# CACHE VALLEY AQUIFER STORAGE AND RECOVERY—SITE ASSESSMENT FOR MILLVILLE CITY, CACHE COUNTY, UTAH

*by Paul Inkenbrandt*

UTAH DNR
GEOLOGICAL SURVEY

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**UTAH GEOLOGICAL SURVEY**
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**2014**

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***Cover photo:*** *Millville, Utah*

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**UTAH GEOLOGICAL SURVEY**
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# CONTENTS

## FIGURES



## TABLES

# CACHE VALLEY AQUIFER STORAGE AND RECOVERY—SITE ASSESSMENT FOR MILLVILLE CITY, CACHE COUNTY, UTAH

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## EXECUTIVE SUMMARY

Cache County is interested in pursuing aquifer storage and recovery (ASR) programs to store excess surface water in the Cache Valley principal aquifer. The City of Millville, located in a prime location for ASR, is having issues with elevated nitrate in the Glenridge well, a public water supply sourced from the Cache Valley principal aquifer. To initiate a small-scale ASR project and alleviate high nitrate, the city performed an initial injection and pumping test using the Glenridge well. Millville injected water from Garr Spring, another public water supply source of which they own water rights, into the Glenridge well for one week at a rate of 500 gallons per minute. Garr Spring water has an average nitrate concentration of 0.8 mg/l nitrate as nitrogen (Utah Division of Drinking Water, 2014). They then pumped the well while monitoring geochemistry to determine the effects on the Cache Valley principal aquifer system.

Results of the test are preliminary and show decreased nitrate values in the Glenridge well. While the increase in potentiometric surface was not precisely measured, it is likely small and widespread due to the high transmissivity of the aquifer, which was determined to be 135,000 ft$^2$/day (12,540 m$^2$/day). The pre-injection nitrate concentration in the Glenridge well was 7.65 mg/l nitrate as nitrogen, and the nitrate concentration after pumping more than 172% of the volume of water injected was 6.52 mg/l nitrate as nitrogen. There is likely some dispersion of the injected spring water via advection in the aquifer. Preliminary results indicate that the nitrate in the aquifer is stable and not reacting (it seems chemically conservative), but reaction rates have not been considered. A better understanding of prolonged injection is recommended before a full-scale ASR project is initiated.

## BACKGROUND

### Problem

Cache County leaders have expressed interest in storing water in aquifers of Cache Valley (figure 1). Based on this interest, the Utah Geological Survey (UGS) conducted an evaluation of potential aquifer storage and recovery (ASR) sites in Cache Valley (Thomas and others, 2011) and examined a gravel pit site north of Logan, Utah (Inkenbrandt and others, 2013). In fall 2012, Millville City approached the UGS to express their interest and ability to participate in an ASR study involving the city's public water sources. They proposed injecting excess spring flow from Garr Spring into the Glenridge well. Millville possesses water rights for Garr Spring and owns Glenridge well, both of which are municipal water supply sources.

While Millville would like to store excess water in the Cache Valley principal aquifer, their greatest interest is diluting high nitrate concentrations within the aquifer. Nitrate values in the Glenridge well have risen by about 4 mg/l over the past 20 years, which correlates with an increase in the population of Millville (figure 2). Under the U.S. Environmental Protection Agency (U.S. EPA) regulations, nitrate cannot exceed a maximum contaminant level (MCL) of 10 mg/l (nitrate as nitrogen) (U.S. EPA, 2014). There are four major potential sources of nitrate for Millville to consider, none of which is exclusive of the others: (1) septic effluent from septic systems, (2) fertilizer, (3) livestock excrement, and (4) geologic sources (Lowe and Wallace, 2001; Roadcap and others, 2002).

### Objective

The objectives of this study are to: (1) determine if the Glenridge well and Garr Spring are suitable for conducting aquifer storage and recovery in the Cache Valley principal aquifer, and (2) determine the potential sources of nitrate contamination in the principal aquifer. As part of the objectives, I want to ensure that injecting water into the Glenridge well will not be detrimental to the aquifer.

### Millville City

Millville is located in southeast Cache Valley, in Cache County Utah, and has a population of 1869 (U.S. Census, 2014). Millville's Utah Division of Drinking Water system number is 03012, and a majority (>90%) of its water use is for domestic purposes (Utah Division of Water Rights, 2014). Millville operates four water sources, three of which—Garr Spring, the Glenridge well, and the Park well (figure 3)—are used as public drinking water sources (Utah Division of Water Rights, 2014).

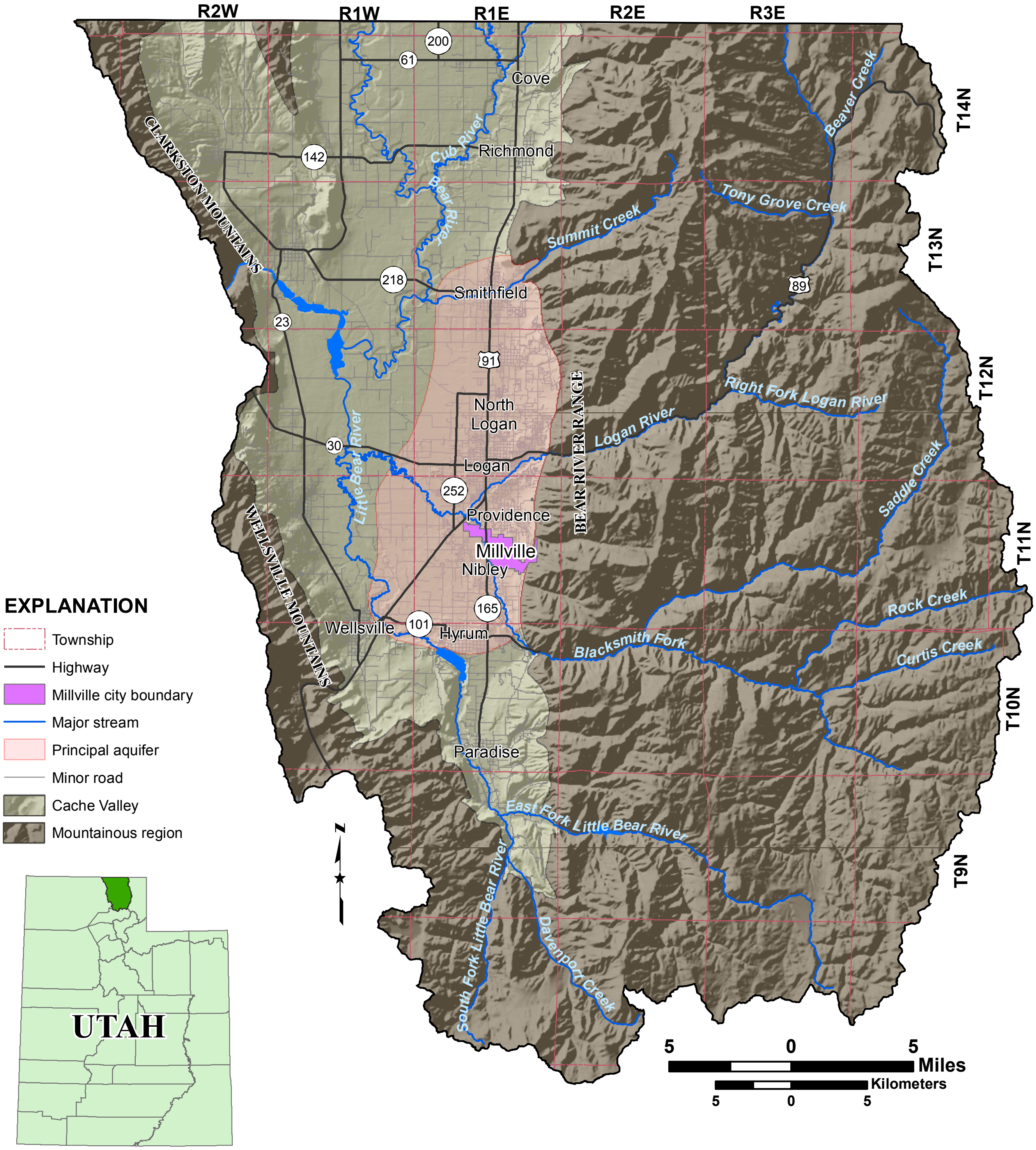


*Figure 1. Location of the study area in Cache County, Utah.*

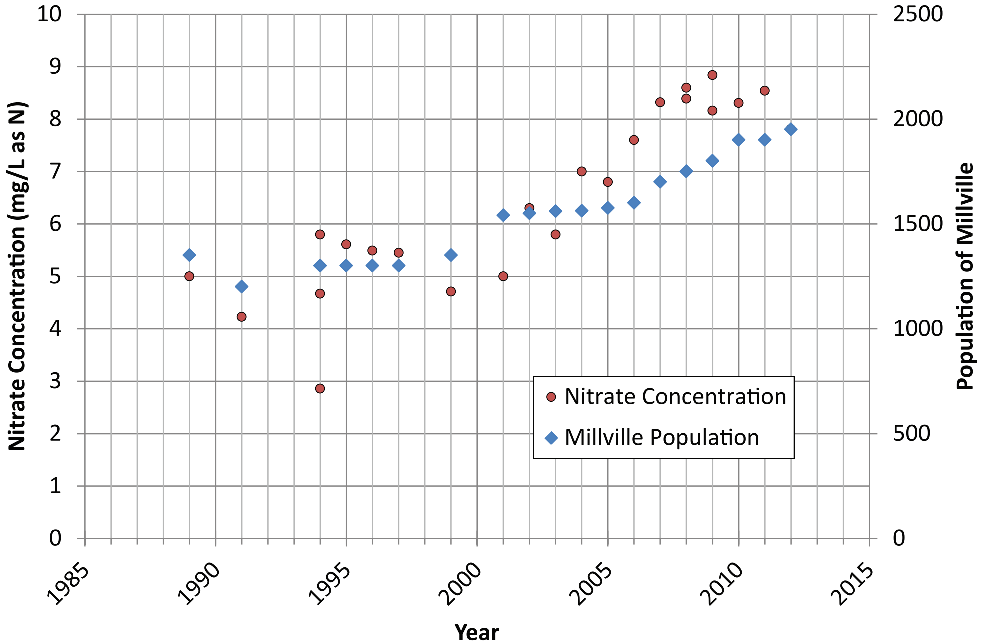


***Figure 2.*** *Trends of population and nitrate over time.*

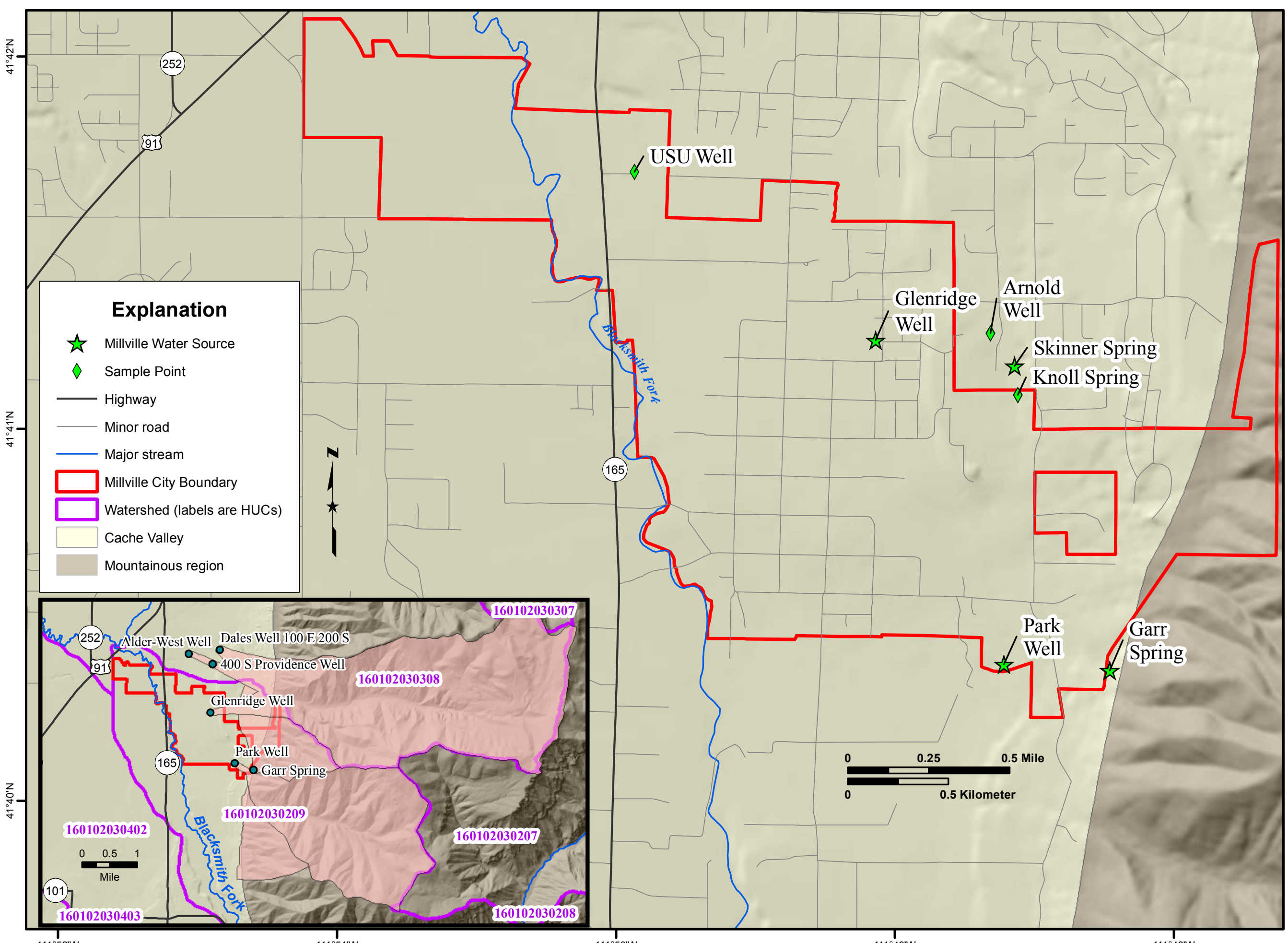


***Figure 3.*** *Locations of Millville water sources and wells of interest. Inset map displays nearby public drinking sources, their protection zones, and associated watersheds labeled with the hydrologic unit codes (HUCs).*

Millville is currently an unsewered community, and each property has its own septic system. Like most communities in Cache Valley, Millville was historically an agricultural community (Millville History Book Committee, 1990), and animal operations that are still active include dairies, a mink farm, and livestock corrals.

### Garr Spring

The collection box of Garr Spring is in the foothills of the Bear River Range and is located at UTM Zone 12 coordinates 4613780 m North and 433079 m East (North American Datum 1983) at a surface elevation of 4849 feet (1478 m) above mean sea level. Millville operates a storage tank immediately west and downhill of the collection area. The area to the east, hydrologically upgradient of Garr Spring, is predominantly undeveloped U.S. Forest Service property.

In 2013, Millville used 524 acre-feet (ac-ft) of water, including irrigation water. About 36% (191 ac-ft) of that came from Garr Spring (Utah Division of Water Rights, 2014), which Mundorff (1971) reported as having relatively fresh water (specific conductance = 465 uS/cm; TDS = 258 mg/l) and a discharge of about 3.5 cubic feet per second (cfs) (2535 ac-ft/yr). Garr Spring water has an average nitrate concentration of 0.8 mg/l of nitrate as nitrogen (Utah Division of Drinking Water, 2014). Peterson (1946) reported the discharge of the spring as 5 cfs (3622 ac-ft/yr), whereas Beer (1967) measured a discharge of 4 cfs (2897 ac-ft/yr). Millville has 1.139 cfs (825 ac-ft/yr) in water rights from the spring (water right numbers 25-3510, 25-3069, 25-5170, 25-8394), which extend from October 1 to March 31 (181 days). The other water right holder on Garr Spring is Garr Spring Water Company (water right number 25-4528), which has 4.133 cfs (2994 ac-ft/yr) in water rights. Millville owns shares in the Garr Spring Water Company.

### Glenridge Well

The Glenridge well is near the center of Millville and is located at UTM Zone 12 4615423 m North and 431914 m East (North American Datum 1983) at a surface elevation of 4675 feet (1425 m) above mean sea level. The Utah Division of Water Rights well identification number (WIN) for the Glenridge well is 2722. Based on the well driller's report and construction information (appendix A), the Glenridge well is 385 feet deep with a 10-inch diameter steel casing and perforations from 269 to 369 feet. The depth to water from ground surface in 1972, the time of drilling, was 180 feet. In 2013, about 12% (61.6 ac-ft) of water used by Millville (524 ac-ft; includes irrigation) came from the Glenridge well (Utah Division of Water Rights, 2014a).

The water quality of the Glenridge well meets drinking water standards, but the nitrate-nitrogen levels are nearing the U.S. EPA MCL of 10.0 mg/l (nitrate as nitrogen) (figure 2). The total dissolved solids concentration of the Glenridge well is 387 mg/l (Utah Division of Drinking Water, 2014). Water right number 25-5171 allots 2 cfs (1449 ac-ft/yr) of water to Millville from the Glenridge well (Utah Division of Water Rights, 2014).

### Park Well

The Park well is located near Garr Spring along the southeast border of Millville at UTM Zone 12 4613811 m North and 432552 m East (North American Datum 1983), and is at a surface elevation of 4705 feet (1434 m) above mean sea level. The Utah Division of Water Rights WIN for the Park well is 2721. In 2013, about 46% (240 ac-ft) of water used by Millville came from the Park well (Utah Division of Water Rights, 2014). Water from this well is relatively fresh, with an average nitrate concentration of 0.73 mg/l nitrate as nitrogen and an average total dissolved solids concentration of 267 mg/l (Utah Division of Drinking Water, 2014). The Park well was drilled in 1976 to a depth of 398 feet and has a 12-inch diameter steel casing. See appendix A for more details of the Park well.

## Aquifer Storage and Recovery

Aquifer storage and recovery (ASR), or conjunctive use, is the method of storing water in an aquifer when the water is available and recovering that water when needed (Pyne, 2005). While groundwater recharge generally occurs naturally, the recharge aspect of ASR is usually induced via human intervention and is commonly referred to as "managed aquifer recharge" (MAR) (Pyne, 2005). MAR is conducted either using a surface recharge basin, as examined by Inkenbrandt and others (2013), or by injection into a well (Pyne, 2005), which is the case for this study.

An injection well offers the advantage of injecting water directly into the target aquifer without encountering confining layers or other impedances that could exist between a surface recharge basin and the target aquifer. In ASR configurations, wells can be used solely for injection or for both injection and pumping. The advantages of using a "dual purpose" well for both injection and extraction are that only one well is required for the operation and the pump in the well can be used to help remediate clogging of the well screen—a major issue with ASR injection wells (Pyne, 2005).

Injecting water into an aquifer system creates an effective "bubble" of the injected water in the aquifer (figure 4). Natural groundwater flow and diffusion disperse that bubble over time, but some quantity of the injected water can usually be retrieved. The proportion of injected water that can be retrieved is known as recovery efficiency.

While stored in the aquifer, the injectate, native aquifer water, and the solid aquifer material can undergo hydrogeochemical changes depending on the relative difference between the chemistries of the two waters. If the aquifer is dominated by reducing conditions and an oxygen-rich injectate is introduced, the chemistry of the injectate water could change the oxidation state of ions in the native aquifer water and/or the aquifer material, resulting in the potential mobilization of ions (figure 5a). Arsenic mobilization is a common issue (figure 5b), via oxidation of arsenopyrite in the aquifer. Other concerns include mobilization of uranium, mercury, nickel, chromium, cobalt, and zinc. Microbiota often play an important role in the mobilization and demobilization of these and other ions, especially in the case of nitrate. A primary concern for the water surrounding the Glenridge well is potentially mobilizing nitrate via the oxidation of nitrite and ammonia (nitrification) (figure 5c). While the U.S. EPA does currently not regulate sulfate, the presence or absence of sulfate can also be indicative of reducing conditions (figure 5d).

