Groundwater Quality from Aquifers in Precambrian Rocks of the Central Black Hills, Pennington County, South Dakota

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Abstract

From 2013 through 2015, faculty members and students in the Department of Geology and Geological Engineering at the South Dakota School of Mines and Technology, with funding from the West Dakota Water Development District, conducted a survey of drinking-water quality from aquifers in the Precambrian core of the Black Hills, in the western half of Pennington County. Samples were collected from private water wells, providing a free-of-cost analysis to the sample donors. Samples were analyzed for hardness, calcium, magnesium, nitrate, arsenic, and sulfate, as well as for the presence of total and fecal coliform bacteria. The analyses were performed by Midcontinent Testing Laboratories Inc. in Rapid City.

A total of 273 samples from 262 private wells were collected and compared to Environmental Protection Agency drinking water standards for public wells. Testing found that 36 (14%) of the wells exceeded the EPA standard levels for arsenic (0.010 mg/L), 81 wells (31%) exceeded the EPA recommended limit for iron (3.0 mg/L), 8 wells (3%) exceeded the EPA standard for nitrate (10 mg/L), and 4 wells (1.5%) exceeded the recommended limit for sulfate (250 mg/L). Total coliform bacteria were detected in 97 wells (37%) and fecal coliform bacteria were detected in 17 wells (6%). The EPA does not specify a recommended limit for hardness, but 49% of samples exceeded 180 mg/L hardness and would be considered very hard or extremely hard water.

High values of arsenic are predominantly located in the area of mineralization and mining between Hill City and Keystone, south of the Empire/Keystone fault system. High iron values are distributed over the entire study area. Both arsenic and iron occurrence appear complexly controlled by structural features and mineralized zones rather than associating with specific rock units, and arsenic/iron values may change abruptly over distances of a kilometer or less. Although high values occur more frequently in certain areas, not every well in an area will have

elevated values, and the only way to know if a well has a problem is to test it. Detailed "report cards" and interactive maps showing the occurrence of each constituent were prepared and are available as appendices in this report and on the web site http://www.sdsmt.edu/aquifers .

Introduction

The Black Hills of South Dakota have been the focus of extensive mining activities for over a century, with the mining areas primarily located in the crystalline metamorphic Precambrian core of the uplift. Residents within this region commonly live on old mining claims and obtain ground water from wells drilled into the crystalline rocks. Both the presence of mineralization and the activities associated with mining can have impacts on the quality of groundwater available. Arsenic and iron in particular are constituents known to occur in wells in the crystalline core (Carter et al., 2002) and isolated problems with nitrate and bacteria also have been reported in association with onsite waste disposal systems. Cleanup of specific streams degraded by mining activities has received much focus, but the overall quality of groundwater in the regions has not been extensively studied. Although some public well data exists for the region, the analyses tend to be spatially and temporally isolated. An understanding of the quality of private wells has not been previously attempted.

This study was conceived to document both naturally occurring and manmade ground water quality issues in the crystalline rocks of the central Black Hills in order to provide guidance to residents on the frequency and distribution of ground water problems. Systematic sampling of private wells through invited homeowner participation over a time span of three years can provide a more complete spatial picture of water quality issues in the crystalline core. The West Dakota Water Development District funded this study, which was carried out by faculty and staff of the South Dakota School of Mines and Technology. This report details the methods and results of the project.

Objective

The objective of this project is to determine if ground water contamination exits in the crystalline rocks of Pennington County and, if so, to communicate that information to homeowners and residents. Knowing that problems are frequent in certain areas will encourage residents to take steps to test wells and verify that their drinking water is safe.

Broader Impacts

As a result of this project, 262 well owners have benefited from free water quality tests that identify common problems of ground water quality and enable them to take steps, if necessary, to treat their water and ensure its safety and quality. In aggregate, the well data have been analyzed to determine the frequency and spatial distribution of water tests with high values of certain contaminants. This summary information has been presented through brochures, a web site, and an interactive map. All homeowners and prospective homeowners in the study area can use this information to make decisions about testing their drinking water.

Finally, the data set provides a snapshot of water quality in western Pennington County during the years 2013-2015. Future residential or urban development in the Black Hills may cause additional impacts on constituents, including nitrate and coliform bacteria, and this study may serve as a baseline for assessing changes in water quality. The data may also help identify the source(s) of ground water quality issues, track or model the movement of contaminants in the bedrock, and identify geologic or structural associations that impact water quality.

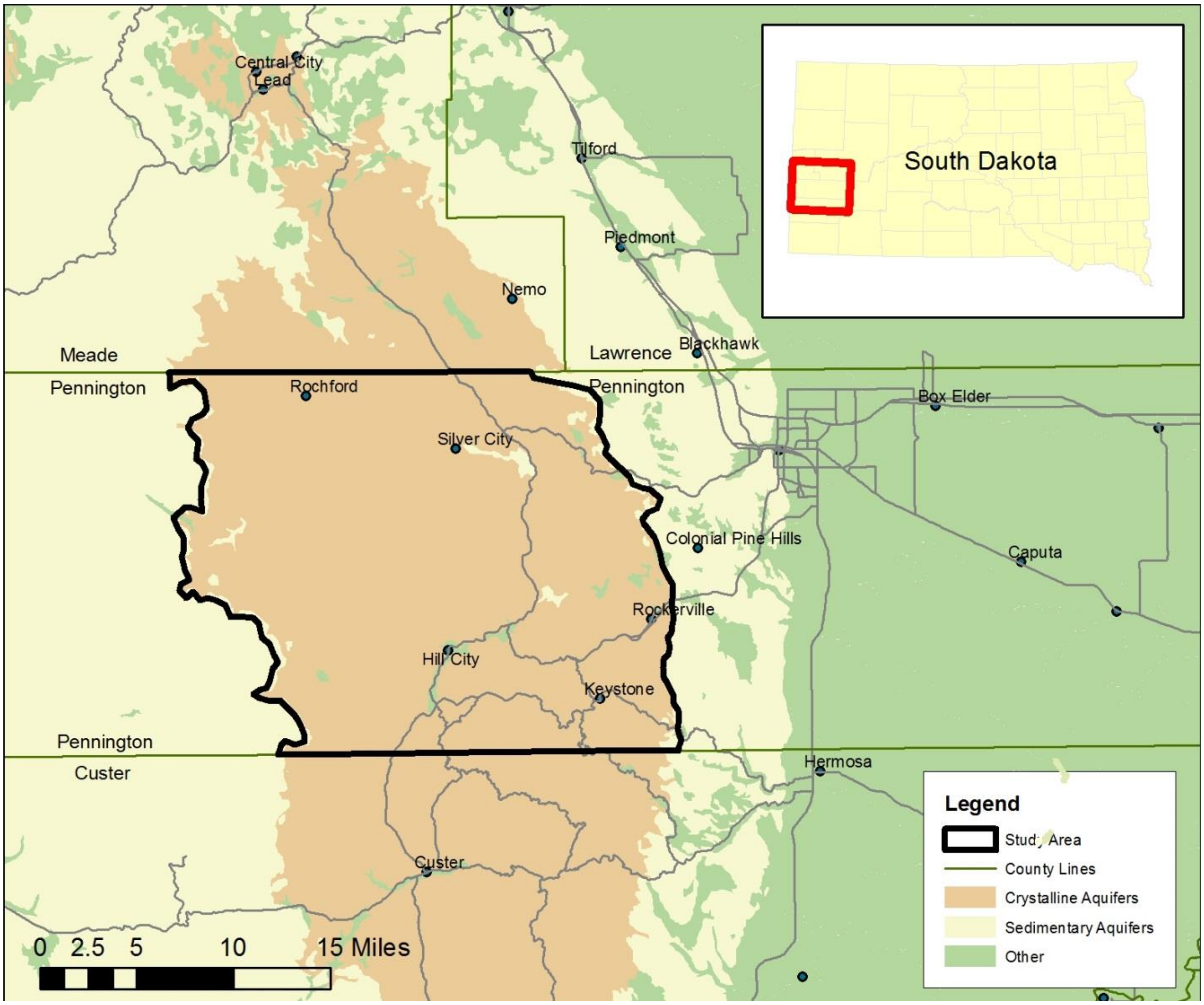

Figure 1. Location and boundary (heavy black line) of study area in western Pennington County, SD

Location

The study is located in the western portion of Pennington County, South Dakota, including Hill City, Medicine Mountain, Silver City, Mount Rushmore and Rochford quadrangles, as well as parts of the adjacent quadrangles in the area. The study area is bounded by the Pennington County boundaries to the north and south and by the geologic contact between the Paleozoic and Proterozoic rocks to the east and west (Figure 1). Significant developments in the region include the towns of Keystone (population 300), Hill City (800), Rockerville, Rochford (500), and Silver City, as well as the Mount Rushmore National Monument west of the town of Keystone, SD. Residences and summer homes are common in the forested areas outside of these towns.

The study area contains approximately 160.6 km^2 (62.0 mi^2) of private land, 944.1 km^2 (364.5 mi^2) of public land managed by the USDA Black Hills National Forest, and 5.2 km^2 (2.0 mi^2) of public land managed by the National Park Service Mount Rushmore National Monument. Private land covers approximately 17% of the study area and typically forms isolated or connected holdings surrounded by the Black Hills National Forest. Approximately 13,500 residences and businesses have been determined to occupy the study area, based on mapping using 1-m (3.2-ft) resolution aerial imagery.

According to the state well completion database (South Dakota Geological Survey, 2016), there are 1326 wells within the study area. Well locations are determined from legal descriptions in many cases and may be several hundred feet away from the actual well, so the number of wells in the study area is approximate.

The towns of Hill City and Keystone have sewer districts and waste water treatment facilities for residences and businesses in town. With these two exceptions, waste water is managed by onsite water treatment systems (septic systems). The precise boundaries of these sewer systems have not been determined for this study.

Geology Background

The Black Hills of South Dakota and Wyoming form a roughly oval dome about 192 km (120 miles) in the north-south direction and about 96 km (60 miles) wide (Carter et al., 2002). The central uplift is composed of Archean and Proterozoic metamorphic and igneous basement rocks, surrounded by a mantle of Phanerozoic sedimentary rocks forming an angular unconformity with the basement.

The Black Hills comprises the recharge area for several important sedimentary aquifers, particularly the Madison (Pahasapa) Aquifer and the Minnelusa Aquifer, which serve communities on the flanks of the Black Hills and beyond. Communities in the metamorphic core of the Black Hills rely on water obtained from wells drilled in the metamorphic and igneous crystalline rocks, which are thus termed the crystalline aquifers. Crystalline rocks have extremely low bulk permeability, so water is found primarily in fractures and shattered quartz veins in the basement rock.

The Black Hills have a long history of mining, which began in 1874 with a gold rush in Dakota Territory in the United States. Although gold deposits spurred the early exploration and mining, many other significant types of metals have been mined (Wilson and DeWitt, 1995), including silver, lead, copper, and iron; pegmatites have also provided significant sources of lithium, beryllium, mica, and feldspar. Figure 2 shows a simplified classification of the mineral districts identified in Wilson and DeWitt (1995), based on commodity type. Early settlements in the Black Hills are closely correlated with these mining districts, leading to potential exposure of current residents to ground water quality issues resulting from both natural occurrences of minerals as well as mining activities.

This study focuses on the crystalline aquifers located in the Precambrian core of the Black Hills. Here, groundwater dominantly flows through regional faults and fractures that cut the low permeability bedrock, making flow conditions strongly anisotropic. The crystalline bedrock also contains mineralized zones that can leach contaminants into groundwater as these naturally occurring minerals weather. It is therefore suspected that certain groundwater contaminants may be associated with the different mineralized zones of the study area.

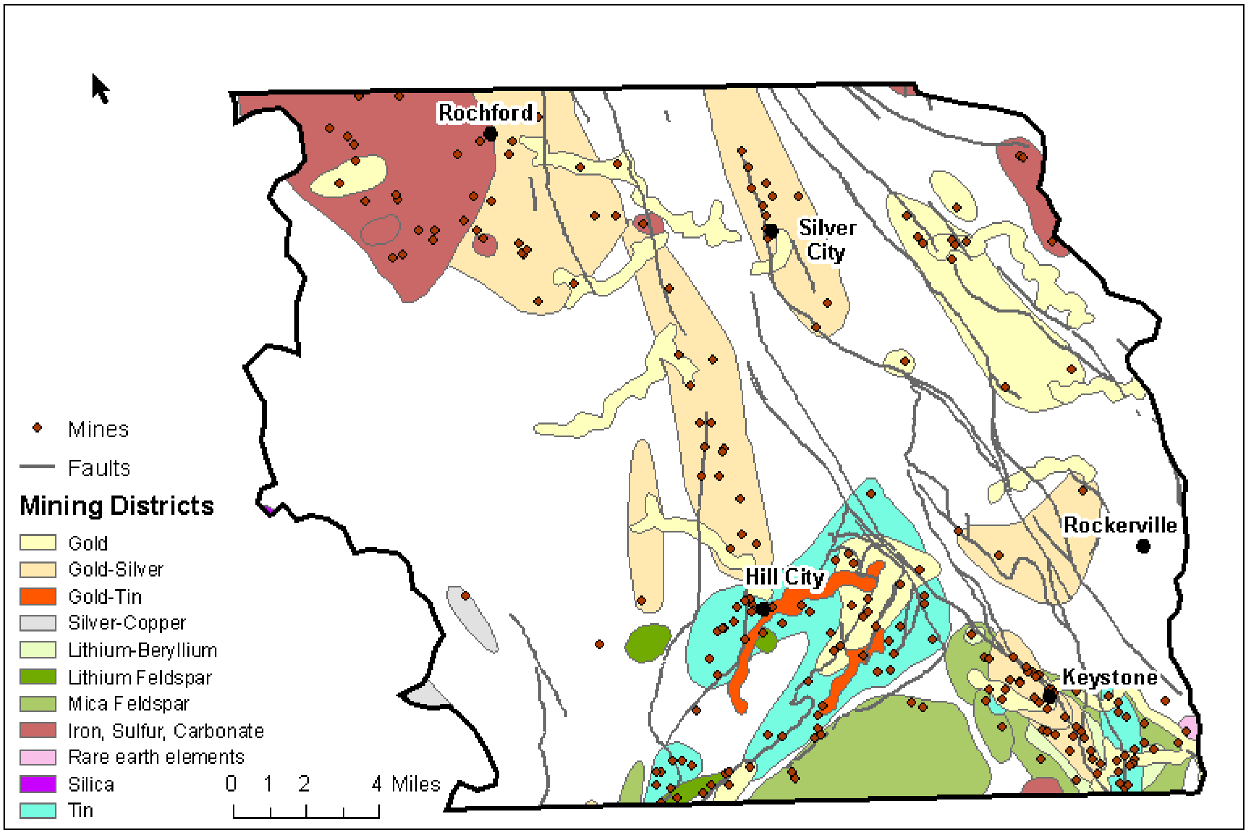

Figure 2. Simplified classification of mining districts and historical mines in the study area

Water quality testing

In 2013, using funding provided by the West Dakota Water Development District, we began a project to test the water quality of samples collected from private wells in order to provide a baseline of water quality in the metamorphic and igneous aquifers in the central Black Hills and to identify areas where specific problems might be a concern. Testing is voluntary and confidential, and the individual results are provided only to the research team and to the homeowner. The tests performed reflect constituents known to affect water quality in general or known to occur in the Black Hills (Carter et al., 2002). It is important to note that the EPA standards cited below are formulated for public drinking water supplies. Private wells are not regulated by the EPA; however, the EPA guidelines and standards may be used as a benchmark to assess the safety of drinking water from private wells.

Arsenic. Dissolved arsenic can occur in water due to natural weathering of arsenic-bearing minerals in rocks. It is also associated with some industrial processes and products, including wood preservation and agricultural products (EPA, 2016a). Arsenic is regulated in public water supplies because of links to cancer. It also can cause nerve damage and other problems. The maximum contaminant level for arsenic in public water supplies is 0.010 mg/L.

Iron. Dissolved iron in water affects the color and taste, and can cause rust-colored stains on plumbing fixtures and clothing. Iron in drinking water is considered a nuisance but is not a health hazard. Problems with iron can occur with levels greater than about 0.3 mg/L.

Nitrate. Nitrate is a nitrogen-oxygen chemical unit present in various organic and inorganic compounds. Nitrate occurs in the soil, animal excreta, crop residues, human wastes, some industrial wastes, and nitrogen fertilizers. When taken into the body, nitrate is converted into nitrite. Excessive levels of nitrate in drinking water can cause serious illness in infants by interfering with the oxygen-carrying capacity of the child's blood. Symptoms include shortness of breath and blueness of the skin. Nitrate also has the potential, after a lifetime of exposure, to cause dieresis, increased starchy deposits, and hemorrhaging of the spleen. The maximum contaminant level for nitrate in public water supplies is 10 mg/L.

Sulfate. Water with sulfate content greater than 250 mg/L can have a laxative effect and a bitter taste. Sulfate is considered a nuisance but is not a health hazard.

Total coliform bacteria. Total coliform bacteria are naturally present in the environment and are not considered a health threat by themselves, but they indicate that other potentially harmful bacteria might be present. Total coliform tests are often used to assess drinking water treatment efficacy.

Fecal coliform bacteria. Fecal coliform bacteria are produced only in the digestive tracts of humans and animals. They are considered an indication of contamination of water by fecal waste and may indicate the presence of other microorganisms, such as viruses, that may cause gastrointestinal illness and other problems.

Hardness. Hardness measures the quantity of dissolved minerals in water, particularly calcium and magnesium, which occur from dissolution as the water percolates through rock. Most people experience hardness in reference to the soap-consuming capacity of water. Hard water requires more soap to produce lather, can cause rings in bathtubs and sinks, and can also result in scale build-up in water lines and equipment. Water with hardness greater than about 180 mg/L generally is considered very hard water. Hardness is considered a nuisance but is not a health hazard. No maximum contaminant levels for calcium, magnesium, or hardness have been set by the State of South Dakota or by the U.S. Environmental Protection Agency.

Methods

The study employed voluntary sampling of private wells throughout the study area. The water quality tests were paid for by the project, and each participant received a copy of the report for his or her own well. A key factor in gaining homeowner cooperation included an agreement that individual sample locations would not be revealed in maps or data presented to the public, in order to protect the privacy and property interests of the participants.

Initial attempts to build participation through media announcements and web sites proved disappointing due to the low number of respondents and the inability to manage the spatial distribution of samples. It also relied on homeowners collecting their own samples, which left opportunities for mistakes and inconsistencies. In the end, the most efficient and effective method of sampling proved to be visiting homes in person to explain the project and elicit participation. Homeowners who decided to participate signed a consent form and the samples were immediately collected on site by the research team. The field team consisted of research assistants (students) and faculty members of the Geology and Geological Engineering Department at the South Dakota School of Mines and Technology. Analyses were performed by Midcontinent Testing Laboratories, Inc., of Rapid City, South Dakota.

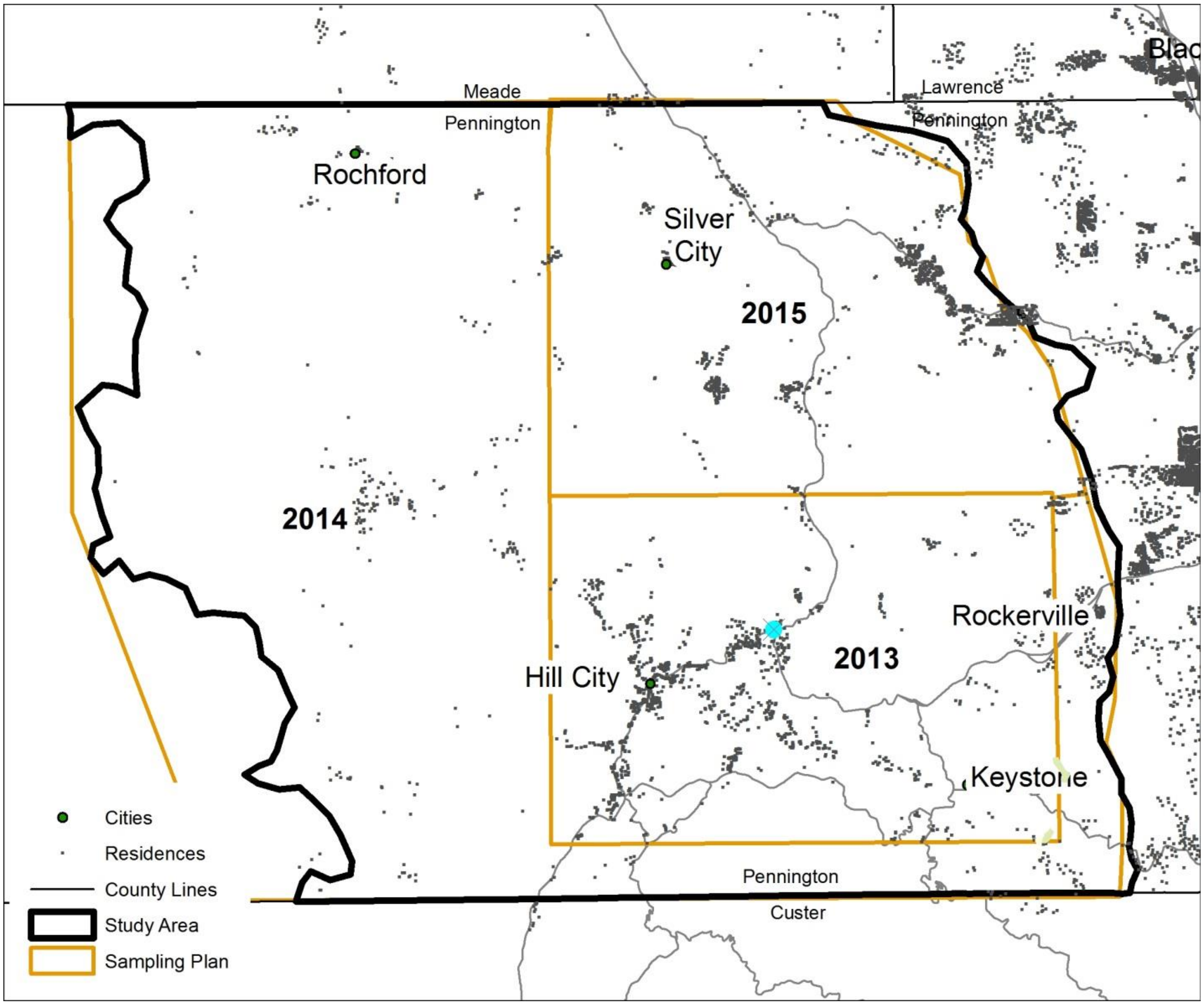

Figure 3. Sampling plan for the three-year study with locations of all mapped residences

Sampling Procedure

Water quality sampling was carried out in three major phases, as determined by the availability of funding. Funding from the West Dakota Water Development District was provided for a pilot study to initiate Phase I in 2013, and additional funding was allocated to support Phases II and III in 2014-2015. The proposed sampling areas for each phase are shown in Figure 3, which also shows the locations of all mapped residences in the study area.

Phase I of the study was conducted between May and November in 2013. It targeted the Hill City and Mount Rushmore 1:24,000 quadrangles in western Pennington County, SD (2013 in Figure 3). This area was chosen because of its relation to a previous aquifer study and because 1:24,000 scale geologic maps are already published or in press for those two quadrangles, providing an understanding of the rock units from which the well water is taken. Additional sampling during 2014 and 2015 extended the study area to the Pennington County boundary in the north and south and to the limit of the Precambrian crystalline rocks to the east and west. Most samples were collected during the fall or spring months.

Sampling was predominantly completed by students who traveled through the community seeking voluntary participation of homeowners. Faculty members participated in the early phase of the sampling in order to assure that appropriate procedures were in place. The research team typically went door to door on Sunday afternoons and Tuesday evenings, asking homeowners who were available whether they would like to participate in the study. If they agreed, they signed a consent form and the samples were taken immediately by the research team and delivered to the water testing laboratory within 24 hours. The cost of testing was covered by the project funding, and each participating homeowner received a copy of the test results for his/her residence.

All of the samples were collected according to directions provided by the testing laboratory, MidContinent Laboratories in Rapid City, South Dakota. The ideal sampling source was an indoor cold water faucet with a non-rotating spigot that pulled water directly from the well before it went through any water softening units or other treatment systems to ensure that the water being sampled was untreated. Not every house had spigots which met this condition, and some accommodations had to be made on a case by case basis. In every case, the water was allowed to run for a minimum of two minutes prior to sampling. The lab provided two sealed plastic bottles for each test: a 500 ml bottle for mineral samples and a 100 ml bottle for bacteria samples. The mineral sample was collected first. A butane lighter was used to flame the faucet for a minimum of 10 seconds before the bacteria sample was collected. Bottles were immediately sealed, labeled, and delivered to the testing laboratory by the following morning to fulfill the requirement that bacteria samples be delivered within 24 hours of testing. Samples testing positive for fecal coliform were retested within a few weeks to rule out possible contamination due to sampling methods; in all cases the positive result was confirmed.

In order to assess reliability of the laboratory analyses, eleven wells were sampled twice in the same day in order to provide replicates. None of the replicates showed significant differences in the test results.

Housing density is not uniform in the Black Hills (see Fig. 3); therefore, wells to sample are not evenly distributed throughout the area. Moreover, the sampling efforts were restricted to owners rather than renters and were subject to the availability of the owners on a particular day when the sampling team was in the area, as well as the willingness of the owners to participate. Thus the sampling sites could not be spatially uniform or randomly selected. We did not sample water from residences using city-supplied water, thus excluding homes within the city limits of Hill City and Keystone. Within these limitations we attempted to provide a broad spatial coverage by sampling every cluster of houses in the study area at least once and distributing the samples within the larger housing clusters as evenly as possible.

Information from each consent form, including the homeowner contact information, residence address, and basic information about the well were entered into an Excel spreadsheet. Each sampled well was assigned a unique integer identification number (IDNum) in the spreadsheet; this ID was written on each document pertaining to that well, including the consent form, lab results, and lab receipts. To protect homeowner privacy, the IDNum and the residence address were the only identifying information used to distinguish wells in data files other than the master participant list. The private well IDNum values range from 1-269, although not every number is used. In the later phases of sampling it was found helpful to assign a location with an IDNum = 0 to indicate residences where the homeowner declined to participate, in order to avoid visiting the location a second time.

The locations of the sampling sites were recorded in a geographic information system (GIS). In Phase I, the location was determined by searching the RapidMap online parcel database (Rapid City GIS Division, 2013) based on the residence address and visually transferring the location to the Streetmap base map in ArcGIS for Desktop. In Phase II and III, locations were determined in the field using the Collector for ArcGIS application and a cloud-based feature service in ArcGIS Online. The sampling localities are maintained in a private, password-protected, user group in an organizational subscription to ArcGIS Online so that all research personnel on the team have access to the data, but it is excluded from outside access. Only the research team has access to site-specific information regarding the private wells. At the conclusion of sampling, the online feature service was downloaded and converted to a feature class so that it could be merged with the public well data locations for analysis of the results.

Constituent measurements from the laboratory were entered in an Excel spreadsheet, identified by IDNum and address. Because the same well might have been sampled more than once, either to provide replicates or to retest coliform results, this file may contain multiple entries for some wells. The final spreadsheet was converted to a file geodatabase table in ArcGIS for use with the well location point data.

The file geodatabase format requires that only numbers may be stored in a numeric field. When a test indicated that the value of a constituent was below the detection limit, the value was entered as zero. A missing test value was flagged by entering it as -99. During analysis, care was used to eliminate both 0 and -99 flag values before calculating statistics on the remaining data.

Public water quality data

In addition to sampling private wells, available water quality data from public sources was compiled to add to the data set. Public water suppliers are required by law to periodically test and publish water quality information. In addition, targeted water study projects may also provide publically available data. Although information on the same constituents tested for the private wells was sought, this data was not available in every public well data set. The three sources used included the National Water Information System (NWIS) maintained by the U.S. Geological Survey (US Geological Survey, 2016) and public water reports maintained by the South Dakota Department of Environment and Natural Resources (SDDENR, 2016). A few wells were also obtained from the South Dakota Geological Survey (SDGS, personal comm., 2014). Data were downloaded for Pennington County and then subset to the study area. Public water reports vary in the frequency of testing and the panel of constituents tested, in the end providing a haphazard picture of water quality over time and space.

During Phase I in 2013, the SDDENR water quality data were manually entered in a spreadsheet from downloaded PDF files available online. Near the end of the sampling project in 2016, the public well data were comprehensively downloaded from online databases to include any new data since 2013.

Well locations for public wells were plotted using the longitude-latitude values in the downloaded tables. In many cases, the locations were derived from public land survey system section, quarter section, or quarter-quarter section information, and the actual well may be several hundred feet from the location shown on the map. Measured values of all tests were converted to mg/L as needed. Many downloaded wells contained no measurements for the constituents used in this study; these wells were ignored and are not included in this report. Figure 4 shows the locations of the 93 public wells with useful data that were included in the study. These wells are listed in Appendix C.

For consistency, each public well was also assigned an IDNum value which reflected the data provenance (Table 1). Matching wells from the second download were assigned the original IDNum value from the first compilation. There are some slight differences between the original manual data entry and the download; for example, the download did not include any data for coliform bacteria data. The reason for this difference has not been determined.

