HYDROGEOLOGY OF MORGAN VALLEY, MORGAN COUNTY, UTAH

By

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EXECUTIVE SUMMARY

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Morgan Valley in the Wasatch Range, like several other hinterland valleys, is a rural area characterized by extensive agricultural activity and increasing population. Ground water in the unconsolidated valley-fill aquifer is Morgan Valley's most important source of drinking water, but there is interest in establishing wells in bedrock aquifers along the valley margins. The purpose of our study is to provide tools for water-resource management and land-use planning. To accomplish this, we (1) characterize the relationship of geology to ground-water conditions as it pertains to the occurrence and flow of ground water, with emphasis on delineating the thickness of the valley-fill aquifer and determining the water-yielding characteristics of fractured-rock aquifers in the study area, (2) map recharge and discharge areas for the valley-fill aquifer, (3) develop a water budget for the drainage basin, (4) classify the ground-water quality of the valley-fill aquifer to formally identify and document the beneficial use of ground-water resources, and (5) identify the likely sources of existing nitrate in ground water from environmental tracer data.

Morgan Valley, within the Wasatch Range, is situated in a structural trough shared by Ogden Valley to the north. The Wasatch Range bounds Morgan Valley to the west, and consists of Precambrian metamorphic rocks of the Farmington Canyon Complex. Most of the area surrounding Morgan Valley consists of Tertiary tuffaceous rocks; Cretaceous to Tertiary conglomerate and conglomeratic sandstone with some siltstone, mudstone, and limestone; and Quaternary alluvial, colluvial, and mass-movement deposits. Precambrian crystalline basement rocks and Paleozoic and Mesozoic sedimentary rocks crop out on the north side of Upper Weber Canyon.

We measured relative gravity and elevation at approximately 350 points throughout the valley during winter and spring 2009 to help delineate the subsurface structure beneath Morgan Valley. These data in conjunction with well data are used to estimate the approximate thickness of the valley-fill aquifer, define the geometry of the valley fill, and locate major concealed faults. The thickness of valley-fill material is greatest in central Morgan Valley, near the towns of Morgan and Enterprise, where the valley fill is estimated to be greater than 600 feet (180 m) thick.

We used 65 drillers' logs of water wells in Morgan Valley to delineate recharge areas and discharge areas, based on the presence of confining layers and relative water levels in the principal and shallow unconfined aquifers. We mapped recharge areas to serve as a tool for protecting ground-water quality and managing potential contaminant sources in Morgan Valley. The primary recharge area for the principal aquifer system consists of uplands along the valley margins and valley-fill material not containing confining layers. No secondary recharge areas exist in Morgan Valley. In discharge areas, water discharges to the land surface or to a shallow unconfined aquifer. Discharge areas for the unconfined aquifer in Morgan Valley occur along gaining reaches of the Weber River, but are not extensive enough to define on the map.

We estimated aquifer characteristics for both the valley-fill aquifer and selected fractured-rock aquifers from existing aquifer tests and specific capacity data from drillers' logs of water wells. Transmissivity values for the valley-fill aquifer from our data range from 6.75 to 8815 square feet per day (0.63-819 m^2/d) with a median of 551 square feet per day (51 m^2/d) and an average of 1340 square feet per day (125 m^2/d). The areas of highest transmissivity in the valley-fill aquifer correspond to the areas having the greatest aquifer thickness. Waters yielding characteristics of fractured-rock aquifers are highly variable and depend primarily on the nature and amount of fractures intercepted by wells completed in these aquifers.

We evaluated inflow and outflow water-budget components in Morgan Valley and created a detailed water budget based on available climatic data, drainage patterns, land use, vegetation cover, water use, geology, soil data, and streamflow measurements. The overall total inflow into and within Morgan Valley is 661,000 acre-feet (815 hm^3) per year. The overall total outflow from Morgan Valley is 600,000 acre-feet (740 hm^3) per year. Many factors explain the difference between the amount of inflow and outflow, including assumptions we used to estimate these parameters based on the best available existing data. Surface-water outflow is the largest source of discharge, followed by evapotranspiration. Precipitation is the largest source of recharge, followed by surface-water inflow.

We used water-quality data based on total-dissolved-solids (TDS) concentrations to produce a ground-water quality classification map. Ground water from 52 water wells was collected and analyzed during spring 2004. The sampled wells were selected without bias to land-use practice. Additional data are from the Utah Department of Agriculture and Food and Utah Division of Drinking Water. Water samples from 76 wells were analyzed for nutrients; 59 of those wells were analyzed for general chemistry and dissolved metals. Of those, five were tested for organics and two for radionuclides. We sampled 10 wells, previously sampled by the Weber-Morgan District Health Department, having relatively high (greater than 4.5 mg/L) nitrate concentration, for nitrogen and oxygen isotopes; we used their data coupled with environmental tracer data to evaluate nitrogen and oxygen isotope data to help determine nitrate source(s).

In 2009 we sampled 20 wells for environmental tracers. Ten of these wells penetrate bedrock and the other 10 are alluvial wells that were previously sampled in 2004. For the 10 bedrock wells, we also sampled for general chemistry (including TDS) and nitrate; we did not use data from bedrock wells to classify the valley-fill aquifer. For all 20 wells, we sampled for tritium, oxygen, and deuterium. For three of the bedrock wells, we sampled for carbon isotopes.

Average nitrate concentration for water wells in the valley fill is 2.6 mg/L. Most alluvial wells have values less than 5 mg/L. Water from three alluvial wells has nitrate values that exceed drinking water-quality standards (greater than 10 mg/L). High-nitrate concentration wells (greater than 5 mg/L) are localized and situated in recharge areas. Nitrogen and oxygen isotope data indicate that sources of nitrate include fertilizer, feed lots, cultivated and non-cultivated soils, and septic-tank systems. Total-dissolved-solids concentration for ground water in alluvial wells ranges from 92 to 1018 mg/L, with an average of 437 mg/L. Total-dissolved-solids concentration for 89% of the wells is less than 500 mg/L. All of Morgan Valley is classified as primary recharge, thus all wells were sampled in the recharge area, the area most vulnerable to contamination. The widespread agricultural activity in Morgan Valley appears to have only a minor impact on ground-water quality. The results of our study indicate the valley-fill aquifer contains mostly high-quality ground-water resources that warrant protection.

INTRODUCTION

Morgan Valley, Morgan County, is located in north central Utah (figure 1). It, like many bedroom communities of the Wasatch Front, is experiencing growth. From 1990 to 2000, the population of Morgan County increased 29%, from 5528 to 7129 (Demographic and Economic Analysis Section, 2001). In 2009, the population of Morgan County was 8908, with Morgan City, the county seat, having 3415 residents, and the unincorporated areas in Morgan County having a population of 5493 (Demographic and Economic Analysis Section, 2010).

Although Morgan City and the community of Mountain Green are on a municipal sewer system, most other development in Morgan Valley uses septic tank soil-absorption systems for wastewater disposal. These septic-tank systems are in the valley-fill deposits where ground water is vulnerable to contamination, and where some wells with high nitrate concentrations have been identified during previous water-quality sampling. Preservation of ground-water quality and the potential for ground-water quality degradation are critical issues that should be considered in determining the extent and nature of future development in Morgan Valley. Local government officials in Morgan Valley have expressed concern about the potential impact that development may have on ground-water quality, particularly development that uses septic tank soil-absorption systems for wastewater disposal, and desire land-use planning tools to help protect water quality. Local government officials would like to formally identify current ground-water quality through ground-water quality classification to provide a basis for defendable land-use regulations to protect ground-water quality. Local government officials would also like to determine the source(s) of existing nitrate contamination.

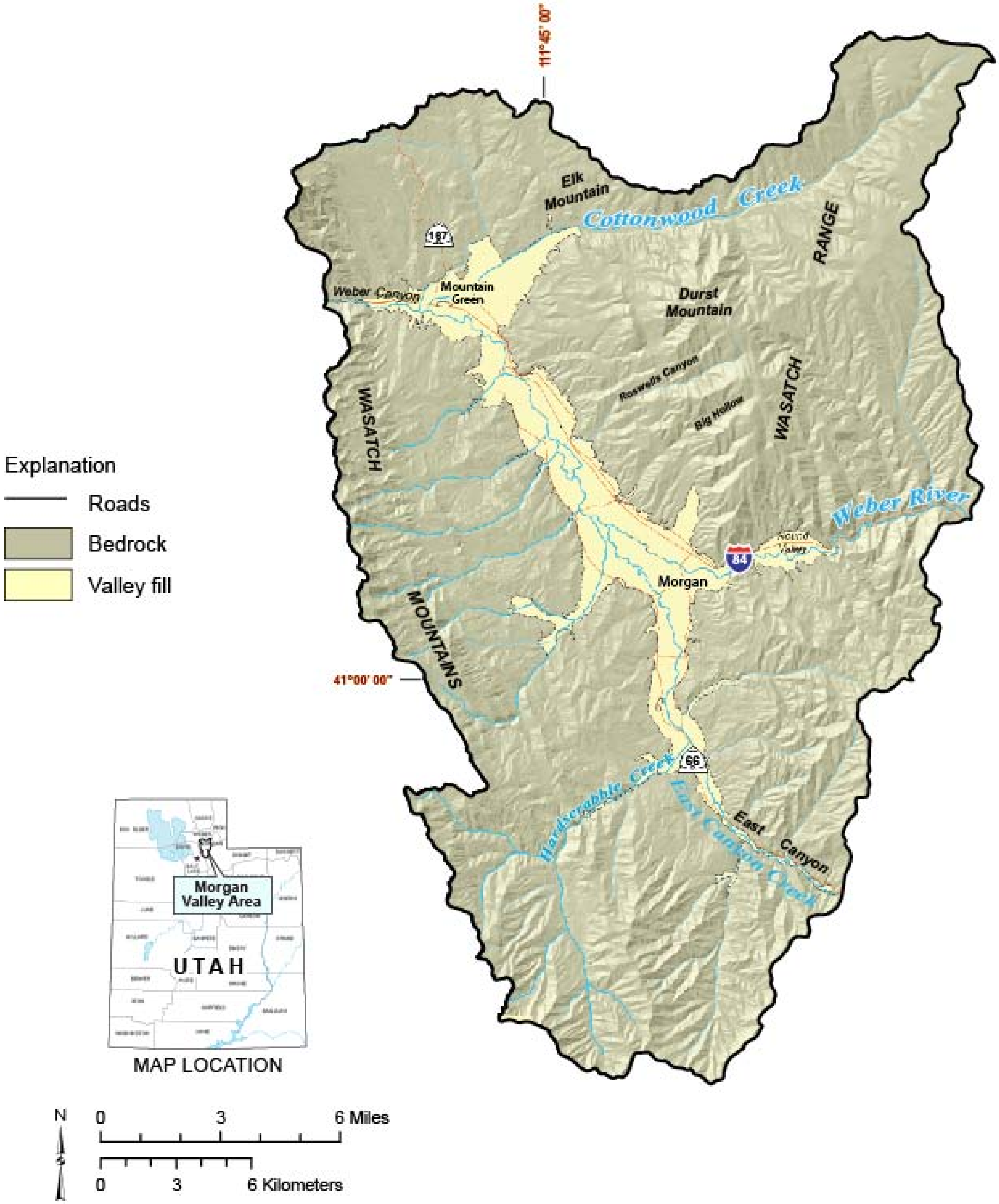


Figure 1. Morgan Valley, Morgan County, Utah, drainage-basin study area.

Purpose and Scope

The purpose of our study is to provide tools for water-resource management and land-use planning. To accomplish this purpose we: (1) characterize the relationship of geology to ground-water conditions as it pertains to the occurrence and flow of ground water, with emphasis on delineating the thickness of the valley-fill aquifer and determining the water-yielding characteristics of fractured-rock aquifers in the study area, (2) develop a water budget for the drainage basin, (3) map recharge and discharge areas for the valley-fill aquifer, (4) classify the ground-water quality of the valley-fill aquifer to formally identify and document the beneficial use of ground-water resources, and (5) identify the likely sources of existing nitrate in ground water.

Aquifer Characteristics Estimates

The purpose of estimating aquifer characteristics is to provide water-resource managers information on how likely aquifers will yield water to wells. We estimate aquifer characteristics for both the valley-fill aquifer and selected fractured-rock aquifers based on existing aquifer tests, and by estimating transmissivity from specific capacity data from drillers' water well logs.

Valley-Fill Isopach Map

The purpose of an isopach map for the valley-fill aquifer is to provide information on depth to the less productive geologic units beneath the valley fill; it is especially useful to well drillers. The isopach maps can also be used in conjunction with potentiometric surface maps for the valley-fill aquifer to estimate water in storage in the aquifer. We produced a valley-fill isopach map by examining drillers' logs of water wells to determine the valley-fill bedrock contacts, and by conducting a gravity survey.

Recharge-Area Delineation

The purpose of recharge-area mapping is to define areas in a valley characterized by vulnerability to contamination. The greatest areas of vulnerability are in primary recharge areas, defined as lacking confining layers, composed of sands and gravels, and having a vertical downward component of ground-water flow. Secondary recharge areas are also considered vulnerable, but to a lesser degree, as they contain confining layers composed of silt/clay and also have a vertical downward component of ground-water flow. The least vulnerable areas in a valley-fill aquifer are discharge areas; these areas have confining layers composed of silt/clay, but have an upward vertical component of ground-water movement and/or are in areas where the land surface and water table intersect.

Water Budget

The purpose of developing a water budget is to estimate the quantity of inflow and outflow to the ground-water system. To develop the water budget, we used information from available climatic data, drainage patterns, land use, vegetation cover, water use, geology, soil data, and streamflow measurements.

Ground-Water Quality Classification

The purpose of ground-water quality classification is to recognize the value of the resource in Utah, as outlined under Administrative Rules for Ground Water Quality Protection R317-6, December 1, 2009, Section 317-6-5, Ground Water Classes for Aquifers, Utah Administrative Code. Ground-water quality classes under the Utah Water Quality Board classification scheme are based largely on total-dissolved-solids (TDS) concentrations (table 1) (for the ranges of chemical-constituent concentrations used in this report, including those for TDS, mg/L equals parts per million). If any contaminant exceeds Utah's ground-water quality standards (appendix A) and, if human caused, cannot be cleaned up within a reasonable time period, the ground water is classified as Class III, Limited Use ground water.

Table 1. *Ground-water quality classes under the Utah Water Quality Board's total-dissolved-solids- (TDS) based classification system (modified from Utah Division of Water Quality, 1998).*

Ground-Water Quality Class	**TDS Concentration**	**Beneficial Use**
Class IA/IB[1]/IC[2]	Less than 500 mg/L[3]	Pristine/Irreplaceable/ Ecologically Important
Class II	500 to less than 3000 mg/L	Drinking Water[4]
Class III	3000 to less than 10,000 mg/L	Limited Use[5]
Class IV	10,000 mg/L and greater	Saline[6]

[1]Irreplaceable ground water (Class IB) is a source of water for a community public drinking-water system for which no other reliable supply of comparable quality and quantity is available due to economic or institutional constraints; it is a ground-water quality class that is not based on TDS.
[2]Ecologically Important ground water (Class IC) is a source of ground-water discharge important to the continued existence of wildlife habitat; it is a ground-water quality class that is not based on TDS.
[3]For concentrations less than 7000 mg/L, mg/L is about equal to parts per million (ppm).
[4]Water having TDS concentrations in the upper range of this class must generally undergo some treatment before being used as drinking water.
[5]Generally used for industrial purposes.
[6]May have economic value as brine.

To classify the quality of ground water in the Morgan Valley valley-fill aquifer, we used ground-water data from 66 wells and 1 spring from the Utah Geological Survey (UGS), Utah Department of Agriculture and Food (UDAF), and the Utah Division of Drinking Water (UDW). Most water samples were analyzed for general chemistry and nutrients by the Utah Department of Epidemiology and Laboratory Services; of the 66 wells, ground water from 5 wells was analyzed for organics and pesticides and ground water from 2 wells was analyzed for radionuclides (appendix B). We did not use water-quality data from wells penetrating bedrock as part of the classification; we classify the valley-fill aquifer and not the bedrock aquifer.

Determine Potential Sources of Nitrate

The Weber-Morgan Health Department and UDAF conducted ground-water quality sampling from water wells in Morgan Valley from 1997 to 2004. Some areas in the valley have wells that consistently yield water with relatively high nitrate concentrations (greater than 4.5 mg/L) that exceed typical background nitrate concentration, and some exceed the U.S. Environmental Protection Agency (EPA) drinking-water standard of 10 mg/L (herein reported as nitrogen as nitrate, and expressed as "nitrate"). One area in particular, Hardscrabble Creek, has relatively high nitrate concentrations and no apparent upgradient land use responsible for such contamination. Common sources of nitrate include agricultural practices (e.g., animal feeding operations and fertilizer), septic-tank systems, nitrate from cultivated and non-cultivated natural soil nitrogen, and, less commonly, bedrock. Nitrate concentrations in the same wells sampled over many intervals have fluctuated: some have decreased, some have increased, and some have maintained similar concentrations. The source(s) of potential nitrate contamination has not been previously identified. An objective of this study is to identify the potential source(s) of nitrate contamination by stable isotope analysis using both nitrogen and oxygen isotopes.

Location and Geography

Physiography

Morgan Valley is a northwest-trending valley approximately 16 miles (26 km) long and 2 miles (3 km) wide with a valley-fill area of 28 square miles (70 km^2). Morgan Valley is a back valley to the Wasatch Front like Cache and Ogden Valleys to the north, and East Canyon, Kamas Valley, and Heber Valley to the south. Morgan Valley is in the Wasatch Hinterlands section of the Rocky Mountain physiographic province (Stokes, 1977), and is in the central part of the Weber River watershed. The study area watershed covers 312 square miles (800 km^2). Morgan Valley is bounded by Weber Canyon and the Wasatch Range to the west, Durst Mountain to the east and north, and Upper Weber Canyon east of Morgan City to the east. Elevation ranges from 9706 feet (2958 m) at Thurston Peak, the highest point in Morgan County, to approximately 4835 feet (1474 m) at the town of Mountain Green, near Weber Canyon.

The Weber River enters the study area (figure 1) at the mouth of Upper Weber Canyon near Morgan City, flows northwest through the middle of Morgan Valley, and leaves the study area near Mountain Green at the head of Weber Canyon. Major tributaries include East Canyon Creek and Hardscrabble Creek at the southern end of the study area, and Cottonwood Creek at the northeast end of the study area. Smaller drainages include the northeast-flowing Deep and Smith Creeks, and southwest-flowing streams in Big Hollow and Roswells Canyon.

Climate

The only weather station in the study area is in the town of Morgan at an elevation of 5090 feet (1550 m). The following climatic information for the Morgan station is for the 1903 to 2000 period and taken from Moller and Gillies (2008). Temperatures reach a normal minimum of 12.9˚F (-10.6˚C) in January and a normal maximum of 88.9˚F (31.6˚C) in July. The normal mean annual temperature is 46.7˚F (8.2˚C). The normal annual precipitation is 18.97 inches (48.2 cm), and the average annual reference evapotranspiration is 46.06 inches (117 cm). The average number of frost-free days is 98. The surrounding mountainous area receives a greater amount of precipitation compared to the valley; recharge recorded in the mountains is 68 inches (173 cm) (Lowe and others, 2004, figure 6).

Population and Land Use

Morgan County, like most of Utah and the western U.S., is experiencing growth. From 2000 to 2007 the average annual rate of change in population growth for Morgan County was 3.7 percent (Demographic and Economic Analysis Section, 2008). In 2009, the population of Morgan County was 8908; Morgan City, the county seat, had a population of 3415 and the unincorporated areas in Morgan County had a population of 5493 (Demographic and Economic Analysis Section, 2010). By 2030, the population in Morgan County is expected to increase to 24,595; Morgan City and the unincorporated areas in Morgan County are expected to increase to 8869 and 15,726, respectively (Demographic and Economic Analysis Section, 2005).