Nitrate can also potentially be mobilized by raising the water table of an unconfined aquifer, as observed by Nishikawa and others (2003). If the aquifer is unconfined and the nitrate source is near the water table, then raising the groundwater level would result in greater contamination of the aquifer water. This is especially true if the recharge source is a recharge basin, as the water will travel through the contaminated unsaturated zone before reaching the saturated zone (figure 6). The geologic setting examined by Nishikawa and others (2003) is very similar to that of Millville, with the important exception of faults dissecting the Cache-Valley basin-fill aquifer into different aquifers.

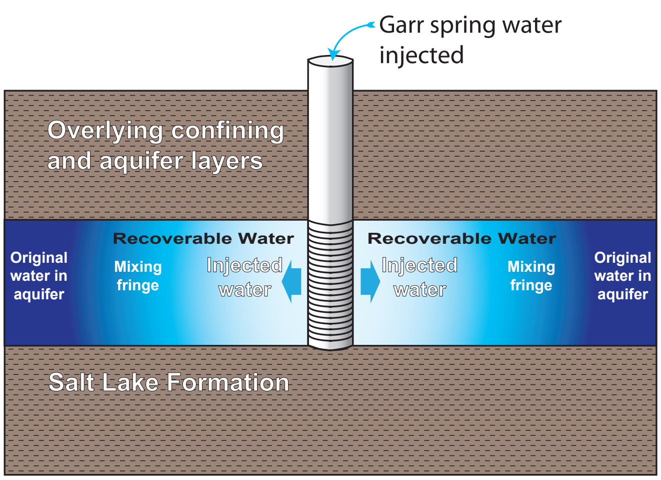


***Figure 4.*** *Conceptual diagram of injected-water storage in the Cache Valley principal aquifer.*

## Regulation

Because water is being injected into a drinking-water aquifer, the injection well used for this study (Millville's Glenridge well) is subject to regulation by the Underground Injection Control (UIC) Program of the Utah Division of Water Quality and the Utah Division of Water Rights (Utah State Legislature, 2014). As a public supply well, it is also subject to the regulatory criteria of the Utah Division of Drinking Water. Any entity injecting water in the state of Utah must follow rules outlined by Title 73, Chapter 3b of the Utah State Code (Utah State Legislature, 2014). The UIC Program classifies ASR wells as Class 5B4 injections wells, which are used to replenish water in an aquifer for subsequent use (Utah Division of Water Quality, 2014). For an entity to inject water into a Class 5B4 well, a permit application must be filed with the UIC Program (appendix B). The entity must also file an application with the Utah Division of Water Rights to both recharge and recover water (appendix C). State entities overseeing the aquifer storage and recovery process either require or have great interest in a hydrologic study defining: (1) the area of the aquifer impacted by injection, (2) implications of injection of foreign water into the groundwater system, (3) the hydrogeology of the area, and (4) the capabilities of the entity injecting water.

## Hydrogeology

The Cache Valley principal aquifer system (figure 1), the primary aquifer for drinking-water supplies, is a complex multiple-aquifer system composed of basin fill under both unconfined and confined conditions (Bjorklund and McGreevy, 1971; Kariya and others, 1994). The basin fill is unconsolidated sediment consisting of silt, sand, and gravel, which were deposited in fluvial, alluvial fan, landslide, and near-shore lacustrine environments. Each layer is bounded by layers of silt and clay primarily deposited by offshore lacustrine environments (Bjorklund and McGreevy, 1971; Lowe, 1987). The basin fill is more than several hundred feet thick at many locations along the valley center (Kariya and others, 1994).

Bjorklund and McGreevy (1971) concluded that groundwater in the principal aquifer is unconfined along the margins of Cache Valley, but is confined in many areas toward the center of the valley where many flowing wells exist. Using over 200 well drillers' logs, isotopic signatures, and carbon-14 age estimates, Robinson (1999) developed and Olsen (2007) improved a conceptual model (figure 7) of the Cache Valley principal aquifer system. Robinson (1999) closely examined the aquifer system in southern Cache Valley to the west and south of Millville and reported that groundwater in the aquifer is relatively old and slow moving.

The boundary between unconfined and confined conditions is gradational near the margins of the basin, which is within a couple miles of the basin-bounding fault and where leaky conditions may exist. The presence or absence of continuous clay layers and the vertical hydrologic gradient dictate where groundwater recharges and discharges. Based on mapping conducted by Anderson and others (1994), groundwater recharge occurs mainly at the margins of Cache Valley, while discharge is predominantly near the center of the valley (figure 8). Using well drillers' logs and the hydrologic gradient, Anderson and others (1994) subdivided the Cache Valley

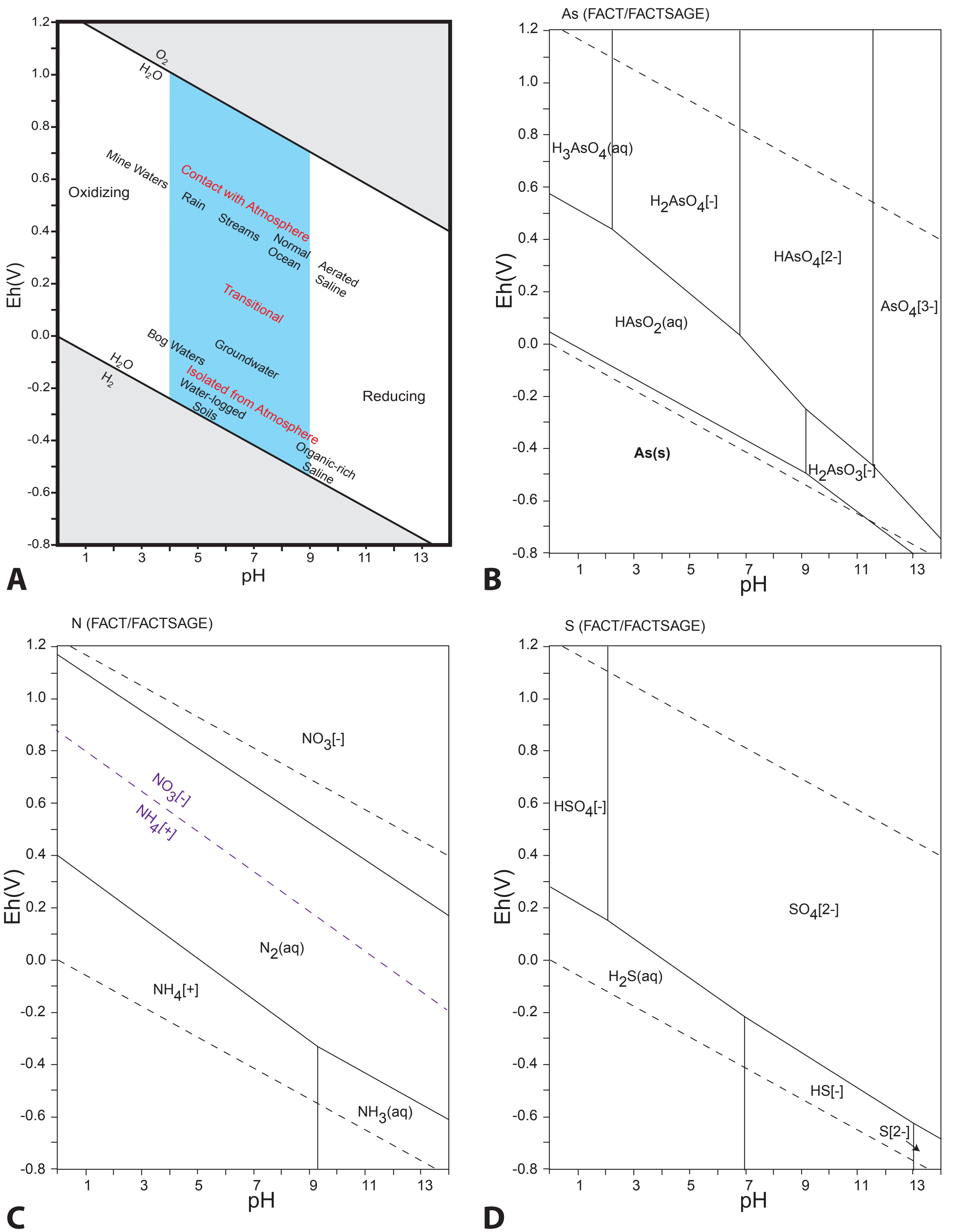


***Figure 5.*** *Pourbaix (Eh-pH) diagrams of (A) natural waters (modified from Garrels and Christ, 1965), (B) arsenic (from Takeno, 2005), (C) nitrogen (modified from Takeno, 2005), and (D) sulfur (from Takeno, 2005).*

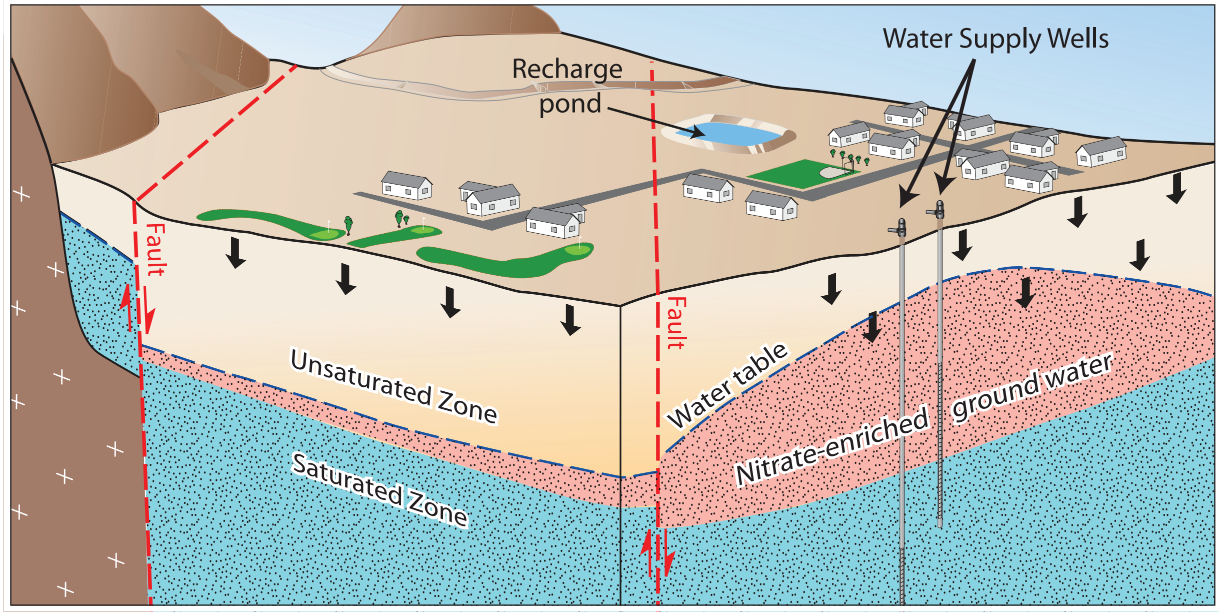


*Figure 6. Conceptual model of water from the recharge pond infiltrating through an area with a high density of septic systems, creating a recharge mound and mobilizing nitrate in an area previously unsaturated (modified from Nishikawa and others, 2003).*

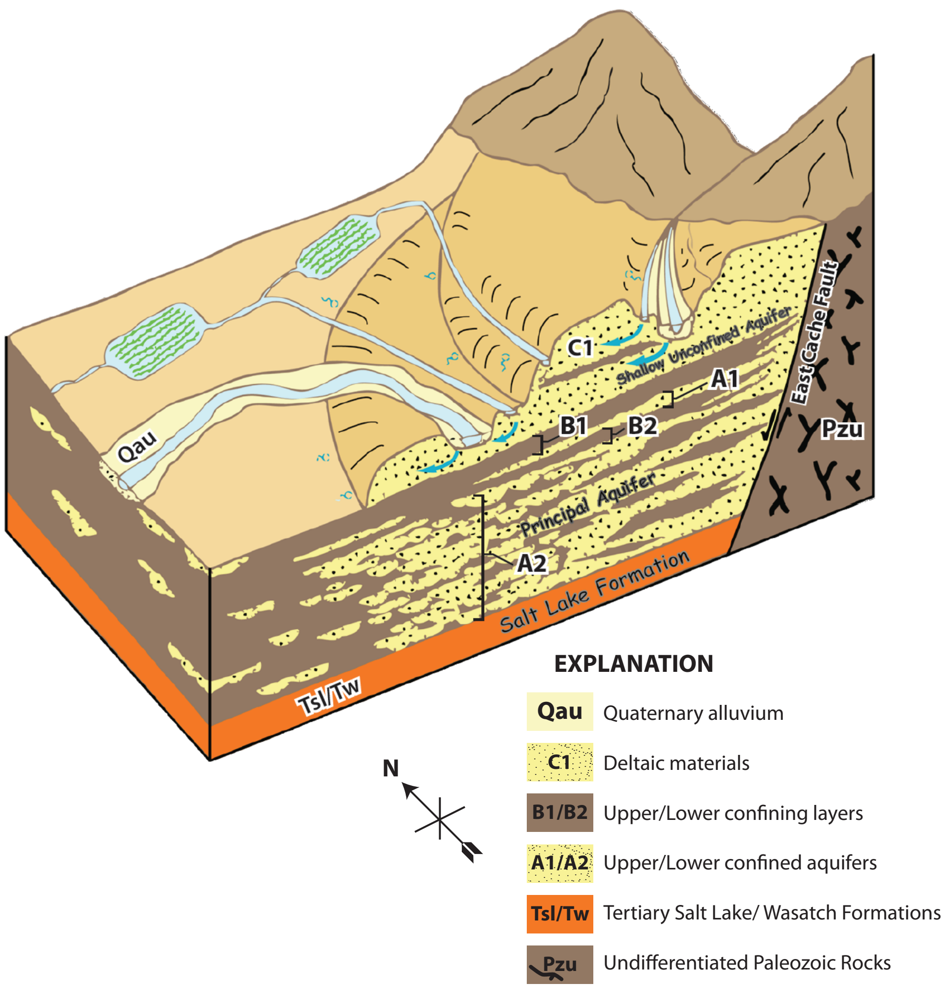


*Figure 7. Conceptual block diagram of Cache Valley hydrostratigraphic units (modified from Olsen, 2007) as defined by Robinson (1999). This conceptual block diagram best represents the area near Logan, Utah.*

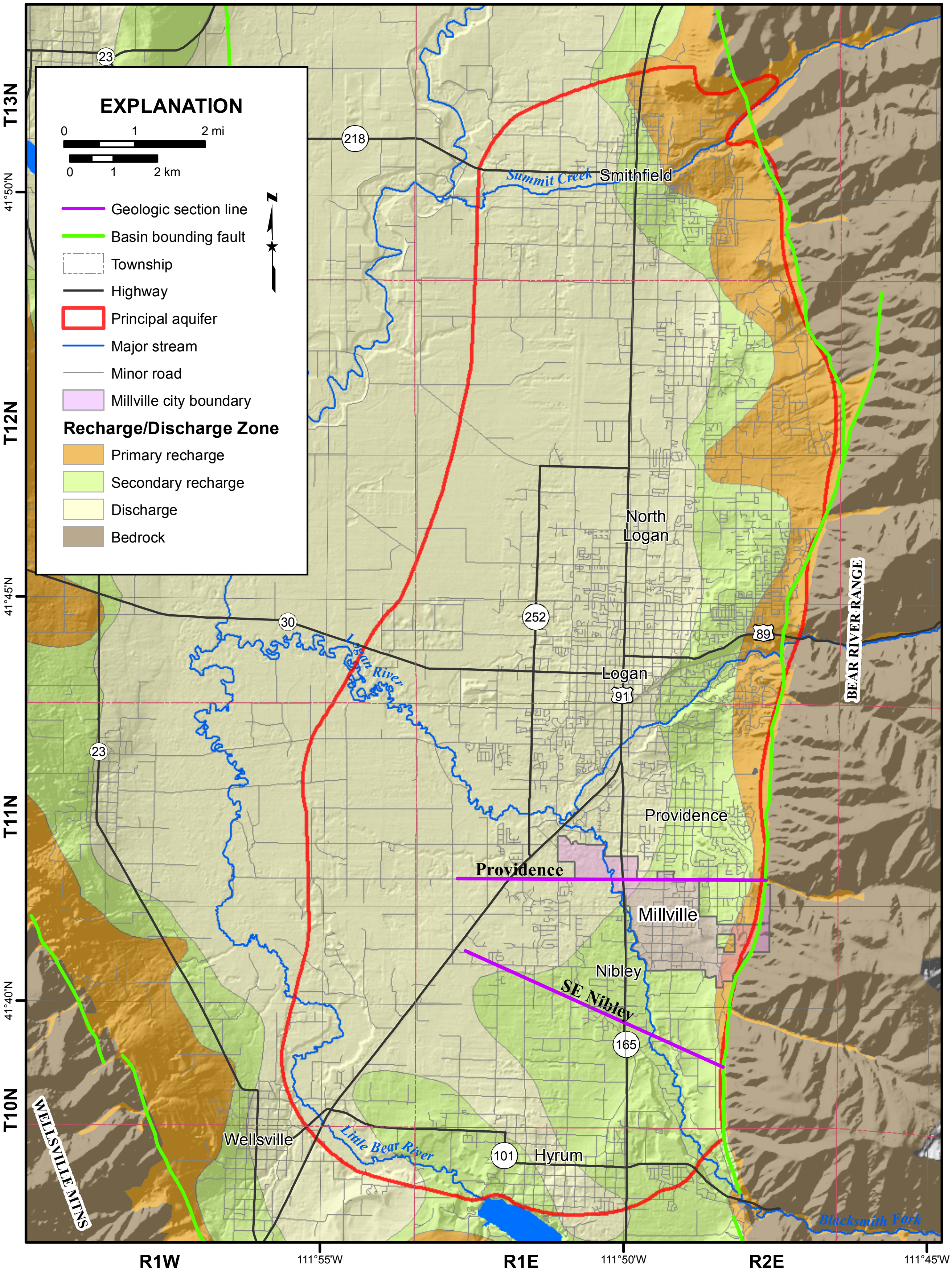


*Figure 8. Recharge and discharge areas in Cache Valley (Anderson and others, 1994). See figure 9 for the geologic cross sections (purple lines).*

basin-fill into three categories: (1) primary recharge—less than 20 feet of clay and a downward hydrologic gradient, (2) secondary recharge—confining layers (greater than 20 feet) and a downward hydrologic gradient, and (3) discharge areas—upward hydrologic gradient.

When selecting potential candidate areas for ASR surface-spreading sites (areas where surface water can infiltrate into the ground), Thomas and others (2011) created several geologic cross sections to gain a better understanding of the continuity of clay layers and aquifer systems within the principal aquifer. Two of those sections bracket the area near Millville (figure 9).

## Groundwater Chemistry

Lowe and others (2003) sampled 165 wells for a study on groundwater quality in Cache Valley and created recommendations for septic tank densities based on their findings. Lowe and others (2003) recommended a maximum of one-third septic system per acre for the Millville area. Using data collected in 1997 by Lowe and others (2003), Robinson (1999) evaluated the southern Cache Valley aquifer system. Robinson (1999) interpolated sulfate values for the southern portion of the valley and found high levels of sulfate near Blacksmith Fork (figure 10).