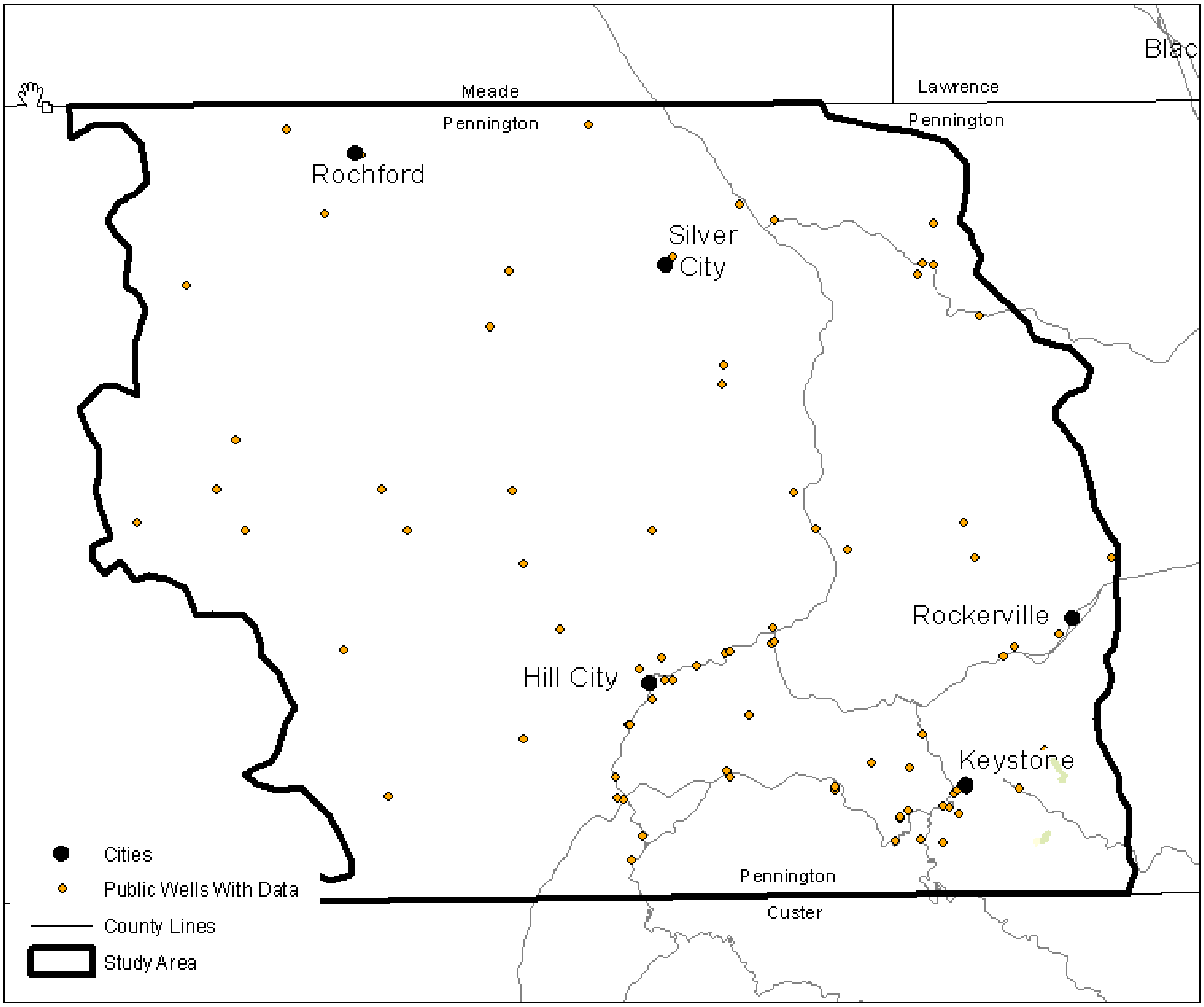

Figure 4. Public wells included in the analysis. Locations are approximate, often to the closest section center, and available analyses are irregular in type and time.

Table 1. Significance of assigned unique IDNum values in the database

Well ID Range	Date data obtained	Data provenance
0	2015 – 2016	Homeowner declined to participate
1 – 299	2013 – 2016	Private well testing by this study
500 – 599	2013	USGS NWIS online database
800 – 899	2013	SDDENR- hand entered data from PDF files
900 – 999	2016	SDDENR online database
5000 – 5999	2016	USGS NWIS online database

The final spreadsheet was converted to a file geodatabase table in ArcGIS for use with the well location point data. The file geodatabase format requires that only numbers may be stored in a numeric field. When a test indicated that the value of a constituent was below the detection limit, the value was entered as zero. A missing test value was entered as -99. The public data had some instances where a constituent was detected, but no specific measurement value was recorded. These analyses were given a flag value of 9999 in the database. During analysis, care was used to eliminate these flag values before calculating statistics on the remaining data.

Final data sets

Three final data sets were derived containing the results of this study, including a GIS data set of all well locations, a table of all water quality analyses, and a table of the participants with their contact information.

Well locations. The final data sets included a well location feature class of all wells, both public and private, stored as a feature class in an ArcGIS for Desktop (Esri, Inc) geodatabase. The attributes for each well include the unique IDNum, the residence address or NWIS/SDDENR well identifier, the status as a public or private well, whether the well serves single or multiple residences, and the longitude-latitude values of the well location. In addition, the geologic unit at the surface location of the well was assigned from 1:24,000 geologic quadrangle maps if available, otherwise it was assigned from the 1:100,000 Black Hills Geology Map (Redden and DeWitt, 2008) or from the 1500,000 state geologic map (Martin et al., 2004). This data set is confidential and cannot be released to anyone but the research team, as stipulated in the homeowner consent form.

Water Quality Analyses. The water quality analysis data from all wells, both public and private, were merged in Excel and converted to a file geodatabase table in ArcGIS for Desktop. This table includes fields for the IDNum, the residence address or well identifier, the sampling date, and the results. This table has a one-to-many cardinality with the well location feature class, with potentially multiple sampling events for each well. A public version of this file was created by removing the address information for private wells. All measurements are recorded in mg/L. A value of 0 indicates that a constituent was below the detection limit. A value of -99 indicates a missing measurement, and a value of 9999 indicates that the constituent was detected but no value was recorded. The -99 and 9999 flags only occurred in the public well data.

Participants. The master spreadsheet of participants with the names and contact information of the participants was retained as an Excel workbook only and is not used for analysis. This data set is confidential and cannot be released to anyone but the research team, as stipulated in the homeowner consent form.

Several supporting data sets were also developed during this project.

Residences. A feature class of all home locations in the study area was developed to aid in planning sampling trips. Although Pennington County keeps a 911 addressing database; it was not available at the time of project initiation or accessible to the research team. We used recent aerial photography available in ArcGIS Online to identify and digitize home sites in the study area. Much of this work had been performed for previous WDWDD projects already, but some of the study area remained undone and were completed as part of this project. Some interpretation is required due to the potential presence of barns or outbuildings; rather than marking each building with a point, a cluster of buildings with a single driveway was considered one residence.

Mineralization Zones. Because water quality issues were expected to correlate to some extent with mining activities in the Black Hills, a map of mineralized zones and districts (Wilson and DeWitt, 1995) was digitized and attributed.

Mines. During Phase I, a set of mine locations in the Hill City and Mount Rushmore quadrangles was compiled and digitized as GIS feature classes. The mine locations came from several sources, including 1:24,000 quadrangle maps (DeWitt et al, 1998a, 1998b), a 1:250,000 mines map (DeWitt et al, 1986), a mineral atlas (Black Hills Mineral Atlas, 1954, 1955), and a spreadsheet of mine locations (SD Geological Survey, personal comm., 2014). This data set was little used and was not expanded to the full study area.

Data analysis

The goals of the data analysis were threefold: 1) to identify the frequency and severity of water quality issues in private wells; 2) to determine whether water quality issues are associated with particular areas or activities, e.g., mining activities; 3) to determine whether water quality issues are associated with particular geologic rock units or structures.

The frequency analysis identified the number and percentage of wells that had at least one test exceeding the EPA regulated or recommended guideline. Each analysis was plotted on a sorted histogram to show the distribution of values. In these analyses, the private wells and the public wells were analyzed separately, because the public well data span a much longer range of time and are inconsistent in the timing of tests and the constituents tested.

The best way to explore and characterize the spatial distribution of problems is to map the actual test values at their locations using size-graduated symbols such as those shown in Figure 5, and the research team has done this for each constituent. The results presented here include our interpretations and conclusions based on such maps, but the maps themselves cannot be presented to the public as per the agreement with the homeowners.

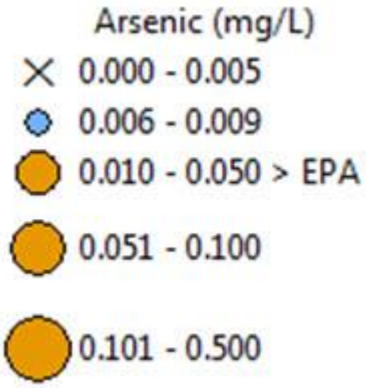

Fig. 5. Symbols used to analyze concentrations

As an alternative, we prepared summary maps showing Areas of Concern, where an elevated frequency of high constituent values was found. The maps were constructed using both public and private well data. Most of the private wells only have one well analysis; however, a few private wells and nearly all public wells had multiple analyses per well. For arsenic, iron, nitrate, and sulfate, we determined the maximum constituent value measured at each well, selected the wells with values greater than or equal to 50% of the EPA limit, and used these selected points to create a density map in ArcGIS Spatial Analyst

(ESRI, Inc.) The density map represents the number of wells per square mi with elevated constituent values.

In creating the density maps, we used a kernel density function with a 4000 meter (2.5 mile) radius to provide smooth result that remained faithful to the local density values; no weighting based on the constituent concentration was employed, such that each well point represents merely the presence of an elevated constituent value and not its magnitude. For total and fecal coliform, the wells were selected if at least one test of the well showed the presence of bacteria, and the density maps were calculated as previously described.

The output maps for all constituents were symbolized using the same density ranges of 0 - 1.5 wells/mi^2. The value of 0.2 wells/mi^2 was selected as the threshold of the shaded areas; this value produced shaded regions that corresponded visually with clusters of the individually mapped elevated values and worked for all constituents. The shaded areas represent regions where a greater frequency, and therefore a higher risk, of elevated values is present. However, it is important to understand that subsurface conditions can change markedly over short distances, and not all wells in the shaded areas will have elevated values.

Because the density of home sites in the study area is not uniform, one should take care in interpreting these maps. It is true that higher densities of elevated values are often spatially associated with higher densities of home sites, where more samples were taken. However, this phenomenon does not imply that the higher density of elevated values is the result of the higher density of sampling, but rather reflects underlying geological or anthropological factors. To help visualize this phenomenon, a kernel density map was also created from all of the sample localities with tests for a particular constituent, using the same 4000 meter (2.5 mile) radius.

There is no EPA guideline or standard for hardness, so the hardness data could not be used to develop Area of Concern maps. Instead, we selected all public and private wells with at least one hardness measurement (n = 299) and calculated the average hardness. Seven wells had a hardness value of 0, which would be highly unusual and was interpreted to mean that the sample was, in spite of our efforts, purified by a water softener installed in the home and, therefore, unreliable. These values were excluded. The remaining values were used to perform an Inverse Distance Weighted (IDW) interpolation.

Because hardness values can vary significantly over short distances due to variable rock characteristics, the parameters for the IDW were chosen to ensure that only the four closest measurements would be used and that no measurements further than 4 km from the interpolation point were used. An inverse distance weight power of three ensured that closest neighbors were more influential in the interpolation. The resulting map appears blocky and abrupt compared to most IDW maps, but remains more true to the local data than would occur with more typical IDW settings. As with any IDW interpolation, the map will be most accurate where the sampling density is high.

To investigate whether water quality problems are associated with specific geologic rock units, a spatial join was used to assign the rock unit at the surface to each well. Most of these units were assigned from the 1:24,000 geologic quadrangle maps, but a small part of the study area lay in unmapped quadrangles, so the rock unit was assigned from the 1:100,000 Black Hills geologic map (Redden and DeWitt, 2008). The drawback of this method is that the surface geology does not necessarily correspond to the rock unit providing the water to the well at depth, but no reliable method of consistently identifying the actual unit is available. Fortunately, dips in the basement rocks are commonly vertical or near-vertical in the Black Hills, making it more likely that the surface and rock unit at depth are similar.

A distance analysis was performed to test whether water quality issues are associated with particular geologic structures, especially faults. A spatial distance join was used to associate each well with the closest fault and the distance from the fault. The wells were separated into two groups with values greater than or less than 50% of the EPA regulated or recommended value and a cumulative value distribution map was created to compare the two groups.

A set of Water Quality Report Cards, one for each constituent, was compiled to summarize and present the analysis results to the public. These report cards were made available on the project web site (URL: http://www.sdsmt.edu/aquifers) and are also included in Appendix A.

Results

A total of 262 private wells were tested in the course of this study, and the analyses are presented in Appendix B. As per agreement with the homeowners, all identifying information has been removed from the private well results. In addition, 93 public wells with data on the studied constituents were found to occur in the study area; these wells are listed in Appendix C and the water quality data for these wells are presented in Appendix D. The availability of test values for the public wells is irregular; many wells have reports for only one or two constituents. Some wells had no data for any of the constituents in this study; these wells and data records were retained in the data files for future reference but deleted from the tables in Appendices C and D.

Frequency and severity of problems

Table 2 summarizes the number of wells tested and the number and percentage of wells that had at least one test that exceeded the EPA regulated or recommended limit. Iron proved to be the most common problem, with 31% of private and 23% of public wells showing tests that exceeded the recommended EPA limit of 0.3 mg/L. Arsenic issues showed up in 14% of private wells and 12% of public wells with tested values above the EPA regulated limit of 0.01 mg/L. Sulfate and nitrate problems are uncommon, appearing in fewer than 4% of the wells tested.

Coliform data are only reported for the private wells tested in the study. In Phase I, we found that fewer than 10 coliform bacteria tests were reported for public wells, and that most of them were positive. It appears that coliform reports are primarily submitted when fecal coliform are present, so the frequency of positive to negative tests cannot be determined. Thus no coliform data are presented for public wells in Table 2.

Table 2. Summary of analysis results for private and public wells

	Arsenic	Iron	Nitrate	Sulfate	Hardness[1]	T. Coliform[2,3]	F. Coliform[2]
EPA recommended limit (mg/L)	0.01	0.3	10	250		Absent	Absent
Private Well Tests							
Number of wells	262	262	262	262	262	262	262
Number of tests	273	273	272	273	272	272	272
Earliest test date	5/5/2013	5/5/2013	5/5/2013	5/5/2013	5/5/2013	5/5/2013	5/5/2013
Latest test date	11/03/2015	11/03/2015	11/03/2015	11/03/2015	11/03/2015	11/03/2015	11/03/2015
Lowest value detected	**	**	**	**	0	Absent	Absent
Highest value detected	0.441	70.2	31.5	1410	1130	Present	Present
Number of wells exceeding EPA[4]	36	81	8	4	129	97	17
Percent wells exceeding EPA	14%	31%	3%	1.5%	49%	37%	6%
Public Well Records							
Number of wells	62	70	45	48	37		
Number of recorded tests	335	534	382	151	126		
Earliest test date	12/5/1977	4/12/1967	6/12/1963	4/12/1967	4/12/1967		
Latest test date	5/19/2014	7/9/2007	9/21/2009	7/9/2007	7/9/2007		
Lowest value detected	**	**	**	**	**		
Highest value detected	0.178	93	20	689	935		
Number of wells exceeding EPA[4]	7	15	2	2	14		
Percent wells exceeding EPA	12%	23%	4%	4%	38%		

** Below detection limit

[1] Hardness is considered a nuisance, but there are no recommended limits. The number of exceedences reported are based on a threshold of 180 mg/L; values above this level are considered to indicate very hard water.

[2] Coliform test results are presented simply as whether bacteria are absent or present.

[3] Total coliform is not itself a problem, but may indicate potential problems with fecal coliform.

[4] Number of wells for which at least one test exceeded the EPA standard or guideline, or had bacteria present.

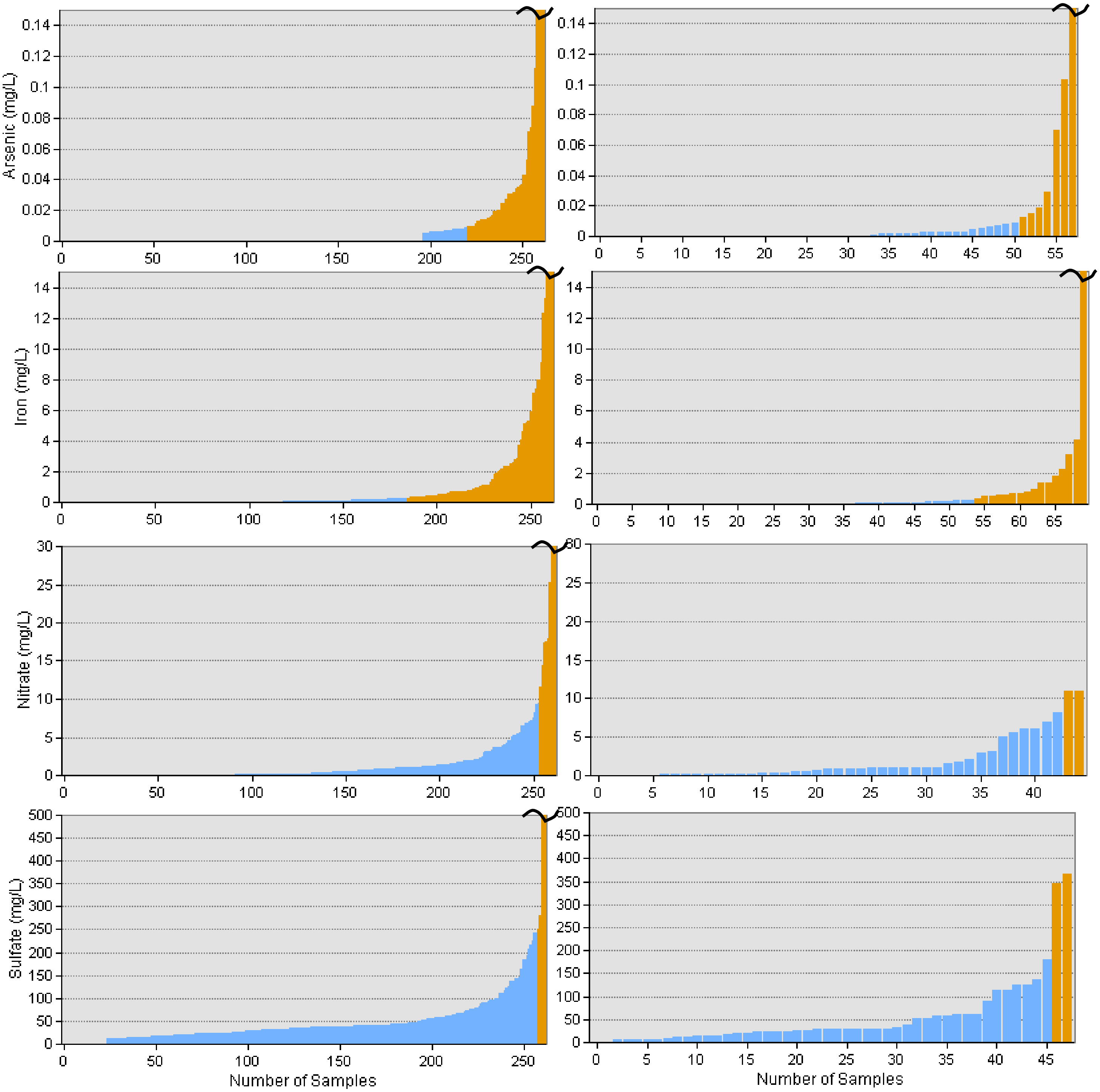

Figure 6. Histograms of measured constituent values in mg/L. Private wells are shown in the left column; public wells are shown in the right column. Blue bars indicate values below the EPA regulated or recommended limit; orange bars indicate values over the limit. Black tilde indicates that the y-axis limit of the plot lies below the maximum value detected.

]

Figure 6 shows histograms of the maximum value of constituents found in tests on private wells (left column) and public wells (right column). Missing bars indicate values below the analytical detection limit, blue bars indicated values below the EPA regulated or recommended maximum value, and orange bars indicate values above the EPA limit. In some cases the y-axis upper limit has been set lower than the maximum value detected in order to make the lower values visible.

The graphs show that some constituents have a few extremely high values. The highest values for arsenic are 0.441 mg/L for private wells and 0.178 mg/L for public wells, about 45 times and 18 times the regulated limit, respectively. The highest measured value for iron is 70.2 mg/L in private wells and 93 mg/L in public wells, or 230 times and 310 times the recommended limit. The highest sulfate value occurs in a private well and is about 6 times the recommended limit. Nitrate has less extreme maximum values, only 2-3 times the regulated limit. Such extremely high values, however, pose a significant threat to residents drinking the water if they are unaware of the problem and the water is not being treated.

The EPA does not have a recommended limit for hardness, although values above 180 mg/L are usually considered to indicate very hard water. A total of 129 private wells (49%) and 14 public wells (37%) exceeded this threshold. Figure 7 shows the range of hardness values detected in the private and public wells in the study area.

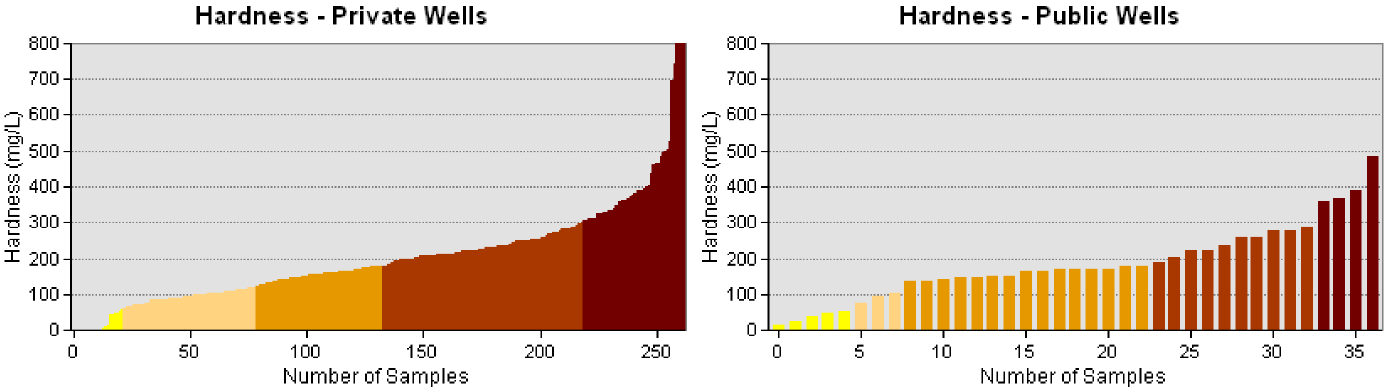

Figure 7. Hardness values detected in private and public wells

Spatial distribution of water quality issues

The spatial autocorrelation of constituent concentrations is generally low, with high values commonly found adjacent to lower ones. Water flow in metamorphic rocks is usually not the same in every direction, due to preferred flow along regional faults and joint sets. Therefore, the only way to tell if a particular well has a problem is to test it. Furthermore, the low spatial autocorrelation and the clustering of the sample locations makes it unsuitable to use interpolation to produce generalize maps of constituent concentrations, so an alternative method was employed by mapping the density of high values.

To analyze the distribution of water quality issues, we have examined the frequency of values greater than 50% of the EPA limits within the study area. For convenience, we designate these wells as ‘hits.’ Unfortunately, interpreting the spatial distribution of hits in the study area is complicated by the fact that the spatial distribution of residences and wells is strongly clustered (see Fig. 3), leading to clustering of the sampled wells. Thus, it is possible that a high frequency of hits may reflect the underlying density of sampling, or a low density of hits might simply mean that the area was not sampled.

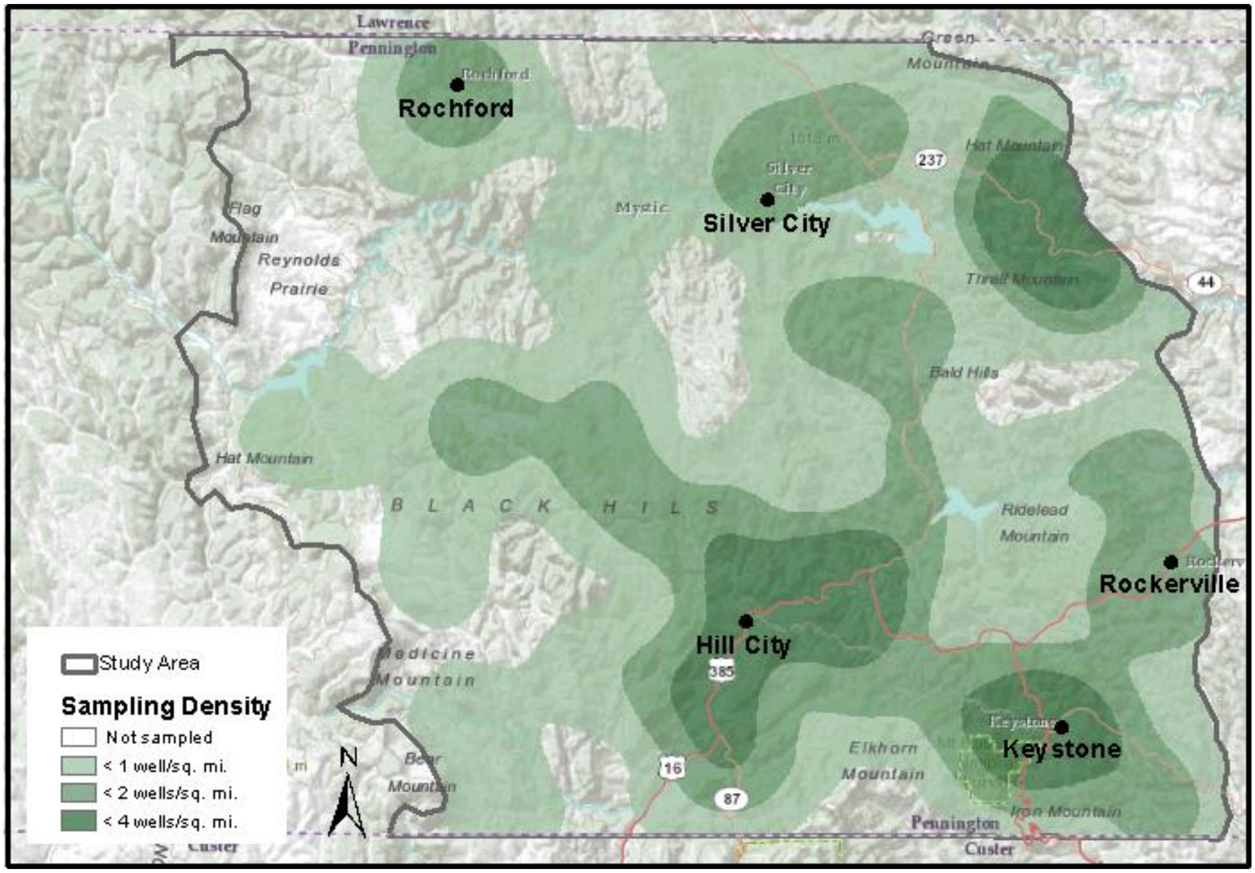

Figure 8. Density of sampled wells in the study area, including public and private wells.

Figure 8 shows a density map of all the sampled wells in the study area, produced using a kernel density algorithm with a search radius of 4000 meters (2.5 mi) and reported in sampled wells per square mile. Dark green areas (at least 4 wells/mi^2) are more intensively sampled than medium green (at least 2 wells/mi^2) or light green areas (at least 1 well/mi^2), and blank areas indicate where sampling is very sparse, indicating that little is known about water quality in those regions.

Arsenic

When the sampling density is combined with the density of hits, a clearer picture emerges. Figure 9 shows the Areas of Concern for arsenic overlaid on the sampling density map. The orange regions indicate areas where a high frequency of arsenic hits was detected. The green areas indicate places where sampling took place but arsenic values were consistently low. Unshaded regions were not sampled and so little is known about arsenic there.

It is important to note that subsurface conditions can change rapidly over short distances. Not all wells in the orange areas have high arsenic values; the only way to know if a particular well has a problem is to test it. Nevertheless, the orange areas do indicate where arsenic problems occur more frequently, and residents living in those areas should be encouraged to test their water to ensure that it is safe.

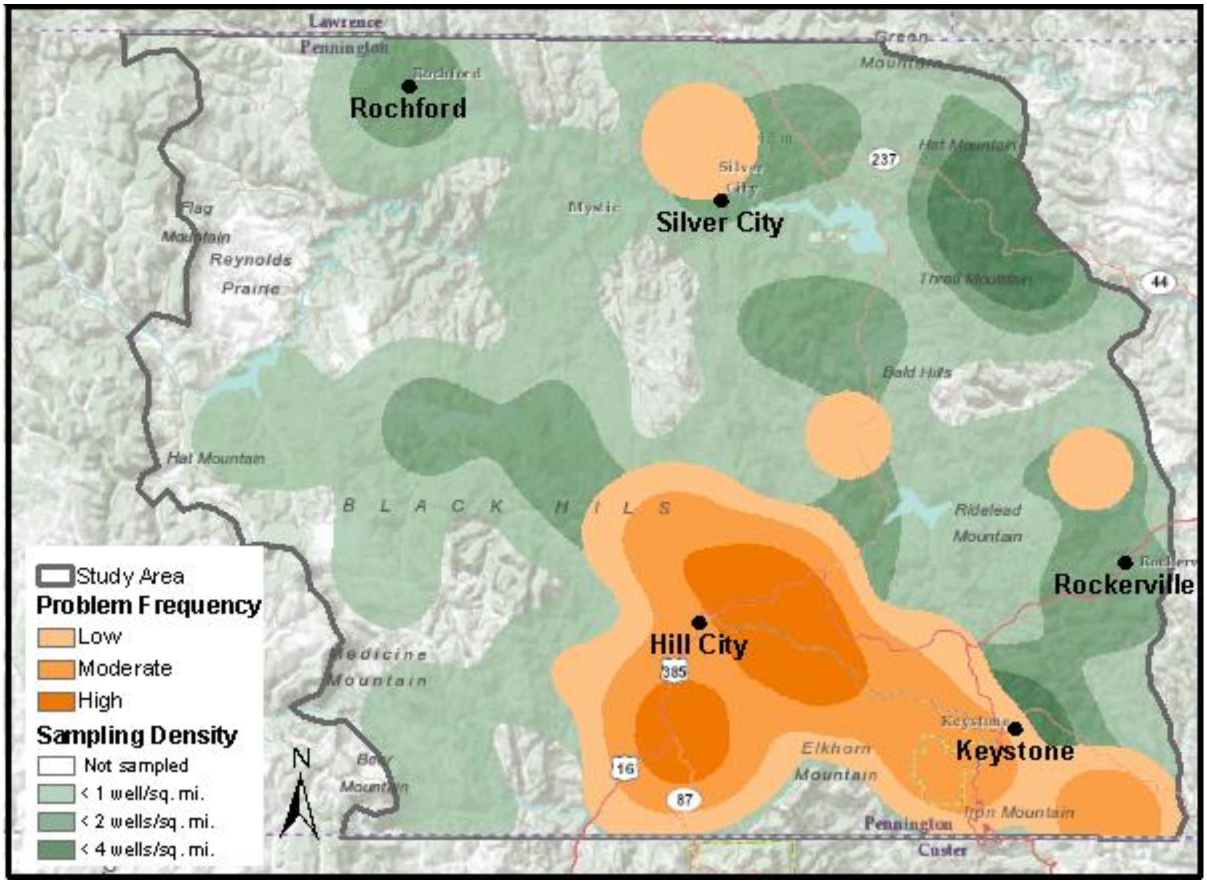

Figure 9. Map showing areas of concern for arsenic

Iron

Iron also has widespread areas where problems are frequent, as shown in Figure 10. Iron problems are especially prevalent in the Hill City and Keystone areas, but unlike arsenic, are also common in the northern part of the study region near Silver City and Rochford.

