Qwggt), lower Hyalite Creek alluvial aquifer (Qlhal), and West Gallatin gravel deposit aquifer (Qwggd) were determined to be statistically indistinguishable as shown in Figure 20 and Table 12; as a result, these units are combined into a single hydrogeologic unit classified as the West Gallatin alluvium aquifer, Qwgal (Figure 21, Plate 1, and Plate 2). The statistical analysis indicates that the transmissivity values of East Gallatin alluvium aquifer (Qegal), small valley stream aquifer (Qssval), basin-fan aquifer (Qaf), and Hyalite alluvial fan aquifer (Qhf) are statistically indistinguishable (Figure 20 and Table 12). Therefore, East Gallatin alluvium aquifer (Qegal), small valley stream aquifer (Qssval), basin-fan aquifer (Qaf), and Hyalite alluvial fan aquifer (Qhf) were combined into a hydrogeologic unit classified as small stream and fan aquifer, Qssf (Figure 21, Plate 1, and Plate 2). Old alluvium aquifer (Qtal) and the Bozeman Group aquifer (Tb) are not statistically different from each other; therefore they are grouped as one hydrogeologic unit and classified as the

Quaternary-Tertiary basin-fill aquifer, QTbf (Figure 21, Plate 1, and Plate 2). The revised hydrogeologic unit transmissivity values are presented in Table 30.

A one way ANOVA test was performed to verify that none of the newly grouped hydrogeologic units were statistically similar to one another (Figure 22). The results of the one way ANOVA clearly shows that the revised hydrogeologic units are distinct units. Box plots of the log transformed transmissivity data in m^2/day for newly revised hydrogeologic units with at least ten or more transmissivity values are presented in Figure 23. The box plots illustrate the range of the transmissivity values in each hydrogeologic unit. Although the ranges of values of hydrogeologic unit overlap each other, the median values are distinct for all of the units.

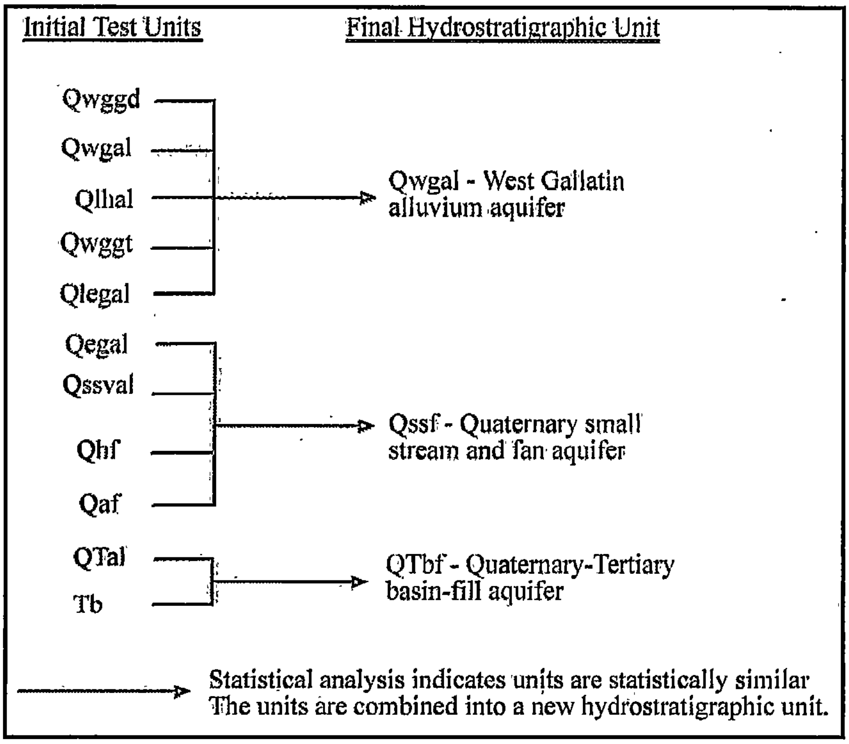

Figure 21. Flow chart of statistical test results and revised hydrogeologic units. Solid line connects units that are statistically similar to one another. The dashed line connects tested units that are statistically different from one another. (Table 13 shows test units that were not statistically similar).

Table 30. Descriptive statistics of the log transformed transmissivity values for the Hydrogeologic units of the GLWQD, Montana.

Hydrogeologic Unit	Number of observations		Geometric Mean	Geometric Median	Geometric Mode	Geometric Mean ± 1 Standard Deviation	Geometric Mean ± 1 Standard Error
Qwgal West Gallatin alluvium aquifer	501	m²/day	17	14	11	6.0-50	16-17
		gpd/ft	1300	1100	880	450-4000	1300-1400
Qssf Small Stream and Fan aquifer	515	m²/day	8.5	8.0	8.0	3.4-22	8.2-8.9
		gpd/ft	680	640	640	270-1,700	660-720
QTbf Quaternary-Tertiary Basin Fill aquifer	98	m²/day	3.4	3.9	4.0	0.75-16	2.9-4.0
		gpd/ft	270	310	320	60-1300	230-320

```
Analysis of Variance
Source     DF        SS        MS        F        P
Factor      2    49.545    24.773   114.34    0.000
Error    1111   240.713     0.217
Total    1113   290.258
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ---+---------+---------+---------+---
Qwgal     501    1.2321    0.4819                                 (*-)
Qssf      515    0.9317    0.4011                       (*-)
QTbf       98    0.5340    0.6574  (--*---)
                                   ---+---------+---------+---------+---
Pooled StDev =   0.4655              0.50      0.75      1.00      1.25
```

Figure 22. One Way Analysis of Variance test results for the revised hydrogeologic units using log transformed transmissivity data.

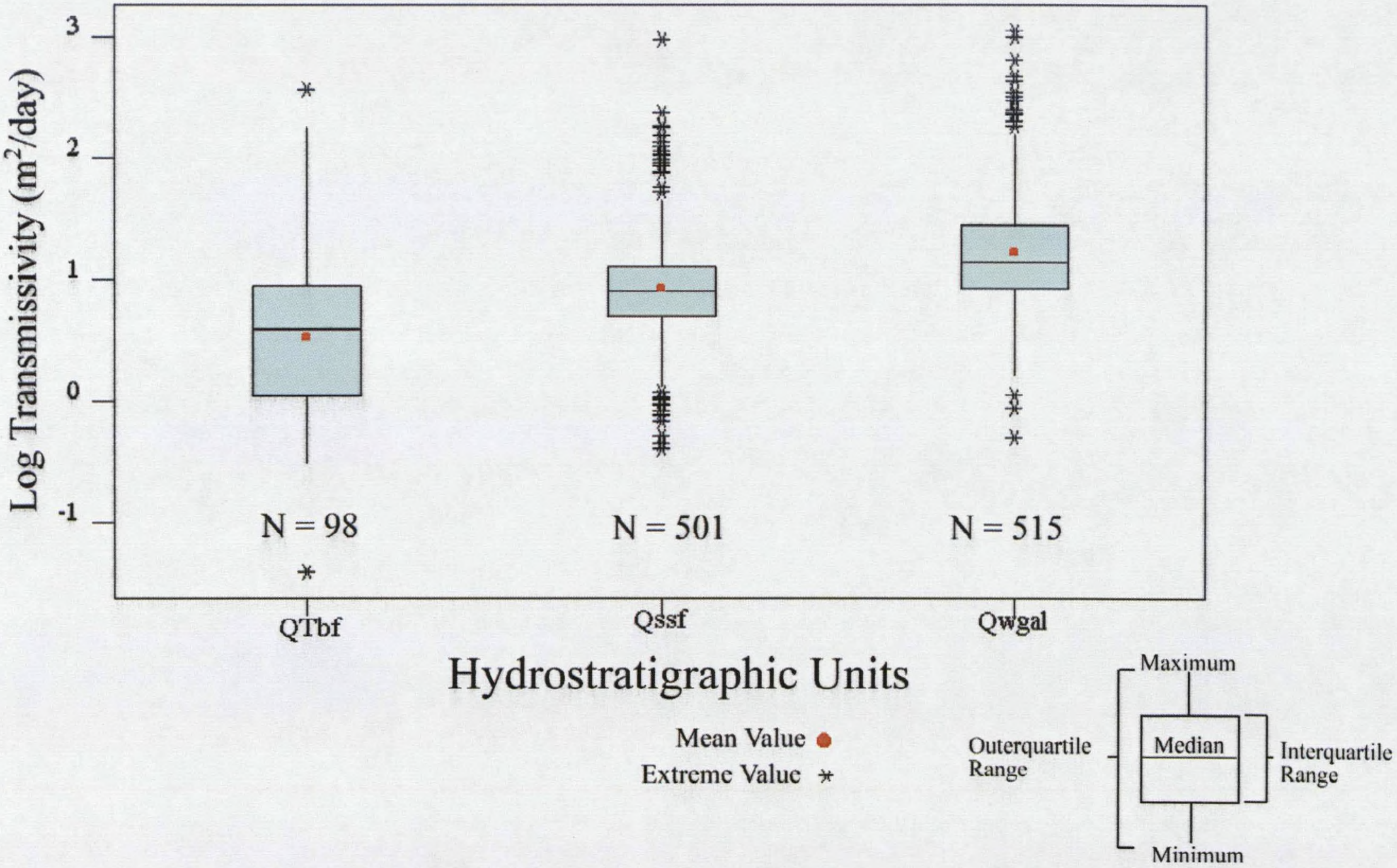

Figure 23. Box plot diagram of the hydrogeologic units of the GLWQD, Gallatin County, Montana with ten or more transmissivity values.

Calculated Transmissivity Values

The transmissivity values calculated from single well tests using unscreened or non-perforated wells produced values consistent with data presented in Hackett and others (1960) (Table 31). A comparison of the range of transmissivity values reported by Hackett and others (1960) for the Bozeman fan alluvium and Tertiary strata of the valley and Quaternary small stream and fan aquifer and Quaternary-Tertiary basin-fill aquifer indicated that the transmissivity values are quite similar to published values (Table 31). Comparison of the range of transmissivity values calculated for West Gallatin alluvium aquifer and the range of transmissivity values reported by Hackett and others (1960) for the Belgrade Subarea indicates that transmissivity values calculated for West Gallatin alluvium aquifer are approximately an order of magnitude lower (Table 31). This was not an entirely unexpected result.

