



Spatial investigation of ground water nitrate-nitrogen and coliform bacteria in the Gallatin Local Water Quality District, Gallatin County, Montana
by Mary Taylor Greenup

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

Rapid growth outside of municipal boundaries in Gallatin County, Montana, has raised concerns over ground water quality. Comprehensive data on ground water quality is needed in order to effectively manage the sustainability of the resource and to protect public health. This study compiled ground water quality data, primarily for nitrate-nitrogen and coliform bacteria in the Gallatin Local Water Quality District (GLWQD). Well locations were plotted within a Geographic Information System (GIS). Then previously cited independent variables were assigned based on spatial location in the GIS. Statistical tests were performed to discern the relationship between ground water nitrate-nitrogen and coliform occurrence and the a priori independent variables. Areas with septic system limitation ratings of shallow soils, insufficient soil percolation rates, and shallow depth to high water table are expected to have an increased risk for bacteria occurrence. The West Gallatin Alluvial aquifer has the lowest levels of both nitrate-nitrogen and coliform bacteria, presumably due to the greatest capacity for dilution. Predictive surfaces of nitrate-nitrogen values were created within GIS using geostatistical methods. An overall lack of presence data for coliform bacteria precluded modeling in GIS, leading to the conclusion that bacterial contamination in the GLWQD is not a regionalized phenomenon. Regional nitrate-nitrogen surfaces created in the GIS revealed that no areas in the GLWQD have a probability greater than 20% for exceeding 10 mg/l. However, areas along the western flanks of the Bridger Range and northern front of the Gallatin Range show a tendency for nitrate-nitrogen levels higher than expected from normal background levels. This pattern corresponds with the Quaternary-Tertiary Basin Fill aquifer. The finding suggests that continual loading of nitrate-nitrogen in these areas may pose future health risks due to limited dilution rates. Findings from this study are not to be used as a substitute for field investigation, nor to draw site-specific conclusions. This water quality database may be useful as a base-line for nitrate-nitrogen and coliform levels in the GLWQD so that managers, scientists, and citizens can make informed decisions regarding ground water quality protection and public health measures.

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APPROVAL

of a thesis submitted by

Mary Taylor Greenup

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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ABSTRACT

Rapid growth outside of municipal boundaries in Gallatin County, Montana, has raised concerns over ground water quality. Comprehensive data on ground water quality is needed in order to effectively manage the sustainability of the resource and to protect public health. This study compiled ground water quality data, primarily for nitrate-nitrogen and coliform bacteria in the Gallatin Local Water Quality District (GLWQD). Well locations were plotted within a Geographic Information System (GIS). Then previously cited independent variables were assigned based on spatial location in the GIS. Statistical tests were performed to discern the relationship between ground water nitrate-nitrogen and coliform occurrence and the *a priori* independent variables. Areas with septic system limitation ratings of shallow soils, insufficient soil percolation rates, and shallow depth to high water table are expected to have an increased risk for bacteria occurrence. The West Gallatin Alluvial aquifer has the lowest levels of both nitrate-nitrogen and coliform bacteria, presumably due to the greatest capacity for dilution. Predictive surfaces of nitrate-nitrogen values were created within GIS using geostatistical methods. An overall lack of presence data for coliform bacteria precluded modeling in GIS, leading to the conclusion that bacterial contamination in the GLWQD is not a regionalized phenomenon. Regional nitrate-nitrogen surfaces created in the GIS revealed that no areas in the GLWQD have a probability greater than 20% for exceeding 10 mg/l. However, areas along the western flanks of the Bridger Range and northern front of the Gallatin Range show a tendency for nitrate-nitrogen levels higher than expected from normal background levels. This pattern corresponds with the Quaternary-Tertiary Basin Fill aquifer. The finding suggests that continual loading of nitrate-nitrogen in these areas may pose future health risks due to limited dilution rates. Findings from this study are not to be used as a substitute for field investigation, nor to draw site-specific conclusions. This water quality database may be useful as a base-line for nitrate-nitrogen and coliform levels in the GLWQD so that managers, scientists, and citizens can make informed decisions regarding ground water quality protection and public health measures.

CHAPTER 1

INTRODUCTION

In the twenty-first century, world population growth is placing increased demands on finite natural resources. Water availability and water quality are of concern. Scientists, managers, and citizens require effective means of evaluating aquifer condition, susceptibility, and sustainability for drinking water needs. This project presents a systematic method of spatially evaluating ground water quality data with respect to physical and cultural variables, and the exploration of the data for patterns of occurrence. This type of information is useful to residents, managers, and scientists in preparing for future population growth and protection of ground water quality.

Montana, like many other states in the Rocky Mountain region has experienced a major influx of population over the last 50 years. Most of this growth has occurred in and around urban areas, where traditional farms and ranches are being converted to subdivisions for single family homes. Gallatin County, Montana, epitomizes this growth trend with nearly all new development occurring beyond municipal limits (Gallatin County Planning Office 1998) (Figure 1). According to the U.S. Census Bureau, the population in Gallatin County has more than tripled from just over 18,000 residents in 1940 to almost 68,000 in 2000. Twenty-five percent of the population has been added since 1990 (Figure 2).

Most family homes and businesses developing outside of the incorporated areas in Gallatin County rely on wells for drinking water and septic systems for on-site waste

removal. The increasing dependence of Gallatin County residents on ground water has led managers, scientists, and residents to investigate the status of ground water quality in the region. There is interest in determining whether growth and land use are impacting ground water quality in the region, and identifying areas at risk for experiencing ground water quality problems.

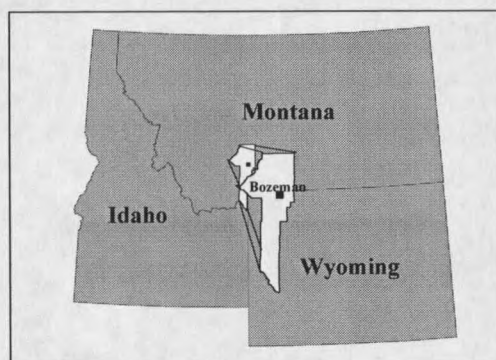


Figure 1. Gallatin County, Montana.

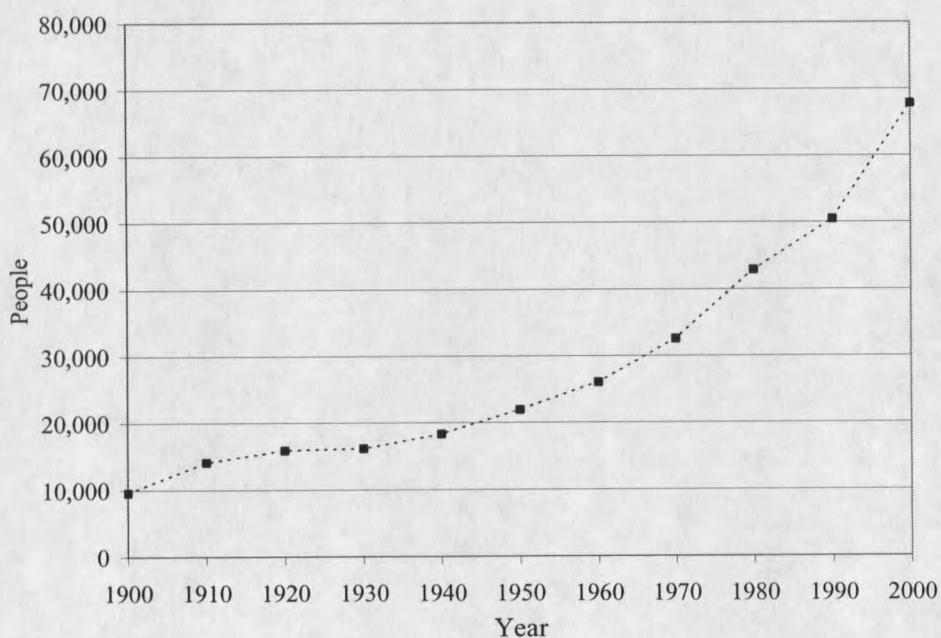


Figure 2. Population Growth in Gallatin County, Montana 1900 to 2000.

Nitrate and coliform bacteria are commonly measured ground water quality properties in Gallatin County. Increased knowledge of ground water nitrate and coliform levels in Gallatin County will provide insight into the possibility of ground water quality degradation. A water quality database with accurately located data can be coupled with a Geographic Information System (GIS), to query the database for spatial relationships with suspected associated variables. GIS investigative modeling for potential ground water health hazards should also be performed.

Nitrate is a danger to infants when the digestive system converts nitrate, NO_3^- , to nitrite, NO_2^- . At high levels, the hemoglobin of red blood cells are converted by nitrite to methemoglobin, which results in the loss of the blood's ability to carry oxygen (Jasa et al. 1998). Methemoglobinemia is thought to be induced when nitrate-nitrogen levels in drinking water reach 10 milligrams per liter (mg/l) or higher (Jasa et al. 1998; EPA 2001). Infants, and the elderly with intestinal disorders, are particularly susceptible to this deadly form of oxygen deprivation, often referred to as 'blue-baby syndrome'. Some documented causes of elevated nitrates in ground water include both point sources (confined stock lots, faulty septic systems) and nonpoint sources (fertilized lawns and farmland, soil organic nitrogen, and naturally occurring nitrogen in substrates).

In addition to nutrients, well owners often test for coliform bacteria as indicators of ground water quality. Although most strains of coliform bacteria do not cause sickness, the presence of the bacteria is thought to signal favorable survival conditions for harmful organic pathogens (ReVelle and ReVelle 1988; Skipton et al. 1998; GLWQD 2001). If coliform are cultivated during a water quality test, the colonies are differentiated

to determine the proportion, if any, of fecal coliform. Fecal coliform occurrence is presumed to indicate contamination from the feces of warm-blooded mammals, likely associated with point sources (EPA 2001; GLWQD 2001). Because of its origin, fecal coliform presence is thought to raise the risk of the existence of other viruses or protozoa like hepatitis and giardia (Wireman and Job 1998). The human health standard for fecal coliform is less than 1 per 100 milliliters (ml) (EPA 2001; MT DEQ 2001a). The elderly, infants, and those with compromised immune systems are most vulnerable to intestinal bacteria infections. Naturally occurring colonies, faulty well construction, and leaking septic systems are some known sources of coliform bacteria in ground water.

Purpose of Project

There are historic as well as current ground water quality records for wells in the Gallatin Valley. Public funded studies have resulted in the establishment of baseline data for the Gallatin Local Water Quality District (GLWQD). The possibility of establishing a larger ground water quality monitoring network exists with inclusion of accurately located private well data. The purpose of this project is to create and spatially investigate a large ground water nitrate-nitrogen and coliform bacteria dataset with representation across the GLWQD. Such knowledge will provide a better understanding of ground water quality within the GLWQD. This information is valuable from the perspective of public health and planning for future growth.

Hackett et al. (1960) with the United States Geological Survey (USGS), began the first, and to date, the most comprehensive evaluation of the ground water resources in the

Gallatin Valley in the early 1950's. During the late 1970's, D. Dunn (1978) attempted to recreate Hackett et al.'s (1960) water quality investigation for a local commission, the Blue Ribbons of the Big Sky Country Areawide Planning Organization. Scientists, S. Slagle (1995a) and E. Kendy (2001) conducted the most recent USGS ground water quality research in the GLWQD.

Another public entity, the state of Montana, also monitors ground water quality in the GLWQD. The Montana Department of Public Health and Human Services (DPHSS), maintains a large database of water quality tests performed across the state. Unfortunately, the DPHSS has made little effort to collect sample site information, which renders the data virtually useless for this type of study. The Montana Department of Environmental Quality (MT DEQ), monitors water quality for Public Water Supply Systems (PWSS). And the Montana Bureau of Mines and Geology's Ground Water Information Center (GWIC), stores readily accessible ground water quality data for public use.

Although public ground water quality data for the GLWQD exists, the largest USGS monitoring network includes only 101 wells of an estimated 10,000 or more. As for state records, the GWIC database contains less than 100 records for ground water quality in the GLWQD. Over half of GWIC's water quality records for the GLWQD are from the USGS monitoring network wells. Other GLWQD well water quality records in the GWIC database may be located at scales too coarse for the study analysis.

In order to create a more comprehensive well water quality monitoring network for the GLWQD, data should be assembled from public studies and a local private

company, Montana Microbiological Services (MMS). MMS has been analyzing and digitally collecting site-specific nutrient and bacterial information for PWSS and private wells within the GLWQD since the mid 1990's. The assimilation of accurately located, public and private ground water quality data enables the building of a robust database for the GLWQD.

Wells in the GLWQD associated with water quality records for nitrate-nitrogen and coliform bacteria information will be located within a GIS. Patterns will be explored as well as relationships with previously cited independent variables. Statistical correlations will be examined between ground water nitrate-nitrogen and coliform bacteria and independent variables of septic system limitation ratings, housing density, proximity to land application of wastes, farming methods, well depth, and hydrogeology. Predictive GIS modeling of regional ground water quality in the GLWQD will also be conducted. The research results and GIS models may have value to homeowners, regulators, and scientists seeking to better understand the relative risk of groundwater contamination in the GLWQD and may provide insight for developing strategies to reduce these risks.

Study Area

The Gallatin Local Water Quality District is located in Gallatin County, southwestern Montana (Figure 1). The semiarid climate and mountainous landscape of the GLWQD reflects its placement east of the Continental Divide in the Northern

Rockies. The borders of the GLWQD conform to that of the county along its eastern margin and to Montana Public Land Survey System (PLSS) townships in all other directions. Altogether the GLQWD ranges from Township 1 North to Township 5 South, and Range 3 East to Range 7 East (Figure 3). The boundaries were chosen to encompass the areas of fastest growth in the county, the lands surrounding Bozeman and Belgrade.

There are over 2,000 square kilometers (km^2) in the GLWQD. This includes the central Gallatin Valley, portions of the Bridger and Gallatin ranges, and a small section of the Madison Range and Plateau. The Gallatin River and its tributaries shape the broad plains of the valley, carrying water from the highlands and draining ultimately into the Missouri River. The river system is a significant source of water in this semi-arid environment and an important component in the recharge and discharge of alluvial aquifers in the valley.

The climate of the GLWQD is influenced by high elevations (1,240 m to 3,350 m), northern latitude ($45^\circ 21'$ to $45^\circ 52'$), and its location east of the divide in the Northern Rockies ($-100^\circ 47'$ to $-111^\circ 24'$). Temperature and precipitation gradients exist between the mountains and the valley. Annual precipitation can range from less than thirty-six centimeters in the northwestern part of the GLWQD to over one-hundred centimeters in the high peaks of the Bridger and Gallatin ranges (Custer et al. 1996; Western Regional Climate Center 2002). Winter temperatures are usually below freezing, with cold spells and snow storms possible anytime of the year. Summers are mild, yet temperatures in July and August are commonly around 30°C . Most of the area's precipitation is received April through June, in the form of snow and spring rains.

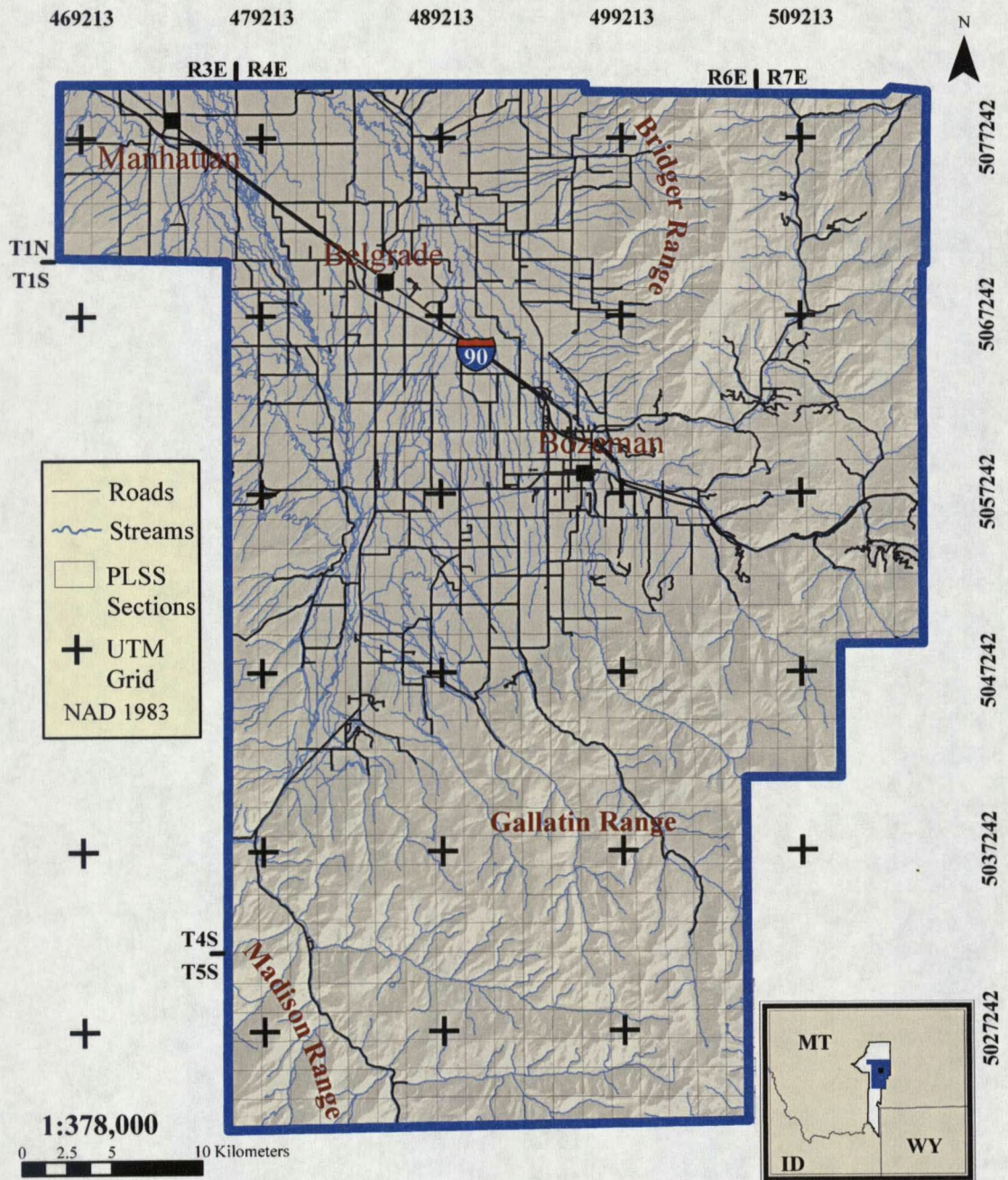


Figure 3. The Gallatin Local Water Quality District, Gallatin County, Montana.

Geology and Hydrogeology

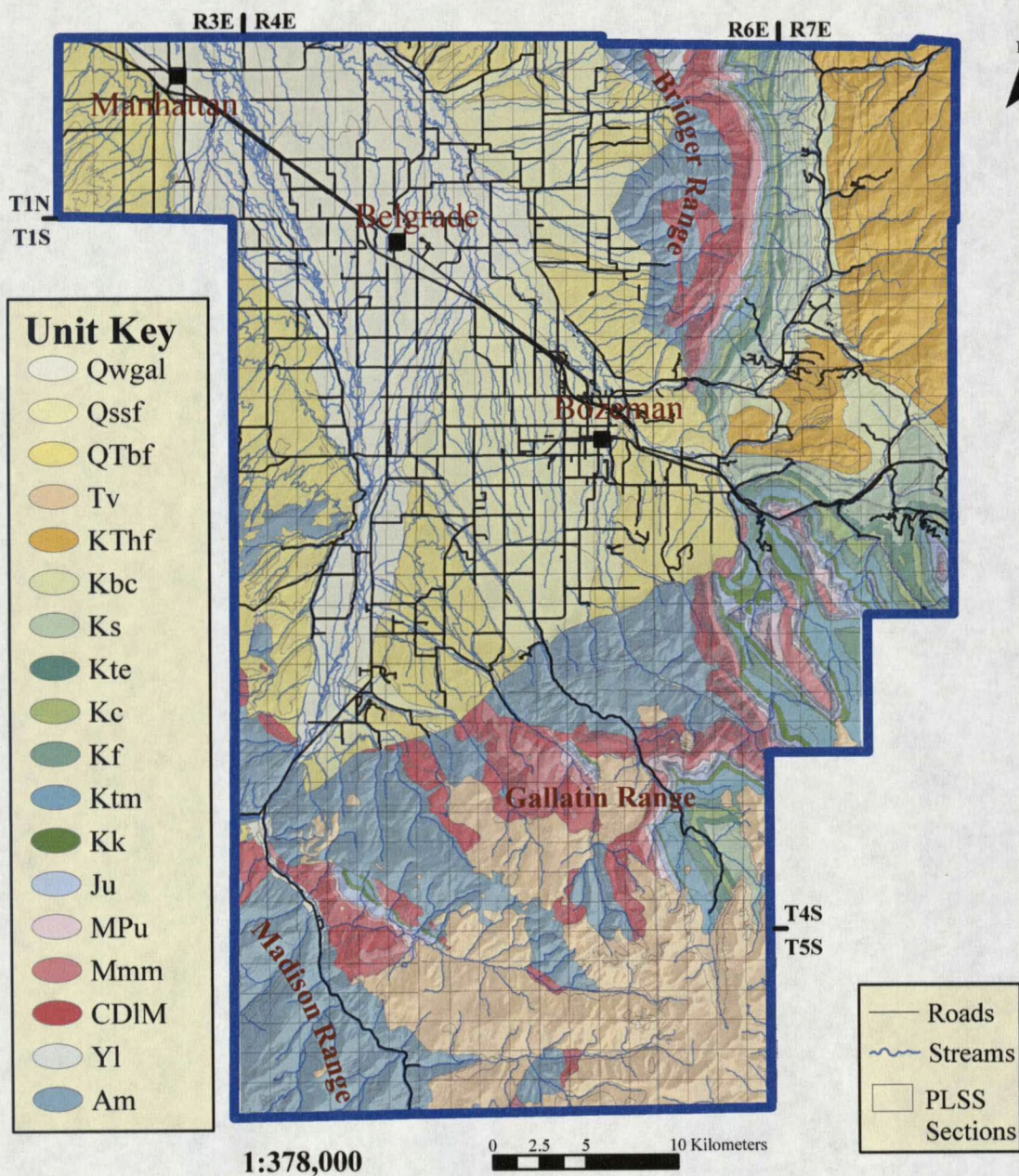
The Gallatin Valley, an eastward tilted graben, is in the Three Forks structural basin (Hackett et al. 1960; Custer 1991; Kendy and Tresch 1996; Kendy 2001). The valley is believed to have been formed during Cenozoic crustal extension of the middle Eocene to late Miocene (Lageson 1989). Valley fill during the Tertiary consisted of sand, silt, clay, gravels, and volcanic ash under fluvial and in some areas lacustrine type conditions (Hackett et al. 1960; Lageson 1989; Custer 1991; Kendy and Tresch 1996; Kendy 2001). Heterogeneous glaciofluvial and coarse grained alluvial materials were deposited in the Quaternary. Alluvial fan formation and floodplain development are believed to have been continuous throughout these periods (Custer 1991; Hackett et al. 1960; Kendy and Tresch 1996; Kendy 2001).

Normal faults exist at the base of the Bridger and Gallatin ranges, and faulting is suspected on the western margin of the valley (Custer 1991; Hackett et al. 1960; Kendy and Tresch 1996; Kendy 2001). Rocks exposed in the Bridger Range vary in age from Archean and Proterozoic basement rocks to Paleozoic through Mesozoic sediments (Lageson 1989). The Gallatin Range has a core of Archean metamorphic crystalline rocks which are overlain by Eocene volcanics (Lageson 1989). Precambrian basement rock outcrops along the western margin of the valley and is believed to underlie the valley floor (Hackett et al. 1960; Kendy and Tresch 1996; Kendy 2001).

Ground water flow direction is generally from the mountains to the valley floor, then towards and eventually parallel with the Gallatin and East Gallatin Rivers (Hackett

et al. 1960; Kendy 2001). Complex local flow systems are expected where fault systems, beds or lenses of low permeability materials, surface water interactions, and or pumping wells are present (Custer 1991; Fetter 2001). Recharge occurs largely by infiltration from influent streams and from precipitation, as water is taken into storage from late spring to early summer (Hackett et al. 1960; Kendy 2001). Irrigation farming also affects recharge locally, leading many to speculate that loss of irrigated farmland may result in a lowering of the water table in some areas (Hackett et al. 1960; Slagle 1995a; Kendy and Tresch 1996; Kendy 2001). Evapotranspiration and loss to effluent streams downgradient are key discharge mechanisms (Hackett et al. 1960; Kendy 2001). Hackett et al. (1960) calculated that close to three million cubic meters of ground water leave the valley each year as surface water. Ground water levels measured during Hackett et al.'s (1960) study are similar to those recorded more recently (Dunn 1978; Custer 1991; Slagle 1995a and 1995b; Kendy 2001).

Most wells within the GLWQD tap Quaternary alluvium of the Gallatin River and associated drainages, and Quaternary-Tertiary basin fill alluvium (Slagle 1995a and 1995b; Kendy and Tresch 1996; Kendy 2001; Dixon and Custer 2002). Gravity data indicate that the alluvium may be as much as 2000 meters deep at its thickest (Lageson 1989; Custer 1991; Kendy 2001). These aquifers are heterogeneous mixtures of sand, gravels, and clays having yields ranging from excellent to fair (Dixon and Custer 2002). With rock exposure dating to the Archean, there are over fifteen distinct lithologic units in the GLWQD (Dixon and Custer 2002) (Figure 4).



Unit Code: QwGal = West Gallatin Alluvial Aquifer, Qssf = Small Stream and Fan Aquifer, QTbf = Quaternary -Tertiary Basin Fill Aquifer, Tv = Volcanic Aquitard, KThf = Hoopers-Fort Union Aquifer, Kbc = Billman Creek Aquitard, Ks = Sedan Aquifer, Kte = Telegraph Creek-Eagle Aquifer, Kc = Cody Aquitard, Kf = Frontier Aquifer, Ktm = Thermopolis-Mowry Aquitard, Kk = Kootenai Aquifer, Ju = Jurassic Aquitard, MPu = Upper Mississippian-Permian Aquitard, Mmm = Mission Canyon Aquifer, CDIM = Cambrian, Devonian, and Lower Mississippian Aquitard, Yl = LaHood Aquitard, Am = Crystalline Aquitard

Figure 4. Hydrogeologic Units in the GLWQD (Dixon and Custer 2002).

Ground Water Quality

The Quaternary and Tertiary aquifers in the GLWQD tend to be of calcium bicarbonate type, with the presence of sodium, magnesium, and increased dissolved solids found in older Tertiary deposits (Hackett et al. 1960; Kendy 2001) (Figure 4). Total dissolved solids generally range from 200 to 500 mg/l. In 1998, Kendy (2001) used CFCs to date ground water recharge, which ranged from less than ten years to over forty years.

Although not statistically significant, researchers have suggested there has been an increase in total dissolved solids and nitrates, since Hackett et al.'s (1960) original study (Dunn 1978; Slagle 1995a; Kendy 2001). The majority of historic and recent nitrate-nitrogen data for the GLWQD are within human health standards; however, the median level, around 2.0 mg/l is greater than what would be expected from atmospheric deposition alone (0.5 mg/l) (Hantzsche and Finnemore 1992; Kendy 2001). Kendy (2001) hypothesizes that soil organic nitrogen and nitrogen from fertilizers are the biggest contributors to nitrates in drinking water. No formal study has been conducted into coliform occurrence in the GLWQD.