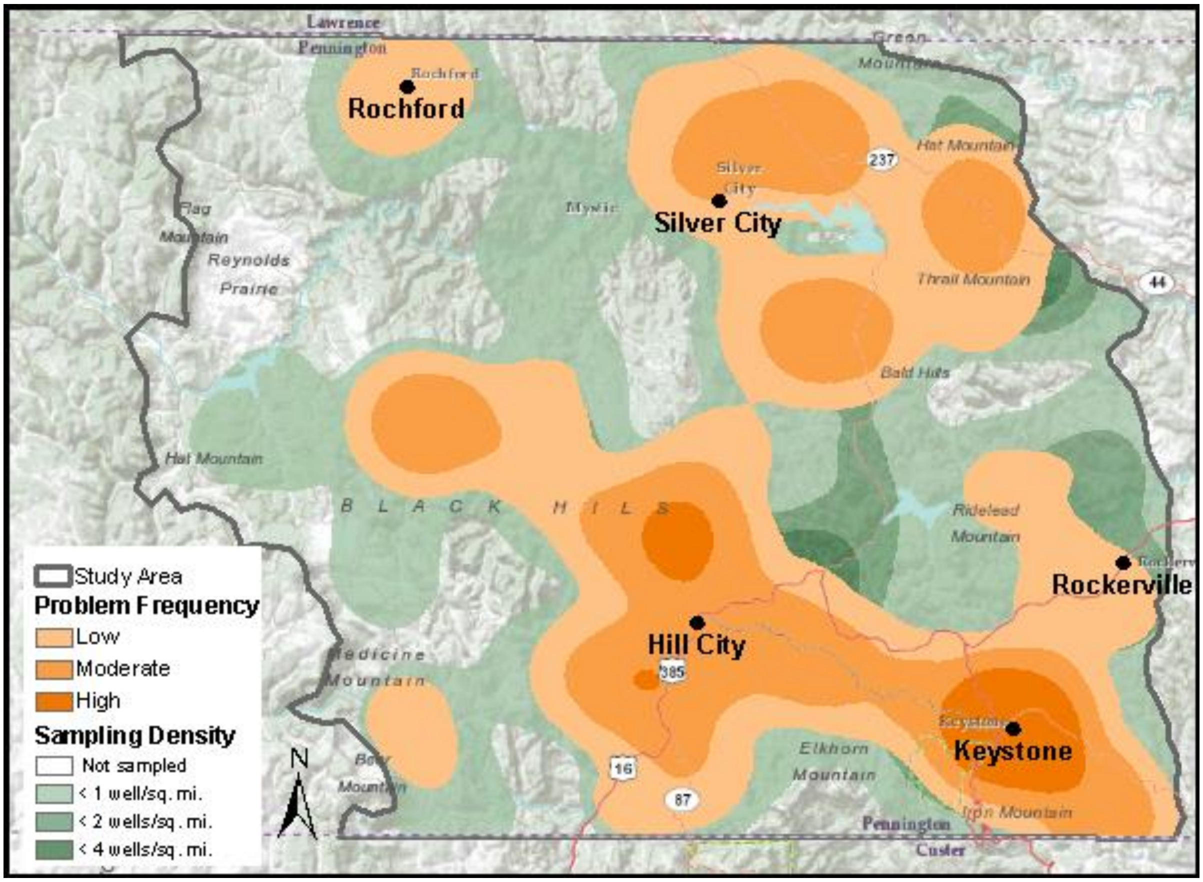

Figure 10. Map showing areas of concern for iron

Nitrate and sulfate

Area of concern maps for nitrate and sulfate were also created, but hits for these constituents are relatively rare in the study area, so the maps are not shown here, although they can be viewed in the Water Quality Report Cards included in Appendix A.

Coliform bacteria

Coliform bacteria are an important indicator of water quality. Although the bacteria are not harmful, the presence of bacteria in water can indicate other problems. Total coliform occurs naturally in the environment but may indicate the presence of more harmful microorganisms. Fecal coliform bacteria occur only in the digestive tracts of humans and animals and are an indicator of fecal contamination from human or animal sources and may point to the presence of harmful microorganisms such as viruses that can cause gastrointestinal illness with cramps, nausea, or vomiting.

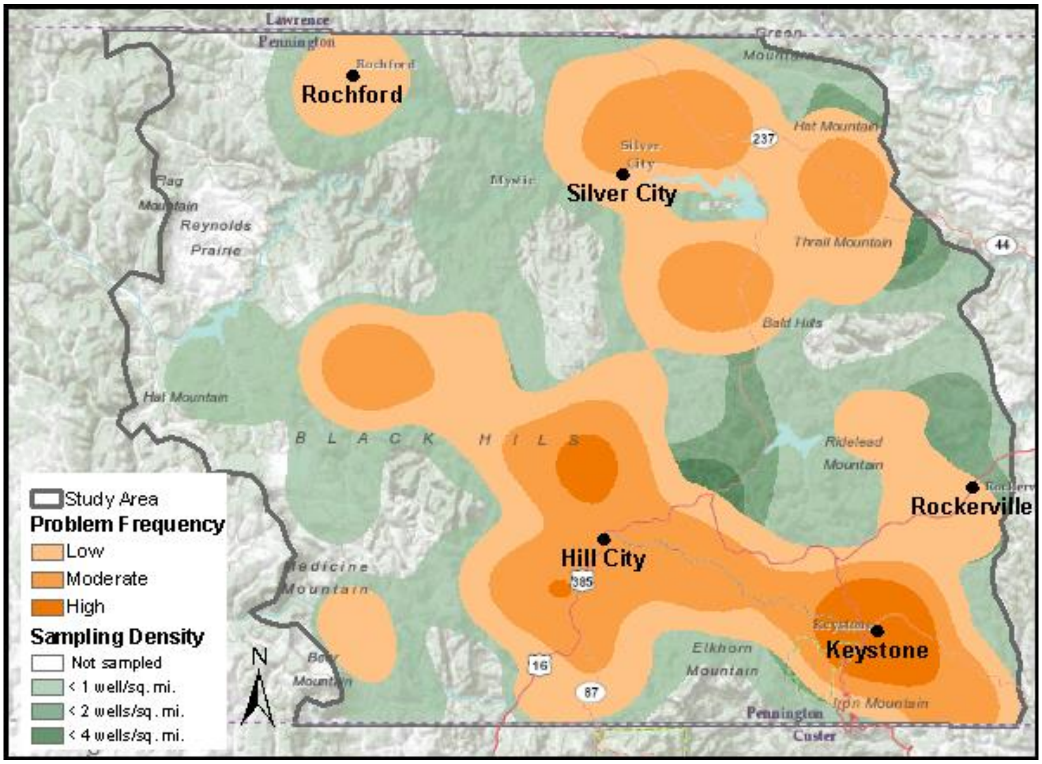

Figure 11. Map showing areas of concern for total coliform

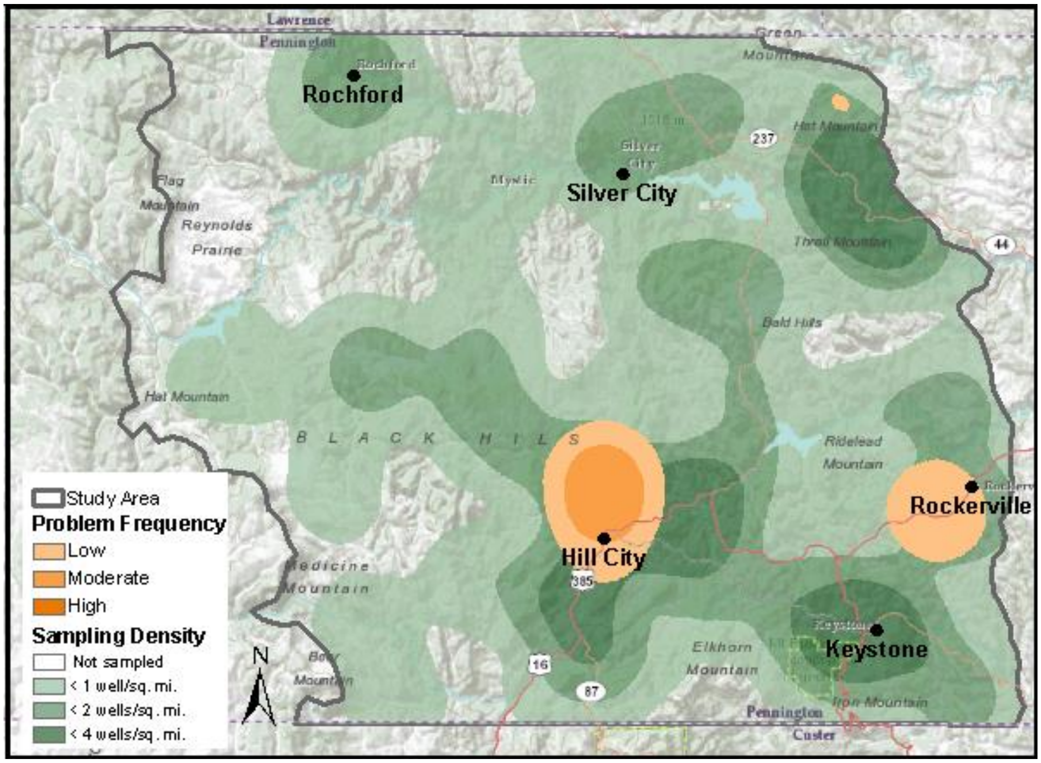

Figure 12. Map showing areas of concern for fecal coliform

Figure 11 shows areas of concern for total coliform, which occurs throughout the study area. Fecal coliform issues are much more restricted, fortunately (Fig. 12), occurring mainly near Hill City and Rockerville. However, the prevalence of total coliform may indicate that potential problems with fecal coliform are on the way. Efforts to educate homeowners and develop monitoring programs may be indicated.

Hardness

Hard water is a common problem in the Black Hills. Hard water requires more soap to produce lather, can cause rings in bathtubs and sinks, and can also result in scale build-up in water lines and equipment. Water with hardness greater than about 180 mg/L generally is considered hard water. Hardness is considered a nuisance but is not a health hazard.

The EPA does not have a recommended limit for water hardness, so area of concern maps would be misleading. Moreover, the sample data are clustered and quite variable over short distances, so they do not lend themselves well to interpolation; however, since individual points cannot be shown because of the homeowner agreement, an inverse distance weighted interpolation can be used to give a rough idea of the variation of hardness in the study area (Fig. 13).

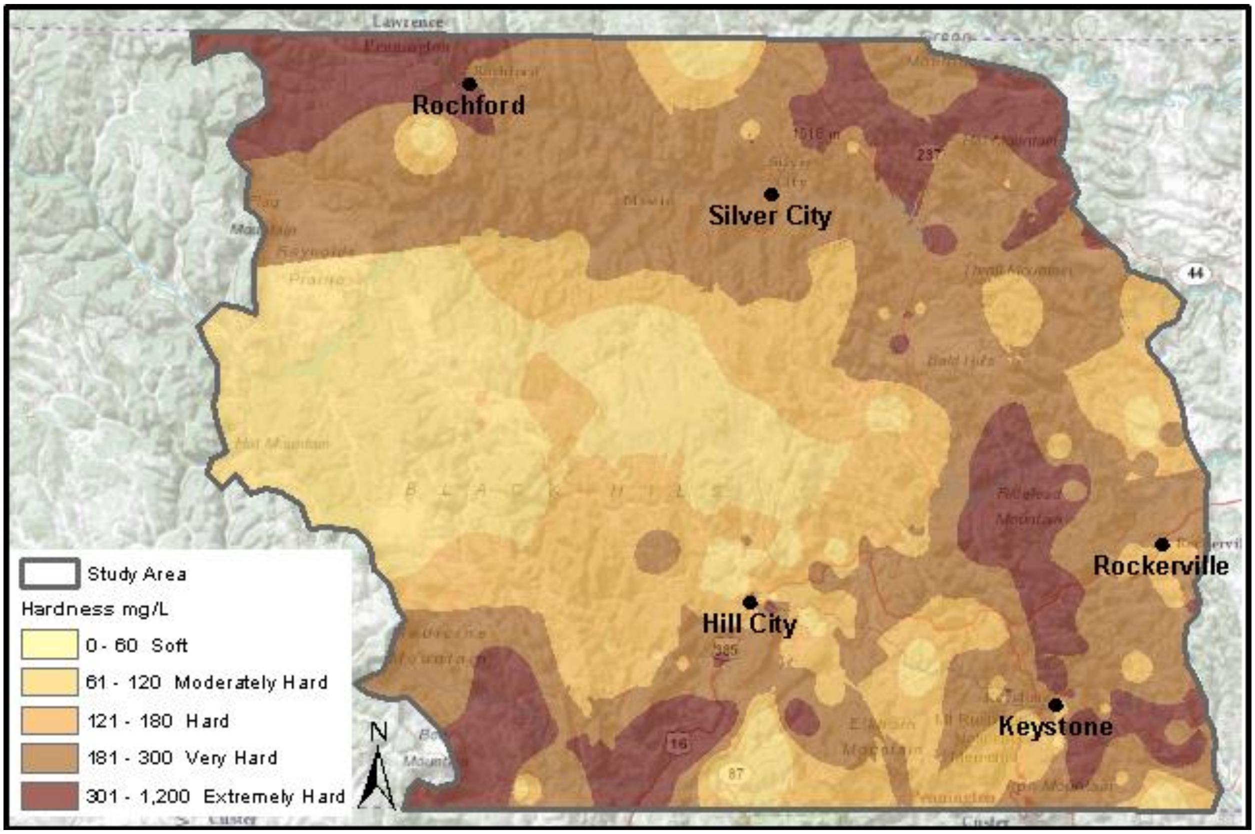

Figure 13. Interpolated map of hardness values in mg/L

Hardness tends to be greater in the northern and eastern regions of the study area, but values are lower in the east central regions of the study area. This might appear to be a result of the low sampling density in that area, but visual inspection of the actual mapped values confirms that the water samples in this area are generally softer.

Correlation of water problems to geology

Particularly for arsenic and iron, the geologic rock types, mineralization and structures are expected to exert a primary influence on the presence of the constituents. In this analysis, we test several hypotheses about the spatial distribution of problems relative to the geology. Although we cannot show individual well locations on public maps, the analysis is based on examining them in detail. The geologic unit and unit symbol for each well was determined from the 1:24,000 geologic quadrangle map if available; if not a 1:100,000 scale map was used (Redden and DeWitt, 2008).

Arsenic

First we approach the question of whether particular rock types show a correlation to arsenic problems. To test this, we calculated the percentage of high arsenic values (>= 50% of the EPA limit) found in each rock formation. Table 3 summarizes the information by geologic rock unit. Figure 14 plots the number of total samples analyzed for arsenic against the fraction of samples classified as arsenic hits (>= 0.005 mg/L), and this graph was used to assign a risk assessment to each geologic unit. Rock formations with three or fewer samples were classified as unknown risk. Samples close to the x-axis, with many samples but fewer than 15% hits, were assigned to the low risk group. Formations with many samples and high fractions above 50% were assigned to the high risk group, and the remaining formations were classified as moderate risk.

This analysis is subject to several caveats. First, the rock unit at the surface may not be the same as the unit producing the water at depth. Second, the geologic units were assigned from several map sources and the same unit may have a different formation symbol on different maps. Third, the locations of the public wells are approximate and may not be assigned the correct unit. Nevertheless, the analysis provides some basic insight into the distribution of arsenic with respect to rock type.

Four map units have arsenic values assigned to the high risk group. These are: Metaquartzite (Xqc), Zimmer Ridge Metagraywacke (Xz), Metagraywacke-distal (Xgwd) , and metagraywacke (Xgw1). Each unit was a form of sandstone before it was affected by metamorphorphism.

Table 3. Percentage of arsenic hits (>= 50% of EPA limit) by rock formation

Symbol	Description	Samples	Hits (50%)	Percent	Risk Category
OCd	Deadwood Formation	4	0	0%	Low Risk
Qal	Alluvial deposits	45	3	7%	Low Risk
Qt	Terrace Deposit	2	0	0%	Unknown Risk
Qtg	Terrace/gravel deposit	1	1	100%	Unknown Risk
Tg	gravel deposit	11	1	9%	Low Risk
Xbm	Buck Mountain Quartzite (also Xbp, Xbq)	16	0	0%	Low Risk
Xbo	Metabasalt (tholeiitic greenstone and amphibolite)	13	0	0%	Low Risk
Xbs1	Slate and phyllite	13	2	15%	Low Risk
Xbs2	Metamorphosed black shale	18	5	28%	Moderate Risk
Xby	Metabasalt	4	1	25%	Moderate Risk
Xcq	Metaconglomerate, quartzite, and metapelite	10	0	0%	Low Risk
Xds	Metamorphosed dolomite and silty pelite	1	0	0%	Unknown Risk
Xeq	Quartzite	1	0	0%	Unknown Risk
Xgg		2	1	50%	Unknown Risk
Xgw	Metagraywacke	1	0	0%	Unknown Risk
Xgw1	Metagraywacke	21	11	52%	High Risk
Xgw2	Metagraywacke	21	6	29%	Moderate Risk
Xgw3	Metagraywacke	6	2	33%	Moderate Risk
Xgwd	Metagraywacke (distal)	10	8	80%	High Risk
Xgwu	Metagraywacke	9	0	0%	Low Risk
Xh	Harney Peak Granite	1	0	0%	Unknown Risk
Xif	Carbonate facies iron formation	3	1	33%	Unknown Risk
Xmg	Metagabbro	1	0	0%	Unknown Risk
Xmt	Metamorphosed impure mafic tuff	3	0	0%	Unknown Risk
Xo	Oreville Formation	15	7	47%	Moderate Risk
Xqc	Metamorphosed quartzite, debris flow conglomerate	7	6	86%	High Risk
Xqs	Metamorphosed quartzite and pelite	2	0	0%	Unknown Risk
Xs	Metamorphosed shale	37	4	11%	Low Risk
Xsic	Metamorphosed shale, siltstone, carbonate-facies	2	0	0%	Unknown Risk
Xss	Schist and Phyllite	2	0	0%	Unknown Risk
Xtg	Tenderfoot Formation (Garnet-rich Schist)	1	1	100%	Unknown Risk
Xts	Metamorphosed tuff and shale	24	9	38%	Moderate Risk
Xtv	Metamorphosed tuffaceous shale, tuff, and volcanics	2	0	0%	Unknown Risk
Xz	Zimmer Ridge Metagraywacke (also Zx)	11	8	72%	High Risk

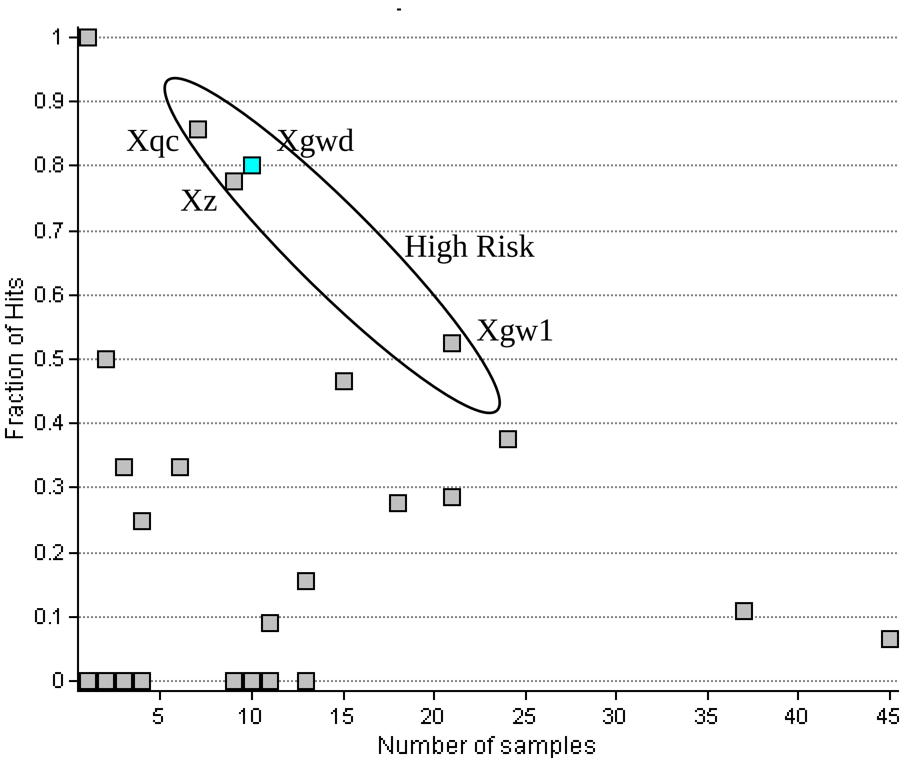

Figure 14. Plot showing the number of samples versus the fraction of arsenic values >= 0.005 mg/L. High risk formations have more than three samples and at least 50% arsenic hits.

Figure 15 presents a map of the study area with the rock formations characterized by the assigned risk factor, with the outline of the Area of Concern (AOC) regions from Figure 9 delineated. The pattern of arsenic occurrence suggests that rock type is not the primary factor, however. The great majority of arsenic hits occur in the southeast quadrant of the study area, southwest of the set of NW-SE striking faults, known in various places as the Empire Fault. Except in this quadrant, arsenic hits are typically isolated occurrences. Although similar rock types may be found on both sides of this boundary, the wells southwest of the boundary are far more likely to contain arsenic hits. This same region is characterized by multiple overlapping mineralization zones and mining districts (DeWitt et al., 1986) containing known arsenic minerals. In such areas, an increase in arsenic values (due to the presence of natural mineralization, mobilization of contaminants due to mining activities, or both) is not unexpected. These later observations suggest that structure and mineralization events play a greater role in affecting the presence of arsenic than do the rock formations.

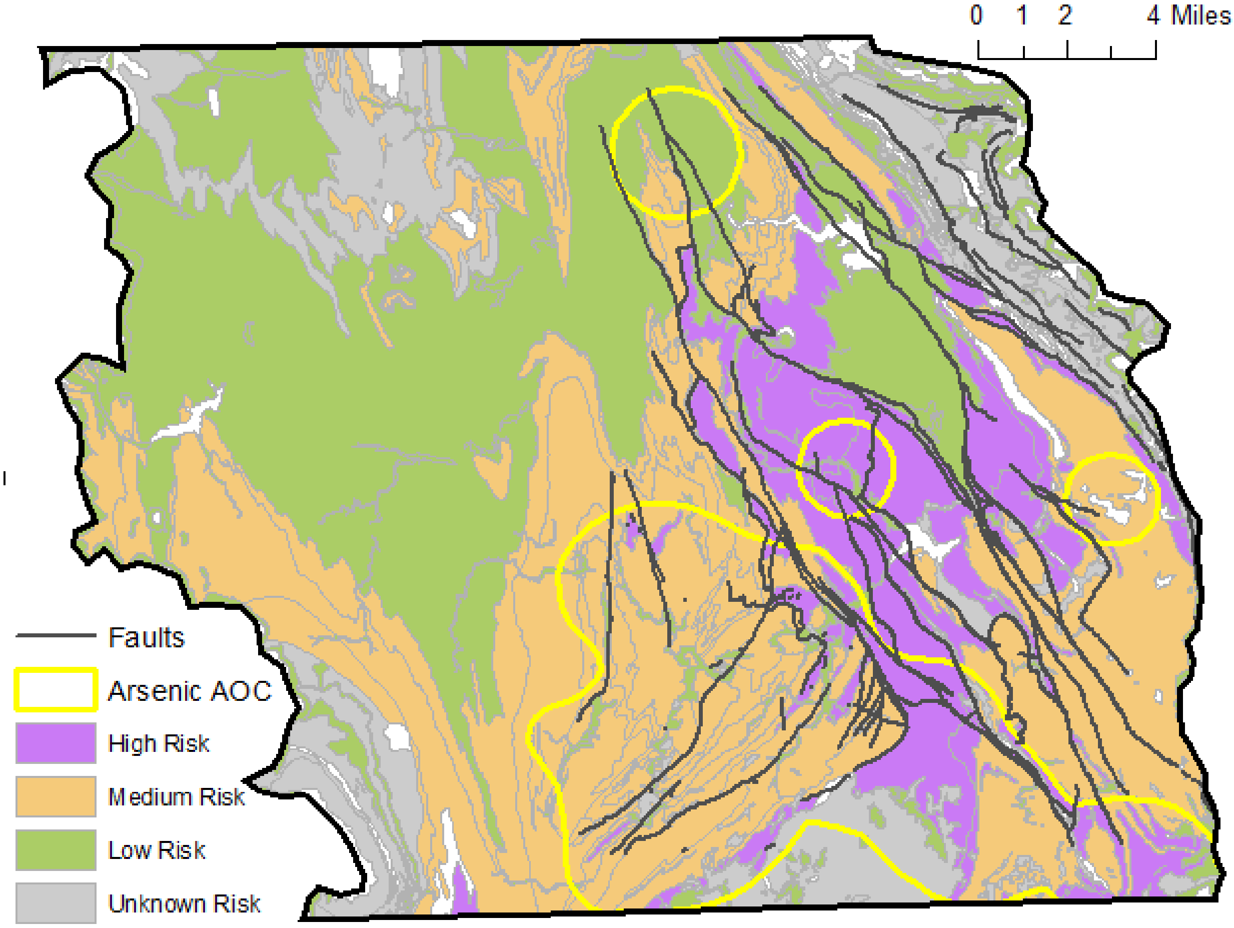

Figure 15. Map of rock units characterized by assigned arsenic risk factor.

Moreover, arsenic values are quite variable over short distances. Consider Figure 16, a map of well locations in an area of about 15 square miles, presented without any identifying geographic information so as to protect homeowner privacy. The labels indicate the location and formation symbol for the sampled well. The red labels indicate arsenic hits, and the black labels indicate low arsenic values. Notice that the same formation Xo has both hits and non-hits over distances less than one-half mile, as do Xbs2 and Xgw1.

Figure 17 shows the arsenic Area of Concern mapped over the mining districts digitized from Wilson and DeWitt (1995), along with the major mines (Wagner, 2016). Most of the arsenic issues

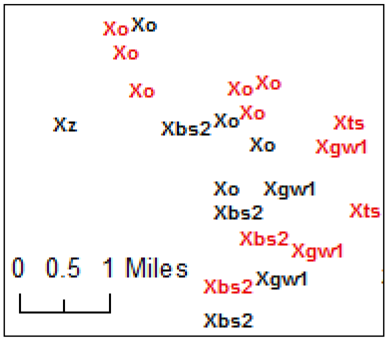

Figure 16. Small area map showing heterogeneity of arsenic hits over short distances. Red formation labels indicate arsenic hits and black labels indicate low arsenic.

are clearly associated with the multiple overlapping mining districts in the southeast quadrant of the map. In particular, especially when the actual arsenic values of the wells are inspected, the Gold-Tin zones appear to have the strongest associations with arsenic issues.

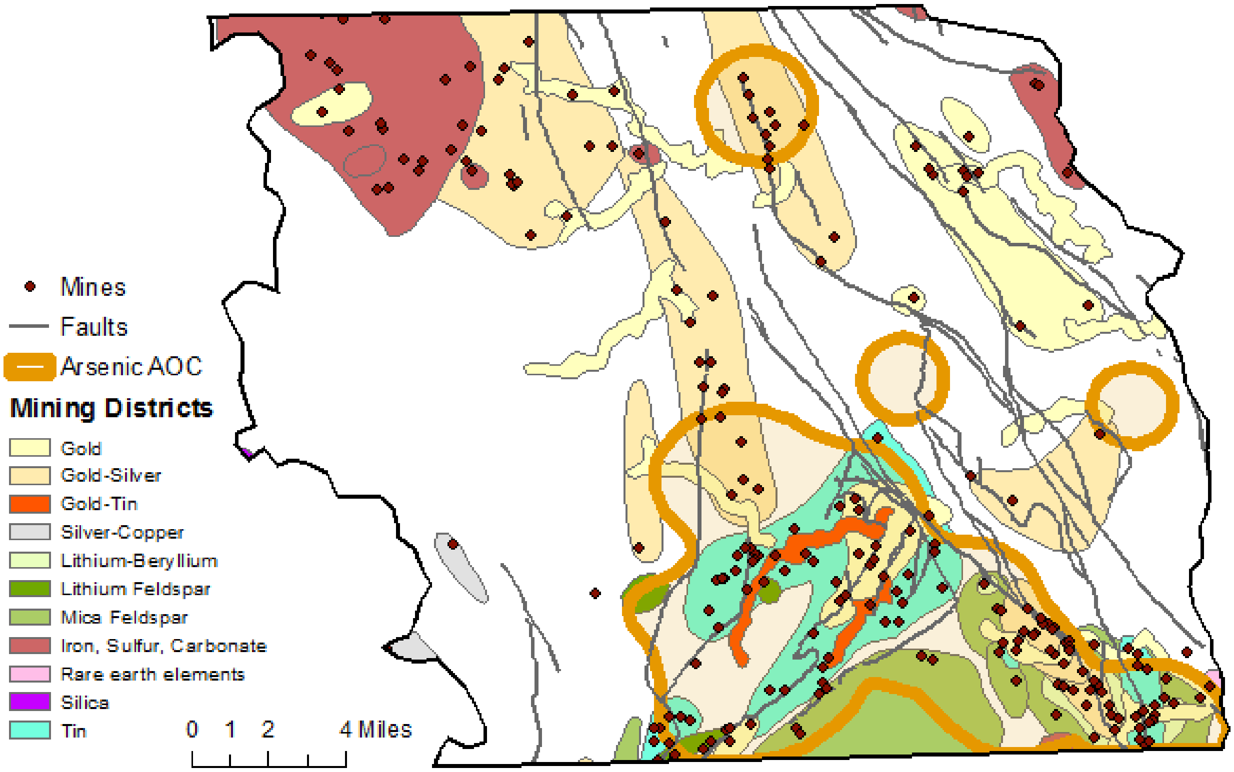

Figure 17. Arsenic Area of Concern mapped over mining districts (Wilson and DeWitt, 1995) and major mines (Wagner, 2016).

Because faults and other structures often control the flow of fluids and thus the regions of mineralization, the data were tested to see whether wells with arsenic hits are more closely associated with faults or fold structures than are wells with low arsenic. For this analysis, only the structures from the 1:24,000 scale geologic maps were used. The area covered by these quadrangles was clipped to the study area. Figure 18 shows the region of the structural study and the 1:24,000 scale faults and fold axes. Fortunately, the arsenic areas of concern predominantly fall within the structural study area.

In interpreting this analysis, it is important to remember that only the largest and most continuous faults and folds will be shown on a geologic map. Many structures are concealed by soils and vegetation, or are too small to map; such structures can still play a locally important role in the transport of fluids and the patterns of mineralization. However, the mapped large structures define potential pathways for especially efficient or long-distance transport of constituents through the bedrock, and they often represent zones of extensive deformation riddled with smaller structures that enhance the permeability of the surrounding bedrock . If arsenic and other constituents are predominantly found near these significant structures, it would indicate that these pathways are of great importance in distributing constituents and may represent regions of concern in themselves. If constituents show no relationship to the mapped faults and folds, it is more likely that constituents are locally controlled and primarily distributed by smaller structures.