Morgan Valley is along a national east-west transportation corridor (U.S. Interstate Highway 84, the Union Pacific Railroad, fiber-optic line(s), and several pipelines). The dominant industries in Morgan County are agriculture and manufacturing (Utah Reach, 2004). Browning Arms Company is one of the major industries operating in the Morgan Valley drainage basin. Historically, Morgan Valley was an agricultural community. Currently, few farmers have farming as their sole source of income due to poor profitability; much of the farmland is being sold for residential development (Utah Reach, 2004). More than half of the people employed in Morgan County work outside of the county, mostly in the Ogden area (Utah Reach, 2004).

Well Numbering System

The numbering system for wells in this study is based on the Federal Government cadastral land-survey system that divides Utah into four quadrants (A-D) separated by the Salt Lake Base Line and Meridian (figure 2). The study area is entirely within the northeastern quadrant (A). The wells are numbered with this quadrant letter A, followed by township and range, enclosed in parentheses. The next set of characters indicates the section, quarter section, quarter-quarter section, and quarter-quarter-quarter section designated by letters a through d, indicating the northeastern, northwestern, southwestern, and southeastern quadrants, respectively. A number after the hyphen corresponds to an individual well within a quarter-quarter-quarter section. For example, the well (A-3-2)9adb-1 is the first well in the northwest quarter of the southeastern quarter of the northeastern quarter of section 9, Township 3 North, Range 2 East (NW1/4SE1/4NE1/4 section 9, T. 3 N., R. 2 E.).

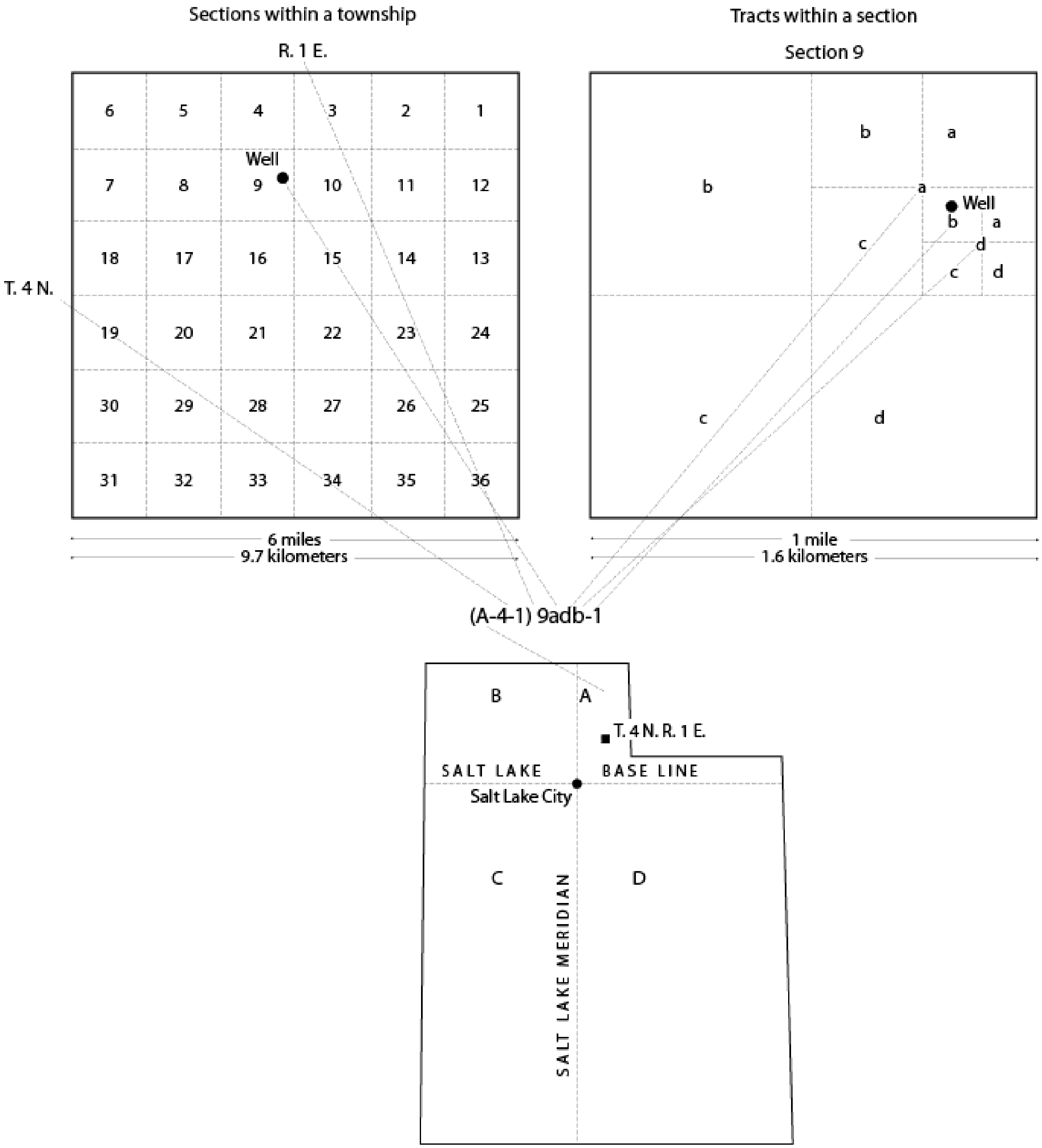


Figure 2. *Numbering system for wells in Utah (see text for additional explanation).*

PREVIOUS INVESTIGATIONS

Saxon (1972) studied ground-water conditions in Morgan Valley, including ground-water quality, and produced a water budget for the Morgan area. Haws and others (1970) produced a hydrologic inventory and water budget for the entire Weber River drainage basin. Mundorff (1970) studied the major thermal springs in Utah, including Como Warm Springs east of Morgan City. Thompson (1982) conducted a reconnaissance of surface-water quality in the Weber River basin. Gates and others (1984) conducted a ground-water reconnaissance of the central Weber River area. Lowe and others (2004) mapped vulnerability and sensitivity to pesticides for the valley-fill aquifer in Morgan Valley.

SCIENTIFIC APPROACH AND BACKGROUND

Geologic Map and Cross Sections

The geologic map (plate 1) compiled for this study is from several sources and is a simplified bedrock map; most of the surficial deposits have been “stripped off”. The map extends beyond the study area because this helps improve control on the cross sections, and made a simple boundary to “clip” the previous mapping. The south third of the map is mostly from the U.S. Geological Survey map of the Salt Lake City 30' × 60' quadrangle (Bryant, 1990). The remainder of the map is from Utah Geological Survey open-file reports for the Snow Basin and Durst Mountain 7.5' quadrangles and unpublished mapping by various authors, including one of us (King).

Three cross sections (plate 2) were drawn and interpreted from this map to estimate the locations and offset on the valley-bounding faults, the depths to Tertiary formations (and the thickness of the valley-fill aquifer), and potential rock types present below the Tertiary formations. The southern cross section (plate 2, cross section C) is based in part on that of Bryant (1990). Interpretation for all cross sections is based on cross section compilation by King's co-mappers Yonkee and Coogan; but their published work is at a smaller scale than those drawn for this report (these cross sections should not be considered their work). Based on the complex geology of Durst Mountain, the simplified geology illustrated beneath Morgan Valley in this report is likely more complicated.

With the exception of East Canyon, on the east end of the southern cross section (plate 2, cross section C), the lack of deep wells and seismic data precludes definitive interpretations of the subsurface geology in Morgan Valley. These cross sections are for illustrative purposes and should be considered a progress report in this study. The northern cross section (plate 2, cross section A) is the least constrained, the configuration of the Willard thrust sheet is very poorly defined, and the depth to Tertiary formations north of Cottonwood Creek is uncertain because these rocks "plunge" to the north and could be deeper than shown when they reach the line of section.

Estimating Aquifer Characteristics

We estimated aquifer characteristics for both fractured-rock and valley-fill aquifers, including storativity, specific capacity, transmissivity, and hydraulic conductivity, using the methods discussed below. The values obtained for the aquifer characteristics are variable and depend on logs created by well drillers and aquifer tests conducted by other scientists.

1. We estimated aquifer storativity using the equation: $S = Sy + (Ss \times b)$; where S is storativity, Sy is the specific yield, Ss is the specific storage, and b is the aquifer thickness. Sy and Ss were estimated based on published values from Johnson (1967) and Domenico (1972), respectively, based on the drillers' well log lithology of the target intake aquifer.

2. Specific capacity is determined by performing a pump test on a well at a known rate for a few hours and observing the resulting overall drawdown. We estimated specific capacity (Sc) using the equation: $Sc = Q/S$, where Q is pumping rate and S is drawdown.

3. We estimated aquifer transmissivity from specific capacity data obtained from drillers' well logs. We used the TGUESS spreadsheet algorithm of Bradbury and Rothschild (1985), which implements the Cooper-Jacob approximation of the Theis equation.

4. We estimated aquifer hydraulic conductivity by dividing transmissivity by the saturated aquifer thickness.

Gravity Survey

We used gravity data to help delineate the subsurface structure beneath Morgan Valley in order to determine the approximate thickness of the valley-fill aquifer. Gravity data can aid in defining the geometry of the valley fill and locating major concealed faults. To provide a sufficient amount of gravity data required for interpretation, we measured relative gravity and elevation at approximately 350 points throughout Morgan Valley (figure 3, appendix C) during early 2009. The gravity data points were collected on a quarter-mile (400-m) grid that aligned with existing streets and adapted to local accessibility constraints.

We collected and processed the gravity data following standard methods (for example, Telford and others, 1976). In addition to subsurface variations in density that reflect geologic structure, raw gravity measurements include the effects of earth tides, latitude, elevation, topography, and instrument drift (e.g., Telford and others, 1976; Milsom, 1996; Parasnis, 1997). Corrections for the non-geologic components of gravity measurements are well established and the corrected gravity value is referred to as the Bouguer gravity anomaly, expressed in units of milligals. The Bouguer anomaly reflects variations in gravity relative to a standard reference plane, typically sea level. Appendix C contains gravity data and equations used in calculating the necessary corrections.

Drillers' Well-Log Analysis for Hydrologic Setting

We used drillers' well logs to determine recharge area type in the valley-fill aquifer by documenting sediment type encountered, presence and thickness of clay/silt layers, and direction of ground-water movement. Hydrogeologic setting is delineated on ground-water recharge-area maps, which typically shows (1) primary recharge areas, (2) secondary recharge areas, and (3) discharge areas (Anderson and others, 1994). Primary recharge areas, commonly the uplands and coarse-grained unconsolidated deposits along basin margins, do not contain thick, continuous, fine-grained layers (confining layers) and have a downward ground-water gradient

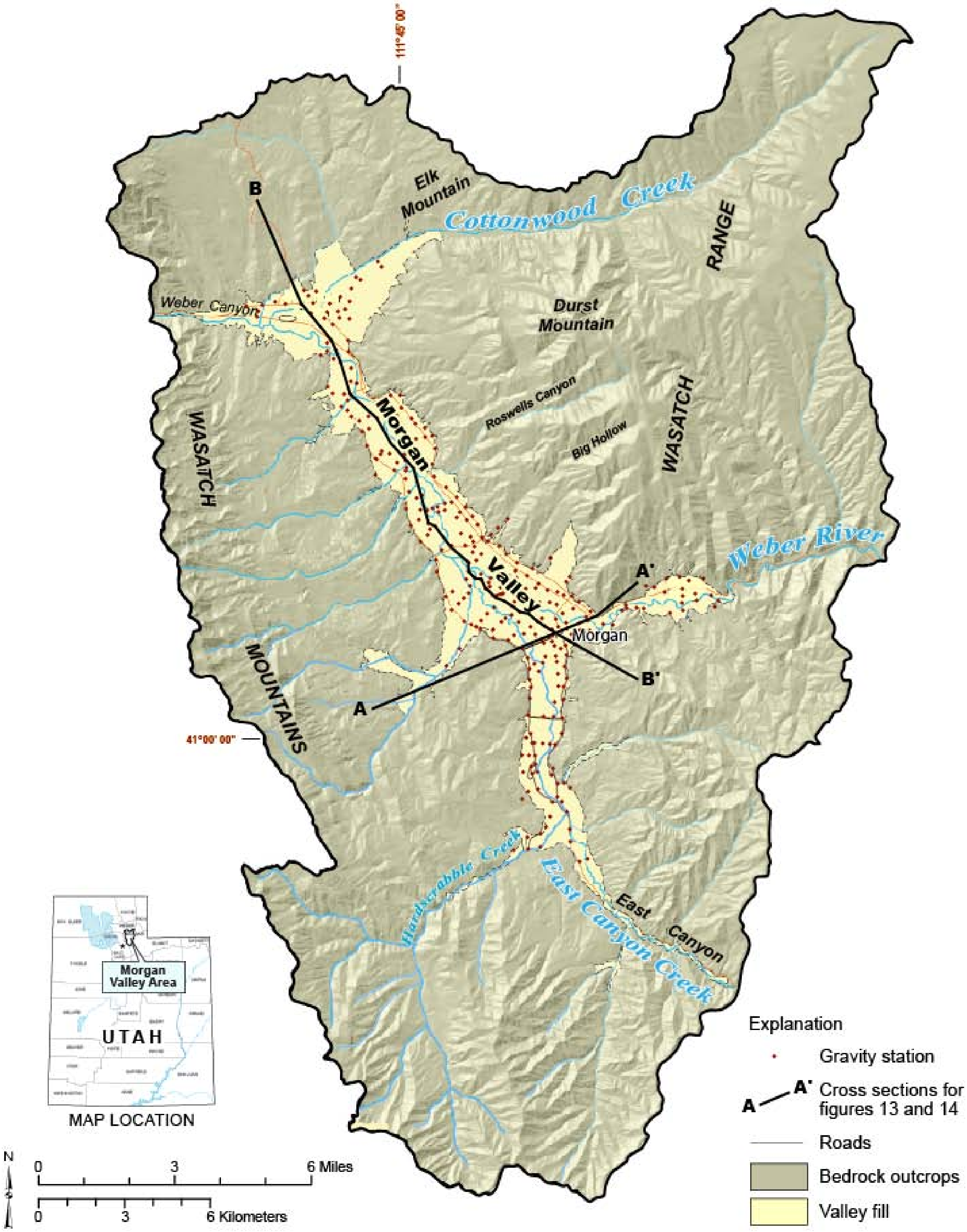


Figure 3. *Locations of gravity data and model cross sections in Morgan Valley, Morgan County, Utah. See plate 3 for details on gravity stations and cross sections.*

(figure 4). Secondary recharge areas, commonly mountain-front benches, have fine-grained layers thicker than 20 feet (6 m) and a downward ground-water gradient (figure 4). Ground-water discharge areas are generally in basin lowlands. Discharge areas for unconfined aquifers occur where the water table intersects the ground surface to form springs, seeps, lakes, wetlands, or gaining streams (figure 4) (Lowe and Snyder, 1996). Discharge areas for confined aquifers occur where the ground-water gradient is upward and water is discharging to a shallow unconfined aquifer above the upper confining bed, or to a spring. Water from wells that penetrate confined aquifers may flow to the surface naturally. The extent of both recharge and discharge areas may vary seasonally and from dry years to wet years.

Confining layers are any fine-grained (clay and/or silt) layer thicker than 20 feet (6 m) (Anderson and others, 1994; Anderson and Susong, 1995). Some drillers’ logs show both clay and sand in the same interval, with no information describing relative percentages; these are not classified as confining layers (Anderson and others, 1994). Some drillers’ logs show both clay and gravel, cobbles, or boulders; these also are not classified as confining layers, although in some areas of Utah layers of clay containing gravel, cobbles, or boulders, can act as confining layers. If both silt and clay are checked on the log and the word "sandy" is written in the remarks column, then the layer is assumed to be a predominantly clay confining layer (Anderson and others, 1994).

Ground-water discharge areas, if present, generally occur at lower elevations than recharge areas. In discharge areas, the water in confined aquifers discharges to the land surface

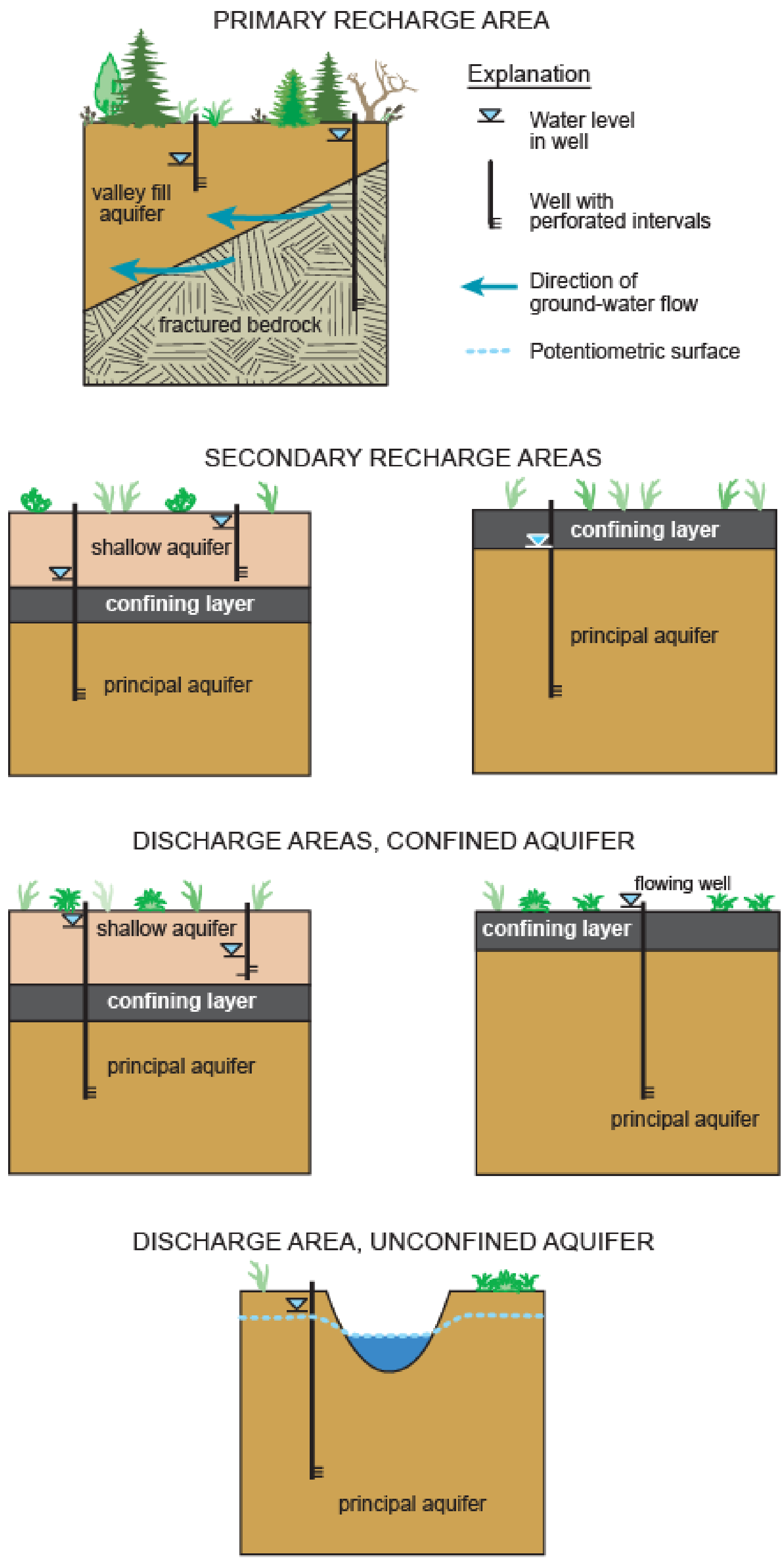


Figure 4. *Schematic block diagrams showing recharge area type characteristics (modified from Snyder and Lowe, 1998).*

or to a shallow unconfined aquifer. For this to happen, the hydraulic head in the principal aquifer system must be higher than the water table in the shallow, unconfined aquifer. Otherwise, downward pressure from the shallow aquifer exceeds the upward pressure from the confined aquifer, creating a net downward gradient indicative of secondary recharge areas. Flowing (artesian) wells, indicative of discharge areas, are marked on drillers' logs and sometimes on U.S. Geological Survey 7.5-minute quadrangle maps. Wells with potentiometric surfaces above the top of the confining layer can be identified from well logs. Surface water, springs, or phreatophytic plants characteristic of wetlands can be another indicator of ground-water discharge. In some instances, however, this discharge may be from a shallow unconfined aquifer.