CHAPTER 2

GROUND WATER QUALITY

Ground Water Quality: Nitrate and Coliform Bacteria

Nitrate and coliform bacteria can degrade ground water quality. Ground water quality is a function of the chemistry of the hydrogeologic environment and can be modified by contamination from point and nonpoint sources (Fetter 2001; Wireman and Job 1998). In aquifers, diffusion and advection are the primary transport mechanisms for dissolved “ionic and molecular species” (Fetter 2001). Nitrate, NO_3^- , an ionic solute, is the most common form of nitrogen dissolved in water. Nitrate is subject to dilution in ground water. Relative to the size of solutes, coliform bacteria are quite large and are subject to filtration (Hagedorn et al. 1981; Wilhelm et al. 1994). Coliform bacteria are also susceptible to die-off. Nitrates and coliform bacteria can enter ground water as a result of contamination, but may also be present due to environmental conditions.

Nitrate in Ground Water

Nitrate is an oxidized form of nitrogen, the most abundant gas in the Earth's atmosphere. During the nitrogen cycle, ammonia is the intermediary form of nitrogen that is nitrified by specialized bacteria to nitrite and nitrate (Ricklefs 1990) (Figure 4). In anaerobic environments, nitrate and nitrite are denitrified to nitrous oxide and nitrogen gas by bacteria (Ricklefs 1990). Denitrification is most likely to occur in saturated or near

saturated soils with relatively high pH values and available organic carbon (Hantzsche and Finnemore 1992; Wilhelm et al. 1994; Gold et al. 2001). On a global scale, the fixing of organic and molecular nitrogen to nitrate is “approximately balanced” with the process of denitrification (Ricklefs 1990).

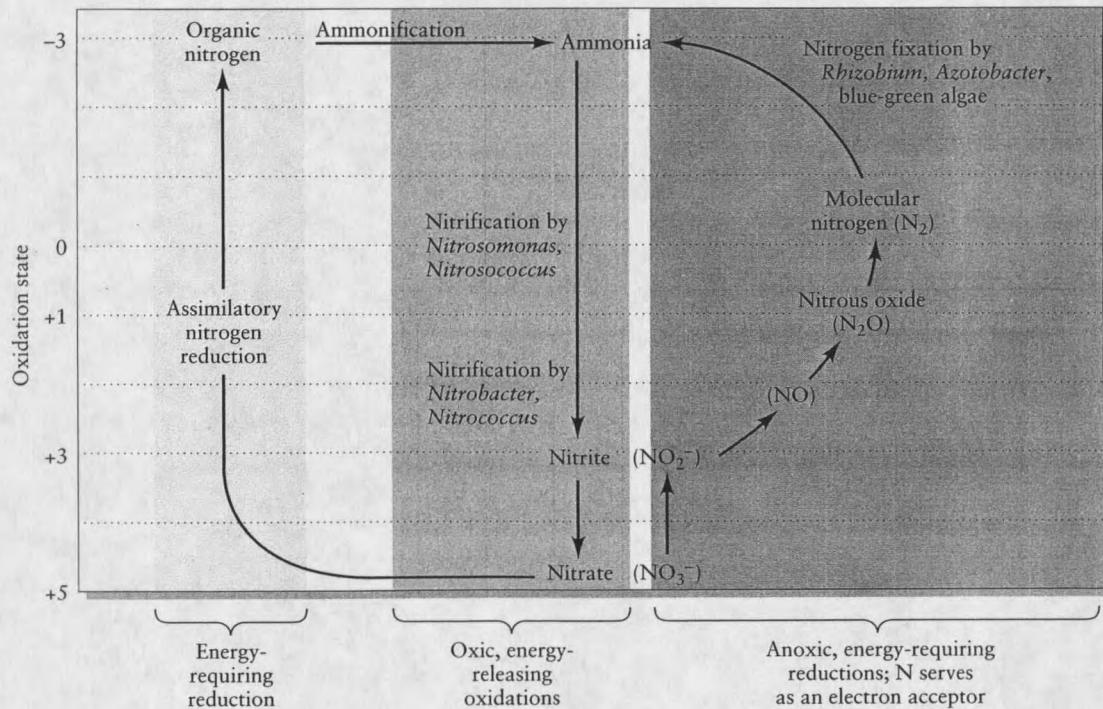


Figure 5. The Nitrogen Cycle (Ricklefs 1990).

Background values for nitrates in ground water are expected to range from 0.5 to 1.0 mg/l from atmospheric deposition and soil organic nitrogen (Hantzsche and Finnemore 1992; Kendy 2001). Bedrock interactions with ground water may also provide a natural geologic source of nitrogen. Power et al. (1974) determined that Paleocene shales with exchangeable ammonium nitrogen can be a significant contribution of nitrate to ground water when exposed to the atmosphere. Commonly documented causes of elevated nitrate levels in ground water include confined stock lots, fertilized

lawns and farmland, faulty septic systems, and excess leaching of soil organic nitrogen (Kreitler and Davis 1975; Bauder et al. 1993; Arnade 1999).

Water quality standards for nitrates are based on the health risk of methemoglobinemia to infants, but nitrates are also known to be poisonous to pigs, chicken, cattle, and sheep (Stuart et al. 1995; EPA 1999). Nitrates are harmful when key bacteria are lacking to prevent the conversion of nitrate to poisonous nitrite (NO_2^-) in the digestive tract. In addition to the risk of methemoglobinemia, some researchers have linked "gastric cancer, lymphoma, thyroid disorder, and birth defects" to elevated nitrate levels in drinking water (Schubert et al. 1999, 243). For ground water in Montana, nitrate as nitrogen ($\text{NO}_3\text{-N}$) has a Human Health Standard of 10 mg/l, a Required Reporting Value of 0.01 mg/l, and the Trigger Value is 5 mg/l (MT DEQ 2001a). Trigger Values indicate the possibility of degradation. Because many nitrate sources are anthropogenic, high values may also signify the possibility of other contaminants, such as pesticides (Tesorio and Voss 1997; Kendy 2001).

Kendy (2001) concluded from ratios of the stable isotopes of nitrogen (N_{14} and N_{15}) in ground water that soil organic nitrogen and fertilizers are the most likely sources of ground water nitrate in the GLQWD. Nitrate is a rather stable ion and can be mobilized through the soil layer to the water table (Hantzsche and Finnemore 1992; Stuart et al. 1995). Nitrate levels are usually low in ground water, owing to uptake by plant roots and recharge from precipitation. Elevated nitrates in ground water have been attributed to septic systems and agricultural practices, such as irrigation, dryland/crop fallow, fertilization, and livestock operations.

Soil denitrification and dilution are crucial mechanisms for the reduction of nitrate levels in ground water (Hantzsche and Finnemore 1992). Denitrification is favored in saturated, basic soils with a carbon source. Low recharge rates and contamination of upgradient water can significantly impact the dilution of nitrate in ground water (Hantzsche and Finnemore 1992). Previous researchers in the GLWQD have detected average ground water nitrate levels below Human Health Standards, but above expected background levels (Hackett et al. 1960; Dunn 1978; Slagle 1995a; Kendy 2001). Because nitrate loadings to ground water from land use practices tend to have cumulative impacts, it is important to identify possible regional landscape variables that may have a significant association with nitrates in the GLWQD.

Coliform and Fecal Coliform in Ground Water

Bacteria are common in soil and surface water (ReVelle and ReVelle 1988; GLWQD 2001). Coliform bacteria have been identified to exist naturally in shallow confined and unconfined aquifers (EPA 1998; Wireman and Job 1998; USGS 2001). The majority of bacteria in ground water may live in symbiotic colonies called biofilms on the aquifer substrate materials or on surfaces of the well like the casing and gravel pack (Schnieders 2001; USGS 2001; Oliphant et al. 2002) (Figure 6). As a general rule, for every free swimming bacterium there are one million sessile (Schneiders 2001). Conversely, fecal type coliform are thought to originate only in the intestines of warm-blooded animals. Animal wastes, faulty well construction, and leaking septic systems are some identified sources of fecal coliform in ground water (Arnade 1999; Entry et al. 2000; Pumley 2001).

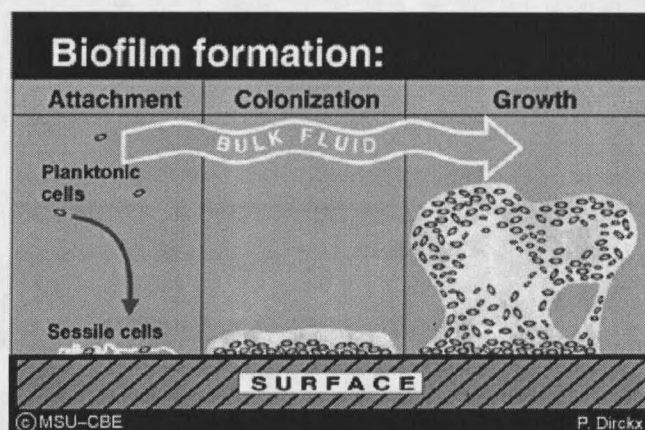


Figure 6. Biofilm Formation (The Center for Biofilm Engineering 2003).

Coliform bacteria, a type of bacteria called *Enterobacteraceae*, are used as indicator organisms in ground water quality tests and are often found in the natural environment (GLWQD 2001). In Montana, human health standards are set only for fecal coliform at less than 1/100 ml, with Trigger and Required Reporting Values also at 1/100 ml (MT DEQ 2001a). Coliform bacteria, including fecal, do not necessarily cause sickness, but their survival could indicate favorable conditions for pathogenic bacteria, protozoa and viruses (ReVelle et al. 1988; Skipton et al. 1998; GLWQD 2001). If coliform are accompanied by harmful pathogens ailments could include "intestinal infections, dysentery, hepatitis, typhoid fever, [and] cholera" (Skipton et al. 1998, online).

Many debate the use of coliform bacteria to indicate the presence of viruses, because research has not proven definite similarities between survival mechanisms (Hagedorn et al. 1981; Reneau et al. 1989; USGS 2001). This is because viruses are much smaller than bacteria and carry a negative charge. Viruses and bacteria likely have differing transport and retention mechanisms (Wilhelm et al. 1994; Hagedorn et al.

1981). Bacteria have been documented to live and grow in soil and hydrologic environments (Reneau et al. 1989; Wilhelm et al. 1994; USGS 2001). In one study, fecal coliform were found to survive for years in lake bed sediments (Reneau et al. 1989). Thus, total coliform presence may indicate nothing more than a microbiologically active environment. But with fecal coliform present, the possibility of health risk must be considered because of the bacteria's origins and possible associations with viruses.

Subsurface survival of coliform bacteria is determined by factors such as moisture content, temperature, pH, and rate of transport. In soil filtration experiments, coliform bacteria, including fecal coliform, have been found to survive from a week to months under favorable conditions: these are moist or saturated settings, with low temperatures, and near neutral pH (Reneau et al. 1989; Wilhelm et al. 1994; Entry et al. 2000). Saturated flow through transmissive soils and soil macropores can result from intense precipitation events, seasonally high water tables, and perched water tables (Hagedorn et al. 1981; Chen 1987; Reneau et al. 1989; Wilhelm et al. 1994; Arnade 1999; Fajardo et al. 2001). These events facilitate transport of microorganisms to the water table, increasing the possibility of survival.

The presence of fecal coliform in well water may indicate either a vulnerable hydrogeologic setting or site specific issues with the well. Aquifer contamination could result from hydraulic connection with tainted surface waters and runoff or from improperly functioning septic systems. When a well sample tests positive for fecal coliform bacteria, owners are advised to 'shock chlorinate' the well (Skipton et al. 1998; GLWQD 2001; Schnieders 2001). However, Oliphant et al. (2002) found shock

chlorination an inadequate treatment for wells in an alluvial aquifer impacted by septic systems. Because fecal coliform indicates a potential health risk, it is important to identify possible regional landscape variables that may have a significant association with their occurrence in the GLWQD.

Hypothesized Nitrate and Coliform Contamination Sources in the GLWQD

Septic Systems

In the U. S., septic systems make the largest contribution of waste water to soils and have been linked to cases of aquifer contamination (Hagedorn et al. 1981; Chen 1987; Reneau et al. 1989; Yates and Yates 1989; Arnade 1999; Oliphant et al. 2001). In the GLWQD, there are more than 4,000 operating septic systems (Custer et al. 2000). According to Rupp (1998, 3), "In the last decade, more than two thousand new septic systems have been installed within the County". Domestic waste water can contain toxic chemicals and pathogens. Reneau et al. (1989) estimate that average nitrate values in septic tank effluent range from 40 to 80 mg/L, with fecal coliform populations on the order of 4×10^5 /100 ml. If the waste water has been treated in a properly sited and functioning septic system, nitrate levels should be low due to denitrification, while microbes should be filtered and retained in the soil. However, many optimum conditions must be met to avoid the release of excess pollutants to ground water (Reneau et al. 1989; Vogel 1994; Wilhelm et al. 1994; Vogel and Rupp 1996).

Conventional septic systems rely on gravity, groundwater flow, microbes, and soil filtration to remove solids, degrade nutrients, and dilute contaminants before the effluent reaches the water table. There are two basic parts to the septic system design: the septic tank and drainfield (Vogel and Rupp 1996). In the septic tank, heavy solids are removed from the wastewater by settling. The drainfield provides an outlet for waste water from the septic tank, and should evenly distribute the water for percolation to the soil. Often a biological mat of organisms will grow in the drainfield, which aids in degrading contaminants and can provide key constituents for chemical reactions (Reneau et al. 1989; Wilhelm et al. 1994). Soils below the drainfield need to be of adequate depth and texture to allow drainage yet provide further attenuation of waste water before contact with the water table.

The chemical conversion of nitrogen compounds in septic system effluent ideally involves three major reactions. First in the anaerobic environment of the septic tank, nitrogen in urea and proteins are converted to ammonia, NH_4^+ (Wilhelm et al. 1994). Secondly, if adequate oxygen is available, almost total conversion of ammonia to nitrate occurs in the drainfield or just below the drainfield in the soil (Hantzsche and Finnemore 1992; Wilhelm et al. 1994; Reneau et al. 1989). Lastly, the denitrification of nitrite to nitrogen or nitrous oxide requires anaerobic conditions, such as, saturated or near saturated soils with high soil pH, and a source of organic carbon (Hantzsche and Finnemore 1992; Wilhelm et al. 1994). Many argue that inadequate denitrification of septic effluent often leads to the release of nitrates to ground water in concentrations many times the human health standard (Wilhelm et al. 1994; Reneau et al. 1989).

Preferably, bacteria and viruses in septic effluents are not released to the water table. In the septic tank, the release of hydrogen ions will reduce the pH of the waste water and could reduce the numbers of microorganisms if no buffering agent is present (Wilhelm et al. 1994). Removal of bacteria and perhaps viruses is attained by straining through the biomat and adsorption on soil particles (Hagedorn et al. 1981; Reneau et al. 1989; Wilhelm et al. 1994). Soils with moderate to high clay content and fine particle sizes have been found to be more effective at retaining bacteria and viruses, and once they are retained in the soil, unsaturated conditions encourage die-off (Hagedorn et al. 1981; Reneau et al. 1989; Wilhelm et al. 1994).

While there are many site specific causes for septic system failure, regional variables may also influence septic system functionality. Landscape variables, such as soil and hydrologic properties influence septic system performance (USDA 1996) (Figure 7). Because septic systems have been linked to aquifer contamination, it would be beneficial to discern if there is a significant link between septic site limitations and ground water contamination in the GLWQD. Following are hypotheses to be tested for associations between septic system limitation ratings and ground water nitrate-nitrogen and coliform bacteria.

Wells in areas of shallow soils are more likely to experience nutrient and coliform degradation owing to less soil area for retention and denitrification to occur.

Wells in areas of soils with insufficient percolation rates are more likely to experience coliform degradation and less likely to experience nutrient contamination owing to favorable environments for bacteria survival and denitrification.

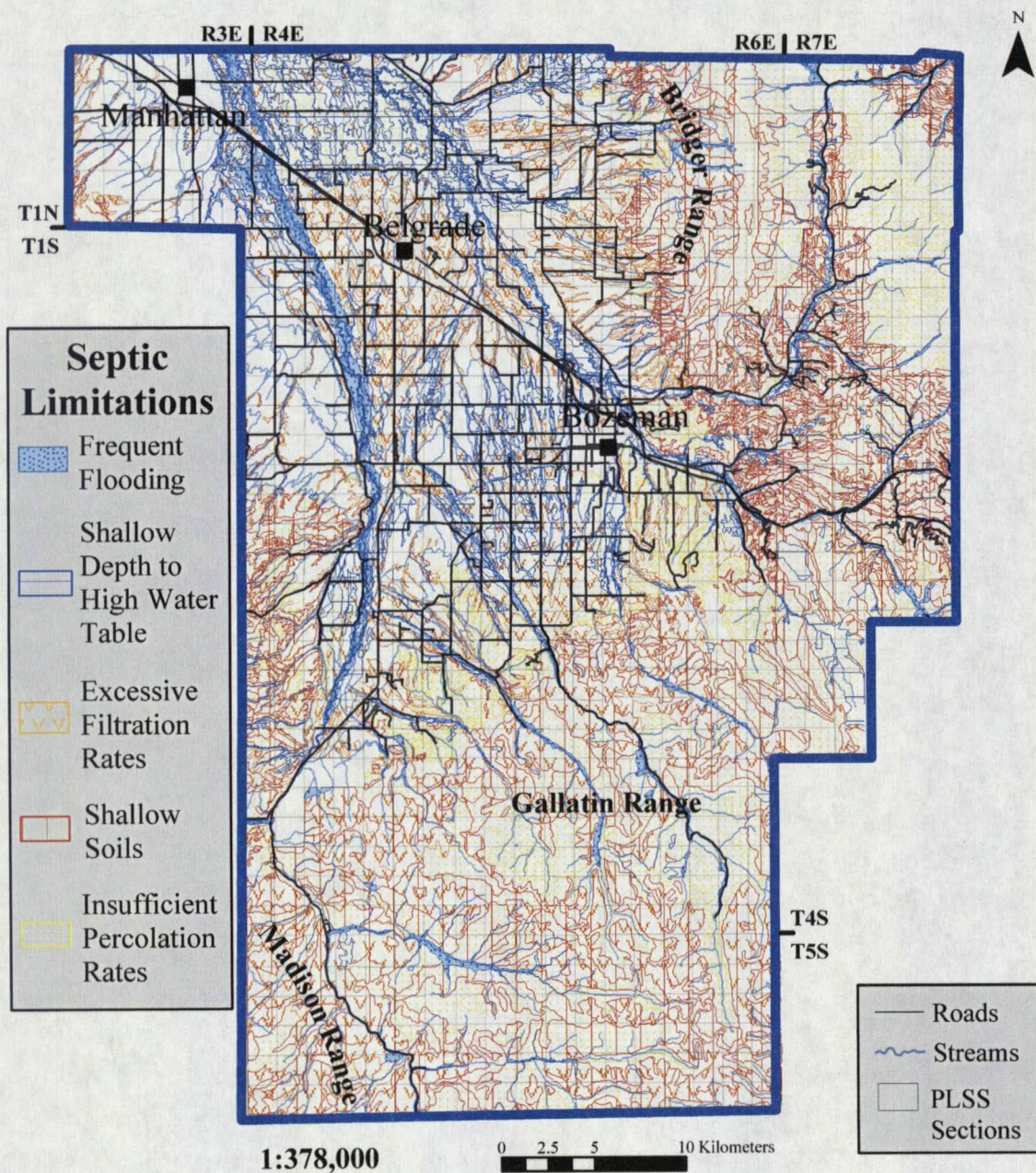


Figure 7. Severe Septic System Limitations Rated by Soil and Hydrologic Properties in the GLWQD (Custer et al. 2000).

Wells in areas of soils with excessive filtration rates are less likely to experience coliform degradation and more likely to experience nutrient contamination owing to unfavorable environments for bacteria survival and denitrification.

Wells in areas of soils with shallow depth to high water table are more likely to experience nutrient and coliform degradation owing to facilitated transport of effluent to the water table.

Wells in areas of soils with high flooding frequency are more likely to experience coliform degradation owing to hydraulic connection with surface waters.

Housing Density

Dense housing developments are thought to increase the risk of well contamination by nitrates and coliform bacteria due both to a concentration of septic systems and lawn fertilizer application (Slagle 1995a; Kendy and Tresch 1996; Tesorio and Voss 1997; Tuthill et al. 1998; Arnade 1999). Within the last twenty years, the Gallatin Valley has experienced an increase in the number of residential subdivisions, in areas that were once predominantly open farmland. The rapid population growth rate coupled with the prevalence of non-sewered subdivisions presents a concern for the integrity of the ground water quality.

Conversion of fertilizer nitrogen to nitrate is similar to the process by which the ammonia in septic effluent is nitrified. Excess water and nitrogen compounds must be available to leach nitrate from the surface to ground water. Septic systems have the potential to discharge not only nitrates, but also bacteria and pathogens. Prior researchers

have used lot size as a measure of housing density and have discovered a statistically significant inverse relationship between lot size and nitrate and coliform occurrence (Tuthill et al. 1998; Arnade 1999). Slagle (1995a) theorized that the high levels of nitrates he measured in ground water could correspond with one of the more densely developed areas of the GLWQD, but the hypothesis has not been rigorously tested.

The rapid population growth and increase of non-sewered subdivisions in the GLWQD has the potential to negatively affect ground water quality. Ground water remediation is costly in comparison to prevention methods, such as waste water treatment facilities (Fetter 2000). In light of previous research, it would be beneficial to discover if there is a relationship between housing density and nitrate and coliform contamination in the GLWQD (Slagle 1995a; Kendy et al. 1996) (Figure 8).

The hypothesis to be tested is that wells in the GLWQD with high numbers of upgradient structures are more prone to coliform and nitrate contamination, than wells with fewer numbers of upgradient structures.

Land Application of Wastes: Septage and Biosolids

The application of biosolids and septic sludge, septage, occur within the GLWQD on approved agricultural lands as a method of fertilization. From 1996 to 2000, biosolids and septic sludge were spread over approximately 5,000 and 1,600 km² respectively (Bozeman Wastewater Treatment Plant 1999; Gallatin County Environmental Health Services 1999) (Figure 9).

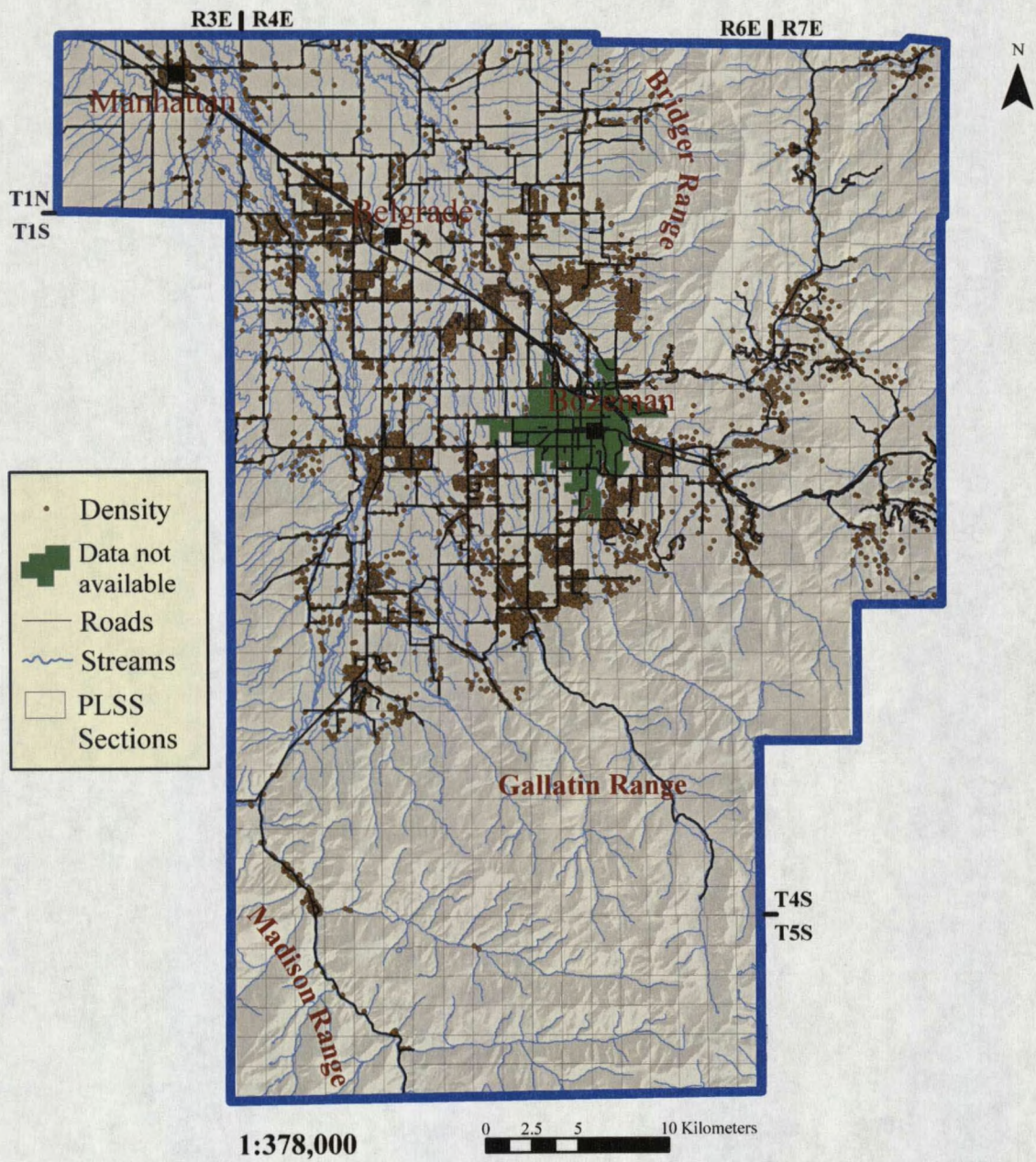


Figure 8. Housing Density in the GLWQD (Gallatin County GIS Department 2002).

Biosolids are heavily treated municipal organic wastes that meet the specific health requirements of pathogen reduction, vector attraction reduction (insects, rodents), pollutant limits, and specified rates and uses (Girovich 1996). Biosolids application is carried out by the City of Bozeman under an EPA initiative. Septic sludge is regulated by the state, through the Department of Environmental Quality and the Gallatin County Environmental Health Department. Minimal treatment is required of the septic sludge; however nitrogen agronomic rates and site conditions must be met (MT DEQ 2001b).

Surface applications of animal wastes have also been cited as causing increased levels of nutrients and coliform bacteria in soil and ground water (Stuart et al. 1995; Entry et al. 2000; Fajardo et al. 2001; Kendy 2001). Entry et al. (2001) detected 10 to 1000 times more total and fecal coliform concentrations in soil and shallow ground water from the land application of swine wastes. Fajardo et al. (2001) concluded that residence time and dilution were the most significant factors affecting reductions in bacteria and nitrate in runoff from waste study plots.

An alkali stabilizer is required for vector reduction in septic wastes, but land owners can waive this option (MT DEQ 2001b). Nitrogen is the most limiting factor for the application biosolids, while pathogen reduction should kill most bacteria (Girovich 1996). For both methods, site requirements must be met, such as, adequate setback distances from dwellings and surface and ground water. Because land application of waste has been associated with increases in nitrates and coliform bacteria the effect, if any, of these applications to ground water quality in the GLWQD is of interest.