The range of calculated transmissivity values for West Gallatin alluvium aquifer is lower than published values for several reasons. First, wells in high transmissivity units that are tested with low pumping rates produce zero drawdown. Therefore, specific capacity cannot be calculated from driller data at low pump rates, and thus the data does not make it into the dataset. Also, some of the aquifer tests conducted by Hackett and others (1960) were done using screened or perforated wells, whereas the wells used in this study were all unscreened or non-perforated. Well efficiency of unscreened or non-perforated wells is low, which causes increased drawdown in the well as compared to the water level in the aquifer and results in lower specific capacity values and lower calculated transmissivity. In high transmissivity aquifers, the approach used during this study will produce low results because of decreased well efficiency of the unscreened or non-perforated wells and because of short pumping times. The method used in this study should be used cautiously in high transmissivity units. The approach used here should also be used cautiously in low transmissivity units. In low transmissivity units, water is moving so slowly from the aquifer to the well that all of the drawdown measured in the well is related to casing storage.

Table 31. Comparison of ranges of transmissivity values calculated from the empirical equation derived for the GLWQD and published ranges of transmissivity values.

Hydrogeologic unit of this study	Range Transmissivity values calculated from empirical equation of this study	Range of Transmissivity Values from Hackett and others (1960)	Subarea from Hackett and others (1960)
West Gallatin alluvium aquifer (Qwgal)	0.5 m^2/day to 1,100 m^2/day 39 gpd/ft to 90,000 gpd/ft	621 m^2/day to 8,322 m^2/day 50,000 gpd/ft to 670,000 gpd/ft	Belgrade Subarea
Small stream and fan aquifer (Qssf)	0.4 m^2/day to 948 m^2/day 32 gpd/ft to 76,000 gpd/ft	56 m^2/day to 807 m^2/day 4,500 gpd/ft to 65,000 gpd/ft	Bozeman Fan (Alluvium)
Quaternary – Tertiary basin-fill aquifer (QTbf)	0.04 m^2/day to 370 m^2/day 3 gpd/ft to 30,000 gpd/ft	3.7 m^2/day to 320 m^2/day 300 gpd/ft to 26,000 gpd/ft	Valley wide Tertiary Strata

Furthermore, transmissivity values calculated using data from unscreened or non-perforated wells have been shown to be as much as two orders of magnitude lower than comparable screened wells because of extremely low well efficiency. The transmissivity value calculated from an aquifer test conducted using an unscreened or non-perforated well by Custer and others (1991) was approximately two orders of magnitude lower than the transmissivity value calculated from an aquifer test conducted using the same well after the installation of the well screen. This test may indicate that the expected difference in transmissivity or specific capacity values calculated from aquifer tests using unscreened or non-perforated wells will need to be adjusted upward. However, this remains to be tested outside of the single data point reported by Custer and others (1991).

There are some problems with shifting the transmissivity values or specific capacity values higher. The transmissivity values calculated from single well tests using unscreened or non-perforated wells produced values consistent with data presented in Hackett and others (1960) (Table 31). Also, the calculated transmissivity values for the Quaternary small stream and fan aquifer and Quaternary-Tertiary basin-fill aquifer are quite similar to published transmissivity values indicating that for lower to moderate yielding units the methods used during this study produce consistent and reasonable transmissivity values.

Custer and others (1991) estimated that the average well efficiency of unscreened or non-perforated wells to be less than 50%. Specific capacity is greatly affected by well efficiency. Therefore, if a major part of the drawdown in the pumping well is the result of well losses (well inefficiency), then the transmissivity based on specific capacity will be too small (Heath, 1998; Newcome, 1993).

There is some reason to accept the groupings based on these tests. Since, only one well type (unscreened or non-perforated) was used in this study, the variability introduced by different well construction techniques between individual wells has been eliminated. Therefore, the calculated transmissivity values for each of the units may be low by a relatively constant factor that represents well efficiency, lower pumping rates, and shorter pumping time. Furthermore, the variability in the aquifer materials is still reflected in the calculated transmissivity values regardless of the type of well tested because transmissivity is an aquifer property that is not dependent on well type, especially if calculated using recovery data as in the case of this study. The recovery method assumes that once a well is pumped and then shut off, the residual drawdown can be measured and considered to be the result of a recharge to the well at a discharge equal to the pumping rate from the aquifer material (Theis, 1935; Ferris et al., 1962; Fetter, 1994; Driscoll, 1986). Although the calculated transmissivity values may be lower than those calculated from aquifer test data conducted with screened and/or multiple wells, the hydrogeologic units of the GLWQD are still valid groupings of wells with similar hydraulic properties.

CHAPTER 6

CONCLUSIONS

Hydraulic properties of geologic units are needed to address groundwater quality and quantity issues. This project was undertaken to define the hydraulic parameters for distinct hydrogeologic units within the GLWQD by testing whether geologic units commonly thought to be different are statistically different based on the hydraulic parameters. Distinct hydrogeologic units were identified and characterized by using estimated transmissivity values calculated from driller reported specific capacity for the wells located within the GLWQD (Plate 1 and Plate 2).

The total number of wells in the GWIC database for the GLWQD in August 1998 was 7,253. However, only 46.4% (3,368 wells) of the wells could be located using a combination of well records, septic permit records, and county property records. Missing or incomplete location information was a major reason that only half of the total number of wells in the GLWQD could be located. This suggests that better reporting of location information is needed, because being able to properly locate data is just as important as the data itself (Custer et al., 1998). Also, only 52.2% (3,786 wells) of the total number of wells contained enough information to calculate specific capacity and ultimately transmissivity. Again the large number of unusable well data points indicates the need for better reporting of well test data.

Unscreened or non-perforated wells comprised 73.3% (5,316 wells) of the total number of wells within the GLWQD in 1998. Therefore, for consistency, only unscreened or non-perforated wells were used to calculate aquifer parameters for this project. When located unscreened or non-perforated wells and wells with specific capacity are combined only 34.8% of the total wells (7,253 wells) could be used in this study.

Fifty data pairs of transmissivity calculated during recovery and specific capacity calculated from single well aquifer tests at unscreened or non-perforated wells were used to develop the empirical relationship. Transmissivity and specific capacity are log-linearly related. The best-fit regression line is Log T = 1.3562(Log Q/s) + 3.5209, where T = transmissivity expressed in m^2/day and Q/s (specific capacity) is in (m^2/min) with a coefficient of determination, R^2, of 0.749. The empirical equation developed for the GLWQD is slightly different compared to empirical equations developed for other regions. The differences in the equations can be related to various drilling and well construction practices, testing methods, pumping time, and pumping rates used.

There are three main water removal methods (air, pump, and bailer) used by drillers who work in the GLWQD. Statistical analysis of the transmissivity values from each water removal method indicated that the pump and air methods produce similar ranges of transmissivity values. Therefore, all pump and air data remained in the database. However, the bailer method and pump method do not produce statistically similar ranges of transmissivity values; therefore all of the bailer data was eliminated from the well dataset. Also, not all of the wells with specific capacity values used to compare the water evacuation methods had a pumping method specified, and therefore those wells without a pumping method indicated were removed from the well dataset. Again, this instance of missing or incomplete data indicates the need for better reporting of well data.

All of the initial test-hydrogeologic units could not be tested because some of the units had a limited number of data points. The elimination of the bailer data and all of the unknown evacuation method wells caused the number of data points in some of the test-hydrogeologic units to drop below ten data points, the minimum number to be included in the statistical analysis. The untested test-hydrogeologic units are Archean Crystalline aquitard, Mission Canyon aquifer, Kootenai aquifer, Thermopolis-Mowry aquitard, Frontier aquifer, Telegraph Creek-Eagle aquifer, Sedan aquifer, Billman Creek aquitard, and Hopper-Fort Union aquifer. These units occur in the mountains. Therefore, the hydrogeologic units tested were all in the Gallatin Valley. More analysis is needed in the pre-Tertiary units. However, the methods used during this study may not be appropriate for some of these units because they are low yielding formations. These low yielding units should be analyzed using recovery transmissivity methods only in order to eliminate the casing storage problem.

The main focus of this study was on the remaining valley test-hydrogeologic units. These units are the small valley stream alluvium aquifer, basin-fan aquifer, Hyalite alluvial fan aquifer, West Gallatin gravel terrace aquifer, East Gallatin alluvium aquifer, Lower East Gallatin alluvium aquifer, Lower Hyalite Creek alluvium aquifer, West Gallatin gravel deposit aquifer, and the West Gallatin alluvium aquifer. The statistical analysis indicated that all of the valley test-hydrogeologic units fit into one of three distinct groupings. All of the similar test-hydrogeologic units were combined into either the West Gallatin alluvium aquifer, the small stream and fan aquifer, or the Quaternary-Tertiary basin-fill aquifer. Units that have deposits formed by streams of similar competence are all grouped together. The unit designations and calculated transmissivity values match the previous work by Hackett and others (1960). However, transmissivity values calculated for the West Gallatin alluvium aquifer are low compared to published values.

In high transmissivity aquifers, such as the West Gallatin alluvium aquifer, the approach used during this study will produce low results because high transmissivity units produce zero drawdown at low pumping rates. The method used in this study produces a conservative estimate for high transmissivity units.

Although some of the calculated transmissivity values of the defined hydrogeologic units presented in this study are "low" compared to published values, these hydrogeologic units are valid groupings representing aquifers with similar hydraulic properties. Variability in well type and driller testing method was eliminated in order to reduce the affects of these items on aquifer hydraulic properties. The elimination of these variables results in the calculated transmissivity values that represent the variability in aquifer materials. Therefore, the defined hydrogeologic units presented in this study are hydraulically distinct units regardless of well type used. This study demonstrates that driller reported specific capacity data can be used to estimate hydraulic parameters and that the values obtained are in good agreement with hydraulic parameters determined by traditional aquifer pump tests. Driller reported specific capacity is a rich but underused database, which can be used to help characterize aquifers in an area.

The range of transmissivity values for Quaternary – Tertiary basin-fill aquifer, small stream and fan aquifer, and the West Gallatin Alluvium aquifer are similar. However, the mean, median, and mode values of these three hydrogeologic units are quite different. The similarity in the range of values of the units is due to natural variations in the deposits. As with any natural system, almost any transmissivity value is possible for a given unit; however, the probability of a well producing an extreme value is low (Figure 24). Transmissivity values from wells within any of the three hydrogeologic units have a higher probability of being within one standard deviation of the mean than being outside of that range.