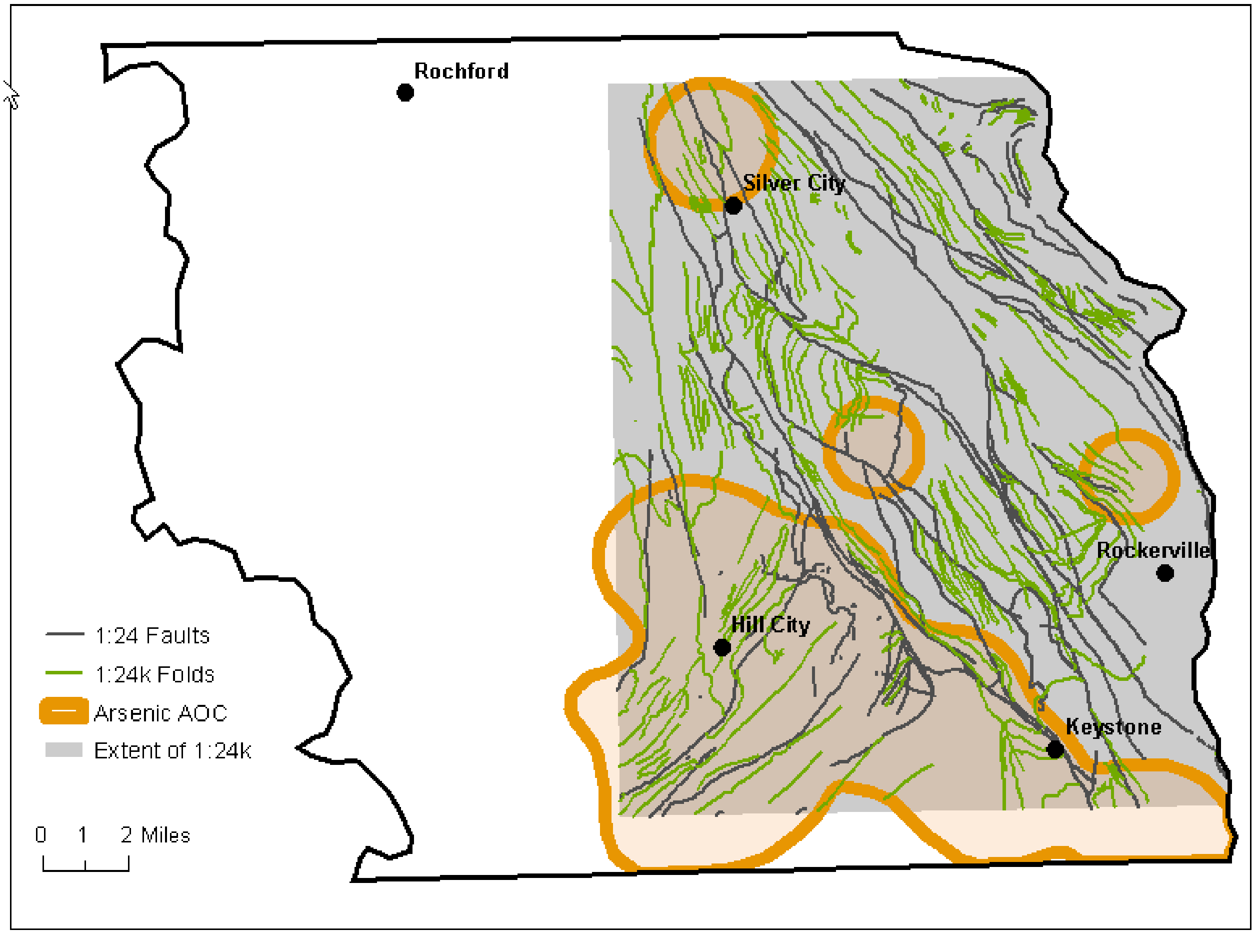

Figure 18. Faults and fold axis structures used to test distance relationships between arsenic hits and structural features.

The wells within the grey structural study area shown in Figure 18 were selected and the distance in meters of each well to the closest fault was determined. A cumulative distribution function was then plotted separately for the wells with arsenic hits and those with low arsenic (Fig. 19). The procedure was repeated for fold axes (Fig 20). The analysis included 244 low arsenic wells and 64 high arsenic wells.

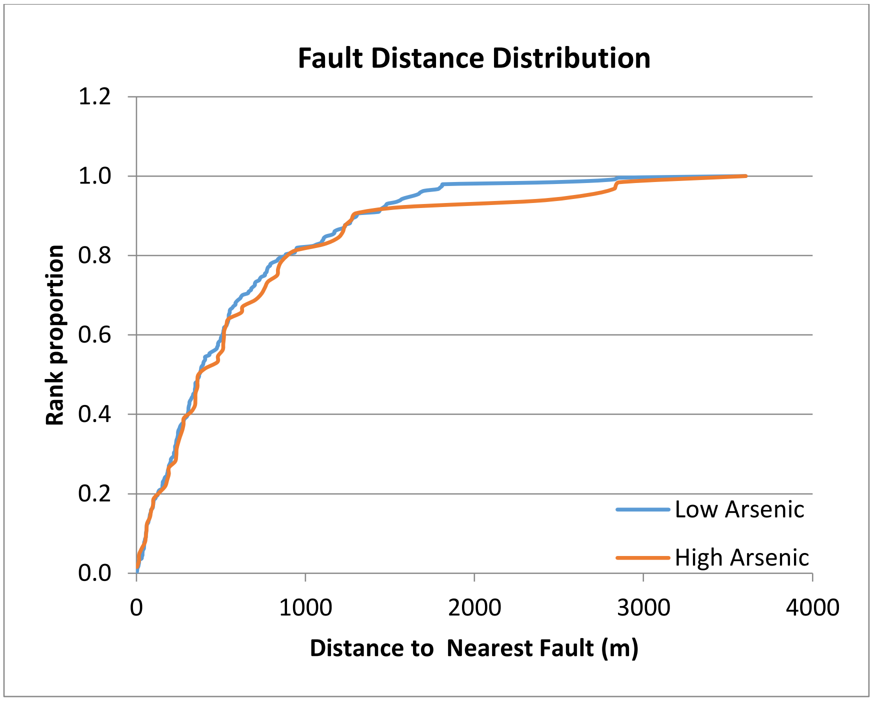

Figure 19. Cumulative distribution function for the distance of each well to the closest fault

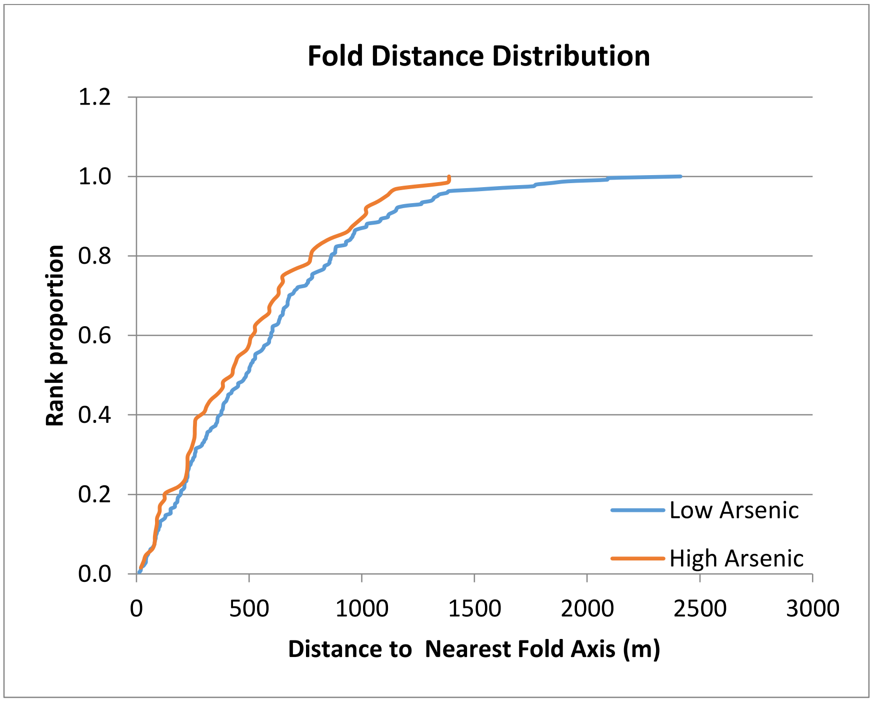

Figure 20. Cumulative distribution function for the distance of each well to the closest fold axis

The distribution of distances of wells with arsenic hits is very similar to the distance distribution for low arsenic wells. Both distributions rise steeply, with more than 80% of the wells occurring within 1 km of a fault. However, the similarity of the distributions suggests that arsenic hits are not more likely to occur near these mapped faults than low-arsenic wells. The mean distance of low arsenic wells to a fault is 562 meters, and the mean distance for high arsenic wells is 662 meters.

For folds, however, the distribution function of the wells with arsenic hits rises more steeply than the distribution for the low arsenic wells, suggesting that arsenic hits are more likely to occur close to a fold axis. The mean distance of low arsenic wells from a fold is 560 m and the mean distance of high arsenic wells to a fold is 482.

From Figure 17, it is clear that the arsenic area of concern occupies a region that is significantly different from the rest of the study area in terms of the rock types, structural trends, mineralization intensity and mining activity. This region is bounded to the north by a set of primarily strike-slip faults known variously as the Empire or Keystone West (Empire) fault. For the purpose of this paper, this region will be called the Hill City-Keystone Mining Region, or the HC-KR. It is possible that the relationship of arsenic hits to faults and folds in this region might be significantly different than the relationship for the entire study area. To investigate, only the wells within the HC-KR were selected and the cumulative distributions were plotted as previously described. The analysis included 41 low arsenic wells and 55 high arsenic wells.

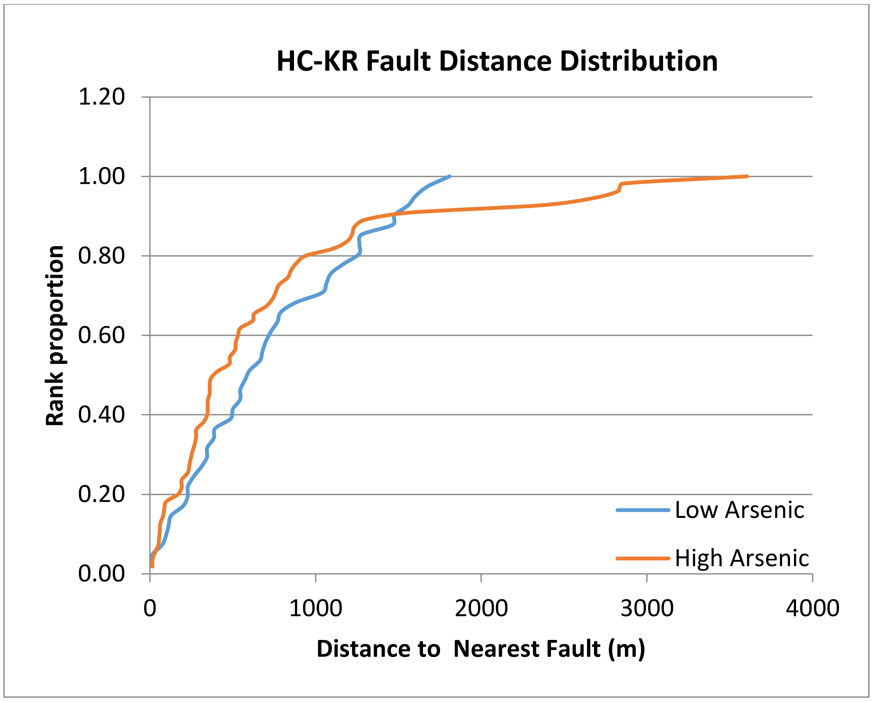

Figure 21. Cumulative distribution function for the distance of each well to the closest fault in the Hill City – Keystone Mining Region.

The fault distance distribution for the HC-KR is quite different than for the structure study area as a whole (Fig 21). Wells with arsenic hits tend to have smaller distances to faults than wells with low arsenic, although there are a few outliers of high arsenic wells that fall three and four km from the nearest fault. This observation suggests that the faults either served as pathways for the original mineralizing fluids or that they are conduits for subsequently moving arsenic-bearing waters through the region.

The fold distance distribution behavior is the opposite of that observed for the structural study as a whole. Low arsenic wells tend to occur at smaller distances to fold axes than high arsenic wells (Figure 22). The cause of such a difference is not immediately clear.

Overall, the distance analysis for arsenic would indicate that the distribution of arsenic is being locally controlled, and that areas close to the major structures do not pose a significantly greater risk of high arsenic levels than areas further away, except perhaps within the HC-KR region.

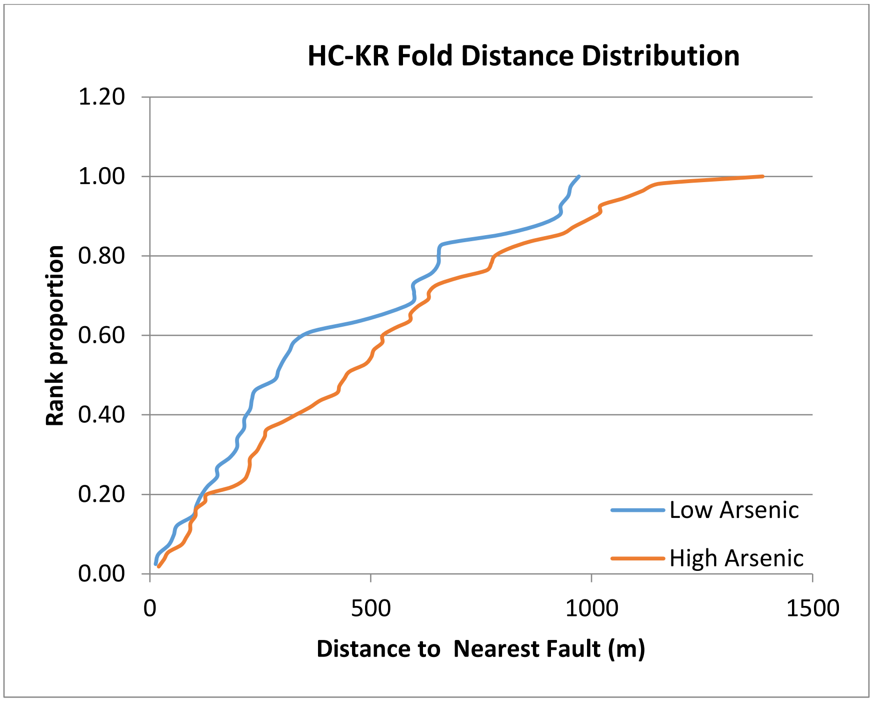

Figure 22. Cumulative distribution function for the distance of each well to the closest fold axis in the Hill City – Keystone Mining Region.

Iron

The iron values were subjected to a similar analysis versus rock type as done for arsenic. We calculated the percentage of high iron values (>= 50% of the EPA recommended value) found in each rock formation. Table 4 summarizes the information by geologic rock unit. Figure 23 plots

Table 4. Percentage of iron hits (>= 50% of EPA recommendation) by rock formation

Symbol	Formation Name	Samples	Iron Hits	Percent	Frequency
OCd	Deadwood Formation	4	0	0%	Rare
Qal	Alluvial deposits	45	16	36%	Common
Qt	Q-T gravel deposits (also Qtg, Tg)	14	0	0%	Rare
Xbm	Buck Mountain Quartzite (also Xbp, Xbq)	16	1	6%	Rare
Xbo	Metabasalt (tholeiitic greenstone and amphibolite)	13	8	62%	Frequent
Xbs1	Slate and phyllite	12	7	58%	Frequent
Xbs2	Metamorphosed black shale	18	8	44%	Common
Xby	Metabasalt	4	2	50%	Common
Xcq	Metaconglomerate, quartzite, and metapelite	11	4	36%	Common
Xds	Metamorphosed dolomite and silty pelite	1	1	100%	Unknown
Xeq	Quartzite	1	0	0%	Unknown
Xgg		2	1	50%	Unknown
Xgw	Metagraywacke	1	1	100%	Unknown
Xgw1	Metagraywacke	21	7	33%	Common
Xgw2	Metagraywacke	25	13	52%	Frequent
Xgw3	Metagraywacke	9	3	33%	Common
Xgwd	Metagraywacke (distal)	10	3	30%	Common
Xgwu	Metagraywacke	9	0	0%	Rare
Xh	Harney Peak Granite	1	0	0%	Unknown
Xif	Carbonate facies iron formation	3	0	0%	Unknown
Xmg	Metagabbro	1	1	100%	Unknown
Xmt	Metamorphosed impure mafic tuff	4	2	50%	Common
Xo	Oreville Formation	15	10	67%	Frequent
Xqc	Metamorphosed quartzite, debris flow conglomerate	6	2	33%	Common
Xqs	Metamorphosed quartzite and pelite	2	0	0%	Unknown
Xs	Metamorphosed shale	38	16	42%	Common
Xsic	Metamorphosed shale, siltstone, carbonate-facies	2	1	50%	Unknown
Xss	Schist and Phyllite	2	1	50%	Unknown
Xtg	Tenderfoot Formation (Garnet-rich Schist)	1	0	0%	Unknown
Xts	Metamorphosed tuff and shale	24	9	38%	Common
Xtv	Metamorphosed tuffaceous shale, tuff, and volcanics	2	1	50%	Unknown
Xz	Zimmer Ridge Metagraywacke (also Zx)	11	6	55%	Frequent

the number of total samples analyzed for iron against the fraction of samples classified as iron hits (>= 0.005 mg/L), and this graph was used to assign a risk assessment to each geologic unit. Rock formations with three or fewer samples were classified as Unknown frequency, samples close to the x-axis, with many samples but less than 15% hits, were assigned to the Rare frequency group. Formations with many samples and high fractions above 50% were assigned to the Frequent group, and the remaining formations were classified as Common frequency. Five formations show a Frequent frequency of iron hits: Xbo, Xbs1, Xgw2, Xo, and Xz. Except for Xo, these units are all different from those classified as High Risk for arsenic.

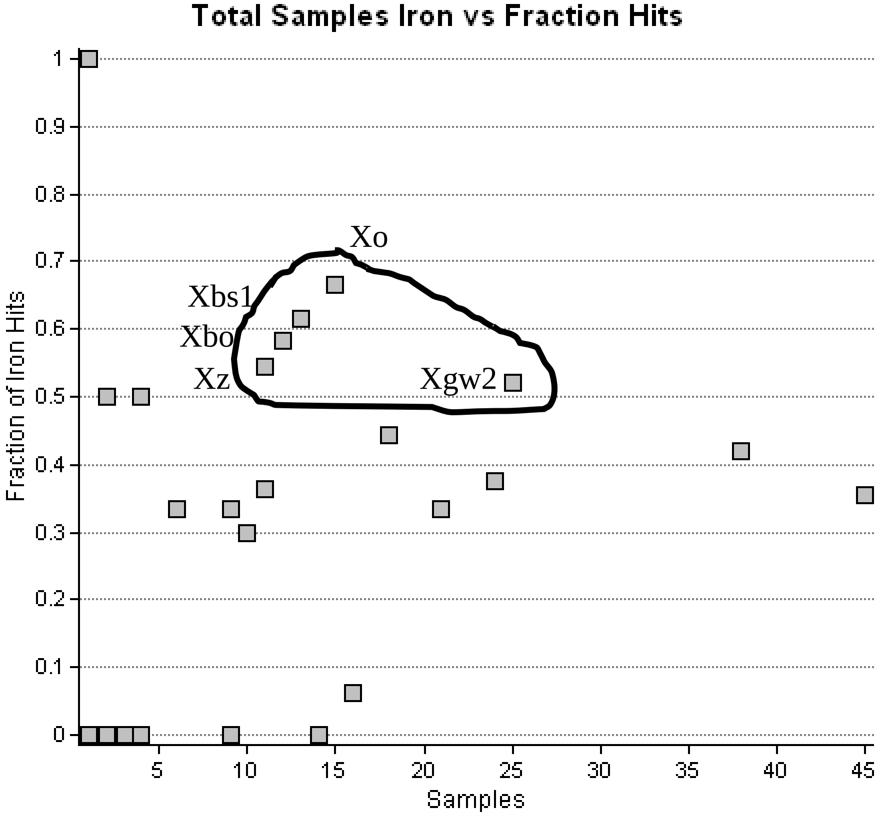

Figure 23. Plot showing the number of samples versus the fraction of iron values >= 10 mg/L. High frequency formations have more than three samples and at least 50% iron hits.

Figure 24 presents a map of the study area with the rock formations characterized by the assigned frequency designation, with the outline of the Iron Area of Concern (AOC) regions from Figure 10 delineated. However, as shown in Figure 23, nearly all of the rock units in the region have iron frequency values > 30%, such that nearly the entire map area falls into the Common or Frequent iron categories, indicating that elevated iron values are a common problem throughout the study area.

Finally, we also tested the distance relationship of iron hits to faults and folds using the same methodology as for arsenic. Because frequent iron hits are not isolated to the HC-KM region, however, we performed the analysis using the entire structural study region. The results are shown in Figures 25 and 26. The fault distance distributions appear similar for both high and low iron values. The fold distance distribution shows a slight tendency for high iron values to appear somewhat closer to folds than low iron values at intermediate distances. However, the areas close to the major structural features do not appear to be at greater or lesser risk of iron problems than other areas.

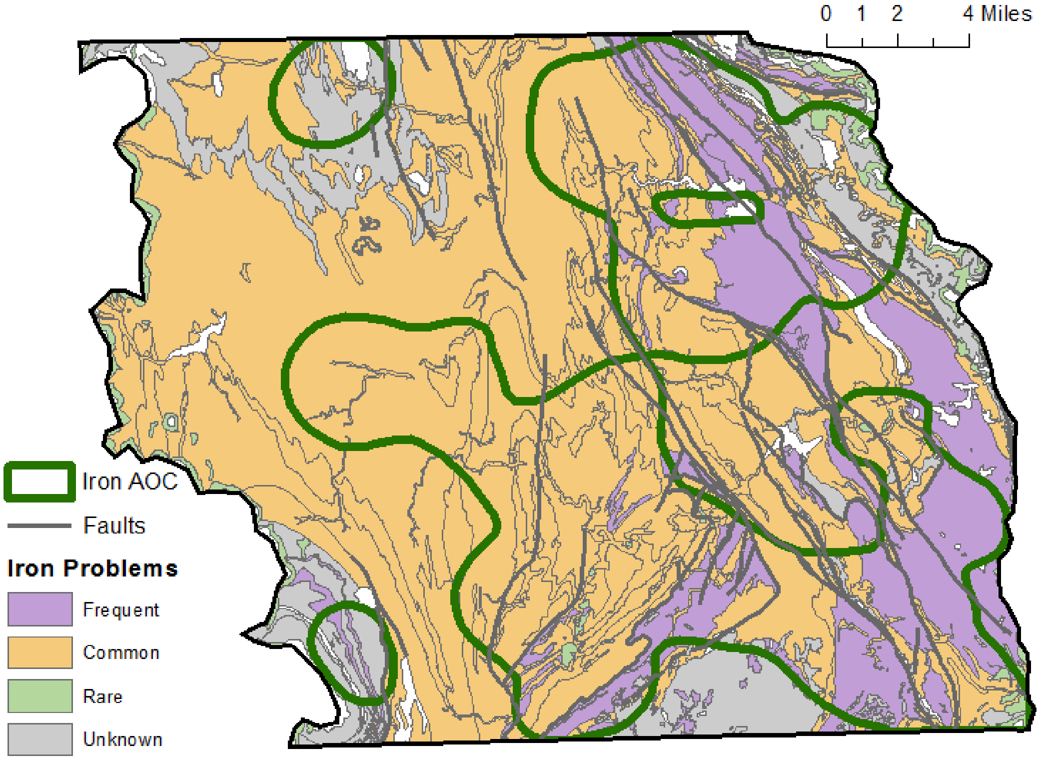

Figure 24. Map of rock units characterized by assigned iron frequency category. The heavy green line outlines the area of concern for iron concentration in well water.

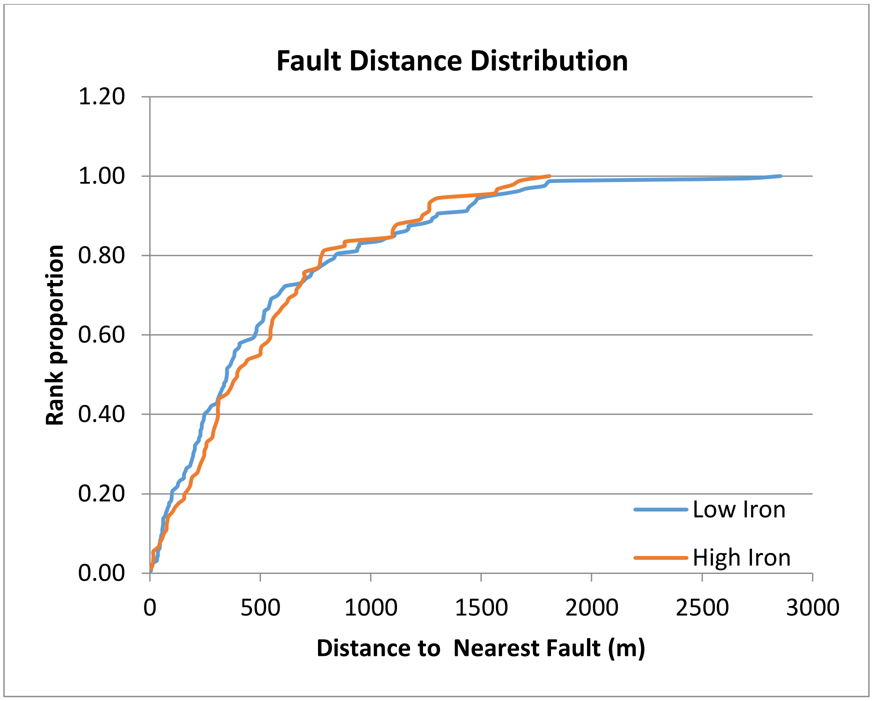

Figure 25. Cumulative distribution functions for the distance of each well to the closest fault in the structural study region

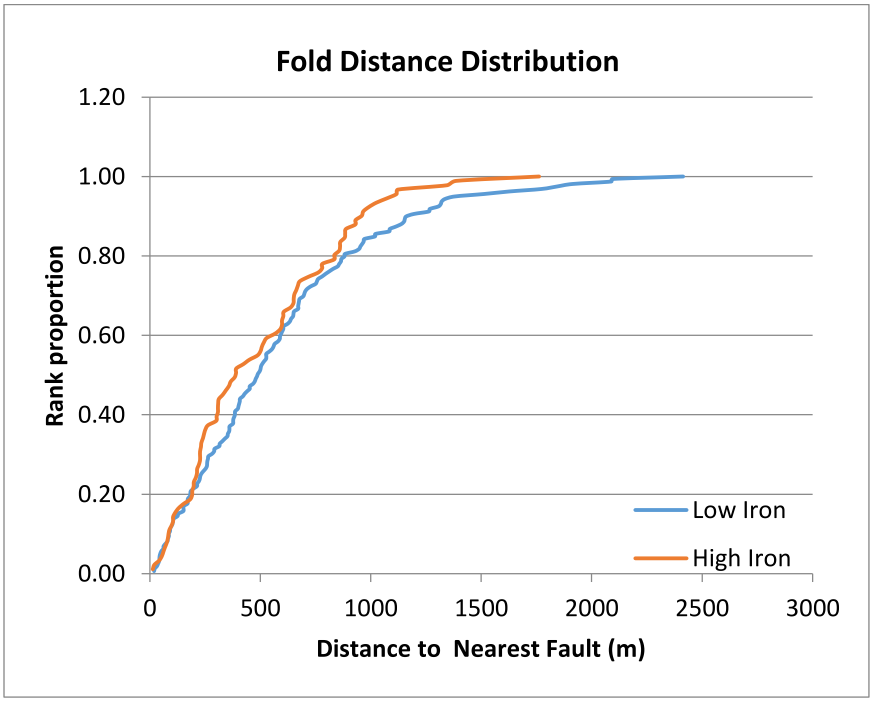

Figure 26. Cumulative distribution functions for the distance of each well to the closest fold in the structural study region

Conclusions

In this study, 268 samples have been collected from private wells and combined with published data for 93 public wells to evaluate the presence of hardness, calcium, magnesium, nitrate, arsenic, sulfate, total coliform bacteria, and fecal coliform bacteria in groundwater in crystalline rocks in the central Black Hills of South Dakota. About 16% of private wells showed arsenic concentrations greater than 0.010 mg/L, and more than 3 % of private wells showed nitrate concentrations greater than 10 mg/L. Sulfate above the recommended limit was rarely found in the study area, with <4% of samples testing above the limit. We also found that 39% of private wells tested positive for total coliform bacteria, and 8% of private wells tested positive for fecal coliform bacteria. The prevalence of total coliform through much of the study area may indicate a need to enhance public awareness of the potential for fecal coliform contamination and foster testing efforts.

The arsenic in water samples is most likely from weathering of arsenopyrite in the study area bedrock. A few rock formations show a higher frequency of arsenic problems than others. However, high arsenic concentrations are most prevalent in the historic mining districts located southwest of the Empire/Keystone fault system in the Hill City-Keystone Mining Region (HC-KR), indicating that structural features and gold, silver, and tin mineralization play a far greater role than does rock type alone. Within this mineralized zone, high arsenic values tend to occur closer to faults and further from folds than low arsenic values.

High levels of iron are common in the study area, with 31% of values exceeding the EPA recommended limit. Like arsenic, the hits occur more frequently within certain rock units, but unlike arsenic, they are common throughout the study area and not just the HC-KR region. High iron levels do not appear to be more likely to occur near faults, but may have a slight tendency to occur near folds.

Nitrate levels appear to be spatially associated with the highest densities of fecal and total coliform contamination. Sulfate issues appear rare in the study area.

The presence of nitrate and arsenic in drinking water can have adverse health effects and tolerable limits of these constituents are enforced for public wells. However, these limits are not enforced for private wells. Thus, in order to best protect their families, homeowners who did not participate in this study are encouraged to test their well water to ensure that is safe to drink. Using the results of this study, owners can identify whether their home sites are in higher risk areas for these contaminants.

ACKNOWLEDGEMENTS

Funding for this research was provided by the West Dakota Water Development District with approval the Board of Directors of that organization. To them, and to executive directors Van Lindquist and, subsequently, Blaise Emerson, we are most appreciative.

Three SDSM&T faculty members supervised the study, including Dr. Arden Davis, Dr. Maribeth Price, and Dr. Alvis Lisenbee. SDSM&T students who have contributed substantially to the project include the following: Katherine Aurand, Deborah Brewer, Andrew Clift, Kathleen Grigg, Kyle Hazelwood, Mackenzie Kester, Kelsey Marzolf, Michael Tekle, Henok Tiruneh, Natalie Toth, and Umit Yildiz. Audra Basal compiled the public well data for the final phase of the project. Houston Wagner compiled a database of major mines in the Black Hills used in this study. Mark Fahrenbach and Joanne Noyes of the South Dakota Geological Survey participated in many research meetings and contributed significantly to the design and execution of this study.