As previously stated, nitrate contamination near the Millville Glenridge well has increased over time approaching the U.S. EPA MCL of 10 mg/l (nitrate as nitrogen). Nitrate concentration in the Glenridge well is high compared to concentrations at Garr Spring and the Park well, which are at or near 1 mg/l (Utah Division of Drinking Water, 2014). As of the publication of this report, one well in Cache Valley (Mendon, Utah) has been shut down due to nitrate contamination.

# METHODS

## Approach

To determine the nitrate source and the suitability of ASR for Millville, we: (1) collected baseline data for the aquifer system, (2) conducted an injection test on the Glenridge well using Garr Spring water, (3) conducted a pumping test on the Glenridge well, and (4) modeled potential impacts on the aquifer system.

I compiled existing geochemical data and sampled groundwater for stable nitrogen, oxygen, and hydrogen isotopes, chemicals from septic systems, and standard major isotopes (including nitrate). In our groundwater-level measurement approach, I compiled water levels, conducted a microgravity survey, and Millville City conducted an injection test and pumping test using the Glenridge well. Based on the information I gained from the geochemistry and water-level data, I revised the drinking water source protection zone for the Glenridge well and predicted future behavior of the aquifer system if subjected to proposed injections. With the revised drinking water source protection zone, I identified additional potential contaminant sources near Millville.

## Background Measurements

### Potential Nitrate Sources

A potential contaminant map showing the location of septic systems and animal operations was created using the Cache County parcel map of Millville (Utah Automated Geographic Reference Center, 2013a). Points were created using the centroid of each parcel. A few older parcels in Providence suspected of having septic systems, as reported in informal communications with Providence city workers, were included. I then generated a point density map from the centroid points. To include potential animal-related sources of nitrate, I used air photos and water-related land use maps (Utah Automated Geographic Reference Center, 2013b) to determine land use change over time.

### Groundwater Levels

To determine groundwater flow direction and gradient, which are important components of Drinking Water Source Protection (DWSP) delineation, contaminant transport, and injection modeling, I created a high-resolution potentiometric surface map using ArcGIS software. A combination of compiled and field-collected data (appendix D) were used to generate the map. I used 30-foot (10m) horizontal resolution digital elevation models (DEM) from the National Elevation Dataset (NED) (USGS, 2014a) to assign land-surface elevations for wells that I did not measure in the field.

To collect field data, I used a high-resolution Trimble real-time kinetic global positioning system in combination with the Utah Reference Network (TURN) (Utah Automated Geographic Reference Center, 2013c) to measure well-casing-top elevations and a Solinst water level sounder to measure depth to water.

I supplemented field measurements with compiled data from the U.S. Geological Survey (USGS) and the Utah Division of Water Rights, and I compiled existing data from the USGS NWIS database (USGS, 2014b). For wells having multiple measurements, an average of depth-to-water data was calculated. I determined that the averaging of measurements was appropriate as I observed no significant long-term trend in water levels for Cache Valley, and I wanted to represent the long-term static groundwater level. I also compiled data from the Utah Division of Water Rights points of diversion (WR-POD) shapefile and associated tables.

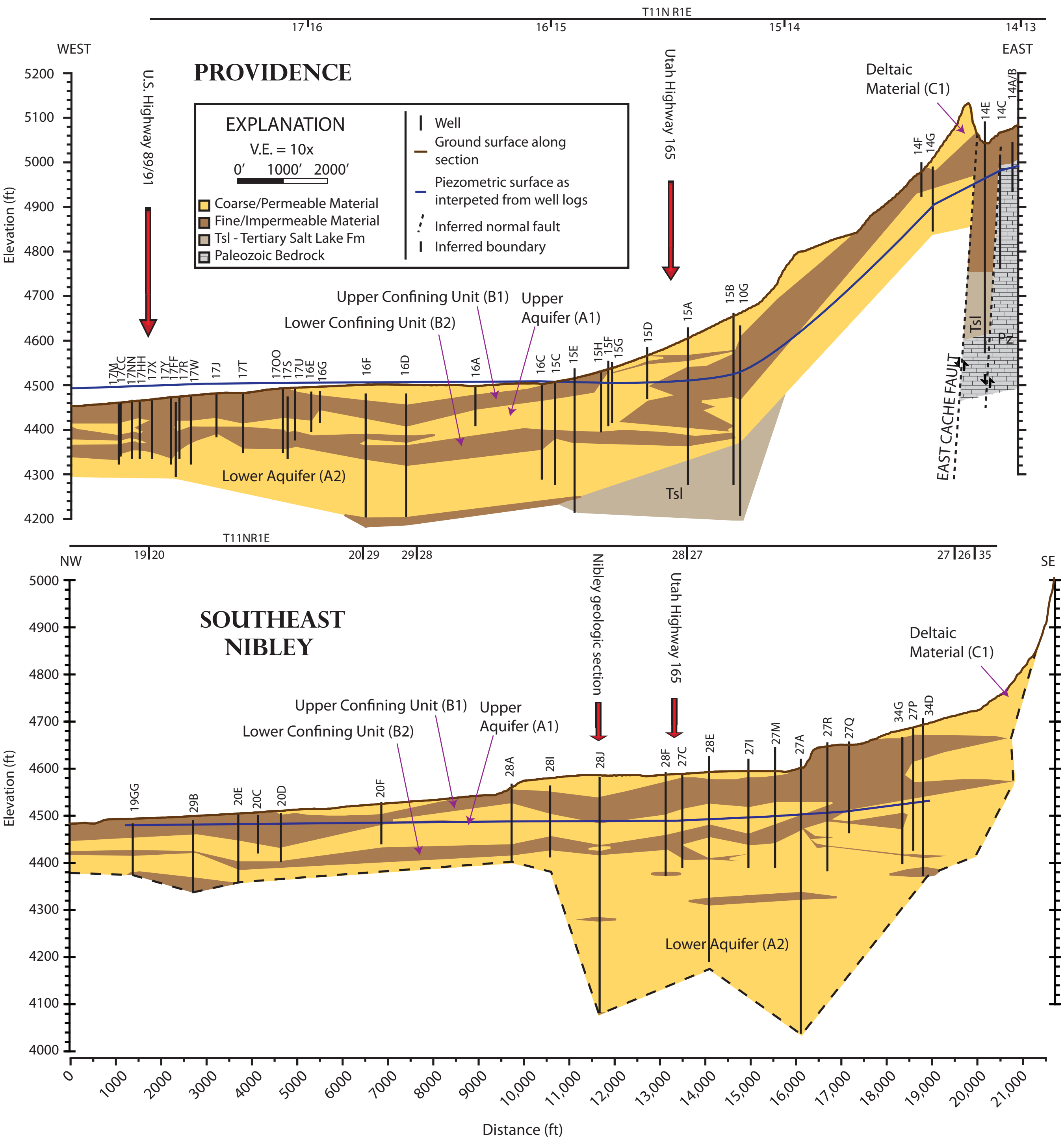


***Figure 9.*** *Geologic cross sections of the Millville area (Thomas and others, 2011). See figure 8 for section locations. Elevation is in feet above mean sea level.*

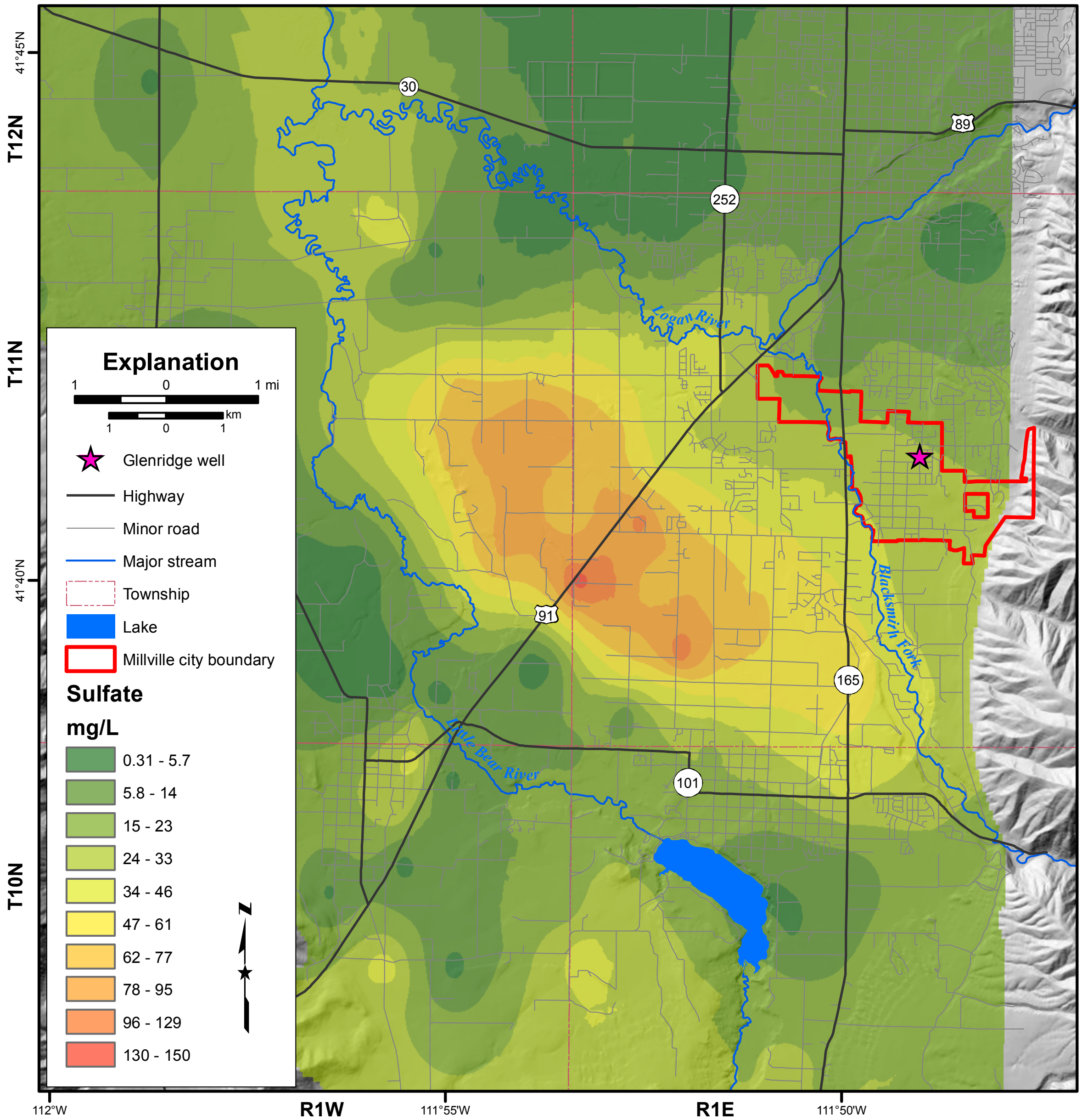


***Figure 10.*** *Sulfate concentrations in the Millville area (modified from Robinson, 1999). Note the high concentration of sulfate downgradient (west) of Blacksmith Fork.*

The cokriging gridding method was used to interpolate the groundwater level elevation data. I used NED data (USGS, 2014a) and 645 groundwater-level measurements compiled from 576 wells in the principal aquifer area for the interpolation. I used the entire principal aquifer area to better model spatial relationships between groundwater levels. Cokriging is a geostatistical method that assumes one can improve estimates of a value of a variable in space if it is spatially dependent on other variables (ESRI, 2014). The advantage of using a geostatistical method is it allows for error estimates in interpolation (ESRI, 2014).

I determined gradient and flow direction by generating slope and aspect rasters of the groundwater level interpolation. I averaged the aspect and slope orientations within a two-mile radius of the well and west of the East Cache Valley bounding fault.

## Hydrogeology

Using data from 60 well drillers' logs (appendix E), I created two hydrogeologic cross sections of the Millville area. I simplified drillers' unit descriptions to "high" and "low" permeability. When permeability information wasn't available, I labeled clay-bearing units as "low" permeability and sand, gravel, and conglomerate units as "high" permeability. To map hydrogeologic units at the surface, I interpreted permeability from the Quaternary units presented in the Logan 1:24,000-scale geologic map (Evans and others 1996).

The same wells were used to determine total clay thickness within the first 150 feet of the subsurface. I chose 150 feet as the cutoff because this is above the depth to water in most of the Millville area. For each well, I summed the thicknesses of layers labeled "clay" by the drillers in the first 150 feet below ground surface. In order to determine the coverage of clay in the area, I used the Empirical Bayesian Kriging (EBK) method to interpolate total clay thickness between wells. EBK is a geostatistical interpolation method used to automatically generate localized geostatistical models that approximate spatial variation in a variable (ESRI, 2014).

### Hydrogeochemistry

Four wells and two springs were sampled (figure 3) for nitrate, and a subset of those sites were sampled for stable oxygen and hydrogen isotopes in water, arsenic, metals, and general chemistry. The Utah State University Water Laboratory conducted a preliminary analysis on a water sample from the Glenridge well for caffeine and a suite of other chemicals commonly sourced from septic system. Presence of these chemicals could indicate septic contribution. Prior to conducting the injection test, I was required by the Department of Environmental Quality to sample for a wide variety of constituents (appendix F).

Prior to the project, Gary Larsen (Millville City public works director) collected nitrate data from several sites over several years. The Utah State Health Department Laboratory analyzed all samples, except for stable isotopes, which were analyzed at the Utah State University Geology Department Isotope Lab.

Stable isotopes of nitrogen and oxygen in nitrate can be used to narrow down potential sources of nitrate in groundwater. Different sources plot in different regions on a graph of the ratios of oxygen and nitrogen isotopes, with some overlap (Clark and Fritz, 1997). The locations of the samples on the graph give some indication as to the source of nitrate. If the samples fall into the overlap areas, the source is mixed or ambiguous (Clark and Fritz, 1997). Waterloo Laboratory analyzed a water sample from the Glenridge well for nitrogen and oxygen isotope ratios in nitrate to determine a possible nitrate source.

I also used stable isotopes of oxygen and hydrogen in water, as well as nitrate concentrations, to determine the "make-up" of the post-injection water extracted from the Glenridge well. Based on ratios of source concentration to point-measurement concentrations, assuming nitrate and stable isotopes are conservative, I determined the percentage of pumped water that is original to the Cache Valley principal aquifer (i.e., non-injected water) relative to the amount of water pumped. Using EBK interpolation on the most recent nitrate values, I created a nitrate concentration map to determine extent and orientation of the nitrate plume.

## Injection and Pumping Test

### Injection Configuration

Water from Garr Spring was injected through existing city water lines into the pump shaft of the Glenridge well. Before injection into the well, the pump was removed and check valves and flow meters were reversed to allow water to flow opposite of the typical (pumping) flow direction. A 4-inch diameter injection pipe with a 1.625-inch diameter orifice at the end was set to 210 feet below ground surface, which is 30 feet below static water level.

Injection began at 10:45 a.m. on 3/10/2014 and continued until 3/17/2014 at 10:51 a.m. (table 1) at a mean rate of 476 gallons per minute (gpm) (1800 liters per minute). I measured injection rate and volume using an in-pipe volume meter. The meter requires the pipe to be full to be accurate, which was the case during the injection test. Millville injected a total of 4,987,000 gallons (15.3 ac-ft; 19,000 $m^3$) of Garr Spring water into the Glenridge well over a period of 7 days (table 1).

### Pumping Configuration

After injecting was complete, the pump was placed back into the well with the pump intake at 231 feet below ground surface. Pumping began at 9:15 am on 3/19/2015 and continued until 3/24/2014 at 10:56 a.m. at a mean rate of 290 gpm. I measured the pumping rate and volume using the same flowmeter used for injection. Millville pumped a total of 2,117,000 gallons (6.5 ac-ft; 8000 $m^3$) from Glenridge well over a period of 5 days (table 2). The well sat idle until 5/5/2014 when the pump was turned on to purge and sample the well. The well pump was turned on for extended municipal use on 7/1/2014.

### Measurements

During the test, I measured water levels with a combination of water level sounders and pressure transducers. Using the pressure transducers, I measured at a minimum frequency of 1 sample every 10 minutes and a maximum frequency of 1 sample every 10 seconds. I increased measurement frequency during the beginning and the end of injection and pumping to capture rapid changes in well water level. Due to well access issues, I was not able to continuously record water levels in the Glenridge well prior to pumping to analyze for antecedent trends. However, I periodically manually measured groundwater levels prior to pumping and extended the duration of post-pumping measurement to examine the well for other water-level-changing influences. See appendix G for a table of well-water level measurements.

***Table 1.*** *Injection record of Glenridge well.*

| Date-Time | Pipe Meter Reading (gallons) | Total Water Injected (gallons) | Total Water Injected (acre-ft) | Injection Rate (gpm) | Time Since Injection Started (days) |
|---|---|---|---|---|---|
| 3/10/2014 10:45 | 393235000 | | | | |
| 3/10/2014 11:02 | 393239250 | 4250 | 0.013 | 250 | 0.0118 |
| 3/10/2014 11:04 | 393241600 | 6600 | 0.0203 | 810.34 | 0.0138 |
| 3/10/2014 11:33 | 393254725 | 19725 | 0.0605 | 463.78 | 0.0335 |
| 3/10/2014 12:16 | 393276300 | 41300 | 0.1267 | 500 | 0.0634 |
| 3/10/2014 14:42 | 393349000 | 114000 | 0.3499 | 498.86 | 0.1646 |
| 3/10/2014 14:46 | 393351300 | 116300 | 0.3569 | 498.19 | 0.1678 |
| 3/10/2014 14:56 | 393356200 | 121200 | 0.3719 | 500 | 0.1747 |
| 3/10/2014 17:16 | 393426000 | 191000 | 0.5862 | 498.69 | 0.2719 |
| 3/10/2014 17:17 | 393426500 | 191500 | 0.5877 | 500 | 0.2725 |
| 3/10/2014 17:19 | 393427500 | 192500 | 0.5908 | 495.87 | 0.2739 |
| 3/11/2014 7:57 | 393864000 | 629000 | 1.9303 | 497.17 | 0.8836 |
| 3/11/2014 7:59 | 393865000 | 630000 | 1.9334 | 500 | 0.885 |
| 3/11/2014 11:43 | 393976000 | 741000 | 2.274 | 496.09 | 1.0404 |
| 3/11/2014 11:44 | 393976500 | 741500 | 2.2756 | 491.8 | 1.0411 |
| 3/11/2014 15:44 | 394095500 | 860500 | 2.6408 | 495.97 | 1.2077 |
| 3/11/2014 15:45 | 394096000 | 861000 | 2.6423 | 491.8 | 1.2084 |
| 3/11/2014 15:46 | 394096500 | 861500 | 2.6438 | 500 | 1.2091 |
| 3/11/2014 17:57 | 394161500 | 926500 | 2.8433 | 495.49 | 1.3002 |
| 3/11/2014 17:58 | 394162000 | 927000 | 2.8449 | 491.8 | 1.3009 |
| 3/11/2014 18:08 | 394167000 | 932000 | 2.8602 | 497.51 | 1.3079 |
| 3/12/2014 7:53 | 394575500 | 1340500 | 4.1138 | 494.93 | 1.8811 |
| 3/12/2014 7:54 | 394576000 | 1341000 | 4.1154 | 491.8 | 1.8818 |
| 3/13/2014 7:10 | 395266000 | 2031000 | 6.2329 | 494.55 | 2.8507 |
| 3/13/2014 15:15 | 395505000 | 2270000 | 6.9664 | 492.78 | 3.1875 |
| 3/13/2014 19:00 | 395613000 | 2378000 | 7.2978 | 480 | 3.3438 |
| 3/14/2014 7:15 | 395980000 | 2745000 | 8.4241 | 499.32 | 3.8542 |
| 3/14/2014 15:30 | 396229000 | 2994000 | 9.1882 | 503.03 | 4.1979 |
| 3/14/2014 20:00 | 396362000 | 3127000 | 9.5964 | 492.59 | 4.3854 |
| 3/15/2014 10:30 | 396793000 | 3558000 | 10.9191 | 495.4 | 4.9896 |
| 3/16/2014 10:00 | 397477000 | 4242000 | 13.0182 | 485.11 | 5.9688 |
| 3/16/2014 18:30 | 397738000 | 4503000 | 13.8192 | 511.76 | 6.3229 |
| 3/17/2014 9:46 | 398190500 | 4955500 | 15.2079 | 493.77 | 6.9593 |
| 3/17/2014 9:47 | 398191000 | 4956000 | 15.2094 | 500 | 6.96 |
| 3/17/2014 10:43 | 398218500 | 4983500 | 15.2938 | 494.6 | 6.9986 |
| 3/17/2014 10:46 | 398220100 | 4985100 | 15.2987 | 477.61 | 7.0009 |
| 3/17/2014 10:46 | 398220200 | 4985200 | 15.299 | 428.57 | 7.0011 |
| 3/17/2014 10:46 | 398220300 | 4985300 | 15.2993 | 428.57 | 7.0013 |
| 3/17/2014 10:47 | 398220400 | 4985400 | 15.2996 | 500 | 7.0014 |
| 3/17/2014 10:47 | 398220500 | 4985500 | 15.2999 | 461.54 | 7.0016 |
| 3/17/2014 10:47 | 398220600 | 4985600 | 15.3002 | 461.54 | 7.0017 |
| 3/17/2014 10:47 | 398220700 | 4985700 | 15.3005 | 461.54 | 7.0019 |
| 3/17/2014 10:47 | 398220800 | 4985800 | 15.3008 | 461.54 | 7.002 |
| 3/17/2014 10:48 | 398220900 | 4985900 | 15.3011 | 500 | 7.0022 |
| 3/17/2014 10:48 | 398221000 | 4986000 | 15.3015 | 428.57 | 7.0023 |
| 3/17/2014 10:49 | 398221300 | 4986300 | 15.3024 | 418.6 | 7.0028 |
| 3/17/2014 10:49 | 398221400 | 4986400 | 15.3027 | 500 | 7.003 |
| 3/17/2014 10:49 | 398221500 | 4986500 | 15.303 | 461.54 | 7.0031 |
| 3/17/2014 10:49 | 398221600 | 4986600 | 15.3033 | 428.57 | 7.0033 |
| 3/17/2014 10:49 | 398221700 | 4986700 | 15.3036 | 461.54 | 7.0034 |
| 3/17/2014 10:50 | 398221800 | 4986800 | 15.3039 | 400 | 7.0036 |
| 3/17/2014 10:50 | 398221900 | 4986900 | 15.3042 | 428.57 | 7.0038 |
| 3/17/2014 10:50 | 398222100 | 4987100 | 15.3048 | 428.57 | 7.0041 |
| 3/17/2014 10:51 | 398222200 | 4987200 | 15.3051 | 375 | 7.0043 |
| 3/17/2014 10:51 | 398222300 | 4987300 | 15.3054 | 352.94 | 7.0045 |
| 3/17/2014 10:51 | 398222400 | 4987400 | 15.3057 | 428.57 | 7.0046 |