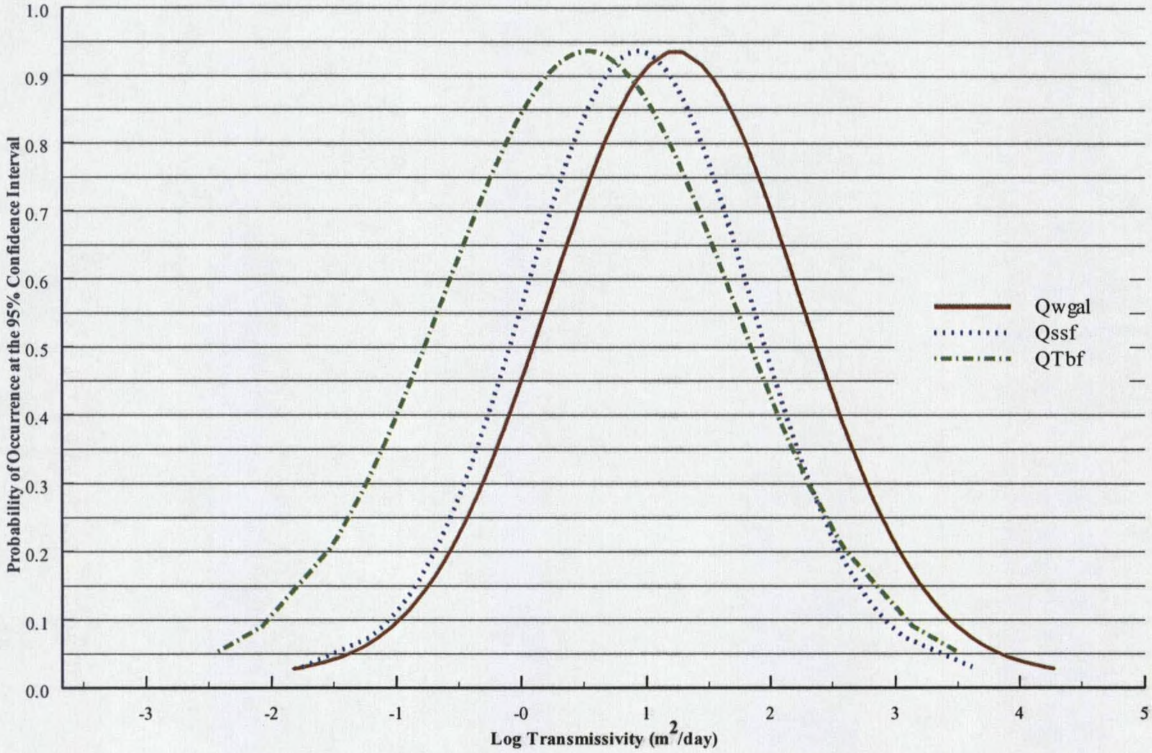

Figure 24. Probability distribution of the log transformed transmissivity data for the hydrogeologic units of the Gallatin Local Water Quality District, Gallatin County, Montana.

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APPENDICES

APPENDIX A

AQUIFER TEST DATA

Table 32. Aquifer test drawdown data from test well M:9858.

Total Time (seconds)	Water level measurement (feet)	Water level Change (feet)
83	17.35	4.2
140	20.25	7.1
160	20.35	7.2
175	20.4	7.25
205	20.47	7.32
238	20.5	7.35
283	20.52	7.37
330	20.55	7.4
364	20.55	7.4
455	20.85	7.7
480	20.85	7.7
510	20.87	7.72
545	20.9	7.75
577	20.91	7.76
608	20.91	7.76
643	20.92	7.77
670	20.92	7.77
689	20.93	7.78
727	20.94	7.79
762	20.95	7.8
778	20.96	7.81
820	20.98	7.83
842	20.99	7.84
875	21	7.85
902	21.01	7.86
970	21.03	7.88
1025	21.04	7.89
1082	21.05	7.9
1140	21.06	7.91
1200	21.07	7.92
1543	21.2	8.05
1805	21.2	8.05
2109	21.21	8.06
2413	21.21	8.06
2815	21.22	8.07
3005	21.22	8.07
331	21.24	8.09
3620	21.26	8.11

Date of Test: July 2, 1998 Static water level: 13.15 feet Average Discharge: 16.88 gpm

Test conducted by: Stewart Dixon and Mike O'Connell

Table 23. Aquifer test recovery data from test well M:9858.

Total Time Since pump started (seconds)	Water level Measurement (feet)	Water level Change (ft)	Time since Pump Off (seconds	Ratio t/t'
3699	18.72	5.57	0	0.00
3719	18.07	4.92	20	185.95
3740	16.85	3.7	41	91.22
3747	16.13	2.98	48	78.06
3757	15.72	2.57	58	64.78
3760	15.55	2.4	61	61.64
3765	15.45	2.3	66	57.05
3782	15.15	2	83	45.57
3798	15.05	1.9	99	38.36
3823	14.45	1.3	124	30.83
3837	14.37	1.22	138	27.80
3848	14.3	1.15	149	25.83
3862	14.2	1.05	163	23.69
3877	14.15	1	178	21.78
3890	14.08	0.93	191	20.37
3901	14.05	0.9	202	19.31
3915	14.03	0.88	216	18.13
3927	14	0.85	228	17.22
3950	13.95	0.8	251	15.74
3976	13.9	0.75	277	14.35
3990	13.85	0.7	291	13.71
4021	13.84	0.69	322	12.49
4049	13.8	0.65	350	11.57
4083	13.75	0.6	384	10.63
4111	13.73	0.58	412	9.98
4140	13.7	0.55	441	9.39
4173	13.68	0.53	474	8.80
4205	13.65	0.5	506	8.31
4235	13.64	0.49	536	7.90
4260	13.63	0.48	561	7.59
4290	13.6	0.45	591	7.26
4320	13.58	0.43	621	6.96
4356	13.57	0.42	657	6.63
4385	13.56	0.41	686	6.39
4418	13.54	0.39	719	6.14
4446	13.53	0.38	747	5.95
4479	13.52	0.37	780	5.74
4504	13.51	0.36	805	5.60
4537	13.5	0.35	838	5.41
4563	13.49	0.34	864	5.28
4594	13.48	0.33	895	5.13
4654	13.46	0.31	955	4.87
4716	13.44	0.29	1017	4.64
4777	13.43	0.28	1078	4.43
5368	13.31	0.16	1669	3.22
5451	13.3	0.15	1752	3.11
5525	13.3	0.15	1826	3.03
5722	13.29	0.14	2023	2.83
6039	13.26	0.11	2340	2.58

Table 34. Aquifer test drawdown data from test well M:96581.

Total Time (seconds)	Water level measurement (feet)	Water level Change (feet)
20	172.8	2.66
75	179.3	9.16
90	181.15	11.01
120	183	12.86
150	183.95	13.81
160	184.95	14.81
180	185.84	15.7
210	186.5	16.36
240	187.45	17.31
270	188.26	18.12
300	186.67	16.53
330	188.99	18.85
360	189.28	19.14
390	189.57	19.43
420	189.73	19.59
450	189.84	19.7
480	189.95	19.81
540	190.13	19.99
600	190.2	20.06
660	190.34	20.2
720	190.42	20.28
780	190.49	20.35
840	190.55	20.41
900	190.6	20.46
960	190.64	20.5
1020	190.68	20.54
1080	190.71	20.57
1140	190.73	20.59
1200	190.74	20.6
1500	190.91	20.77
1800	190.87	20.73
2100	190.95	20.81
2400	190.98	20.84
2700	191.09	20.95
3000	191.13	20.99
3300	191.13	20.99
3600	191.15	21.01
3639	190.5	20.36
3657	189.23	19.09
3679	188.1	17.96
3712	186.26	16.12
3738	184.95	14.81
3750	184.35	14.21
3764	183.43	13.29

Date of Test 11/7/1997   Static water level: 170.14 feet   Average Discharge: 18.43 gpm
Test conducted by: Stewart Dixon and Dr. Steve Custer

Table 35. Aquifer test recovery data from test well M:96581.

Total Time Since pump started (seconds)	Water level Measurement (feet)	Water level Change (ft)	Time since Pump Off (seconds	Ratio t/t'
3795	181.45	11.31	15	247.47
3806	180.4	10.26	26	143.77
3817	179.4	9.26	37	101.35
3827	178.85	8.71	47	80.09
3836	177.95	7.81	56	67.50
3847	177.55	7.41	67	56.64
3852	177.05	6.91	72	52.86
3860	176.69	6.55	80	47.71
3870	176.05	5.91	90	42.52
3891	175.26	5.12	111	34.56
3899	174.91	4.77	119	32.33
3920	174.2	4.06	140	27.51
3930	174.01	3.87	150	25.73
3940	173.92	3.78	160	24.19
3949	173.67	3.53	169	23.02
3959	173.45	3.31	179	21.78
3964	173.36	3.22	184	21.30
3975	173.11	2.97	195	20.15
3995	172.83	2.69	215	18.33
4003	172.75	2.61	223	17.71
4020	172.55	2.41	240	16.50
4036	172.39	2.25	256	15.48
4041	172.32	2.18	261	15.23
4053	172.22	2.08	273	14.63
4078	172.06	1.92	298	13.43
4090	171.98	1.84	310	12.97
4107	171.87	1.73	327	12.34
4117	171.79	1.65	337	11.99
4132	171.75	1.61	352	11.51
4200	171.48	1.34	420	9.71
4260	171.34	1.2	480	8.52
4320	171.23	1.09	540	7.61
4390	171.15	1.01	610	6.75
4440	171.09	0.95	660	6.26
4500	171.04	0.9	720	5.83
4560	171	0.86	780	5.46
4620	170.97	0.83	840	5.14
4680	170.94	0.8	900	4.88
4740	170.91	0.77	960	4.63
4810	170.81	0.67	1030	4.37
5100	170.71	0.57	1320	3.45
5400	170.69	0.55	1620	2.85
5700	170.55	0.41	1920	2.44
6030	170.6	0.46	2250	2.11
6300	170.56	0.42	2520	1.91
6600	170.55	0.41	2820	1.81
7020	170.49	0.35	3240	1.67
7267	170.49	0.35	3487	1.63
7520	170.49	0.35	3740	1.61
7910	170.45	0.31	4130	1.53
8180	170.42	0.28	4400	1.50
8475	170.42	0.28	4695	1.50
8720	170.41	0.27	4940	1.47
9010	170.4	0.26	5230	1.44
9300	170.39	0.25	5520	1.43

Table 36. Aquifer test drawdown data from test well M:91730.

Total Time(seconds)	Water level measurement (feet)	Water level Change (feet)
16	49.95	4.13
39	49.65	3.83
52	49.94	4.12
64	50.05	4.23
90	50.13	4.31
128	50.16	4.34
156	50.17	4.35
182	50.18	4.36
210	50.18	4.36
240	50.19	4.37
270	50.19	4.37
300	50.16	4.34
380	50.17	4.35
438	50.17	4.35
483	50.16	4.34
545	50.18	4.36
602	50.18	4.36
660	50.18	4.36
733	50.18	4.36
796	50.17	4.35
854	50.19	4.37
905	50.19	4.37
1208	50.2	4.38
1505	50.18	4.36
1808	50.16	4.34
2102	50.17	4.35
2410	50.15	4.33
2735	50.16	4.34
3015	50.16	4.34
3320	50.18	4.36
3635	50.18	4.36
3719	48.85	3.03
3745	48.25	2.43

Date of Test: July 8, 1998 Static water level: 45.82 feet. Average Discharge: 16.97 gpm
Test conducted by: Stewart Dixon and Walt Kelly

Table 37. Aquifer test recovery data from test well M:91730.