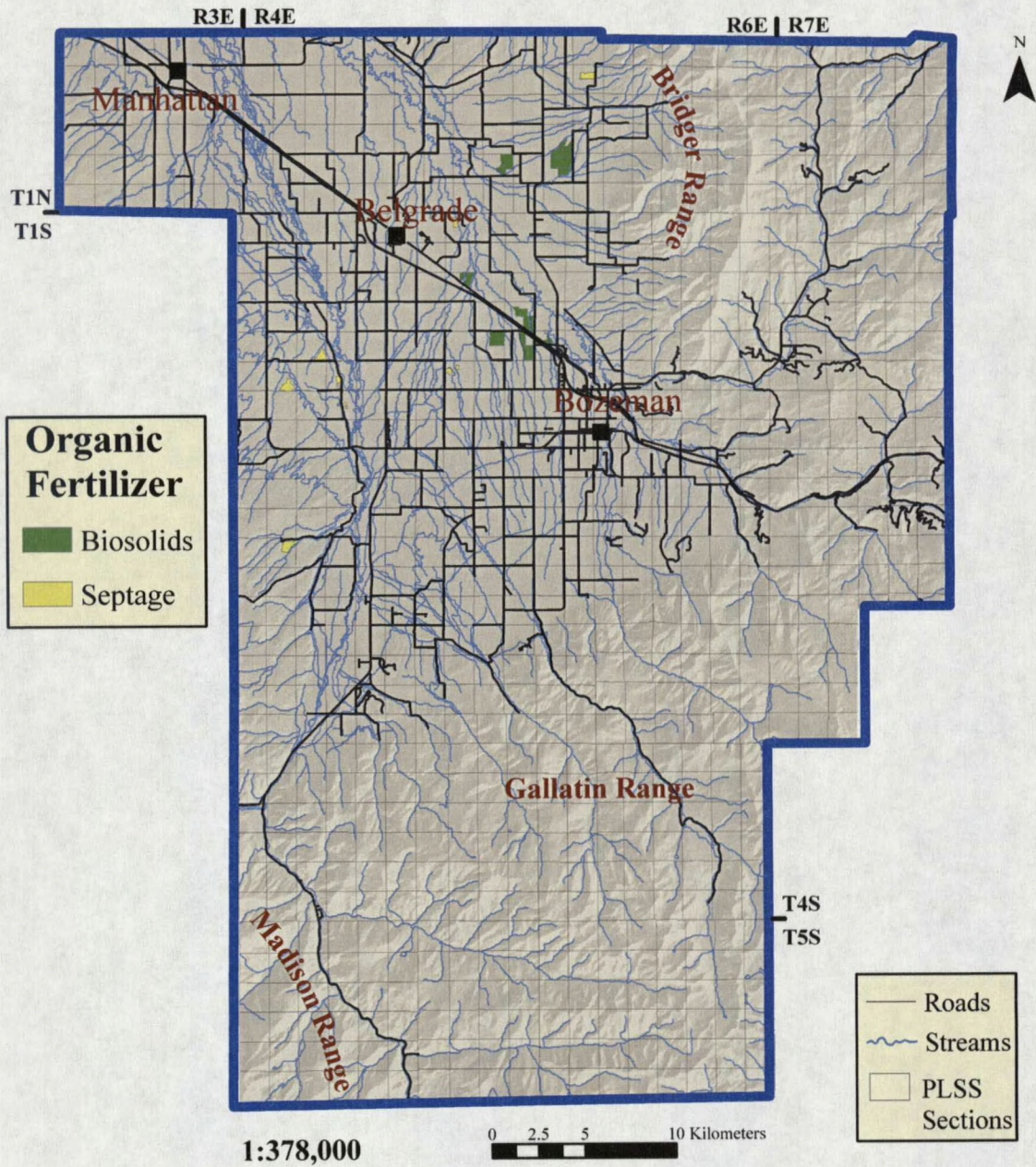


Figure 9. Designated Lands for the Application of Septage and Biosolids in the GLWQD.

The hypothesis to be tested is that GLWQD wells within a fixed radius of septage spreading operations are more likely to show contamination than those within the same fixed radius of biosolids applications.

Farming Practices:

Irrigation and Dryland Farming

Agricultural practices have frequently been cited as a cause for elevated dissolved solids, including nitrate in ground water (Kreitler and Davis 1975; Custer 1976; Dunn 1979; Bauder et al. 1993; Wylie et al. 1994; Slagle 1995a). Although development is occurring at a rapid pace in the Gallatin Valley, agricultural practices are still common. Hay, wheat, and barley are the most abundant crops grown, while potatoes and oats are also a mainstay. Dryland/crop fallow and irrigation farming are the dominant practices in the GLWQD (USDA 2002). Dryland/crop fallow sites have the potential to release soil organic nitrogen from decaying plant matter, which is mobilized by the increased infiltration of precipitation. Researchers theorize that irrigation farming causes excess water to leach nutrients and fertilizers to the ground water.

Kreitler and Davis (1976) discovered that nitrate contamination of ground water in a predominantly agricultural region of Texas is attributed to soil organic nitrogen, released in response to dryland farming techniques. Custer (1976) found that cultivated fallow wheat sites in eastern Montana had ground water nitrate levels thirty to fifty times that of native sod. In a study of ground water nitrate levels in Montana, Bauder et al. (1993, 255) concluded that "summer fallow practices ...may be contributing to regionalized [nitrate-nitrogen] contamination of shallow groundwater in Montana".

The artificial recharge provided by irrigation in some parts of the Gallatin Valley has been documented since the 1950s (Hackett et al. 1960; Dunn 1978; Custer 1991; Slagle 1995a; Kendy and Tresch 1996; Kendy 2001). Carlson and Osiensky (2002) witnessed increased levels of nitrates in ground water in eastern Idaho as a result of irrigation. Several researchers have proposed a linkage between elevated nitrate values in ground water and irrigation and dryland/crop fallow farming practices in the Gallatin Valley (Slagle 1995a; Dunn 1978; Bauder et al. 1993; Kendy 2001).

Irrigation and dryland farming are common practices in the GLWQD, and, while farmland is on the decline, fertilizer application has increased (Kendy, 2001) (Figure 10). Kendy (2001) concluded that fertilizers and soil organic nitrogen are probably the greatest sources of ground water nitrate in the GLWQD. Considering previous research, it would be beneficial to discover if there is an association between elevated nitrates in ground water and farming practices in the GLWQD.

The hypothesis to be tested is that wells near irrigated and dryland farming operations are more susceptible to nitrate contamination than those that are not.

Well depth

Wells that are shallow have been found to be susceptible to surface and soil contaminants, as well as insect and animal invasion (Hagedorn et al. 1981; Tuthill et al. 1998; Skipton et al. 1998; Pumley 2001). Well data from over 8,700 wells in the GLWQD indicates that depth ranges from 1 to 299 meters, with a mean of 30 meters and a median of 21 meters (GWIC 2001). In the absence of large fractures or solution

openings, ground water moves much slower than surface water. Therefore, infiltrating surface contaminants would be expected to concentrate in the upper portion an aquifer.

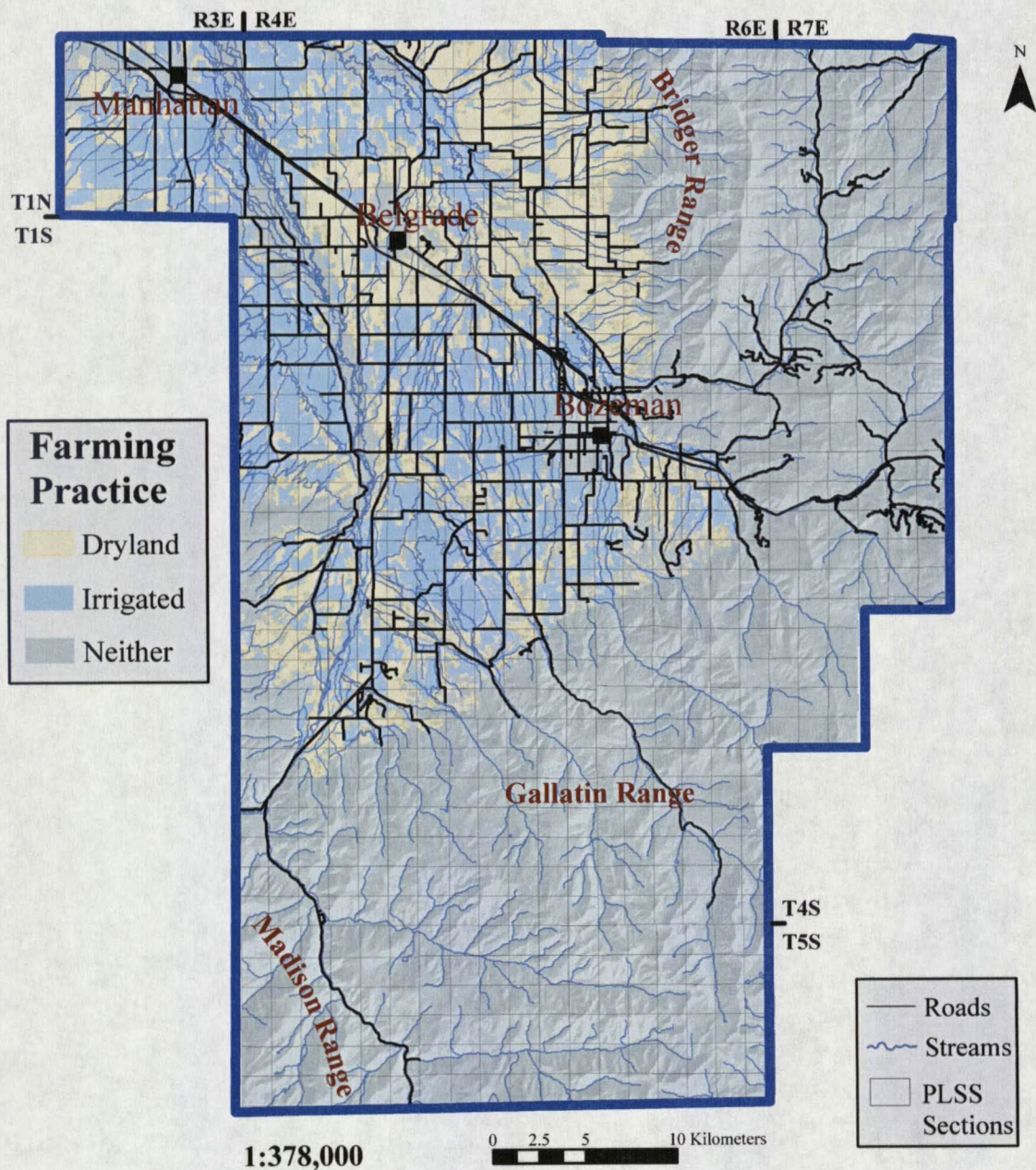


Figure 10. Dryland and Irrigation Farming in the GLWQD (Montana Natural Resource Information System 2002).

Nitrate and fecal coliform contamination have been cited as shallow ground water conditions (Hagedorn et al. 1981; Hantzsche and Finnemore 1992; Wireman and Job 1997). Tuthill et al. (1998) discovered an inverse relationship between casing length and coliform occurrence and a possible positive association with nitrate levels. However, Schubert et al. (1999) concluded that the highest nitrate levels were found in shallow wells.

The cost of drilling a well is based on its depth, so that drilling beyond what is needed to sustain water supplies is usually unnecessary and expensive. In many areas of the GLWQD, well depths are rather shallow (Figure 11). Because shallow well depth has been associated with increases in nitrates and coliform bacteria, the significance of well depth to ground water quality in the GLWQD is of interest.

The hypothesis to be tested is that wells depth is negatively correlated with nutrient and coliform contamination.

Aquifer Characteristics

An aquifer is defined as having “reasonably uniform water storage and transmitting properties” (Dingman 1994). Most wells in the GLWQD tap the Quaternary West Gallatin Alluvium (Qwgal), Quaternary Small Stream and Fan Alluvium (Qssf), and Quaternary Tertiary Basin Fill (QTbf), aquifers (Kendy 2001; Dixon 2002) (Figure 4). These aquifers are heterogeneous mixtures of sand, silt, gravel, and clay. Qwgal is the most productive aquifer with transmissivities averaging $17 \text{ m}^2/\text{day}$ (Dixon 2002). Yields tend to decrease with increasing age of the aquifer, owing to compaction of

aquifer materials, poor sorting, and finer grain size. Water yield in the QTbf aquifer is variable, with an average of $3.4 \text{ m}^2/\text{day}$ (Dixon 2002).

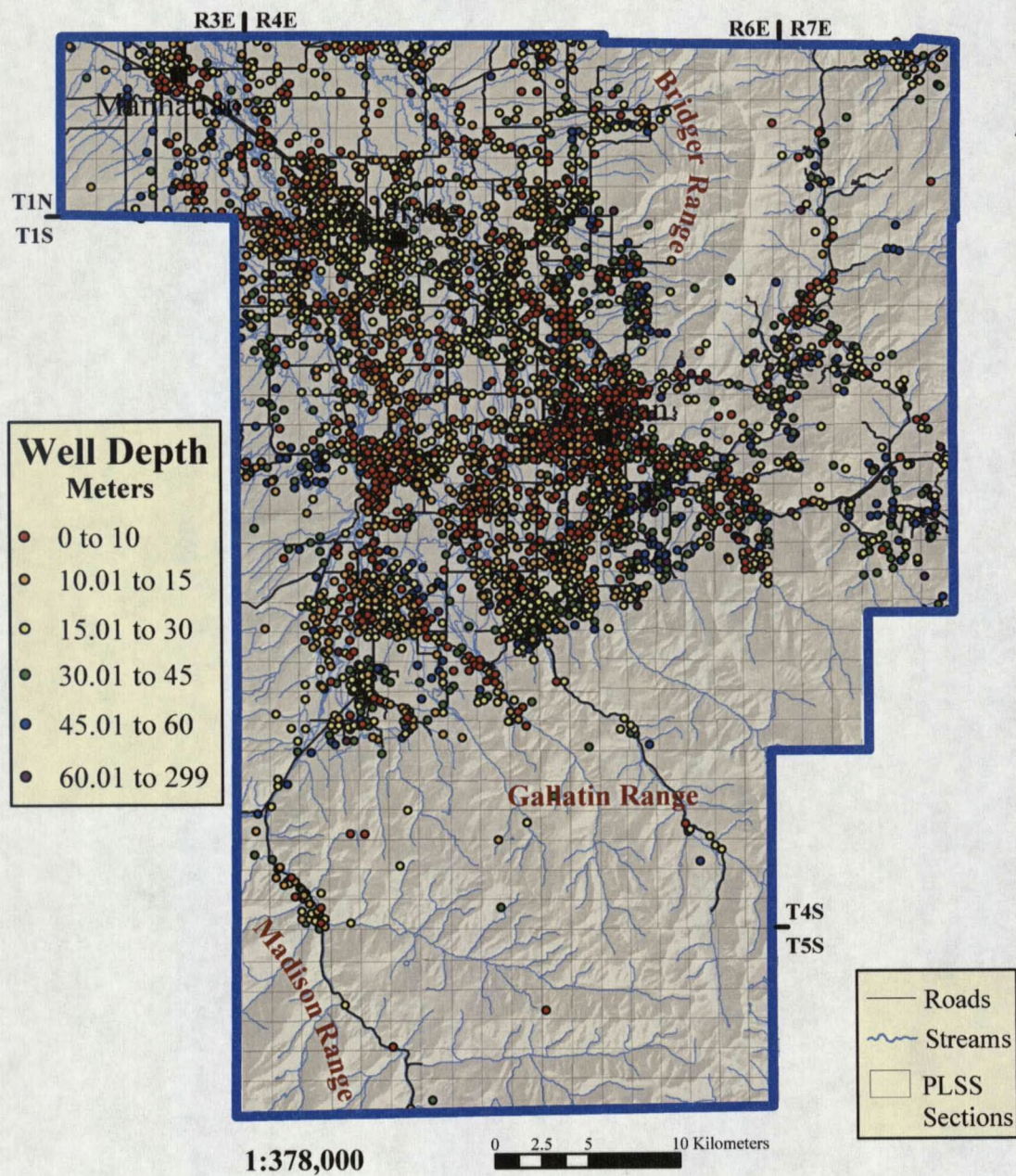


Figure 11. Well Depth in the GLWQD (GWIC 2001).

According to Fetter (2001, 401), "contaminants that are advecting are traveling at the same rate as the average linear velocity of the ground water". Transmissivity is a measure of the transmission capacity of the aquifer materials by the saturated thickness of an aquifer (Dingman 1994; Fetter 2001). Thus, transmissivity is related to the rate at which an aquifer conveys water. Aquifers with high transmissivity rates would be expected to have augmented contaminant dilution, versus those aquifers with low rates of transmission.

During Kendy's (2001) investigation of ground water nitrate in the GLWQD, she observed differences in nitrate concentrations when categorized by hydrologic units. From a small sampling distribution the Quaternary and Tertiary undifferentiated deposits, equivalent to Dixon and Custer's (2002) QTbf, exhibited the highest mean and variability among values (Kendy 2001). It would be of interest to establish if there is an association between elevated nitrates and coliform bacteria in ground water and the average transmissivity values of identified hydrogeologic units in the GLWQD.

The hypothesis to be tested is that wells with high rates of transmissivity are less likely to experience nutrient and microbial contamination than wells situated in low transmissivity aquifers, owing to dilution and transport.

CHAPTER 3

METHODS

Data Standardization and Spatial Conversion

Ground water quality records for nitrate-nitrogen and coliform bacteria in the GLWQD were obtained from seven sources and entered into a standardized database. Data from three USGS Water Resources Investigations Reports and one USGS comparison study were input for nitrate-nitrogen and other chemical parameters. Coliform and nitrate-nitrogen records from a private analytical laboratory were gathered in various digital and hard copy formats. Other records for nitrate-nitrogen and coliform were acquired from two public studies in the GLWQD. For all sources, samples analyses were performed by either a federal or state certified laboratory.

United States Geological Survey Water
Resources Investigations Reports and
Comparison Study

The USGS Water Resources division has conducted detailed ground water research in the Gallatin Valley. The oldest study from the early 1950s, USGS Water Supply Paper 1482, by O. M. Hackett et al. (1962) is considered the most thorough review of the valley's water resources. In the late 1970s, D. Dunn (1978) attempted to reconstruct Hackett et al.'s (1962) research to provide input on change in ground water supply and chemistry spurred by growth in the region for the Blue Ribbons of the Big Sky Areawide Planning Organization (1979). During the 1990s, two USGS Water

Resources Investigations Reports, 95-4034 and 01-4037 by S. Slagle (1995a) and E. Kendy (2001) respectively, continued investigation into the area's ground water quality and quantity.

"Geology and Ground-Water Resources of the Gallatin Valley, Gallatin County, Montana". Hackett et al. 1960. Data from Table 27, "Chemical analyses of ground water in the Gallatin Valley", were entered into an M.S Access™ database table, except for records from springs. Ground water samples were collected in 1951, 1952, and 1953 from July through September. The waters were analyzed for major and minor ions, pH, conductivity, hardness, and temperature. Also recorded were well Public Land Survey System (PLSS) location, geomorphic location, suspected hydrogeologic unit, depth of measurement, and sample date. Later, well depth and well type were entered from Table 36, "Record of wells and springs". In total, 52 records for ground water quality were entered.

On-screen digitizing with ArcGIS™ software, ArcMap™, from Plate 1, "Location of Wells, Test Holes, Stream-Gaging Stations and Precipitation Stations", was used to locate sample wells. In order to accurately represent a well's position, the view scale was set to the same as that of the map at 1: 63,360. However, well location was originally recorded to one sixteenth of a PLSS section, or to within a 162 meter radius of true well position. The boundary of the GLWQD was used to plot only those wells within the district. 29 wells were located within the GLWQD with 42 associated records.

“Ground Water Levels and Ground Water Chemistry, Gallatin Valley Montana, 1977”. Dunn, 1978. 35 records from Table A-2, “Chemical analyses of ground water in the Gallatin Valley, 1977”, were entered into a M.S. Access database table. Sampling occurred in September of 1977 with analysis for major and minor ions, pH, conductivity, hardness, and temperature. Well PLSS location, geomorphic location, suspected hydrogeologic unit, depth of measurement, sample date, and well class were also recorded. Except for those wells designated as resamples of Hackett et al. (1960), well depth is unknown.

30 wells were located in the GLWQD. 13 of these wells were resampled from Hackett et al.’s (1960) study, 10 of which were already spatially located. The other 3 were plotted in ArcMap using Hackett et al.’s (1960) Plate 1, because the scale was more detailed than that of Dunn’s well map. 17 wells were on-screen digitized in ArcMap, using PLSS coordinates and Plate 2, “Report to Blue Ribbons of the Big Sky Areawide Planning Organization: Ground Water Levels and Ground Water Chemistry of the Gallatin Valley, Montana 1977” (1: 126,720). Similar to Hackett et al. (1960), well location was recorded to one sixteenth of a PLSS section.

“Geohydrologic Conditions and Land Use in the Gallatin Valley, Southwestern Montana, 1992-1993”. Slagle, 1995. Records with nitrate values were entered into a M.S. Access™ database table from Table 1, “Records of selected wells in the Gallatin Valley”. Slagle sampled June through August in 1991, 1992, and 1993. Chemical data were input for nitrate as nitrogen, pH, conductivity, and temperature. Well PLSS location, likely hydrogeologic unit, depth of measurement, and sample date were also

recorded. Well characteristics for altitude, casing diameter, water level, and discharge were also logged. Altogether, 42 records were entered.

37 wells were plotted within the GLWQD, 26 using latitude and longitude coordinates obtained from the Montana District of the USGS, and 11 were mapped using four-quarter section PLSS data. The degree coordinates were used in ArcMap™ to create a spatial GIS layer.

“Magnitude, Extent, and Potential Sources of Nitrate in Ground Water in the Gallatin Local Water Quality District, Southwestern Montana, 1997-98”. Kendy, 2001. 221 ground water quality records were entered into a M.S. Access™ database table from Table 1, “Well data and chloride and nitrate concentrations in ground water in the Gallatin Local Water District, Montana”. The well samples were collected April through November and in January from 1997 to 1998. Chemical parameters analyzed were field nitrate-nitrogen or lab nitrite-nitrate as nitrogen, chloride, pH, and conductivity. PLSS well location, probable hydrogeologic unit, depth of measurement, depth to water, and sample date were also recorded.

Coordinate data was obtained in latitude and longitude coordinates for 151 wells from the Montana District of the USGS. Well locations for 3 wells were downloaded from the USGS National Water Information System. 7 wells were mapped using four-quarter section PLSS coordinates. 9 of the wells in this study were previously sampled by Slagle so that 152 new wells were added from this study and plotted in ArcMap™.

Montana Microbiological Services (MMS)

Data were acquired in three phases over an eight month period. First, an edited version of the M.S. Access™ database with bacterial and some chemical (2001) records for the years of 1998 to 2001 was received in the fall of 2001. There were 10,900 records along with photocopies of the chemical analyses log book for the years of 1999 to 2001. Later, 357 M.S. Word™ documents containing letters to recipients of chemical analyses for the years of 1996 to 1999 were acquired. The last installment of data was the complete 2001 MMS Access™ database, which created an addition of approximately 600 new records.

The framework of MMS's database evolved from 1998 to 2001. However, three crucial attribute fields were constant throughout: LabNum, System Name, and Sample Site. LabNum is a unique identifier for each record which is a 'primary key' field and is never duplicated. The System Name and Sample Site fields enabled accurate location of well samples. System Name was used to identify well owner in the case of Public Water Supply Systems (PWSS). In most cases, the Sample Site field was used to locate a well as it recorded the true location of the well sample. A well was always located by either the name or address given in the System Name or Sample Site fields. The Address field reflected the mailing address of the client and was not used for location of a well.

Due to the nature of data acquisition, database standardization occurred in many phases. First, nitrate-nitrogen and conductivity data from the log books and then from the letters were entered into a working version of the MMS database, if a match was made to a record's LabNum. Some of the letters contained records predating the electronic

version (1996, 1997) of the database, in which instance a new record was created. Once all the nitrate data were entered, every record had to be reviewed and assigned the true address of the sampled well's location from the System Name and Sample Site fields. If an address number or street name was absent from the true address fields, the record was deleted. If a partial address was available and the client's name was given in the System Name and Sample Site fields, the record was tagged for lookup in the phonebook.

Address standardization was necessary for plotting well locations using county data. A database table of Gallatin County road names was used to create six consistent address fields for each record: ADDRESS, DIRPRE, ROADNAME, ROADTYPE, DIRSUF, and COMMUNITY. A form was created in Access™ to simplify the process and reduce errors. Once the records had been standardized, queries were run to find duplicate addresses so that only one well would be plotted in the case of multiple samples per well. A new field, WELLID was created to act as a link field between the chemical analyses and well site. Thus there is only one WELLID per well, but multiple records for the same well will be indicated by repeated WELLIDs in the well samples table. LabNum was assigned as a primary key ensuring that each sample record was unique. Queries were run to verify that every record matched an associated WELLID.

In total, 2,169 unique well addresses were standardized in M.S. Access™ for address geocoding with ArcGIS™ software. A geocoding service was created in ArcCatalog™, using the Gallatin County structures data layer. The roads layer could have been used to locate wells, because a home's address reflects its measured distance along a street in the county. However due to differing lot sizes and house setback

distances from the road, it was believed that use of the structures layer would be more accurate of well location. Strict address matching requirements were set, which ultimately resulted in no wells plotting with a score lower than what ArcCatalog™ defines as a “good match”, 75 to 100 (Vienneau 2001, 217). Once the wells were located spatially, an ArcMap™ project was created to delete wells that fell within subdivisions or towns served by a PWSS.

Altogether 1,521 wells plotted directly using the geocoding service in ArcCatalog™. An additional 38 wells were interactively mapped during the geocoding process in ArcMap™ as a result of records missing street prefixes or suffixes, and addresses with multiple structures. Over ninety percent of these wells received a score of 90 or greater. An additional 15 wells were mapped either using the parcels and structures layer from the county or using a combination of MBMG GWIC data and USGS digital orthographic quadrangles.

Well samples from PWSS were also part of the MMS database, but were located using a data layer obtained from the GLWQD. The GLWQD data layer was created with a Global Positioning System (GPS) unit and then converted into GIS format. Often PWSS mix water from multiple wells in a distribution system. In order to avoid statistical association, PWSS with MMS sample data were reviewed at the Gallatin County Health Department. Those systems with waters mixing from more than one well were excluded from the study. Three PWSS wells that were not in the GLWQD layer were located using the structures layer. 54 single-well PWSS were located in the GLWQD that are associated with 1820 sample records.

Public Studies within the GLWQD

Ground water quality data from two projects within the GLWQD were also entered into the database.

“Citizen’s Review of Impacts to Ground Water Quality and Supply from the Proposed Green Hills Ranch Subdivision, Gallatin County, MT”. Sturman et al. 2002.

The study area included homes in the Hyalite Foothills subdivision and surrounding vicinity. It is located in the north central sections of Township 3 South Range 5 East. Samples were collected in May of 2001 and analyzed by Peak Analytical Services of Bozeman. The parameters measured were pH, conductivity, nitrite plus nitrate as nitrogen, ammonia, total coliform and fecal coliform. The wells were plotted with the MMS wells. 5 wells from this study had also been previously sampled by MMS. 24 wells were located by address geocoding with the MMS database table in ArcCatalog™ and 1 well was interactively mapped in ArcMap™.