***Table 2.** Pumping record of Glenridge well.*

| Date-Time | Pipe Meter Reading (gallons) | Total Volume Pumped (acre-feet) | Time Since Pumping Started (days) | Total Volume Pumped (gallons) | Pumping Flow Rate (gpm) | Volume Pumped Relative to Volume Injected |
|---|---|---|---|---|---|---|
| 3/19/2014 9:15 | 398221530 | | | | | |
| 3/19/2014 10:18 | 398221530 | | 0.0000 | | 0.0 | |
| 3/19/2014 10:24 | 398223500 | 0.006 | 0.0046 | 1970 | 295.5 | 0.04% |
| 3/19/2014 10:25 | 398223600 | 0.0064 | 0.0049 | 2070 | 300.0 | 0.04% |
| 3/19/2014 10:25 | 398223700 | 0.0067 | 0.0051 | 2170 | 315.8 | 0.04% |
| 3/19/2014 10:25 | 398223800 | 0.007 | 0.0053 | 2270 | 300.0 | 0.05% |
| 3/19/2014 10:26 | 398224000 | 0.0076 | 0.0058 | 2470 | 279.1 | 0.05% |
| 3/19/2014 10:26 | 398224100 | 0.0079 | 0.0061 | 2570 | 285.7 | 0.05% |
| 3/19/2014 10:27 | 398224200 | 0.0082 | 0.0063 | 2670 | 300.0 | 0.05% |
| 3/19/2014 10:27 | 398224300 | 0.0085 | 0.0065 | 2770 | 272.7 | 0.06% |
| 3/19/2014 10:27 | 398224400 | 0.0088 | 0.0068 | 2870 | 285.7 | 0.06% |
| 3/19/2014 10:28 | 398224700 | 0.0097 | 0.0075 | 3170 | 305.1 | 0.06% |
| 3/19/2014 10:29 | 398224800 | 0.01 | 0.0077 | 3270 | 285.7 | 0.07% |
| 3/19/2014 10:31 | 398225350 | 0.0117 | 0.0090 | 3820 | 289.5 | 0.08% |
| 3/19/2014 10:31 | 398225400 | 0.0119 | 0.0092 | 3870 | 272.7 | 0.08% |
| 3/19/2014 10:31 | 398225500 | 0.0122 | 0.0094 | 3970 | 315.8 | 0.08% |
| 3/19/2014 11:18 | 398239300 | 0.0545 | 0.0422 | 17770 | 291.8 | 0.36% |
| 3/19/2014 11:19 | 398239400 | 0.0548 | 0.0425 | 17870 | 285.7 | 0.36% |
| 3/19/2014 13:20 | 398274900 | 0.1638 | 0.1268 | 53370 | 292.4 | 1.07% |
| 3/19/2014 13:20 | 398275000 | 0.1641 | 0.1270 | 53470 | 285.7 | 1.07% |
| 3/19/2014 13:51 | 398283800 | 0.1911 | 0.1479 | 62270 | 292.4 | 1.25% |
| 3/19/2014 17:43 | 398350650 | 0.3963 | 0.3091 | 129120 | 288.1 | 2.59% |
| 3/19/2014 22:22 | 398433400 | 0.6502 | 0.5031 | 211870 | 296.1 | 4.25% |
| 3/19/2014 22:22 | 398433500 | 0.6505 | 0.5034 | 211970 | 285.7 | 4.25% |
| 3/19/2014 22:23 | 398433600 | 0.6508 | 0.5036 | 212070 | 300.0 | 4.25% |
| 3/19/2014 22:23 | 398433800 | 0.6514 | 0.5041 | 212270 | 292.7 | 4.26% |
| 3/19/2014 22:33 | 398436500 | 0.6597 | 0.5105 | 214970 | 291.4 | 4.31% |
| 3/20/2014 9:16 | 398625700 | 1.2404 | 0.9570 | 404170 | 294.3 | 8.10% |
| 3/20/2014 9:39 | 398631500 | 1.2582 | 0.9731 | 409970 | 249.3 | 8.22% |
| 3/20/2014 10:44 | 398650500 | 1.3165 | 1.0183 | 428970 | 292.5 | 8.60% |
| 3/20/2014 10:44 | 398650700 | 1.3171 | 1.0187 | 429170 | 292.7 | 8.61% |
| 3/20/2014 10:51 | 398652600 | 1.3229 | 1.0232 | 431070 | 292.3 | 8.64% |
| 3/20/2014 10:51 | 398652700 | 1.3232 | 1.0235 | 431170 | 300.0 | 8.65% |
| 3/20/2014 10:52 | 398652800 | 1.3235 | 1.0237 | 431270 | 272.7 | 8.65% |
| 3/20/2014 10:52 | 398652900 | 1.3238 | 1.0239 | 431370 | 315.8 | 8.65% |
| 3/21/2014 8:49 | 399038300 | 2.5066 | 1.9383 | 816770 | 292.7 | 16.38% |
| 3/21/2014 8:49 | 399038500 | 2.5072 | 1.9388 | 816970 | 307.7 | 16.38% |
| 3/21/2014 8:50 | 399038700 | 2.5078 | 1.9393 | 817170 | 292.7 | 16.38% |
| 3/21/2014 8:51 | 399039000 | 2.5087 | 1.9400 | 817470 | 281.3 | 16.39% |
| 3/21/2014 8:51 | 399039100 | 2.509 | 1.9402 | 817570 | 300.0 | 16.39% |
| 3/21/2014 9:23 | 399048200 | 2.537 | 1.9618 | 826670 | 292.6 | 16.58% |
| 3/21/2014 12:43 | 399106800 | 2.7168 | 2.1010 | 885270 | 292.4 | 17.75% |
| 3/21/2014 14:28 | 399137500 | 2.811 | 2.1739 | 915970 | 292.5 | 18.37% |
| 3/21/2014 14:36 | 399139800 | 2.8181 | 2.1793 | 918270 | 293.0 | 18.41% |
| 3/21/2014 16:16 | 399169000 | 2.9077 | 2.2486 | 947470 | 292.6 | 19.00% |
| 3/21/2014 16:16 | 399169100 | 2.908 | 2.2489 | 947570 | 285.7 | 19.00% |
| 3/21/2014 16:16 | 399169200 | 2.9083 | 2.2491 | 947670 | 285.7 | 19.00% |
| 3/21/2014 16:17 | 399169300 | 2.9086 | 2.2494 | 947770 | 285.7 | 19.00% |
| 3/22/2014 7:45 | 399441200 | 3.743 | 2.8944 | 1219670 | 292.7 | 24.46% |
| 3/22/2014 7:46 | 399441400 | 3.7436 | 2.8949 | 1219870 | 285.7 | 24.46% |
| 3/22/2014 7:46 | 399441500 | 3.7439 | 2.8951 | 1219970 | 300.0 | 24.46% |
| 3/24/2014 10:31 | 400332600 | 6.4786 | 5.0091 | 2111070 | 292.7 | 42.33% |
| 3/24/2014 10:31 | 400332700 | 6.4789 | 5.0093 | 2111170 | 315.8 | 42.33% |

***Table 2.*** *Continued*

| Date-Time | Pipe Meter Reading (gallons) | Total Volume Pumped (acre-feet) | Time Since Pumping Started (days) | Total Volume Pumped (gallons) | Pumping Flow Rate (gpm) | Volume Pumped Relative to Volume Injected |
|---|---|---|---|---|---|---|
| 3/24/2014 10:48 | 400337800 | 6.4946 | 5.0214 | 2116270 | 292.5 | 42.43% |
| 3/24/2014 10:49 | 400337900 | 6.4949 | 5.0217 | 2116370 | 260.9 | 42.43% |
| 3/24/2014 10:49 | 400338000 | 6.4952 | 5.0219 | 2116470 | 260.9 | 42.44% |
| 3/24/2014 10:50 | 400338100 | 6.4955 | 5.0222 | 2116570 | 240.0 | 42.44% |
| 3/24/2014 10:50 | 400338150 | 6.4957 | 5.0223 | 2116620 | 272.7 | 42.44% |
| 3/24/2014 10:50 | 400338200 | 6.4958 | 5.0225 | 2116670 | 187.5 | 42.44% |
| 3/24/2014 10:50 | 400338250 | 6.496 | 5.0227 | 2116720 | 214.3 | 42.44% |
| 3/24/2014 10:50 | 400338300 | 6.4961 | 5.0229 | 2116770 | 214.3 | 42.44% |
| 3/24/2014 10:51 | 400338350 | 6.4963 | 5.0230 | 2116820 | 214.3 | 42.44% |
| 3/24/2014 10:51 | 400338400 | 6.4964 | 5.0232 | 2116870 | 230.8 | 42.44% |
| 3/24/2014 10:51 | 400338450 | 6.4966 | 5.0233 | 2116920 | 230.8 | 42.45% |
| 3/24/2014 10:51 | 400338500 | 6.4967 | 5.0235 | 2116970 | 214.3 | 42.45% |
| 3/24/2014 10:52 | 400338550 | 6.4969 | 5.0236 | 2117020 | 250.0 | 42.45% |
| 3/24/2014 10:52 | 400338600 | 6.497 | 5.0238 | 2117070 | 214.3 | 42.45% |
| 3/24/2014 10:52 | 400338650 | 6.4972 | 5.0240 | 2117120 | 200.0 | 42.45% |
| 3/24/2014 10:52 | 400338700 | 6.4973 | 5.0241 | 2117170 | 187.5 | 42.45% |
| 3/24/2014 10:53 | 400338750 | 6.4975 | 5.0243 | 2117220 | 187.5 | 42.45% |
| 3/24/2014 10:53 | 400338800 | 6.4977 | 5.0245 | 2117270 | 187.5 | 42.45% |
| 3/24/2014 10:56 | 400338950 | 6.4981 | 5.0264 | 2117420 | 55.6 | 42.46% |
| 3/24/2014 10:56 | 400338950 | 6.4981 | 5.0264 | 2117420 | 0.0 | 42.46% |

## Modeling

### Aquifer Test Analyses

I used AQTESOLV (Duffield, 2007) computer software to determine aquifer transmissivity from test data collected during the pumping period. I did not analyze the injection data. I applied a Theis (1935)/Hantush (1961) solution for a confined aquifer. Variation in the groundwater level data prevented a more precise analysis and model of the drawdown and recovery curves. I applied alternate solutions that produced results within an order of magnitude of the Theis (1935)/Hantush (1961) approximation.

### Injection Model

I used AQTESOLV (Duffield, 2007) to determine potentiometric surface changes due to injection and to create an area of influence (AOI). Using the parameters determined from aquifer test analyses, the groundwater level map, and geologic cross sections, I modeled the magnitude of potentiometric changes in the aquifer that various rates of injection would induce. For injection, I assumed that Millville would inject water into the aquifer system at 300 gallons per minute for 181 days per year and then pump out about 60 ac-ft/yr of that water during July, August, and September.

### Drinking Water Source Protection Zones

I reevaluated the DWSP zones based on recalculated aquifer properties and the presence of the East Cache fault. I determined horizontal hydrologic gradient using the groundwater level map created for this study. I used cross sections created for this study and the Glenridge well log (appendix A) to determine aquifer thickness.

To determine hydraulic conductivity, I recalculated data from Inkenbrandt (2010) using information gained from the aquifer test analyses and incorporated more recent data collected during the pumping test. I used the EBK method to interpolate both lower confined aquifer (A2) and bulk aquifer properties.

### Geochemical Modeling

I used PHREEQC software to conduct a very basic mixing model to determine the various phases produced when the Garr Spring water was mixed with the Glenridge well water. I then compared the results of the model to the analysis of samples collected on 3/24/2014. See appendix H for the details of this model.

# RESULTS AND DISCUSSION

## Background Chemistry

Garr Spring and Glenridge well water have very similar geochemistry (figure 11; table 3). Both are calcium-magnesium-bicarbonate water. Geochemical modeling does not suggest that mixing of Garr Spring water with Cache Valley principal aquifer (Glenridge well) water would cause mobilization of nitrate. However, the mixing model does not account for material of other phases (liquid or solid) in the aquifer, which may change phase if exposed to this water. Appendices I and J have the complete results of laboratory analyses.

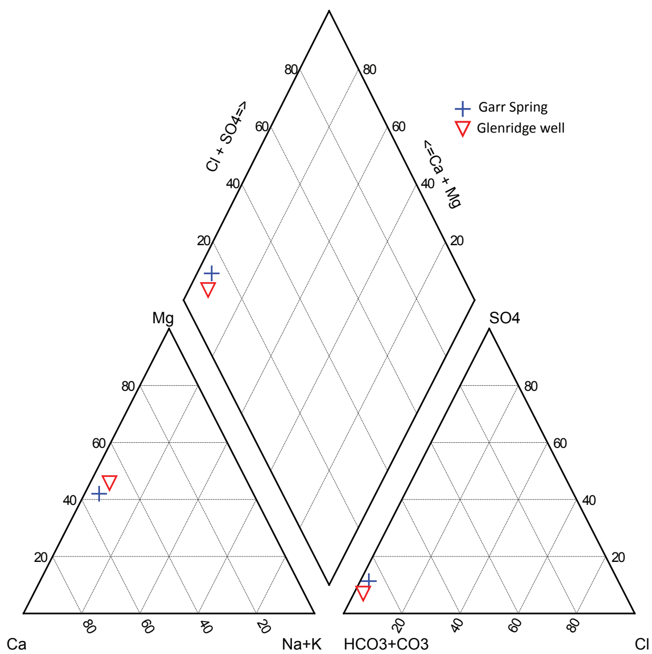


***Figure 11.*** *Piper (trilinear) diagram showing Garr Spring and Glenridge well water chemistry.*

## Aquifer Properties

Based on the interpolated potentiometric surface of the principal aquifer (figure 12), the horizontal hydrologic gradient near the Glenridge well is 0.004. The mean horizontal hydraulic gradient direction in the area of Millville is down to the west (278 degrees from north) near the well (figure 12).

The aquifers vary in thickness depending on location. Based on the cross section (figures 13 and 14) and the Glenridge well driller's log, the aquifer is about 100 feet thick near the Glenridge well. Most of the clay within 0.25 mile (0.4 km) of the Glenridge well is greater than 80-feet (24m) thick (figure 13). If the interpretation of driller's logs is correct, then the aquifer in the region of Millville coincides well with the conceptual model presented by Robinson (1999) (figure 7). Clay thickness calculations (figure 13) substantiate the recharge areas designated in the map from Anderson and others (1994). However, the clay layers thin substantially upgradient (east) of the Glenridge well, where Provo-level Bonneville lake gravels are predominant at the surface (Evans and others, 1996). There may be some thin, intermittent clay layers east of the Glenridge well, allowing for the flow observed at Skinner and Knoll springs (figure 13 and figure 14).

Based on aquifer test analyses (figure 15), the transmissivity of the principal aquifer near the Glenridge well is 135,000 $ft^2$/day (12,540 $m^2$/day), which, based on an aquifer thickness of 100 feet (30.5 m), equals a hydraulic conductivity of 1350 ft/day (411 m/day). The hydraulic conductivity is extremely high and would be an appropriate value for gravel (Heath, 1983). The transmissivity from the test fits well with other values reinterpolated from Inkenbrandt (2010) (figure 16).

Injection test data were not analyzed due to disruption of the water-level data during injection (figure 17). During the injection portion of the test, the water level in the well dropped about six feet immediately after injection began and stayed at the depressed level until injection stopped (figure 17). This depressed water level is likely due to jetting of water from the injection column (pipe) into the well. There is a significant change in fluid velocity from the port of the injection column, which can lead to a Venturi (Bernoulli) effect in the well casing.

A cone of depression or recharge mound created by a well in a high transmissivity aquifer will exhibit small amounts of potentiometric surface change over a very large area. Based on the transmissivity from the aquifer test using the Glenridge well, injection modeling displays a wide swath of influence. The maximum increase would be about 0.3 feet near the well after an injection cycle and that increase would be negligible after a post-injection pumping cycle. The maximum rate possible for the current injection column is 300 gallons per minute. Based on water rights, Millville would inject from the beginning of October to the end of May the following year (181 days).

Fining of the aquifer material to the west, change of the vertical hydraulic gradient from recharge to discharge zones, and a decrease in horizontal hydraulic gradient all account for lower hydraulic conductivities to the west of Millville (Inkenbrandt, 2010).

## Nitrate Source(s)

The Utah State University Water Laboratory tests detected, but did not measure, small amounts of DEET and pharmaceuticals in water from the Glenridge well, indicating that septic systems are likely contributing contaminants to the principal aquifer system near the well.