Total Time Since pump started (seconds)	Water level Measurement (feet)	Water level Change (ft)	Time since Pump Off (seconds	Ratio t/t'
3775	46.95	1.13	16	235.94
3790	46.5	0.68	31	122.26
3805	46.15	0.33	46	82.72
3821	46	0.18	62	61.63
3835	45.9	0.08	76	50.46
3844	45.85	0.03	85	45.22
3865	45.81	-0.01	106	36.46
3893	45.81	-0.01	134	29.05
3925	45.81	-0.01	166	23.64
3775	46.95	1.13	16	235.94

Table 38. Aquifer test drawdown data from test well M:92206.

Total Time (seconds)	Water level measurement (feet)	Water level Change (feet)
7	39.91	0.81
13	41.05	1.95
40	46.45	7.35
50	48.3	9.2
65	50.5	11.4
74	52.35	13.25
85	54.98	15.88
120	59.95	20.85
150	66.78	27.68
180	69.65	30.55
210	74.65	35.55
240	77.7	38.6
270	80.55	41.45
300	87.2	48.1
403	96.65	57.55
454	102.25	63.15
519	109.35	70.25
585	118.5	79.4
652	127.03	87.93
712	136.75	97.65
772	144.13	105.03
832	150.15	111.05
892	157.25	118.15

Date of Test: June 24, 1998 Static water level: 39.10 feet. Average Discharge: 16.28 gpm
Test conducted by: Stewart Dixon and S. Smith

Table 39. Aquifer test recovery data from test well M:92206.

Total Time Since pump started (seconds)	Water level Measurement (feet)	Water level Change (ft)	Time since Pump Off (seconds	Ratio t/t'
1548	157.6	118.5	0	0.00
1596	156.15	117.05	48	33.25
1627	155.45	116.35	79	20.59
1643	155.15	116.05	95	17.29
1669	154.65	115.55	121	13.79
1729	153.71	114.61	181	9.55
1789	152.73	113.63	241	7.42
1849	151.68	112.58	301	6.14
1909	150.8	111.7	361	5.29
1969	149.85	110.75	421	4.68
2029	148.83	109.73	481	4.22
2089	147.93	108.83	541	3.86
2149	147	107.9	601	3.58
2209	145.98	106.88	661	3.34
2269	145.18	106.08	721	3.15
2580	140.35	101.25	1032	2.50
2880	136.04	96.94	1332	2.16
3240	130.72	91.62	1692	1.91
3540	126.5	87.4	1992	1.78
3840	122.43	83.33	2292	1.68
4140	118.37	79.27	2592	1.60
4476	114.3	75.2	2928	1.53
4776	110.3	71.2	3228	1.48

Table 40. Aquifer test drawdown data from test well M:128350.

Total Time (seconds)	Water level measurement (feet)	Water level Change (feet)
30	28.35	2.51
60	30.95	5.11
90	31.05	5.21
120	31.11	5.27
150	31.15	5.31
180	31.15	5.31
210	31.15	5.31
240	31.15	5.31
270	31.15	5.31
300	31.15	5.31
360	31.15	5.31
420	31.15	5.31
480	31.15	5.31
540	31.15	5.31
600	31.15	5.31
660	31.15	5.31
720	31.15	5.31
780	31.15	5.31
840	31.15	5.31
900	31.15	5.31
1200	31.15	5.31
1680	31.11	5.27
1800	31.11	5.27
2100	31.11	5.27
2400	31.11	5.27
2700	31.11	5.27
3000	31.11	5.27
3300	31.11	5.27
3600	31.11	5.27
3630	31.00	5.16

Date of Test 10/18/1997 Static water level: 25.84 feet Average Discharge: 14.86 gpm
Test conducted by: Stewart Dixon and Martha Kauffman

Table 41. Aquifer test recovery data from test well M:128350.

Total Time Since pump started (seconds)	Water level Measurement (feet)	Water level Change (ft)	Time since Pump Off (seconds	Ratio t/t'
3697	27.95	2.11	37	99.92
3720	26.55	0.71	60	62.00
3750	26.28	0.44	90	41.67
3780	26.10	0.26	120	31.50
3810	26.00	0.16	150	25.40
3840	26.00	0.16	180	21.33
3870	26.00	0.16	210	18.43
3900	26.00	0.16	240	16.25
3930	26.00	0.16	270	14.56
3960	26.00	0.16	300	13.20
3990	26.00	0.16	330	12.09
4020	26.00	0.16	360	11.17
4080	26.00	0.16	420	9.71
4140	26.00	0.16	480	8.63
4200	26.00	0.16	540	7.78
4260	26.00	0.16	600	7.10
4320	26.00	0.16	660	6.55
4380	26.00	0.16	720	6.08
4440	25.98	0.14	780	5.69
4500	25.98	0.14	840	5.36
4560	25.98	0.14	900	5.07
4620	25.98	0.14	960	4.81
4680	25.98	0.14	1020	4.59
4980	25.98	0.14	1320	3.77
5280	25.98	0.14	1620	3.26
5580	25.97	0.13	1920	2.91
5880	25.97	0.13	2220	2.65
6180	25.97	0.13	2520	2.45
6480	25.97	0.13	2820	2.30
6780	25.97	0.13	3120	2.17
7080	25.85	0.01	3420	2.07

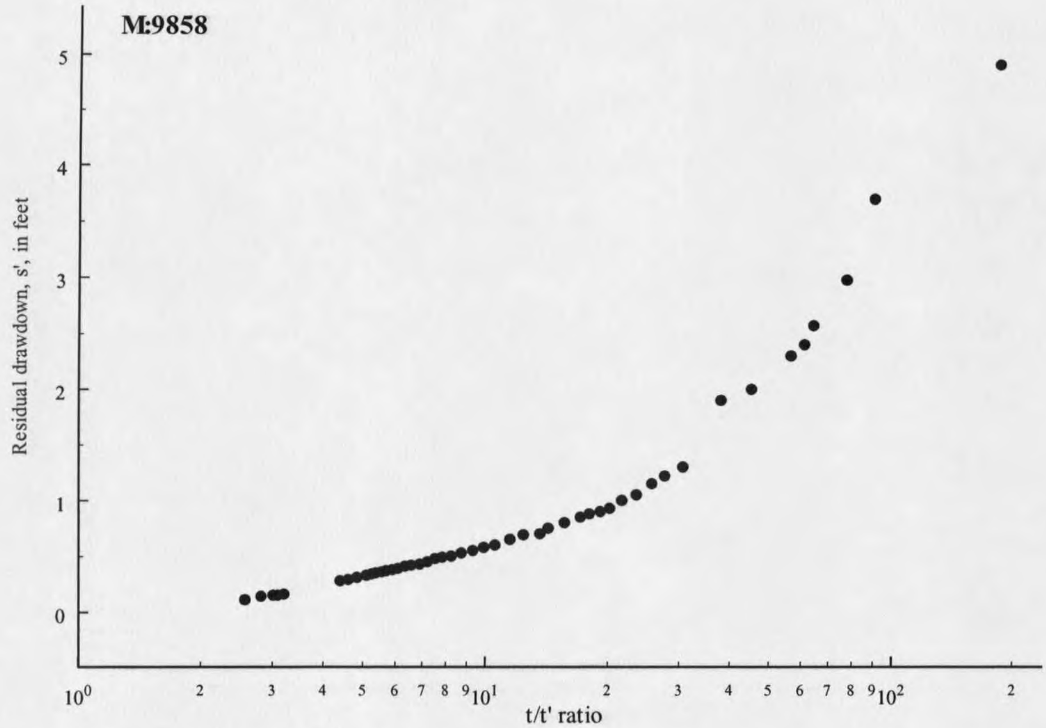


Figure 25. Residual drawdown graph for test well M:9858.

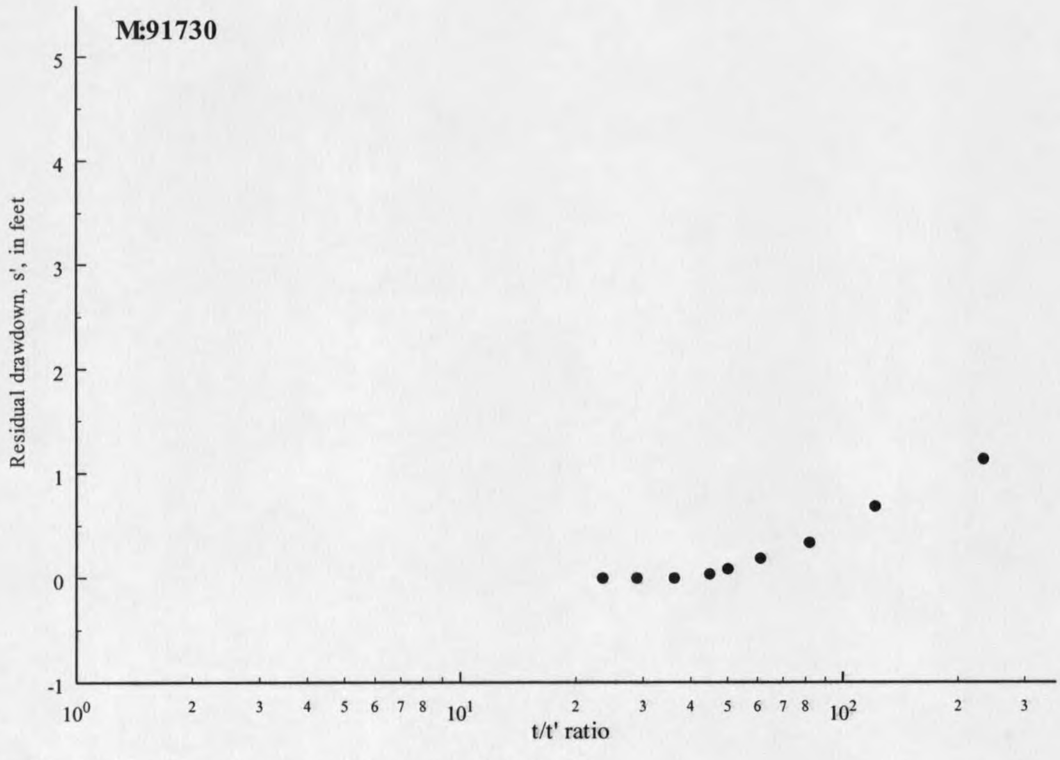


Figure 26. Residual drawdown graph for test well M:91730.