“The Effects of Septic Systems on Groundwater and Surface Water Quality in Two Subdivisions in the Gallatin County Local Water Quality District, Montana”. Flemming 2003. 77 wells were sampled during the spring in 1999 and fall of 2000. The wells in the Gardiner Park Subdivision are located in section 30 of Township 2 South Range 6 East, while the wells in Middle Creek Meadows Subdivision are located in section 13 of Township 2S Range 4E. The Helena laboratory of the Department of Public Health and Human Services analyzed the samples for temperature, dissolved oxygen, pH, specific conductivity, total coliform, nitrate-nitrogen, phosphorus, and

chloride. Well locations were collected by a GPS receiver and later converted into a spatial GIS layer. The analysis data was included in the attribute table of the GIS well layer. In total, 150 records were acquired.

Ground Water Characterization

Well data from the seven sources were grouped into categories based on the dates of sampling. Historic wells were not analyzed in this study due to coarse mapping scales and the long time period between study sampling (pre 1980). Current well locations were assigned characteristics for *a priori* independent variables (1992 to 2001). Current data records were grouped together, under the assumption that the samples were taken from the same population. The current data values for nitrate-nitrogen and coliform bacteria were then standardized for analysis. Descriptive statistics were utilized to characterize the sample values and explore the data for violations of statistical assumptions. Statistical tests for Analysis of Variance (ANOVA), Chi Square (χ^2), and Regression were employed to discern the relationships between *a priori* variables and nitrate-nitrogen and coliform values. Finally, spatial modeling techniques were explored for predicting regional nitrate-nitrogen and coliform values in the GLWQD.

A Priori Variable Assignment

All wells that were sampled from 1992 to 2001 were combined into one spatial data layer in ArcMap™. In order to test the hypotheses, well samples had to be assigned values for independent variables in ArcMap™. Spatial resolution of the well locations varied. The USGS wells located with four-quarter section PLSS data are accurate to

about an 81 meter radius of a well's location, while the degree coordinates have been field verified with a 7.5 minute topographic map. Wells located by address and on-screen digitizing were assumed to be within a thirty meter radius of the plotted point. Wells plotted by GPS are accurate to within a 15 meter radius of the true location. Therefore a thirty meter radius was chosen as an appropriate modeling resolution.

Each well's point location was buffered to a 30 meter radius so that area values for independent variables could be assigned in ArcMap™. This was done with a script in ArcView™ that maintained the well identifier attribute field that would link to the water quality sample values (Tilton 2000). This new buffered layer was used to intersect area variables, such as septic limitation ratings, proximity to land application of waste, and hydrogeology. Some wells overlapped more than one value per *a priori* area variable. This issue was resolved by summing the area of each rating and assigning the majority value. A few wells were deleted in the instance of no clear majority values. Well values for housing density and in some instances, depth were assigned in a different manner.

Septic System Limitation Ratings Wells sampled in the GLWQD were assigned a value of slight, moderate, or severe based on occurrence with the chosen soil class ratings of the "Most Limiting Surficial Material" GIS layer (Custer et al. 2000). The soil class ratings chosen to investigate were depth to bedrock, depth to high water table, soil percolation and filtration rates, and flooding frequency. The data layer was compiled from soil maps of varying resolutions and was believed to be appropriate for this regional analysis. There are a few areas of 'no data' within the GLWQD which could not be analyzed.

Housing Density Housing density in the GLWQD was approximated per well location by assigning the number of upgradient structures in an area most likely to be above the flow lines of the aquifer. A "structures" layer received from the Gallatin County GIS Department in the Fall of 2002 was used. Twelve iterations were run per well which counted the structures within 1 kilometer, 500 meters, and 100 meters from a 90, 60, 30, and 15 degree wedge radius on the 'sharp end' of the point plotted for a well (Aspinall 2003). This calculation used the assumption that the hydraulic gradient of the water table approximates the surface topography at a regional scale. First a looping process was used to fill the 'sinks' in the 30 meter Digital Elevation Model for the GLWQD (USGS NED 2003). Then a flow direction grid was calculated from this surface. The values of the flow direction calculate the outflow along the direction of steepest descent. The algorithm assumes inflow is in the opposite diagonal direction of outflow (Figure 12). The calculation should remove any bias that use of lot sizes may have for subdivisions of fixed lot sizes.

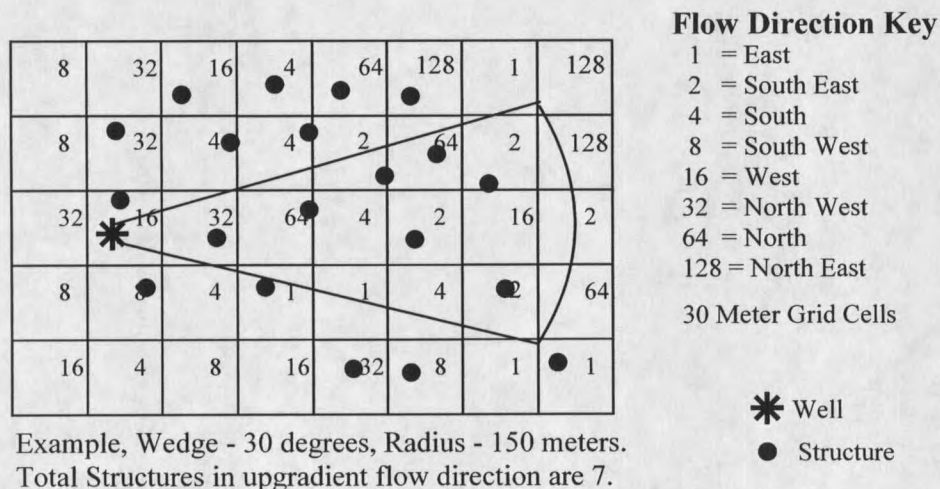


Figure 12. Conceptual Diagram of Housing Density Algorithm.

Land Application of Wastes The effects of biosolids and septage operations were evaluated by creating a 1 kilometer radius buffer of the septage and biosolids application sites within the GLWQD. Data for the sites were obtained from the City of Bozeman and the Gallatin County Environmental Health Services for the years of 1995 to 2001. The GIS layers were created by on-screen digitizing of the sites from hand drawings on large scale maps using the 30 meter Digital Orthophoto Quadrangle (DOQ), and 7.5 minute Digital Raster Graphic (DRG), of Gallatin County for screen reference. Sampled wells that fell within the radii of the buffered plots were assigned the appropriate value.

Farming Practices Farming practices in the GLWQD were acquired from a 30 meter version of the USGS Montana GAP coverage. This version was produced by the Wildlife Spatial Analysis Lab at the University of Montana (Montana Natural Resource Information System 2002). The coverage was examined for correspondence with agricultural fields on the 30 meter DOQ of Gallatin County, and was determined to be too inaccurate for analysis. The landuse in the GLWQD is much more complex than displayed by this data layer.

Well Depth Most values for well depth were originally entered into the database with the USGS data. 34 of the PWSS wells were assigned depth values from the GPS layer. Approximately 100 wells from the MMS database were assigned depth values in ArcMap™. The values were spatially assigned on a PLSS section basis by matching a well owner's name in the MMS database with a GWIC registered well owner in the same

section. Most well records from MMS did not have an associated owner name, as this field was edited out to maintain privacy.

Hydrogeology Well values for hydrogeology were assigned from the GIS layer, “Lithostratigraphic and Hydrogeologic Units of the Gallatin Local Water Quality District” (Dixon and Custer 2002). The GIS layer was compiled from sources of varying resolutions and was believed to be appropriate for regional analysis. The hydrogeologic units were categorized based on the assembly of geologic maps and well log data. Average transmissivity values were calculated for hydrogeologic units using pump test data.

Preparation for Statistical Tests

First, the data values for nitrate-nitrogen and coliform were standardized. For nitrate-nitrogen, this involved using nitrite plus nitrate as nitrogen values for almost half of Kendy’s (2001) samples. The “nitrite plus nitrate concentrations are considered essentially equivalent to nitrate concentrations” (Kendy 2001, 23). If both nitrate-nitrogen and nitrite plus nitrate-nitrogen values were available for a sample, only the value for nitrate-nitrogen was used. Nitrate-nitrogen samples from Kendy’s (2001) study and MMS that fell below the minimum reporting level were given the value of the minimum reporting level. Standardization of coliform records involved converting the various test results to categorical responses. This was done because almost 70 percent of the coliform samples were reported as presence or absence. Therefore, values of absent,

less than one, and zero were coded to 0. Values of present, too numerous to count, or greater than zero were coded to 1.

After all values for nitrate and coliform were standardized, three tables were created in MS Access™, one for all nitrate records and two for total coliform and fecal coliform records. The tables were then exported to MS Excel™ for analysis. Descriptive statistics were calculated to analyze the general condition of ground water nitrate and coliform bacteria in the GLWQD. Frequency histograms were constructed for nitrate-nitrogen, total coliform, and fecal coliform. A natural log transformation of the nitrate-nitrogen data was chosen to normalize the sample values. Ground water characterizations for fecal coliform were discontinued due to the small proportion of fecal coliform presence values. The standardized records for nitrate-nitrogen and total coliform were linked in MS Access™ to tables of assigned *a priori* variables on the basis of the WELLID. The merged well data was then queried to produce files for use with hypothesis testing in SAS™.

Hypothesis Testing

All nitrate-nitrogen values were natural log transformed in SAS Analyst™ for subsequent statistical analysis. The transformed nitrate-nitrogen values associated with categorical variables of septic system limitation ratings, proximity to biosolids or septage application, and hydrogeologic units were tested for a difference of means with the ANOVA procedure using a 95% confidence interval (Table 1). Some septic system limitation rating had only two responses, in which case the categories were tested for a difference of means with the Student's t test procedure using a 95% confidence interval

(Table 1). Simple linear regressions were run for the natural log transformation of well depth and housing density versus nitrate-nitrogen (Table 1).

Table 1. Statistical Tests Employed (Ramsay and Schafer 1997; Ebdon 1999; Boik 2001).

Statistical Test	Equation	Assumptions	Rationale
ANOVA F statistic	$F = \frac{MS \text{ Treat}}{MSE}$ $df \text{ between samples} = k - 1$ $df \text{ within samples} = N - k$	- independent random samples from responses of independent cases - each population is normally distributed with identical sample variance - n/N is small for each population	Test if difference between sample sets is greater than difference within sample sets.
Student's t test	$t = \frac{(\bar{x}_1 - \bar{x}_2)}{(Sp \sqrt{1/n_1 + 1/n_2})}$ Sp = pooled sample variance $df = n_1 + n_2 - 2$	- independent random samples from responses of independent cases - each population is normally distributed with identical sample variance - n/N is small for each population	Test if difference between sample sets is greater than difference within sample sets.
Chi Square	$\chi^2 = \sum d^2/e$ $df = k - 1$	- independent observations - large sample size, no expected frequencies less than 5 - n/N is small	To discern differences between observed and expected frequencies.
Simple Linear Regression	$y = mx + b$ Goodness of fit determined by the coefficient of determination, r^2 . $r = S_{xy} / \sqrt{S_{xx} S_{yy}}$	- dependent variable normally distributed with a constant variance - values of residuals are independent and normally distributed	To determine if the values of the dependent variable are associated with the values of the independent variable.
Logistic Regression Probability Model	2 Parts: Logit or log odds $\text{logit}(\Phi) = \hat{\alpha}_0 + \dots + \hat{\alpha}_p x_p$ logistic function if $\text{logit}(\Phi) = n$ then $\Phi = e^n / (1 + e^n)$ Goodness of fit determined by the Wald's X^2 value.	- mean of the responses is equal to Φ - variance is equal to $\Phi(1 - \Phi)$	Allows the non normality of a binary response to be modeled using generalized linear regression model techniques.

All coliform samples sets, except for housing density and well depth were tested using the χ^2 frequency distribution with a 95% confidence interval (Table 1). To satisfy test requirements, the datasets were preprocessed in MS Excel™ spreadsheets to calculate expected frequency classes for each variable. Logistic regressions were used to evaluate housing density and well depth and coliform occurrence (Table 1). Sample sizes for each hypothesis test varied due to well elimination during majority categorization, or lack of an associated variable.

Predictive Modeling

Geostatistical techniques were employed for modeling regional nitrate-nitrogen values in the GLWQD. Predictive modeling for coliform bacteria was discontinued due to the small proportion of coliform presence values. Geostatistical kriging methods are commonly employed to model ground water contaminants like nitrate-nitrogen (Yates and Yates 1989; Dingman 1993; Rautman and Istok 1996; Burrough and McDonnell 1998; Carlson and Osienky 2002). Rautman and Istok (1996) defend the use of geostatistics to model ground water transport processes because of the relatively slow flow rates and the ability of the model to account for anisotropy. The ArcGIS Geostatistical Analyst™ extension was used to 'krig' continuous nitrate surfaces. Kriging is a form of least squares regression with a statistical component that accounts for the stochastic variance, covariance, and spatial dependence of the event being modeled (Figure 13). The model incorporates Tobler's First Law of Geography and operates under the assumption of the 'regionalized variable theory', which implies a stationary mean of the value being modeled (Burrough and McDonnell 1998). Due to this assumption,

modeling occurred with natural log transformed values of the nitrate-nitrogen. Ordinary kriging was used to predict values for nitrate concentrations at unsampled locations. Indicator kriging was used to predict nitrate-nitrogen values exceeding 10 mg/l and 3 mg/l. The value of 10 mg/l was chosen to model as it is currently the Human Health Standard for nitrate-nitrogen, while previous researchers have cited 3 mg/l as an indicator of contamination (Tesorio and Voss 1997).

Kriging Equation

$$Z(\mathbf{x}) = m(\mathbf{x}) + \gamma(\mathbf{h}) + \tilde{\epsilon}$$

Where $Z(\mathbf{x})$ is the value at a point, $m(\mathbf{x})$ is the deterministic function describing the structural component of Z at $\mathbf{x}$, $\gamma(\mathbf{h})$ (sill), describes the semivariance between values points separated by a distance vector $\mathbf{h}$ (lag), and $\tilde{\epsilon}$ is the residual error (nugget).

Semivariance estimate-

$$\hat{\gamma}(\mathbf{h}) = \frac{1}{2n} \sum_{i=1}^n \{z(\mathbf{x}_i) - z(\mathbf{x}_i + \mathbf{h})\}^2$$

Where $\mathbf{x}_i$ are known data points.

Figure 13. Kriging Equation (Burrough and McDonnel 1998).

CHAPTER 4

RESULTS

Well Data Summary

Altogether 49 historic and 1,907 current, unique wells were located within the GLWQD. It was decided that data from studies conducted after 1990 should be used to test the hypotheses, as the records would be most indicative of current situation. The current wells were sufficiently represented on private land in the GLWQD; with notable clustering in subdivisions (Figure 14). Table 2 presents a summary of the total number of wells located from each study and the number of associated nitrate-nitrogen and coliform records. Due to the dynamic nature of the ground water flow field, it was hypothesized that multiple samples from the same well could be used without introducing bias. Thus if a well was sampled more than once, the sample locations were assumed to represent values from a thirty meter radius of the well's plotted position.

Table 2. Nitrate-Nitrogen and Coliform Data Summary for Wells Located in the GLWQD

Historical Records	Wells in the GLWQD	Nitrate-Nitrogen Records	
Hackett et al. 1960	37	37	
Dunn 1978	30	30	
Total Unique	49*	72	
Current Records	Wells in the GLWQD	Nitrate-Nitrogen Records	Coliform Records
Slagle 1995a	37	37	0
Kendy 2001	161	221	0
MMS 2001	1624	537	3908
Sturman et al. 2001	25	25	25
Flemming 2003	77	150	141
Total Unique	1907*	970	4074

*Resampled wells among Dunn and Hackett et al., Kendy and Slagle, Kendy and MMS, and Sturman et al. and MMS lead to totals that are different from the sum of unique wells from each study.

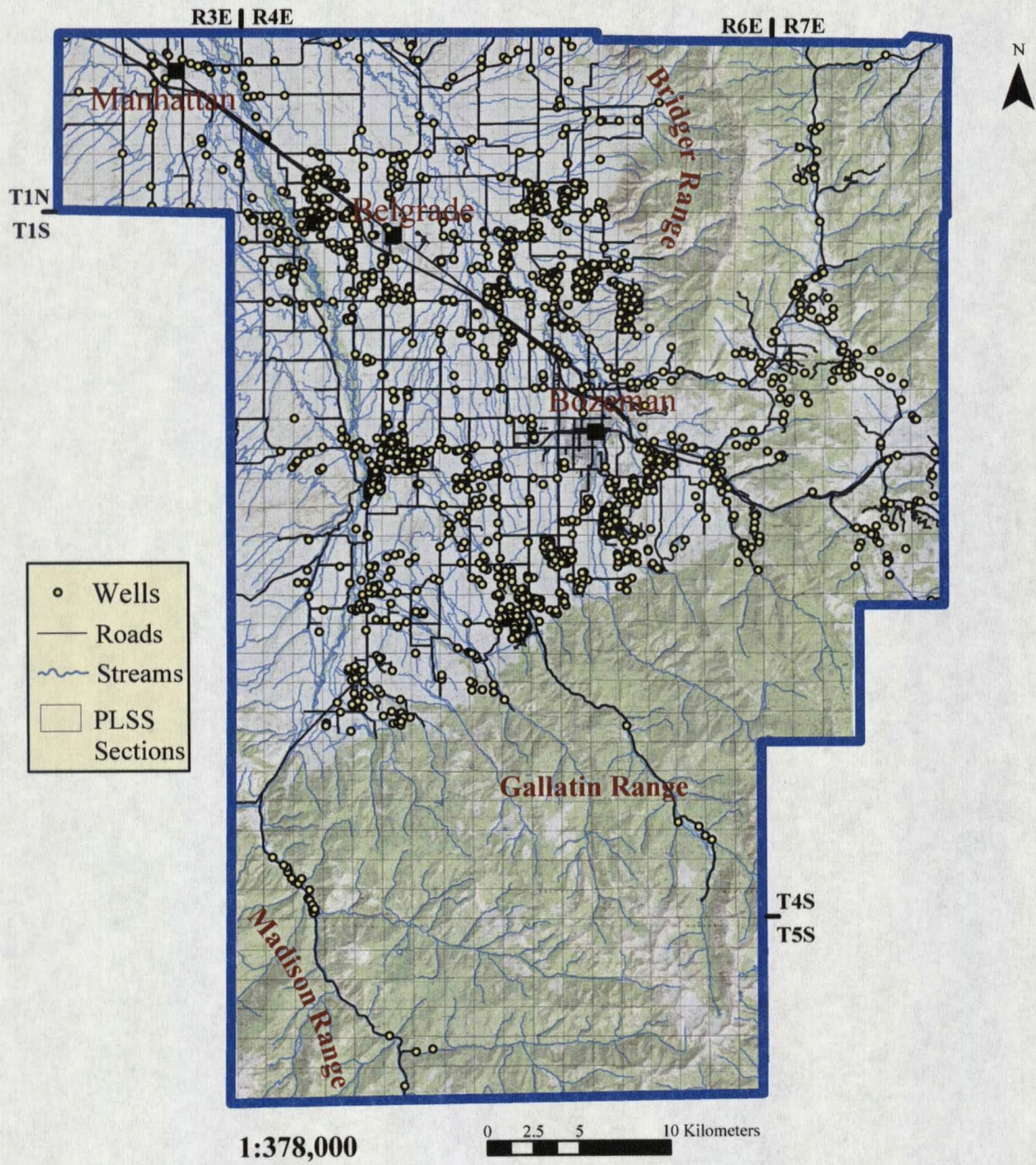


Figure 14. Current Well Distribution in the GLWQD.

Descriptive statistics for all nitrate-nitrogen and coliform data analyzed from the current wells are displayed in Tables 3, 4, 5, and 6. Frequency histograms for the natural log transformed values of nitrate-nitrogen, total coliform, and fecal coliform are displayed in Figures 15, 16, and 17. The location and magnitude of the untransformed nitrate-nitrogen values are mapped in Figure 18; while the coliform values categorized by presence and absence are spatially represented in Figure 19.

Table 3. Descriptive Statistics for Standardized Raw Nitrate-Nitrogen Values.

Parameter	Value
Mean	1.89
Standard Error	0.07
Median	1.40
Mode	0.50
Standard Deviation	2.06
Range	24.99
Minimum	0.01
Maximum	25.00
Sum	1843.23
Count	970

Table 4. Descriptive Statistics for Standardized Natural Log Transformed Nitrate-Nitrogen Values.

Parameter	Ln Value	Converted Value
Mean	0.21	1.23
Standard Error	0.03	
Median	0.34	1.40
Mode	-0.69	0.50
Standard Deviation	1.01	
Range	7.82	
Minimum	-4.61	0.01
Maximum	3.22	25.00
Sum	200.43	
Count	970	

Table 5. Descriptive Statistics for Standardized Total Coliform Values.

Value	Count	Frequency
Present	544	0.13
Absent	3530	0.87
Sum	4074	

Table 6. Descriptive Statistics for Standardized Fecal Coliform Values.

Value	Count	Frequency
Present	30	0.01
Absent	3791	0.99
Sum	3821	

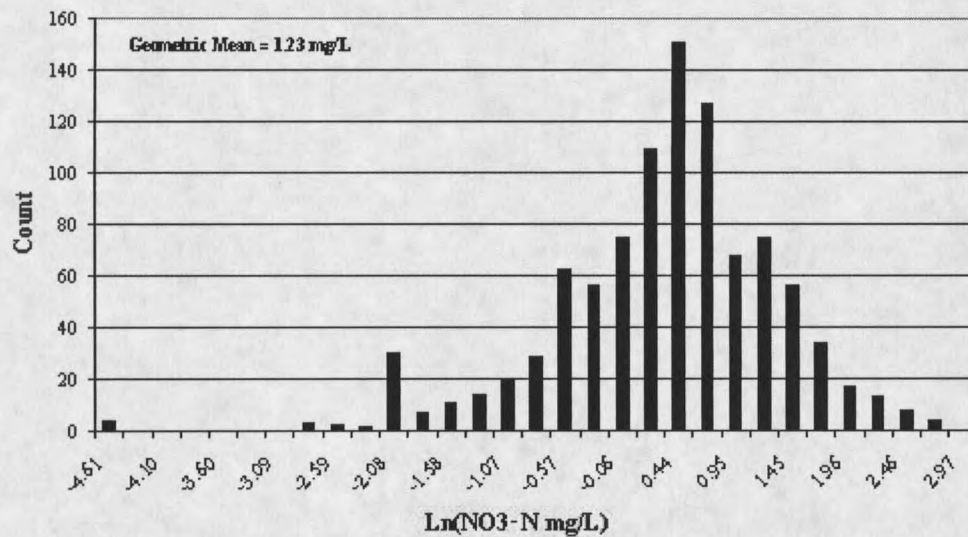


Figure 15. Frequency Histogram for Standardized Natural Log Transformed Nitrate-Nitrogen Values.

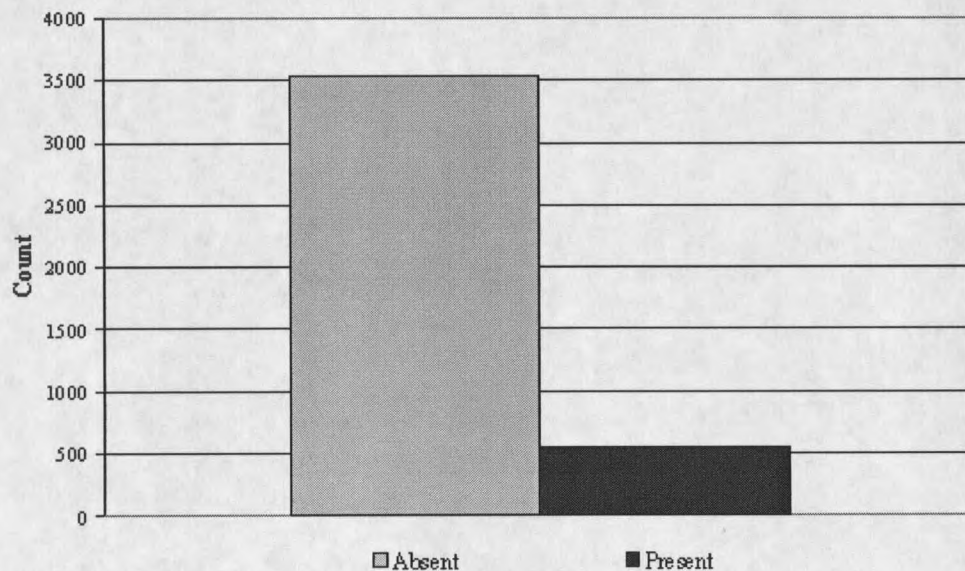


Figure 16. Frequency Histogram for Standardized Total Coliform Values.

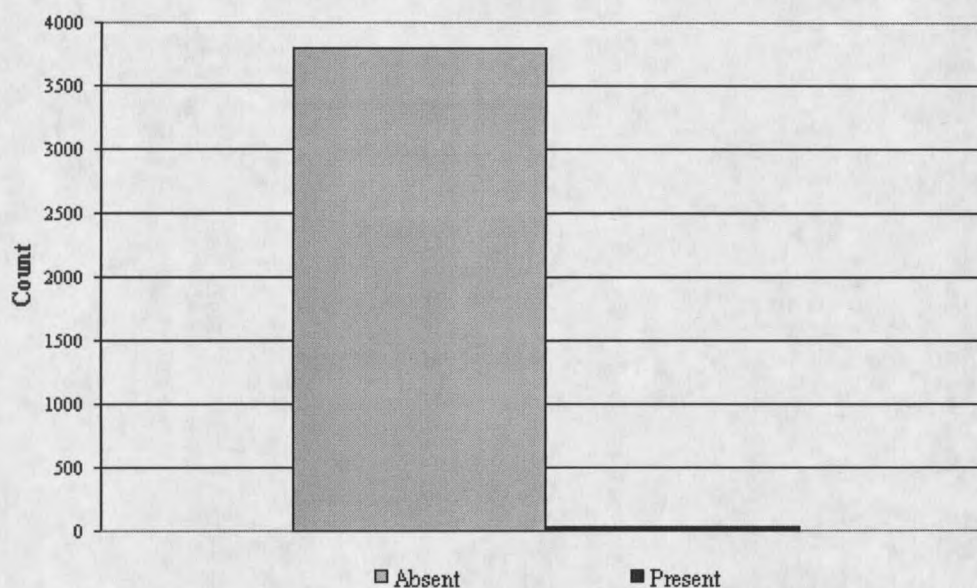


Figure 17. Frequency Histogram for Standardized Fecal Coliform Values.

Hypothesis Testing

ANOVA and χ^2 frequency tests were used to test for associations between nitrate-nitrogen and coliform values and independent categorical variables. Regression was employed to test the relationships between nitrate-nitrogen and coliform values and numeric variables. All tests were performed with version 8 of the SASTM System.

Septic System Limitation Ratings

Two ANOVA tests were conducted for nitrate-nitrogen values categorized by the septic system limitation ratings of soil depth and percolation rate. Two Student's t tests were performed for nitrate-nitrogen soil filtration rate and depth to high water table.