Water-Budget Development

We estimated a water budget for the study area by quantifying both inflow and outflow components. The inflow component consists of precipitation, streamflow entering the valley, and return flow from unconsumed water provided for irrigation, municipal, and industrial purposes. The outflow component consists of streamflow leaving the valley, evapotranspiration, and water use for irrigation, municipal, and industrial purposes.

1. We integrated a precipitation map from the 4-kilometer (2.5-mi) grid cell size PRISM data (PRISM Group, 2009) after it was downscaled to a 500-meter (1640-ft) cell size. Ten ArcInfo grid precipitation maps representing the water years 1998 to 2007 were averaged to get the 10-year average precipitation map. The water year begins on October 1 and ends on September 30 of the following year.

2. We estimated the average annual evapotranspiration (ET) based on the current dominant water-related land use and natural vegetation patterns in study area. We derived the natural vegetation patterns from a Utah vegetation map developed by Lowry and others (2005), within the Southwest Regional Gap Analysis Project. The current water-related land-use map and cropping patterns were adapted from the Automated Geographic Reference Center (AGRC, 2010). Those two maps were intersected using the Intersect Geo-processing Tool in ArcGIS to integrate the final combined natural and human-related land-use patterns and their acreages in the study area. Evapotranspiration rates for natural vegetation were derived from a study conducted by the American Society of Civil Engineers in 1989. Evapotranspiration rates for human-related land-use patterns were derived from a study conducted by Utah State University in 1994. The ET volumes were integrated by multiplying the acreage of each land use and/or vegetation pattern by its specific ET rate.
3. We estimated the 10-year average annual flow entering and/or leaving the study area using the measured streamflow records of the U.S. Geological Survey streamflow stations which are available online at the link: http://waterdata.usgs.gov/ut/nwis/nwis. Streamflow entering the valley is estimated from measured records at the U.S. Geological Survey streamflow stations near the Devils Slide and East Canyon Creek. Since the current streamflow records for the Devils Slide streamflow station are missing because it has not been in operation since 1956, its streamflow for the last 10 years (1998-2008) were estimated using a linear regression equation derived from measured flow at Devils Slide station and the nearest streamflow station (Weber River at Echo Dam) when both

stations were in operation from 1932 to 1955. Similarly, the 10-year average streamflow leaving Morgan Valley drainage basin was estimated from the streamflow and water diversions recorded by the U.S. Geological Survey streamflow stations (Weber River at gateway and the diversion to the gateway canal/tunnel).

4. Other minor water-budget items including water used for irrigation, municipal, and industrial purposes and their unconsumed portions (which are returned to the water system) were integrated from a study conducted by the Utah Division of Water Resources (2008).

Water-Well Sampling

We selected 52 wells (appendix B) for sampling, completed in the principal valley-fill aquifer. We sampled wells during spring of 2004; water was analyzed for general chemistry and nutrient (nitrate, nitrite, ammonia, and phosphorous) content by the Utah Division of Epidemiology and Laboratory Services for most of the wells. The Utah Geological Survey (UGS) resampled high-nitrate-concentration wells (greater than 4.5 mg/L) identified by the Weber-Morgan Health Department (WMHD) during previous sampling events. Of the 52 wells, water from five was analyzed for organics and pesticides and from three for radionuclides. Ten previously sampled wells having relatively high (greater than 4.5 mg/L) nitrate concentration were sampled for nitrogen and oxygen isotopes. The constituents sampled for, the U.S. Environmental Protection Agency (EPA) analysis method, and drinking-water quality standard (if the constituent has been assigned one) are provided in appendix A. Samples were obtained following protocol as outlined in a UGS 2003 Quality Assurance Project Plan (QAPP) approved by the EPA. We used data from six wells sampled by the Utah Department of Agriculture and Food (UDAF) following their protocol and outlined in a 2004 online report (http://ag.utah.gov/divisions/conservation/ documents/gw_report04.pdf) and data from 9 sites provided by the Utah Division of Drinking Water, who likely follow protocol outlined by the EPA.

In 2009, we sampled 18 wells and two springs for environmental tracers. Ten of the samples were from valley-fill wells previously sampled in 2004; 10 of the samples were obtained from bedrock sources and these were also analyzed for general chemistry and nutrients. Samples were obtained following protocol as outlined in the 2003 QAPP approved by the EPA.

Stable Isotopes/Environmental Tracers

Stable isotopes can be useful tracers of ground-water flow paths (Kendall and Caldwell, 1998) and may indicate the source(s) of waters bearing similar isotopic signatures. To gain a better understanding of the ground-water hydrology in Morgan Valley, water samples were collected and analyzed for the following isotopes: nitrogen-15 and oxygen-18 in nitrate (expressed as $\delta^{15}N_{NO3}$ and $\delta^{18}O_{NO3}$); oxygen-18 (expressed as $\delta^{18}O_{H20}$), deuterium ($\delta^{2}H$), and tritium (^{3}H) in water; and carbon-14 (^{14}C) and carbon-13 ($\delta^{13}C$) in dissolved inorganic carbon (DIC). Ten samples were tested for $\delta^{15}N_{NO3}$ and $\delta^{18}O_{NO3}$, 20 for $\delta^{18}O_{H20}$ and $\delta^{2}H$ isotopes in water, 20 for ^{3}H, and 3 wells for ^{14}C and $\delta^{13}C$. Nitrogen and oxygen isotopes in nitrate will help determine the source of nitrate; we sampled 10 wells that had previous high nitrate concentrations (greater than 4.5 mg/L) for the stable isotopes of nitrogen and oxygen to identify source(s) of nitrate. The $\delta^{18}O_{H20}$ and deuterium isotopes are used to identify sources of recharge water. Data from samples tested for tritium and carbon isotopes will help determine the age of the ground water.

Nitrogen and Oxygen

Nitrogen and oxygen isotopes have been used to help determine sources of nitrate, can be useful tracers of ground-water flow paths (Kendall and Caldwell, 1998), and hence are indicators of source(s) of waters bearing similar isotopic signatures. By measuring the ratio of isotopes taken from different sources and environments and comparing them to ratios of the same ground-water isotopes (e.g., comparing nitrogen isotope ratios from a documented source [such as fertilizer] to nitrogen isotope ratios of nitrate in ground water) the source of potential contamination to aquifers can be determined (Canter, 1997). In general, stable isotopes are reported as a ratio of the relative abundance of the isotope in the sample to the relative abundance of the isotope in a standard and expressed as:

$$\delta \text{ Isotope (in ‰)} = [(R_{sample}/R_{Standard}) - 1] \times 1000 \qquad (1)$$

where R is the ratio of the "heavy" isotope to the "light" isotope in the sample or standard. Isotopes are reported as parts per thousand, commonly termed as parts per mil, or symbolically as ‰, and can be expressed as positive or negative numbers depending on the relationship to the given standard. Negative numbers indicate a deficiency of the sampled isotope compared to the standard (e.g., less negative numbers indicate the samples are more enriched in that particular isotope). For nitrate, the standard is atmospheric nitrogen (N_2) and nitrogen isotopes are commonly represented as $\delta^{15}N$ (where $\delta^{15}N$=0‰ for N in air); the standard for oxygen is Vienna Standard Mean Ocean Water (VSMOW) (Gonfiantini, 1978), with the oxygen isotope reported as $\delta^{18}O$. Nitrogen has two common stable isotopes: ^{15}N and ^{14}N. Oxygen has three common stable isotopes: ^{16}O, ^{17}O, and ^{18}O.

Figure 5 shows the relationship between nitrogen/oxygen isotopes of nitrate and selected nitrate source types (Kendall, 1998); figure 6 shows the common ranges for nitrogen isotope composition for septic waste, animal waste, fertilized soil, and natural soil (Kendall, 1998). Fertilizer typically has a $\delta^{15}N$ value range from –2 to +2‰, non-cultivated fertilized soils typically have a $\delta^{15}N$ value range from +2 to +8‰ (Canter, 1997), and values that range between -5 and 5‰ are typically associated with ammonium, NH_4^+, in fertilizer and rain. Animal and human waste are generally isotopically indistinguishable, $\delta^{15}N$ ranging between +10 and +20‰ (Kendall, 1998); Canter (1997) reported decomposed animal waste has a range from +10 to +22‰. Animal waste is common to barnyard and feed lots, whereas human waste is found in effluent from septic-tank systems. Nitrate derived from nitrate in precipitation, desert nitrate deposits, and nitrate fertilizer typically has $\delta^{18}O_{NO3}$ values greater than 15‰ and lower $\delta^{15}N_{NO3}$ values (less than 10‰) (figure 6). Processes such as denitrification and mixing of ground water can affect isotopic signature, and thus mask the actual source(s) of nitrate. Isotopic analysis for $\delta^{15}N_{NO3}$ and $\delta^{18}O_{NO3}$ was performed on our samples by the University of Waterloo, Ontario, Canada.

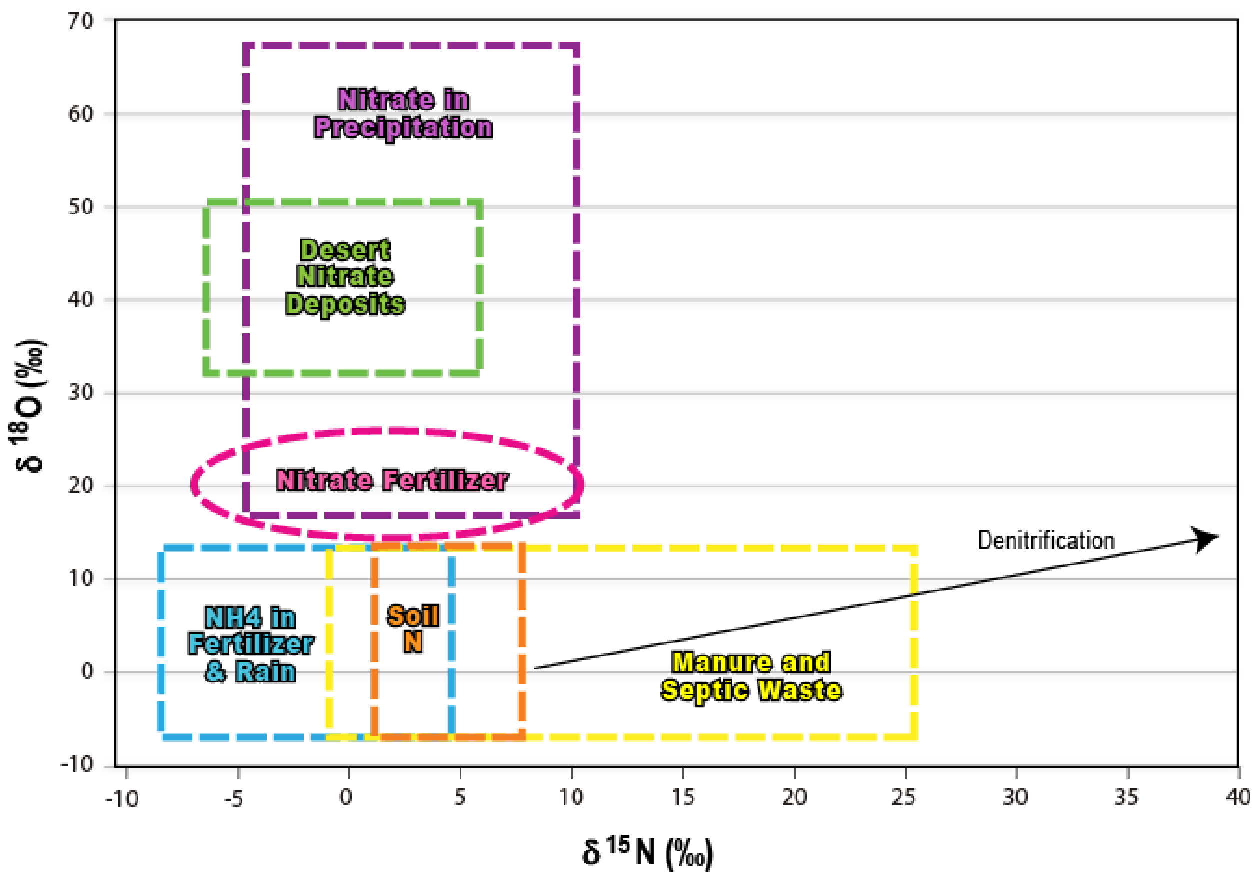


Figure 5. *Plot of nitrogen and oxygen isotopes characterizing sources of nitrate (from Kendall, 1998).*

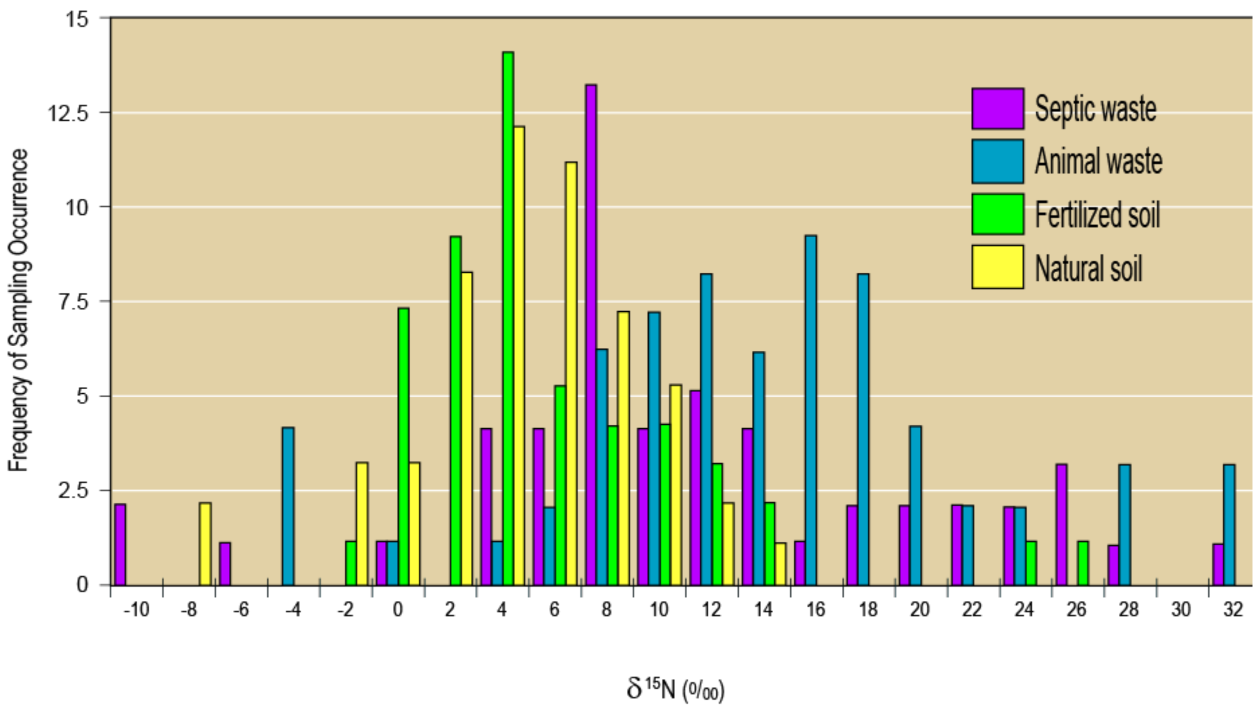


Figure 6. *Summary of the range of δ ^{15}N values for septic waste, animal waste, fertilized soil, and natural soil compiled from global sources (modified from Kendall, 1998).*

Oxygen-18 and Deuterium

Oxygen-18 and deuterium are naturally occurring stable isotopes of oxygen and hydrogen. Values for the stable isotopes oxygen-18 and deuterium are expressed as ratios in delta notation (δ) as ‰ relative to a reference standard according to equation 1 above. The reference standard for oxygen-18 and deuterium is VSMOW (Gonfiantini, 1978). The isotopic ratio of the sample is the ratio of the heavy isotope to the light isotope. The global meteoric water line (GMWL) is modified from Craig (1961), Rozanski and others (1993), and Clark and Fritz (1997) (figure 7). The GMWL represents approximate isotopic composition for oxygen and deuterium of rain and snow on the Earth, where:

$$\delta^2H = 8(\delta^{18}O) + 10 \qquad (2)$$

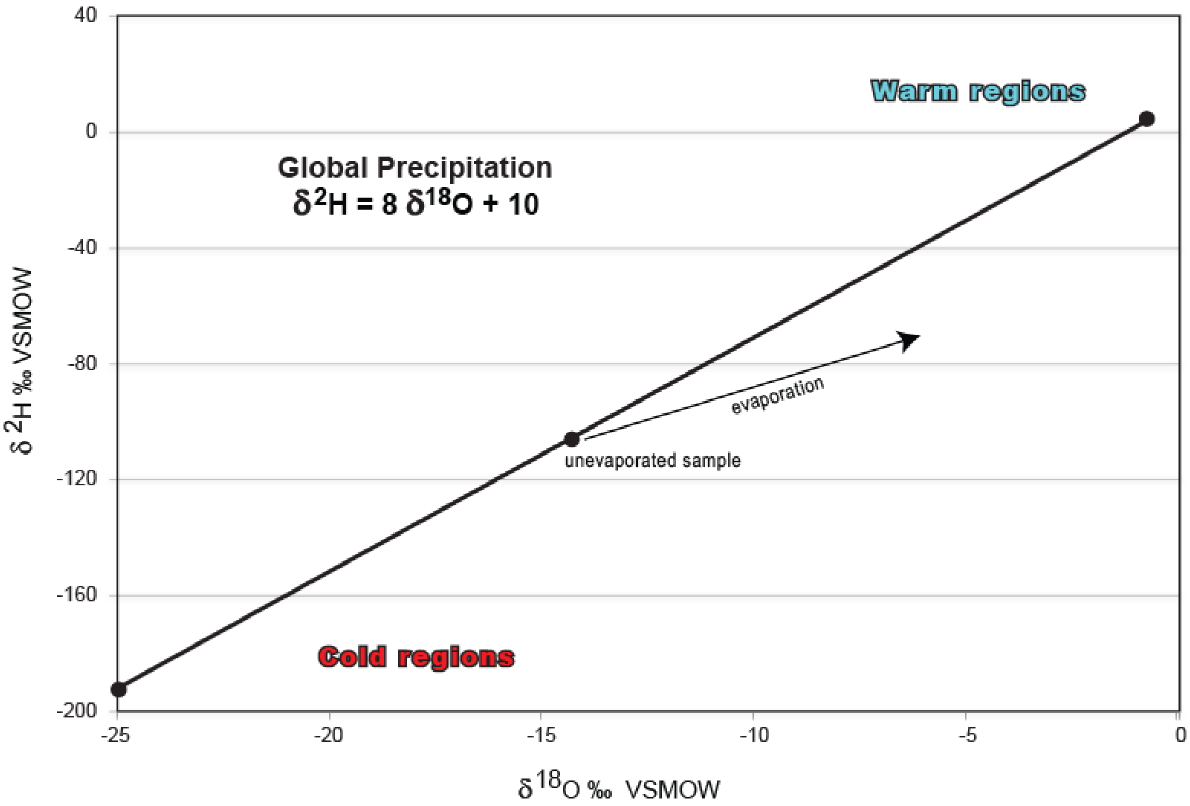


Figure 7. *Plot of the global meteoric water line (GMWL) (modified from Rozanski and others, 1993; Clark and Fritz, 1997).*

Isotopic signatures from seawater fall below the GMWL; precipitation from cooler places plot along the GMWL with coldest places plotting farther to the lower left. Rain at low latitude plots along the GMWL left of seawater; higher latitude samples typically plot to the lower left.