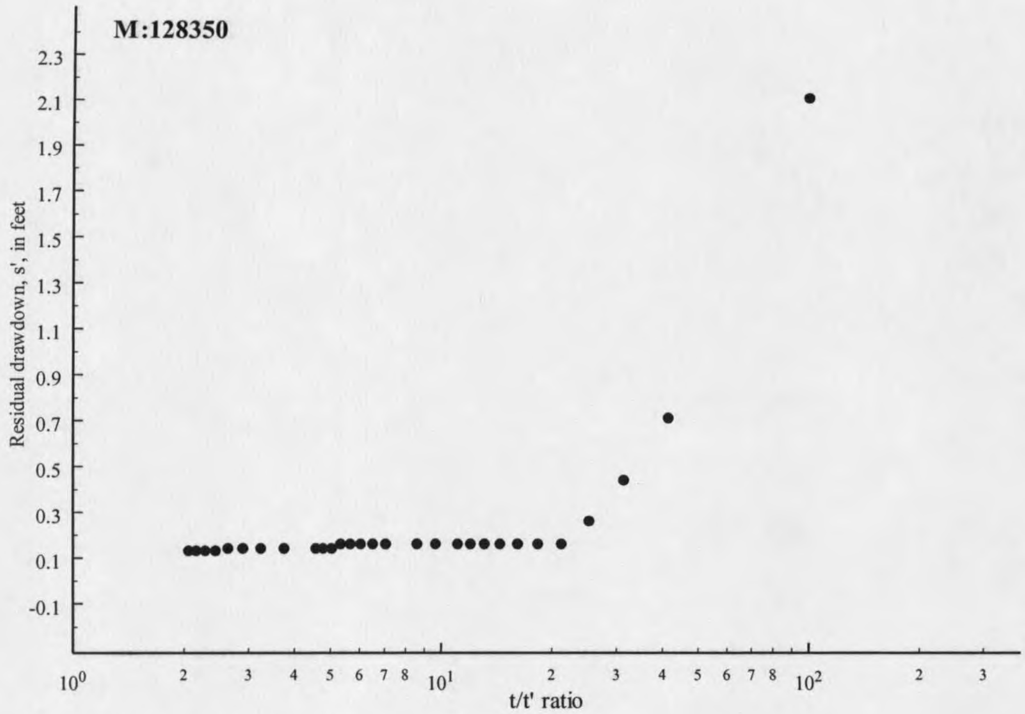


Figure 27. Residual drawdown graph for test well M:128350.

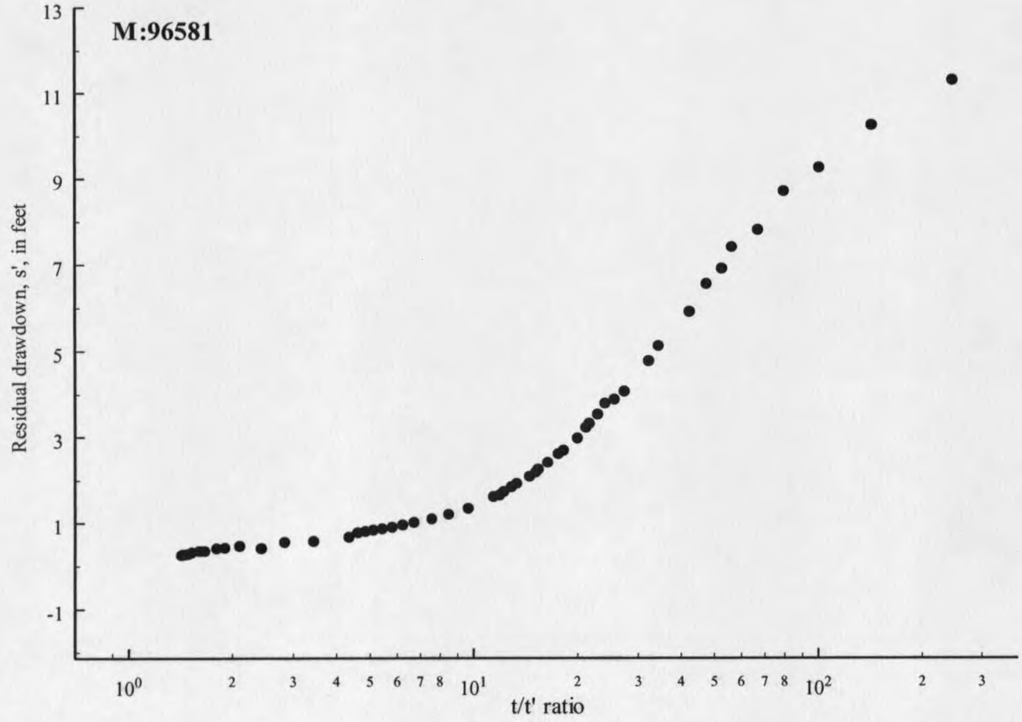


Figure 28. Residual drawdown graph for test well M:96581

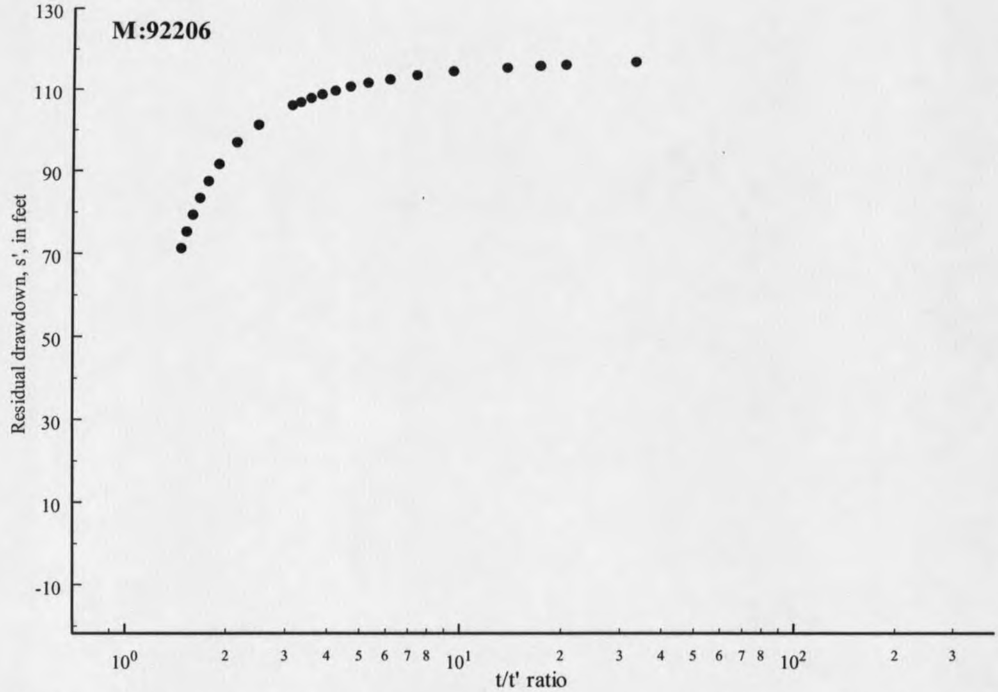


Figure 29. Residual drawdown graph for test well M:92206. The recovery data from this test was not used to calculate a transmissivity. This well was only pumped for 15 minutes.

APPENDIX B

WELL DATA FOR INDIVIDUAL TEST-HYDROGEOLOGIC UNITS

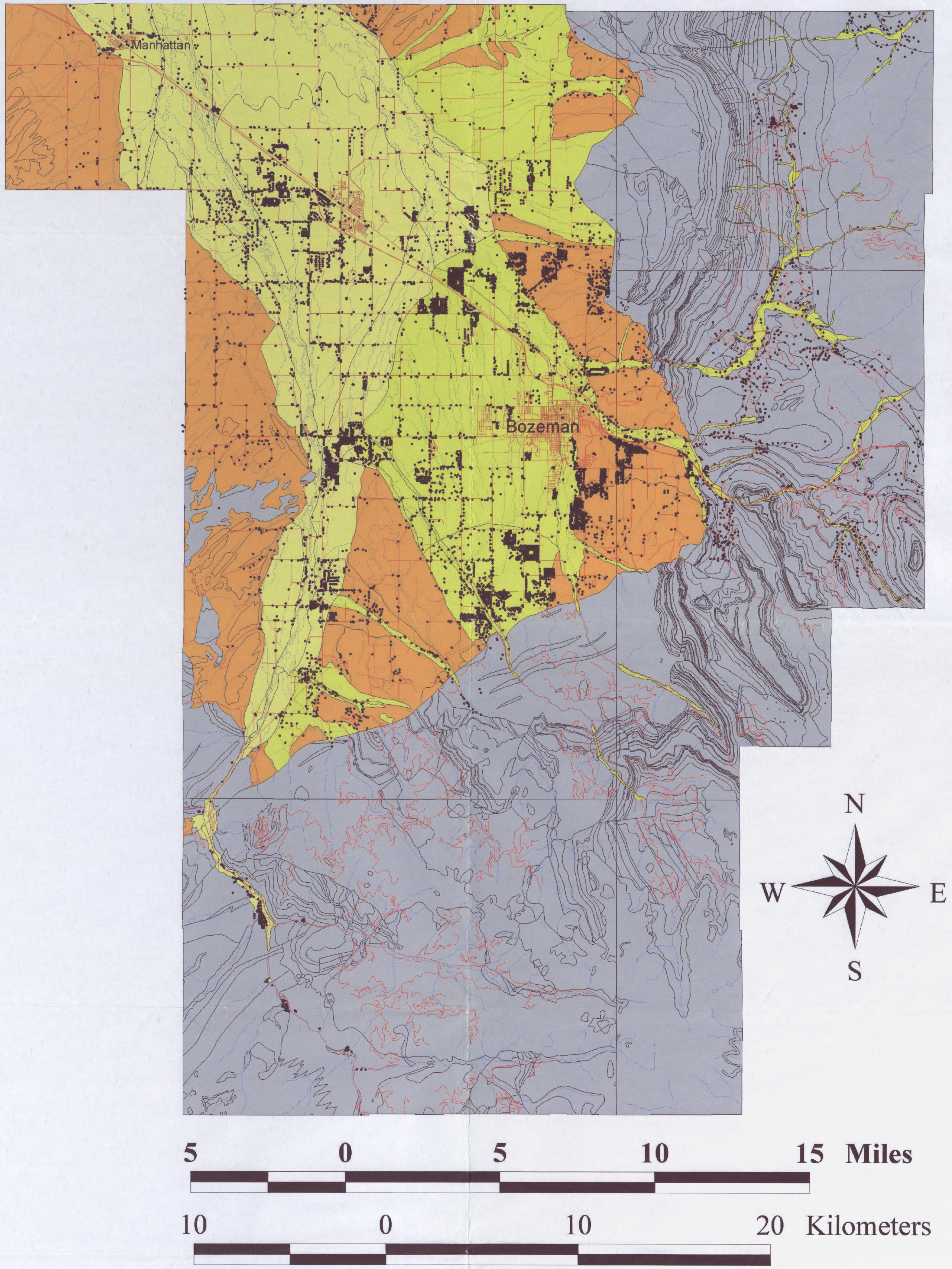
Test-Hydrogeologic Unit Well Data

All located well data for the test-hydrogeologic units are contained on the CD ROM in the pocket at the end of this thesis. The files on the CD are named as shown below. These files contain the following basic information from the located wells within each test-hydrogeologic unit: M:number, location (Township, range, section data), total depth, driller specific capacity, calculated transmissivity, driller pumping method, length of driller test, driller reported yield, driller reported pumping level, and static water level. All of the files are spreadsheets created in Microsoft Excel 97-2002.