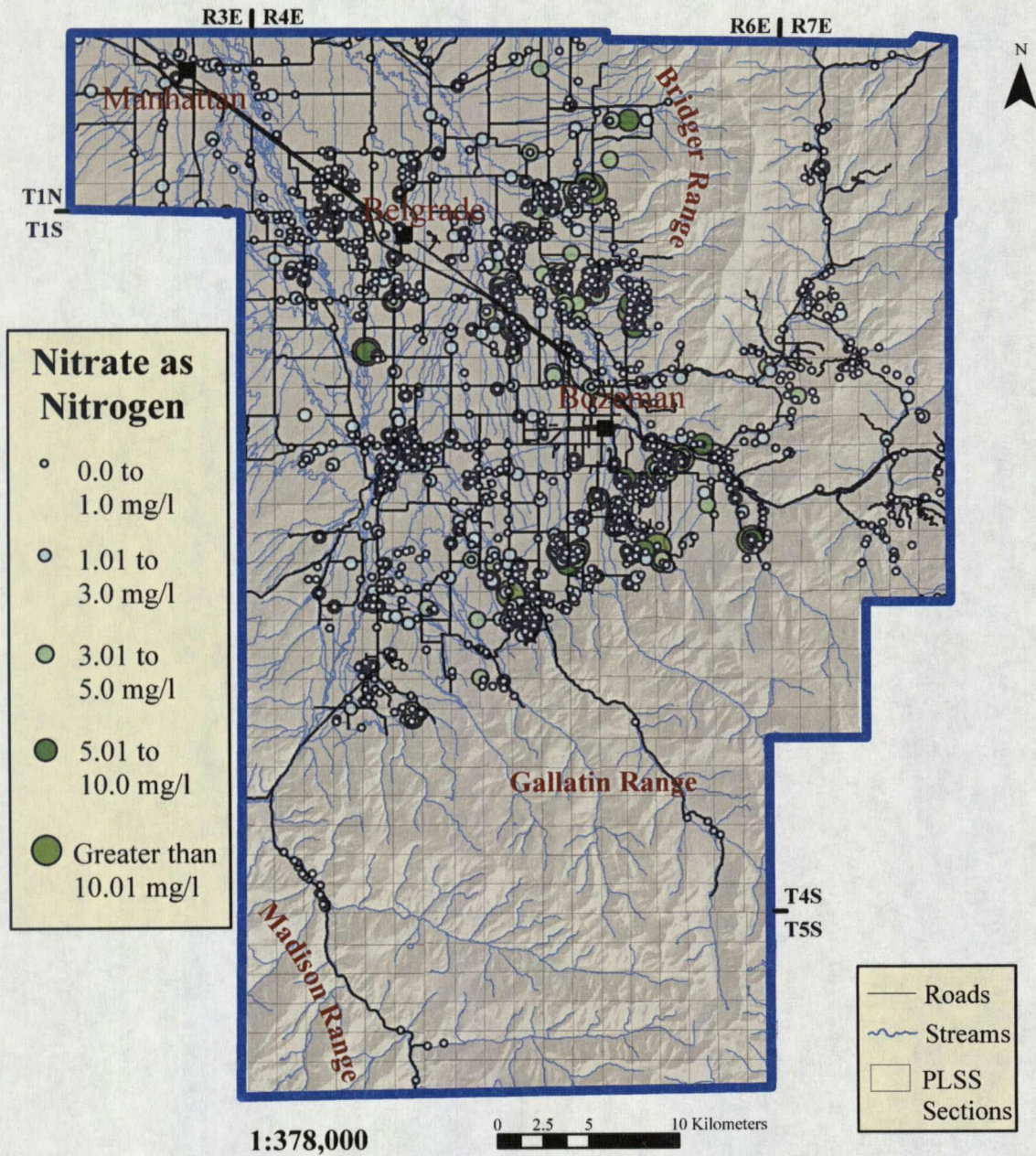


Figure 18. Location of Standardized Raw Nitrate-Nitrogen Values in the GLWQD.

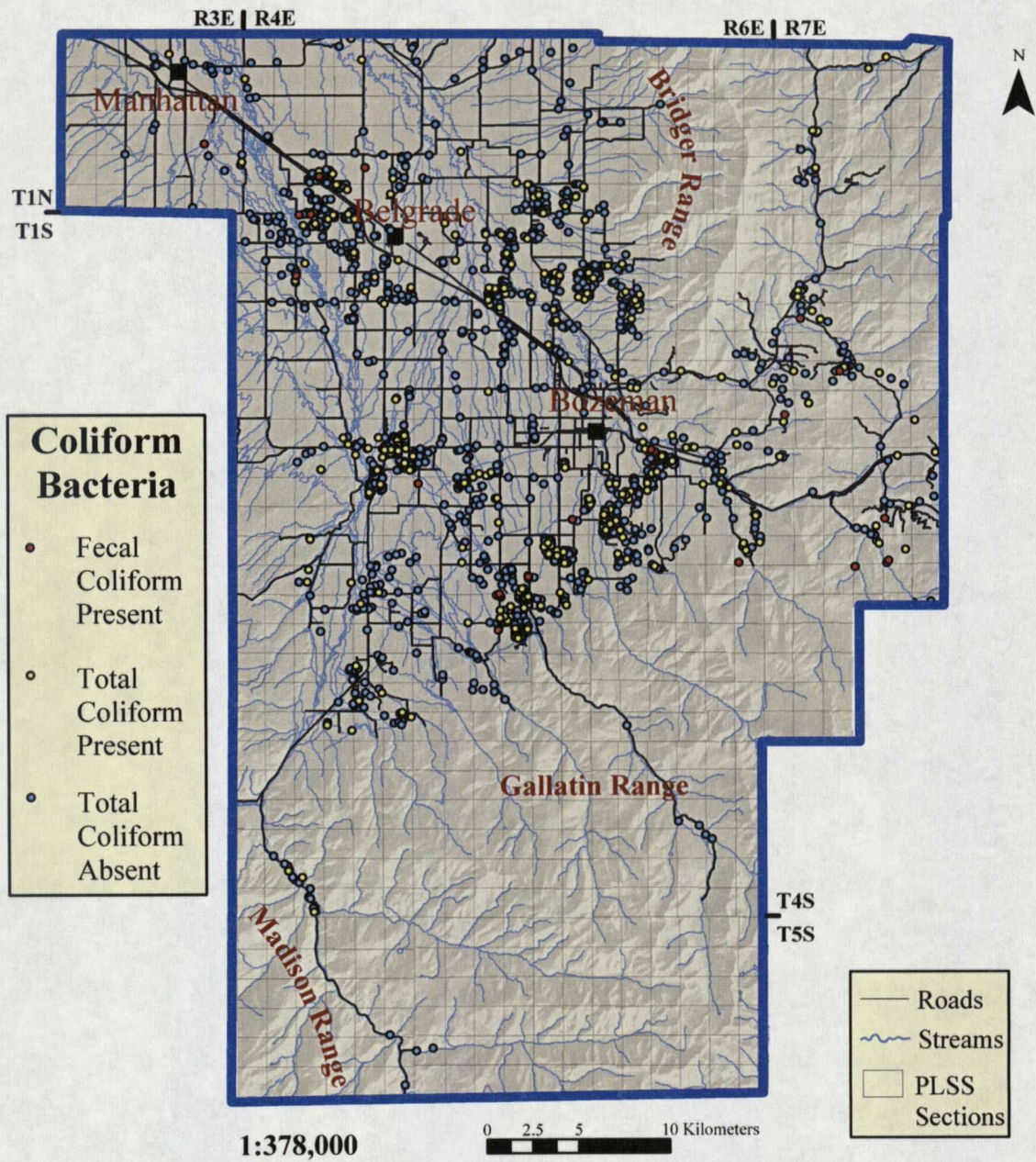


Figure 19. Location of Standardized Coliform Values in the GLWQD.

The results of the hypothesis tests are listed in Table 7. Figures 20 to 23 display the distribution of the natural log transformed nitrate-nitrogen values among the analyzed categories of septic system limitation ratings.

Table 7. Results of the Hypothesis Tests Conducted for the Natural Log Transformed Nitrate-Nitrogen Values Associated with Septic System Limitation Ratings.

Hypothesis Test, $\alpha = 0.05$	Test Statistic	p value	Reject H_0
Soil Depth	$F = 9.92$	< 0.0001	yes
Soil Percolation Rate	$F = 3.90$	0.0205	yes
Soil Filtration Rate	$t = 0.717$	0.4734	no
Depth to High Water Table	$t = 5.149$	< 0.0001	yes

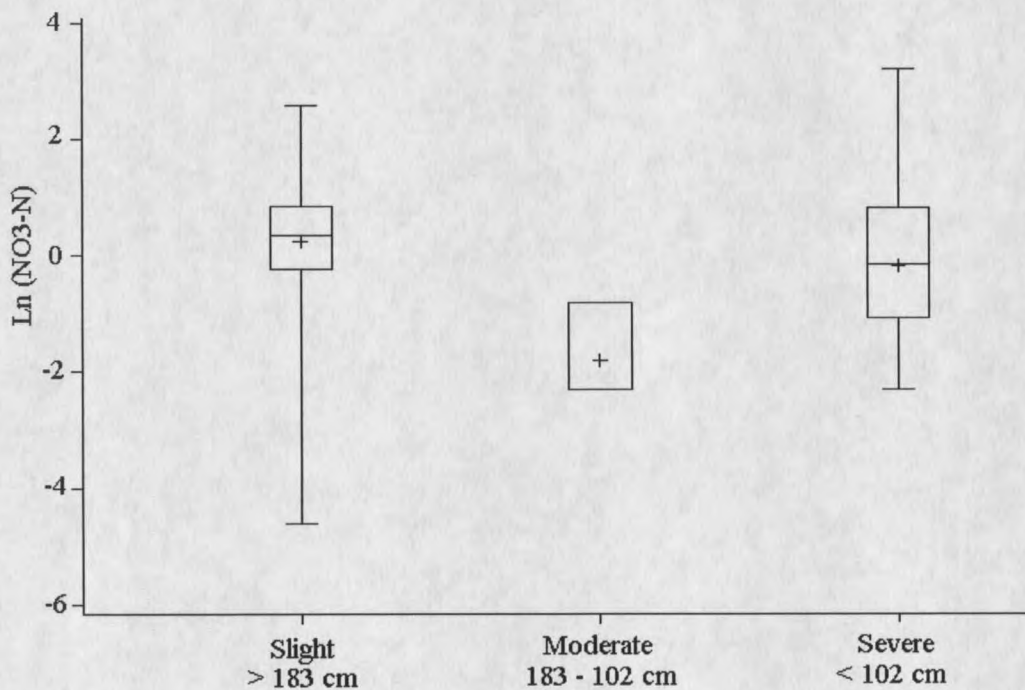


Figure 20. Natural Log Nitrate-Nitrogen Distribution by the Septic System Limitation Rating of Soil Depth.

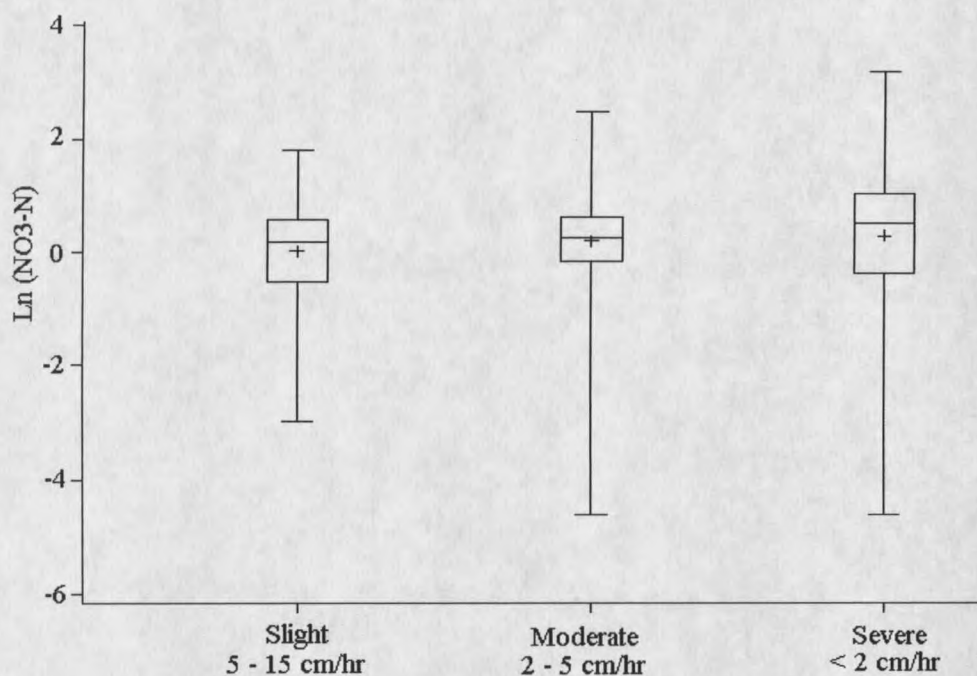


Figure 21. Natural Log Nitrate-Nitrogen Distribution by the Septic System Limitation Rating of Soil Percolation Rate.

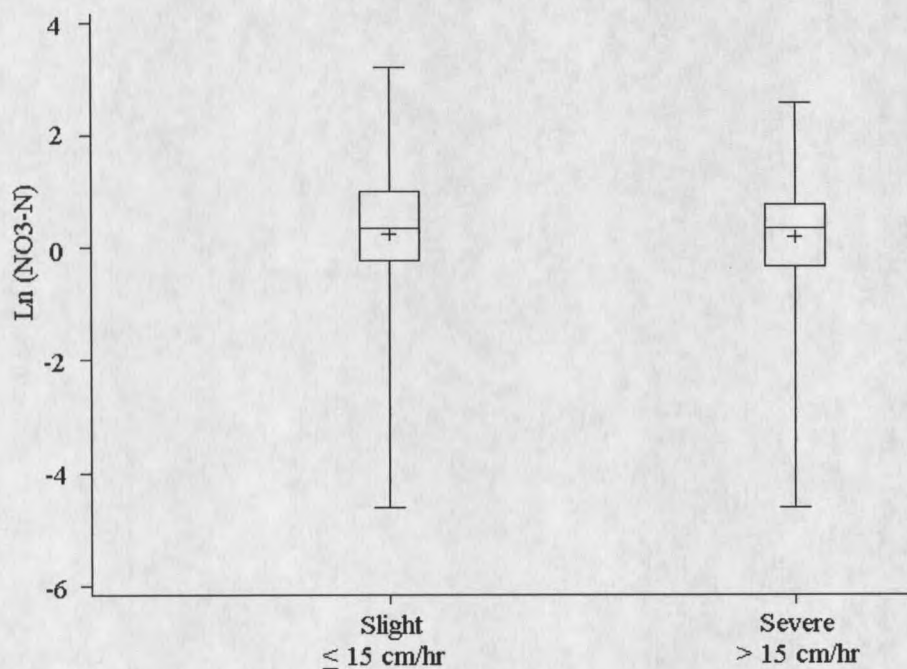


Figure 22. Natural Log Nitrate-Nitrogen Distribution by the Septic System Limitation Rating of Soil Filtration Rate.

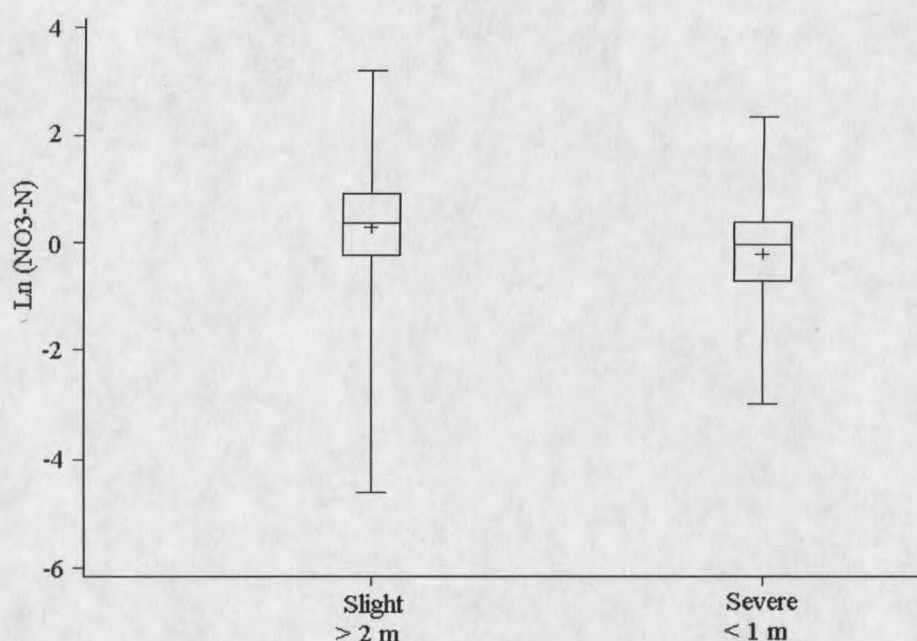


Figure 23. Natural Log Nitrate-Nitrogen Distribution by the Septic System Limitation Rating of Depth to High Water Table.

Preliminary tests revealed sufficient data in all septic limitation categories to conduct χ^2 analysis. χ^2 frequency tests were performed to assess associations of total coliform values among the septic limitation ratings of soil depth, soil percolation rate, soil filtration rate, depth to high water table, and flooding frequency. The results of the hypothesis tests are listed in Table 8. Figures 24 to 27 display the distribution of the total coliform values among the selected categories of septic system limitation ratings.

Table 8. Results of the Hypothesis Tests Conducted for Total Coliform Occurrence Values and Septic System Limitation Ratings.

Hypothesis Test, alpha = 0.05	Test Statistic	p value	Reject Ho
Soil Depth	$\chi^2 = 41.28$	< 0.0001	yes
Soil Percolation Rate	$\chi^2 = 49.11$	< 0.0001	yes
Soil Filtration Rate	$\chi^2 = 35.42$	< 0.0001	yes
Depth to High Water Table	$\chi^2 = 35.75$	< 0.0001	yes
Flooding Frequency	$\chi^2 = 5.94$	0.05	no

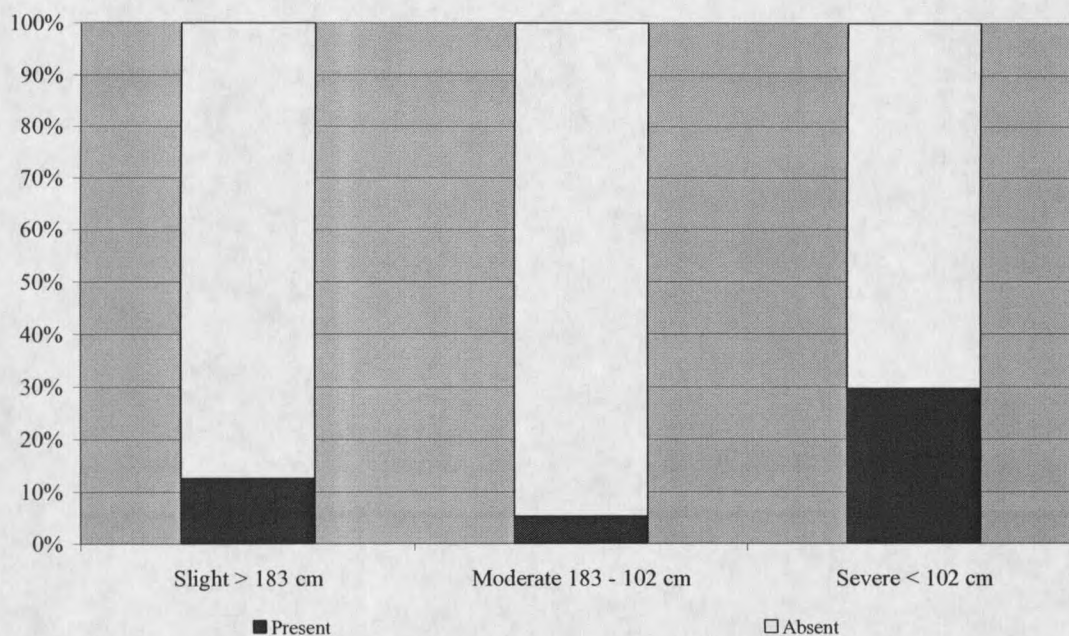


Figure 24. Total Coliform Occurrence by the Septic System Limitation Rating of Soil Depth.

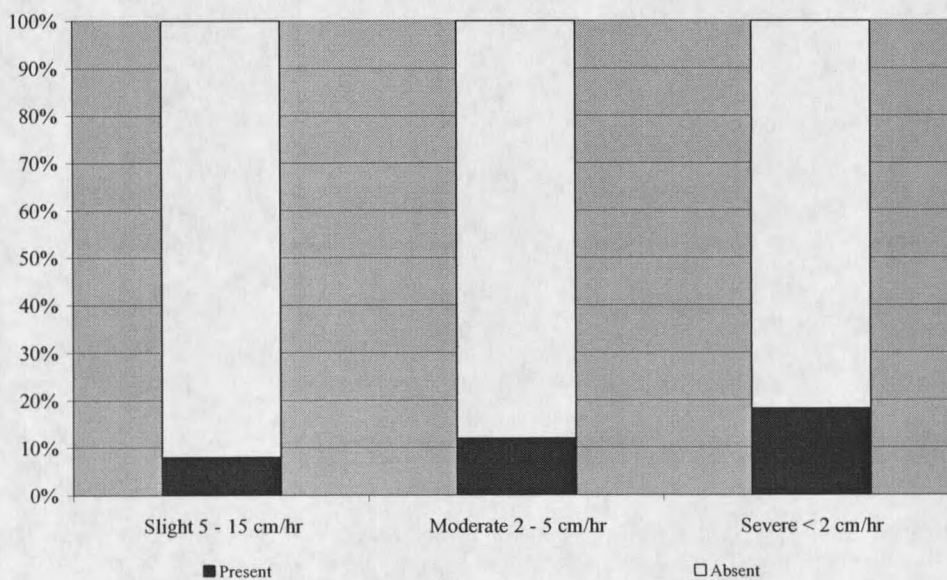


Figure 25. Total Coliform Occurrence Values by the Septic System Limitation Rating of Soil Percolation Rate.

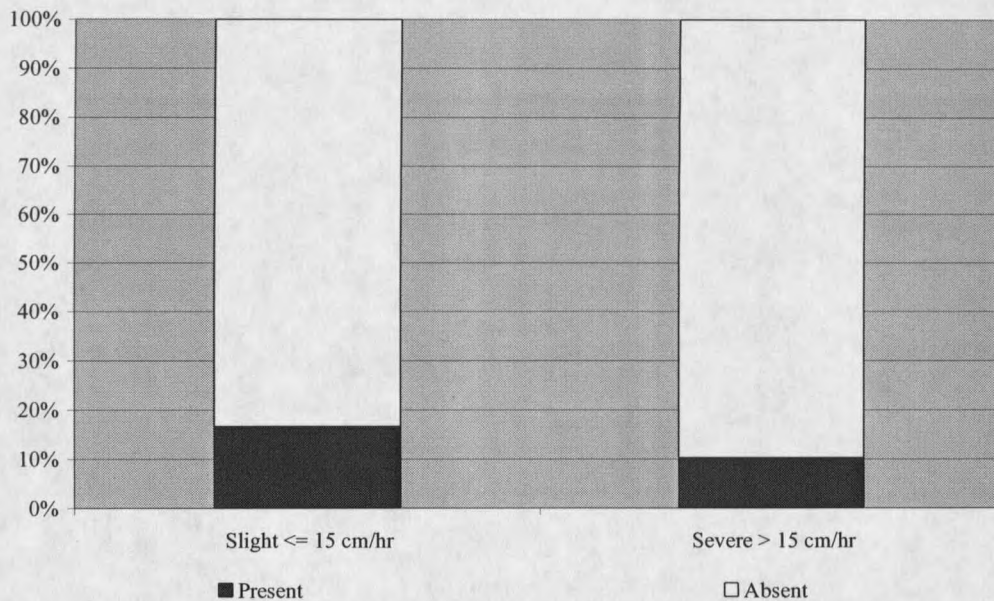


Figure 26. Total Coliform Occurrence Values by the Septic System Limitation Rating of Soil Filtration Rate.

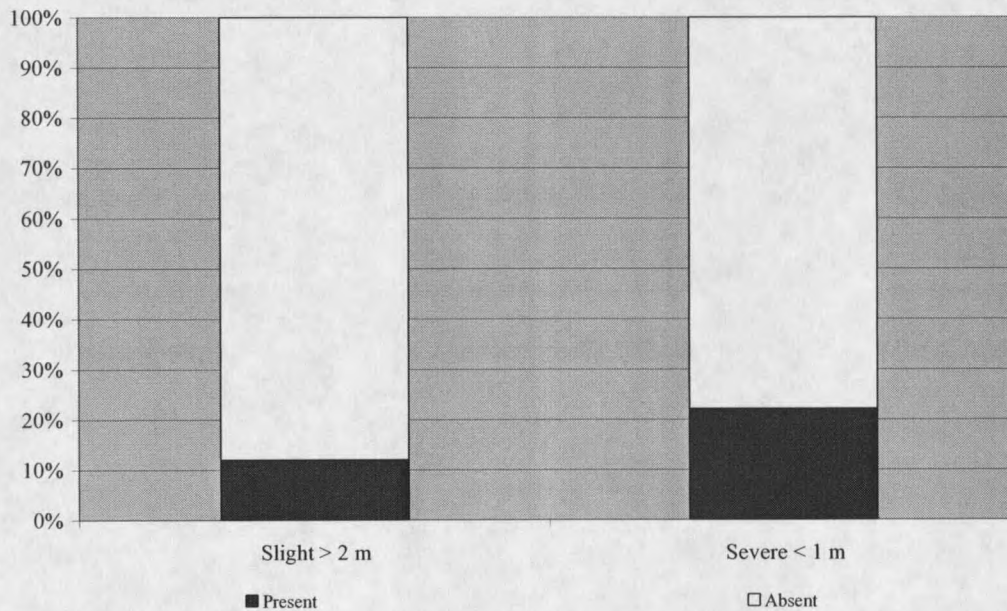


Figure 27. Total Coliform Occurrence Values by the Septic System Limitation Rating of Depth to High Water Table.

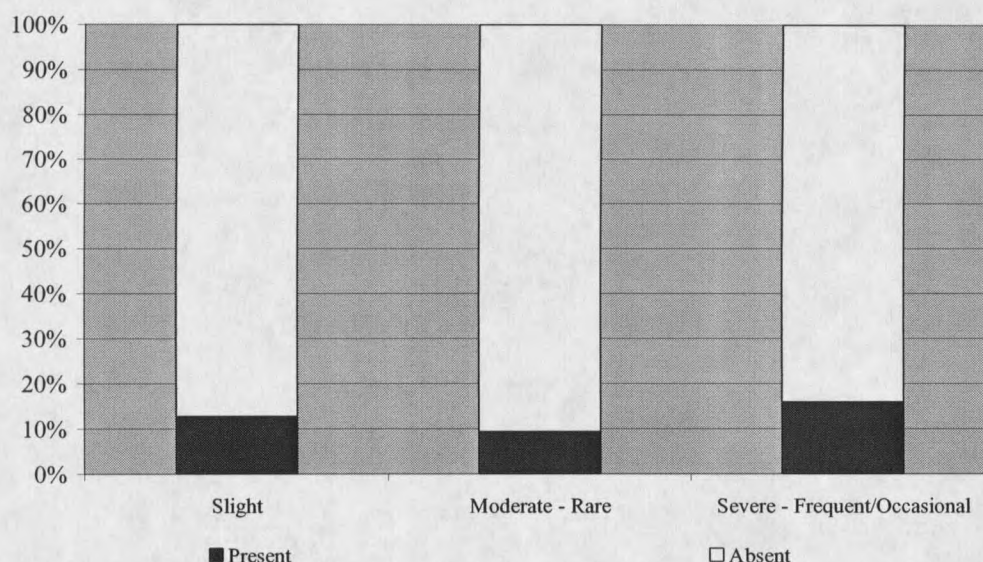


Figure 28. Total Coliform Occurrence Values by the Septic System Limitation Rating of Flooding Frequency.