Nitrate values interpolated in the area (figure 18; table 4) indicate that an extensive nitrate plume covers most of the central

***Table 3.*** *Results of analyses from the Utah State Health Department laboratory. See appendices I and J for a full discloser of results.*

| Station | Date-time | Aluminum | Ammonia as N | Antimony | Arsenic | Barium | Beryllium | Bicarbonate | Boron | Cadmium | Calcium | Carbon Dioxide | Carbonate | Chloride | Chromium | Copper | Cyanide | Fluoride | Hardness | Hydroxide | Iron | Lead | Magnesium |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | ug/l | mg/l | ug/l | ug/l | mg/l | ug/l | mg/l | ug/l | ug/l | mg/l | mg/l | mg/l | mg/l | ug/l | ug/l | mg/l | mg/l | mg/l | mg/l | mg/l | ug/l | mg/l |
| Hancey Well | 2/28/14 12:50 PM | | | | | | | | | | | | | | | | | | | | | | |
| | 3/19/14 4:00 PM | | | | | | | | | | | | | | | | | | | | | | |
| Garr Spring | 2/28/14 9:15 AM | | <0.045 | <3 | <1 | <0.1 | <1 | | | 0.20 | | | | | 9.7 | 2.19 | <0.01 | 0.09 | | | | 0.12 | |
| Glenridge Well | 2/28/14 11:15 AM | | <0.045 | <3 | 1.09 | 0.22 | <1 | | | 0.13 | | | | | 15.9 | 1.63 | <0.01 | 0.11 | | | | 0.48 | |
| | 3/19/14 2:05 PM | | <0.045 | | | | | | | | | | | | | | | | | | | | |
| | 3/19/14 10:15 PM | | | | | | | | | | | | | | | | | | | | | | |
| | 3/19/14 4:30 PM | | | | | | | | | | | | | | | | | | | | | | |
| | 3/20/14 8:50 AM | | | | | | | | | | | | | | | | | | | | | | |
| | 3/24/14 10:15 AM | <10 | <0.045 | | <1 | 0.13 | | 302 | <30 | <0.1 | 60.9 | 10 | 0 | 11.7 | <2 | 1.402 | | | 274.1 | 0 | <0.02 | 0.26 | 31.1 |
| USU WELL | 2/28/14 2:06 PM | | | | | | | | | | | | | | | | | | | | | | |
| | 3/31/14 11:55 AM | <10 | | | <1 | <0.1 | | | <30 | <0.1 | 66 | | | | <2 | <1 | | | | | 0.62 | <0.1 | 25.4 |

| Station | Date-time | Manganese | Mercury | Nickel | Nitrate + Nitrite as N | Nitrate as N | Nitrite as N | pH | Phosphate (as P) | Potassium | Selenium | Silver | Sodium | Sp. Cond. | Sulfate | T. Alk/CaCO3 | T. Sus. Solids | TDS @ 180 C | Thallium | Turbidity | Uranium 238 | Zinc |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | ug/l | ug/l | ug/l | mg/l | mg/l | mg/l | | mg/l | mg/l | ug/l | ug/l | mg/l | umhos/cm | mg/l | mg/l | mg/l | mg/l | ug/l | ntu | ug/l | ug/l |
| Hancey Well | 2/28/14 12:50 PM | | | | | 2.00 | <0.11 | | | | | | | | | | | | | | | |
| | 3/19/14 4:00 PM | | | | 1.82 | | | | | | | | | | | | | | | | | |
| Garr Spring | 2/28/14 9:15 AM | | <0.2 | <5 | 0.76 | 0.73 | <0.11 | | 0.02 | | <3.28 | | 4.28 | | 27 | | | 254 | <0.1 | | 1.22 | |
| Glenridge Well | 2/28/14 11:15 AM | | <0.2 | <5 | 7.65 | 7.65 | <0.11 | | 0.06 | | <3.28 | | 12.6 | | 23.3 | | | 426 | <0.1 | <0.1 | 1.74 | |
| | 3/19/14 2:05 PM | | | | 0.77 | | | | 0.03 | | | | | | | | | | | | | |
| | 3/19/14 10:15 PM | | | | | 0.85 | | | | | | | | | | | | | | | | |
| | 3/19/14 4:30 PM | | | | 0.80 | | | | | | | | | | | | | | | | | |
| | 3/20/14 8:50 AM | | | | 1.04 | | | | | | | | | | | | | | | | | |
| | 3/24/14 10:15 AM | <5 | <0.2 | <5 | 0.05 | | | 7.68 | 0.05 | 1.16 | <3.28 | <1.64 | 7.62 | 562 | 25.1 | 248 | <4 | 332 | | | | <10 |
| USU WELL | 2/28/14 2:06 PM | | | | | 1.08 | <0.11 | | | | | | | | | | | | | | | |
| | 3/31/14 11:55 AM | 7.401 | <0.2 | <5 | 0.95 | | | | 0.04 | 1.47 | <3.28 | <1.64 | 6.66 | | | | | | | | | 98.65 |

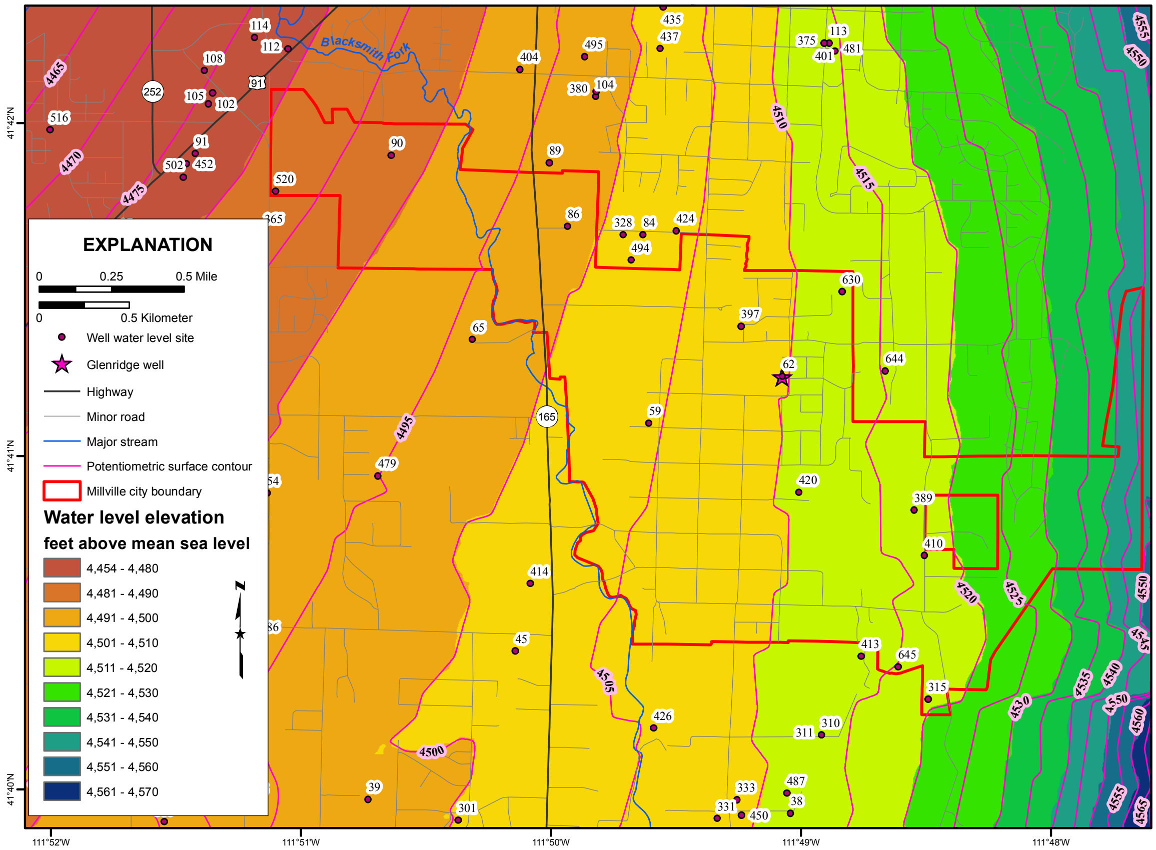


*Figure 12. Potentiometric surface contours created using cokriging interpolation of groundwater levels and elevation data in the Millville area. Numbers adjacent to sample sites are sample numbers listed in appendix D.*

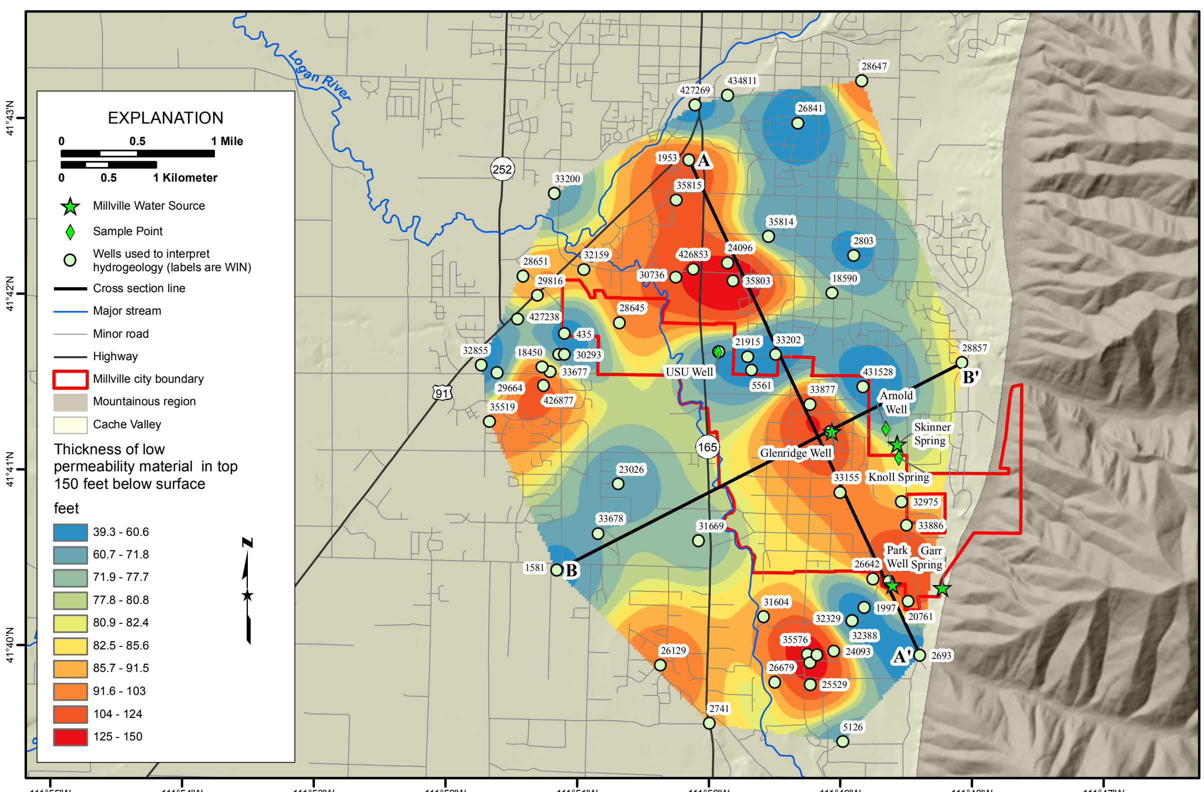


*Figure 13. Thickness and distribution of low permeability units and cross section locations. Wells are labeled by their Utah Division of Water Rights well identification number (WIN). See figure 14 for cross sections.*

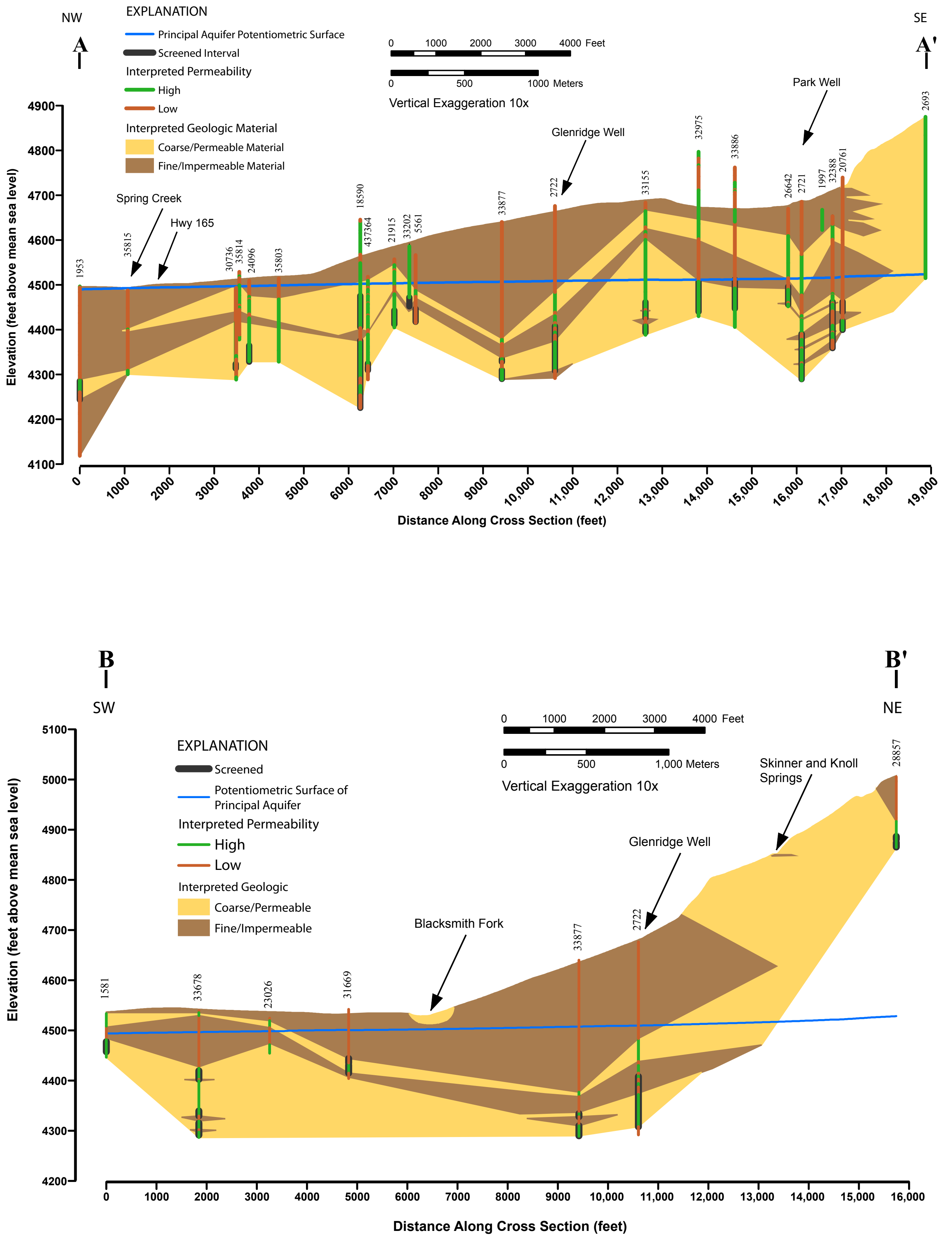


***Figure 14.*** *Geologic cross sections of Millville area. See figure 13 for location of sections. See appendix E for a summary of the well logs used to make these sections. Numbers above wells indicate the Utah Division of Water Rights well identification number (WIN).*