Table 42. Test-hydrogeologic units and the corresponding Microsoft Excel 97-2002 file name containing the basic well information from located wells in each unit.

Test-hydrogeologic Unit	Excel File Name
Small valley Stream alluvium aquifer (Qssval)	Table 43. Qssval Well data
Small mountain stream alluvium aquifer (Qssmal)	Table 44. Qssmal Well data
Quaternary basin-fan aquifer (Qaf)	Table 45. Qaf Well data
Hyalite alluvium fan aquifer (Qhf)	Table 46. Qhf Well data
West Gallatin gravel terrace aquifer (Qwggt)	Table 47. Qwggt Well data
East Gallatin alluvium aquifer (Qegal)	Table 48. Qegal Well data
Lower East Gallatin alluvium aquifer (Qlegal)	Table 49. Qlegal Well data
Lower Hyalite Creek alluvium aquifer (Qlhal)	Table 50. Qlhal Well data
West Gallatin Gravel Deposit aquifer (Qwggd)	Table 51. Qwggd Well data
West Gallatin alluvium aquifer (Qwgal)	Table 52. Qwgal Well data
Old alluvium aquifer (QTal)	Table 53. QTal Well data
Bozeman Group aquifer (Tb)	Table 54. Tb Well data
Hoppers-Fort Union aquifer (KThf)	Table 55. KThf Well data
Billman Creek aquitard (Kbc)	Table 56. Kbc Well data
Sedan aquifer (Ks)	Table 57. Ks Well data
Telegraph Creek-Eagle aquifer (Kte)	Table 58. Kte Well data
Frontier aquifer (Kf)	Table 59. Kf Well data
Thermopolis-Mowry aquitard (Ktm)	Table 60. Ktm Well data
Kootenai aquifer (Kk)	Table 61. Kk Well data
Jurassic aquitard (Ju)	Table 62. Ju Well data
Mmm Mission Canyon aquifer (Mmm)	Table 63. Mmm Well data
Crystalline aquitard (Am)	Table 64. Am Well data

Plate 1. Hydrogeologic Map of the Gallatin Local Water Quality District, Gallatin County, Montana.



Explanation

- Wells
- Streams
- Roads
- Lwqdbound

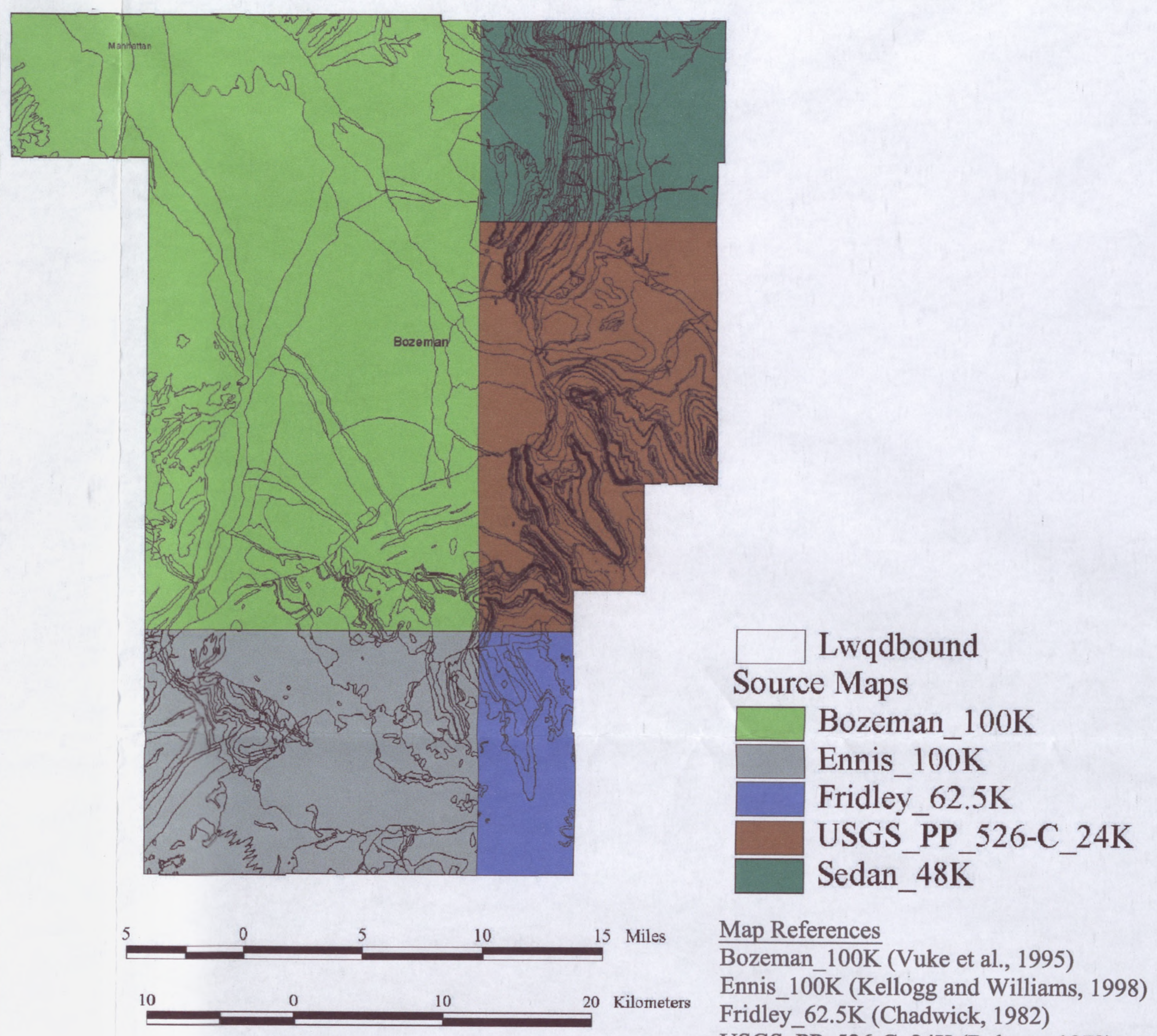
Hydrogeologic Units

- Qwgal
- Qssf
- QTbf
- Rock

Descriptive statistics of the log transformed transmissivity values for the Hydrogeologic units of the GLWQD, Montana.

Hydrogeologic Unit	Number of observations		Geometric Mean	Geometric Median	Geometric Mode	Geometric Standard Deviation	Geometric Standard Error of Mean
Qwgal West Gallatin alluvium aquifer	501	m^2/day	17	14	11	6.0-50	16-17
		gpd/ft	1300	1100	880	450-4000	1300-1400
Qssf Small Stream and Fan aquifer	515	m^2/day	8.5	8.0	8.0	3.4-22	8.2-8.9
		gpd/ft	680	640	640	270-1,700	660-720
QTbf Quaternary-Tertiary Basin Fill aquifer	98	m^2/day	3.4	3.9	4.0	0.75-16	2.9-4.0
		gpd/ft	270	310	320	60-1300	230-320

Index to Source Maps



Map References
Bozeman_100K (Vuke et al., 1995)
Ennis_100K (Kellogg and Williams, 1998)
Fridley_62.5K (Chadwick, 1982)
USGS_PP_526-C_24K (Roberts, 1972)
Sedan_48K (Skipp et al., 1999)

Study Area Location Map (From Kendy, 2001, page 3)

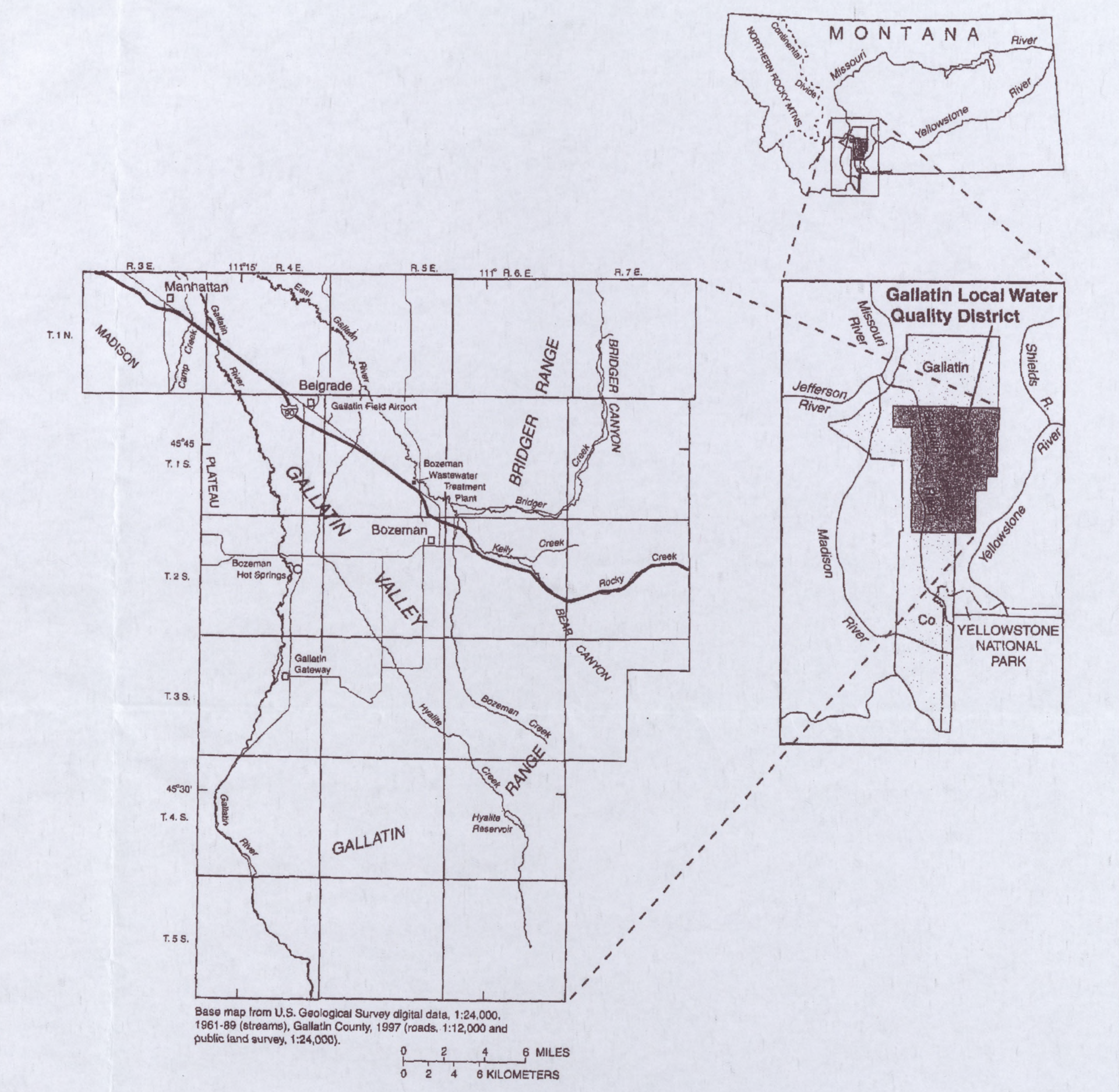
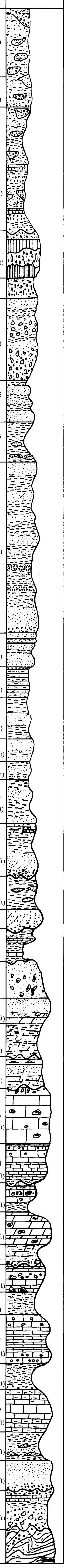