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Appendix A. Water Quality Report Cards

List of Appendices

Appendix A. Water Quality Report Cards

http://www.sdsmt.edu/aquifers

WDWDD-SDSMT Report Card for Arsenic

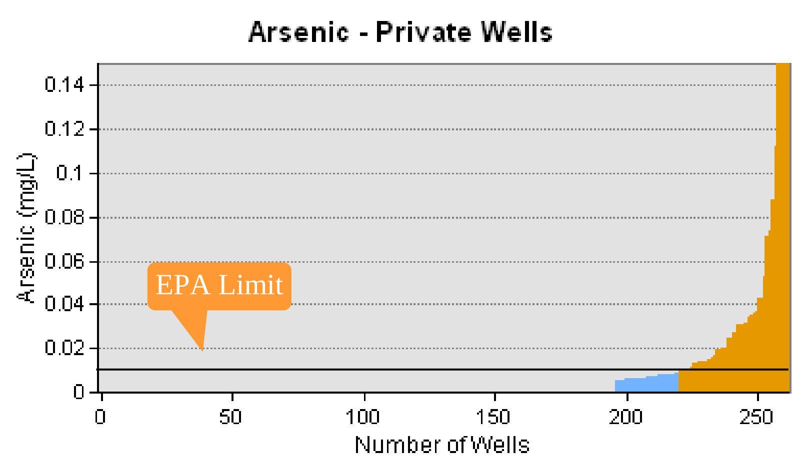
Private Well Tests	
Number of wells	262
Number of tests	273
Earliest test date	5/5/2013
Latest test date	11/03/2015
Lowest value detected	**
Highest value detected	0.441
Number of wells exceeding EPA[4]	36
Percent wells exceeding EPA	14%
Public Well Records	
Number of wells	62
Number of recorded tests	335
Earliest test date	12/5/1977
Latest test date	5/19/2014
Lowest value detected	**
Highest value detected	0.178
Number of wells exceeding EPA[4]	7
Percent wells exceeding EPA	12%

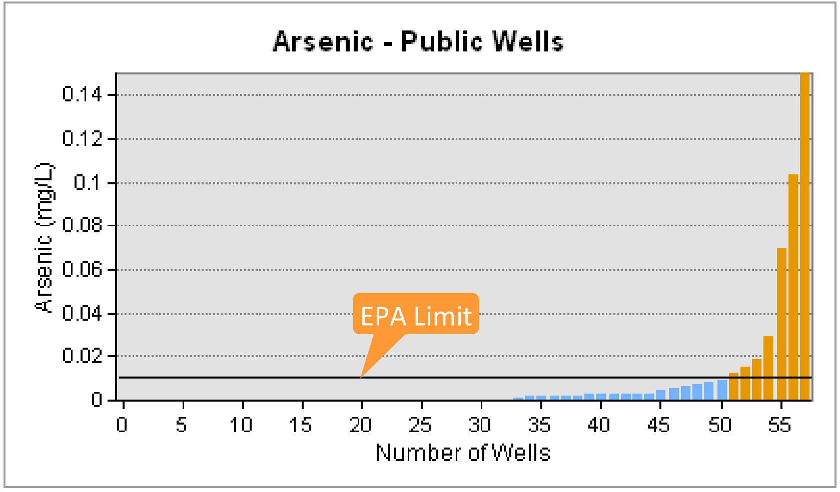
** Below detection limit of 0.005 mg/L

Dissolved arsenic can occur in well water because of natural weathering of certain minerals in rocks. The maximum contaminant level for arsenic in public water supplies is 0.010 mg/L. Arsenic is regulated in public water supplies because of links to cancer. It can also cause nerve damage and other problems.

We sampled 262 private wells and compiled published data from 62 public wells to evaluate the presence of arsenic in well water in central Pennington County, SD. In some cases the wells were tested multiple times; we show the highest test value in each case. We found that 14% of private wells and 12% of public wells had tests that exceeded the EPA standard. The maximum value detected was 0.441 mg/L, nearly 44 times the EPA standard.

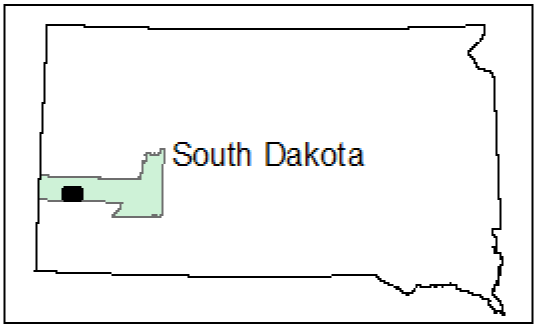
In the graphs, the blue bars represent arsenic values below the EPA standard; the orange bars represent values above the standard, and the standard is indicated by a black horizontal line at 0.01 mg/L. Arsenic was below the detection limit of 0.005 in many wells and have no bars shown. The graphs show that many arsenic values are much higher than the EPA standard; a few are extremely high and sever extend beyond the top of the graph.





Arsenic problems can be treated so that the water is safe to drink. Public water supplies are regulated by law. Although the tests are performed prior to treatment, water from public wells should be safe.

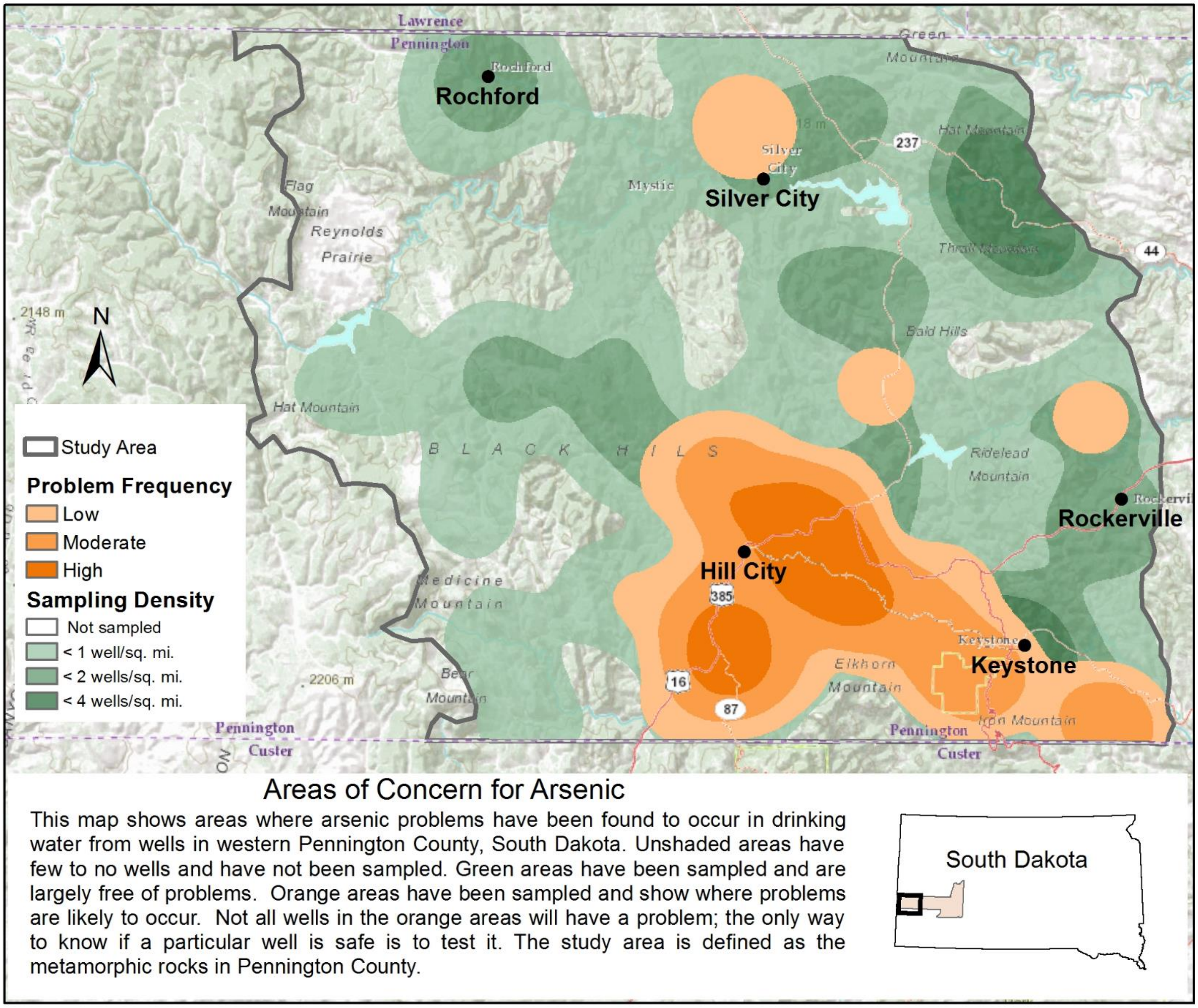
Private wells are not regulated by law and homeowners are not required to meet drinking water standards set by the EPA. However, homeowners are encouraged to test their water to ensure that it is safe to drink and to protect their families.



This document describes the results of a study conducted by the South Dakota School of Mines and Technology from 2013 to 2015 and funded by the West Dakota Water Development district to assess potential water quality issues in Pennington County.

To protect the privacy of homeowners who participated in the study, we do not plot individual well test locations on maps shown to the public. Instead, we selected the private and public wells with arsenic values greater than or equal to 50% of the EPA standard and created a density map showing areas with more frequent arsenic problems. These regions are considered to represent a higher *risk* of arsenic issues. **It is important to understand that subsurface conditions can change rapidly from place to place, and not all wells in the shaded areas will have arsenic problems.** The only way to know whether a particular well has elevated arsenic levels is to test it. Homeowners in the shaded areas are especially encouraged to test their well water to ensure that it is safe.

Problems with arsenic show a strong association with historic mining districts in the Black Hills, which is also where home sites tend to cluster. For interactive maps showing these associations, click here.



Areas of Concern for Arsenic

This map shows areas where arsenic problems have been found to occur in drinking water from wells in western Pennington County, South Dakota. Unshaded areas have few to no wells and have not been sampled. Green areas have been sampled and are largely free of problems. Orange areas have been sampled and show where problems are likely to occur. Not all wells in the orange areas will have a problem; the only way to know if a particular well is safe is to test it. The study area is defined as the metamorphic rocks in Pennington County.

WDWDD-SDSMT Report Card for Iron

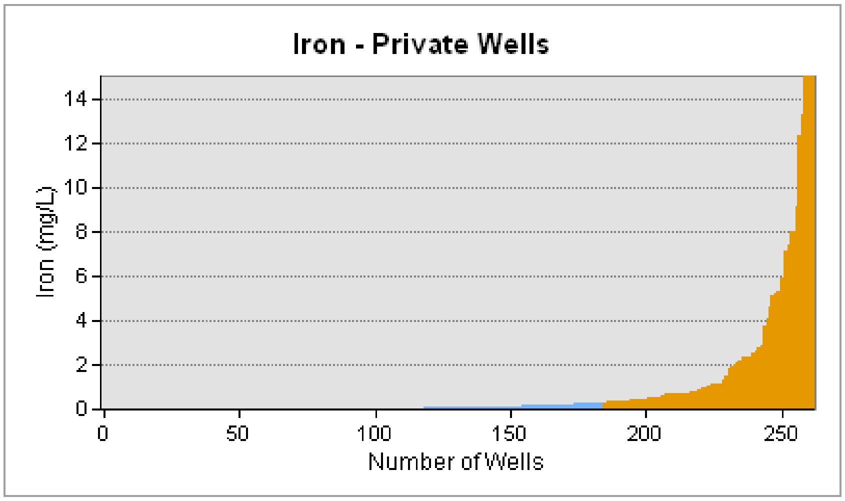
Private Well Tests	
Number of wells	262
Number of tests	273
Earliest test date	5/5/2013
Latest test date	11/03/2015
Lowest value detected	**
Highest value detected (mg/L)	70.2
Number of wells above 0.3 mg/L	81
Percent wells above 0.3 mg/L	31%
Public Well Records	
Number of wells	70
Number of recorded tests	534
Earliest test date	4/12/1967
Latest test date	7/9/2007
Lowest value detected	**
Highest value detected (mg/L)	93
Number of wells above 0.3 mg/L	15
Percent wells above 0.3 mg/L	23%

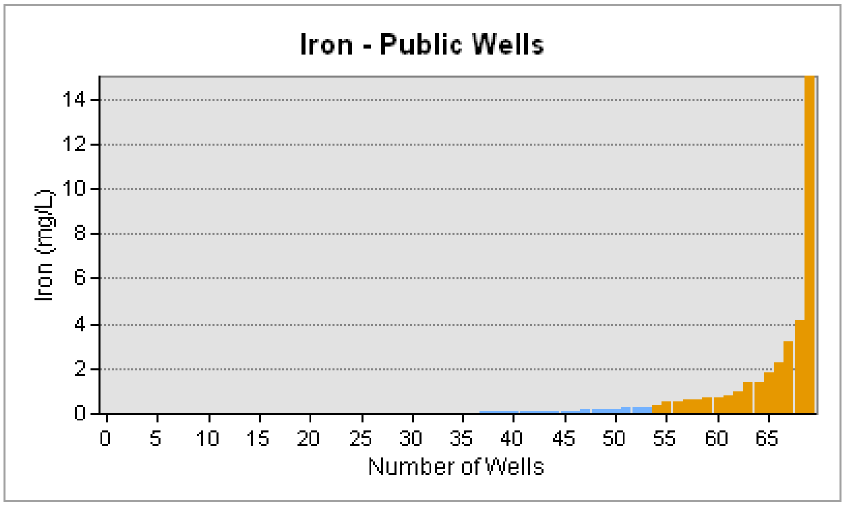
** Below detection limit of 0.015 mg/L

Dissolved iron can occur in well water because of natural weathering of certain minerals in rocks. Dissolved iron in well water can cause rust-colored stains on plumbing fixtures and clothing. The recommended maximum contaminant level for iron in public water supplies is 0.3 mg/L; this is an EPA recommended guideline rather than an enforced standard.

We sampled 262 private wells between 2013 and 2015, and compiled published data from 70 public wells to evaluate the presence of iron in well water in western Pennington County, SD. In some cases the wells were tested multiple times; we took the highest test in each case. We found that 31% of private wells and 23% of public wells had tests that exceeded recommended limit of 0.3 mg/L. The maximum value detected was 93 mg/L, more than 300 times the recommended limit.

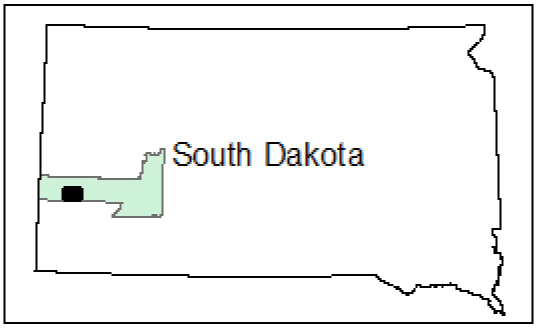
In the graphs, the (tiny) blue bars represent dissolved iron values below the EPA standard of 0.3 mg/L; the orange bars represent values above the standard. The graphs show that many iron values are much higher than the recommended limit; a few are extremely high and two extend beyond the top of the graph.





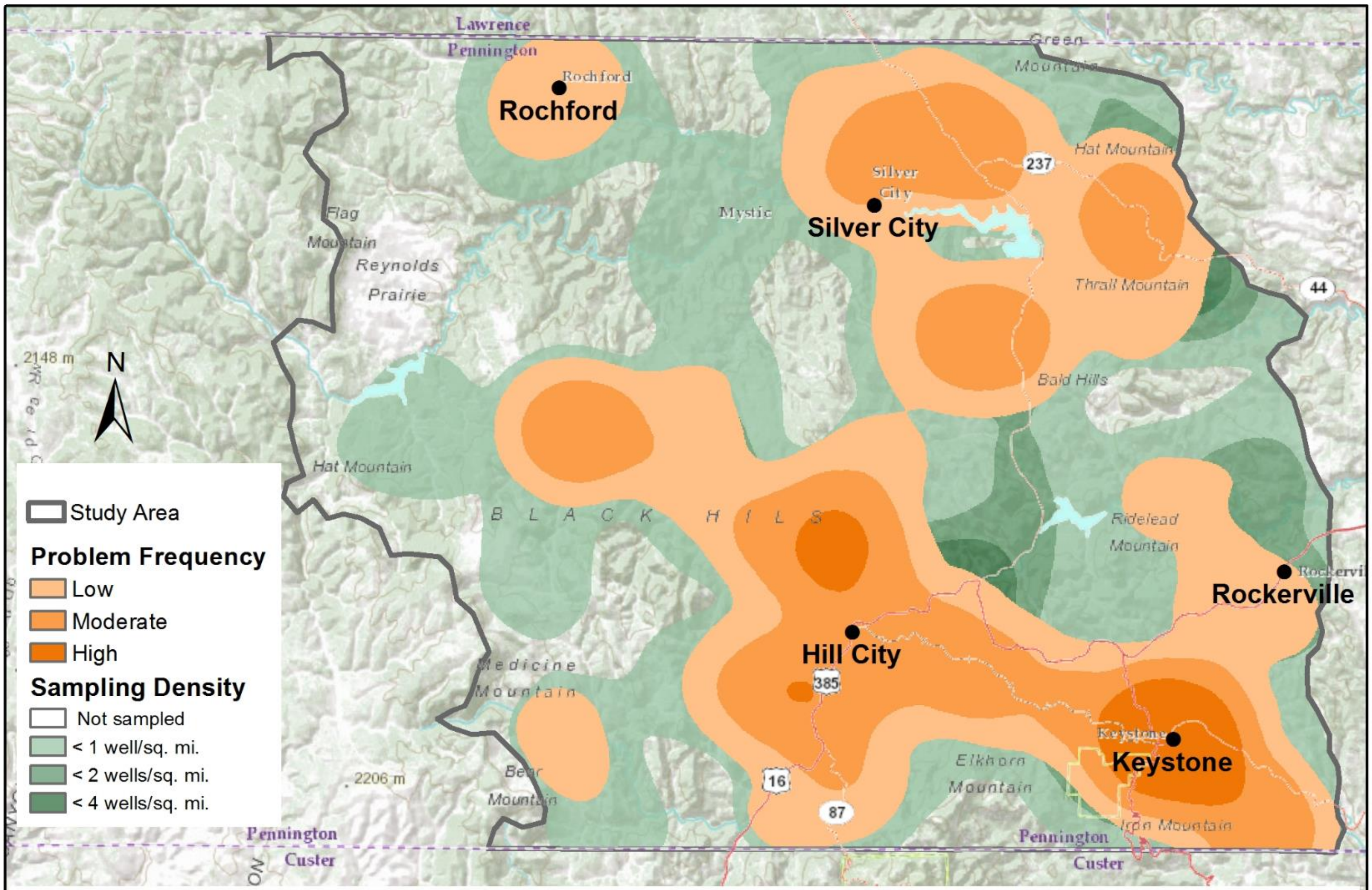
Well water can be treated to reduce the nuisances associated with high iron content. Public water supplies are regulated by law. Although the tests are performed prior to treatment, water from public wells should be within recommended limits for iron.

Private wells are not regulated by law and homeowners are not required to meet drinking water standards set by the EPA. However, homeowners are encouraged to test their water to ensure that it is healthy to drink and to protect their families.



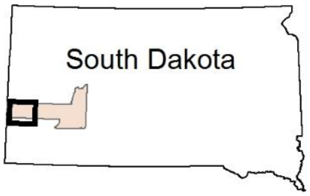
To protect the privacy of homeowners who participated in the study, we do not plot individual well test locations on maps shown to the public. Instead, we selected the private and public wells with iron values greater than or equal to 50% of the recommended limit and created a density map showing areas with more frequent iron problems. These regions are considered to represent a higher *risk* of iron issues. **It is important to understand that subsurface conditions can change rapidly from place to place, and not all wells in the shaded areas will have iron problems.** The only way to know whether a particular well has elevated iron levels is to test it. Homeowners in the shaded areas are especially encouraged to test their well water to ensure that it is healthy.

Problems with iron show a strong association with historic mining districts in the Black Hills, which is also where home sites tend to cluster. For interactive maps showing these associations, click here.



Areas of Concern for Iron

This map shows areas where iron problems have been found to occur in drinking water from wells in western Pennington County, South Dakota. Unshaded areas have few to no wells and have not been sampled. Green areas have been sampled and are largely free of problems. Orange areas have been sampled and show where problems are likely to occur. Not all wells in the orange areas will have a problem; the only way to know if a particular well is safe is to test it. The study area is defined as the metamorphic rocks in Pennington County.



http://www.sdsmt.edu/aquifers

WDWDD-SDSMT Report Card for Nitrate

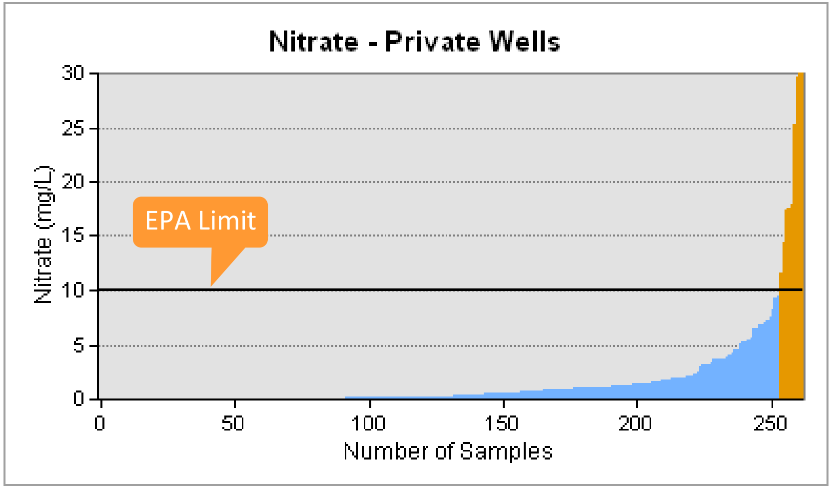
Private Well Tests	
Number of wells	262
Number of tests	272
Earliest test date	5/5/2013
Latest test date	11/03/2015
Lowest value detected	**
Highest value detected (mg/L)	31.5
Number of wells above EPA limit	8
Percent wells above limit	3%
Public Well Records	
Number of wells	45
Number of recorded tests	382
Earliest test date	6/12/1963
Latest test date	9/21/2009
Lowest value detected	**
Highest value detected (mg/L)	20
Number of wells above EPA limit	2
Percent wells above limit EPA limit	4%

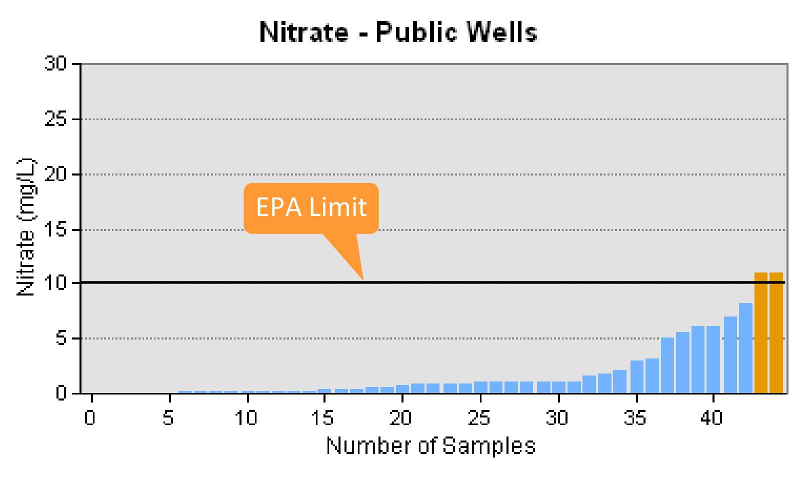
** Below detection limit of 0.04 mg/L

Dissolved nitrate can occur in well water because of human activities, including runoff from fertilizer or improperly maintained septic tanks, or, more rarely, from weathering of certain rock types. The maximum contaminant level for nitrate in public water supplies is 10 mg/L. Nitrate is regulated in public water supplies because it can cause illness and death in infants due to blue-baby syndrome.

We sampled 262 private wells between 2013 and 2015, and compiled published data from 45 public wells to evaluate the presence of nitrate in well water in western Pennington County, SD. In some cases the wells were tested multiple times; we took the highest test in each case. We found that 3% of private wells and 4% of public wells had tests that exceeded the EPA standard. The maximum value detected was 31.5 mg/L, about three times the EPA standard.

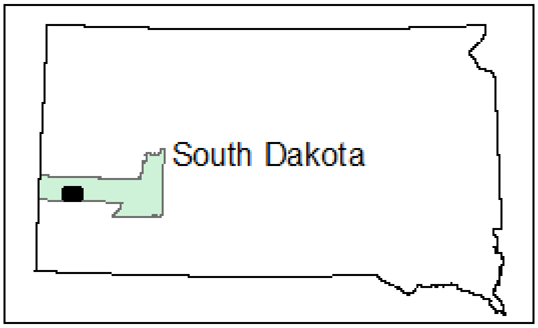
In the graphs, the blue bars represent nitrate values below the EPA standard; the orange bars represent values above the standard, and the standard is indicated by a black horizontal line at 10 mg/L. The graphs show only a few values above the EPA standard.


Nitrate - Private Wells


Nitrate - Public Wells

Nitrate problems can be treated so that the water is safe to drink. Public water supplies are regulated by law. Although the tests are performed prior to treatment, water from public wells should be safe.

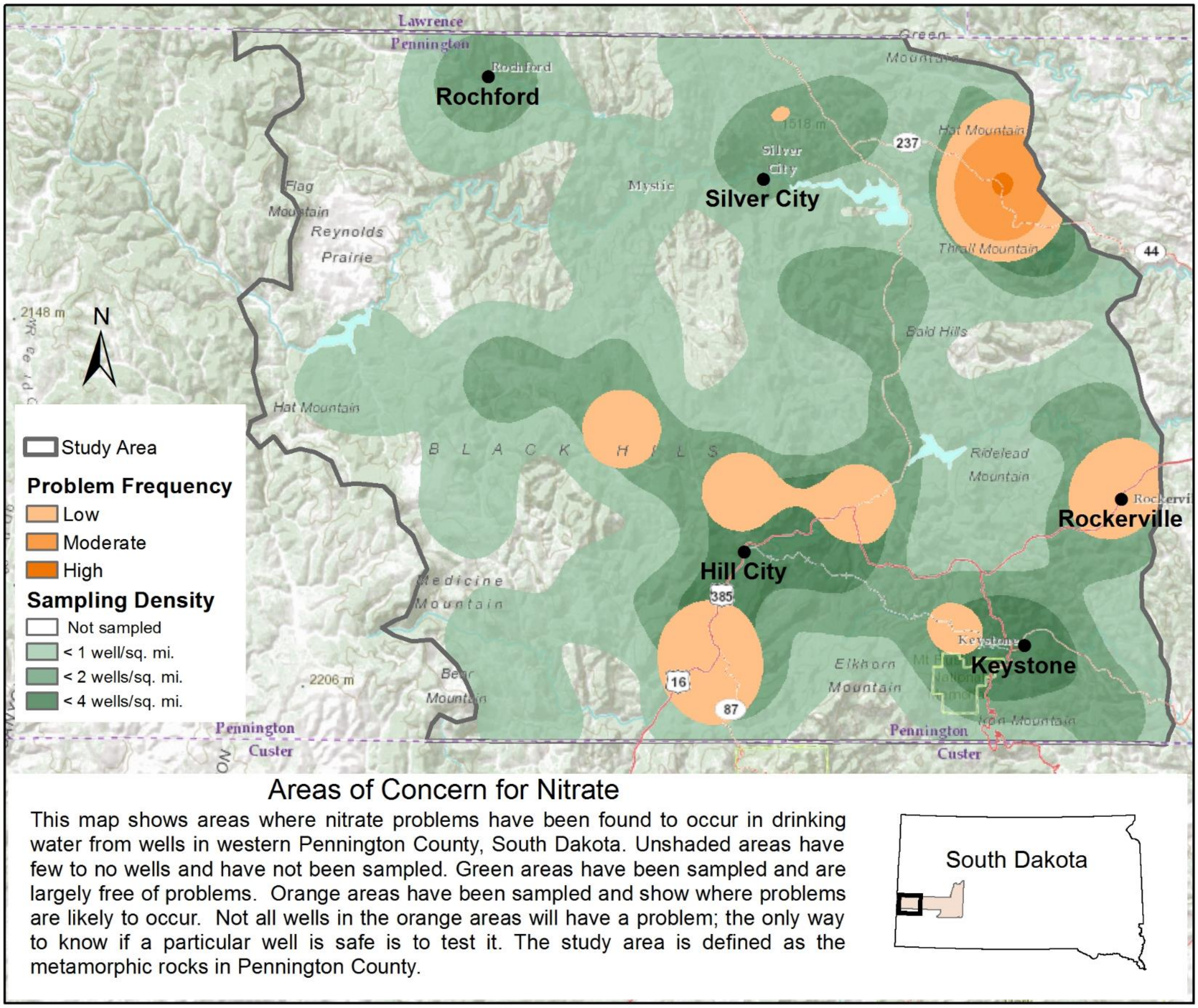
Private wells are not regulated by law and homeowners are not required to meet drinking water standards set by the EPA. However, homeowners are encouraged to test their water to ensure that it is safe to drink and to protect their families.



This document describes the results of a study conducted by the South Dakota School of Mines and Technology in 2013 and funded by the West Dakota Water Development district to assess potential water quality issues in Pennington County.

To protect the privacy of homeowners who participated in the study, we do not plot individual well test locations on maps shown to the public. Instead, we selected the private and public wells with nitrate values greater than or equal to 50% of the EPA standard and created a density map showing areas with more frequent nitrate problems. These regions are considered to represent a higher *risk* of nitrate issues. **It is important to understand that subsurface conditions can change rapidly from place to place, and not all wells in the shaded areas will have nitrate problems.** The only way to know whether a particular well has elevated nitrate levels is to test it. Homeowners in the shaded areas are especially encouraged to test their well water to ensure that it is safe.

Nitrate does not appear to be a widespread problem in the study area. However, the higher values are associated with areas where fecal coliform bacteria have also been detected in wells, which is consistent with the impact of human activities. For interactive maps showing these associations, click here.



Areas of Concern for Nitrate

This map shows areas where nitrate problems have been found to occur in drinking water from wells in western Pennington County, South Dakota. Unshaded areas have few to no wells and have not been sampled. Green areas have been sampled and are largely free of problems. Orange areas have been sampled and show where problems are likely to occur. Not all wells in the orange areas will have a problem; the only way to know if a particular well is safe is to test it. The study area is defined as the metamorphic rocks in Pennington County.