Housing Density

To begin, 12 scripts were run in ArcView™ to calculate structure density in an upgradient flow wedge from each well. Figures 29 through 34 display the relationship between varying wedge angles and distances. The mean from the twelve trials was taken to represent housing density at a well. This value weights the number of structures closest to a well, because as the radius expands the structures closest to the well will be counted in addition to new wells captured in the upgradient wedge. The mean housing density values used for analyzing the upgradient structures ranged from 0 to 54, with an average of 3.5.

First, a simple linear regression was performed for the natural log nitrate-nitrogen values versus the average number of structures within 1 kilometer, 500 meters, and 150

meters upgradient wedge radii, at 90, 60, 30, and 15 degree intervals. The resultant r^2 value was 0.01 (Figure 35).

The coliform data were analyzed with a logistic regression against of the mean number of structures within 1 kilometer, 500 meters, and 150 meters upgradient wedge radii, at 90, 60, 30, and 15 degree intervals. The Wald's X^2 scores ranged from 0 to 0.0006 with an average probability value of 0.99, resulting in a rejection of the null hypothesis.

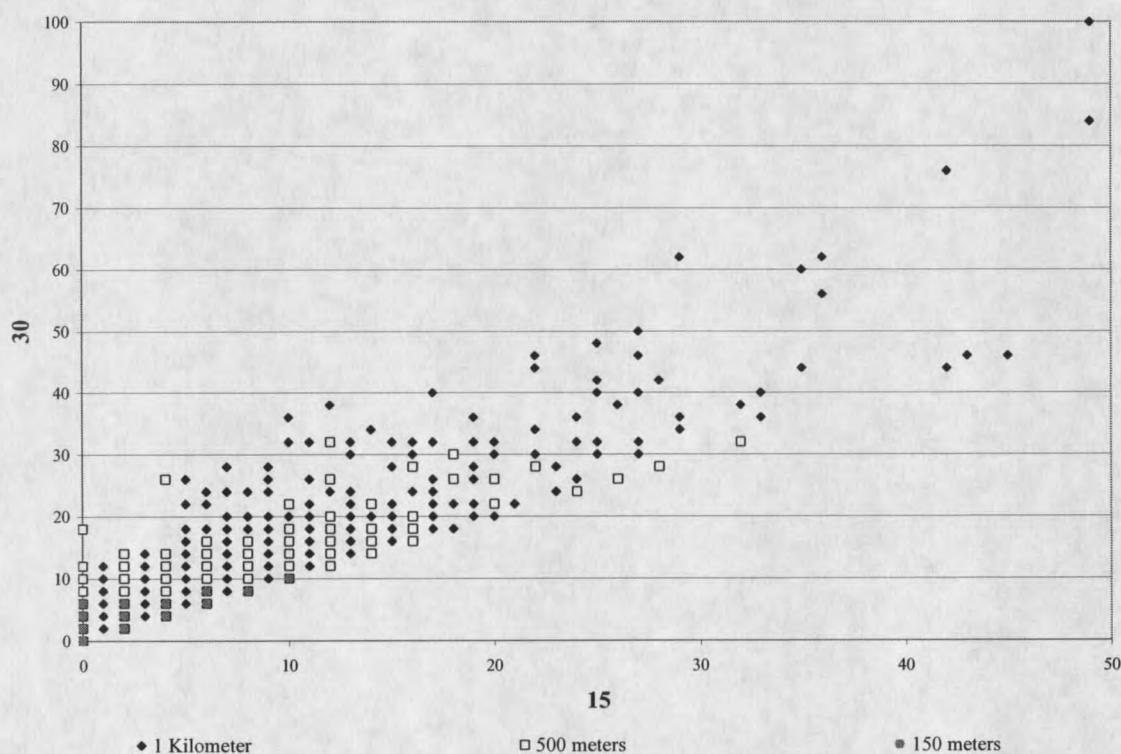


Figure 29. Housing Density per Well at 15 and 30 Degrees.

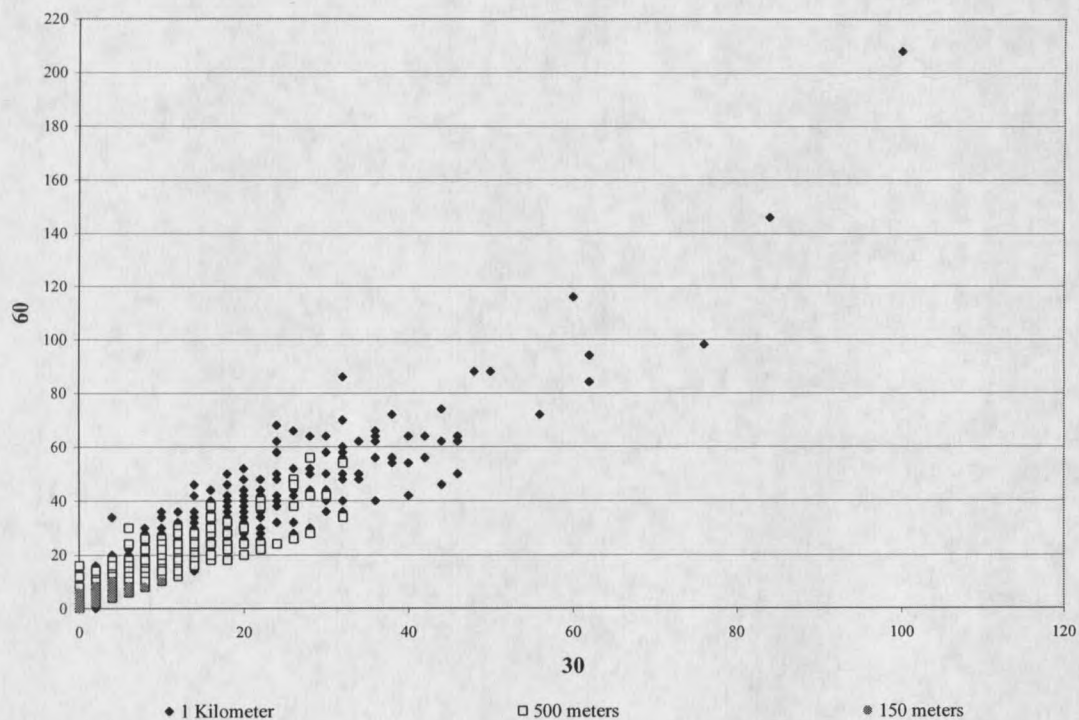


Figure 30. Housing Density per Well at 30 and 60 Degrees.

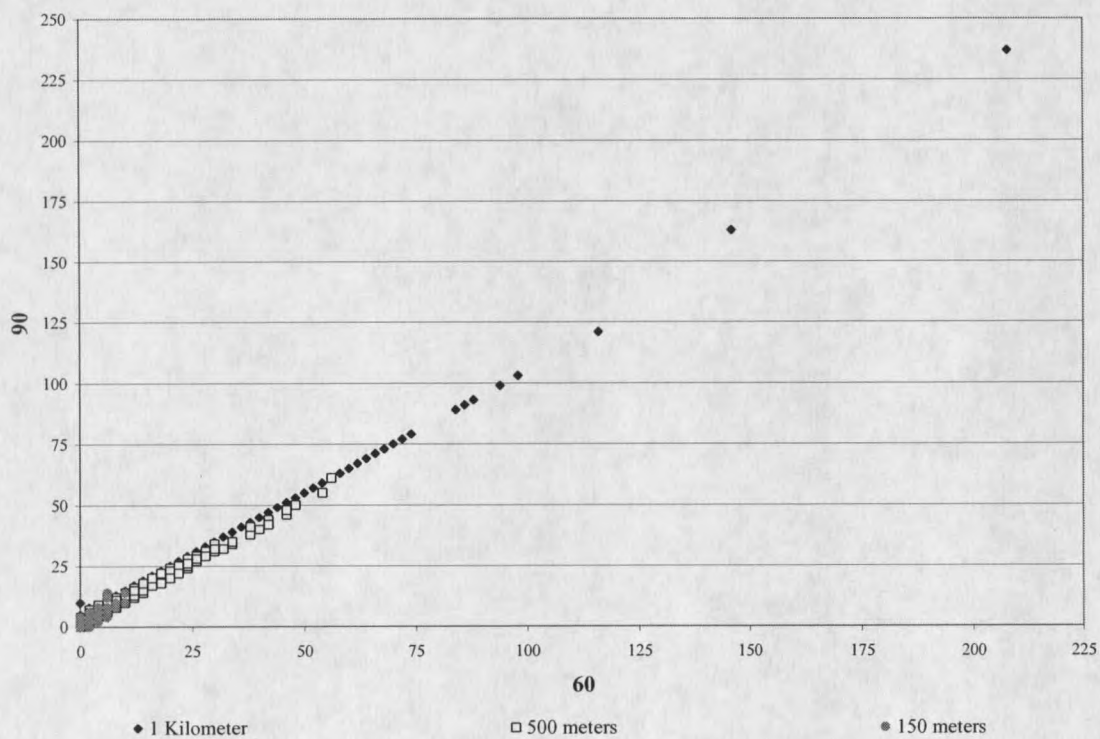


Figure 31. Housing Density per Well at 60 and 90 Degrees.

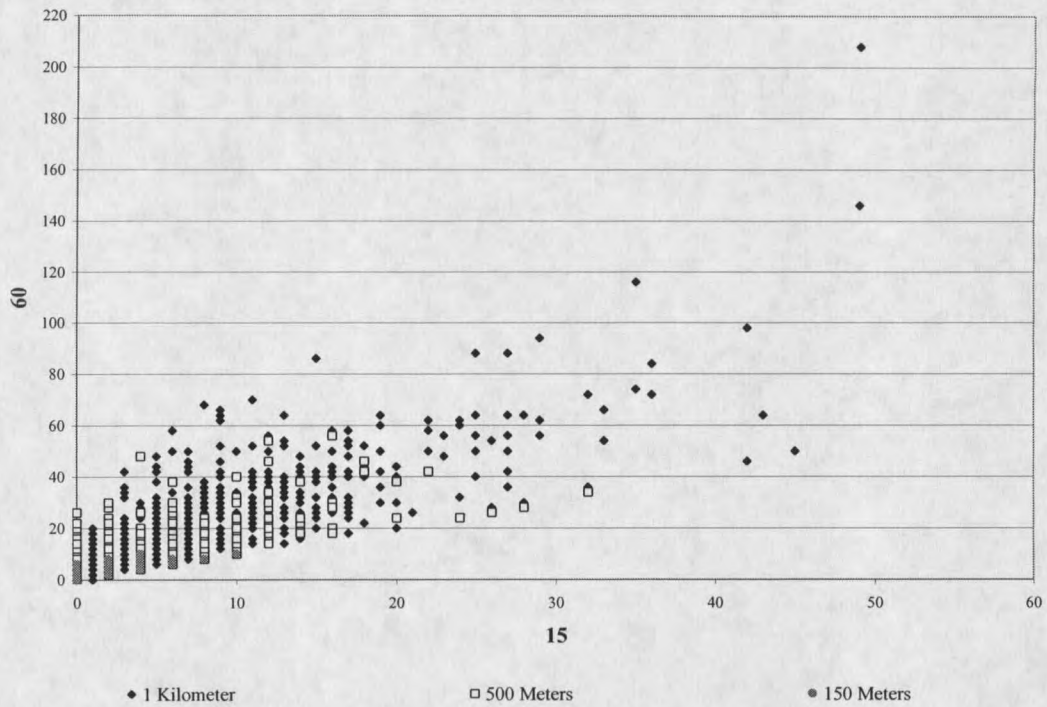


Figure 32. Housing Density per Well at 15 and 60 Degrees.

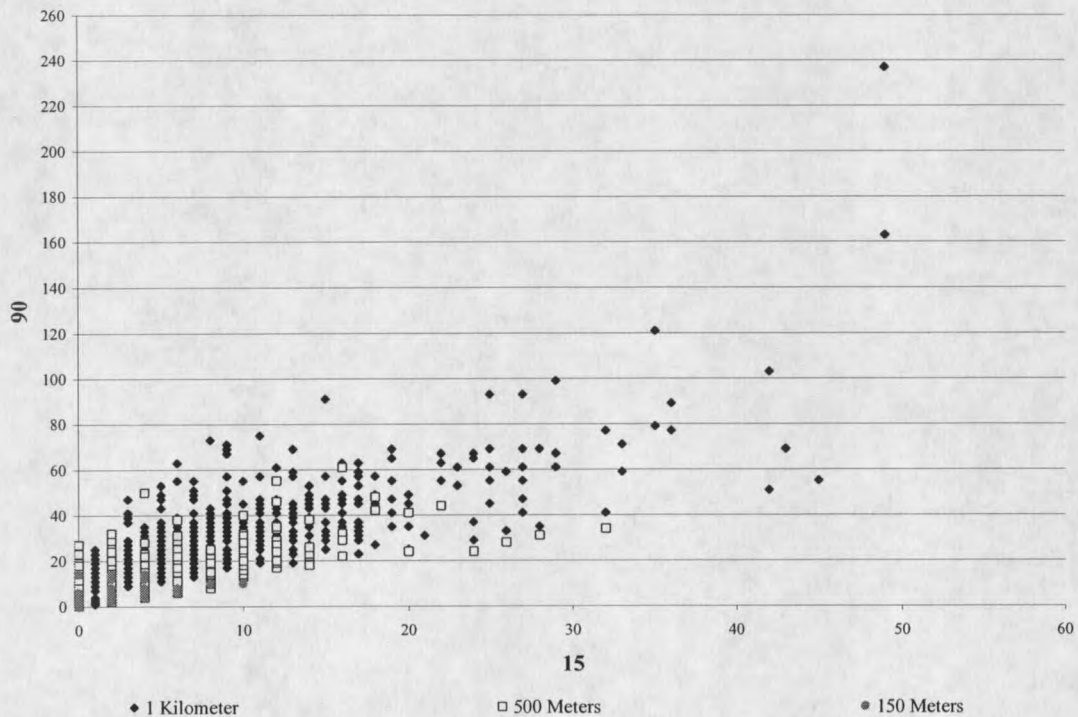


Figure 33. Housing Density per Well at 15 and 90 Degrees.

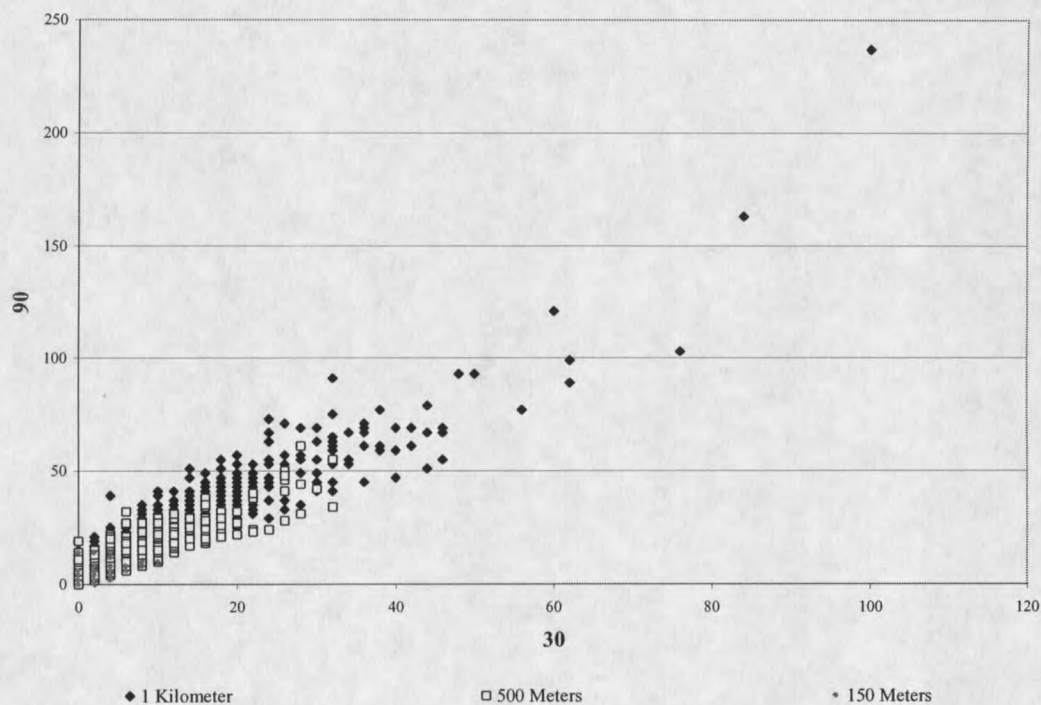


Figure 34. Housing Density per Well at 30 and 90 Degrees.

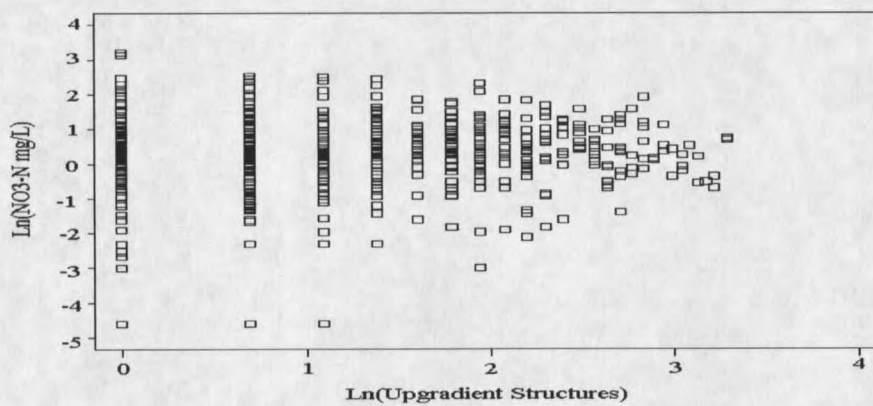


Figure 35. Scatterplot for the Natural Log Nitrate-Nitrogen Values versus the Natural Log Housing Density.

Land Application of Wastes

Datasets were prepared for testing the difference among means of nitrate-nitrogen values associated with septage and biosolids application sites. Preliminary summary statistics revealed that there were an insufficient amount of septage wells with which to conduct the hypothesis tests (Table 9).

Table 9. Natural Log Nitrate-Nitrogen Values Associated with Biosolids and Septage.

Class	Observations	Mean	Converted	Standard	Minimum	Converted	Maximum	Converted
			Mean	Deviation		Minimum		Maximum
Biosolids	44	0.78	2.18	0.85	-2.3	0.1	2.4	11.
Septage	6	0.44	1.55	0.43	10.12	0.89	1.1	3

Frequency table analysis was performed with the coliform data sorted by septage and biosolids application sites. The expected value for coliform presence within the category of septage application fell below 5, which violated the assumption of large sample sizes for the χ^2 test (Table 10).

Table 10. Frequency Table for Total Coliform Occurrence and Septage and Biosolids.

Observed			
Coliform	Biosolids	Septage	Total
Present	8	9	17
Absent	160	37	197
Total	168	46	214
Expected			
Coliform	Biosolids	Septage	
Present	13.35	3.65	
Absent	154.65	42.35	
violates assumptions of test			

Well Depth

289 unique wells associated with 309 records had both nitrate-nitrogen and well depth data. The natural log nitrate-nitrogen data were prepared for a simple linear

regression against the natural log of well depth. The regression resulted in an r^2 value of 0.02 (Figure 36).

105 unique wells associated with 1,265 records had both total coliform and well depth data. The total coliform data were prepared for a logistic regression of presence versus well depth. The Wald's X^2 score was 1.59 with a probability of 0.21, resulting in a rejection of the null hypothesis.

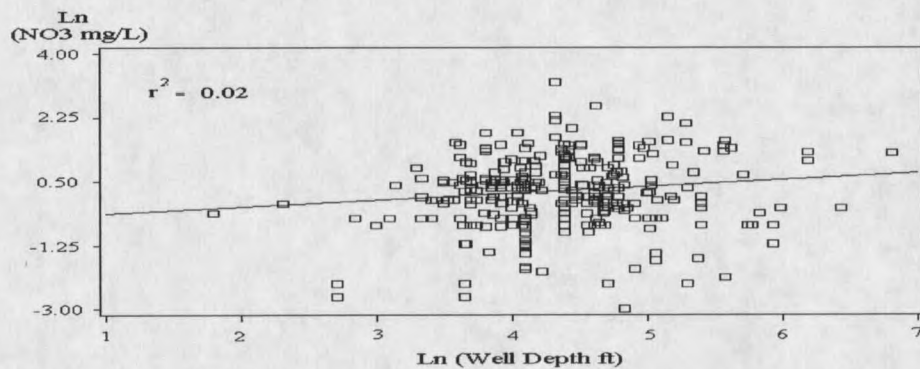


Figure 36. Scatterplot of Natural Log Nitrate-Nitrogen Values versus Well Depth.

Hydrogeology

Preliminary statistics revealed that many of the different hydrologic units in the GLWQD were represented in the dataset (Table 11). However, the rather sparse sample sizes among some units prohibited inclusion in the analysis. The West Gallatin Alluvial Aquifer, Small Stream and Fan Aquifer, Quaternary-Tertiary Basin Fill Aquifer, and Billman Creek Aquifer were tested for a difference of means with a one-way ANOVA. The calculated F statistic of 24.58 was associated with a probability of less than 0.001. This value signified rejection of the null hypothesis at the 95% confidence level,

indicating that there is statistical evidence to conclude that the aquifers are part of different populations with different distributions (Figure 37).

Frequency table analysis was preformed with the coliform data sorted by hydrogeologic unit in the GLWQD. Three trials were run in MS Excel™ before distinguishing the hydrogeologic units with sufficient samples for testing (Table 12). The Gallatin Alluvial Aquifer, Small Stream and Fan Aquifer, and Quaternary -Tertiary Basin Fill Aquifer were tested for differences between observed and expected counts for total coliform. The calculated χ^2 value of 19.44 had a probability of less than 0.0001. This value implied rejection of the null hypothesis at the 95% confidence level, indicating that there is a difference among coliform occurrence by hydrogeologic unit (Figure 38).

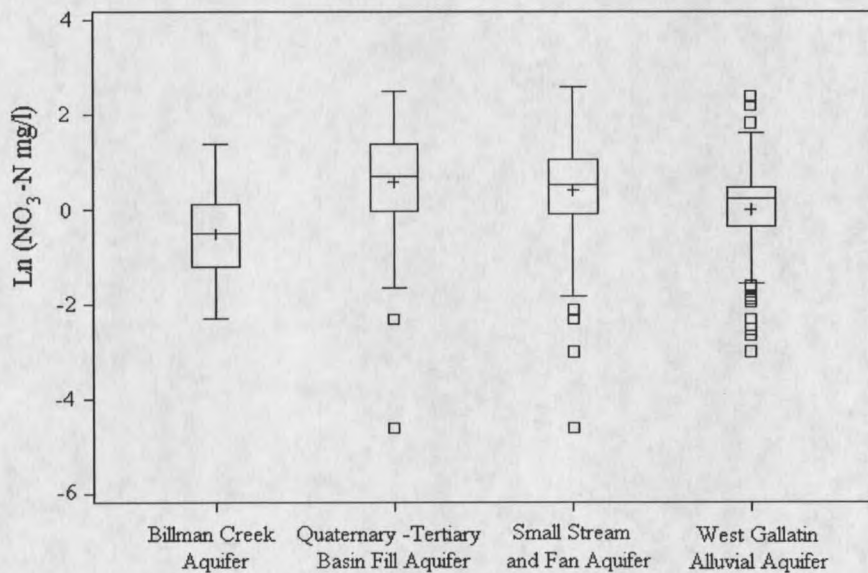


Figure 37. Natural Log Nitrate-Nitrogen Distribution by Tested Aquifers.

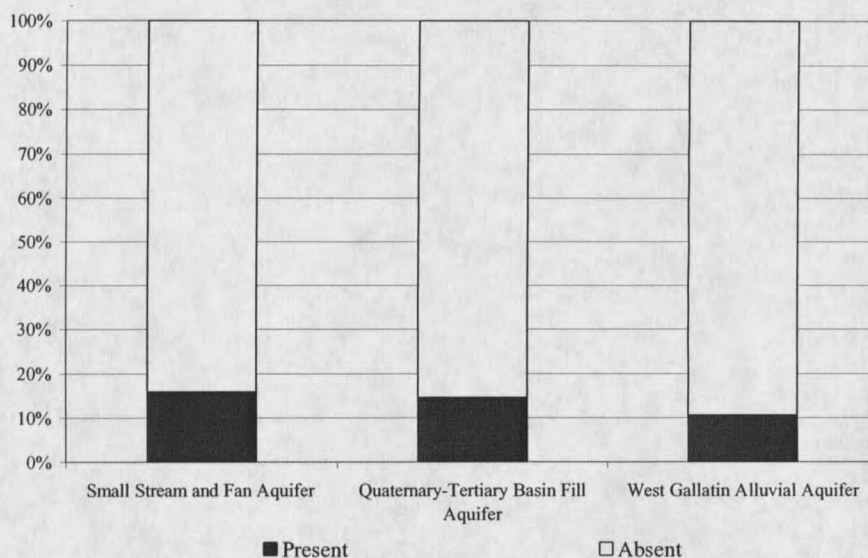


Figure 38. Total Coliform Occurrence by Major Hydrogeologic Units in the GLWQD.

Table 11. Natural Log Nitrate-Nitrogen Values Associated with Hydrogeologic Units.