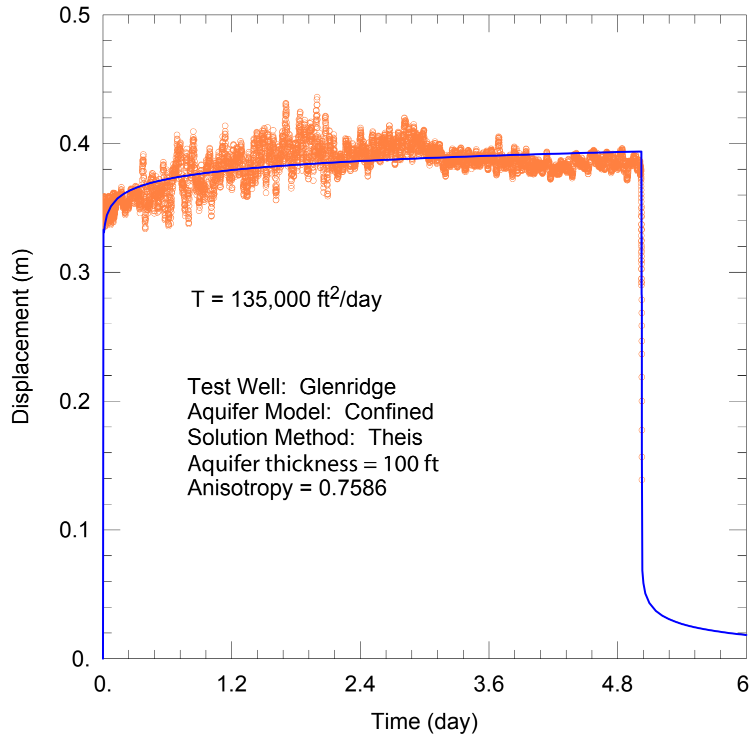


***Figure 15.** Aquifer test analysis of post-injection pumping data.*

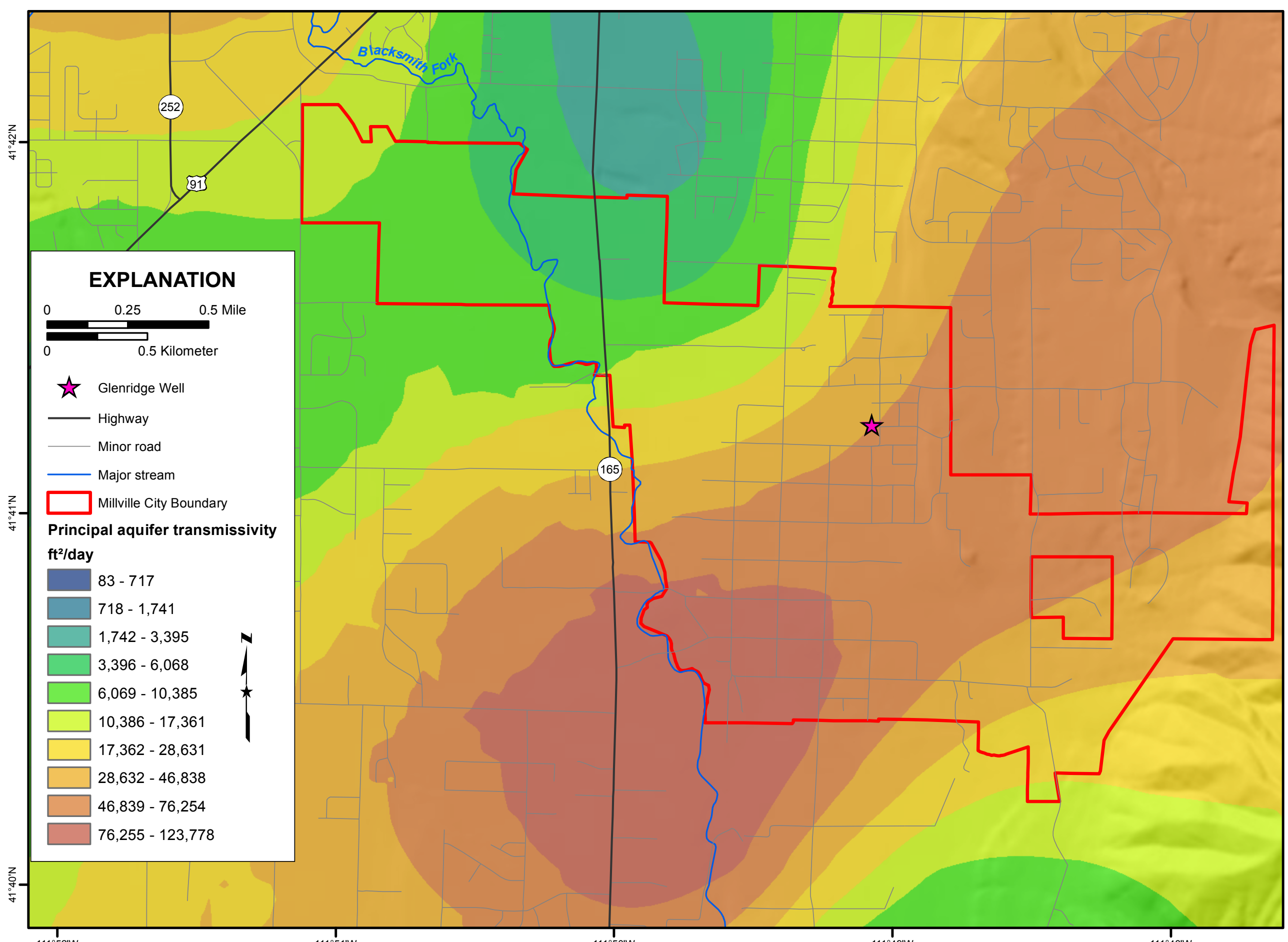


***Figure 16.** Transmissivity of the Cache Valley principal aquifer modified from Inkenbrandt (2010).*

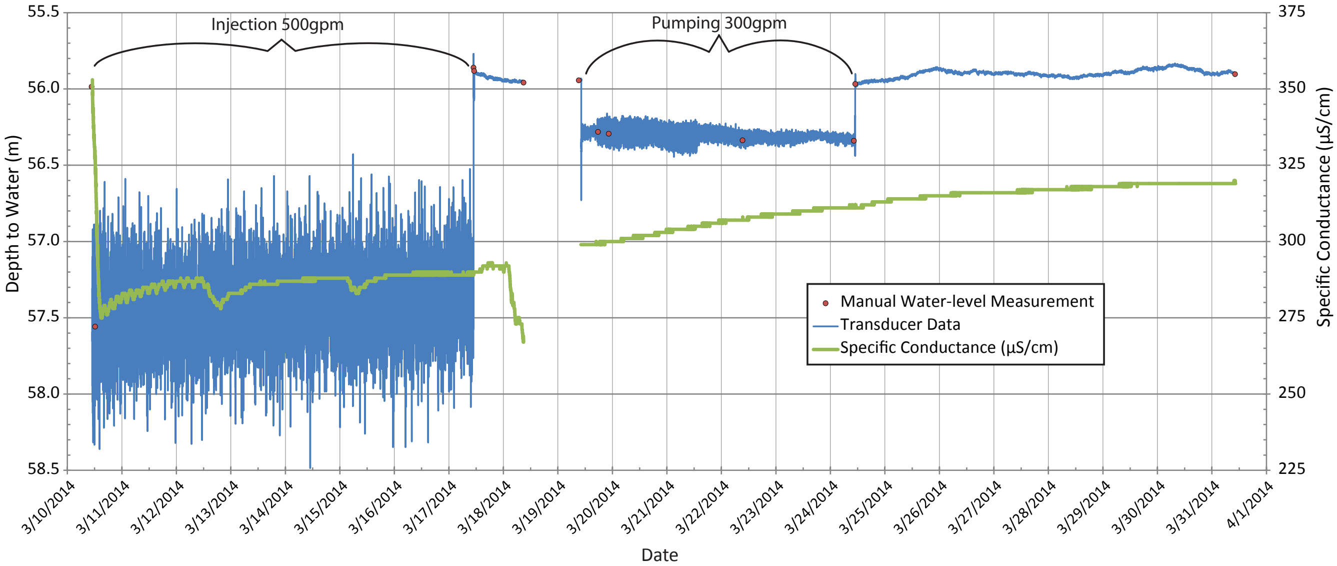


***Figure 17.*** *Hydrograph of injection and pumping test of the Glenridge well.*

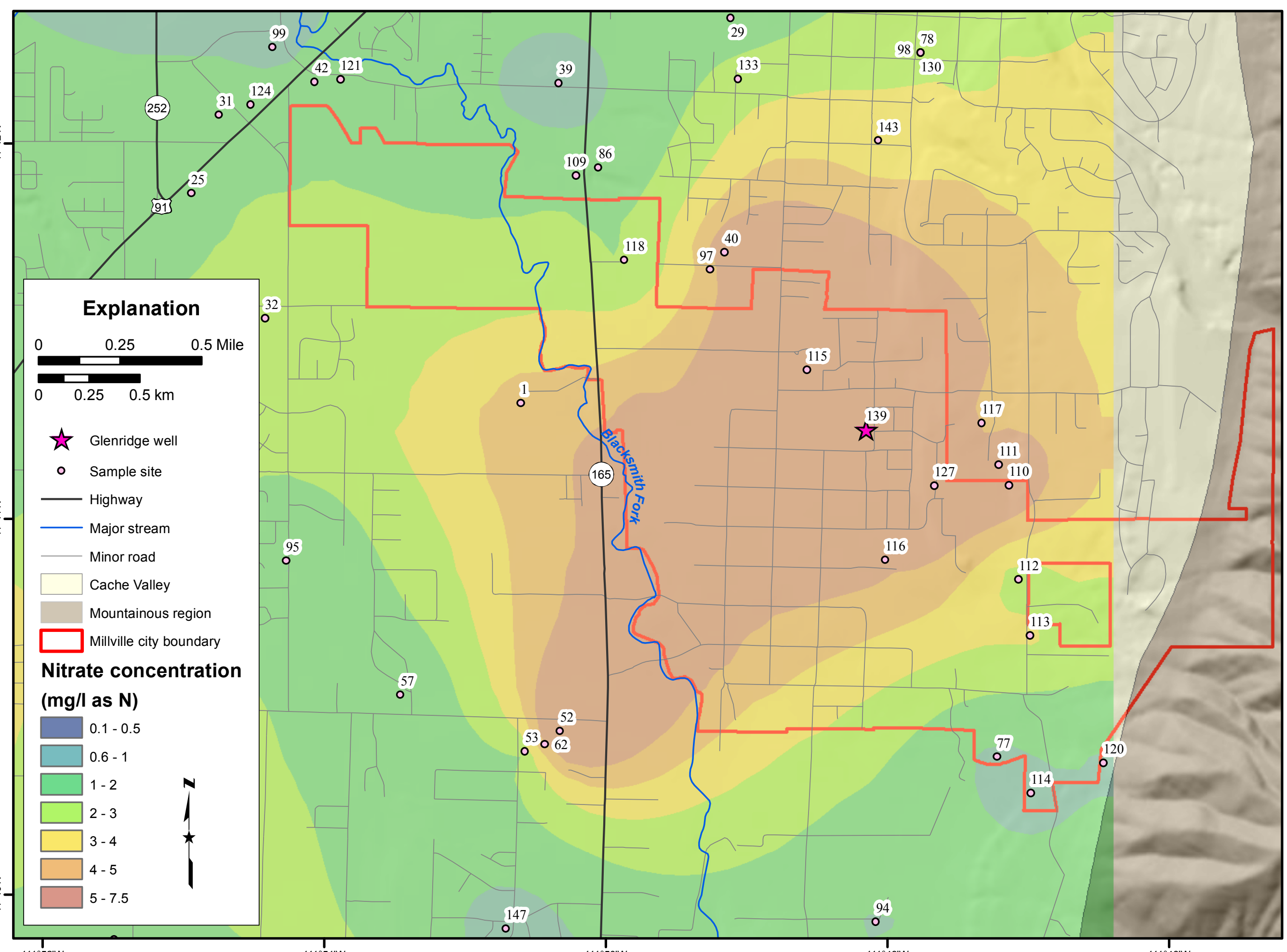


***Figure 18.*** *Nitrate concentrations in the Millville area. Numbers adjacent to sample sites are the nitrate sample numbers listed in table 4.*

*Table 4.* Nitrate samples interpolated and examined in this study. See figure 18 for the interpolated values.

| Map ID | Longitude | Latitude | Sample Date | Concentration (mg/L NO3-N) | Data Source | Site Name |
|---|---|---|---|---|---|---|
| 1 | -111.8386 | 41.6887 | 11/9/2004 | 5.2 | UGS | CVSS13 |
| 2 | -111.8532 | 41.7505 | 12/3/1997 | 0.86 | UGS | Quayle, James W. |
| 3 | -111.8966 | 41.6541 | 12/3/1997 | 0.1 | UGS | USU |
| 4 | -111.8794 | 41.7254 | 11/20/1997 | 0.43 | UGS | Potter, Charles |
| 5 | -111.8838 | 41.7087 | 11/20/1997 | 1.46 | UGS | Thompson, Leslie |
| 6 | -111.8998 | 41.6545 | 12/2/1997 | 0.1 | UGS | USU #2 |
| 7 | -111.9006 | 41.6904 | 11/20/1997 | 0.56 | UGS | Jensen, Alvin |
| 8 | -111.8955 | 41.6999 | 11/20/1997 | 0.47 | UGS | Israelsen, Clark |
| 9 | -111.9000 | 41.6419 | 12/2/1997 | 0.1 | UGS | Leishman, Kendall |
| 10 | -111.8795 | 41.6469 | 12/2/1997 | 4.09 | UGS | Miller, Richard L. |
| 11 | -111.8978 | 41.6666 | 12/2/1997 | 0.29 | UGS | Anderson, A. James |
| 12 | -111.8967 | 41.7217 | 11/20/1997 | 0.1 | UGS | Thalman, Richard |
| 13 | -111.8934 | 41.6782 | 11/20/1997 | 0.46 | UGS | Skidmore, Kimberly |
| 14 | -111.8902 | 41.7367 | 12/2/1997 | 2.54 | UGS | Eliason Packing Co. |
| 15 | -111.8913 | 41.6834 | 12/16/1997 | 0.75 | UGS | Olsen, Kent L. |
| 16 | -111.8894 | 41.6708 | 12/16/1997 | 0.18 | UGS | Bridges, Seldon |
| 17 | -111.8869 | 41.6358 | 12/16/1997 | 0.1 | UGS | Austin, Richard |
| 18 | -111.8897 | 41.6686 | 12/3/1997 | 0.61 | UGS | Utah State University |
| 19 | -111.8726 | 41.6921 | 11/19/1997 | 0.75 | UGS | Kunsman, Lisa |
| 20 | -111.8649 | 41.7400 | 11/20/1997 | 0.5 | UGS | Thalman, Robert |
| 21 | -111.8060 | 41.7213 | 11/19/1997 | 3.58 | UGS | Andrews, Ronald |
| 22 | -111.8604 | 41.7449 | 11/20/1997 | 0.4 | UGS | Bodrero, Darrell |
| 23 | -111.8155 | 41.7204 | 11/19/1997 | 0.1 | UGS | Rounds, Arlyn |
| 24 | -111.8642 | 41.6926 | 11/19/1997 | 1.4 | UGS | Hansen, Kay D. |
| 25 | -111.8583 | 41.6979 | 11/19/1997 | 1.47 | UGS | Russell, Bert |
| 26 | -111.8634 | 41.6752 | 11/19/1997 | 1.38 | UGS | Floyd, W.D. |
| 27 | -111.8734 | 41.7226 | 11/19/1997 | 2.32 | UGS | Jensen, Robert L. |
| 28 | -111.8730 | 41.7017 | 11/19/1997 | 1.41 | UGS | Isaacson, Merl |
| 29 | -111.8264 | 41.7059 | 11/19/1997 | 0.57 | UGS | Gustaveson, Rex |
| 30 | -111.8605 | 41.7317 | 11/20/1997 | 0.1 | UGS | Clark, Darala & Merril, Glacus |
| 31 | -111.8567 | 41.7013 | 11/19/1997 | 1.58 | UGS | Hyclone |
| 32 | -111.8538 | 41.6923 | 11/19/1997 | 1.88 | UGS | Smith, Claine |
| 33 | -111.8674 | 41.7390 | 11/20/1997 | 0.1 | UGS | Holographic Products |
| 34 | -111.8744 | 41.6852 | 11/19/1997 | 0.7 | UGS | Hansen, Hal |
| 35 | -111.8371 | 41.7102 | 11/19/1997 | 3.14 | UGS | Weston, Todd G. |
| 36 | -111.8459 | 41.6621 | 11/19/1997 | 2.14 | UGS | Peterson, Steve and Cindy |
| 37 | -111.8352 | 41.6476 | 11/18/1997 | 0.51 | UGS | Larsen, Kent |
| 38 | -111.8639 | 41.6556 | 11/19/1997 | 0.26 | UGS | Miller, E.A. - Corp. |
| 39 | -111.8366 | 41.7029 | 11/19/1997 | 0.1 | UGS | Alder, Seth L. |
| 40 | -111.8267 | 41.6955 | 11/19/1997 | 9.71 | UGS | Olsen, David |
| 41 | -111.8736 | 41.6932 | 11/19/1997 | 0.58 | UGS | Jenson, Edwin |
| 42 | -111.8510 | 41.7029 | 11/19/1997 | 1.54 | UGS | Zollinger, LA |
| 43 | -111.8206 | 41.7158 | 11/19/1997 | 0.83 | UGS | Smith, Arthur D. |
| 44 | -111.8630 | 41.6930 | 11/19/1997 | 1.16 | UGS | Isaacson, Merle |
| 45 | -111.8624 | 41.6647 | 11/19/1997 | 1.25 | UGS | Wright, Steven |
| 46 | -111.8716 | 41.6746 | 12/16/1997 | 4.03 | UGS | Zollinger, Sid |
| 47 | -111.8970 | 41.6245 | 5/13/1998 | 0.27 | UGS | Nielsen |
| 48 | -111.8486 | 41.6433 | 3/9/1998 | 0.352 | UGS | well 1, hyrum |
| 49 | -111.8567 | 41.6475 | 3/9/1998 | 3.46 | UGS | well 2, hyrum |
| 50 | -111.8686 | 41.6517 | 3/9/1998 | 5.23 | UGS | well 4, hyrum |
| 51 | -111.8792 | 41.6522 | 3/9/1998 | 3.54 | UGS | well 5, hyrum |
| 52 | -111.8361 | 41.6742 | 9/1/2004 | 9 | UDAF | 1488 |
| 53 | -111.8382 | 41.6732 | 9/6/2000 | 1.5 | UDAF | 1489 |
| 54 | -111.8927 | 41.6304 | 9/1/2004 | 3.2 | UDAF | 1490 |
| 55 | -111.8911 | 41.6833 | 9/13/2000 | 1.2 | UDAF | 1492 |
| 56 | -111.8912 | 41.6850 | 9/13/2000 | 1.5 | UDAF | 1493 |
| 57 | -111.8456 | 41.6757 | 10/10/2000 | 0.9 | UDAF | 1494 |
| 58 | -111.8617 | 41.6747 | 8/1/2002 | 2 | UDAF | 1501 |
| 59 | -111.8169 | 41.6461 | 8/1/2002 | 0.6 | UDAF | 1502 |
| 60 | -111.8168 | 41.6458 | 8/1/2002 | 0.8 | UDAF | 1503 |
| 61 | -111.8905 | 41.6850 | 9/1/2004 | 1 | UDAF | 1509 |

***Table 4.*** *Continued*

| Map ID | Longitude | Latitude | Sample Date | Concentration (mg/L NO3-N) | Data Source | Site Name |
|---|---|---|---|---|---|---|
| 62 | -111.8370 | 41.6736 | 9/1/2004 | 5.8 | UDAF | 1511 |
| 63 | -111.8932 | 41.6297 | 9/1/2004 | 3.5 | UDAF | 1514 |
| 64 | -111.8903 | 41.6306 | 9/1/2004 | 2 | UDAF | 1523 |
| 65 | -111.8553 | 41.7336 | 9/6/2000 | 0.5 | UDAF | 1569 |
| 66 | -111.8574 | 41.7236 | 6/27/2001 | 3.8 | UDAF | 1572 |
| 67 | -111.8621 | 41.7106 | 9/1/2004 | 0.1 | UDAF | 1590 |
| 68 | -111.8853 | 41.7192 | 9/6/2000 | 0.8 | UDAF | 2823 |
| 69 | -111.8935 | 41.6985 | 9/6/2000 | 0.1 | UDAF | 2824 |
| 70 | -111.8602 | 41.7279 | 9/13/2006 | 0.8608 | UDAF | 3162 |
| 71 | -111.8734 | 41.6931 | 9/13/2006 | 0.8022 | UDAF | 3165 |
| 72 | -111.8933 | 41.7185 | 9/13/2006 | 0.4634 | UDAF | 3166 |
| 73 | -111.8191 | 41.6427 | 6/20/1988 | 1 | STORET_Leg | 300102 |
| 74 | -111.8187 | 41.6413 | 6/20/1982 | 3.2 | STORET_Leg | 300103 |
| 75 | -111.8336 | 41.6341 | 6/20/1988 | 1 | STORET_Leg | 300803 |
| 76 | -111.8319 | 41.6272 | 6/20/1988 | 0.5 | STORET_Leg | 300804 |
| 77 | -111.8102 | 41.6732 | 6/20/1978 | 0.6 | STORET_Leg | 301203 |
| 78 | -111.8151 | 41.7045 | 6/20/1988 | 2.6 | STORET_Leg | 301702 |
| 79 | -111.8261 | 41.7235 | 6/20/1985 | 1.7 | STORET_Leg | 301901 |
| 80 | -111.8186 | 41.7233 | 6/20/1988 | 0.4 | STORET_Leg | 301904 |
| 81 | -111.8972 | 41.6588 | 6/20/1988 | 0.2 | STORET_Leg | 309001 |
| 82 | -111.8897 | 41.6981 | 12/2/1980 | 0.146835 | STORET | 4904980 |
| 83 | -111.8997 | 41.7394 | 9/24/1991 | 0.249619 | STORET | 4905070 |
| 84 | -111.8686 | 41.7364 | 2/7/1979 | 0.2259 | STORET | 4905110 |
| 85 | -111.8694 | 41.7367 | 12/2/1980 | 0.1 | STORET | 4905120 |
| 86 | -111.8342 | 41.6992 | 6/6/1978 | 0.4518 | STORET | 4905410 |
| 87 | -111.8803 | 41.6519 | 7/20/1988 | 2.085057 | STORET | 4905520 |
| 88 | -111.8683 | 41.6558 | 7/9/1985 | 0.137799 | STORET | 4905540 |
| 89 | -111.8905 | 41.6269 | 4/18/1968 | 0.1 | USGS_NWIS | (A-10- 1) 6ccc- 1 |
| 90 | -111.8333 | 41.6338 | 6/17/1968 | 0.203 | USGS_NWIS | (A-10- 1) 4daa- 1 |
| 91 | -111.8605 | 41.6438 | 3/28/1968 | 0.136 | USGS_NWIS | (A-11- 1)32dcb- 1 |
| 92 | -111.8924 | 41.6466 | 3/20/1968 | 0.339 | USGS_NWIS | (B-11- 1)36dad- 1 |
| 93 | -111.8272 | 41.6566 | 7/4/1968 | 0.361 | USGS_NWIS | (A-11- 1)27cdc- 1 |
| 94 | -111.8173 | 41.6658 | 10/6/1998 | 0.826 | USGS_NWIS | (A-11- 1)27adb- 1 |
| 95 | -111.8524 | 41.6816 | 7/4/1968 | 0.745 | USGS_NWIS | (A-11- 1)20ada- 1 |
| 96 | -111.8733 | 41.6858 | 8/31/1962 | 0.339 | USGS_NWIS | (A-11- 1)18ddd- 1 |
| 97 | -111.8275 | 41.6947 | 8/17/2011 | 3.85 | USGS_NWIS | (A-11- 1)15bdb- 1 S29 |
| 98 | -111.8152 | 41.7044 | 8/31/1966 | 2.48 | USGS_NWIS | (A-11- 1)10dad- 1 |
| 99 | -111.8536 | 41.7044 | 4/4/1961 | 0.361 | USGS_NWIS | (A-11- 1) 8dda- 3 |
| 100 | -111.8416 | 41.7102 | 7/20/1960 | 1.69 | USGS_NWIS | (A-11- 1) 9acb- 2 |
| 101 | -111.8258 | 41.7244 | 3/12/1954 | 1.6 | USGS_NWIS | (A-11- 1) 3bda- 1 |
| 102 | -111.8202 | 41.7255 | 3/12/1954 | 2.17 | USGS_NWIS | (A-11- 1) 3aca- 1 |
| 103 | -111.8286 | 41.7313 | 2/1/1963 | 0.271 | USGS_NWIS | (A-12- 1)34cca- 1 |
| 104 | -111.8772 | 41.7358 | 8/31/1962 | 0.429 | USGS_NWIS | (A-12- 1)31dab- 1 |
| 105 | -111.8705 | 41.7360 | 2/6/1963 | 0.294 | USGS_NWIS | (A-12- 1)32cbb- 1 |
| 106 | -111.8127 | 41.7380 | 3/14/1963 | 0.203 | USGS_NWIS | (A-12- 1)35bcc- 1 |
| 107 | -111.8194 | 41.7447 | 6/15/1962 | 0.136 | USGS_NWIS | (A-12- 1)27dcd- 1 |
| 108 | -111.8274 | 41.7497 | 1/3/1964 | 0.181 | USGS_NWIS | (A-12- 1)27cab- 1 |
| 109 | -111.8355 | 41.6988 | 5/8/1968 | 3.16 | USGS_NWIS | (A-11- 1)15bbc-S1 |
| 110 | -111.8097 | 41.6853 | 6/20/2012 | 6.89 | Millville City | Knowles Springs |
| 111 | -111.8103 | 41.6862 | 6/20/2012 | 6.03 | Millville City | Mathews Spring |
| 112 | -111.8091 | 41.6811 | 6/20/2012 | 1.91 | Millville City | Owen Hancey Well |
| 113 | -111.8084 | 41.6786 | 6/20/2012 | 3.48 | Millville City | K. Hancey Well |
| 114 | -111.8082 | 41.6716 | 6/20/2012 | 0.73 | Millville City | Postma Well |
| 115 | -111.8217 | 41.6903 | 6/20/2012 | 6.83 | Millville City | LEGRAND MATHEWS |
| 116 | -111.8170 | 41.6819 | 6/20/2009 | 5.43 | Millville City | Cox Well |
| 117 | -111.8113 | 41.6880 | 3/21/2014 | 4.07 | UGS | Arnold Well |
| 118 | -111.8326 | 41.6951 | 2/28/2014 | 1.08 | UGS | <Null> |
| 119 | -111.8097 | 41.7433 | 9/18/2012 | 0.6 | SDWIS | NATURAL RESOURCES BUILDING WELL |
| 120 | -111.8039 | 41.6730 | 8/24/2012 | 0.778 | SDWIS | GARR SPRING |
| 121 | -111.8495 | 41.7030 | 8/23/2012 | 1.24 | SDWIS | ZOLLINGER WELL |
| 122 | -111.8226 | 41.6444 | 7/31/2012 | 5.4 | SDWIS | NUMBER ONE SPRING |