WDWDD-SDSMT Report Card for Sulfate

Private Well Tests

Number of wells	262
Number of tests	273
Earliest test date	5/5/2013
Latest test date	11/03/2015
Lowest value detected	**
Highest value detected (mg/L)	1410
Number of wells above guideline	4
Percent wells above guideline	1.5%

Public Well Records

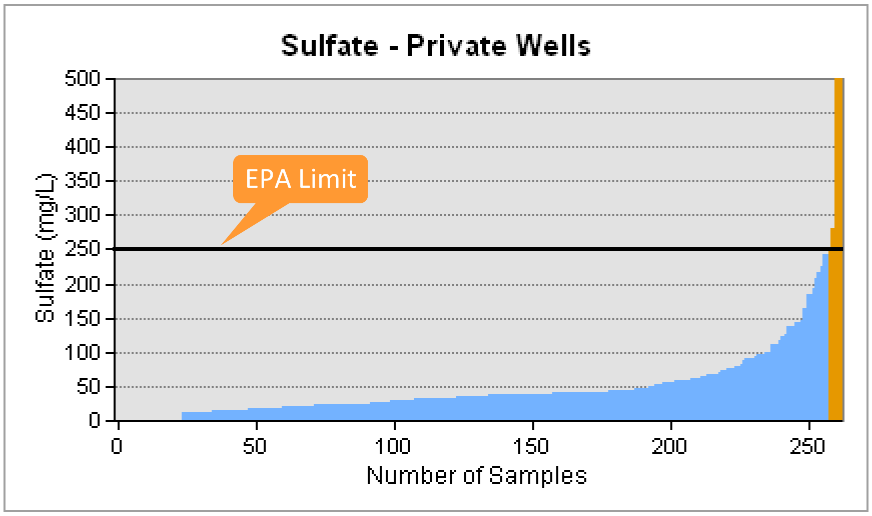
Number of wells	48
Number of recorded tests	151
Earliest test date	4/12/1967
Latest test date	7/9/2007
Lowest value detected	**
Highest value detected	689
Number of wells above guideline	2
Percent wells above guideline	4%

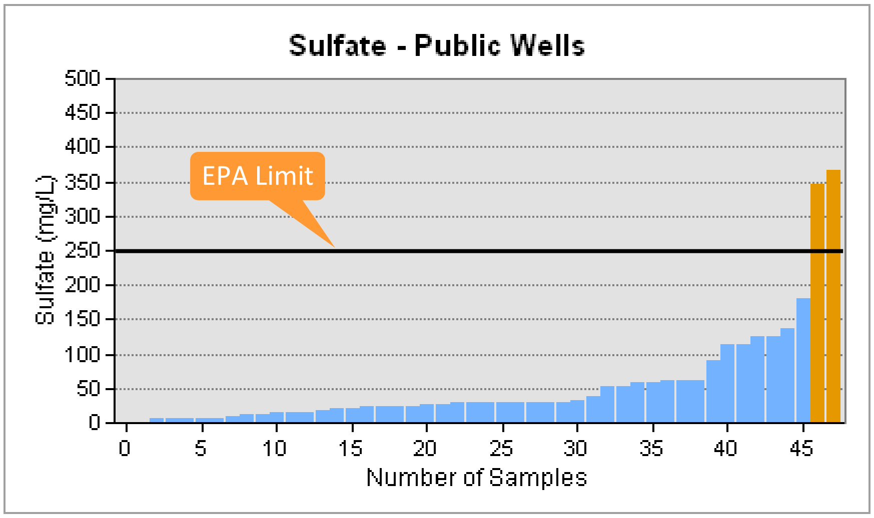
** Below detection limit of 0.685 mg/L

Dissolved sulfate occurs in well water because of natural weathering of certain minerals in rocks. It affects taste and odor of the water, and may cause laxative effects or diarrhea at high concentrations. The recommended maximum contaminant level for sulfate in public water supplies is 250 mg/L; this is an EPA recommended guideline rather than an enforced standard.

We sampled 262 private wells between 2013 and 2015, and compiled published data from 48 public wells to evaluate the presence of sulfate in well water in western Pennington County, SD. In some cases the wells were tested multiple times; we took the highest test in each case. We found that 1.5% of private wells and 4% of public wells had tests that exceeded the EPA guideline. The maximum value detected was 1410 mg/L, over five times the EPA guideline.

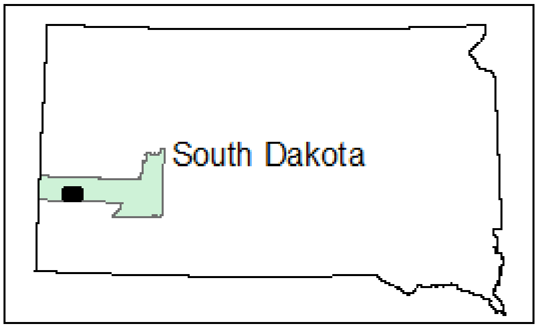
In the graphs, the blue bars represent arsenic values below the EPA guideline; the orange bars represent values above the guideline, and the guideline is indicated by a black horizontal line at 250 mg/L. The graphs show that only a few sulfate values are higher than the EPA standard; one is extremely high and extends beyond the top of the graph.





Sulfate problems can be treated so that the water is safe to drink. Public water supplies are regulated by law. Public well managers are not required to mitigate sulfate in wells, although they may do so.

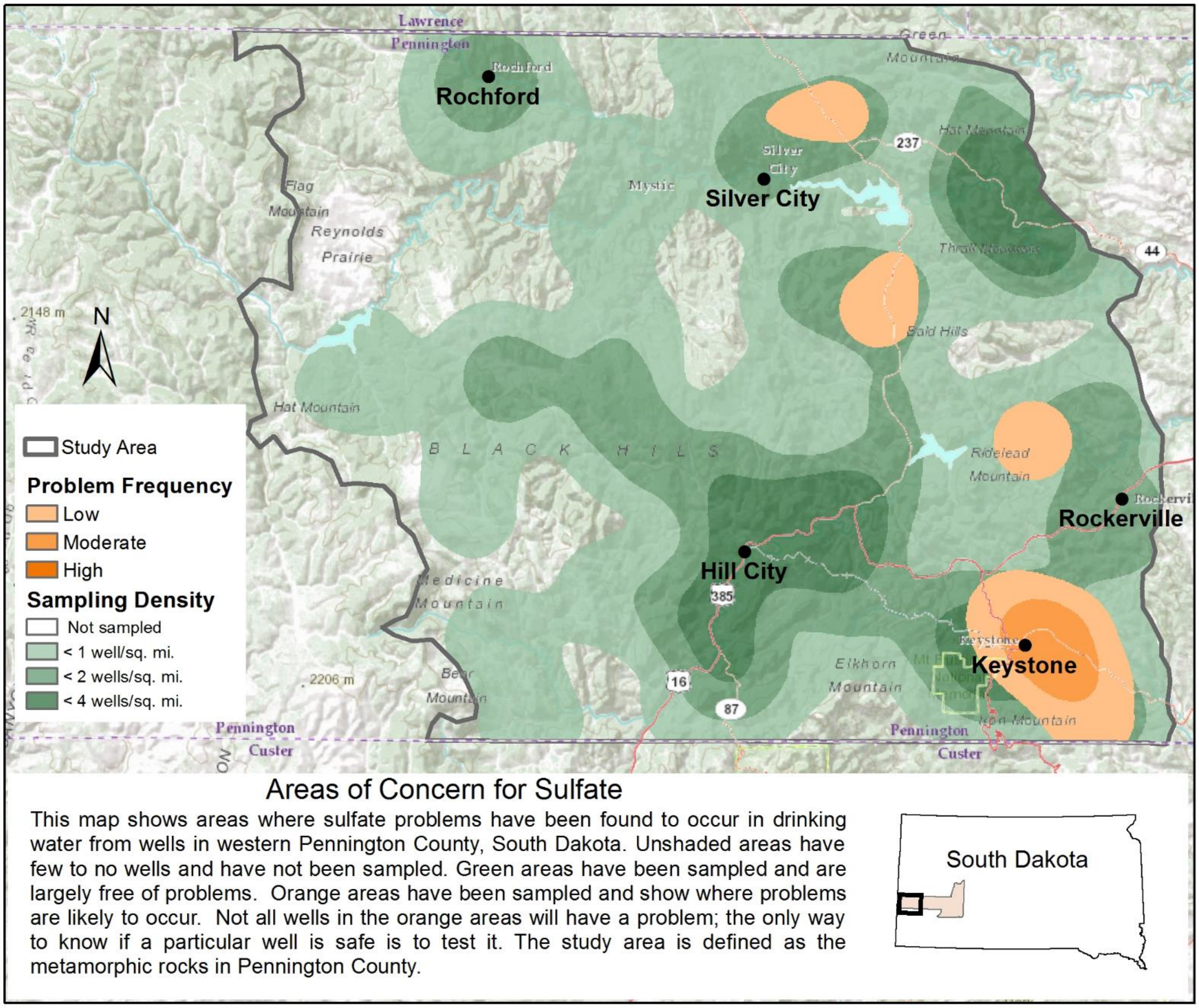
Private wells are not regulated by law and homeowners are not required to meet drinking water standards set by the EPA. However, homeowners are encouraged to test their water to ensure that it is healthy to drink and to protect their families.



This document describes the results of a study conducted by the South Dakota School of Mines and Technology in 2013 and funded by the West Dakota Water Development district to assess potential water quality issues in Pennington County.

To protect the privacy of homeowners who participated in the study, we do not plot individual well test locations on maps shown to the public. Instead, we selected the private and public wells with sulfate values greater than or equal to 50% of the EPA guideline and created a density map showing areas with more frequent sulfate problems. These regions are considered to represent a higher *risk* of sulfate issues. **It is important to understand that subsurface conditions can change rapidly from place to place, and not all wells in the shaded areas will have sulfate problems.** The only way to know whether a particular well has elevated sulfate levels is to test it. Homeowners in the shaded areas are especially encouraged to test their well water to ensure that it is healthy.

Sulfate does not appear to be a widespread problem in central Pennington County. Values on the eastern side of the study area tend to be higher, and the highest values are located along major faults. Several rock types that appear only on the eastern side of the map may play a role in the elevated sulfate values. For interactive maps showing sulfate and other contaminants in wells, click here.



Areas of Concern for Sulfate

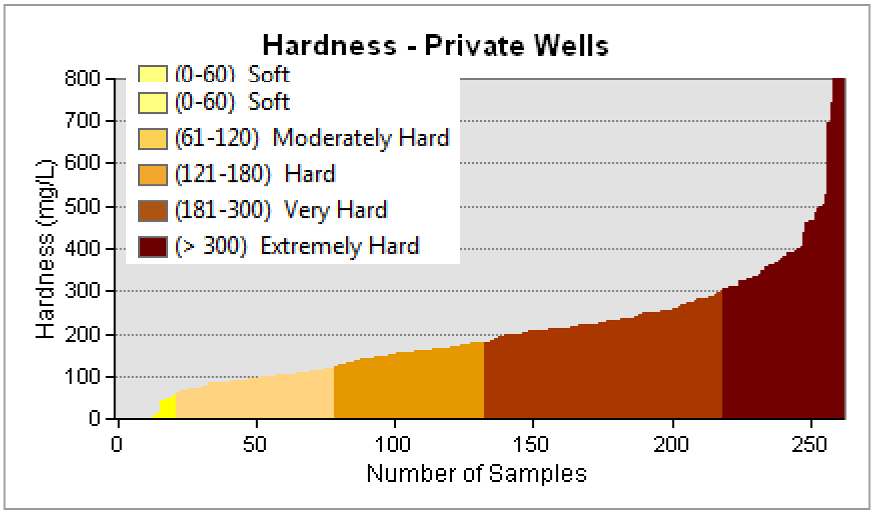
This map shows areas where sulfate problems have been found to occur in drinking water from wells in western Pennington County, South Dakota. Unshaded areas have few to no wells and have not been sampled. Green areas have been sampled and are largely free of problems. Orange areas have been sampled and show where problems are likely to occur. Not all wells in the orange areas will have a problem; the only way to know if a particular well is safe is to test it. The study area is defined as the metamorphic rocks in Pennington County.

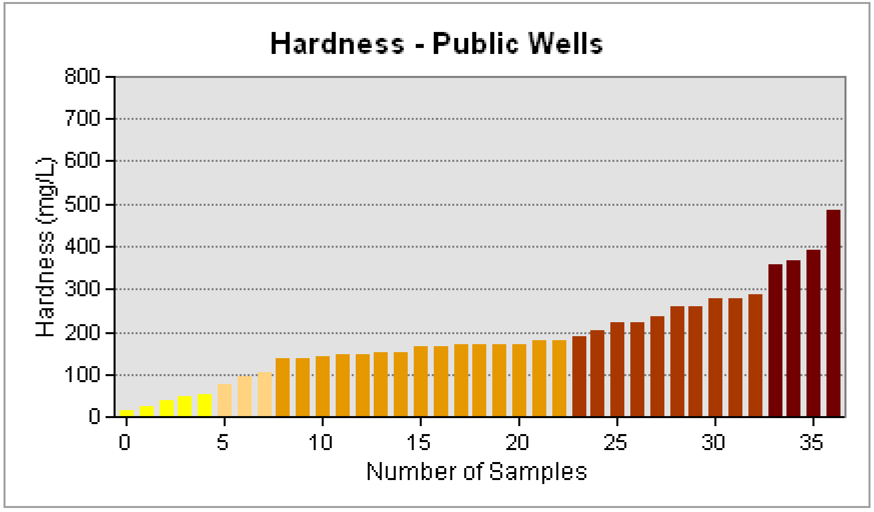
WDWDD-SDSMT Report Card for Hardness

Private Well Tests	
Number of wells	262
Number of tests	272
Earliest test date	5/5/2013
Latest test date	11/03/2015
Lowest value detected	0
Highest value detected (mg/L)	1130
Number of wells < 180 mg/L	
Percent wells > 180 mg/L	
Public Well Records	
Number of wells	37
Number of recorded tests	126
Earliest test date	4/12/1967
Latest test date	7/9/2007
Lowest value detected	**
Highest value detected (mg/L)	935
Number of wells < 180 mg/L	
Percent wells > 180 mg/L	

Hardness measures the quantity of dissolved minerals in water, particularly calcium and magnesium, which occur from dissolution as the water percolates through rock. Most people experience hardness in reference to the soap-consuming capacity of water. Hard water requires more soap to produce lather, can cause rings in bathtubs and sinks, and can also result in scale build-up in water lines and equipment. Water with hardness greater than about 180 mg/L generally is considered very hard water. Hardness is considered a nuisance but it is not a health hazard.

We sampled 262 private wells from 2013 to 2015 and compiled published data from 37 public wells to evaluate the hardness in well water in western Pennington County, SD. In some cases the wells were tested multiple times; we took the highest test in each case. We found that 41% of private wells and 31% of public wells had water with hardness higher than 180 mg/L. The maximum value detected was 1130 mg/L.

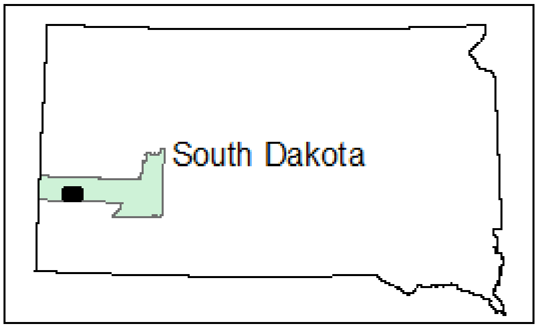




In the graphs, the height of the bar indicates the hardness, and the colors indicate the name of the ranges; several measurements extend beyond the top of the graph. Hard water is a common problem in the Black Hills.

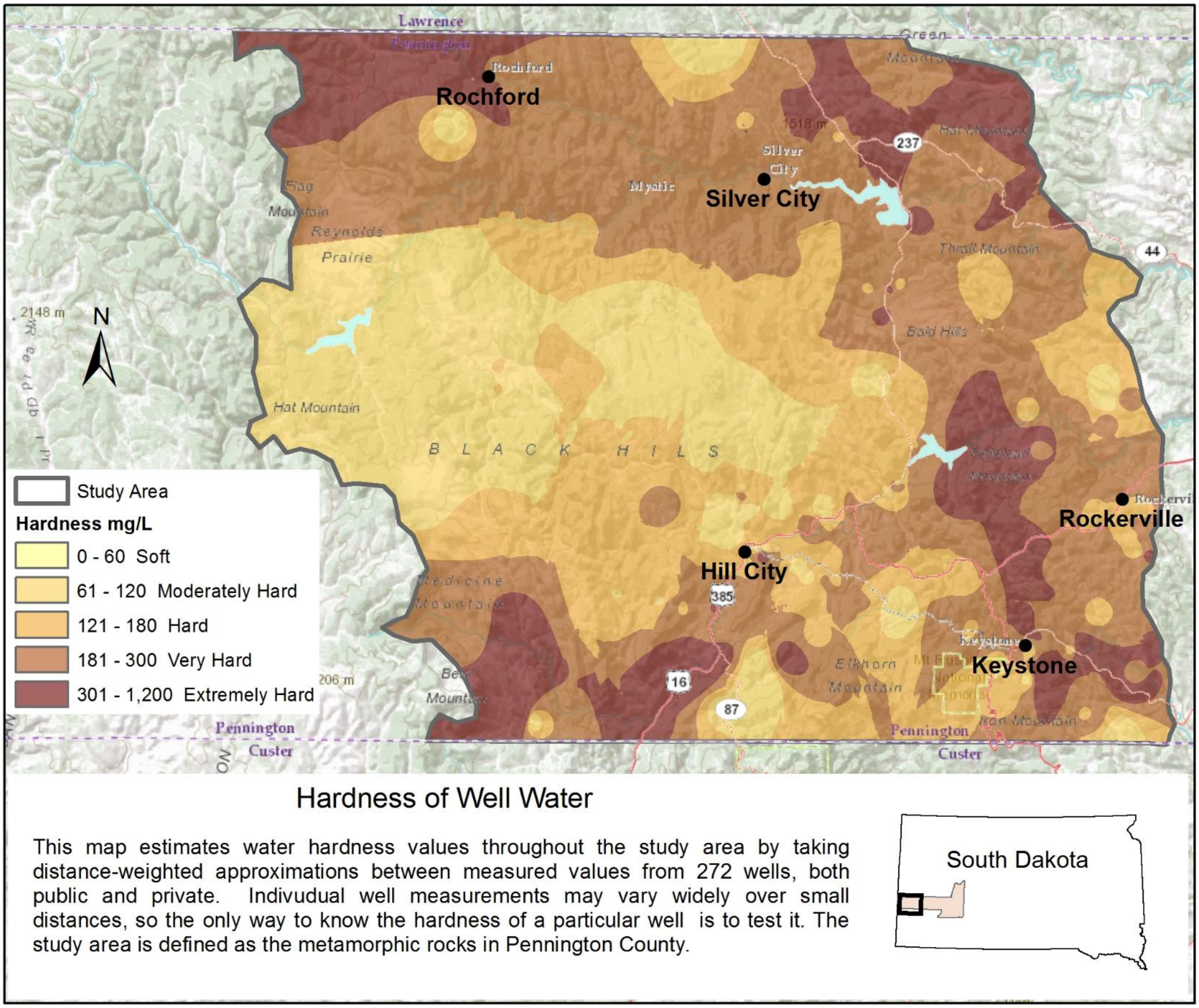
Public water systems generally do not treat hard water, but consumers often purchase water softening units for their homes to mitigate the problems caused by hard water.

Private wells are not regulated by law and homeowners are not required to meet drinking water standards set by the EPA. However, homeowners are encouraged to test their water to ensure that it is safe to drink and to protect their families.



To protect the privacy of homeowners who participated in the study, we do not plot individual well test locations on maps shown to the public. Instead, we used the sampling locations to estimate values between the measurements to create a continuous map of hardness--a process called interpolation. Because subsurface conditions can change rapidly from place to place, we used only a few of each sampling point's closest neighbors to derive distance-weighted estimates, and so the map has a rough appearance rather than smooth contours, but it is more true to the data in any one place. However, the only way to know the hardness of the water in a particular well is to test it.

The highest hardness values occur in the eastern side of the study area and in the southwest corner. High values appear to be associated with quartzite and greywacke metamorphic rocks and lower values with metamorphosed shales. For interactive maps showing these associations, click here.



Hardness of Well Water

This map estimates water hardness values throughout the study area by taking distance-weighted approximations between measured values from 272 wells, both public and private. Indivudual well measurements may vary widely over small distances, so the only way to know the hardness of a particular well is to test it. The study area is defined as the metamorphic rocks in Pennington County.

WDWDD-SDSMT Report Card for Coliform Bacteria

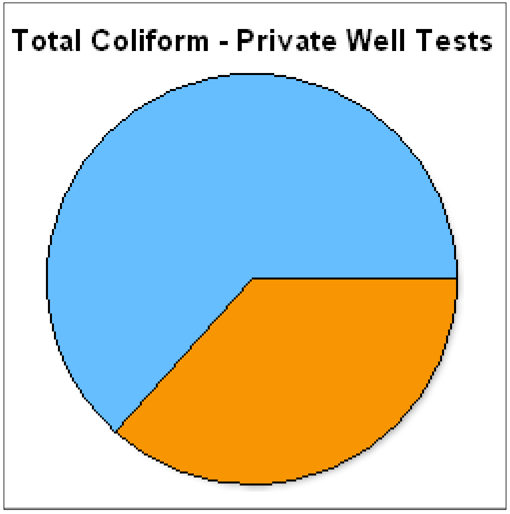
Private Well Tests	**Total col.**	**Fecal col.**
Number of wells	262	262
Number of tests	272	272
Earliest test date	5/5/2013	5/5/2013
Latest test date	11/03/2015	11/03/2015
Lowest value detected	Absent	Absent
Highest value detected	Present	Present
Number of wells with bacteria	97	17
Percent wells with bacteria	37%	6%
Public Well Records		
Number of wells	18	3
Number of recorded tests	32	5
Earliest test date	8/18/2001	6/1/2008
Latest test date	6/1/2013	6/1/2013
Lowest value detected	Absent	Present
Highest value detected	Present	Present
Number of wells with bacteria	17	3
Percent wells with bacteria	94%	100%

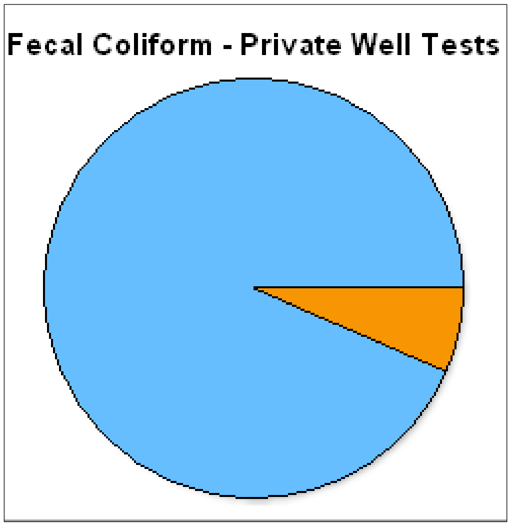
Coliform bacteria are naturally present in the environment. Some types, including *E. Coli* and fecal coliform, only come from human and animal feces. We tested for both total coliform and fecal coliform bacteria in well water. Total coliform is not considered a health threat in itself, but it is tested because it may be an indicator of whether other potentially harmful bacteria may be present. The presence of fecal coliform is considered an indication of contamination of the water by fecal waste from humans or animals, and may carry with it threats from other sources, such as viruses, and cause gastrointestinal illness such as diarrhea, vomiting, or cramps. There is no maximum contaminant guideline for bacteria; tests simply record whether bacteria are absent or present.

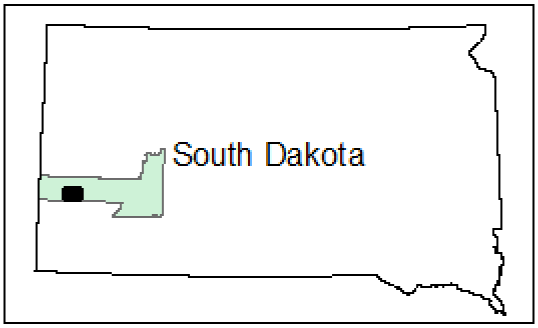
We sampled 262 private wells between 2013 and 2015, and compiled published data from public wells to evaluate the presence of coliform bacteria in well water in western Pennington County, SD. In some cases the wells were tested multiple times. We found that 37% of private wells tested positive for total coliform, and 6% of private wells tested positive for fecal coliform. In public wells, nearly all of the tests were positive; it appears that public wells may only report positive tests, so that the actual detection rate in public wells is impossible to determine.

Bacteria problems can be treated so that the water is safe to drink. Public water supplies are regulated by law. Although the tests are performed prior to treatment, water from public wells should be safe.

Private wells are not regulated by law and homeowners are not required to meet drinking water standards set by the EPA. However, homeowners are encouraged to test their water to ensure that it is safe to drink and to protect their families.



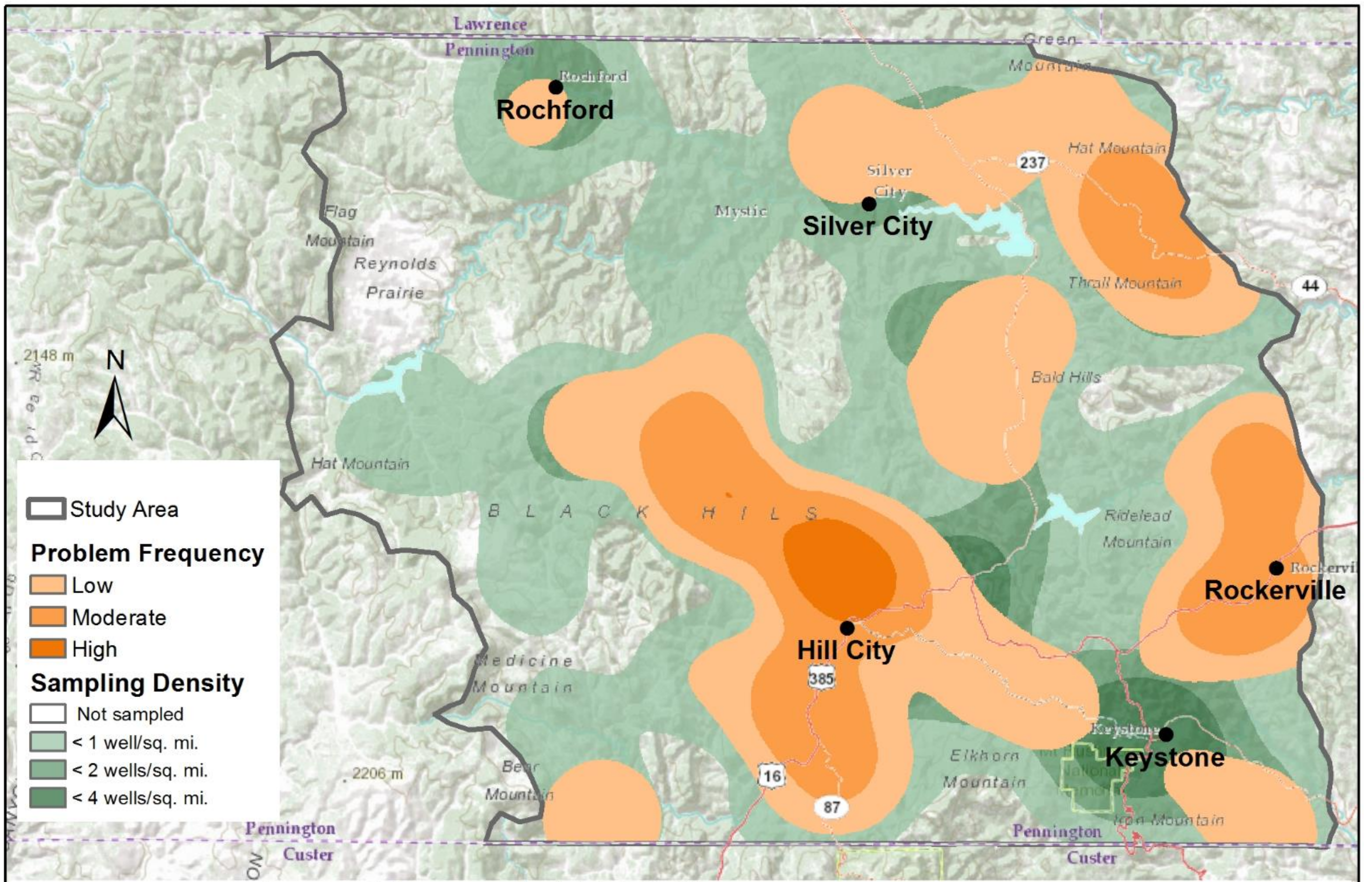




This document describes the results of a study conducted by the South Dakota School of Mines and Technology from 2013 to 2015 and funded by the West Dakota Water Development district to assess potential water quality issues in Pennington County.

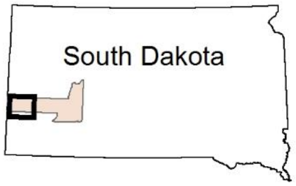
To protect the privacy of homeowners who participated in the study, we do not plot individual well test locations on maps shown to the public. Instead, we selected the private and public wells that tested positive for bacteria at least once and created a density map showing areas with a higher density of wells with bacteria. The total coliform higher-density areas are shown in the orange shades on the map; these represent regions where positive tests for total coliform are more frequent and periodic testing may be helpful to provide prompt warning of fecal coliform problems. The black contour lines enclose areas with more frequent occurrences of fecal coliform and represent areas of greater concern, where fecal contamination of groundwater may be occurring. **It is important to understand that subsurface conditions can change rapidly from place to place, and not all wells in the shaded areas will have bacteria problems.** The only way to know whether a particular well has coliform bacteria is to test it. Homeowners in the shaded areas are especially encouraged to test their well water to ensure that it is safe. Note that the fecal coliform areas of concern are associated with elevated densities of total coliform, as would be expected.