Plate 2. Lithostratigraphic and Hydrogeologic Units of the Gallatin Local Water Quality District, Gallatin County, Montana.

Compiled by:
Stewart A. Dixon, and Dr. Stephan G. Custer
Montana State University
Department of Earth Sciences
March 2002

Modified from: Hackett et al., 1960; Roberts, 1963; Groff, 1965; Balster, 1971; Kuenzi and Fields, 1971;Skipp and McMannis, 1971 Roberts,1972; Montagne, 1976; Skipp and McGrew, 1977; Aram, 1979; Bonnet, 1979; Balster, 1980; Hughes, 1980; Levings et al., 1981; Chadwick, 1982; Smith and Welker, 1982; Smith, 1983; Moore, 1984; Lambing et al., 1987; Custer et al., 1991; Hiza, 1994; Dyman et al., 1995; Vuke et al., 1995; Kendy and Tresch, 1996; Skipp et al., 1999.

Erathem	System	Series	Unit Name	Map Symbol	MBMG Geologic Source Codes	Unit Thickness (meters)	Lithologic Description	Hydrogeologic Units	Water-yielding characteristics	Number of Observations	measurement units	Geometric Mean	Geometric Median	Geometric Mode	Geometric Mean ± 1 Standard Deviation	Geometric Mean ± 1 Standard Error
Cenozoic	Quaternary		West Gallatin River Alluvium	Qwgal	110ALVM	0-100 (0-300 ft)	Unconsolidated gravel deposits interbedded with lenses and some beds of sand, silt, and clay deposited by the West Gallatin River.	West Gallatin Alluvial Aquifer	Yeilds excellent to good expected to be ample for municipal,commercial, irrigation, domestic, and stock uses.	501	m^2/day	17	14	11	5.6-52	16-17
											gpd/ft	1400	1100	890	450-4200	1300-1400
Cenozoic	Quaternary		Small Stream and Fan Alluvium	Qssf	110ALVM 110ALVF		Mixture of unconsolidated lenticular gravel, sand, silt, and clay deposited by streams smaller than the West Gallatin River.	Small Stream and Fan Aquifer	Yields generally good to fair, water supplies for light irrigation, industrial use as well as domestic and	515	m^2/day	8.5	8.0	8.0	3.4-22	8.2-8.9
											gpd/ft	680	640	640	270-1700	660-720
Cenozoic	Tertiary	Pliocene	Old Alluvium: Fan, pediment, stream deposits	QTbf		0-100 (0-300 ft)	Similar to small stream and fan alluvium, but in high landscape position well above other alluvial deposits and sometimes more coarse grained.	Quaternay-Tertiary Basin Fill Aquifer	Variable, generally fair to good, water supplies expected to be good for light irrigation, domestic and stock use.	98	m^2/day	3.4	3.9	4.0	0.75-16	2.9-4.0
Cenozoic	Tertiary	Miocene, Oligocene	Bozeman Group (includes Sixmile Creek, Madison Valley Formation, and Renova Formation)	QTbf	120SDMS 120UDFD	0-1525 (0-5000ft)	Sixmile Creek and Madison Valley Frm: Lenticular pebble conglomerate, arkose, and cross-bedded sandstone surrounded by mudstone and siltstone. Locally volcanic ash beds. Some fine-grained ostracode-bearing limestone; less lenticular (more extensive) beds to the west. Renova Frm: Alternating sequence of fine-grained limestone, montmorillonite mudstone, siltstone, with minor sandstone, arkose, conglomerate. Local virtric ash beds.	Quaternay-Tertiary Basin Fill Aquifer	Generally fair to good, in channel gravels and sandstones, less so in silty and muddy units.		gpd/ft	270	310	320	60-1300	230-320
Cenozoic	Tertiary	Eocene	Gallatin-Absaroka Volcanics	Tv	124VLCC	0-2745 (0-9000ft)	Light to dark grayish brown andesite and basalt flows, flow breccia, debris flow deposits, and tuff.	Volcanic Aquitard*	Not an aquifer, except where jointed and fractured	No Data						
Cenozoic	Tertiary	Eocene	unamed gravels, sands, and siltstone			0-17 (0-50ft)	Loosely consolidated conglomerate of Precambrian rock and Paleozoic and Mesozoic sedimentary rock. Matrix is poorly sorted sand and silt derived from similar rocks.	Volcanic Aquitard*								
Cenozoic	Tertiary	Paleocene	Fort Union Formation	KThf	125FRUN	0-185 (0-600ft)	Massive to thin-bedded, fine to coarse grained, slightly calcareous, andesitic greenish-gray sandstone, and massive olive -gray mudstone. Lower Conglomeratic Sandstone-massive to thin-bedded, cross-bedded fine grained to conglomeratic andesitic yellow green sandstone with interbedded siltstone and claystone. Pebbles of volcanic rock, quartzite, gneiss and limestone.	Hoppers-Fort Union Aquifer*	Fort Union: Variable , but generally good, conglomerates and sandstones especially where not cemented should be good water yielding units.	8	m^2/day	0.94	0.88	19	0.07-13	0.37-2.4
Mesozoic	Cretaceous	Upper	Montana Group, Livingston Group: Hoppers Formation	KThf	211HPRS	460-735 (1500-2400ft)	Massive to thin-bedded, cross-bedded, poorly sorted andesitic yellow-green sandstone with interbedded claystone and siltstone. Locally conglomeratic. Contains fresh-water mollusks and wood and plant fragments.	Hoppers-Fort Union Aquifer*	Hoppers: Generally good where adequate thickness, possible poor zones are intermittent claystones and siltstones.		gpd/ft	75	71	1500	5.4 - 1100	30 -190
Mesozoic	Cretaceous	Upper	Montana Group, Livingston Group: Billman Creek Formation	Kbc	211BMCK	765-915 (2500-3000ft)	Massive olive gray to grayish red claystone with interbedded fine to coarse grained andesitic sandstone. Contains fresh-water mollusks and dinosaur bones.	Billman Creek Aquitard*	Used as a local aquifer, but water quantity and quality is poor to very poor throughout unit.	3	m^2/day	1.7	0.92	N/A	0.07-41	0.27 - 11
											gpd/ft	140	74	N/A	5.7-3300	22 - 860
Mesozoic	Cretaceous	Upper	Montana Group, Livingston Group, Sedan Formation: Miner Creek Formation	Ks	211MRCK 211SLPF (Sulphur Flats)	0-915 (0-3000ft)	Sedan Formation: Olive gray to brownish gray volcaniclastic sandstones, mudstones, and minor ash-flow tuffs. Formation consists of five members:Lennep Sandstone Mbr., Mudstone Mbr., Middle Sandstone Mbr., Ash-Flow Mbr., Lower Sandstone. Miner Creek: massive tuffaceous olive-gray siltstone with interbedded fine-grained andesitic sandstone. Contains petrified wood, leaf impressions, spores, and dinosaur bones. Sulphur Flats Sandstone- massive cross-bedded poorly sorted grayish green andesitic sandstone with interbedded tuff and bentonite.	Sedan Aquifer*	Sedan: Variable from poor to good, The sandstone members have the greatest potential for good water yield while the mudstone and Ash-flow tuff members should have the poorest water yield. Miner Creek: Variable from poor to good, in the Sulphur Flats mbr. of the Miner Creek Fm.	4	m^2/day	4.7	1.8	N/A	0.27 - 81	1.1 - 20
Mesozoic	Cretaceous	Upper	Montana Group, Livingston Group, Sedan Formation: Cokedale Formation	Ks	211CKDL		Cokedale Formation: Massive to thin-bedded poorly sorted andesitic olive-gray siltstone and sandstone with interbedded conglomerate, claystone, and tuff. Thin beds of bentonite and lignite in lower part of formation. Contains petrified wood, leaf impressions, spores, fresh water mollusks, and dinosaur bones.	Sedan Aquifer*	Cokedale Fm. variable from poor to good, the siltstones and claystones will poor aquifers while the sandstones may be better.		gpd/ft	380	150	N/A	22-6500	90-1600
Mesozoic	Cretaceous	Upper	Montana Group: Eagle Sandstone	Kte	211EGLE	0-185 (0-600ft)	Light gray, thin to thick bedded, locally cross-bedded, fine to medium grained, white and black chert bearing sandstone with some intercalated carbonaceous shale and coal beds.	Telegraph Creek-Eagle Aquifer*	Water yield in the Eagle Sandstone should be good where the sandstone is the thickest.	No Data						
Mesozoic	Cretaceous	Upper	Montana Group: Telegraph Creek Formation	Kte	211TPCK	0-80 (0-250ft)	Medium gray, thin-bedded siltstone containing calcareous concretions and some resistant sandstone beds	Telegraph Creek-Eagle Aquifer*	Variable from poor to good, poor availability in the siltstones and good in the sandstones							
Mesozoic	Cretaceous	Upper	Colorado Group, Cody Shale: Upper Shale mbr., Eldridge Creek mbr., Lower Shale mbr.	Kc	211CODY	15-185 (50-600ft)	Medium to dark gray and brown thin bedded shale with some beds of siltstone and sandstone, especially in middle part. Locally fossiliferous.	Cody Aquitard*	Not an aquifer, shales nearly impermeable	No Data						
Mesozoic	Cretaceous	Upper	Colorado Group: Frontier Formation	Kf	211FRNR	15-70 (50-200ft)	Buff to medium gray, thin to medium bedded, fine to coarse grained arkosic sandstone, locally silty.	Frontier Aquifer*	Possible aquifer, sandstones may yield water.	6	7.1 m^2/day; 570 gpd/ft					
Mesozoic	Cretaceous	Lower	Colorado Group: Mowry Shale	Ktm	217MWRY	10-125 (30-400ft)	Grayish-brown and green shale and siltstone with some sandstone beds. Locally carbonaceous.	Thermopolis-Mowry Aquitard* (basal water)	Not an aquifer, shales nearly impermeable, Locally lower sandstone of Thermopolis may contain water as may local sandbeds in Mowry.	2	m^2/day	0.2	0.2	N/A	0.045 - 1	0.07-0.63