The hydrologic cycle fractionates light and heavy water during evaporation and condensation; molecules of water having lighter isotopes evaporate more readily and molecules of heavy water condense more readily (Clark and Fritz, 1997). Evaporation of surface water or soil water, prior to recharge, can cause enrichment of heavier isotopes in ground water. If snowmelt is a significant recharge source, heavy isotope enrichment could be from sublimation of the snow and evaporation of surface runoff. During evaporation, $\delta^{18}O$ is enriched more than $\delta^{2}H$, so samples that have been evaporated will deviate from the GWML (figure 7). However, if ground water is recharged episodically by heavy precipitation events, ground-water data plot along the meteoric water line. Isotopic analysis of $\delta^{18}O$ and $\delta^{2}H$ was performed by Brigham Young University (BYU), Provo, Utah.

Tritium

Tritium (^{3}H) provides a qualitative age of ground water for determining the relative time when water entered the ground-water system (Clark and Fritz, 1997). Tritium is an unstable isotope of hydrogen with a half-life of 12.3 years; tritium concentration in ground water isolated from other water will decrease by one-half after 12.3 years. Tritium occurs naturally in the atmosphere, but above-ground nuclear testing from 1952 to 1969 added tritium to the atmosphere in amounts that far exceed the natural production rates, and, as a result, tritium concentrations in precipitation also increased. The amount of tritium in the atmosphere from weapons testing probably peaked in the early to mid-1960s, and has been declining since atmospheric nuclear testing ceased. Modern concentrations are typically between 5 and 10 tritium units (1 tritium unit [TU] equals 1 tritium atom per 10^{18} H atoms) (Clark and Fritz, 1997). Tritium in the atmosphere incorporates into water molecules and enters the ground-water system as recharge from precipitation. Because tritium is part of the water molecule, it is not affected by chemical reactions other than radioactive decay, and thus can be used as a tracer of ground water on a time scale of less than 10 to about 55 years before present. Water that entered the ground-water system before 1952 and has remained isolated from younger water contains negligible tritium (<0.8 TU), and is interpreted to have recharged before 1952. Therefore, tritium can be used to distinguish between water that entered an aquifer before 1952 and water that entered the aquifer after 1952. A mixture of waters having different tritium ages complicates interpretation. Tritium analysis was performed by BYU, Provo, Utah.

Carbon

Carbon-14 (^{14}C) is a naturally occurring radioactive isotope of carbon that has a half-life of about 5730 years (Clark and Fritz, 1997). Carbon-14 data can provide information on ground water of greater ages than the other environmental tracers, which only provide relative ground-water ages for water dating to the 20th century. Carbon-14 data are expressed as percent modern carbon (pmC) based on the National Bureau of Standards oxalic acid standard. Atmospheric testing of nuclear weapons also produced ^{14}C, so in some instances values greater than 100 pmC can occur in ground water that contains tritium, because the water was recharged when the atmosphere had above natural levels of ^{14}C. Carbon-14 is not part of the water molecule, so ^{14}C activities are affected by chemical reactions between the aquifer material and the dissolved constituents in the water. Chemical reactions can either add or remove carbon; therefore, knowledge of chemical reactions that occur during recharge and transport through the aquifer are necessary for estimating the initial activity of ^{14}C, which is the most difficult aspect in using ^{14}C for dating ground water. The methods for dating carbon in ground water are complex and beyond the scope of this report; only a brief description is provided. Age calculations require estimates of some chemical parameters during recharge and model calculations of reactions during ground-water transport. Calculation of ground-water age from raw carbon isotope data was performed by Dr. Alan Mayo of Brigham Young University (written communication, May 25, 2008). Percent modern carbon (pmC) values were calculated following the procedure of Stuiver and Polach (1977). Clark and Fritz (1997) provide a more detailed description of carbon isotope dating and the various required parameters to calculate carbon-based ages.

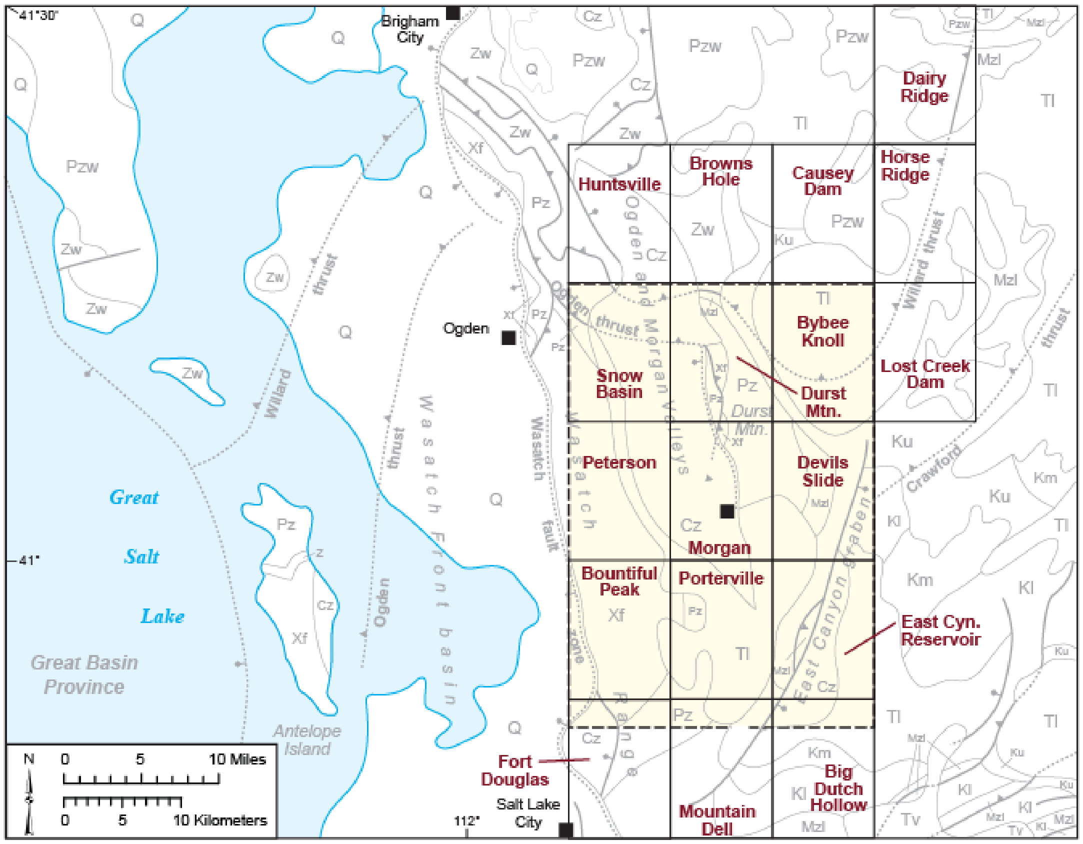
Carbon-13 is a naturally occurring stable isotope of carbon that is used to evaluate chemical reactions involving carbon (Clark and Fritz, 1997). Carbon-13 is expressed using the delta notation as a ratio with carbon-12, similar to $\delta^{18}O_{H20}$ and $\delta^{2}H$, but with the Vienna Pee Dee Belemnite (VPDB) as the reference standard. The $\delta^{13}C$ concentration in ground water depends upon numerous factors, which include the type of vegetation in the recharge area, whether carbonates (and the $\delta^{13}C$ compositions of those minerals) are dissolved or precipitated during recharge, and whether the system is open or closed. Carbon isotope analysis was performed by BYU, Provo, Utah.

GEOHYDROLOGIC CONDITIONS

Geologic setting

Introduction

Geologic units in the Morgan Valley area range from early Proterozoic to Holocene age. The geology of the Morgan Valley area is shown on plate 1, and geologic cross sections are presented on plate 2. Figure 8 shows the area covered by plate 1. Lithologic columns for the



Q	Quaternary deposits	Kl	Cretaceous, lower
Cz	Cenozoic basin fill	Mzl	Mesozoic, lower
Tl	Tertiary, lower	Pz	Paleozoic
Tv	Tertiary volcanics	Pzw	Paleozoic, Willard thrust sheet
Ku	Cretaceous, upper	Zw	Late Proterozoic, Willard thrust sheet
Km	Cretaceous, middle	Xf	Farmington Canyon Complex

Figure 8. *Generalized geologic map (modified from Yonkee and others, 1997), showing map area and quadrangles noted in text.*

Morgan Valley area and the Willard thrust sheet (northeast corner of the map) are presented on figures 9 and 10, respectively. Detailed descriptions of geologic units are presented in appendix D.

The Morgan Valley area is in a region with complex structural features (plates 1 and 2), mostly related to three major episodes of mountain building. During the early Proterozoic, island arcs were accreted onto the southern margin of the Wyoming Province, resulting in intense deformation that occurred at approximately the same time as high-grade metamorphism and widespread igneous intrusion (Bryant, 1988). During mostly Cretaceous time, compression resulted in shortening and development of the Sevier fold and thrust belt (Yonkee and others, 1997). During the late Cenozoic, extension, which continues today, resulted in the development of basin-and-range-type features (Smith and Bruhn, 1984), including the trough shared by Ogden Valley to the north (Saxon, 1972) and the East Canyon Graben. Morgan Valley is bounded on the west and east sides by normal faults (plate 2, cross section B), though the locations of and offset on these faults may vary; the faults may not be continuous along the sides of the valley.

Stratigraphy

Precambrian (early Proterozoic) Farmington Canyon crystalline rock complex and unconformably overlying Paleozoic (Cambrian to Permian) marine sedimentary strata are exposed on Durst and Elk Mountains and the Wasatch Range (plate 1). Permian and Mesozoic (Triassic and Jurassic) strata are exposed east of Durst and Elk Mountains and on both sides of upper Weber Canyon (plates 1 and 2).

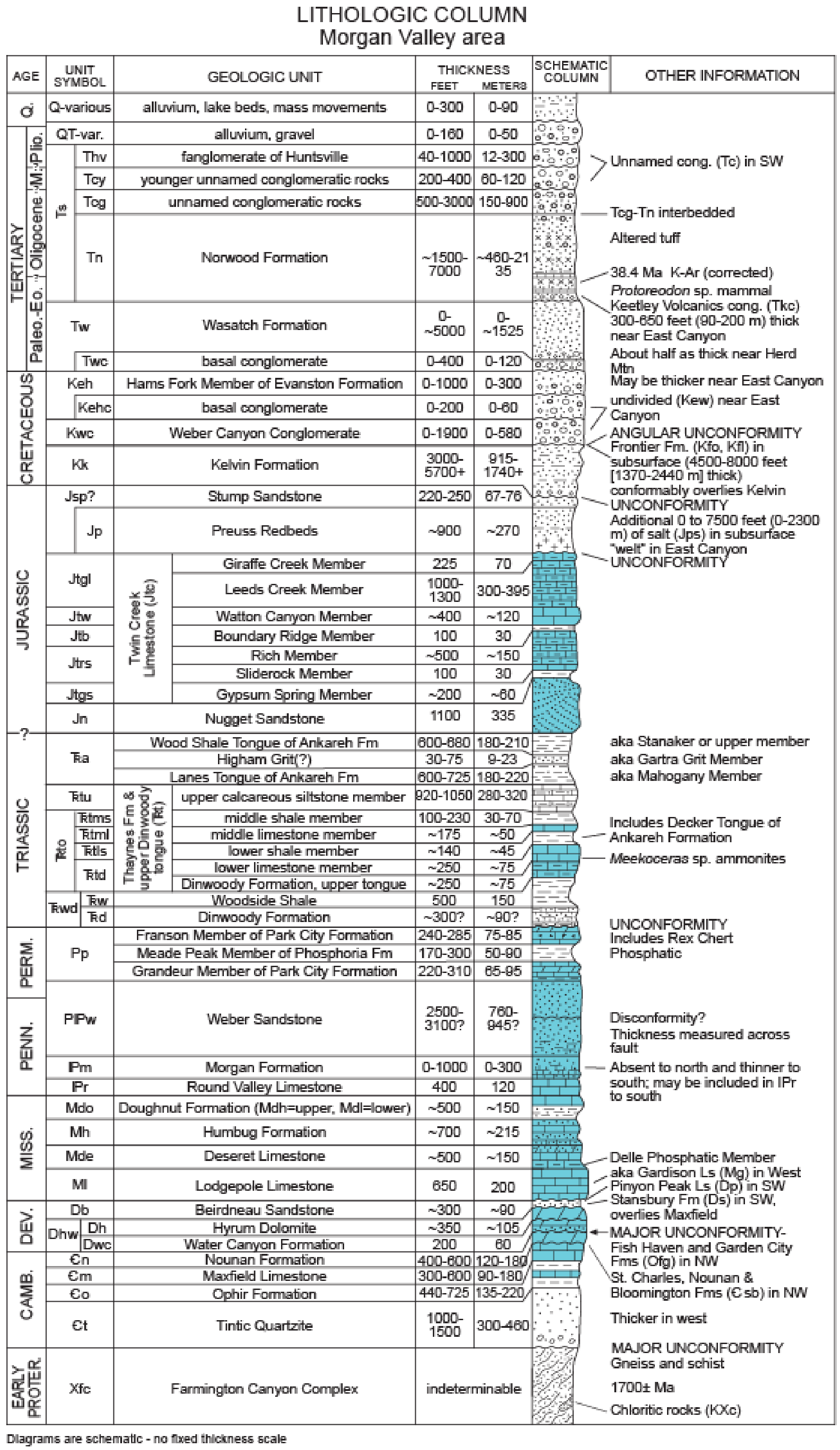


***Figure 9.** Lithologic column and hydrostratigraphy for Morgan Valley, Morgan County, Utah. Layers highlighted in blue are designated as potential aquifers.*

WILLARD THRUST SHEET LITHOLOGIC COLUMN (Mostly concealed)

AGE	GROUP	UNIT SYMBOL	GEOLOGIC UNIT	THICKNESS FEET	THICKNESS METERS	OTHER INFORMATION
TERT. PAL-EO		Tw	Wasatch Formation	up to 2600	up to 800	
CRET		Keh	Hams Fork Member of Evanston Formation	0-1000	0-300	Atypical clasts
CRET		Kwc	Weber Canyon Conglomerate	0-300	0-90	ANGULAR UNCONFORMITY
PERM		Pp+	Franson Member, Park City Formation	~400	~120	Includes Retort Shale, Rex Chert
PERM		Pp+	Meade Peak Member, Phosphoria Fm	250	75	
PERM		Pp+	Grandeur Member, Park City Formation	260	77	Phosphate
IP		PIPw+	Wells Formation	400	120	
MISSISSIPPIAN	MDS* (Units included uncertain)	Mmc+	Monroe Canyon Limestone	1200	320	UNCONFORMITY? *Stratiferia* sp. brachiopods
MISSISSIPPIAN	MDS* (Units included uncertain)	Mlf+	Little Flat Formation	800-1100	245-335	*Faberophyllum* sp. (coral zone IIID-IV) Delle Phosphatic Member
MISSISSIPPIAN	MDS* (Units included uncertain)	Ml+	Lodgepole Limestone	~800	~245	Fossiliferous
MISSISSIPPIAN	MDS* (Units included uncertain)		Leatham Formation	35-70	10-20	Cottonwood Canyon Mbr, Lodgepole Limestone
DEV	MDS* (Units included uncertain)	Db+	Beirdneau Sandstone	400-550	120-170	
DEV	MDS* (Units included uncertain)	Dh+	Hyrum Dolomite	400-500	120-150	
DEV	MDS* (Units included uncertain)	Dwc+	Water Canyon Formation	120-250	35-75	Thins to east
S	MDS* (Units included uncertain)	SOlf+	Laketown Dolomite	~500	~150	
ORD	MDS* (Units included uncertain)	SOlf+	Fish Haven Dolomite	100-135	30-40	Swan Peak Quartzite missing
ORD	OЄc*	Ogc*	Garden City Formation	500-700	150-215	Thins to west Intraformational conglomerate
CAMBRIAN	OЄc*	Єsc*	St. Charles Formation	500-900	150-275	Thins to east
CAMBRIAN	OЄc*	Єsc*	Worm Creek Member	50-100	15-30	
CAMBRIAN	Єc*	Єn*	Nounan Formation	570-675	175-205	Thins to south
CAMBRIAN	Єc*	Єbo*	Bloomington Formation: Calls Fort Shale Member	30-125	9-40	Intraformational conglomerate
CAMBRIAN	Єc*	Єbo*	Bloomington Formation: Middle limestone member	400-550	120-170	Thins to north
CAMBRIAN	Єc*	Єbo*	Bloomington Formation: Hodges Shale Member	280-600	85-180	Thins to north
CAMBRIAN	Єc*	Єbk*	Blacksmith Dolomite	500-530	150-160	Limestone in places
CAMBRIAN	Єc*	Єu*	Ute Formation	450-660	140-200	
CAMBRIAN	Єc*	Єl*	Langston Dolomite	200-300	60-90	
CAMBRIAN / UPPER PROTEROZOIC	CZq*; Bingham Group	Єgc*	Geertsen Canyon Quartzite	3200-4000	975-1200	Thins to east and south; Purplish upper part; feldspathic; light-colored lower part
UPPER PROTEROZOIC	CZq*; Bingham Group	Zb*	Browns Hole Formation	20-200	6-60	Not exposed
UPPER PROTEROZOIC	CZq*; Bingham Group	Zm	Mutual Formation	435	135	Purple to pink Some feldspar locally
UPPER PROTEROZOIC	CZq*; Bingham Group	Zi	Inkom Formation	360-450	110-140	Not present to east
UPPER PROTEROZOIC	CZq*; Bingham Group	Zcc	Caddy Canyon Quartzite	<1500	<460	Thins to east
UPPER PROTEROZOIC		Zkc	Kelley Canyon Formation	2000	610	Argillitic to phyllitic Base truncated by thrust fault where exposed

Not in contact

AGE	UNIT SYMBOL	GEOLOGIC UNIT	THICKNESS FEET	THICKNESS METERS	OTHER INFORMATION
PROT.	ZYp	Formation of Perry Canyon	<2000	<600	Meta-sedimentary Late and Middle(?) Proterozoic

* = Cross section only   + = not shown but may be under Tw and Keh
Diagram is schematic - no fixed thickness scale

***Figure 10.** Lithologic column and hydrostratigraphy for the Willard thrust sheet. Layers highlighted in blue are designated as potential aquifers.*

East of Durst Mountain and south of upper Weber Canyon, the Late Cretaceous synorogenic Weber Canyon Conglomerate and Evanston Formation unconformably overlie Paleozoic and Mesozoic rocks; these rocks and the Cretaceous thrust sheets are unconformably overlain by the Cenozoic (Eocene) Wasatch Formation (plate 1). These Late Cretaceous and Eocene rocks are related to the tectonics of the overthrust belt and provide clues to the timing and locations of uplifts in northern Utah (see DeCelles, 1994; Yonkee and others, 1997). Older Cretaceous strata underlie these synorogenic rocks on the east margin of the map area and are present in subsurface in the East Canyon graben. The Wasatch Formation is present on both sides of the East Canyon graben and Morgan Valley, and is found in scattered patches "resting" unconformably on Precambrian and Paleozoic rocks in the Wasatch Range and on Durst and Elk Mountains.

Morgan Valley and the East Canyon graben are "filled" with probable Oligocene Norwood Formation and slightly older tuffaceous to volcaniclastic, lacustrine and fluvial sedimentary rocks (plate 1). The Norwood strata extend north of Morgan Valley across the topographic divide (Morgan-Weber County line) into Ogden Valley. The Norwood Formation unconformably overlies the Wasatch Formation and is folded with the Wasatch Formation in the Morgan Valley syncline. On the west sides of Durst Mountain and Elk Mountain (east side of Morgan Valley), the Norwood is overlain by and intertongues with unnamed Oligocene(?) conglomeratic strata. These conglomeratic strata are unconformably overlain by younger conglomeratic rocks of possible Miocene and/or Pliocene age.