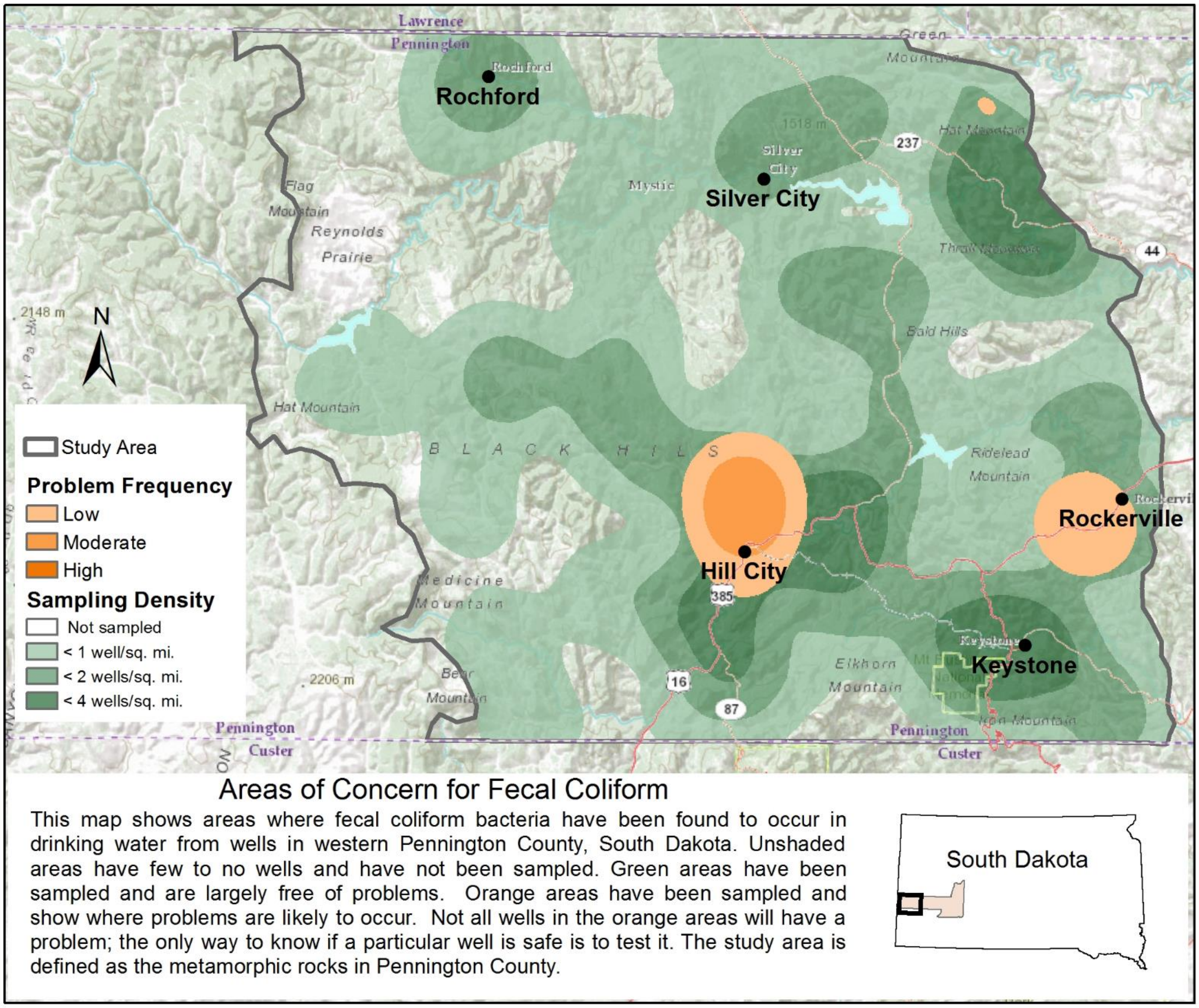
For interactive maps showing bacteria and other groundwater constituents, click here.



Areas of Concern for Total Coliform

This map shows areas where coliform bacteria have been found to occur in drinking water from wells in western Pennington County, South Dakota. Unshaded areas have few to no wells and have not been sampled. Green areas have been sampled and are largely free of problems. Orange areas have been sampled and show where problems are likely to occur. Not all wells in the orange areas will have a problem; the only way to know if a particular well is safe is to test it. The study area is defined as the metamorphic rocks in Pennington County.





Areas of Concern for Fecal Coliform

This map shows areas where fecal coliform bacteria have been found to occur in drinking water from wells in western Pennington County, South Dakota. Unshaded areas have few to no wells and have not been sampled. Green areas have been sampled and are largely free of problems. Orange areas have been sampled and show where problems are likely to occur. Not all wells in the orange areas will have a problem; the only way to know if a particular well is safe is to test it. The study area is defined as the metamorphic rocks in Pennington County.

Appendix B. Table of private well analyses

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Notes: nd: not detected; constituent below detection limit

IDNum	Sample Date	Hardness	Nitrate	Sulfate	Calcium	Magnesium	Arsenic	Iron	Fecal Col.	Total Col.
1	5/12/2013	164	3.6	18	44.6	12.9	0.032	nd	Absent	Absent
2	5/12/2013	157	0.1	14	44.6	11.1	0.025	nd	Absent	Absent
4	5/5/2013	348	1.9	110	92.3	28.5	nd	nd	Absent	Absent
7	5/12/2013	0	nd	59	0.0	0.0	0.043	0.7	Absent	Absent
8	5/5/2013	277	0.5	61	77.1	20.4	nd	nd	Absent	Absent
9	5/5/2013	127	0.7	35	34.1	10.1	nd	0.2	Absent	Absent
10	5/5/2013	330	0.1	43	76.7	33.6	nd	nd	Absent	Absent
13	5/12/2013	167	nd	98	45.0	13.3	nd	0.4	Absent	Absent
15	5/12/2013	271	5.0	24	74.4	20.7	nd	nd	Absent	Absent
16	5/12/2013	500	nd	192	120.0	48.3	nd	27.2	Absent	Absent
17	5/12/2013	336	nd	280	79.9	33.1	nd	13.3	Absent	Absent
18	5/12/2013	179	nd	38	36.6	21.4	0.007	2.3	Absent	Absent
19	5/12/2013	169	0.3	34	44.5	14.1	nd	0.3	Absent	Absent
20	5/12/2013	153	0.2	40	42.4	11.5	nd	0.3	Absent	Absent
21	9/8/2013	0	0.3	18	0.0	0.0	nd	0.1	Absent	Present
22	9/8/2013	93	0.5	63	25.7	6.9	nd	0.7	Absent	Present
23	9/8/2013	107	0.1	24	30.0	7.9	nd	nd	Absent	Present
24	9/8/2013	172	0.1	51	46.5	13.5	0.006	0.7	Absent	Absent
25	9/8/2013	90	nd	50	23.6	7.5	nd	7.4	Absent	Absent
26	9/8/2013	83	7.0	nd	21.6	7.0	0.036	0.2	Absent	Present
28	9/15/2013	193	nd	11	53.3	14.6	0.299	1.3	Absent	Absent
29	9/15/2013	229	nd	26	54.1	22.9	0.009	1.2	Absent	Present
30	9/15/2013	110	nd	52	27.9	9.8	0.159	12.3	Absent	Absent
31	9/15/2013	281	3.8	42	62.5	30.3	0.008	nd	Absent	Absent
32	9/15/2013	119	0.4	14	31.9	9.6	0.008	nd	Present	Present

Appendix B. Table of private well analyses

IDNum	Sample Date	Hardness	Nitrate	Sulfate	Calcium	Magnesium	Arsenic	Iron	Fecal Col.	Total Col.
33	9/15/2013	0	2.9	13	0.0	0.0	nd	nd	Absent	Absent
34	9/15/2013	222	0.6	17	63.3	15.5	0.007	nd	Absent	Present
35	9/15/2013	365	0.9	117	104.0	25.3	nd	0.2	Absent	Absent
36	9/13/2013	486	6.9	73	153.0	25.3	nd	0.1	Absent	Present
37	9/15/2013	131	0.9	23	36.0	9.9	nd	nd	Absent	Absent
38	9/15/2013	116	2.2	22	32.5	8.4	0.020	0.1	Absent	Absent
39	9/15/2013	102	0.8	21	28.1	7.7	0.014	nd	Absent	Present
40	9/15/2013	116	2.0	22	32.5	8.5	0.019	nd	Absent	Absent
41	9/15/2013	270	0.5	60	72.5	21.6	nd	nd	Absent	Absent
42	9/15/2013	236	0.2	37	60.7	20.4	nd	nd	Absent	Absent
43	9/8/2013	141	1.3	24	40.7	9.4	0.010	0.1	Absent	Present
44	5/12/2013	0	nd	44	0.0	0.0	nd	nd	Absent	Absent
45	9/22/2013	99	0.2	13	27.2	7.7	0.007	0.5	Absent	Present
46	9/22/2013	0	0.1	19	0.0	0.0	0.006	0.1	Absent	Present
47	9/22/2013	99	nd	29	26.4	8.0	nd	0.1	Absent	Present
48	9/22/2013	0	1.3	11	0.0	0.0	0.037	0.1	Absent	Present
49	9/22/2013	341	8.3	33	96.2	24.4	0.112	nd	Absent	Present
50	9/22/2013	152	0.2	36	40.4	12.4	nd	0.8	Absent	Present
51	9/22/2013	212	0.1	25	60.0	15.1	nd	0.1	Absent	Present
52	9/22/2013	266	1.1	33	72.2	20.8	nd	nd	Absent	Absent
53	9/29/2013	255	nd	45	56.0	28.1	0.034	0.5	Absent	Present
54	9/29/2013	148	nd	13	42.9	10.0	nd	0.1	Absent	Absent
55	9/29/2013	1130	nd	1410	216.0	143.0	nd	5.9	Absent	Absent
56	9/29/2013	101	0.2	nd	25.5	9.0	0.013	nd	Absent	Present
57	9/29/2013	162	nd	19	46.6	11.1	0.017	0.2	Absent	Absent
58	9/29/2013	505	nd	100	148.0	32.5	0.005	1.0	Absent	Present
59	9/29/2013	260	3.7	19	76.1	16.9	nd	nd	Present	Present
60	9/29/2013	136	0.2	nd	36.7	10.7	nd	0.2	Present	Present
61	10/13/2013	175	25.3	25	49.3	12.7	nd	0.3	Absent	Present
62	10/13/2013	52	0.9	nd	13.3	4.5	0.010	0.5	Present	Present

Appendix B. Table of private well analyses

IDNum	Sample Date	Hardness	Nitrate	Sulfate	Calcium	Magnesium	Arsenic	Iron	Fecal Col.	Total Col.
63	10/13/2013	115	14.3	22	31.0	9.1	0.008	0.6	Present	Present
64	10/13/2013	49	2.0	13	12.6	4.1	0.014	2.3	Present	Present
65	10/13/2013	170	2.0	29	51.4	10.1	0.006	1.8	Absent	Present
66	10/13/2013	144	0.1	43	35.6	13.4	nd	0.6	Absent	Present
67	10/13/2013	85	0.1	nd	24.0	6.2	0.006	2.8	Absent	Present
68	10/13/2013	72	0.2	nd	19.9	5.3	nd	nd	Absent	Present
69	10/13/2013	407	4.1	55	107.0	33.7	0.027	nd	Present	Present
70	10/13/2013	114	0.2	48	33.3	14.9	nd	0.8	Absent	Absent
71	10/20/2013	212	1.6	nd	57.4	16.8	nd	nd	Present	Present
72	10/20/2013	178	1.1	26	45.5	15.6	nd	nd	Absent	Absent
73	10/20/2013	198	0.9	29	50.0	17.9	nd	nd	Absent	Absent
74	10/20/2013	389	1.0	184	112.0	26.8	nd	0.1	Absent	Absent
75	10/20/2013	389	1.0	184	112.0	26.6	nd	0.2	Absent	Absent
76	10/20/2013	109	2.0	nd	30.7	7.8	nd	0.1	Present	Present
77	10/20/2013	215	29.6	24	56.4	18.0	nd	0.1	Present	Present
78	10/20/2013	92	0.6	14	24.3	7.5	nd	0.2	Present	Present
79	10/20/2013	401	0.4	48	101.0	36.0	0.010	0.1	Absent	Absent
80	10/20/2013	362	0.2	17	96.7	29.2	0.006	5.2	Absent	Absent
81	10/20/2013	139	0.2	38	38.0	10.7	nd	0.2	Absent	Present
82	10/20/2013	292	nd	42	85.1	19.2	0.013	70.2	Absent	Present
83	10/27/2013	196	0.2	25	49.0	18.0	0.015	0.1	Absent	Absent
84	10/27/2013	200	1.2	38	50.4	17.9	0.008	nd	Absent	Absent
85	10/27/2013	133	nd	42	33.1	12.3	0.025	nd	Absent	Absent
86	11/3/2013	0	nd	42	0.0	0.0	0.043	nd	Absent	Absent
87	3/17/2003			21	24.0	12.0	0.010	2.4		
87	11/3/2013	147	nd	nd	34.9	14.6	0.020	4.1	Absent	Absent
88	11/17/2013	744	17.4	73	195.0	62.7	0.011	nd	Present	Present
89	11/17/2013	118	0.7	40	31.3	9.8	0.008	nd	Present	Present
90	11/17/2013	209	0.2	38	53.1	18.5	nd	0.5	Absent	Absent
91	11/17/2013	203	nd	33	50.1	19.0	nd	0.3	Absent	Absent

Appendix B. Table of private well analyses

IDNum	Sample Date	Hardness	Nitrate	Sulfate	Calcium	Magnesium	Arsenic	Iron	Fecal Col.	Total Col.
92	11/17/2013	105	0.3	32	27.5	8.8	nd	nd	Absent	Absent
93	11/17/2013	6	0.3	37	1.4	0.0	0.009	nd	Absent	Absent
94	11/17/2013	232	0.2	79	61.1	19.2	nd	0.1	Absent	Present
95	11/17/2013	205	1.3	97	45.8	22.1	nd	nd	Absent	Present
96	11/17/2013	139	nd	33	36.4	11.8	nd	0.4	Absent	Absent
97	11/17/2013	248	0.1	58	65.2	20.7	nd	nd	Absent	Present
98	11/17/2013	158	nd	31	39.0	14.7	0.006	0.3	Absent	Present
99	11/17/2013	88	3.7	17	23.4	7.3	0.016	0.3	Absent	Present
100	3/23/2014	150	0.2	nd	42.0	11.0	nd	nd	Absent	Absent
101	3/23/2014	243	7.6	16	71.4	15.8	nd	nd	Absent	Present
102	3/23/2014	148	nd	nd	36.3	14.0	nd	nd	Absent	Absent
103	3/23/2014	193	5.5	17	56.2	12.7	nd	nd	Absent	Present
104	3/23/2014	163	nd	35	45.1	12.3	0.027	5.3	Absent	Absent
105	3/19/2015	0	nd	16	0.0	0.0	nd	0.2	Absent	Absent
105	3/23/2014	167	nd	14	19.8	7.8	0.031	8.0	Absent	Present
106	3/23/2014	197	0.3	nd	51.9	16.3	nd	nd	Absent	Present
107	3/23/2014	219	1.3	13	59.5	17.2	nd	nd	Absent	Absent
108	3/23/2014	158	nd	44	33.0	18.3	0.441	2.4	Absent	Absent
109	3/23/2014	300	nd	137	72.7	28.8	nd	17.5	Absent	Absent
110	3/23/2014	526	1.1	56	143.0	41.1	nd	nd	Absent	Absent
111	3/30/2014	212	nd	91	55.2	18.0	nd	nd	Absent	Absent
112	3/30/2014	275	nd	243	70.5	24.1	nd	0.3	Absent	Absent
113	3/30/2014	241	nd	67	57.8	23.4	nd	2.5	Absent	Absent
114	3/30/2014	105	1.5	16	28.4	8.3	0.010	nd	Absent	Present
115	4/6/2014	98	0.8	nd	25.2	8.5	nd	nd	Absent	Present
116	4/6/2014	134	3.3	12	35.6	11.1	nd	nd	Absent	Absent
117	4/6/2014	90	5.3	nd	22.9	7.9	nd	0.2	Absent	Present
118	4/6/2014	71	0.2	59	15.4	7.8	nd	2.3	Absent	Absent
119	4/6/2014	156	0.1	42	38.8	14.4	nd	nd	Absent	Absent
120	4/6/2014	44	0.6	nd	10.3	4.4	nd	0.1	Absent	Present

Appendix B. Table of private well analyses

IDNum	Sample Date	Hardness	Nitrate	Sulfate	Calcium	Magnesium	Arsenic	Iron	Fecal Col.	Total Col.
122	4/13/2014	110	nd	41	28.4	9.5	0.053	5.1	Absent	Absent
123	4/13/2014	113	0.2	24	30.3	9.0	nd	0.9	Absent	Absent
124	4/13/2014	100	nd	34	23.4	10.1	0.019	0.1	Absent	Absent
125	4/13/2014	64	1.3	12	15.2	6.4	nd	nd	Present	Present
126	4/13/2014	86	1.4	14	21.7	7.7	nd	nd	Absent	Present
127	4/13/2014	102	0.7	12	27.5	8.2	nd	0.2	Absent	Present
128	4/13/2014	333	nd	11	60.7	44.1	nd	nd	Absent	Absent
129	4/13/2014	295	nd	nd	65.0	32.3	nd	nd	Absent	Absent
130	9/21/2014	1030	nd	848	171.0	146.0	nd	0.4	Absent	Absent
131	9/21/2014	181	nd	125	38.8	20.4	nd	0.1	Absent	Absent
132	9/21/2014	251	2.2	44	59.4	24.9	nd	0.1	Absent	Absent
133	9/23/2014	236	3.1	nd	63.8	18.6	nd	0.1	Absent	Present
134	9/23/2014	94	1.0	nd	25.1	7.5	nd	0.2	Absent	Present
135	9/23/2014	204	0.8	nd	56.5	15.3	0.014	nd	Absent	Present
136	9/23/2014	84	1.4	nd	23.2	6.4	nd	0.1	Absent	Absent
137	9/23/2014	85	1.4	nd	23.4	6.5	nd	0.1	Absent	Absent
138	9/28/2014	90	1.1	23	20.2	9.6	nd	nd	Absent	Present
139	9/30/2014	221	nd	59	49.1	23.9	0.320	0.4	Absent	Absent
140	9/30/2014	82	0.1	37	20.6	7.5	nd	0.5	Absent	Present
141	9/30/2014	216	nd	112	54.8	19.2	0.005	3.7	Absent	Absent
142	9/30/2014	308	0.1	76	85.7	22.9	nd	nd	Absent	Present
143	10/5/2014	69	0.6	16	16.9	6.4	nd	0.2	Absent	Present
144	10/5/2014	883	31.5	136	226.0	77.5	nd	0.2	Absent	Present
145	10/5/2014	393	nd	124	90.3	40.7	nd	0.5	Absent	Absent
146	10/7/2014	211	nd	108	55.6	17.4	nd	0.1	Absent	Absent
146	10/7/2014	210	nd	110	55.6	172.0	nd	0.1	Absent	Absent
147	10/7/2014	165	nd	209	28.7	22.7	nd	9.1	Absent	Absent
148	10/14/2014	0	3.7	33	0.0	0.0	nd	nd	Absent	Absent
149	10/14/2014	87	0.1	38	21.4	8.2	nd	5.1	Absent	Absent
149	10/14/2014	86	nd	37	21.1	8.2	nd	5.9	Absent	Absent

Appendix B. Table of private well analyses

IDNum	Sample Date	Hardness	Nitrate	Sulfate	Calcium	Magnesium	Arsenic	Iron	Fecal Col.	Total Col.
150	10/14/2014	104	nd	39	24.4	10.6	nd	1.9	Absent	Absent
151	10/14/2014	122	nd	38	31.0	10.9	nd	1.5	Absent	Absent
151	10/14/2014	126	nd	39	32.3	11.1	nd	1.5	Absent	Absent
152	10/19/2014	104	4.4	29	26.8	8.9	0.006	nd	Absent	Absent
152	10/19/2014	105	4.5	27	26.9	9.3	0.006	nd	Absent	Absent
153	10/19/2014	106	0.3	38	26.2	9.9	0.005	0.7	Absent	Present
154	10/21/2014	97	0.2	28	24.0	9.0	nd	nd	Absent	Absent
155	10/21/2014	76	2.4	20	19.3	6.8	nd	nd	Absent	Present
156	10/21/2014	69	0.2	15	18.8	5.5	nd	0.1	Absent	Present
156	10/21/2014	65	0.2	16	17.3	5.3	nd	0.1	Absent	Present
157	10/26/2014	93	0.3	22	22.8	8.8	nd	nd	Absent	Absent
157	10/26/2014	93	0.4	22	23.1	8.7	nd	nd	Absent	Absent
158	10/26/2014	248	nd	91	51.9	28.7	nd	0.3	Absent	Absent
159	10/26/2014	57	0.6	nd	15.3	4.4	nd	0.2	Present	Present
160	10/28/2014	150	1.5	31	39.8	12.3	nd	nd	Absent	Present
160	10/28/2014	153	1.6	28	40.9	12.5	nd	nd	Absent	Present
161	10/28/2014	136	5.2	22	35.6	11.4	nd	0.1	Absent	Present
162	11/2/2014	311	nd	144	85.4	23.8	nd	0.5	Absent	Absent
162	11/2/2014	301	nd	144	80.0	24.4	nd	1.1	Absent	Absent
163	11/2/2014	359	0.3	137	71.5	43.9	nd	0.4	Absent	Absent
164	11/2/2014	265	17.9	45	73.9	19.5	nd	0.9	Absent	Present
165	11/2/2014	115	1.4	33	25.9	12.3	0.014	0.1	Absent	Present
166	11/2/2014	163	1.3	31	37.8	16.7	nd	0.2	Absent	Absent
167	11/2/2014	152	1.0	26	33.6	16.5	nd	nd	Absent	Absent
168	11/2/2014	205	1.1	42	44.3	22.9	nd	nd	Absent	Absent
169	11/2/2014	105	0.7	14	26.0	9.6	0.035	0.4	Absent	Absent
170	11/2/2014	122	0.6	44	26.5	13.5	0.007	0.1	Absent	Present
171	11/4/2014	183	0.1	41	41.5	19.4	nd	nd	Absent	Absent
172	11/4/2014	465	4.5	21	75.7	67.0	nd	nd	Absent	Present
173	11/4/2014	281	nd	78	53.6	35.9	nd	0.4	Absent	Absent

Appendix B. Table of private well analyses

IDNum	Sample Date	Hardness	Nitrate	Sulfate	Calcium	Magnesium	Arsenic	Iron	Fecal Col.	Total Col.
174	11/4/2014	180	0.1	41	40.5	19.2	nd	nd	Absent	Absent
175	11/18/2014	281	0.6	48	73.5	23.6	nd	nd	Absent	Absent
176	11/18/2014	360	9.3	42	96.8	28.8	nd	nd	Absent	Absent
177	11/18/2014	0	1.8	36	0.0	0.0	nd	nd	Absent	Absent
178	11/18/2014	207	0.3	38	45.7	22.5	nd	nd	Absent	Present
179	12/9/2014	252	9.5	30	63.9	22.5	nd	nd	Absent	Present
180	12/9/2014	253	1.0	36	63.9	22.7	nd	0.1	Absent	Present
181	12/9/2014	251	1.7	40	59.1	25.2	nd	nd	Absent	Present
182	12/9/2014	219	0.5	35	57.1	18.6	nd	nd	Absent	Absent
182	12/9/2014	219	0.3	33	59.8	17.0	nd	0.2	Absent	Present
183	12/2/2014	216	0.2	28	48.6	23.1	nd	nd	Absent	Absent
184	12/2/2014	13	1.5	38	0.0	2.6	nd	nd	Absent	Absent
185	12/2/2014	287	1.5	38	73.9	24.9	nd	nd	Absent	Absent
186	12/2/2014	325	6.5	55	69.1	37.0	nd	nd	Absent	Absent
187	12/2/2014	271	1.5	38	69.6	23.6	nd	nd	Absent	Absent
188	10/26/2014	213	0.3	55	43.4	25.5	nd	nd	Absent	Absent
189	12/2/2014	329	7.3	38	86.8	27.3	nd	nd	Absent	Absent
190	1/26/2015	221	3.1	26	61.8	16.2	nd	0.1	Absent	Absent
191	1/26/2015	467	17.6	58	149.0	22.8	nd	nd	Absent	Absent
192	1/26/2015	372	6.4	46	95.2	32.5	nd	nd	Absent	Absent
193	1/26/2015	200	0.8	35	47.3	19.9	nd	nd	Absent	Absent
194	1/26/2015	209	0.2	33	51.4	19.7	nd	0.4	Absent	Absent
195	1/26/2015	214	0.4	38	53.2	19.6	nd	nd	Absent	Absent
196	1/30/2015	173	nd	24	45.2	14.5	nd	nd	Absent	Present
197	1/30/2015	155	nd	24	38.4	14.4	nd	1.2	Absent	Absent
198	1/30/2015	0	0.4	27	0.0	0.0	nd	nd	Absent	Absent
199	2/3/2015	237	nd	48	54.4	24.6	nd	0.1	Absent	Absent
200	2/3/2015	233	nd	97	51.3	25.4	nd	nd	Absent	Present
201	2/3/2015	161	3.2	53	40.1	14.8	nd	nd	Absent	Absent
202	2/3/2015	221	0.2	67	49.8	23.6	nd	nd	Absent	Present

Appendix B. Table of private well analyses

IDNum	Sample Date	Hardness	Nitrate	Sulfate	Calcium	Magnesium	Arsenic	Iron	Fecal Col.	Total Col.
203	2/5/2015	171	1.9	24	48.5	12.2	nd	nd	Absent	Absent
204	2/5/2015	252	0.7	11	81.6	11.8	nd	nd	Absent	Absent
205	2/5/2015	310	nd	60	87.6	22.0	nd	1.1	Absent	Absent
206	2/5/2015	288	0.8	76	75.5	24.2	nd	0.2	Absent	Present
207	2/5/2015	142	0.1	14	35.6	13.0	nd	nd	Absent	Present
208	2/5/2015	225	0.4	31	61.1	17.7	nd	nd	Absent	Absent
209	2/23/2015	309	nd	75	91.3	19.7	nd	2.2	Absent	Absent
210	2/23/2015	697	11.5	41	218.0	37.2	nd	nd	Absent	Absent
211	2/23/2015	11	nd	217	2.5	1.1	nd	0.3	Absent	Absent
212	2/23/2015	0	0.1	38	0.0	0.0	nd	nd	Absent	Absent
213	2/23/2015	65	0.2	21	14.6	7.0	nd	nd	Absent	Absent
214	2/23/2015	310	nd	60	88.3	21.7	nd	0.3	Absent	Present
215	11/9/2014	462	0.1	243	124.0	36.9	nd	0.3	Absent	Absent
216	11/9/2014	248	0.1	44	54.8	27.0	nd	0.7	Absent	Absent
217	11/9/2014	260	0.1	95	67.9	21.9	nd	0.4	Absent	Absent
218	11/23/2014	239	nd	65	61.0	21.0	nd	0.7	Absent	Absent
219	3/5/2015	178	nd	24	46.1	15.1	nd	0.2	Absent	Absent
220	3/5/2015	180	nd	23	47.4	14.9	nd	nd	Absent	Absent
221	3/5/2015	175	0.5	24	44.6	15.4	nd	nd	Absent	Absent
222	3/5/2015	154	0.3	25	35.0	16.3	nd	nd	Absent	Absent
223	3/5/2015	190	nd	32	42.9	20.2	nd	0.1	Absent	Absent
224	3/16/2015	229	2.2	40	62.6	17.7	nd	nd	Absent	Absent
225	3/16/2015	183	nd	41	40.5	19.9	nd	nd	Absent	Absent
226	3/16/2015	206	0.2	37	47.1	21.5	nd	nd	Absent	Absent
227	3/16/2015	230	0.5	37	54.9	22.5	nd	nd	Absent	Absent
228	3/16/2015	198	0.2	38	44.8	20.9	nd	0.1	Absent	Absent
229	3/23/2015	228	1.0	40	54.2	22.6	nd	nd	Absent	Present
230	3/23/2015	205	1.0	39	48.1	20.7	nd	nd	Absent	Present
231	2/12/2015	161	nd	36	39.8	15.0	nd	0.7	Absent	Absent
232	2/12/2015	151	nd	37	36.3	14.8	nd	0.8	Absent	Absent

Appendix B. Table of private well analyses

IDNum	Sample Date	Hardness	Nitrate	Sulfate	Calcium	Magnesium	Arsenic	Iron	Fecal Col.	Total Col.
233	2/12/2015	326	nd	252	78.9	31.3	nd	2.9	Absent	Absent
234	3/1/2015	494	nd	165	102.0	58.1	nd	nd	Present	Present
235	3/1/2015	0	nd	88	0.0	0.0	nd	nd	Absent	Absent
236	3/1/2015	381	nd	42	93.1	36.1	nd	0.7	Absent	Absent
237	3/1/2015	214	0.1	20	55.2	18.6	nd	nd	Absent	Absent
238	3/1/2015	233	0.2	21	61.0	19.5	nd	nd	Absent	Present
239	3/1/2015	210	1.1	43	49.8	20.9	nd	0.1	Absent	Absent
240	3/10/2015	436	6.8	34	69.7	63.6	nd	nd	Present	Present
241	3/10/2015	375	3.6	28	66.3	50.8	nd	nd	Absent	Absent
242	3/10/2015	326	0.2	16	38.9	55.7	nd	0.1	Absent	Absent
243	3/10/2015	391	4.3	33	82.3	45.0	nd	nd	Absent	Absent
244	3/19/2015	0	nd	224	0.0	0.0	0.006	0.4	Absent	Absent
245	3/19/2015	71	0.7	20	17.5	6.6	nd	0.1	Absent	Absent
246	3/19/2015	41	1.1	nd	11.5	3.0	0.008	nd	Absent	Absent
247	3/19/2015	224	5.5	12	63.1	16.1	nd	nd	Absent	Absent
248	3/23/2015	240	nd	50	73.8	13.4	nd	nd	Absent	Absent
248	3/23/2015	250	nd	50	77.6	13.7	nd	nd	Absent	Absent
249	4/7/2015	284	0.8	42	67.8	27.8	nd	nd	Absent	Absent
250	6/18/2015	200	nd	98	38.7	25.1	nd	nd	Absent	Absent
251	6/18/2015	231	0.2	82	40.0	31.7	nd	0.1	Absent	Absent
252	6/18/2015	361	0.3	91	86.6	35.2	nd	0.7	Absent	Present
253	6/18/2015	112	0.1	33	26.6	11.2	nd	0.1	Absent	Absent
254	6/19/2015	142	nd	18	36.4	12.4	nd	1.1	Absent	Absent
255	6/16/2015	181	1.8	12	45.8	16.2	0.074	nd	Absent	Absent
256	9/22/2015	46	nd	67	7.6	6.5	nd	0.1	Absent	Absent
257	9/22/2015	250	0.1	40	63.4	22.3	nd	nd	Absent	Absent
258	10/20/2015	89	nd	68	20.8	9.1	nd	7.1	Absent	Present
259	10/20/2015	145	nd	35	38.4	11.8	nd	0.7	Absent	Present
260	10/26/2015	66	0.2	nd	16.7	5.8	nd	0.2	Absent	Absent
261	10/27/2015	62	0.4	nd	15.9	5.6	0.007	1.1	Absent	Absent

Appendix B. Table of private well analyses

IDNum	Sample Date	Hardness	Nitrate	Sulfate	Calcium	Magnesium	Arsenic	Iron	Fecal Col.	Total Col.
262	10/26/2015	154	1.4	71	34.9	16.2	nd	0.1	Absent	Present
263	10/26/2015	77	2.0	19	19.4	6.9	nd	nd	Absent	Absent
264	10/26/2015	84	0.1	62	16.6	10.3	nd	4.6	Absent	Absent
265	10/26/2015	161	nd	143	38.0	16.0	nd	2.1	Absent	Present
266	11/3/2015	96	0.8	24	25.0	8.1	0.088	0.1	Absent	Absent
267	11/3/2015	72	1.2	24	17.0	7.2	0.071	2.6	Absent	Absent
268	11/3/2015	308	nd	38	71.4	31.5	0.031	2.0	Absent	Absent
269	10/6/2015	127	nd	146	22.2	17.2	nd	0.1	Absent	Present