Class	Observations	Mean	Converted Mean	Standard Deviation	Minimum	Converted Minimum	Maximum	Converted Maximum
QwGal	403	0	1.00	0.8	-3	0.05	2.38	10.80
Qssf	321	0.39	1.48	1	-4.61	0.01	2.56	13.00
QTbf	176	0.58	1.79	1.04	-4.61	0.01	2.5	12.18
KThf	8	-0.49	0.61	1.38	-2.3	0.10	1.28	3.60
Kbc	21	-0.51	0.60	1.05	-2.3	0.10	1.39	4.01
Ks	9	-0.73	0.48	0.76	-2.3	0.10	-0.11	0.90
Kte	4	-1.56	0.21	1.33	-3	0.05	-0.11	0.90
Kc	1	-2.3	0.10		-2.3	0.10	-2.3	0.10
Kf	5	-1.9	0.15	0.8	-2.3	0.10	-0.69	0.50
Ktm	10	1.37	3.94	1.71	-2.3	0.10	3.21	25.00
Kk	1	0.1	1.11		0.1	1.11	0.1	1.11
Ju	1	-0.11	0.90		-0.11	0.90	-0.11	0.90
Mmm	1	0.96	2.61		0.96	2.61	0.96	2.61
Am	6	-0.14	0.87	0.47	-0.69	0.50	0.41	1.51

Unit Key

QwGal	West Gallatin Alluvial Aquifer
Qssf	Small Stream and Fan Aquifer
QTbf	Quaternary -Tertiary Basin Fill Aquifer
KThf	Hoopers-Fort Union Aquifer
Kbc	Billman Creek Aquifer
Ks	Sedan Aquifer
Kte	Telegraph Creek- Eagle Aquifer
Kc	Cody Aquitard
Kf	Frontier Aquifer
Ktm	Thermopolis-Mowry Aquitard
Kk	Kootenai Aquifer
Ju	Jurassic Aquitard
Mmm	Mission Canyon Aquifer
Am	Crystalline Metamorphic

Table 13. Two Way Trials for Total Coliform Occurrence and Hydrogeologic Units

Observed																
TRAIL 1	Coliform	QwGal	Qssf	QTbf	KThf	Kbc	Ks	Kte	Kc	Kf	Ktm	Kk	Ju	Mmm	CDIM	Am
	Present	172	228	84	12	18	4	4	4	0	8	0	1	0	5	1
	Absent	1455	1211	491	24	76	38	21	12	17	8	14	0	1	110	50
	Total	1627	1439	575	36	94	42	25	16	17	16	14	1	1	115	51
Expected																
	Coliform	QwGal	Qssf	QTbf	KThf	Kbc	Ks	Kte	Kc	Kf	Ktm	Kk	Ju	Mmm	CDIM	Am
	Present	216.32	191.32	76.45	4.79	12.50	5.58	3.32	2.13	2.26	2.13	1.86	0.13	0.13	15.29	6.78
	Absent	1410.68	1247.68	498.55	31.21	81.50	36.42	21.68	13.87	14.74	13.87	12.14	0.87	0.87	99.71	44.22

Observed								
TRAIL 2	Coliform	QwGal	Qssf	QTbf	Kbc	Ks	CDIM	Am
	Present	172	228	84	18	4	5	1
	Absent	1455	1211	491	76	38	110	50
	Total	1627	1439	575	94	42	115	51
Expected								
	Coliform	QwGal	Qssf	QTbf	Kbc	Ks	CDIM	Am
	Present	22.33	29.61	10.91	2.34	0.52	0.65	0.13
	Absent	1266.07	1053.75	427.24	66.13	33.07	95.72	43.51

Observed				
TRAIL 3	Coliform	QwGal	Qssf	QTbf
	Present	172	228	84
	Absent	1455	1211	491
	Total	1627	1439	575
Expected				
	Coliform	QwGal	Qssf	QTbf
	Present	22.86	30.31	11.17
	Absent	1261.59	1050.02	425.73

Unit Key	
QwGal	West Gallatin Alluvial Aquifer
Qssf	Small Stream and Fan Aquifer
QTbf	Quaternary -Tertiary Basin Fill Aquifer
KThf	Hoopers-Fort Union Aquifer
Kbc	Billman Creek Aquifer
Ks	Sedan Aquifer
Kte	Telegraph Creek- Eagle Aquifer
Kc	Cody Aquitard
Kf	Frontier Aquifer
Ktm	Thermopolis-Mowry Aquitard
Kk	Kootenai Aquifer
Ju	Jurassic Aquitard
Mmm	Mission Canyon Aquifer
CDIM	Cambrian, Devonian, and Lower Mississippian Aquitard
Am	Crystalline Metamorphic

Predictive Modeling

Three predictive models were created in ArcMap using the geostatistical methods of kriging. First, multiple values per well were given the mean value to conform with the assumptions of the model. This resulted in total of 766 point values for nitrate-nitrogen. The data values were examined for normality and trends. A bell shaped histogram and relatively straight line normal quantile plots indicated that the log transformed dataset was fairly normally distributed (Figure 39 and 40). A prediction map of nitrate-nitrogen values was created using ordinary kriging. Indicator kriging was used to create two probability maps for threshold values of nitrate-nitrogen.

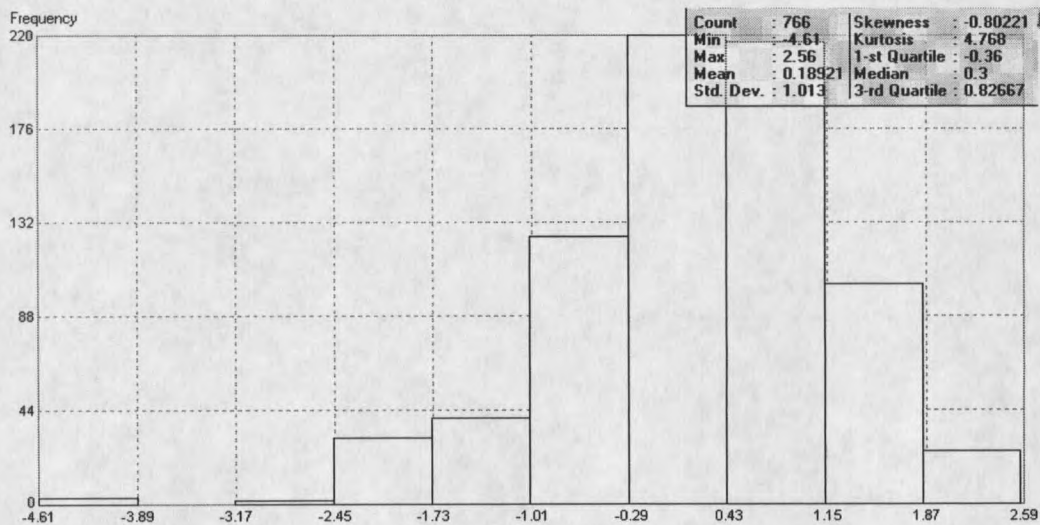


Figure 39. Frequency Histogram for the Natural Log Nitrate-Nitrogen Kriging Model Values.

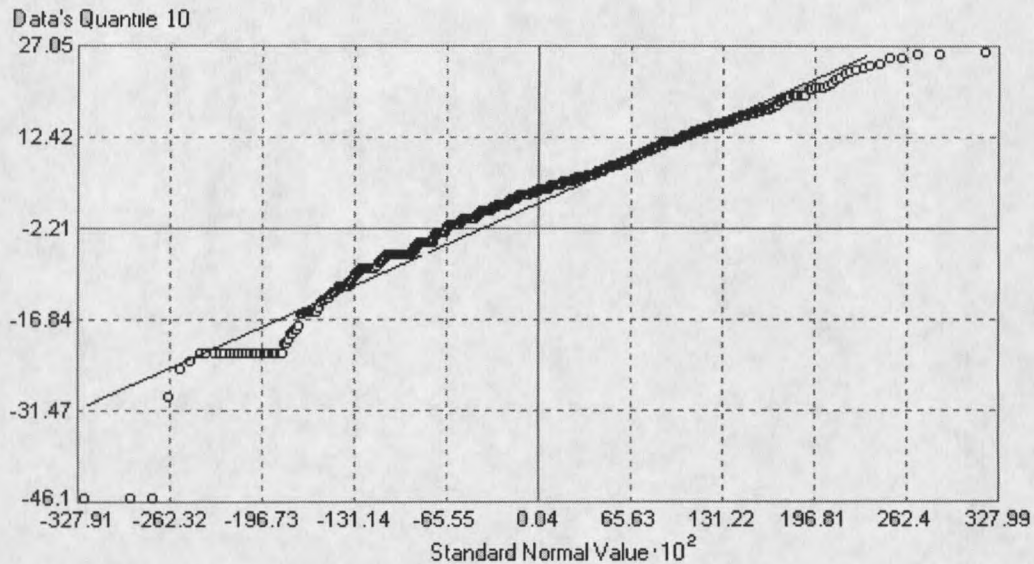


Figure 40. Normal Quantile Plot for the Natural Log Nitrate-Nitrogen Kriging Model Values.

Ordinary Kriging

Spatial trend analysis revealed the possibility of a 3rd order global trend, which was incorporated into the model (Figure 41). The global trend was weighted equally with the local influences. Anisotropy was also incorporated into the model, resulting in an elliptic search angle of 325° . A lag distance of 1000 meters by 9 lags was chosen using the guideline that the product should be about half of the largest distance between two points (Johnston et al. 2001). An exponential variogram model was chosen fit to the data, resulting in the prediction equation

$[0.57882 \cdot \text{Exponential}(8594.2, 5191.9, 324.9) + 0.3151 \cdot \text{Nugget}]$ (Figure 42). The final model has a mean prediction error and mean standardized error of 0.0 (Figure 43). The root mean square error was 0.83, with an average standard error of 0.70, and a root mean square standardized error of 1.18.

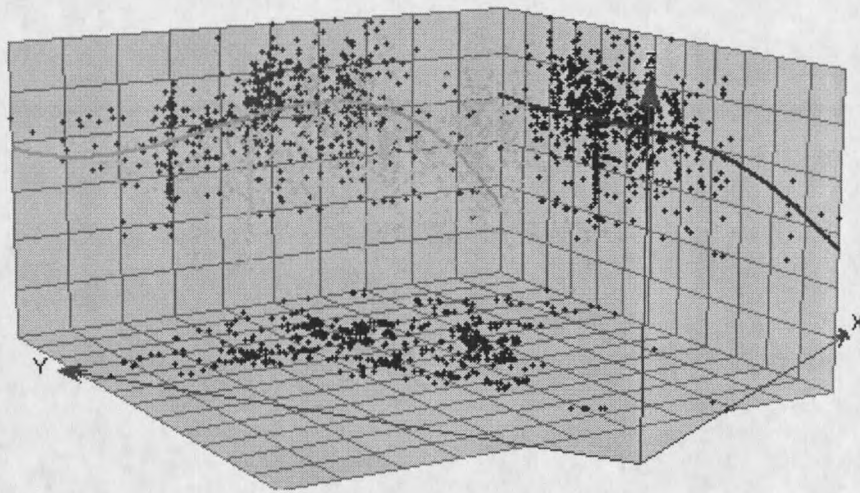
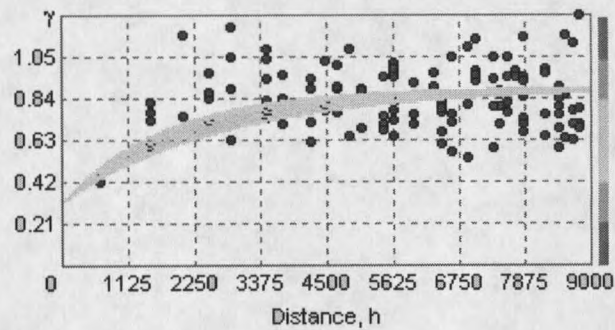


Figure 41. Fitted Third Order Trend Removal through Spatial Locations of Natural Log Nitrate-Nitrogen Values.



$$0.57882 * \text{Exponential}(8594.2, 5191.9, 324.9) + 0.3151 * \text{Nugget}$$

Lag Distance of 1000 meters, 9 lags

Anisotropy Angle: 325, Major Semiaxis: 8594.2, Minor Semiaxis: 5191.9, Angular Sectors: 4

Figure 42. Semivariogram Model for Ordinary Kriging the Natural Log Nitrate-Nitrogen in the GLWQD.

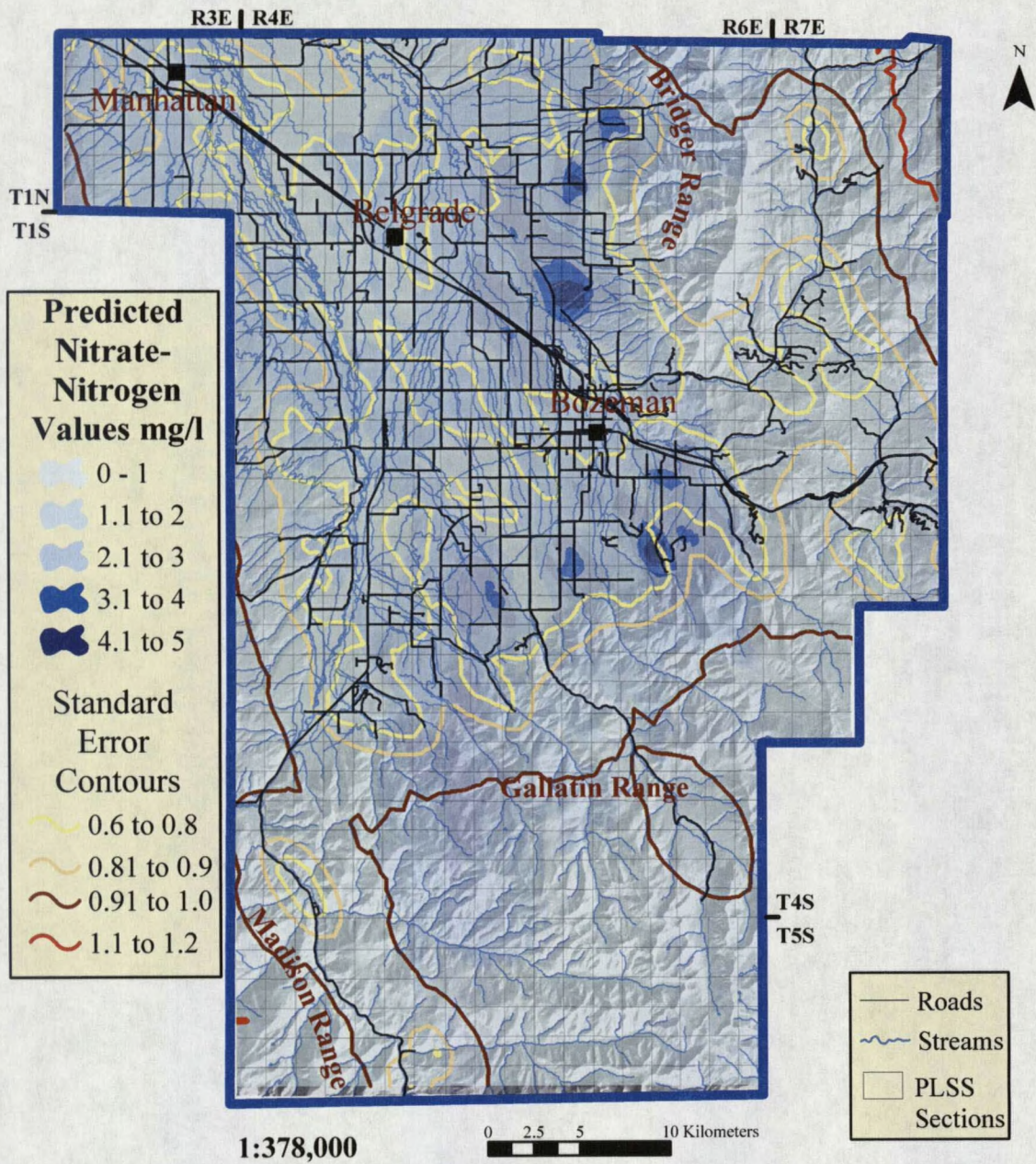


Figure 43. Ordinary Kriging Prediction Surface for Nitrate-Nitrogen Values in the GLWQD.

Indicator Kriging

Two different probability surfaces were created using the indicator kriging model. There was no option to remove a global trend when modeling with the indicator kriging module in ArcMap™. However, anisotropy was included in the models. Two models were created with equal lag distances of 1000 meters by 10 lags.

The first model was chosen to predict the likelihood of nitrate values exceeding 10 mg/L, the human health standard. An elliptic search angle of 1.6° was employed with an exponential variogram model. The prediction equation used was $[0.0059735 * \text{Exponential}(9924.7, 7221.5, 1.6) + 0.0041926 * \text{Nugget}]$ (Figure 44). The final model resulted in a mean prediction error and mean standardized error of 0.0 (Figure 46). The root mean square error was 0.1, with an average standard error of 0.08, and a root mean square standardized error of 1.35.

The second model was chosen to predict the likelihood of exceeding a nitrate threshold value of 3 mg/L in the GLWQD. An elliptic search angle of 330° was employed with an exponential variogram model. The prediction equation used was $[0.12283 * \text{Exponential}(9595.1, 6169.6, 329.5) + 0.031286 * \text{Nugget}]$ (Figure 45). The final model resulted with a mean prediction error and mean standardized errors of 0.0 (Figure 47). The root mean square error was 0.3, with an average standard error of 0.24, and a root mean square standardized error of 1.27.

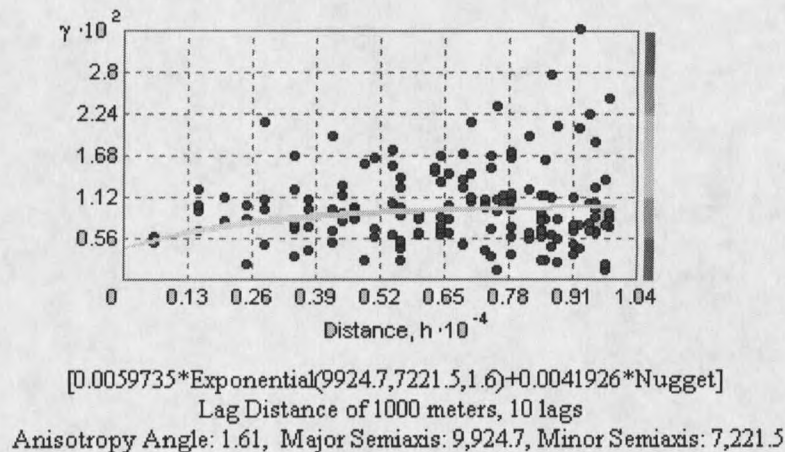


Figure 44. Semivariogram Model for Indicator Kriging the Natural Log Nitrate-Nitrogen Exceeding Human Health Standards (10 mg/l) in the GLWQD.

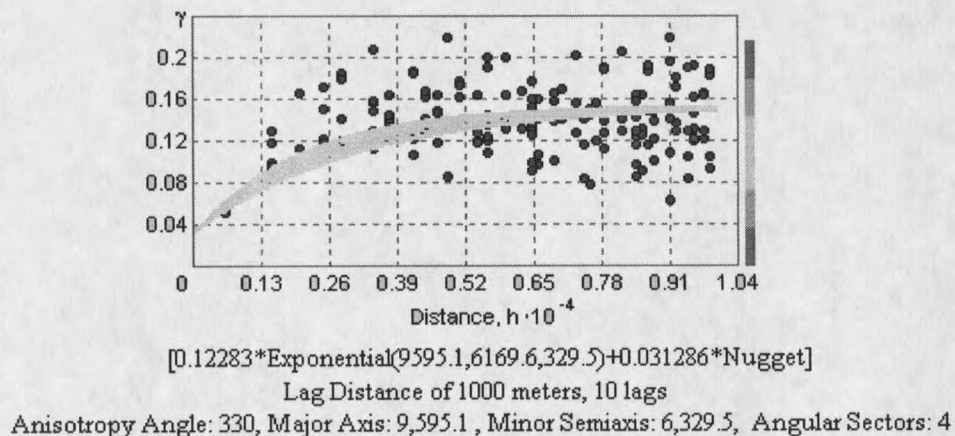


Figure 45. Semivariogram Model for Indicator Kriging the Natural Log Nitrate-Nitrogen Exceeding Hypothesized Contamination Threshold (3 mg/l) in the GLWQD.

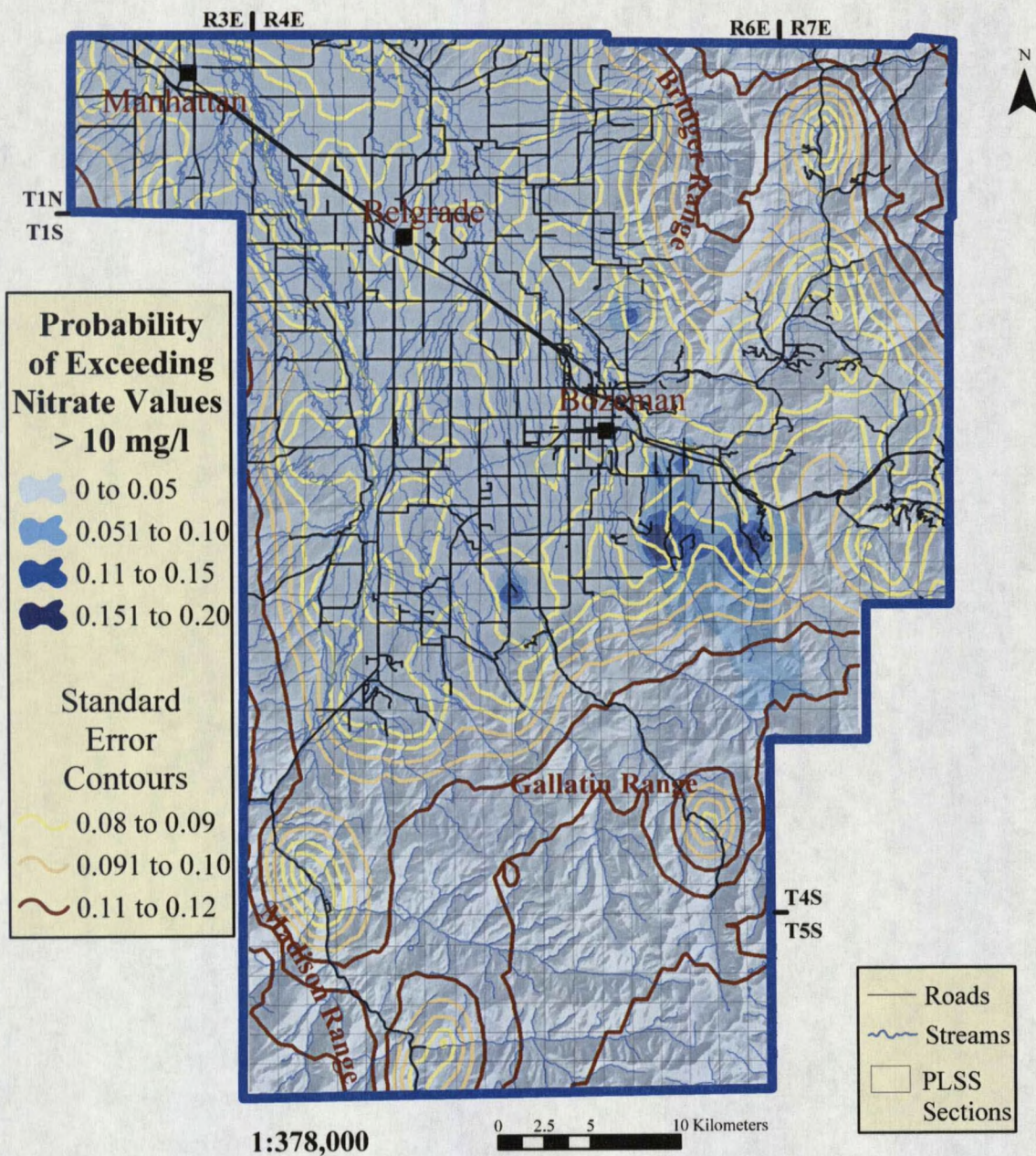


Figure 46. Indicator Kriging Probability Surface for Exceeding Human Health Standards for Nitrate-Nitrogen (10 mg/l) in the GLWQD.

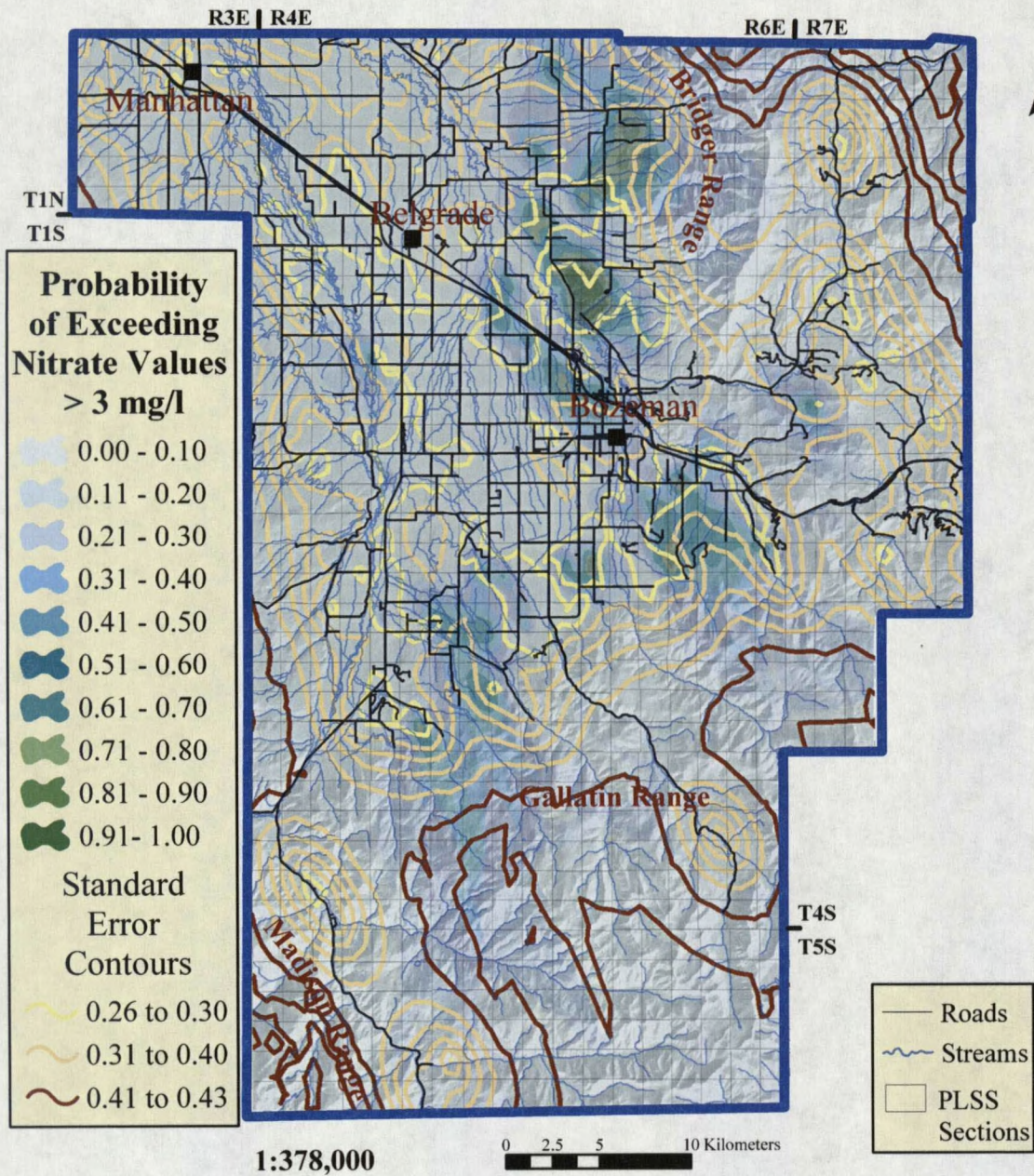


Figure 47. Indicator Kriging Probability Surface for Exceeding Hypothesized Contamination Threshold for Nitrate-Nitrogen (3 mg/l) in the GLWQD.

CHAPTER 5

DISCUSSION

Hypothesis Testing

Results from the hypothesis testing performed with the nitrate-nitrogen and coliform data rely to a large extent on the precision of the spatial data. Well location was presumed to be within a thirty meter radius of the plotted location. Independent spatial data layers were acquired from a variety of sources with different spatial resolutions. The possibility of erroneous classification must be considered. Also, because this was an observational study, interference from confounding variables and bias can not be ruled out. Therefore, significant statistical results should be interpreted in this context.

Septic System Limitation Ratings

Statistical tests for both nitrate-nitrogen and coliform occurrence produced significant results. For the natural log of nitrate-nitrogen, the septic limitation ratings of soil depth, soil percolation rate and depth to high water table produced significant results (Table 7). For soil depth ratings, natural log nitrate-nitrogen values for slight ratings were the least variable, negatively skewed, and had the highest mean (1.28 mg/l); moderate ratings were underrepresented, but had the lowest mean (0.17 mg/l); while severe ratings were the most variable, positively skewed, but with a mean (0.84 mg/l) lower than the values for the slight category (Figure 20). Soil percolation ratings associated with natural log nitrate-nitrogen values were fairly normally distributed for

slight ratings; moderate ratings were the least variable, with a negative skew; while severe ratings were the most variable, with a negative skew (Figure 21). Means for the natural log nitrate-nitrogen values grouped by soil percolation ratings ascended from slight to severe, with no class mean above 3.0 mg/l. Ratings associated with natural log nitrate-nitrogen values for depth to high water table were negatively skewed for slight ratings, but with a mean (1.32 mg/l) higher than the values for the severe category (0.83 mg/l); while severe ratings were fairly normally distributed (Figure 23). Ratings for soil filtration rates failed to produce significant results, as evidenced by the similar distribution of natural log nitrate-nitrogen values for slight and severe ratings (Figure 22).