Numerous kinds of Quaternary deposits are present in the map area (plate 1). Remnants of Pliocene and/or Pleistocene (lower Quaternary) alluvial deposits are present on both sides of Morgan Valley, in the East Canyon graben, and along Cottonwood Creek. Quaternary (upper and middle Pleistocene) glacial deposits cover bedrock on the east flank of the Wasatch Range and are in the well-developed cirques on the crest of the Wasatch Range; glacial deposits locally cover bedrock east of Durst Mountain. Quaternary (upper Pleistocene) lacustrine, deltaic, and alluvial deposits related to Lake Bonneville are present in Morgan, Ogden, and Round Valleys, though the lake did not occupy the valleys after it dropped to the Provo shoreline. Deposits younger than Lake Bonneville are mostly Holocene alluvium in the valleys and drainages noted above, and Quaternary mass-movement deposits like landslides and slumps.

Most of the alluvium in Morgan Valley greater than 10 feet (3 m) thick is located along the major tributaries and the flood plain of the Weber River (Gates and others, 1984). The alluvium is mainly derived from the Cretaceous and Tertiary sedimentary rocks surrounding the valley. The main aquifer in Morgan Valley is in these alluvial valley-fill deposits, which consist primarily of clay, silt, sand, and gravel up to 200 feet (60 m) thick (Gates and others, 1984). The silt and clay, which may be derived primarily from weathering of the Tertiary Norwood Tuff, form discontinuous lenses in the valley-fill alluvium (Saxon, 1972). Eardley (1944) suggests that Morgan Valley did not accumulate the large thickness of alluvium present in Ogden Valley to the north because Morgan Valley alluvium was eroded by the Weber River in response to uplift and faulting.

Structure

Precambrian structures within the Morgan Valley area are exposed primarily in the Wasatch Range in the western part of the study area. Precambrian structures include foliation, gneissic layering, lineations, and complex minor folds within Farmington Canyon Complex basement rocks (Yonkee and Lowe, 2004).

Paleozoic and Mesozoic strata are in an east-dipping homocline that is locally complicated by Cretaceous folding and east- and west-directed thrusts (like the East Canyon thrust). This homocline extends to the southwest beneath cover to exposures in the Wasatch Range northeast of Salt Lake City (plate1).

Several thrust sheets in the Cretaceous to Eocene "overthrust" belt of Utah, Idaho, and Wyoming (Coogan, 1992; Royse, 1993) are present in the map area (plate 1). The Cretaceous Ogden roof thrust is exposed to the northwest in the Wasatch Range and on Durst Mountain; its trace between these exposures is likely buried under several thousand feet of Cenozoic fill in the northern part of the map area. The Ogden roof thrust appears to be exposed on the east flank of the Wasatch Range in the Hardscrabble Creek area (after Bryant, 1990; Yonkee and others, 1997); the concealed trace between this exposure and exposures on Durst Mountain, is likely present in the deep subsurface of Morgan Valley below about 5000 feet (1525 m) of Cenozoic valley fill and about the same thickness of Wasatch Formation. This roof thrust is east-directed and, due to rotation of Durst Mountain, is now east dipping. Rotation likely occurred during late Cretaceous to Eocene uplift of the Wasatch culmination (Yonkee and others, 1997), rather than during Cenozoic listric normal faulting, because significant normal faulting, in the form of a large valley, is not present to the east.

The southern edge of the Cretaceous Willard thrust sheet, that contains late Proterozoic meta-sedimentary and Paleozoic sedimentary strata, is exposed on the north margin of the map area in the Wasatch Range and north of Elk Mountain. The thrust sheet is buried under several thousand feet of Cenozoic valley fill, so the location of the concealed trace of the thrust between these exposures is not known. The likely location of the concealed trace of the Willard thrust east of Elk Mountain is shown on plate 1. Folding and faulting exposed to the north in the Causey Dam quadrangle (Mullens, 1969) imply the subsurface geology of the thrust sheet is more complex than the simple broad synform shown by Yonkee and others (1997); the synform likely plunges to the north, "diverting" ground water to the north, out of the map and study areas. The roughly east-west-trending normal faults cutting the Wasatch Formation and north-south-trending folds in the Wasatch Formation (and subsurface Willard thrust sheet) may be the result of Eocene (Hogsback) thrusting, with a leading edge in Wyoming (Yonkee and others, 1997).

Roughly north-south-trending normal faults in the Wasatch Formation are likely due to post-thrust Cenozoic extension, either Oligocene relaxation (collapse) of the Cordilleran fold-and-thrust belt (see Constenius, 1996), or Miocene and younger Basin-and-Range extension (see for example McCalpin, 1993). Morgan Valley and East Canyon graben formed due to this Cenozoic extension, likely during both relaxation and basin-and-range faulting.

Probable Quaternary scarps and faults in the map area (plate 1) are part of the 10-mile (16-km) long fault system that bounds the west side of the Durst Mountain block (east side of Morgan Valley). At the north end of the fault system, north of Cottonwood Creek, fault scarps are in middle or lower Pleistocene alluvial deposits (older than 730 ka), and extensions of the fault do not cut younger deposits, though changes in slope are present in Tertiary bedrock. To the south on the west side of Durst Mountain, scarps are on mass movements of uncertain Quaternary age. Farther south, but north of Morgan, Quaternary deposits are likely cut by extensional faults along the west side of Durst Mountain, but no scarps are visible. Quaternary faults have been shown south of Morgan, but no scarps in Quaternary deposits are visible. Pliocene and/or Quaternary (lower Pleistocene) deposits may be cut by extensional faults in the East Canyon graben southwest of Henefer, but the faults may be related to movement of a salt welt in the East Canyon graben rather than basin-and-range extension.

Ground-Water Conditions

Introduction

Ground-water resources, which are locally used for domestic and public supplies and livestock watering and irrigation, are of secondary importance compared to surface water in Morgan Valley in terms of development issues (impoundment, diversion, and regulation) and annual supply. The data collected by Gates and others (1984) indicate that most reaches of the Weber River in Morgan Valley and the downstream reaches of East Canyon Creek are gaining reaches, and factors affecting surface-water resources in the Morgan Valley area can also affect ground-water resources.

In the Morgan Valley area, ground water from the valley-fill aquifer is the source of most domestic and municipal culinary water for people living within the valley; surface water is an important source of water used for agricultural irrigation (Gates and others, 1984). Some wells are in fractured-rock aquifers, which may become important sources of ground water in the future. Ground-water use in 2003 consisted of 78% for domestic supply and municipal supply, 7% for commercial and industrial use, 3% for irrigation and stock water, and the remaining 12% for other use (Utah Division of Water Rights, 2004).

Valley-Fill Aquifer

Occurrence: Valley-fill alluvium is the most important aquifer in the Morgan Valley area due to its permeability and because it contains fresh water. Ground-water resources in Morgan Valley are developed by means of small-capacity wells for domestic use at farms and individual residences, and in large-capacity wells for public-supply and some industrial uses (such as Browning Arms Company) (Gates and others, 1984). Many wells are screened in both Quaternary alluvium and Cretaceous and Tertiary semiconsolidated rocks such as the Norwood Tuff and Wasatch Formation (Gates and others, 1984).

Gates and others (1984) summarized the hydrogeology of Morgan Valley including recharge, discharge, and estimates of water volume stored in the valley-fill aquifer; the information described below is from their 1978 to 1980 study.

Recharge to the valley-fill aquifer in Morgan Valley is from precipitation, downward seepage from losing stretches of perennial and ephemeral streams (mostly along the valley margins), underflow to alluvium from older rock units, infiltration from irrigation, and seepage from irrigation canals located along the valley margins. In terms of quantity, the main sources of recharge are seepage from streams, infiltration from irrigation, and canal losses.

Discharge of ground water from the valley-fill aquifer in the Morgan Valley area is by seepage to the Weber River and East Canyon Creek; transpiration by phreatophytes, crops, and pasture vegetation; discharge from wells and springs; and underflow out of the valley through valley-fill alluvium at the head of Weber Canyon. Gates and others (1984) estimated that the minimum ground-water discharge from the area is about 40,000 acre-feet per year (49 hm^3); this estimate does not include discharge from phreatophytes (estimated at about 5000 acre-feet per year [(6 hm^3]). Total ground-water discharge from wells and springs for public, domestic, and industrial use is estimated to be about 1200 acre-feet per year (1.5 hm^3). Ground water that leaves valley-fill alluvium in Morgan Valley as underflow in Weber Canyon is estimated to be about 1000 acre-feet per year (1.2 hm^3).

Ground water in the unconsolidated alluvium is generally under water-table conditions (Saxon, 1972). Ground water moves from the valley margins toward East Canyon Creek and the Weber River, and then downstream toward the head of Weber Canyon (Gates and others, 1984) (figures 11 and 12).

Gates and others (1984) estimated the volume of water stored in valley-fill in the study area to be 1,700,000 acre-feet (2100 hm^3), and assuming a specific yield of 0.10, the estimated theoretically recoverable ground water is 170,000 acre-feet (210 hm^3). This is about 50% of the average annual flow of the Weber River at Gateway in Weber Canyon.

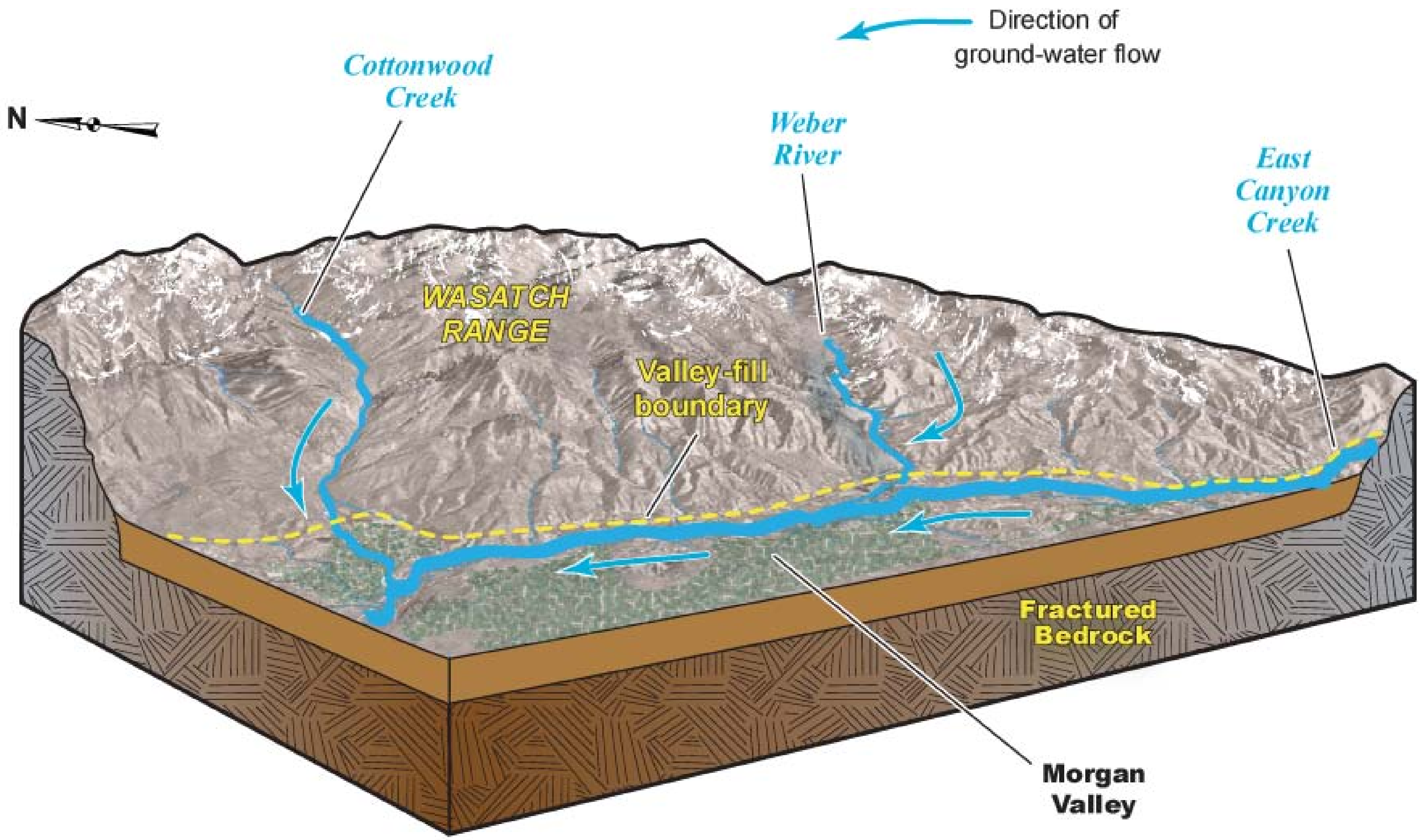


Figure 11. *Schematic block diagram showing ground-water flow in Morgan County, Morgan Valley, Utah (based in part on U.S. Geological Survey digital elevation model data) .*

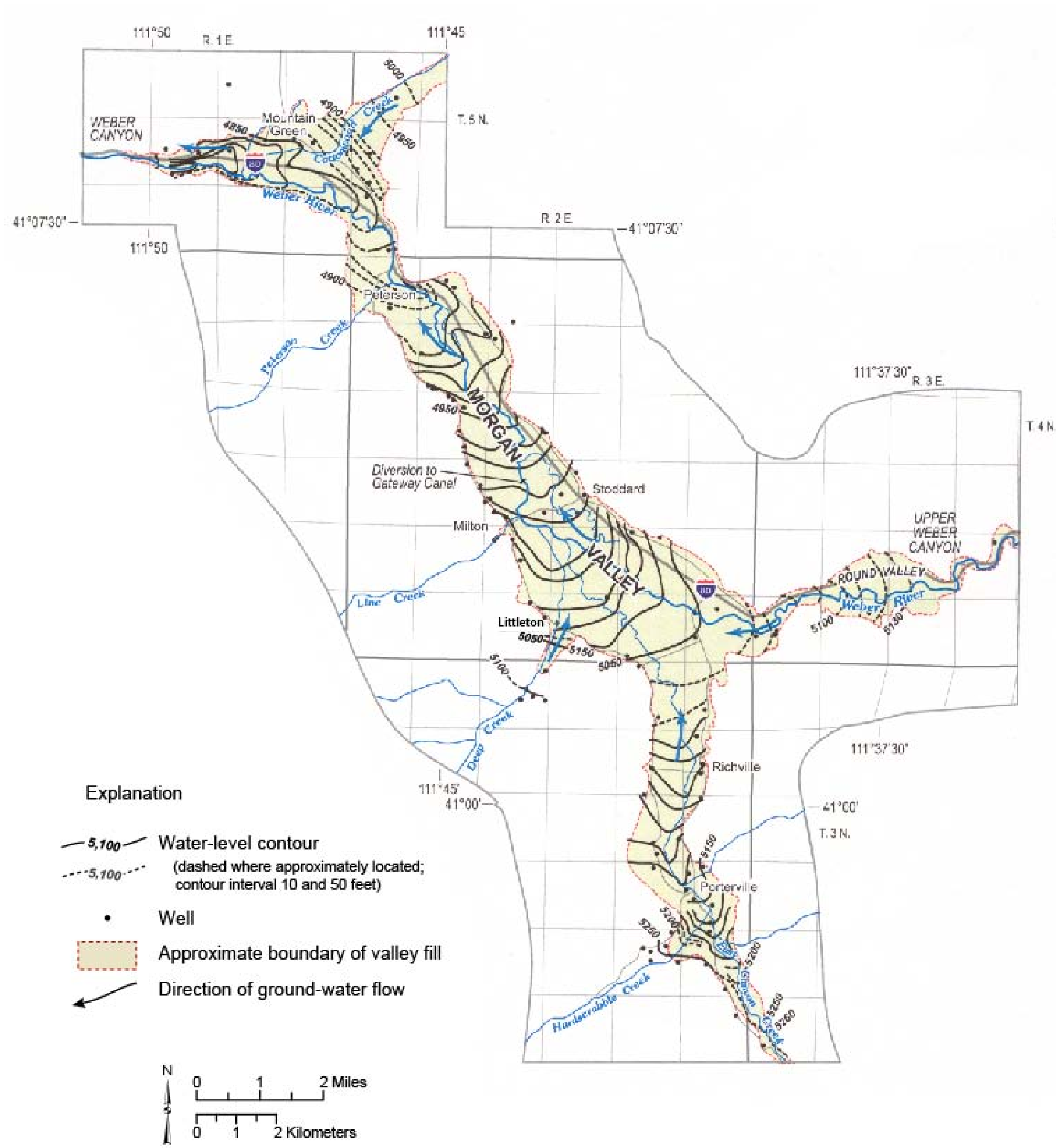


Figure 12. Potentiometric-surface map of northern Morgan Valley, Morgan County, Utah (from Gates and others, 1984).

Water-level measurements from wells in Morgan Valley during the 40 to 50 years prior to 1984 indicate long-term changes in ground-water storage have not occurred; this suggests that during this period ground-water recharge and discharge were in equilibrium. Hydrographs from wells in the study area show seasonal and year-to-year fluctuations in ground-water levels; this illustrates the relationships among ground-water levels, run-off, and seepage from irrigation canals. In many cases, ground-water levels are higher during late summer and fall than during the spring, showing the effects of recharge during the irrigation season (Gates and others, 1984).

Nature and thickness: Plate 3 is a contoured complete Bouguer anomaly map for the Morgan Valley area based on gravity data collected at the stations shown on figure 3. Gravity values ranged from -201 milligals to -226.5 milligals. Based on these data, model cross sections were constructed across Morgan Valley in the Morgan area (figure 13) and along Morgan Valley from Mountain Green to Morgan (figure 14). We compiled a schematic isopach map of the unconsolidated valley-fill deposits (plate 4) based on information from drillers' well logs, the model cross sections (figures 13 and 14), and the gravity survey (appendix C). The majority of wells penetrating to bedrock are along the perimeter of the valley; we determined the bedrock depth based on some of those wells.