Mesozoic	Cretaceous	Lower	Colorado Group, Thermopolis Shale: Muddy Sandstone mbr., Shale mbr., Lower Sandstone mbr.	Ktm	217MDDY 217TMPL	15-120 (50-380ft)	Medium gray to black shale with numerous fine to medium grained gray sandstone beds. Locally arkosic, glauconitic, or carbonaceous. Lower resistant silical cemented quartz sandstone.	Thermopolis-Mowry Aquitard* (basal water)			gpd/ft	17	17	N/A	3.6 - 80	5.7 - 52
Mesozoic	Cretaceous	Lower	Kootenai Formation	Kk	217KOTN	30-155 (100-500ft)	Upper interbedded fine-grained gastropod-bearing limestone interbedded with red or black mudstone. Middle red mudstone with interbedded buff to white chert bearing sandstone. Lower chert pebble conglomerate interbedded with sandstone and red mudstone locally absent.	Kootenai Aquifer*	Upper portion of formation not considered an aquifer. Lower portion of unit is a potential aquifer, sandstone and conglomerate units may be good water yielding units where not cemented.	No Data						
Mesozoic	Jurassic	Upper	Morrison Formation	Ju	221MRSN	30-140 (100-450ft)	Upper carbonaceous shale, variegated red, locally green, thin to thick bedded mudstone and siltstone with intercalated yellowish-brown calcareous siltstone and sandstone often in lenses. May contain dinosaur bones.	Jurassic Aquitard*	Not an aquifer.	No Data						
Mesozoic	Jurassic	Lower	Ellis Group: Swift Formation	Ju	221SWFT	30 (100ft)	Yellowish-brown, medium bedded, fine-grained, calcareous, glauconitic, sandstone. Local basal chert conglomerate.	Jurassic Aquitard*	Not an aquifer, locally Swift Formation may contain small amounts of water.							
Mesozoic	Jurassic	Lower	Ellis Group: Rierdon Formation	Ju	221RRDN	60 (200ft)	Upper calcareous mudstone and thin-bedded fine limestone, lower resistant oolitic limestone.	Jurassic Aquitard*								
Mesozoic	Jurassic	Lower	Ellis Group: Piper Formation	Ju	221PIPR		Red calcareous siltstone and limestone with lower (?) fine-grained reddish pelecypod bearing limestone and black shale	Jurassic Aquitard*								
Paleozoic	Permian		Phosphoria Formation	MPu	310PSPR	0-10 (0-30ft)	Pale yellowish-brown, carbonate or chert cemented sandstone, may locally contain chert and chert-cemented breccias in Southern Gallatin County near base of formation.	Upper Mississippian-Permian Aquitard*	Potential aquifer, sandstone beds may yield water. In the Phosphoria Formation only the sandy Shedhorn is known to exist in area.	No Data						
Paleozoic	Penn.		Quadrant Formation	MPu	320QDRN	40-80 (130-250ft)	White to pinkish-gray, medium to thick-bedded (locally cross-bedded), subrounded, fine to medium-grained silica or carbonate cemented quartz sandstone;and a lower dolostone.	Upper Mississippian-Permian Aquitard*	Quadrant may be a potential aquifer if the sandstones are not cemented.							
Paleozoic	Penn.		Amsden Group	MPu	320AMSD	0-60 (0-200ft)	Pale yellow to reddish-brown, medium to thick-bedded siltstone with some dolomite and impure fossiliferous limestone beds.	Upper Mississippian-Permian Aquitard*								
Paleozoic	Mississippian		Big Snowy Group	MPu	331BGSN	0-80 (0-250ft)	Upper dark-gray to black, cherty, fossiliferous shale and limestone. Middle, pink-bluff, platy to massive-bedded sandstone and siltstone. Lower pink to buff dolomite and siltstone.	Upper Mississippian-Permian Aquitard*	Generally not considered an aquifer. Lower dolomite may contain water of poor quality.							
Paleozoic	Mississippian		Madison Group: Mission Canyon Limestone (includes Charles Formation, collapse breccia)	Mmm	337MSNC	130-290 (430-950ft)	Light gray, massive or poorly bedded, resistant fossiliferous limestone with solution breccias at top. Locally contains chert nodules.	Mission Canyon Aquifer*	Potential aquifer if solution channels are extensive.	No Data						
Paleozoic	Mississippian		Madison Group: Lodgepole Limestone	CDlM	337LDGP	185-250 (600-810ft)	Dark gray thin to medium-bedded fossiliferous, limestone. Lower medium to dark gray, thin-bedded, sparsely fossiliferous limestone with occasional chert nodules. Black shale at the base.	Cambrian, Devonian, and Lower Mississippian Aquitard*	Lacks the collapse breccia and evaporite zones where solution channels could develop, probably not an aquifer.	No Data						
Paleozoic	Devonian		Three Forks Formation	CDlM	337TRFK	30-50 (100-150ft)	Upper gray, thin-bedded silty yellow limestone. Middle buff, medium to thick bedded, brecciated limestone. Basal, red-orange limonite-nodule shale, and siltstone.	Cambrian, Devonian, and Lower Mississippian Aquitard*								
Paleozoic	Devonian		Jefferson Dolomite	CDlM	341JFRS	120-190 (400-620ft)	Light and dark-brown, medium to thick-bedded, fine to medium-grained, dolostone and limestone. Often petroliferous and containing stromatoporoids and amphipora. Locally contains chert nodules.	Cambrian, Devonian, and Lower Mississippian Aquitard*	Jefferson may contain water, but because of its high hydrocarbon content it is expected to produce poor quality water.							
Paleozoic	Devonian		Maywood Formation	CDlM	344MYWD	10-30 (40-90ft)	Red, yellow or brown, thin-bedded calcareous siltstone with some dolomite, trilobite-brachiopod fossil hash in lower part	Cambrian, Devonian, and Lower Mississippian Aquitard*								
Paleozoic	Cambrian	Upper	Snowy Range Formation: Sage Pebble Conglomerate member	CDlM		40-60 (120-200ft)	Yellow-brown to olive, thin to medium bedded, fine to coarse grained, commonly glauconitic and fossiliferous limestone and limestone pebble conglomerate with columella magna beds at base.	Cambrian, Devonian, and Lower Mississippian Aquitard*								
Paleozoic	Cambrian	Upper	Snowy Range Formation: Dry Creek Shale member	CDlM	371DRCK	15-25 (50-80ft)	Gray-green shale with intercalated pale-orange to buff calcareous siltstone and sandstone.	Cambrian, Devonian, and Lower Mississippian Aquitard*								
Paleozoic	Cambrian	Upper	Pilgrim Limestone	CDlM	374PLGM	110-130 (360-430ft)	Dark and light-gray mottled, medium-thick bedded, ledge-forming, oolitic limestone. Gray to yellow-brown, thin to medium-bedded limestone with limestone-pebble conglomerate and interbedded green shale. Gray, limestone-pebble conglomeratic massive oolitic, limestone.	Cambrian, Devonian, and Lower Mississippian Aquitard*								
Paleozoic	Cambrian	Lower	Park Shale	CDlM	374PARK	30-60 (100-200ft)	Gray-green and maroon shale with interbedded brown very fine grained quartz sandstone, arkosic limestone and arkosic conglomerate.	Cambrian, Devonian, and Lower Mississippian Aquitard*								
Paleozoic	Cambrian	Lower	Meagher Limestone	CDlM	374MGHR	110-140 (350-450ft)	Light to dark-gray, thin-bedded, fine-grained, trilobite and brachiopod bearing mottled limestone with some inter-bedded green shale. Dark gray massive resistant limestone. Gray, thin-bedded, fine-grained, limestone with interbedded green shale. Blue and gold mottled.	Cambrian, Devonian, and Lower Mississippian Aquitard*								
Paleozoic	Cambrian	Lower	Wolsey Shale	CDlM	374WLSY	50-64 (150-210ft)	Green and maroon, micaceous shale with interbedded micaceous sandstone and siltstone. Locally contains glauconitic, arkosic limestone.	Cambrian, Devonian, and Lower Mississippian Aquitard*								
Paleozoic	Cambrian	Lower	Flathead Sandstone	CDlM	374FLTD	40-45 (120-140ft)	White, buff, and orange, thin- to medium-bedded, fine-to coarse-grained quartz sandstone. Locally highly feldspatic, glauconitic beds and conglomerate.	Cambrian, Devonian, and Lower Mississippian Aquitard*								
	Precambrian		LaHood Formation (Belt)	Yl	400LHOD	0-3050 (0-10000ft)	Dark grayish-green, coarse- to very coarse-grained, poorly bedded arkose and conglomeratic arkose. Interbedded dark-gray argillite and siliceous limestone beds in northern part of area. Thickens to the north	LaHood Aquitard*	Potential aquifer if fractured and the fractures are interconnected.	No Data						
	Precambrian		Crystalline Metamorphic	Am	400PRBL 400MMPC		Gneiss, schist, metaquartzite, marble, injection gneiss, amphibolite, numerous pegmatite dikes and veins.	Crystalline Aquitard*	Potential aquifer if fractured and the fractures are interconnected or rock is weathered to grus even in subsurface.	4	m^2/day	1.7	1.5	N/A	0.5 - 5.6	0.9 - 3.1
											gpd/ft	130	120	N/A	40 - 450	74 - 250



*Insufficient well data available for statistical analysis. Designation based on regional hydrogeologic interpretation.