For all analyzed septic limitation ratings, no class had mean or median natural log nitrate-nitrogen values greater than the hypothesized contamination threshold, 3.0 mg/l. The results of the soil depth tests fail to prove the hypothesis that shallow soils are more prone to nitrate contamination in the GLWQD. The results of the soil percolation tests fail to prove the hypothesis that insufficient soil percolation rates are favorable for denitrification in the GLWQD. The results of the soil filtration tests fail to prove the hypothesis that excessive soil filtration rates are favorable for nitrification in the GLWQD. The results of the depth to high water table tests fail to prove the hypothesis that shallow water tables increase transport of nitrates to ground water in the GLWQD. However, the negative skew of the data class for insufficient percolation rates could correlate to Reneau et al.'s (1989) conclusion that soils most suitable for septic systems have a limited capacity for denitrification (well aerated). All classes exhibited a mean

well below the human health standards and about what would be expected from normal background levels.

Total coliform occurrence with the septic limitation ratings of soil depth, soil percolation rate, soil filtration rate, and depth to high water table produced significant results (Table 8). With soil depth ratings, total coliform occurrence for severe ratings was just over twice that of slight ratings and almost five times that of moderate ratings (Figure 24). Soil percolation rates associated with total coliform occurrence ascended in magnitude from slight to severe (Figure 25). On the other hand, soil filtration ratings associated with total coliform occurrence descended in magnitude from slight to severe (Figure 26). Ratings associated with total coliform occurrence for depth to high water table were almost twice as high for severe, than for the slight category (Figure 27). Ratings for flooding frequency rates failed to produce significant results, as evidenced by the small variability among total coliform presence values between the slight, moderate, and severe classes (Figure 28).

The results of the soil depth tests appear to prove the hypothesis that shallow soils are more prone to ground water coliform contamination in the GLWQD. The results of the soil percolation tests appear to prove the hypothesis that insufficient soil percolation rates are favorable for coliform survival in ground water in the GLWQD. Likewise, the results of the soil filtration tests appear to prove the hypothesis that excessive soil filtration rates are unfavorable for coliform survival in ground water in the GLWQD. The results of the depth to high water table tests appear to prove the hypothesis that shallow water tables increase transport of coliform bacteria to ground water in the

GLWQD. The results of the flooding frequency tests fail to prove the hypothesis that ground water in flood prone areas is more prone to coliform degradation in the GLWQD. The significant septic limitation ratings correlated with increased coliform occurrence in the GLWQD have a greater likelihood of saturated soil conditions, which are necessary for coliform survival. However, fecal coliform, not total coliform, pose a potential health concern and fecal coliform occurrence was unable to be tested. Thus, it was concluded that the potential exists for increased chance of bacterial occurrence with saturated soil conditions in the GLWQD.

Housing Density

Statistical tests for relationships between housing density and nitrate-nitrogen levels and coliform occurrence failed to produce significant results. The well with the highest nitrate-nitrogen value had only 1 upgradient structure and was not tested for coliform. From this study, it cannot be concluded that housing density in the GLWQD does or does not affect nitrate-nitrogen and coliform levels in ground water.

Land Application of Wastes

An insufficient amount of data precluded hypothesis testing for the effects of biosolids and septage applications on ground water quality in the GLWQD. Descriptive statistics revealed that wells in areas of biosolids had a higher mean value of nitrate-nitrogen which is opposite the hypothesized relationship. But, coliform occurrence in areas of septage application was almost four times the occurrence for biosolids which aligns with the hypothesized relationship. However, due to small sample sizes these

results may not reflect the true population of ground water in areas of septage and biosolids applications.

Well Depth

Regressions of well depth versus nitrate-nitrogen and versus coliform occurrence did not generate significant results. However, only a small proportion of the total current wells had well depth data (15%). From this study, it cannot be concluded that well depth in the GLWQD does or does not affect nitrate-nitrogen and coliform levels in ground water.

Hydrogeology

Statistical tests for differences of nitrate-nitrogen and coliform levels associated with hydrogeologic units in the GLWQD exhibited significant results. For nitrate-nitrogen only four units were tested with one-way ANOVA, and inclusion of the Billman Creek Aquifer with only 21 samples was questionable. The test detected that samples from the Quaternary-Tertiary Basin Fill Aquifer and Small Stream and Fan Aquifer differed among means from the West Gallatin Alluvial Aquifer and Billman Creek Aquifer (Figure 37). The difference identified with the West Gallatin Alluvial Aquifer coincides with the original hypothesis that aquifers with high rates of transmissivity will experience lower rates of nitrate contamination. Yet, the Billman Creek Aquifer had the lowest mean rate of transmissivity as well as nitrate-nitrogen values of any of the units tested. Mirroring Kendy's (2001) findings, the Quaternary-Tertiary Basin Fill Aquifer had the most variation among nitrate-nitrogen values with the Small Stream and Fan

Aquifer closely following (Figure 37). This was probably a reflection of the heterogeneity of aquifer materials as a result of deposition processes. From the descriptive statistics, the Thermopolis-Mowry Aquitard samples tended to have the highest nitrate-nitrogen values but with 10 samples, this could not be tested. However, this may correspond with Power et al.'s (1974) findings that shales with exchangeable ammonium nitrogen can be a significant contribution of nitrate to ground water when exposed to the atmosphere.

Coliform results paralleled nitrate-nitrogen findings, but only the West Gallatin Alluvial Aquifer, Small Stream and Fan Aquifer, and Quaternary-Tertiary Basin Fill Aquifer could be tested. The West Gallatin Alluvial Aquifer had the lowest occurrence of coliform, while the Small Stream and Fan Aquifer had the highest (Figure 38).

Although the lowest levels of coliform were observed in the most transmissive aquifer, the hypothesis was foiled by results from least transmissive aquifer, the Quaternary-Tertiary Basin Fill aquifer (Figure 38). However, none of the units tested appear to have abnormally high coliform occurrence levels and without sufficient data on fecal coliform presence little can be said about the potential health threats. Therefore it was concluded that water quality in the three major aquifers of the GLWQD is expected to be within Human Health Standards for nitrate-nitrogen and coliform, with the least chance of contamination in the West Gallatin Alluvial Aquifer.

Predictive Modeling

A model is a simplification of reality and as such, requires assumptions to be made that are often too strict for complex environments. That said, a model can also be a useful tool for exploring subjects that are difficult to thoroughly investigate, such as ground water. However, a model must be interpreted with the limitations of the assumptions in mind. The abundance of wells located in the GLWQD presented the opportunity for spatial modeling. Modeling for coliform was abandoned due to the lack of presence data to model. The continuous nature of the nitrate data enabled geostatistical interpolation of values for the entire GLWQD.

The geostatistical method of kriging is termed the "Best Linear Unbiased Estimator" to use for continuous surface interpolation (Burrough and McDonnel 1998). The kriging assumption is that of a stationary mean value, which may be difficult to justify in complex geologic environments. Yet evidence from the natural log transformed nitrate data revealed a normal distribution. The ability of the kriging methods to account for spatial autocorrelation, random error, anisotropy and, in the instance of ordinary kriging, a global trend, were believed to strengthen the ground water modeling procedure. The third order trend employed was a reflection of the valley topography, while the northern anisotropic angles rotated the surface towards the outlet of the Gallatin River. The contours of standard errors on the maps display the uncertainty of prediction in areas where data points are sparse (mountains).

Ordinary Kriging

The prediction of natural log nitrate-nitrogen values with ordinary kriging was the best model of the three concerning statistical results. The mean prediction and mean standard error of 0.0 proved that the model created an unbiased estimate of the values. The root mean square error of 0.83, revealed the tendency of the model to over predict lower values, while under predicting high values of nitrate (Figure 48). This is typical of the regression procedure used. The average standard error of 0.70 and a root mean square standardized error of 1.18 should have been close to one. The fact that the root mean square standardized error was greater than 1 indicated that the model underestimated the variability of the predictions.

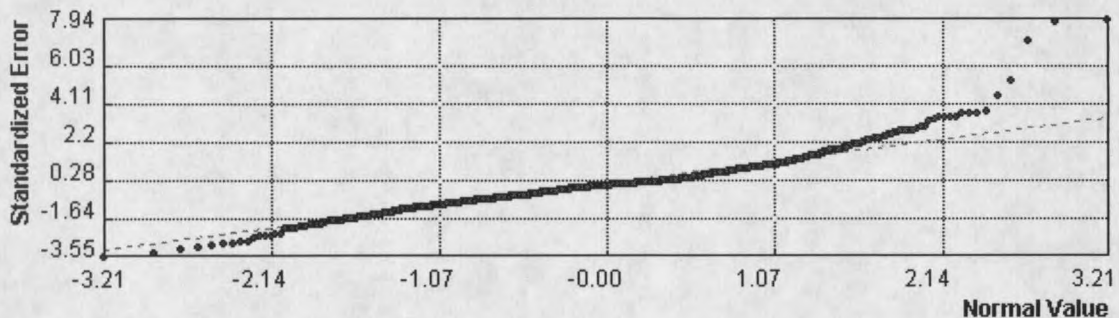


Figure 48. Standardized Error Plot for the Predicted Natural Log Nitrate-Nitrogen Values in the GLWQD.

The overall assessment of the map revealed that no areas of the prediction surface in the GLWQD are expected to exceed 5 mg/l of nitrate-nitrogen. This fits with the assumption of a stationary mean value somewhere around 1.3 mg/l. The areas that do show the highest tendency for elevated nitrate-nitrogen values are along the western flanks of the Bridger Range and along the northern front of the Gallatin Range (Figure 43). Kendy (2001, 37) concluded that the "the higher nitrate concentrations in water

beneath the eastern benches probably are related more to the quantity of ground-water recharge than to the source of the nitrate". Thus, the predicted nitrate surface may reveal a pattern of low recharge affected areas along the western flanks of the Bridger Range. This should be of concern for down gradient wells as continual loading of nitrate-nitrogen from septic systems and fertilizers may not receive adequate dilution. Yet, the high rates of ground water recharge along the northern front of the Gallatin Range do not conform to this hypothesis (Hackett et al. 1960). The Quaternary-Tertiary Basin Fill aquifer appears to be the only common, significant *a priori* variable in the areas of highest tendency for elevated nitrate-nitrogen values (Figure 4). Therefore, higher nitrate-nitrogen values modeled in the Quaternary-Tertiary Basin Fill aquifer may be the result of a natural geologic source.

Indicator Kriging

For health concerns, modeling for probability of exceeding a threshold value and discerning the confidence of the prediction are more appropriate than trying to predict nitrate values (Rautman and Istok 1996; Burrough and McDonnel 1998). The prediction of natural log nitrate-nitrogen values with indicator kriging was conducted twice. The first model was the probability of nitrate-nitrogen values exceeding 10 mg/l, and was the poorest fit of the three models (Figure 49). This had to do with the fact that nitrate values that high are rare in the GLWQD (11 out of 970). Once again, the mean prediction and mean standard error of 0.0 showed that the model created an unbiased estimate of the values. The root mean square error of 0.1 revealed how poor the model was at predicting the surface, as areas with the highest probabilities were below 10 mg/l whereas those that

were above had low probabilities (Figure 49). The average standard error of 0.08 and a root mean square standardized error of 1.35 indicated that again the procedure underestimated the variability of the prediction.

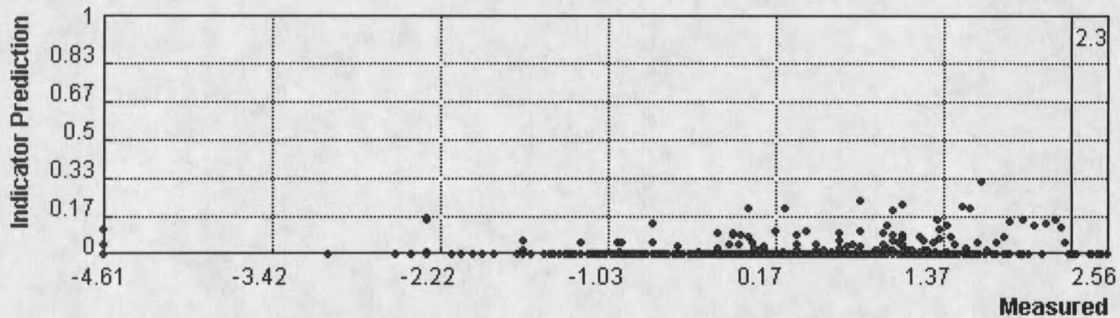


Figure 49. Standardized Error Plot for the Probability of Nitrate-Nitrogen Values Exceeding 10 mg/ in the GLWQD.

The overall assessment of the map showed that no areas of the prediction surface in the GLWQD have greater than a 30% percent chance of exceeding nitrate levels of 10 mg/l. The areas of higher probable risk were once again located along the western flanks of the Bridger Range and along the northern front of the Gallatin Range, mostly corresponding with the Quaternary-Tertiary Basin Fill aquifer (Figure 46). The localized zones of higher probability displayed the 'neighborhood' influence that the wells with higher nitrate values had in the prediction of unknown values.

The second indicator kriging model produced a surface of the likelihood of nitrate values greater than 3 mg/l. This value was chosen in part as a reflection of the "statistical contamination threshold", whereby the geometric mean and standard deviation are used to evaluate the maximum expected value (Aspinall et al. 1988). But because the geometric mean was only 1.28 mg/l, a value of 3 mg/l was chosen based on a value above 'normal' background levels (Tesorio and Voss 1997). The model predictions were more

accurate than the 10 mg/l model as nitrate values around 3 mg/l are much more common than 10 mg/l in the GLWQD (167 out of 970) (Figure 50). Yet again, the mean prediction and mean standard error of 0.0 confirmed that the model created an unbiased estimate of the values. The root mean square error of 0.3 indicated the model was slightly better at predicting the surface, yet still exhibited the tendencies of over and under prediction (Figure 50). Underestimation of the variability of the prediction was again displayed with an average standard error of 0.24 and a root mean square standardized error of 1.27.

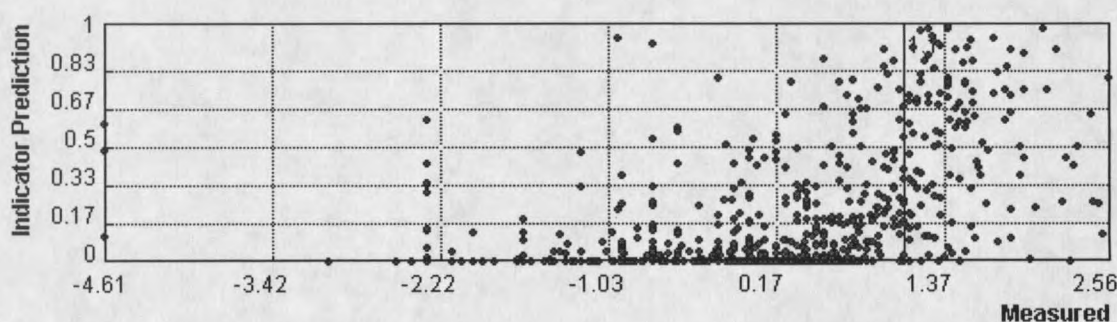


Figure 50. Standardized Error Plot for the Probability of Nitrate-Nitrogen Values Exceeding 3 mg/l in the GLWQD.

An overall review of the map revealed that there are areas in the GLWQD predicted to have nitrate-nitrogen values greater than 3 mg/l. The areas of highest probable risk were as expected, located along the western flanks of the Bridger Range, the northern front of the Gallatin Range, and areas surrounding the city of Bozeman (Figure 47). Again, these areas along the mountain fronts mostly correspond with the Quaternary-Tertiary Basin Fill aquifer, while areas outlying Bozeman correspond with the Quaternary Small Stream and Fan aquifer (Figure 4). The fact that each model tended to highlight the same areas served as quality control on the modeling procedure.

Another check on the modeling procedure was the small distribution of higher nitrate-nitrogen value areas. Slight differences in the direction of patterns can be explained by the use of a different angle of anisotropy for each model (predicted during variogram modeling during kriging).

CHAPTER 6

CONCLUSIONS

Knowledge of water quality is important for protection of the public health. This project sought to investigate ground water nitrate-nitrogen and coliform bacteria levels in the GLWQD by compiling, standardizing, and locating existing well water quality data for nitrates and coliform bacteria. The data were used to investigate associations with *a priori* variables and, in the case of nitrate-nitrogen, were used to model predictive surfaces in a GIS. Some statistical tests yielded significant results and potential problem areas for ground water nitrate-nitrogen were identified during the modeling procedures. This data is not to be used as a substitute for field investigation, nor to draw site-specific conclusions.

The abundance of Gallatin County residents who rely on ground water for drinking water supplies coupled with increased dependence on this resource from burgeoning population growth signaled the need to establish and investigate a comprehensive well monitoring network. Although close to 2000 wells were located in the GLWQD during this investigation, thousands more remain absent from the database. Over half of the records acquired from MMS were excluded due to insufficient information on well location. Other private analytical companies in the region who frequently test ground water from the GLWQD have not expressed an interest in sharing their data. As well, the Montana Department of Public Health and Human Services is remiss in collecting location specific information for the numerous water quality samples

maintained in their database. A better system needs to be enacted whereby a state or county standardized reporting form for well location could be attached to water quality samples for those volunteers who choose to share this information with an option for retention of anonymity. The addition of new wells and data to the GLQWD Ground Water Quality Database is strongly encouraged.

Overall descriptive statistics revealed that ground water in the GLWQD is generally low in nitrate-nitrogen and coliform bacteria. For nitrate, less than 1% of the 970 wells tested had levels greater than or equal to 10 mg/l. Total coliform occurrence was more prevalent with 13% of the 4,074 records indicating presence. Yet fecal coliform occurrence, the more significant potential bacterial health threat in the GLWQD, was found in only 1% of the 3,821 records. This evidence points to the probability of site specific influences, such as point sources or improper well construction as the most likely contributors to nitrate contamination and fecal coliform occurrence and not a region wide influence.

The hypothesis tests conducted must be evaluated with the possibility of erroneous classification due to reliance on previously existing spatial data layers and suspected well location. Also, bias from self-selected samples at MMS and confounding variables from a lack of experimental control cannot be ruled out. Hypothesis tests that could not be conducted for farming practices revealed the need for a higher resolution, contemporary, landuse data layer for the GLWQD. Hypothesis tests for the land application of wastes and well depth brought to light the need for increased data collection. In light of what is known, the tests that produced meaningful results, septic

limitation ratings and hydrogeologic units, suggest that natural processes, not anthropogenic are most likely related to regional differences in nitrate-nitrogen and coliform levels in ground water.

Areas with septic limitation ratings of shallow soils, insufficient soil percolation rates, and shallow depth to high water table in the GLWQD are expected to provide essential moisture needed for bacterial survival. Ground water from the West Gallatin Alluvial aquifer is expected to have the lowest levels of nitrate-nitrogen and coliform bacteria owing to high rates of dilution. Of the major alluvial aquifers, water quality in the Quaternary-Tertiary Basin Fill and Small Stream and Fan aquifers is expected to be most variable owing to the heterogeneity of substrate materials. Research should be conducted into ground water quality in the Thermopolis-Mowry aquitard to discern if exchangeable ammonium (NH_4^+), from the shale is nitrifying to create abnormally high nitrate-nitrogen concentrations (Power et al. 1974). 4 of the 11 samples in excess of Human Health Standards were detected in the Thermopolis-Mowry aquitard.

Continuous surface modeling of ground water nitrate-nitrogen in the GLWQD with kriging methods produced simplified, yet meaningful results. The assumption of a stationary mean was justified in light of previous research with the use of natural log transformed nitrate-nitrogen values (Yates and Yates 1989; Dingman 1993; Rautman and Istok 1996; Burrough and McDonnell 1998; Carlson and Osiensky 2002). Anisotropic angles, which trended to the northwest in the best fitting models, were thought to improve the model by capturing the general direction of ground water flow in the valley. A third order trend removal was thought to enhance the ordinary kriging model by mirroring the

bowl shaped topography from the mountains to the valley floor. Because kriging is essentially based on a form of least squares regression, the values predicted should be regarded as conservative estimates of regional nitrate-nitrogen levels. Contours of standard errors on the maps displayed the need for more comprehensive ground water quality monitoring in the mountains of the GLWQD.

All three predictive models for ground water nitrate-nitrogen in the GLWQD highlighted zones along the western flanks of the Bridger Range and the northern front of the Gallatin Range as potential problem areas. The probability model for exceeding 3 mg/l nitrate-nitrogen expanded to areas outlying Bozeman. These areas mainly correspond with the Quaternary-Tertiary Basin Fill aquifer, while areas outlying Bozeman correspond with the Quaternary Small Stream and Fan Aquifer. Because loading of nitrates to the water table from septic systems and lawn fertilizers tend to have cumulative impacts, downgradient wells in these aquifers areas may be at future risk owing to inadequate rates of dilution. Well water quality in the Quaternary-Tertiary Basin Fill and Quaternary Small Stream and Fan aquifers should be further monitored and investigated for the feasibility and/or necessity of municipal wastewater treatment facilities.

Aside from the findings of this research project, the water quality database itself is an important component for establishing widespread base-line knowledge of ground water nitrate and coliform levels in the GLWQD. This public information can be used by citizens, managers, and scientists in the GLWQD to make informed choices about water quality protection measures. To make this project truly successful, future water quality

data and new well locations need to be incorporated into the database in order to provide a greater breadth of understanding of the complex processes affecting ground water quality in the GLWQD. With the addition of new ground water quality data, more variables could be investigated, such as seasonal changes in ground water quality, and additional models and maps could be constructed for ground water quality in the GLWQD.

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APPENDICES

APPENDIX A

GROUND WATER QUALITY DATABASE

Ground Water Quality Data for the Gallatin Local Water Quality District

MS Access™ Database

All well water quality data collected and standardized for this study are located on the CD ROM in the right sleeve of this thesis. There are complete tables from the original source investigations and compiled nitrate-nitrogen and bacteria tables from the thesis preparation and analysis (Table 13). Other tables include Public Water Supply Systems with standardized samples but not analyzed due to mixing wells, and the results from the address geocoding process (Table 13). All of the tables are part of the MS Access 2000™ database, "GLWQD Ground Water Quality Data". Due to MS Access™ table naming conventions, table names have been shortened and lack appropriate punctuation in the database. Refer to Appendix B, "Ground Water Quality Database Dictionary", for explanations of database conventions and table fields.

Table 13. Data Index for Tables Corresponding to the MS Access 2000 Database
"GLWQD Ground Water Quality Data".

Table Name
Table 17. Hackett et. al Study
Table 18. Dunn Study
Table 19. Slagle Study
Table 20. Kendy Study
Table 21. MMS Private Wells and PWSS with a Single Source
Table 22. MMS PWSS with Multiple Sources
Table 23. Hyalite Foothills Study
Table 24. Extra Chemistry from MMS and Hyalite Foothills
Table 25. Flemming Study
Table 26. Data Used in Thesis Analysis
Table 27. Geocode Results

GIS Files for Wells Located in the GLWQD

Two separate GIS layers for wells located in the GLWQD are located on the CD ROM in the right sleeve of this thesis. There is one layer for historical wells (pre 1980) and another for current wells (1992 to 2001) (Table 14). The layers are in ESRI™ shapefile format. The .htm files for each GIS layer contain metadata in the Federal Geographic Data Commission outline. Refer to Appendix B, "Ground Water Quality Database Dictionary", for definitions of GIS layer table fields and values.

The GIS layers can be linked to the "GLWQD Ground Water Quality Data" database tables via common table fields: USGSID (historic wells) and WELLID (current wells). ArcView™ users with versions 3.x and lower will have to export the desired tables from the ground water quality database in dbaseIV format and then bring these tables in an ArcView™ project to link with the well layers. GIS users with ArcView™ versions 8.x can link directly to the database in an ArcMap™ project.

Table 14. GIS Data Files for Wells in the Gallatin Local Water Quality District.

GIS Dataset Filename	Associated Files:
GLWQD_Current	.dbf, .htm, .prj, .shp, .shx
GLWQD_Historic	.dbf, .htm, .prj, .shp, .shx

APPENDIX B

GROUND WATER QUALITY DATABASE DICTIONARY

Data Information for Use

MS Access™ Database

The structure of the database "GLWQD Ground Water Quality Data" reflects formats from original data sources, standardization processes for this analysis, and relations to other water quality databases. Many table field names are self-descriptive and represent items such as sample date, location, and elemental symbols for tested ground water constituents. Unless otherwise noted, all ions are measured in parts per million (ppm or mg/l). Those field names that necessitate further explanation are listed in Table 15. Field values that are abbreviated are defined within the table structure either by placing the cursor in the column so that definitions can be seen at the lower left corner of the MS Access™ datasheet view or by viewing the table design view.

Table 15. Database Abbreviation Key Codes for Table Column Names in "GLWQD Ground Water Quality Data" Database.

Field Name	Description
WELLID	Unique current well identifier
SAMPLEID	Unique sample identifier that ensures no duplication of records
USGSID	Well identifier used in the USGS and Dunn studies, reflects PLSS coordinates
MNUMBER	Well identifier used by Montana's Ground Water Information Center
System Name - P	Name of Public Water Supply System and number given by the state
Address Source	For MMS records, refers to completeness of an address given in a record
Level*	For MMS records, refers to accuracy of an address used to plot the well
NO3-N	Nitrate measured as nitrogen
TC	Total Coliform
FECAL	Fecal Coliform
SEC	Specific Electrical Conductance
TEMP	Temperature
DO	Dissolved Oxygen
DS	Dissolved Solids
HPC	Heterotrophic Plate Count (population of carbon dependent organisms)

*Level is either 1, 1v, or 2. 1 means that the record had enough information in the System Name and Sample Site fields to at least fill in the street address and roadname fields. The original Address field was

only used as secondary verification to rate location precision as 1v. This rating means a person's name and a street or location reference were given in the System Name and Sample Site fields, yet no address numbers were given. If this name was then assigned only one address in the Bozeman Area Qwest phonebook for the year of the sample with an identical match to the original Address field, a rating of 1v was given. A rating of 2 implies a full name was given in the Sample Site field and only one name was listed in the Bozeman Area Qwest phonebook for the year of the sample matching the person's name given. A 2 can also mean that a sample was only identified by an assigned number in the System Name or Sample Site fields which matches with another record's System Name or Sample Site fields. Less than 2 percent of the wells that plotted from the MMS data in the GLWQD were rated level 2.

GIS Files for Wells Located in the GLWQD

The database tables for the current and historic GIS layers identify location information and the process used to plot each well. Each layer has a 'link field' so that wells can be matched to records in the "GLWQD Ground Water Quality Data" database.

Table 16 defines fields common to both the current and historic GIS data layers.

Table 16. Database Abbreviation Key Codes for Table Column Names and Values in Historic and Current GIS Data Layers.

Field Name	Description
WELLID	Unique current well identifier
USGSID	Well identifier used in the USGS and Dunn studies, reflects PLSS coordinates
X	UTM Easting for Zone 12 North using the North American Datum of 1983
Y	UTM Northing for Zone 12 North using the North American Datum of 1984
GEOMETHOD	Method used to spatially locate the wells, see below
	MH Mapped using Hackett et.al's original map
	PLSS Mapped using PLSS coordinates
	GS Mapped by geocoding structures in ArcCatalog™
	IM Mapped interactively by geocoding with ArcMap™
	GPS Mapped with coordinates obtained in the field with a GPS system
	UMLL Mapped with coordinates obtained from the USGS Montana Field Office
	UILL Mapped with coordinates from the USGS National Water Information System
	SM Mapped with the Gallatin County Structures Layer
	PM Mapped with the Gallatin County Parcels Layer
	MI Mapped with USGS topographic maps and Montana's Ground Water Information Center

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