*Table 4. Continued*

| Map ID | Longitude | Latitude | Sample Date | Concentration (mg/L NO3-N) | Data Source | Site Name |
|---|---|---|---|---|---|---|
| 123 | -111.8264 | 41.7243 | 12/13/2005 | 2.01 | SDWIS | LOWER WELL |
| 124 | -111.8548 | 41.7018 | 11/30/1998 | 1.52 | SDWIS | ARTESIAN WELL |
| 125 | -111.8972 | 41.6588 | 2/24/1998 | 0.4 | SDWIS | THATCHER WELL |
| 126 | -111.9014 | 41.6587 | 9/8/1994 | 0.1 | SDWIS | NEW WELL |
| 127 | -111.8141 | 41.6852 | 8/23/2012 | 6.03 | SDWIS | MATTHEWS SPRING |
| 128 | -111.8133 | 41.7382 | 1/11/2012 | 0.4 | SDWIS | CROCKETT AVE#1 WELL |
| 130 | -111.8150 | 41.7043 | 8/15/2007 | 2.71 | SDWIS | DALES WELL 100 E 200 S |
| 131 | -111.8205 | 41.7247 | 12/13/2005 | 1.86 | SDWIS | UPPER WELL |
| 132 | -111.8335 | 41.6339 | 11/1/2012 | 0.7 | SDWIS | WELL #1 |
| 133 | -111.8260 | 41.7032 | 9/27/2012 | 3.6 | SDWIS | ALDER-WEST WELL |
| 134 | -111.8072 | 41.7439 | 9/18/2012 | 0.5 | SDWIS | INDUSTRIAL SCIENCE WELL |
| 136 | -111.8289 | 41.7306 | 8/15/2012 | 0.5 | SDWIS | 200 E CENTER WELL |
| 138 | -111.8997 | 41.6598 | 11/14/1991 | 0.1 | SDWIS | OLD FARM N WELL |
| 139 | -111.8182 | 41.6877 | 8/24/2012 | 7.81 | SDWIS | GLENRIDGE WELL |
| 140 | -111.8332 | 41.6600 | 7/31/2012 | 0.5 | SDWIS | 4000 SOUTH MAIN WELL |
| 141 | -111.8189 | 41.7229 | 6/29/2012 | 2.4 | SDWIS | MUNICIPAL WELL |
| 142 | -111.8196 | 41.7444 | 1/11/2012 | 0.4 | SDWIS | 700 N 600 E WELL |
| 143 | -111.8176 | 41.7005 | 9/30/2008 | 2.84 | SDWIS | 400 S PROVIDENCE WELL |
| 144 | -111.8319 | 41.6272 | 10/14/1988 | 0.57 | SDWIS | WELL #2 DISCONNECTED |
| 145 | -111.8478 | 41.7194 | 8/15/2012 | 0.4 | SDWIS | WILLOW PARK WELL |
| 146 | -111.8188 | 41.6402 | 9/4/1990 | 0.51 | SDWIS | THOMAS IRR WELL |
| 147 | -111.8392 | 41.6654 | 7/31/2012 | 0.4 | SDWIS | NELSON WELL |
| 148 | -111.8279 | 41.7495 | 11/7/2002 | 0.84 | SDWIS | 1000 N 300 E WELL |
| 150 | -111.9347 | 41.6924 | 7/21/1948 | 0.045001 | WQP | USGS-414133111560201 |
| 152 | -111.9111 | 41.7416 | 6/30/1948 | 0.02259 | WQP | USGS-414430111543701 |
| 155 | -111.9180 | 41.7860 | 7/12/1948 | 1.310019 | WQP | USGS-414710111550201 |
| 158 | -111.9791 | 41.7874 | 10/27/1949 | 0.1 | WQP | USGS-414715111584201 |
| 159 | -111.9277 | 41.8005 | 7/12/1948 | 0.090001 | WQP | USGS-414802111553701 |
| 168 | -111.9077 | 41.8447 | 10/27/1949 | 0.1 | WQP | USGS-415041111542501 |
| 176 | -111.9163 | 41.5930 | 4/18/1968 | 2.71004 | WQP | USGS-413535111545601 |
| 178 | -111.8474 | 41.6110 | 3/20/1968 | 2.259 | WQP | USGS-413640111504801 |
| 180 | -111.9436 | 41.6185 | 4/18/1968 | 1.310019 | WQP | USGS-413707111563400 |
| 182 | -111.9327 | 41.6244 | 5/9/1968 | 1.92015 | WQP | USGS-413728111555501 |
| 186 | -111.9338 | 41.6444 | 4/18/1968 | 1.53612 | WQP | USGS-413840111555901 |
| 192 | -111.9211 | 41.6472 | 5/27/1968 | 0.068001 | WQP | USGS-413850111551301 |
| 194 | -111.9183 | 41.6488 | 3/20/1968 | 0.904013 | WQP | USGS-413856111550301 |
| 196 | -111.9313 | 41.6733 | 5/27/1968 | 0.1 | WQP | USGS-414024111555001 |
| 197 | -111.9536 | 41.6752 | 5/7/1968 | 4.518 | WQP | USGS-414031111571001 |
| 199 | -111.8824 | 41.6941 | 5/8/1968 | 0.565008 | WQP | USGS-414139111525401 |
| 201 | -111.9111 | 41.6994 | 4/18/1968 | 0.1 | WQP | USGS-414158111543701 |
| 202 | -111.9619 | 41.7024 | 4/17/1968 | 0.15813 | WQP | USGS-414209111574001 |
| 204 | -112.0069 | 41.7119 | 9/4/1959 | 0.520008 | WQP | USGS-414243112002201 |
| 211 | -111.9358 | 41.7463 | 4/18/1968 | 0.02259 | WQP | USGS-414447111560601 |
| 213 | -111.8388 | 41.7555 | 7/13/1960 | 0.06777 | WQP | USGS-414520111501701 |
| 215 | -111.8444 | 41.7569 | 7/13/1960 | 0.045001 | WQP | USGS-414525111503705 |
| 217 | -111.8061 | 41.7588 | 3/31/1955 | 1.36002 | WQP | USGS-414532111481901 |
| 227 | -111.8352 | 41.7747 | 4/17/1968 | 3.610053 | WQP | USGS-414629111500401 |
| 229 | -111.8327 | 41.7760 | 9/30/1965 | 1.67166 | WQP | USGS-414634111495501 |
| 231 | -111.8894 | 41.7794 | 4/18/1968 | 0.045001 | WQP | USGS-414646111531901 |
| 233 | -111.8536 | 41.7827 | 5/27/1959 | 0.99396 | WQP | USGS-414658111511001 |
| 237 | -111.9788 | 41.7874 | 8/21/1950 | 0.06777 | WQP | USGS-414715111584101 |
| 243 | -111.8338 | 41.7927 | 4/11/1963 | 0.76806 | WQP | USGS-414734111495901 |
| 245 | -111.9047 | 41.7952 | 12/10/1957 | 0.15813 | WQP | USGS-414743111541401 |
| 251 | -111.8311 | 41.8066 | 8/19/1966 | 4.290063 | WQP | USGS-414824111494901 |
| 253 | -111.9286 | 41.8088 | 4/18/1968 | 0.1 | WQP | USGS-414832111554001 |
| 254 | -111.8486 | 41.8152 | 5/8/1968 | 3.840057 | WQP | USGS-414855111505201 |
| 256 | -111.8574 | 41.8247 | 5/8/1968 | 5.1957 | WQP | USGS-414929111512401 |
| 258 | -111.8647 | 41.8313 | 7/20/1960 | 0.40662 | WQP | USGS-414953111515001 |
| 268 | -111.8349 | 41.8449 | 7/9/1968 | 1.76202 | WQP | USGS-415042111500301 |
| 270 | -111.8883 | 41.8499 | 7/9/1957 | 0.068001 | WQP | USGS-415100111531501 |
| 314 | -111.8686 | 41.8388 | 9/2/1970 | 0.045001 | WQP | USGS-415020111520401 |

***Table 4.*** *Continued*

| Map ID | Longitude | Latitude | Sample Date | Concentration (mg/L NO3-N) | Data Source | Site Name |
|---|---|---|---|---|---|---|
| 316 | -111.9514 | 41.6474 | 8/19/1998 | 3.8403 | WQP | USGS-413850111570301 |
| 322 | -111.8908 | 41.6781 | 4/4/2001 | 0.480007 | WQP | UTAHDWQ-4904060 |
| 323 | -111.8585 | 41.6748 | 4/4/2001 | 2.490037 | WQP | UTAHDWQ-4904010 |
| 325 | -111.8817 | 41.6925 | 4/4/2001 | 1.260019 | WQP | UTAHDWQ-4904050 |
| 327 | -111.8762 | 41.6776 | 4/4/2001 | 14.700217 | WQP | UTAHDWQ-4904020 |
| 329 | -111.8622 | 41.6897 | 4/4/2001 | 3.830057 | WQP | UTAHDWQ-4904030 |

part of Millville. The contamination extends in both the unconfined and confined aquifers in the principal aquifer system, as observed by measured values of nitrate in both springs and deeper wells.

A map of septic tank density of the Millville area (figure 19) indicates a large quantity of septic systems upgradient of Glenridge well. However, based on observed nitrate concentrations of Skinner and Knoll springs, the distribution of confining clay thickness in the area (figure 13), and the extent of the nitrate contamination plume, major contributing sources likely exist upgradient of the springs. While most of the parcels within the town of Providence are connected to the city's sewer system, there are likely some exceptions immediately upgradient of Skinner and Knoll springs where older homes are present that may not have connected to the Providence system. After carefully reviewing historical aerial photography and land-use maps, I found no major livestock or agricultural activities upgradient of the Glenridge well. However, a small farm is located east of the well, with some llamas and evidence of historic manure piles, that could potentially contribute to nitrate observed in the Glenridge well.

Results of analyses of nitrogen and oxygen isotopes in nitrate from Glenridge well water are ambiguous. The average nitrogen and oxygen isotope concentration ratios were 5.75 and -5.78 ‰, respectively. Many different nitrate sources could produce these isotope concentration ratios (figure 20). However, based on these values, manufactured nitrate is likely not a source.

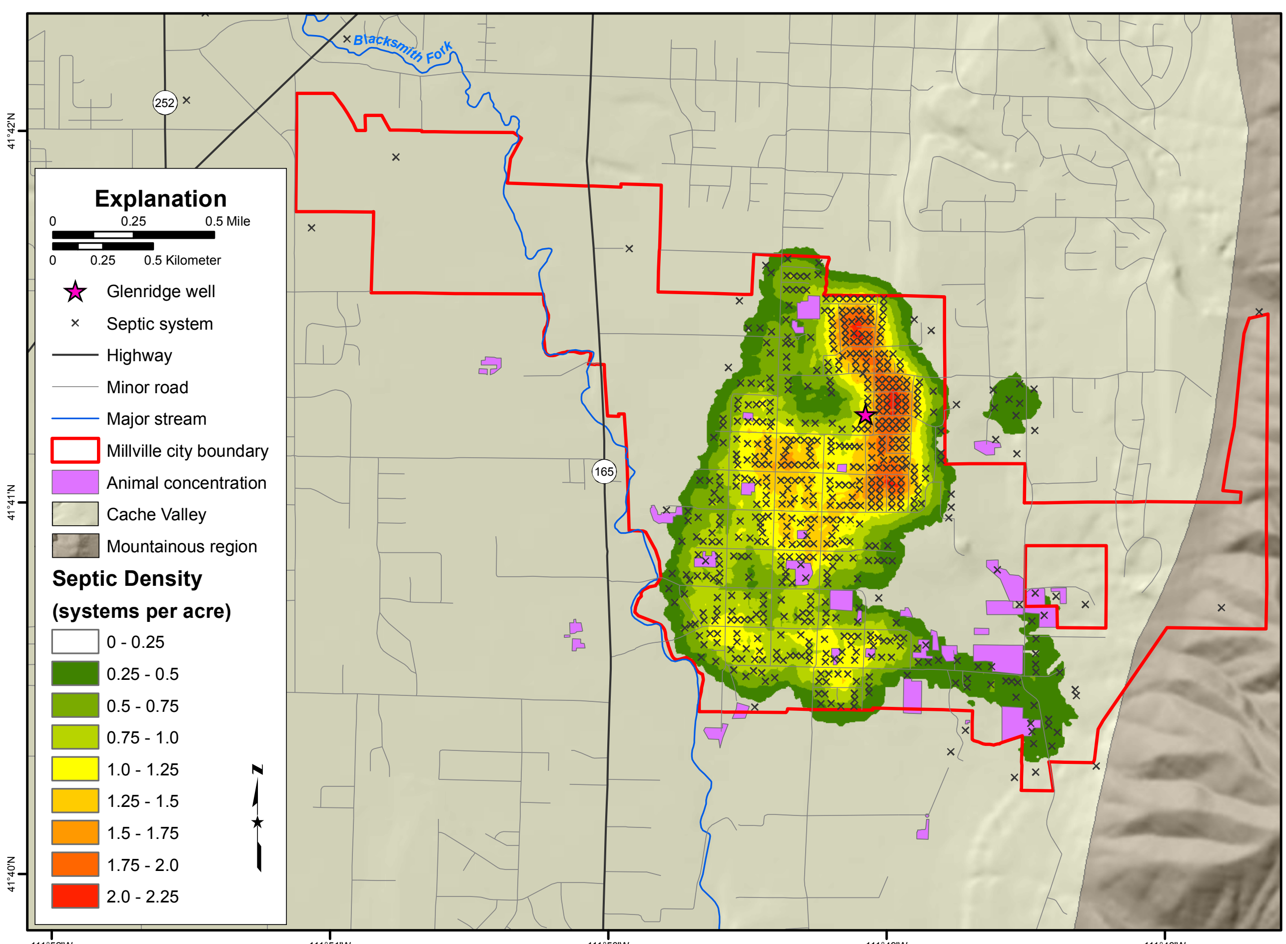


***Figure 19.*** *Septic tank locations, septic tank density, and locations of animal concentrations.*

## Recovery Efficiency

During the initial post-injection pumping, Millville pumped out 42.5% of the total volume of water that was injected. However, the water extracted did not have the same composition of the water that was injected. I used ratios of oxygen and deuterium isotopes (table 5; figure 21) and nitrate concentrations (figure 22; table 4) to determine how much of the pumped water was the injectate.

Isotope and nitrate concentrations show that the water extracted from the Glenridge well was 95% Garr Spring water up to 10.75 hours after post-injection pumping began (figure 22). For the first five days of pumping, nitrate concentration increased in a near-linear fashion at a rate of about 0.5 mg/l for every acre-feet of water pumped. At the end of the initial interval of pumping, on 3/24/2014 at 10:30 a.m., the water extracted from the well was 68% Garr Spring water (figure 23). Nitrate values increased logarithmically during the post-injection pumping period (figure 22a). This is best explained by diffusion of the Garr Spring water with the original aquifer water. Relatively fast-flowing groundwater likely exists near the well, allowing for further mixing of the two waters. The asymptote of the nitrate trend approaches 7 mg/l, which is a relatively high value, but lower than the initial value.