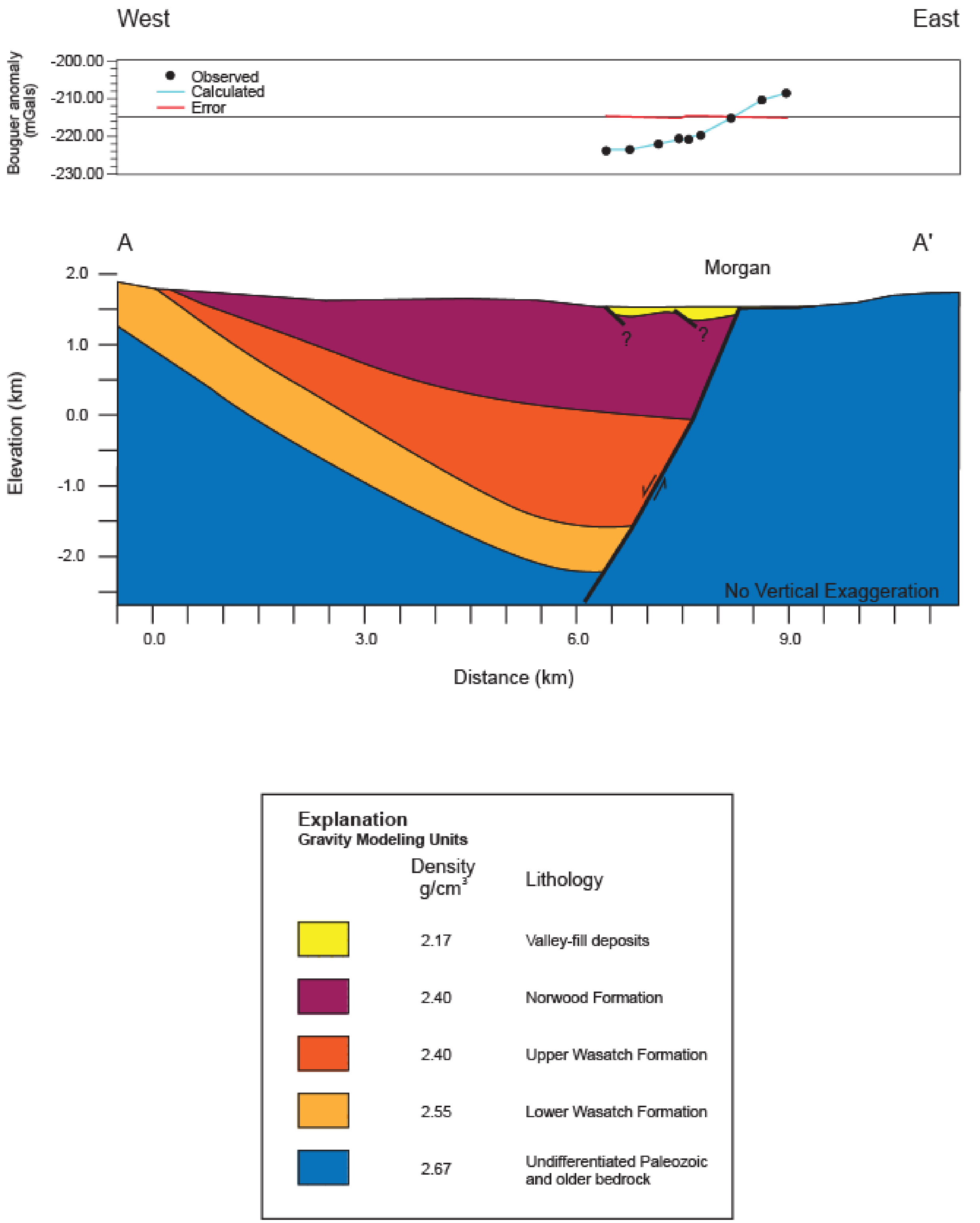


Figure 13. *Gravity data and model cross section A-A' for traverse along Young Street in Morgan City. See figure 3 for traverse location.*

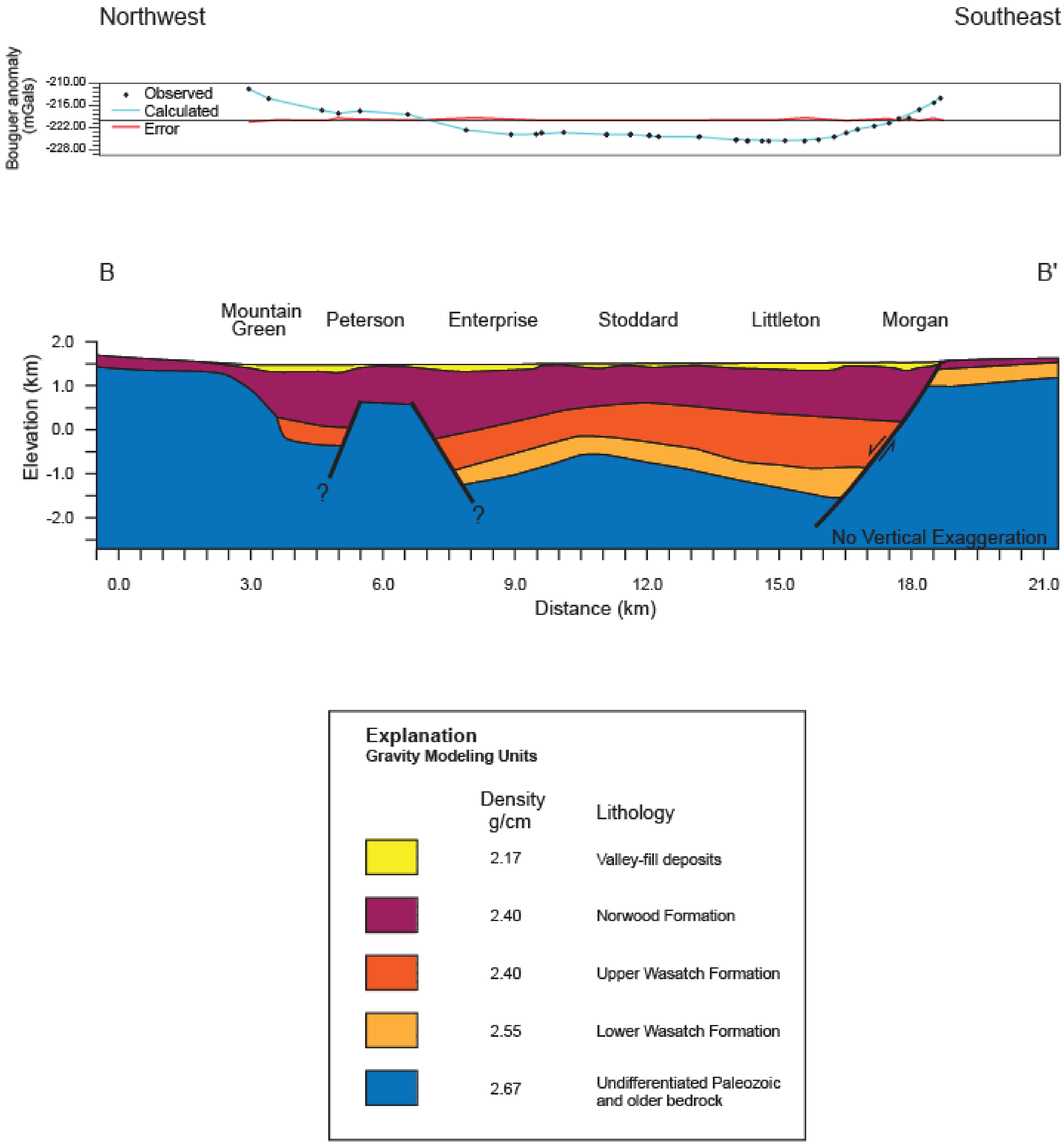


Figure 14. *Gravity data and model cross section B-B' for traverse from Mountain Green to Morgan City. See figure 3 for traverse location.*

The thickness of valley-fill material is greatest in central Morgan Valley, near the towns of Morgan and Enterprise, where the valley fill is estimated to be greater than 600 feet (180 m) thick (plate 4). The valley fill exceeds 400 feet (120 m) in thickness southeast of Mountain Green and 200 feet (60 m) in thickness northwest of Stoddard and from east of Milton to south of Richville (plate 4). Valley-fill deposits in the rest of the Morgan Valley are less than 200 feet (60 m) thick (plate 4).

We examined 65 drillers' well logs to produce a recharge area map for the valley-fill aquifer. Although wells exist having discharge-area characteristics (i.e., flowing or having an upward vertical gradient) in the Mountain Green, Stoddard, Littleton, Morgan, and Porterville areas, they are not extensive enough to create a map showing a discrete discharge area. Based on the drillers' logs we evaluated, the valley fill is predominantly coarse grained and is a primary recharge area (plate 5).

Water-yielding characteristics: We used information from 79 drillers' logs of water wells to estimate aquifer properties for the valley-fill aquifer (figure 15, table E1). Specific capacity ranges from 0.07 to 50 gallons per minute per foot (0.001-1 L/s/m) and averages 8.4 gallons per minute per foot (0.16 L/s/m), with the areas having the highest specific capacity (table E1, figure 16) generally corresponding to areas having the greatest aquifer thickness (plate 4). Transmissivity ranges from 6.75 to 8815 square feet per day (0.63-819 m^2/d), has a median of 551 square feet per day (51 m^2/d), and averages 1340 square feet per day (125 m^2/d), with the areas having the highest transmissivity (figure 17) also corresponding to areas having the

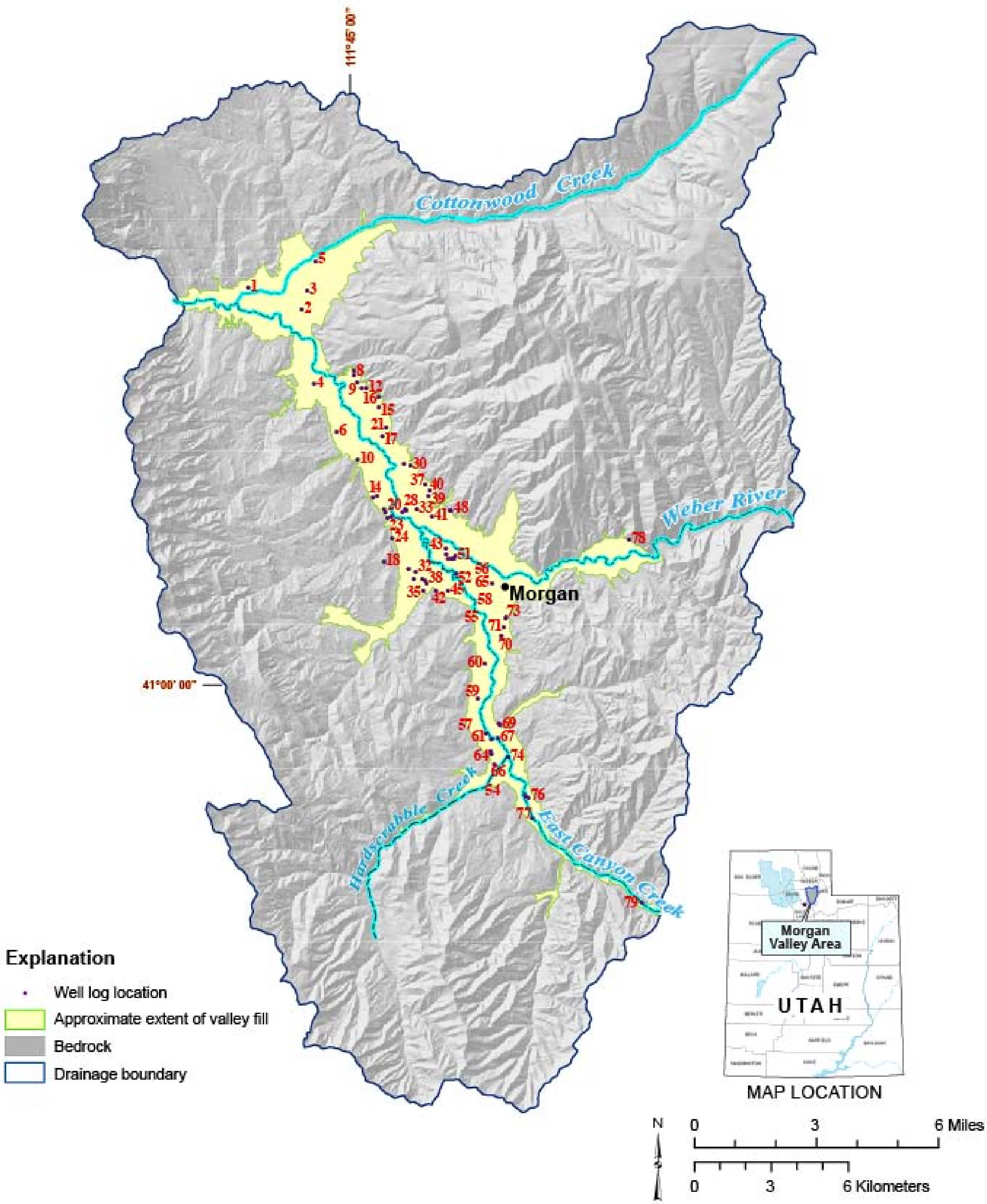


Figure 15. Location of valley-fill well logs in Morgan Valley, Morgan County, Utah (well log details are shown in table E-1; label IDs refer to well logs on this map).

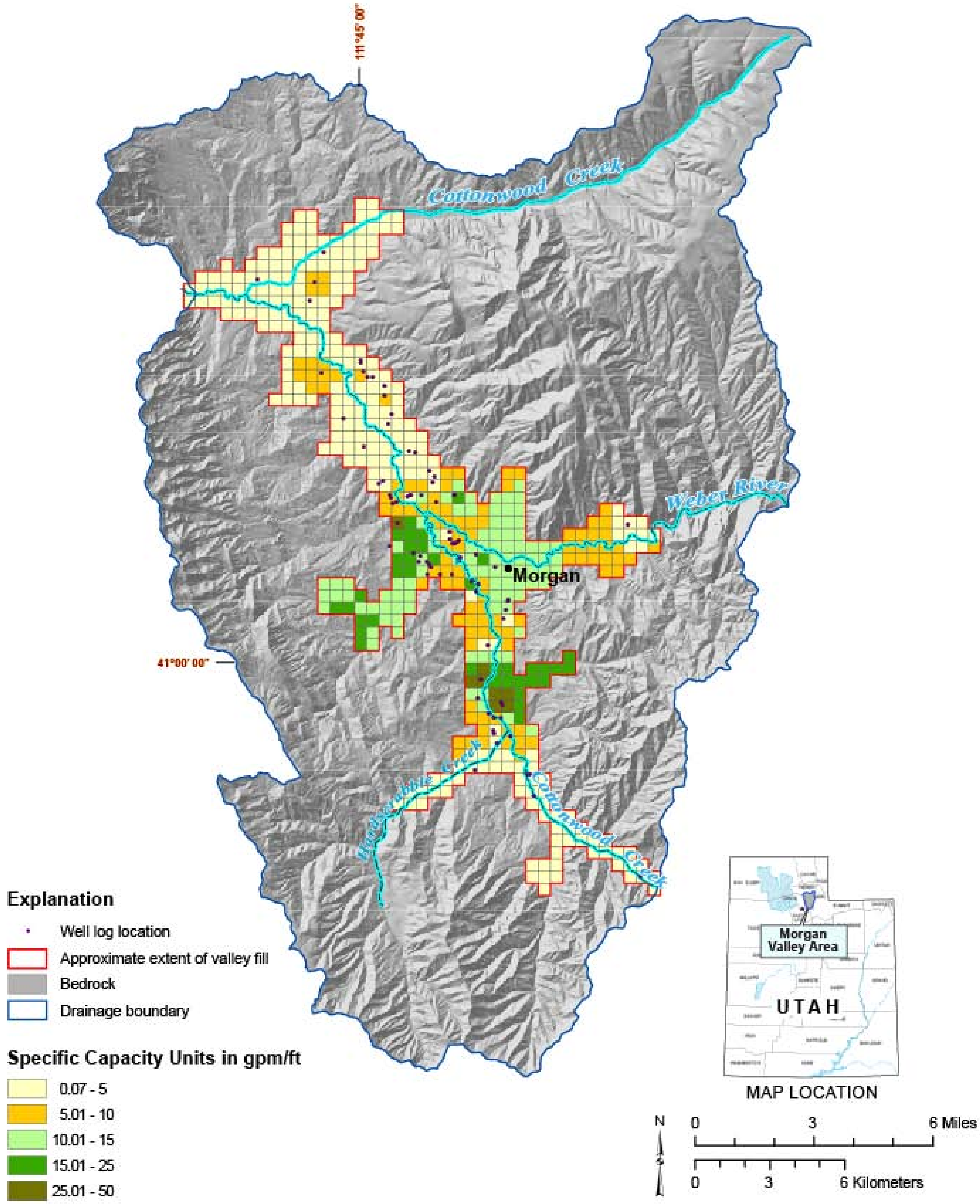


Figure 16. *Valley-fill aquifer specific capacity in Morgan Valley, Morgan County, Utah (specific capacity was estimated from drillers' log well test data by dividing the well pumping rate by drawdown).*

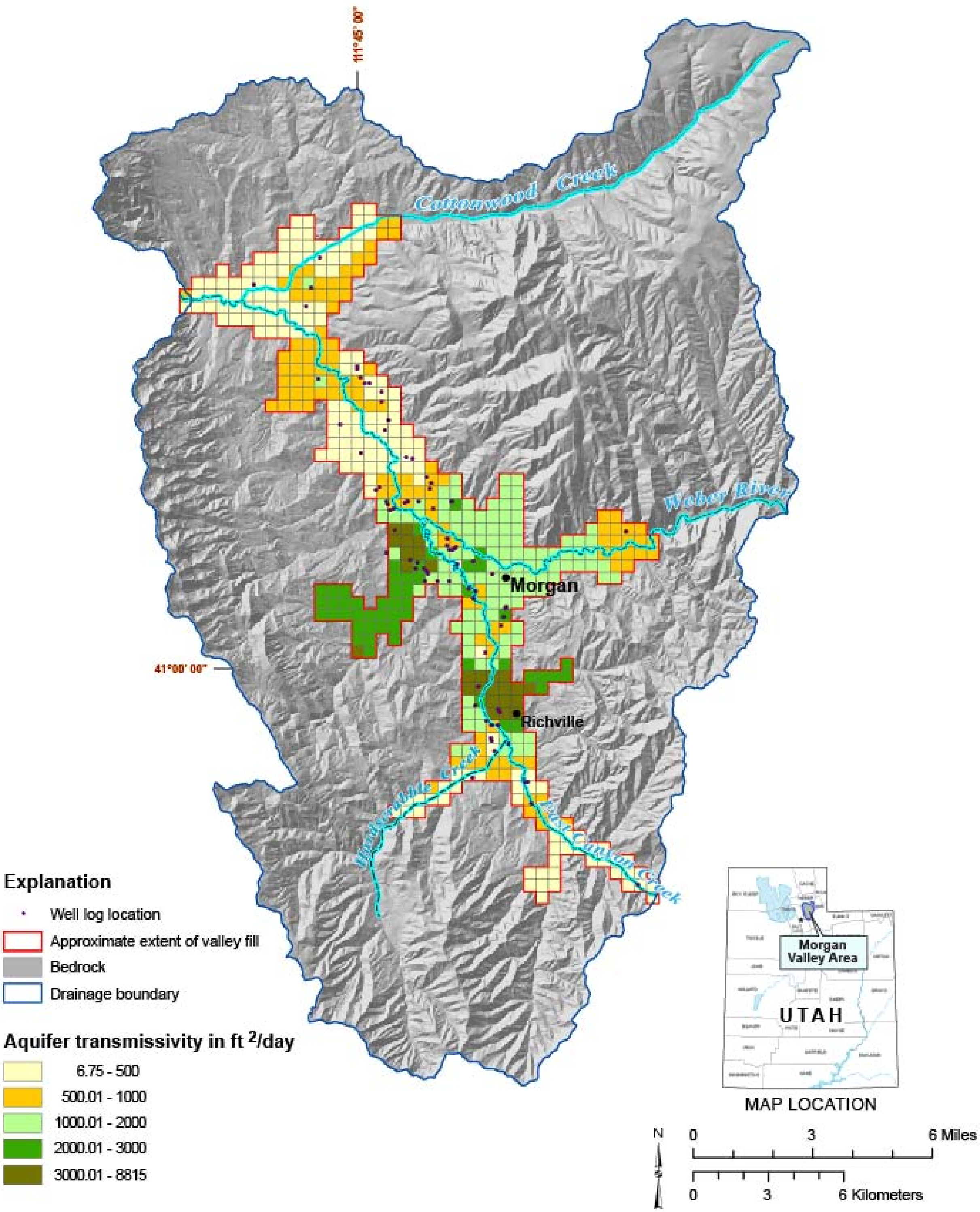


Figure 17. Valley-fill aquifer transmissivity (feet ^{2}/day) in Morgan Valley, Morgan County, Utah (transmissivity was estimated following TGUESS spreadsheet algorithm of Bradbury and Rothschild [1985] which applies the Cooper-Jacob approximation of the Theis equation).

greatest aquifer thickness (plate 4), although transmissivity is particularly high near Richville. Gates and others (1984) estimated transmissivity to range between 40,000 to 50,000 square feet per day (3700-4600 m^2/d) for a Morgan City well ([A-4-2] 36bca-1) from the driller's log using the method of Hurr (1966), which is much higher than our highest transmissivity estimate; we believe the well may have been inducing recharge from the Weber River, located 125 feet (38 m) from the well, during the 8-hour pump test, resulting in an inaccurate transmissivity estimate. Hydraulic conductivity ranges from 0.08 to 2155 feet per day (0.02-657 m/d) and averages 183 feet per day (56 m/d), with the areas of highest hydraulic conductivity (figure 18) near Richville and mouth of Deep Creek areas. Storativity ranges from 0.02 to 0.26 and averages 0.2, with the areas of highest storativity (figure 19) near Stoddard, Enterprise, and Mountain Green.

Fractured Rock Aquifers

Although some rock units have primary porosity, the density, openness, and types of rock fractures can be more important in terms of overall water-yielding characteristics. Well yield is determined by the number of faults or joints (fractures along which no displacement has occurred) intercepted by the well bore. Faults (fractures along which relative displacement has occurred) may conduct water in directions parallel to the fault, but may be filled with gouge that can inhibit the flow of ground water perpendicular to fault orientation.