Notes:
nd: not detected; constituent below detection limit

Appendix C. List of public wells

IDNum	Well Identifer	Formation	Source	Geology Source	Longitude	Latitude
500	USGS_site_no__435230103254501	Xgw2	NWIS	Quad map	-103.42963	43.88776
501	USGS_site_no__435230103254502	Xgw2	NWIS	Redden et al	-103.42963	43.87499
503	USGS_site_no__435242103261801	Xgw2	NWIS	Quad map	-103.44047	43.87610
504	USGS_site_no__435300103265001	Xgw1	NWIS	Quad map	-103.45074	43.88332
506	USGS_site_no__435302103270501	Xgw1	NWIS	Quad map	-103.45139	43.88389
507	USGS_site_no__435327103351601	Xtg	NWIS	Quad map	-103.58825	43.89082
508	USGS_site_no__435334103233401	Xbs2	NWIS	Quad map	-103.39185	43.89415
509	USGS_site_no__435338103285801	Xbs1	NWIS	Quad map	-103.48325	43.89388
510	USGS_site_no__435342103285801	Xbs1	NWIS	Quad map	-103.48325	43.89499
511	USGS_site_no__435356103320601	Xgwd	NWIS	Quad map	-103.53547	43.89888
512	USGS_site_no__435404103245501	Xgw2	NWIS	Quad map	-103.41575	43.90110
513	USGS_site_no__435408103243201	Xgw2	NWIS	Quad map	-103.40936	43.90221
514	USGS_site_no__435428103224101	Xgw2	NWIS	Quad map	-103.37852	43.90776
516	USGS_site_no__435515103313001	Xgwd	NWIS	Quad map	-103.52547	43.92082
517	USGS_site_no__435537103342501	Xgw1	NWIS	Quad map	-103.57408	43.92693
518	USGS_site_no__435549103342001	Xgw1	NWIS	Quad map	-103.56325	43.93388
519	USGS_site_no__435602103340201	Xgw3	NWIS	Quad map	-103.56770	43.93388
520	USGS_site_no__435616103344801	Xbs2	NWIS	Quad map	-103.58047	43.93776
523	USGS_site_no__435630103340601	Xgw1	NWIS	Quad map	-103.56880	43.94165
524	USGS_site_no__435637103321201	Xgw3	NWIS	Quad map	-103.53714	43.94360
525	USGS_site_no__435642103233401	Xgw2	NWIS	Quad map	-103.39324	43.94499
526	USGS_site_no__435645103211801	Xqc	NWIS	Quad map	-103.41824	43.98943
532	USGS_site_no__435709103370801	Xz	NWIS	Quad map	-103.61936	43.95248
535	USGS_site_no__435837103244601	Xcq	NWIS	Quad map	-103.41325	43.97693
536	USGS_site_no__435848103283301	Xqc	NWIS	Redden et al	-103.47630	43.97999
537	USGS_site_no__435916103342201	Xo	NWIS	Quad map	-103.57325	43.98776
803	Camp Judson 12965 Old Hill City Road	Xgw1	SDDENR	Quad map	-103.46511	43.90372
804	Circle B Ranch 22735 Hwy 385	Xss	SDDENR	Quad map	-103.52945	44.10447

Appendix C. List of public wells

805	Creekside Country Resort 12647 S Highway 16	Xqc	SDDENR	Quad map	-103.51484	43.94682
806	Crooked_Creek_Campground_I 24184 U.S. 385	Xts	SDDENR	Quad map	-103.59209	43.89922
807	Crooked_Creek_Campground_II 24184 U.S. 385	Xts	SDDENR	Quad map	-103.59209	43.89922
809	Deerfield Lake Resort 11321 Gillette Prairie Rd	Xts	SDDENR	Redden et al	-103.79049	44.00307
810	Deerfield Lake Trailer Court 11321 Gillette Prair*	Xts	SDDENR	Redden et al	-103.79049	44.00307
812	Harney Camp, Inc. 24345 SD Hwy 87	Xz	SDDENR	Quad map	-103.57895	43.87788
813	Hill City	Xbs2	SDDENR	Quad map	-103.57465	43.93338
814	Hillside Country Cabins 13315 U.S. 16	Xgw2	SDDENR	Quad map	-103.39933	43.94141
815	24105 U.S. 16 Alt Holy Smoke Cabins	Xif	SDDENR	Quad map	-103.43988	43.91404
816	24105 U.S. 16 Alt Holy Smoke Restaurant	Xif	SDDENR	Quad map	-103.43988	43.91404
819	Horse_Creek_Inn_Restaurant_Well 23570 U.S. 385	Xgw1	SDDENR	Quad map	-103.49172	43.98789
820	Horse_Thief_Campground_Resort 24391 S Dakota 87	Xgw2	SDDENR	Redden et al	-103.58436	43.86942
821	Kemps_Kamp_East 1022 Old Hill City Rd	Xcq	SDDENR	Quad map	-103.44646	43.90176
822	Keystone	Xgw2	SDDENR	Quad map	-103.42434	43.89263
824	Moonshine_Gulch_Saloon 22635 N Rochford Rd	Xby	SDDENR	Redden et al	-103.72015	44.12470
825	Mt_View_Lodge 12654 U.S. 16	Xgwd	SDDENR	Quad map	-103.51325	43.94724
827	NPS_Mt_Rushmore 13000 Hwy 244 Bldg 31 Ste 1	Xgw1	SDDENR	Quad map	-103.45320	43.87537
828	Palmer_Gulch_Lodge 12620 S Dakota 244	Xgwd	SDDENR	Quad map	-103.53680	43.90118
829	Pine_Rest_Cabins 24063 U.S. 385	Xo	SDDENR	Quad map	-103.58585	43.91772
832	Robins_Roost_Cabins 12630 Robins Roost Rd	Xz	SDDENR	Quad map	-103.53472	43.94405
835	Rushmore_Tramway 203 Cemetery Rd	Xgw2	SDDENR	Quad map	-103.42647	43.88733
837	Spring_Creek_Inn 23900 U.S. 385	Xgw3	SDDENR	Quad map	-103.55154	43.93872
838	The_Quails_Crossing 24060 U.S. 385	Xbs2	SDDENR	Quad map	-103.58480	43.91782
839	The Rafter J Bar Ranch 12325 Rafter J-Bar Rd	Xgw3	SDDENR	Quad map	-103.59170	43.89141
840	Three_Forks_Campground_RV_Park/Timber Lodge Retre*	Xgw3	SDDENR	Quad map	-103.51350	43.95238
944	002S06E04CACD	Qal	SDGS	Quad map	-103.41201	43.90107
947	002S06E04CADC	Qal	SDGS	Quad map	-103.41077	43.90157
949	002S06E04CDAB	Xgw	SDGS	Quad map	-103.41128	43.90071
952	002S06E04DBCB	Qal	SDGS	Quad map	-103.40853	43.90193
955	002S06E08AACD	Qal	SDGS	Quad map	-103.42228	43.89376

Appendix C. List of public wells

969	002S06E08DDAC	Qal	SDGS	Quad map	-103.42162	43.88527
972	002S06E09BBCA	Qal	SDGS	Quad map	-103.41698	43.89511
972	002S06E09BBBC	Qal	SDGS	Quad map	-103.41819	43.89604
974	002S06E09BBCD	Qal	SDGS	Quad map	-103.41789	43.89395
5034	USGS_site_no_435334103421801	Xsic	NWIS	Redden et al	-103.70500	43.89278
5040	USGS_site_no_435446103381601	Qal	NWIS	Redden et al	-103.63778	43.91278
5050	USGS_site_no_435642103433701	Xts	NWIS	Redden et al	-103.72694	43.94500
5054	USGS_site_no_435657103221801	Xgw2	NWIS	Redden et al	-103.37167	43.94917
5062	USGS_site_no_435833103381601	Xbs2	NWIS	Redden et al	-103.63778	43.97583
5064	USGS_site_no_435837103204201	Xqs	NWIS	Redden et al	-103.34500	43.97694
5077	USGS_site_no_435916103414201	Xs	NWIS	Redden et al	-103.69500	43.98778
5078	USGS_site_no_435916103463301	Xts	NWIS	Redden et al	-103.77583	43.98778
5085	USGS_site_no_435927103494801	Xgw3	NWIS	Redden et al	-103.83000	43.99083
5101	USGS_site_no_440003103301001	Qal	NWIS	Redden et al	-103.50278	44.00083
5102	USGS_site_no_440007103383401	Xts	NWIS	Redden et al	-103.64278	44.00195
5103	USGS_site_no_440010103422801	Xs	NWIS	Redden et al	-103.70778	44.00278
5115	USGS_site_no_440115103465101	Xs	NWIS	Redden et al	-103.78083	44.02083
5133	USGS_site_no_440223103321701	Xgw1	NWIS	Redden et al	-103.53806	44.03972
5138	USGS_site_no_440248103321601	Xgw1	NWIS	Redden et al	-103.53778	44.04667
5154	USGS_site_no_440339103391401	Xs	NWIS	Redden et al	-103.65389	44.06083
5157	USGS_site_no_440350103243401	Qal	NWIS	Redden et al	-103.40945	44.06389
5165	USGS_site_no_440433103481801	Xs	NWIS	Redden et al	-103.80500	44.07583
5169	USGS_site_no_440444103262601	Xqs	NWIS	Redden et al	-103.44055	44.07889
5173	USGS_site_no_440451103383801	Xs	NWIS	Redden et al	-103.64389	44.08083
5175	USGS_site_no_440456103255701	Xmt	NWIS	Redden et al	-103.43250	44.08222
5176	USGS_site_no_440456103255702	Xmt	NWIS	Redden et al	-103.43250	44.08222
5177	USGS_site_no_440458103261601	Xmt	NWIS	Redden et al	-103.43777	44.08278
5182	USGS_site_no_440509103334601	Qal	NWIS	Redden et al	-103.56277	44.08583
5200	USGS_site_no_440550103255801	Xeq	NWIS	Redden et al	-103.43278	44.09722
5201	USGS_site_no_440556103304301	Xbo	NWIS	Redden et al	-103.51195	44.09889
5204	USGS_site_no_440607103440901	Xs	NWIS	Redden et al	-103.73583	44.10194

Appendix C. List of public wells

5223	USGS_site_no_440722103430401	Xby	NWIS	Redden et al	-103.71778	44.12278
5233	USGS_site_no_440755103451801	Xs	NWIS	Redden et al	-103.75500	44.13194
5235	USGS_site_no_440759103361501	Xs	NWIS	Redden et al	-103.60416	44.13306
5276	USGS_site_no_435312103264801	Xqc	NWIS	Redden et al	-103.44666	43.88667

Notes:
NWIS: USGS National Water Information Service
SDDENR: South Dakota Department of Environment and Natural Resources
SDGS: South Dakota Geological Survey
Quad map: Geologic unit determined from 1:24,000 geologic quadrangle map
Redden et al.: Geologic unit determined from 1:200,000 map of Redden and DeWitt (2008)

Appendix D. Table of public well analyses

Appendix D. Table of public well analysis

All constituents reported in mg/L

IDNum	Date	Hardness	Nitrate	Sulfate	Calcium	Magnesium	Arsenic	Iron
500	8/1/1961	nd	*	*	*	*	*	nd
500	4/12/1967	140	nd	12.0	33.0	11.0	*	0.26
501	9/19/1967	150	0.1	23.0	38.0	*	*	4.10
501	9/22/1967	170	nd	31.0	43.0	15.0	*	1.00
503	5/15/1967	22	0.0	12.0	6.0	1.7	*	0.05
503	6/4/2013	*	*	*	*	*	0.007	*
503	6/4/2013	*	*	*	*	*	0.007	*
503	8/15/2013	*	*	*	*	*	0.001	*
503	8/15/2013	*	*	*	*	*	0.001	*
503	6/18/2014	*	*	*	*	*	0.008	*
504	7/17/1967	36	5.5	7.0	11.0	2.2	*	0.08
504	1/23/2001	37	*	6.3	10.5	2.5	0.014	*
504	4/11/2001	35	*	6.6	9.9	2.4	0.013	*
504	6/12/2001	37	*	6.9	10.6	2.6	0.014	*
504	7/19/2001	37	*	6.9	10.5	2.6	0.013	*
504	5/1/2012	*	*	*	*	*	0.014	*
504	5/1/2012	*	*	*	*	*	0.014	*
504	6/5/2012	*	*	*	*	*	0.014	*
504	6/5/2012	*	*	*	*	*	0.014	*
504	7/10/2012	*	*	*	*	*	0.015	*
504	7/10/2012	*	*	*	*	*	0.015	*
504	8/14/2012	*	*	*	*	*	0.015	*
504	8/14/2012	*	*	*	*	*	0.015	*
504	5/7/2013	*	*	*	*	*	0.014	*
504	6/4/2013	*	*	*	*	*	0.015	*
504	7/9/2013	*	*	*	*	*	0.015	*
504	8/6/2013	*	*	*	*	*	0.015	*
504	5/15/2014	*	*	*	*	*	0.014	*
504	6/18/2014	*	*	*	*	*	0.018	*
504	7/16/2014	*	*	*	*	*	0.015	*
504	8/26/2014	*	*	*	*	*	0.014	*
504	12/9/2014	*	*	*	*	*	0.014	*
504	2/18/2015	*	*	*	*	*	0.015	*
506	5/1/2012	*	*	*	9.2	*	0.028	*
506	5/1/2012	*	*	*	*	*	0.028	*
506	6/5/2012	*	*	*	9.0	*	0.026	*
506	6/5/2012	*	*	*	*	*	0.026	*

IDNum	Date	Hardness	Nitrate	Sulfate	Calcium	Magnesium	Arsenic	Iron
506	7/10/2012	*	*	*	*	*	0.027	*
506	7/10/2012	*	*	*	9.1	2.3	0.027	*
506	8/14/2012	*	*	*	9.0	2.3	0.027	*
506	8/14/2012	*	*	*	*	*	0.028	*
506	5/7/2013	*	*	*	*	*	0.023	*
506	6/4/2013	*	*	*	*	*	0.025	*
506	7/9/2013	*	*	*	*	*	0.029	*
506	8/6/2013	*	*	*	*	*	0.026	*
506	5/15/2014	*	*	*	*	*	0.029	*
506	6/18/2014	*	*	*	*	*	0.026	*
506	7/16/2014	*	*	*	*	*	0.028	*
506	8/26/2014	*	*	*	*	*	0.028	*
506	12/9/2014	*	*	*	*	*	0.026	*
506	2/18/2015	*	*	*	*	*	0.024	*
507	6/11/1979	*	*	*	*	*	0.103	nd
507	6/11/1979	367	*	52.0	104.0	26.0	0.103	nd
508	6/10/1979	*	*	*	*	*	0.003	nd
508	6/10/1979	104	*	5.0	25.0	10.0	0.003	nd
509	6/10/1979	*	*	*	*	*	0.007	nd
509	6/10/1979	53	*	nd	15.0	3.8	0.007	nd
510	6/6/2013	*	*	*	*	*	0.084	*
510	6/6/2013	*	*	*	20.2	5.1	0.084	*
510	8/15/2013	*	*	*	*	*	0.178	*
510	8/15/2013	*	*	*	19.7	5.2	0.178	*
510	6/18/2014	*	*	*	*	*	0.062	*
511	6/12/1979	170	*	14.0	40.0	17.0	0.012	*
511	6/12/1979	*	*	*	*	*	0.012	nd
512	5/15/1967	484	*	345.0	108.0	52.0	*	*
512	5/15/1967	*		*	*	*	*	0.48
512	5/15/1967	480	nd	345.0	108.0	52.0	*	0.48
513	9/22/1976	*	3.2	*	*	*	*	nd
513	9/22/1976	258	3.2	114.0	59.6	26.6	*	nd
513	12/10/1979	*	1.3	*	*	*	*	nd
513	12/10/1979	245	1.3	98.0	57.2	24.9	*	nd
513	2/11/1980	*	1.2	*	*	*	nd	*
513	2/11/1980	*	1.2	*	*	*	nd	*
513	2/17/1982	*	1.4	*	*	*	*	0.10
513	2/17/1982	243	1.4	107.0	56.0	25.0	*	0.10
514	10/22/1975	*	nd	*	*	*	*	nd
514	10/22/1975	150	nd	49.8	39.5	13.1	*	nd
514	1/17/1978	*	0.3	*	*	*	*	0.07
514	1/17/1978	150	0.3	46.0	38.5	13.3	*	0.07

Appendix D. Table of public well analyses

IDNum	Date	Hardness	Nitrate	Sulfate	Calcium	Magnesium	Arsenic	Iron
514	2/15/1979	*	0.4	*	*	*	0.001	*
514	2/15/1979	*	0.4	*	*	*	0.001	*
514	5/3/1979	*	*	*	*	*	nd	0.07
514	8/12/1980	*	0.5	*	*	*	*	0.03
514	8/12/1980	160	0.5	54.0	43.0	14.0	*	0.03
514	2/9/1982	*	0.5	*	*	*	nd	*
514	2/9/1982	*	0.5	*	*	*	nd	*
514	1/12/1983	*	0.8	*	*	*	*	nd
514	1/12/1983	180	0.8	58.0	48.0	17.0	*	nd
516	6/12/1979	*	*	*	*	*	0.006	0.01
516	6/12/1979	147	*	19.0	34.0	15.0	0.006	0.01
517	2/3/1966	*	1.7	*	*	*	*	nd
517	2/3/1966	190	1.7	30.0	50.5	15.6	*	nd
517	6/1/1971	*	1.7	*	*	*	*	0.02
517	6/1/1971	148	1.7	28.0	43.2	9.7	*	0.02
517	8/21/1974	*	0.3	*	*	*	*	0.04
517	8/21/1974	149	0.3	25.5	39.9	12.0	*	0.04
517	5/6/1976	*	nd	*	*	*	*	*
517	5/6/1976	*	nd	*	*	*	*	*
517	5/6/1976	*	1.0	*	*	*	*	0.03
517	5/6/1976	143	1.0	27.2	37.0	12.4	*	0.03
517	12/5/1977	*	0.3	*	*	*	0.003	*
517	12/5/1977	*	0.3	*	*	*	0.003	*
517	11/18/1981	*	0.3	*	*	*	*	0.08
517	11/18/1981	152	0.3	16.0	36.0	15.0	*	0.08
518	8/21/1974	*	0.5	*	*	*	*	0.08
518	8/21/1974	96	0.5	*	26.1	7.5	*	0.08
519	5/28/1957	*	0.8	*	*	*	*	0.05
519	5/28/1957	84	0.8	17.3	25.6	4.9	*	0.05
519	6/1/1971	*	0.1	*	*	*	*	1.80
519	6/1/1971	76	0.1	22.9	20.8	5.8	*	1.80
519	5/10/1976	*	nd	*	*	*	*	0.06
519	5/10/1976	144	nd	28.7	37.2	12.5	*	0.06
519	11/18/1981	*	0.2	*	*	*	*	nd
519	11/18/1981	76	0.2	25.0	19.0	7.0	*	nd
520	6/11/1979	*	*	*	*	*	0.002	0.01
520	6/11/1979	76	*	27.0	20.0	6.3	0.002	0.01
523	12/5/1977	*	0.3	*	*	*	0.003	*
523	12/5/1977	*	0.3	*	*	*	0.003	*
523	3/25/1980	*	0.4	*	*	*	*	nd
523	3/25/1980	171	0.4	20.0	42.0	16.0	*	nd
523	3/10/1981	*	0.5	*	*	*	0.001	*

Appendix D. Table of public well analyses

IDNum	Date	Hardness	Nitrate	Sulfate	Calcium	Magnesium	Arsenic	Iron
523	3/10/1981	*	0.5	*	*	*	0.001	*
524	7/9/2007	237	0.4	53.3	59.7	21.5	*	0.03
525	6/10/1979	*	*	*	*	*	0.003	0.01
525	6/10/1979	171	*	7.0	54.0	8.8	0.003	0.01
526	6/8/1979	135	*	6.0	38.0	9.8	0.005	nd
526	6/8/1979	*	*	*	*	*	0.005	nd
532	10/9/1979	*	0.2	*	*	*	*	0.85
532	10/9/1979	220	0.2	56.0	57.1	19.8	*	0.85
532	2/7/1980	*	1.5	*	*	*	nd	*
532	2/7/1980	*	1.5	*	*	*	nd	*
532	2/9/1982	*	0.1	*	*	*	*	2.20
532	2/9/1982	180	0.1	62.0	48.0	17.0	*	2.20
532	2/10/1983	*	0.1	*	*	*	0.002	*
532	2/10/1983	*	0.1	*	*	*	0.002	*
535	6/10/1979	*	*	*	*	*	nd	nd
535	6/10/1979	202	*	60.0	58.0	14.0	nd	nd
536	6/10/1979	*	*	*	*	*	0.002	nd
536	6/10/1979	15	*	nd	4.5	0.8	0.002	nd
537	6/11/1979	*	*	*	*	*	0.002	0.02
537	6/11/1979	46	*	7.0	12.0	3.9	0.002	0.20
803	5/13/1992	*	0.1	*	*	*	*	*
803	7/22/1998	*	0.1	15.0	*	*	*	*
804	8/24/1993	*	0.1	*	*	*	*	*
805	5/20/1992	*	0.5	*	*	*	*	*
805	9/21/2009	*	1.0	*	*	*	*	*
806	6/12/1996	*	2.0	23.0	*	*	*	*
806	5/21/2009	*	2.0	*	*	*	*	*
807	6/12/1996	*	2.0	23.0	*	*	*	*
807	4/30/2009	*	7.0	*	*	*	*	*
809	4/14/1992	*	0.1	*	*	*	*	*
809	8/31/1998	*	0.1	37.0	*	*	*	*
810	4/14/1992	*	0.4	*	*	*	*	*
810	8/31/1998	*	0.3	10.0	*	*	*	*
812	6/15/1994	*	*	25.0	*	*	*	*
813	1/19/2006	182	0.6	21.0	45.4	16.7	*	0.05
813	1/19/2006	219	0.4	24.0	55.1	19.8	*	0.10
813	8/26/2008	*	0.8	*	*	*	0.008	*
813	1/14/2009	*	0.7	*	*	*	*	*
813	4/5/2011	*	*	*	*	*	0.009	*
813	4/4/2012	*	0.8	*	*	*	*	*
814	5/20/1992	*	0.5	*	*	*	*	*
814	12/1/2009	*	1.0	*	*	*	*	*

Appendix D. Table of public well analyses

IDNum	Date	Hardness	Nitrate	Sulfate	Calcium	Magnesium	Arsenic	Iron
815	5/18/2009	*	11.0	*	*	*	*	*
816	4/11/1994	*	*	367.0	*	*	*	*
819	8/16/1995	*	*	14.0	*	*	*	*
820	6/8/2009	*	6.0	*	*	*	*	*
821	5/22/1991	178	1.6	30.0	51.2	12.1	*	0.20
821	5/22/1991	128	0.1	15.0	34.3	10.3	*	0.93
821	6/15/1994	*	0.1	18.0	*	*	*	*
821	6/2/2009	*	5.0	*	*	*	*	*
822	9/26/1990	183	0.3	82.0	47.0	16.0	*	0.05
822	12/1/1993	185	0.5	65.0	46.0	17.0	*	0.05
822	4/27/1995	199	0.2	48.0	55.0	15.0	*	0.05
822	4/27/1995	240	0.2	124.0	62.0	21.0	*	0.05
822	12/30/1997	235	0.2	62.0	64.0	18.0	*	0.03
822	12/30/1997	216	0.1	90.0	55.0	19.0	*	0.08
822	12/30/1997	206	0.1	91.0	53.0	18.0	*	0.11
822	3/21/2001	264	0.2	86.0	69.0	22.0	*	0.55
822	11/19/2003	225	0.2	32.0	60.1	18.2	*	0.28
822	10/11/2006	197	0.4	71.0	46.7	19.5	*	0.05
822	10/11/2006	252	0.1	30.0	69.6	18.9	*	0.18
822	10/11/2006	255	0.1	122.0	62.7	23.9	*	0.20
822	11/3/2009	230	0.8	95.0	55.5	22.2	*	0.19
822	10/24/2012	270	0.6	72.0	74.0	20.6	*	0.06
822	10/24/2012	359	0.3	53.0	103.0	24.5	*	0.07
822	10/24/2012	293	0.1	122.0	76.5	24.8	*	21.40
824	5/26/1993	*	8.1	114.0	*	*	*	*
825	5/20/1992	*	0.3	*	*	*	*	*
827	1/1/2007	*	*	*	*	*	+	*
827	4/1/2007	*	*	*	*	*	+	*
827	7/1/2007	*	*	*	*	*	+	*
827	10/1/2007	*	*	*	*	*	+	*
827	1/1/2008	*	*	*	*	*	+	*
827	4/1/2008	*	*	*	*	*	+	*
827	7/1/2008	*	*	*	*	*	+	*
827	10/1/2008	*	*	*	*	*	+	*
827	1/1/2009	*	*	*	*	*	+	*
827	4/1/2009	*	*	*	*	*	+	*
827	4/14/2009	*	*	*	*	*	0.015	*
827	7/1/2009	*	*	*	*	*	+	*
827	10/1/2009	*	*	*	*	*	+	*
827	1/1/2010	*	*	*	*	*	+	*
827	4/1/2010	*	*	*	*	*	+	*
827	7/1/2010	*	*	*	*	*	+	*

Appendix D. Table of public well analyses

IDNum	Date	Hardness	Nitrate	Sulfate	Calcium	Magnesium	Arsenic	Iron
827	10/1/2010	*	*	*	*	*	+	*
827	1/1/2011	*	*	*	*	*	+	*
827	4/1/2011	*	*	*	*	*	+	*
827	7/1/2011	*	*	*	*	*	+	*
827	10/1/2011	*	*	*	*	*	+	*
828	5/29/1984	*	0.1	*	*	*	*	*
828	5/29/1984	*	0.1	*	*	*	*	*
828	5/29/1984	*	0.1	*	*	*	*	*
828	4/24/1990	*	0.1	*	*	*	*	*
829	7/8/1998	*	0.1	57.0	*	*	*	*
832	5/20/1992	*	0.1	*	*	*	*	*
832	5/20/1999	*	0.1	*	*	*	*	*
835	6/15/2009	*	3.0	*	*	*	*	*
837	5/23/1991	165	0.7	17.0	46.3	12.0	*	0.05
838	7/21/1994	*	0.2	28.0	*	*	*	*
838	5/18/2009	*	1.0	*	*	*	*	*
839	6/12/1996	*	0.1	30.0	*	*	*	*
840	7/16/2009	*	6.0	*	*	*	*	*
944	9/11/1983	276	*	40.0	56.0	33.0	nd	0.17
944	9/17/1984	278	*	138.0	70.0	25.0	nd	0.14
947	9/6/1983	231	*	109.0	58.0	21.0	*	0.23
947	6/6/1984	233	*	124.0	67.0	16.0	*	0.13
947	6/6/1984	247	*	119.0	68.3	18.7	nd	0.14
947	6/7/1984	278	*	124.0	80.0	19.0	*	0.05
949	9/11/1983	390	*	180.0	97.0	36.0	nd	0.77
952	11/20/1983	258	*	90.0	67.0	22.0	nd	0.24
955	9/7/1983	285	*	60.0	68.0	28.0	nd	0.62
969	9/11/1983	163	*	23.0	39.0	16.0	nd	1.40
972	9/7/1983	151	*	28.0	34.0	16.0	nd	0.52
972	9/7/1983	151	*	28.0	34.0	16.0	nd	0.52
972	9/11/1983	133	*	23.0	35.0	11.0	nd	0.69
972	9/11/1983	133	*	23.0	35.0	11.0	nd	0.69
974	9/13/1983	135	*	28.0	36.0	11.0	nd	0.05
5034	6/7/1979	*	*	*	*	*	nd	0.01
5040	6/11/1979	*	*	*	*	*	nd	nd
5050	6/11/1979	*	*	*	*	*	nd	nd
5054	6/12/1963	*	0.2	*	*	*	*	*
5062	6/8/1979	*	*	*	*	*	0.004	nd
5064	6/1/1979	*	*	*	*	*	nd	0.01
5077	6/11/1979	*	*	*	*	*	nd	nd
5078	6/8/1979	*	*	*	*	*	nd	nd
5085	6/8/1979	*	*	*	*	*	nd	nd

Appendix D. Table of public well analyses

IDNum	Date	Hardness	Nitrate	Sulfate	Calcium	Magnesium	Arsenic	Iron
5101	8/9/1979	*	*	*	*	*	0.002	0.02
5102	8/8/1979	*	*	*	*	*	nd	nd
5103	8/8/1979	*	*	*	*	*	nd	nd
5115	7/19/1979	*	*	*	*	*	nd	nd
5133	9/23/1974	*	0.0	*	*	*	*	0.60
5133	4/23/1976	*	nd	*	*	*	*	0.05
5133	1/9/1978	*	nd	*	*	*	*	0.05
5133	5/12/1979	*	*	*	*	*	nd	*
5133	2/19/1981	*	nd	*	*	*	*	nd
5133	9/2/1982	*	*	*	*	*	nd	*
5133	1/18/1983	*	nd	*	*	*	*	nd
5138	4/7/1976	*	nd	*	*	*	*	0.50
5154	8/9/1979	*	*	*	*	*	0.003	0.01
5157	12/15/1976	*	nd	*	*	*	*	0.09
5157	12/15/1976	*	nd	*	*	*	*	0.20
5157	5/25/1979	*	0.4	*	*	*	nd	*
5157	5/7/1980	*	0.2	*	*	*	*	0.04
5157	12/8/1981	*	1.0	*	*	*	*	nd
5165	8/2/1979	*	*	*	*	*	nd	nd
5169	12/21/1978	*	0.2	*	*	*	*	nd
5169	8/12/1979	*	1.1	*	*	*	nd	*
5169	3/31/1981	*	0.3	*	*	*	*	nd
5169	2/17/1983	*	0.3	*	*	*	*	0.05
5173	8/9/1979	*	*	*	*	*	0.003	0.01
5175	4/4/1975	*	0.9	*	*	*	*	1.34
5175	10/11/1979	*	1.1	*	*	*	*	nd
5176	10/11/1979	*	1.0	*	*	*	*	0.17
5176	2/6/1980	*	0.6	*	*	*	nd	*
5176	2/16/1982	*	1.0	*	*	*	*	nd
5176	2/15/1983	*	1.1	*	*	*	nd	*
5177	6/6/1979	*	*	*	*	*	nd	0.01
5182	7/19/1979	*	*	*	*	*	nd	nd
5200	5/20/1976	*	5.3	*	*	*	*	nd
5200	12/12/1979	*	5.9	*	*	*	*	nd
5200	4/2/1980	*	5.5	*	*	*	nd	*
5200	12/9/1981	*	11.0	*	*	*	*	nd
5200	5/4/1983	*	*	*	*	*	nd	*
5201	8/9/1979	*	*	*	*	*	nd	nd
5204	8/2/1979	*	*	*	*	*	nd	0.01
5223	8/6/1979	*	*	*	*	*	nd	nd
5233	10/13/1979	*	*	*	*	*	nd	0.02
5235	3/2/1981	*	nd	*	*	*	*	3.15

Appendix D. Table of public well analyses

IDNum	Date	Hardness	Nitrate	Sulfate	Calcium	Magnesium	Arsenic	Iron
5276	5/19/2014	*	*	*	*	*	0.070	*

Notes:
All constituents reported in mg/L.
nd: not detected; constituent below detection limit
*: no value reported
+: constituent reported present but no value given