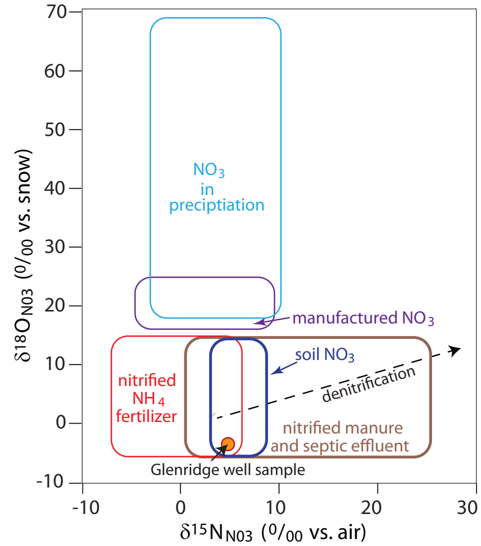


***Figure 20.*** *Standard ranges for isotope concentrations of nitrate-15 and oxygen-18 for various nitrate sources (modified from Kendall, 1998). Nitrate from water in the Glenridge well falls within several categories.*

***Table 5.*** *Results of stable isotope analyses.*

| Site | Date-Time | d18O (‰) | +/- d18O (‰) | dD (‰) | +/- dD (‰) |
|---|---|---|---|---|---|
| USU well | 3/31/2014 11:55 | -16.95 | 0.04 | -126.0 | 3.1 |
| Knoll Spring | 3/31/2014 10:00 | -15.93 | 0.04 | -114.7 | 3.1 |
| Arnold well | 3/21/2014 10:00 | -16.46 | 0.04 | -123.6 | 3.1 |
| Glenridge well | 3/19/2014 22:15 | -16.88 | 0.04 | -128.1 | 3.1 |
| Garr Spring | 2/28/2014 | -16.92 | 0.04 | -127.1 | 3.1 |
| Glenridge well | 3/24/2014 | -16.70 | 0.04 | -123.8 | 3.1 |
| Glenridge well | 2/28/2014 11:45 | -16.15 | 0.04 | -115.5 | 3.1 |
| Glenridge well | 4/17/2014 | -16.50 | 0.06 | -121.8 | 2.1 |

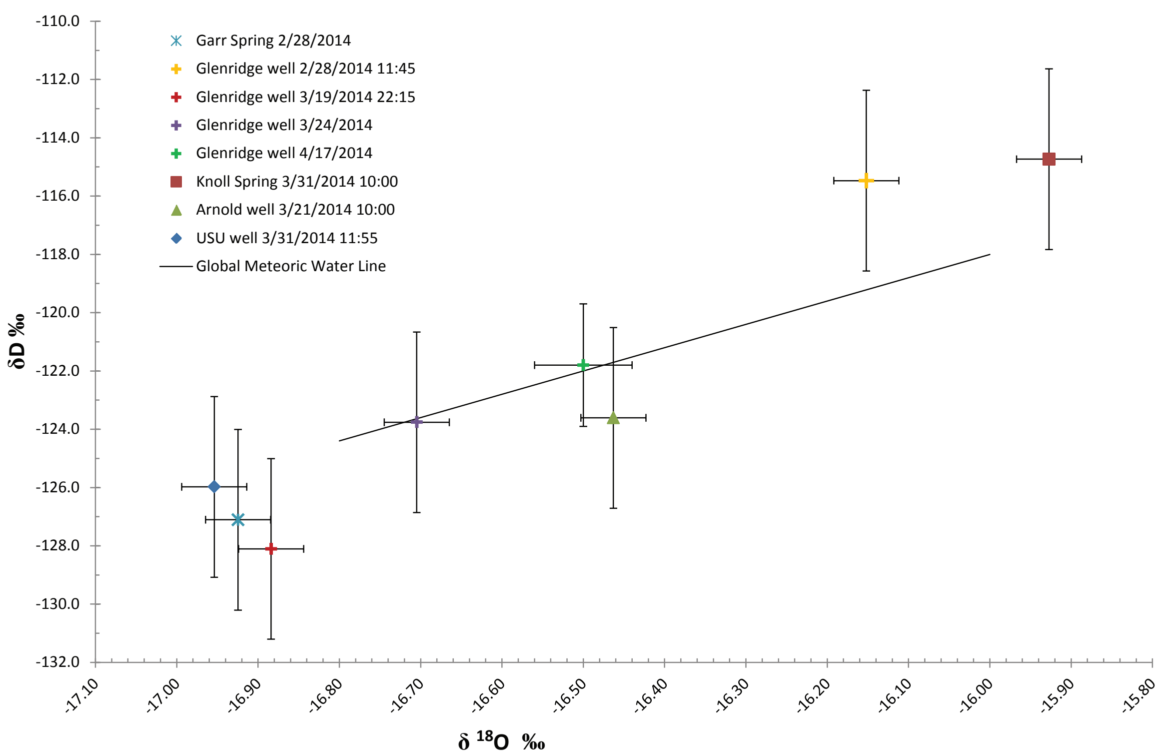


***Figure 21.*** *Deuterium and oxygen stable isotope ratios from sources in Millville area.*

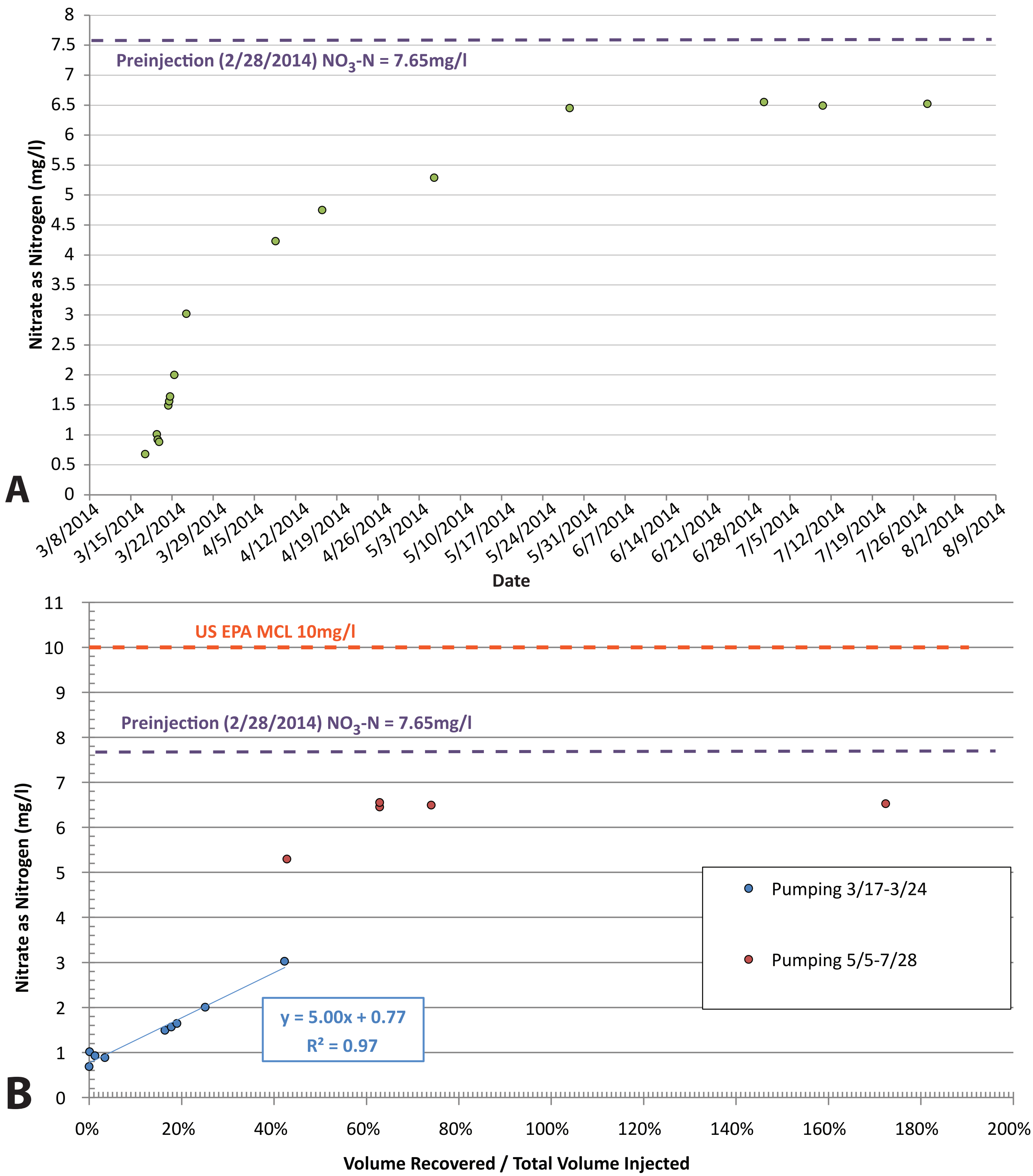


***Figure 22.*** *A) Concentration of nitrate in the Glenridge well over time for the duration of post-injection pumping. B) Concentration of nitrate as a function of volume of water pumped from the Glenridge well.*

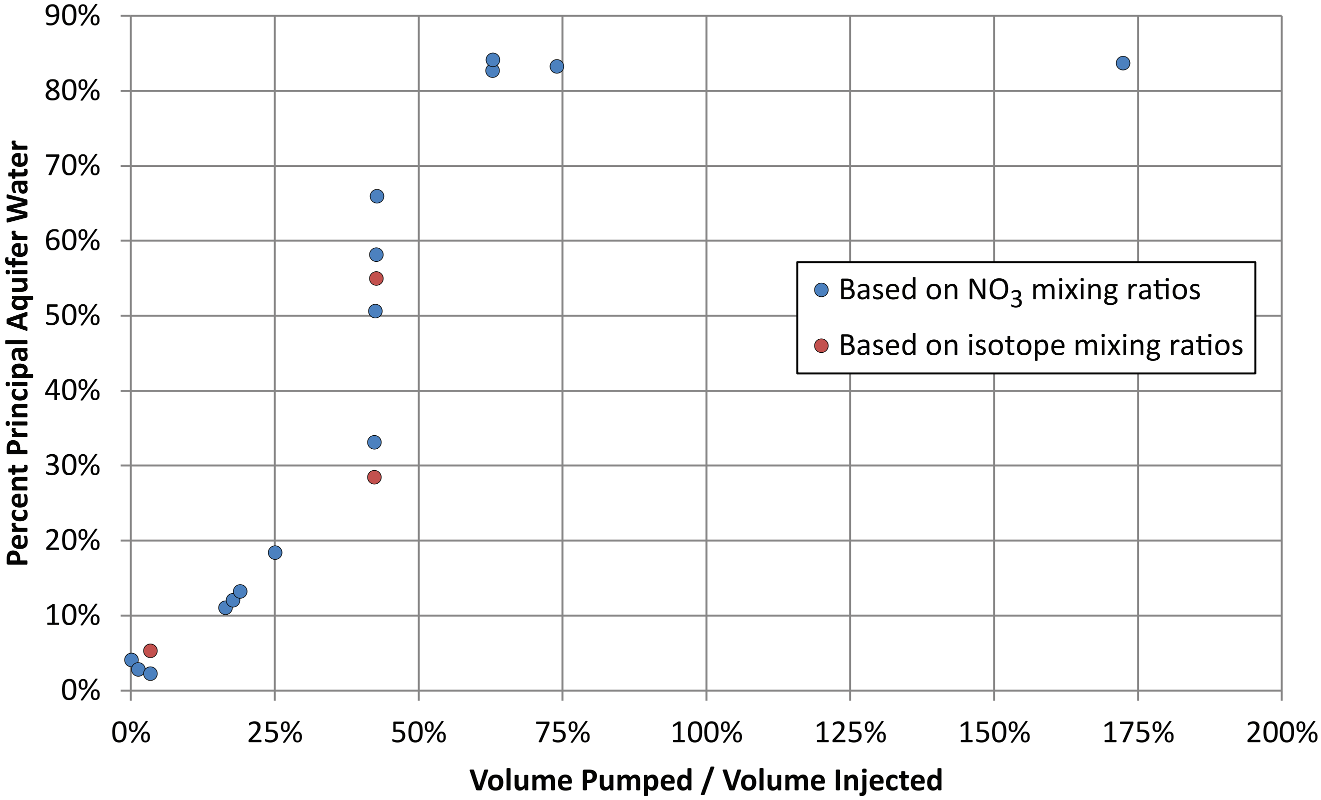


***Figure 23.*** *Percentage of pumped water that is original to the Cache Valley principal aquifer relative to the amount of water pumped from the Glenridge well.*

## SUMMARY

The aquifer system is likely contaminated upgradient (east) of the Glenridge well, especially in areas to the northeast where clay layers are thin. Much of the area of greatest apparent vulnerability is within Providence City limits.

Based on a short-term preliminary injection test, introducing Garr Spring water into Glenridge well does not significantly alter the chemistry of the Cache Valley principal aquifer system and effectively stores Garr Spring water in the aquifer. However, prolonged residence time of Garr Spring water could allow dilution of the spring water with native aquifer water.

## RECOMMENDATIONS

I suggest that Millville locate and remediate the high nitrate sources upgradient of their well. A more thorough analysis of Glenridge well water for common byproducts of septic contamination is recommended before injection occurs. A longer-term injection test is necessary before impact on the aquifer system can be successful. For the long-term test, the chemistry of the solid phase of the geochemical system should be modeled.

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## REFERENCES


Anderson, P.B., Susong, D.D., Wold, S.R., Heilweil, V.M., and Baskin, R.L., 1994, Hydrogeology of recharge areas and water quality of the principal aquifers along the Wasatch Front and adjacent areas, Utah: U.S. Geological Survey Water–Resources Investigations Report 93-4221, 74 p.

Beer, L.P., 1967, Ground-water hydrology of southern Cache Valley, Utah: Salt Lake City, University of Utah, Ph.D. dissertation, 104 p.

Bjorklund, L.J., and McGreevy, L.J., 1971, Ground-water resources of Cache Valley, Utah and Idaho: Utah Department of Natural Resources Technical Publication No. 36, 72 p.

Clark, I., and Fritz, P., 1997, Environmental isotopes in hydrogeology: New York, NY, Lewis Publishers, 328 p.

Duffield, G.M., 2007, AQTESOLV for Windows - Version 4.50 pro: computer software, HydroSOLVE, Inc.

ESRI, 2014, ArcGIS Help 10.2 - Geostatistical Analyst: online, http://resources.arcgis.com/en/help/main/10.2/index.html#/What_is_geostatistics/003100000001000000, accessed July 2014.

Evans, J.P., McCalpin, J.P., and Holmes, D.C., 1996, Geologic map of the Logan Quadrangle, Cache County, Utah: Utah Geological Survey Miscellaneous Publication 96-1, scale 1:24,000.

Garrels, R.M., and Christ, C.L., 1965, Solutions, Minerals, and Equilibria: New York, Harper and Row, 450 p.

Hantush, M.S., 1961, Drawdown around a partially penetrating well: Journal of the Hydrologic Division, Proceedings of the American Society of Civil Engineers, v. 87, n. HY4, p. 83–98.

Heath, R.C., 1983, Basic ground-water hydrology: U.S. Geological Survey Water Supply Paper 2220, 86 p.

Inkenbrandt, P.C., 2010, Estimates of the hydraulic parameters of aquifers in Cache Valley, Utah and Idaho: Logan, Utah State University unpublished M.S. thesis, 167 p.

Inkenbrandt, P.C., Thomas, K., and Hardwick, C., 2013, Cache Valley aquifer storage and recovery—Phase II: Utah Geological Survey Open-File Report 615, 45 p.

Kariya, K.A., Roark, D.M., and Hanson, K.M., 1994, Hydrology of Cache Valley, Cache County, Utah, and adjacent part of Idaho, with emphasis on simulation of groundwater flow: Utah Department of Natural Resources Technical Publication No. 108, 120 p.

Kendall, C., 1998, Tracing nitrogen sources and cycling in catchments, *in* C. Kendall and J.J. McDonnell, editors, Isotope tracers in catchment hydrology: Amsterdam, Elsevier, p. 519–576.

Lowe, M.V., Wallace, J., and Bishop, C.E., 2003, Soil-absorption-system density maps, Cache Valley, Cache County, Utah: Utah Geological Survey Special Study 101, 54 p.

Lowe, M.V., 1987, Surficial geology of the Smithfield quadrangle, Cache County, Utah: Logan, Utah State University, unpublished M.S. thesis, 143 p.

Lowe, M.V., and Wallace, J., 2001, Evaluation of potential geologic sources of nitrate contamination in groundwater Cedar Valley, Iron County, Utah with emphasis on the Enoch area: Utah Geological Survey Special Study 100, 57 p.

Millville History Book Committee, 1990, Millville memories—A history of Millville, Utah from 1860 to 1990: Logan, Utah, Exemplar Press, 433 p.

Mundorff, J.C., 1971, Nonthermal springs of Utah: Utah Geological Survey Water-Resources Bulletin 16, 70 p.

Nishikawa, T., Densmore, J.N., Martin, P., and Matti, J., 2003, Evaluation of the source and transport of high nitrate concentrations in ground water, Warren Subbasin, California: U.S. Geological Survey Water-Resources Investigations Report 03-4009, 146 p.

Olsen, A.A., 2007, Discharge monitoring, chemical characterization, and source identification of springs along the east side of southern Cache Valley, Utah: Logan, Utah State University, unpublished M.S. thesis, 185 p.

Peterson, W., 1946, Ground-water supply in Cache Valley, Cache and Box Elder Counties, Utah, and Bannock and Franklin Counties, Idaho, *in* Peterson, W., editor, Geological Survey Research 1970: U.S. Geological Survey Professional Paper 700-C, p. C114–C118.

Pyne, R.D.G., 2005, Aquifer storage recovery—A guide to groundwater recharge through wells: Gainesville, Florida, ASR Systems LLC., 608 p.

Roadcap, G.S., Hackley, K.C., and Hwang, H.H., 2002, Application of nitrogen and oxygen isotopes to identify sources of nitrate: unpublished consultant's report to the Illinois Groundwater Consortium of Southern Illinois University, 31 p.

Robinson, J.M., 1999, Chemical and hydrostratigraphic characterization of groundwater and surface water interaction in Cache Valley, Utah: Logan, Utah State University, unpublished M.S. thesis, 184 p.

Takeno, N., 2005, Atlas of Eh-pH diagrams—Intercomparison of thermodynamic databases: Geological Survey of Japan Open-File Report 419, 287 p.

Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage: American Geophysical Union Transactions, v. 16, p. 519–524.

Thomas, K., Oaks, R.Q., Jr., Inkenbrandt, P.C., Sabbah, W., and Lowe, M., 2011, Cache Valley principal aquifer storage and recovery site assessment—Phase I: Utah Geological Survey Open-File Report 579, 56 p.

United States Census, 2014, Incorporated Places and Minor Civil Divisions Datasets: Subcounty Resident Population Estimates—April 1, 2010 to July 1, 2013: Online, http://www.census.gov/popest/data/cities/totals/2013/files/SUB-EST2013_49.csv, accessed July 2014.

United States Environmental Protection Agency (U.S. EPA), 2014, National Primary Drinking Water Regulations: Online, http://water.epa.gov/drink/contaminants, accessed July 2014.

United States Geological Survey (USGS), 2014a, National elevation data (NED): Online, http://ned.usgs.gov, accessed July 2014.

United States Geological Survey (USGS), 2014b, National groundwater information system (NWIS): Online, http://waterdata.usgs.gov/nwis, accessed July 2014.

Utah Automated Geographic Reference Center (AGRC), 2013a, Cache County parcels: Online, http://gis.utah.gov/data/sgid-cadastre/parcels/, digital data, accessed March 2013.

Utah Automated Geographic Reference Center (AGRC), 2013b, Water related land use: Online, http://gis.utah.gov/data/planning/water-related-land/, digital data, accessed March 2013.

Utah Automated Geographic Reference Center (AGRC), 2013c, The Utah Reference Network (TURN): Online, http://gis.utah.gov/data/planning/water-related-land/, digital data, accessed March 2013.

Utah Division of Drinking Water, 2014, Safe Drinking Water Information System (SDWIS): unpublished digital data, accessed March 2014.

Utah Division of Water Quality, 2014, Utah Underground Injection Control (UIC) Program Well Classes: Online, http://www.waterquality.utah.gov/UIC/UICWellClasses/UICWellClasses.htm, digital data, accessed July 2014.

Utah Division of Water Rights, 2014, Public water supplier information for Millville City: Online, http://www.waterrights.utah.gov/cgi-bin/wuseview.exe?Modinfo=Pwsview&SYSTEM_ID=1332, digital data, accessed July 2014.

Utah State Legislature, 2014, Title 73 water and irrigation—Chapter 3b groundwater recharge and recovery act: Online, http://www.le.utah.gov/UtahCode/section.jsp?code=73-3b, digital data, accessed July 2014.