Figures 9 and 10 are lithologic columns on which geologic units with the highest potential for use as fractured-rock aquifers have been identified. Water-yielding characteristics 4

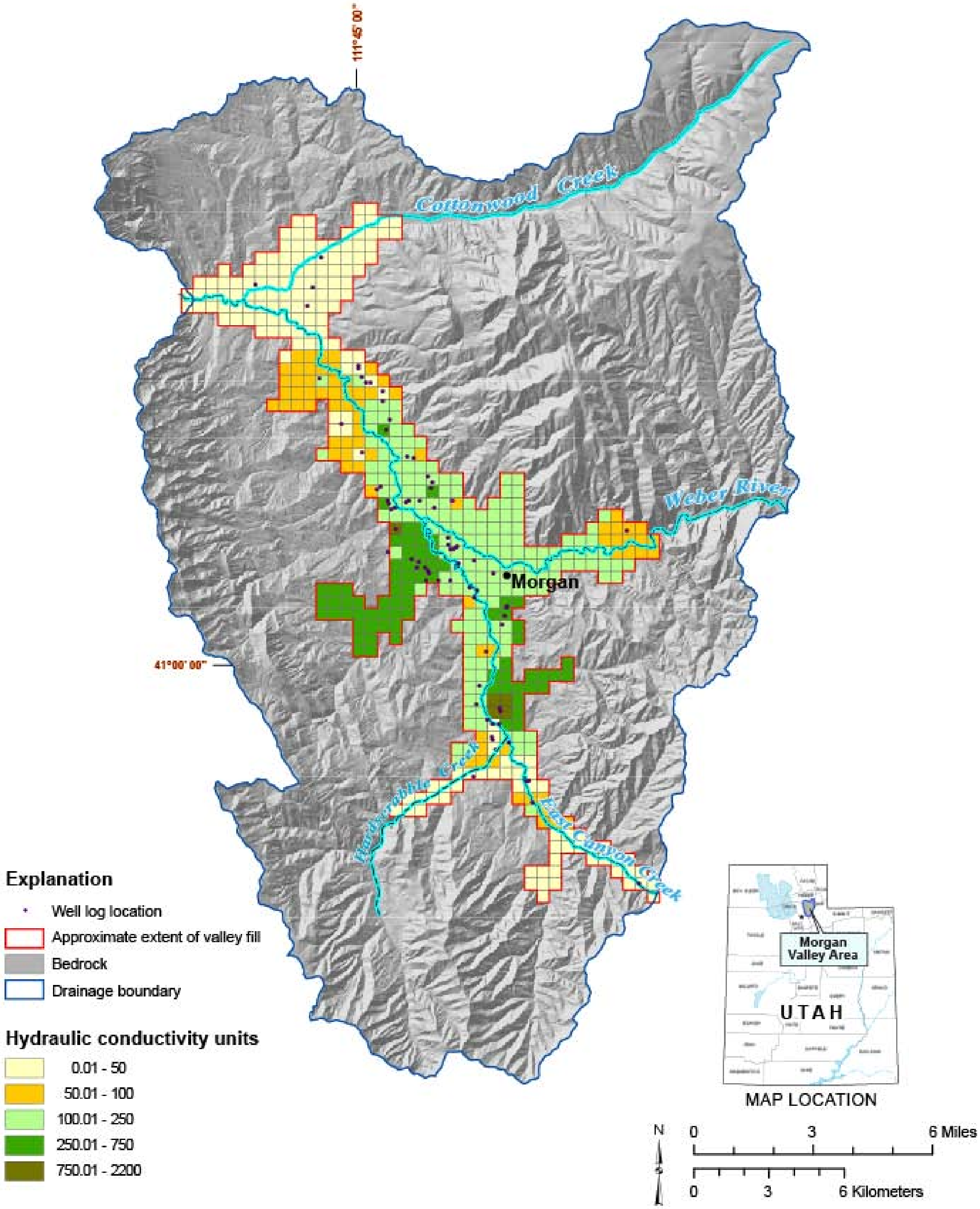


Figure 18. *Valley-fill aquifer hydraulic conductivity (feet/day) in Morgan Valley, Morgan County, Utah (hydraulic conductivity was estimated following TGUESS algorithm of Bradbury and Rothschild [1985] which applies the Cooper-Jacob approximation of the Theis equation).*

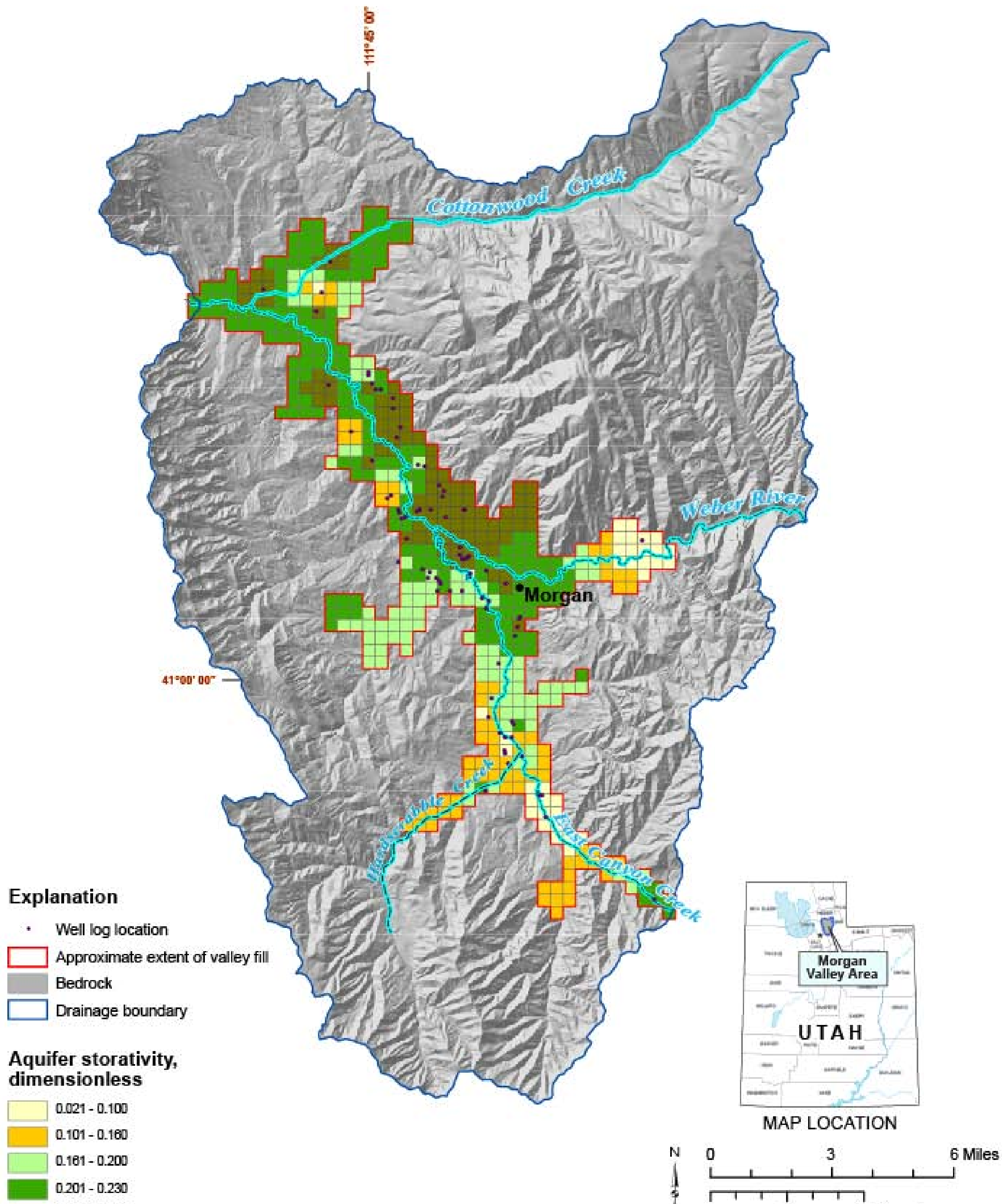


Figure 19. *Valley-fill aquifer storativity in Morgan Valley, Morgan County, Utah (aquifer storativity was estimated using the equation: S=Sy+Ss X b, where Sy was adapted from Johnson [1967], Ss was adapted from Domenico [1972] based on their well log lithology, and b is the saturated thickness).*

for 14 fractured rock wells in the Morgan Valley area (figure 20) are presented in appendix E (table E2); note the high variability of values for those fractured rock aquifers with more than one set of data. Because of the complex structural setting of the Morgan Valley area, not all geologic units will exist in the subsurface at all locations, and if present may be too deep below the surface to be viable economic targets for water wells. Cover by the Tertiary Wasatch and Norwood Formations precludes estimations of the depth to the older units.

Cross sections (plate 2) show variation in faulting and depth of valley fill. The south part of the valley is shallower (plate 1) and, therefore, we surmise this is where potential recharge areas for fractured-rock aquifers below Tertiary formations may occur. The potential pre-Tertiary aquifers are shown highlighted on the lithologic columns (figures 9 and 10).

Farther north near Morgan, the sub-fill aquifers are prohibitively deep, thousands of feet down; and recharge to these aquifers is limited by the fault on the east side of the valley and cover by clay-rich rocks, particularly on the west side of the valley. Durst Mountain is a recharge area, but ground water in potential aquifers, shown on lithologic columns (figures 9 and 10), probably moves north into Cottonwood Canyon, south into Round Valley, and east out of the study area.

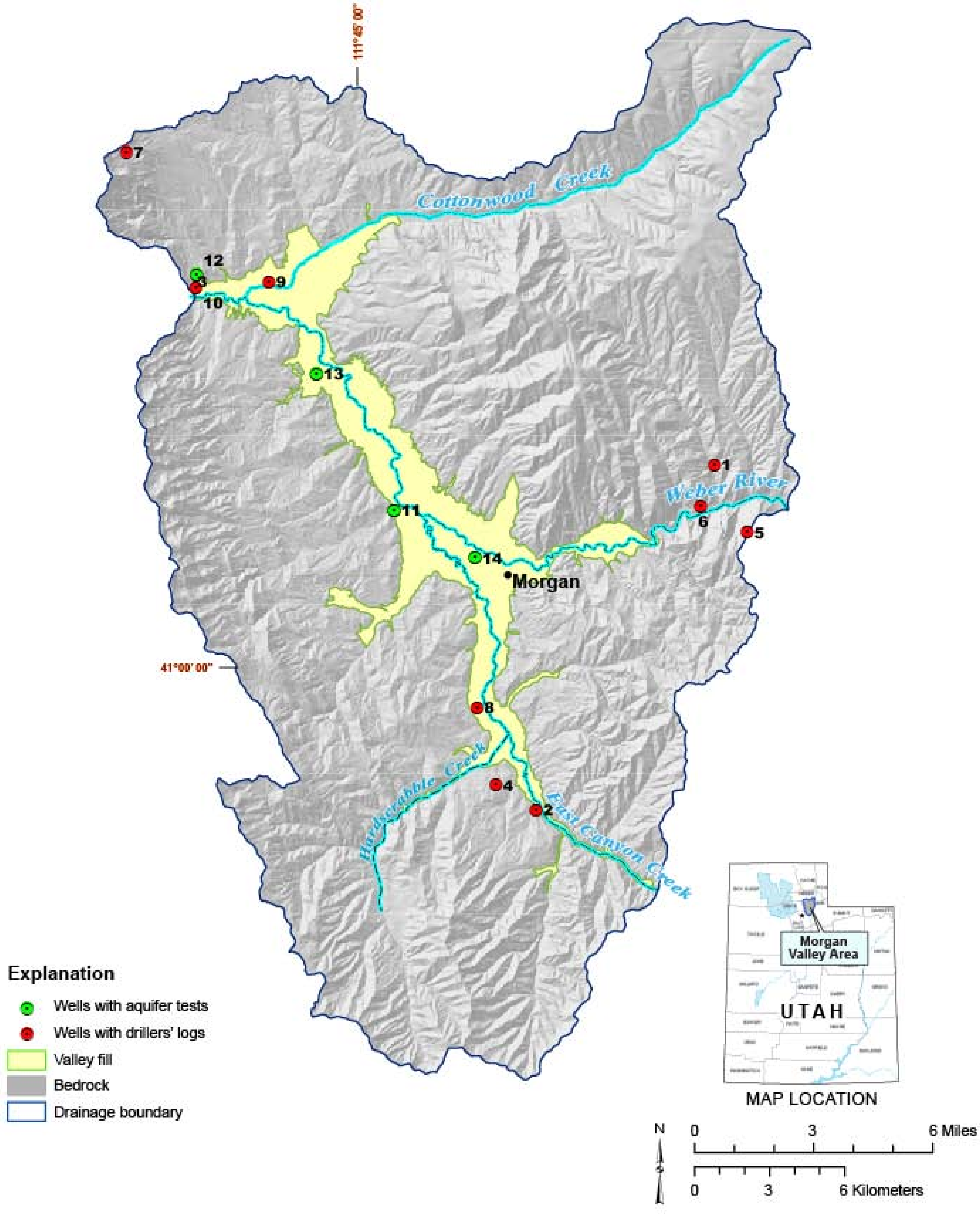


Figure 20. *Location of fractured-rock wells and aquifer tests in Morgan Valley, Morgan County, Utah (well log details are shown in table E-2; label IDs refer to well log label IDs on this map).*

Ground-Water Quality From Previous Studies

Ground-water quality in Morgan Valley is generally good and the water is suitable for most uses. Under drinking-water and ground-water protection regulations, ground water is classified based largely on TDS concentrations as shown in table 1. Class IA and II water is considered suitable for drinking, provided concentrations of individual constituents do not exceed state and federal drinking-water standards. Class III water is generally suitable for drinking water only if treated, but can be used for some agricultural or industrial purposes without treatment; ground water that falls within classes IA or II based on TDS concentrations, but with individual constituents that exceed drinking-water standards, fall within Class III. Class IV water, though not suitable for drinking, may in some instances be mined for its dissolved minerals. Two other ground-water quality classes, Class IB (Irreplaceable) and Class IC (Ecologically Important), are not based on TDS concentrations.

Ground-water samples collected by Gates and others (1984) indicate that ground water within Morgan Valley is good quality. Total-dissolved-solids concentrations from 57 samples collected in 1979 from wells completed in a variety of geologic units range from 127 to 754 mg/L and average 387 mg/L (Gates and others, 1984). Average TDS concentration is 361 mg/L for alluvium, 375 mg/L for the Norwood Tuff, and 478 mg/L for the Wasatch Formation. Some wells in several areas of Morgan Valley, including the Hardscrabble Creek area, have yielded nitrate concentrations above 3 mg/L (Quilter, 1997; Ray Bakker, Weber-Morgan Health Department, verbal and written communication, 2003). This includes areas that were sampled by the Weber-Morgan Health Department (WMHD) during the mid 1990s prior to the establishment of much development (Ray Bakker, WMHD, personal communication, 2003).

WATER BUDGET

Morgan Valley is located within the lower Weber River basin, which receives a considerable amount of streamflow from the Weber River and East Canyon Creek; these streams enter Morgan Valley from the eastern and southeastern boundaries, respectively (figure 21). We created a detailed water budget for Morgan Valley based on available climatic data, drainage patterns, land use, vegetation cover, water use, geology, soil data, and streamflow measurements. We evaluated both inflow and outflow water-budget components for the Morgan Valley.

Inflow

The inflow component in Morgan Valley study area consists of precipitation (both rainfall and snow fall), streamflow from the Weber River crossing its drainage boundary at Devils Slide, and streamflow from East Canyon Creek.

Precipitation

Elevation data must be considered for a reliable spatial distribution estimate for precipitation (P); this was not possible using standard interpolation methods from point data. Instead, ArcInfo precipitation grids for the water years 1998 through 2007 were adapted from PRISM data (PRISM Group, University of Oregon, 2010) after downscaling the grids from a 4-kilometer (2.5-mi) cell size to a 500-meter (1640-ft) cell size using the Resample Tool in ArcGIS software. The 10 downscaled precipitation grids were used to integrate the 10-year average annual precipitation distribution map (figure 22). The 10-year average annual precipitation rate ranges from less than 20 inches (508 mm) per year in the lower areas surrounding Weber River

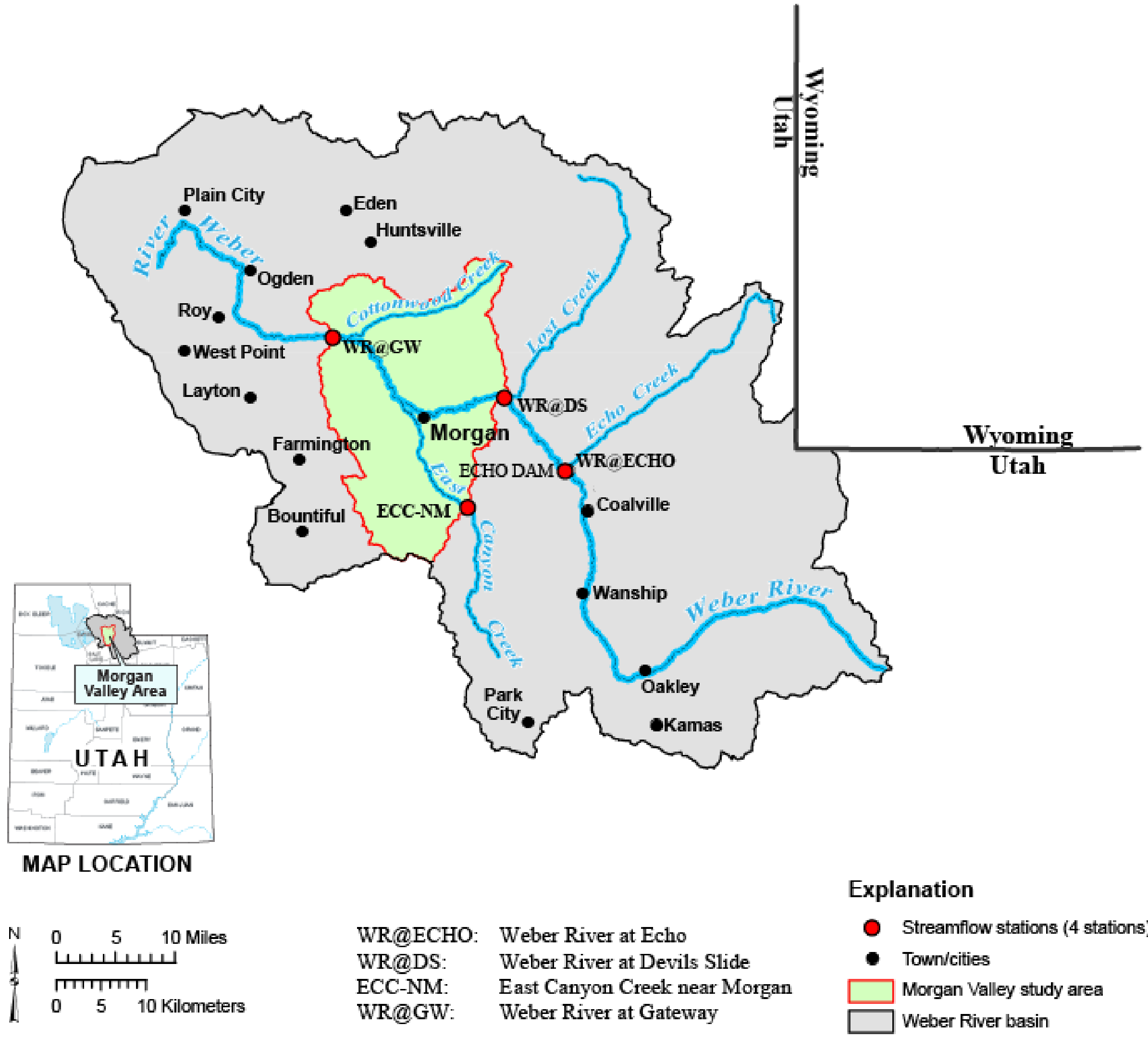


***Figure 21.** Location of main streams and streamflow stations in Morgan Valley, Morgan County, Utah.*

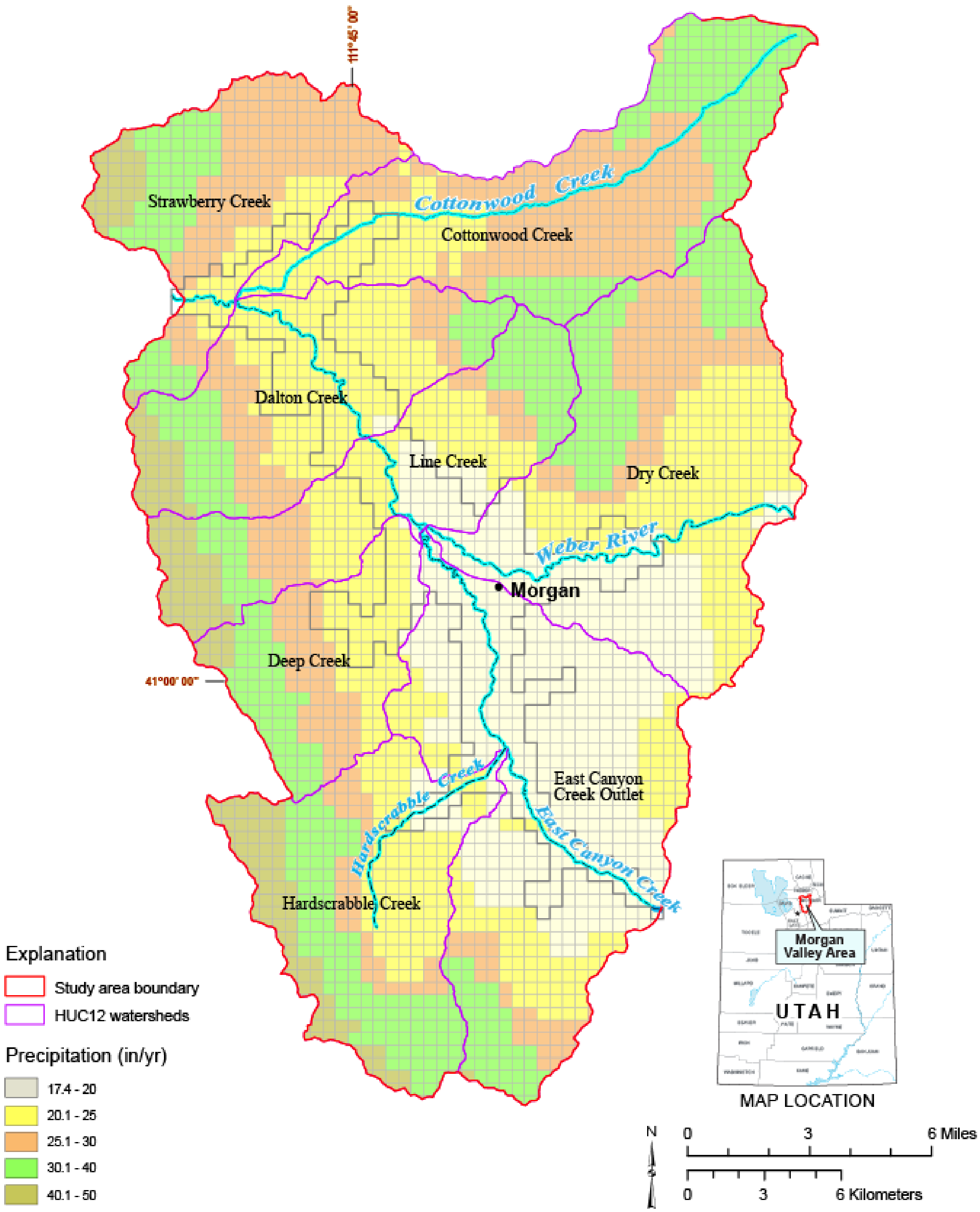


Figure 22. *Ten-year average annual precipitation in Morgan Valley, Morgan County, Utah (1998/1999 - 2007/2008) derived from (PRISM Group database, 2009). (The grid cell size was downscaled from the original 4-kilometer data cell size to 500-meter cell size).*

and East Canyon Creek to more than 40 inches (1016 mm) per year in the western mountains bordering Morgan Valley. The upstream portions of Line Creek, Dry Creek, and Cottonwood Creek in the northeastern area of Morgan Valley show high precipitation rates ranging from 25 to 40 inches (635-1016 mm) per year. The 10-year average annual weighted precipitation rate in Morgan Valley was estimated at 26.4 inches (670 mm) per year with an equivalent total annual volume of about 436,000 acre-feet (538 hm^3) per year.

Stream Inflow

The annual total streamflow in Morgan Valley was estimated for water years 1998 to 2008 based on streamflow measurements at four U.S. Geological Survey (USGS) streamflow stations (http://waterdata.usgs.gov/ut/nwis/nwis) and one Utah Division of Water Rights measurement station (U.S. Geological Survey, 2009; Utah Division of Water Rights, 2010). Inflow to the study area consists of streamflow from East Canyon Creek and from Weber River at Devils Slide (figure 21). Ten-year average annual inflow at East Canyon Creek measured at USGS station #10134500 (U.S. Geological Survey, 2009) near Morgan is about 35,000 acre-feet (43 hm^3) per year.

Current streamflow records for the Devils Slide streamflow station (USGS 10133500 Weber River at Devils Slide), which is located at the boundary where Weber River enters Morgan Valley, do not exist because the station has not been in operation since 1956. Devils Slide streamflow for the last 10 years (1998-2008) was estimated using a linear regression equation derived from measured flow at the Devils Slide station and the nearest streamflow station (USGS 10132000 Weber River at Echo) when both stations were in operation (1932 to 1955) (figure 23). The resulting linear regression equation is (in acre-feet per year):

$$\text{Weber River flow at Devils Slide} = 1.41 \times \text{Weber River flow at Echo} - 23{,}862 \qquad (3)$$

Table 2 shows measured and estimated streamflow records for the last 10 water years (1998 to 2008) at all available streamflow stations in Morgan Valley. We estimated the 10-year average inter-basin flow of Weber River at Devils Slide using the above equation at about 190,000 acre-feet (234 hm^3) per year (table 2) with an equivalent weighted rate of 7 inches (178 mm) per year. Thus the 10-year average combined inter-basin inflow from East Canyon Creek and Weber River at Devils Slide into Morgan Valley is about 225,000 acre-feet (277 hm^3) per year (table 2). The total inflow into and within Morgan Valley drainage basin is about 661,000 acre-feet (815 hm^3) per year (figure 24).

Table 2. *Summary of 10-year average measured and estimated streamflow and water diversions in Morgan Valley, Morgan County, Utah.*

Stream flow Station	**East Canyon Creek Near Morgan**	**Weber River at Gateway**	**Diversion from Weber River to Gateway Tunnel**	**Weber River at Echo**	**Weber River at Devils Slide** [1]
USGS Station ID	**10134500**	**10136500**		**1013200**	**10133500**
Year	***acre-ft/yr***	***acre-ft/yr***	***acre-ft/yr***	***acre-ft/yr***	***acre-ft/yr***
1999	55,824	452,945	96,240	275,430	364,495
2000	31,598	199,356	109,745	167,738	212,649
2001	31,751	160,076	92,392	91,419	105,038
2002	20,327	134,800	85,602	79,860	88,740
2003	20,014	103,335	82,647	89,751	102,687
2004	19,461	133,595	91,824	83,166	93,402
2005	47,047	406,268	85,912	212,671	276,004
2006	61,024	446,738	101,790	225,017	293,412
2007	34,087	192,231	90,126	137,655	170,231
2008	32,830	262,321	82,315	153,265	192,241
10-Yr Average	**35,396**	**249,167**	**93,050**	**151,597**	**189,890**

[1] *Estimated streamflow at Devils Slide station (USGS 10133500 WEBER RIVER AT DEVILS SLIDE) which was operational until 1955. The Devils Slide streamflow for the last 10-years (1999-2008) was estimated by correlating its flow to measured flow at the closest streamflow station (USGS 10132000 WEBER RIVER AT ECHO) using the linear equation derived based on their measured flow when both stations were in operation from 1932 to 1955 (see figure 23).*

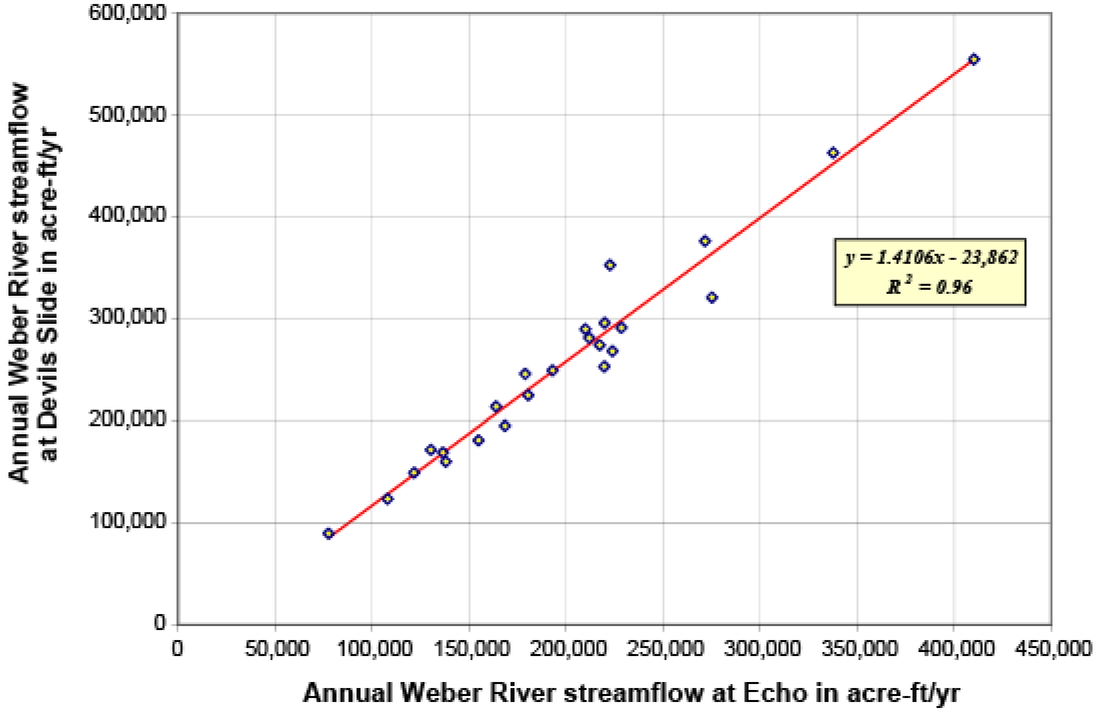
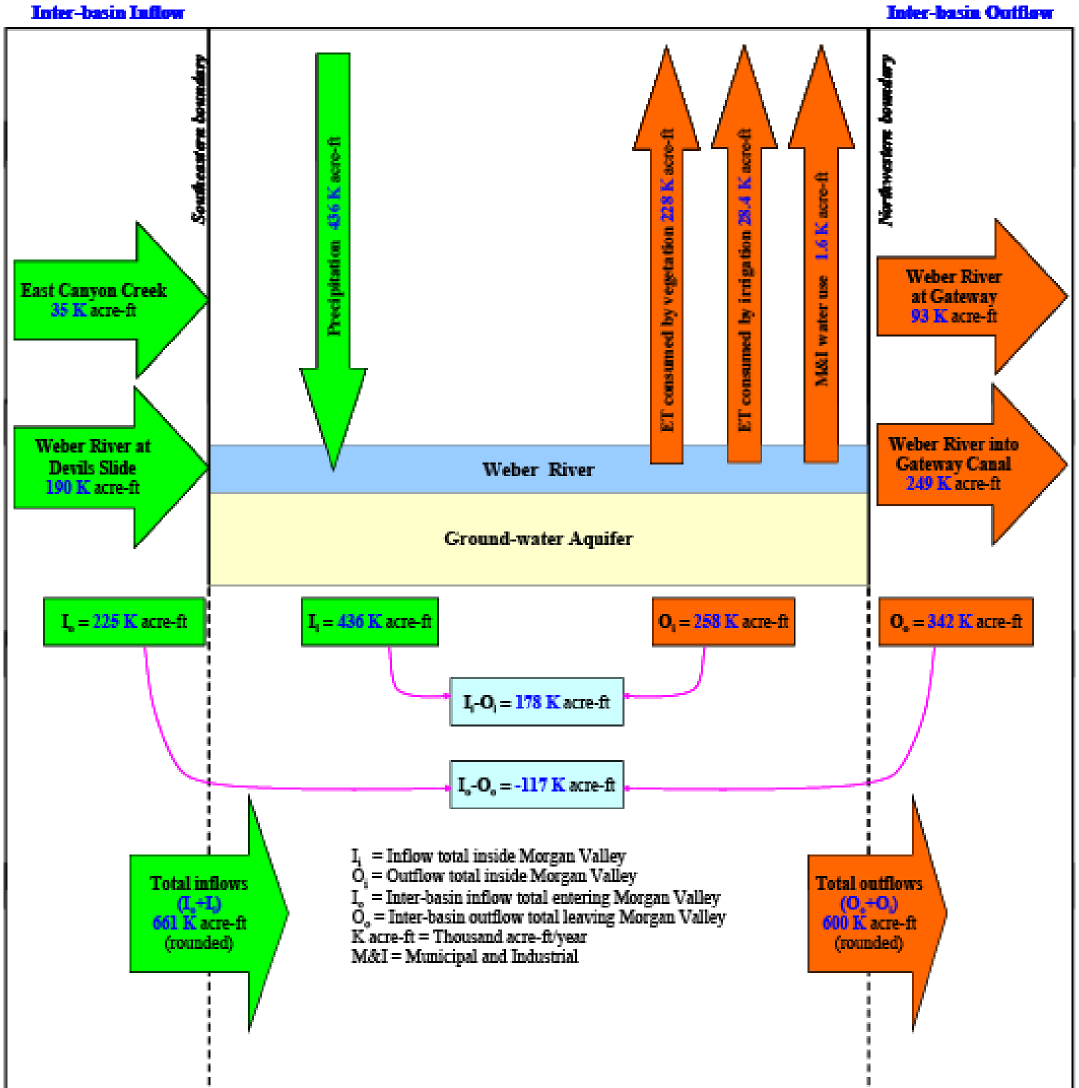


Figure 23. *Linear-regression equation correlating Weber River streamflow at Devils Slide and Weber River streamflow at Echo.*



Inflow Item	acre-ft/yr	Outflow Item	acre-ft/yr
Stream flow from Weber River at Devils Slide [1]	190,000	Stream flow into Weber River at Gateway [2]	249,000
Stream flow from East Canyon Creek [2]	35,000	Stream flow from Weber River into Gateway tunnel/canal [2]	93,000
Precipitation (combined rainfall and snow fall) [3]	436,000	ET water consumed by natural vegetation	228,000
		ET water consumed by irrigated agriculture	28,400
		Municipal and industrial water use [4]	1,600
Total (rounded to 1000)	**661,000**	**Total** (rounded to 1000)	**600,000**

[1] *Estimated using linear regression*

[2] *Adapted from U.S. Geological Survey, 2009 and Utah Division of Water Rights, 2010*

[3] *Adapted from PRISM Group website, University of Oregon, 2010*

[4] *Net municipal and industrial water use adapted from Utah Division of Water Resources, 2008*

Figure 24. *Summary and schematic diagram of estimated water budget in Morgan Valley, Morgan County, Utah.*

Outflow

The outflow component in Morgan Valley consists of evapotranspiration, stream outflow from the Weber River at Weber Canyon and into Gateway canal/tunnel, and water used for municipal and industrial purposes (figure 24).

Evapotranspiration

We estimated the average annual evapotranspiration (ET) based on the current water-related land use and natural vegetation patterns in Morgan Valley (table 3). We derived the natural vegetation patterns in the study area from a Utah vegetation map within the Southwest Regional Gap Analysis Project (Lowry and others, 2005). The current water-related land-use map and cropping patterns in Morgan Valley were adapted from the Automated Geographic Reference Center (AGRC), 2010. The above two maps were intersected using the Intersect Geo-processing Tool in ArcGIS to combine natural and human-related land-use and vegetation cover maps with acreages for the dominant integrated land-use patterns (figure 25). Evapotranspiration rates for natural vegetation and water-related land-use patterns were derived from a study conducted by the American Society of Civil Engineers in 1989 and Utah State University in 1994, respectively. The ET volumes were integrated by multiplying the acreage of each land-use and/or natural vegetation pattern by its specific ET rate. The estimated ET volume is a combined ET value from both surface water and ground-water sources. The average annual ET volume consumed by irrigated agriculture in Morgan Valley is estimated at about 28,400 acre-feet (35

Table 3. *Estimated evapotranspiration rates and volumes for dominant vegetation and land-use patterns in Morgan Valley, Morgan County, Utah.*

ID	Vegetation/Landuse Pattern	Area	Precipitation		Evapotranspiration		Reference
		acres	inch/yr	acre-ft/yr	inch/yr	acre-ft/yr	
1	Alfalfa	4,710	19.6	7,706	26	10,197	Utah State University (1994, p. 184, table 25), alfalfa ET from Echo Dam station 10 miles southeast of Morgan Valley
2	Aspen Forest	21,503	30.5	54,644	18	32,182	American Society of Civil Engineers (1989, p. 16, table 2 (average from Tew [1967], Johnson and others [1969], Johnson [1970], Croft and Monniger [1953], and Brown and Thompson [1965])
3	Barren land	2,585	31.4	6,763	9	1,938	ET approximated for Barren and sparsely vegetated landscapes
4	Corn	321	18.2	487	20	537	Utah State University (1994, p. 300, table 25) Pine View Dam station 5 miles northwest of Morgan Valley
5	Developed Area	1,167	20.3	1,977	1.2	117	Cederberg and others (2009, p. 35, table 11)
6	Gambel Oak	37,784	26.3	82,681	15.9	50,095	American Society of Civil Engineers (1989, p. 19, table 2) (average from Johnson and others [1969] and Tew [1966])
7	General Forest	35,164	28.6	83,906	17.3	50,695	American Society of Civil Engineers (1989, p. 16, table 2) (average from Leaf [1975])
8	Grain	3,573	19.2	5,706	20.4	6,062	Utah State University (1994, p. 184, table 25); pasture ET from Echo Dam station 10 miles southeast of Morgan Valley
9	Grass-Hay	2,031	20.1	3,407	22.8	3,859	Utah State University (1994, p. 184, table 25) pasture ET from Echo Dam station 10 miles southeast of Morgan Valley
10	Grass-Native	4,817	22.7	9,107	14.3	5,733	American Society of Civil Engineers (1989, p. 17, table 2) (average from Johnson and others [1969], Harrison [1983], and Rich [1952])
11	Grass-Perennial	7,334	21.8	13,329	21.8	13,329	Brooks and others [1998, p. 8, table 1) and Wright Water Engineers, Inc. (1986, table 2) (all precpitation is consumed by plants)
12	Grass-Turf	22	17.6	33	23.1	43	Utah State University (1994, p. 185, table 25); pasture ET from Echo Dam station 10 miles southeast of Morgan Valley
13	Mountain Meadow	4,910	30.6	12,512	19.1	7,832	American Society of Civil Engineers (1989, p. 18, table 2) (average from Borrelli and others [1981], Swartz and others [1972], Burman and Pochop [1986], and Pochop and others [1975])
14	Mountain Shrub	1,837	29.7	4,542	8.7	1,332	American Society of Civil Engineers (1989, p. 20, table 2) (average from Branson and others [1970])
15	Open Water	1,665	20.5	2,837	34.5	4,791	Utah State University (1994, p. 185, table 25), E-lake ET from Echo Dam station 10 miles southeast of Morgan Valley
16	Pasture	4,532	20.5	7,735	20.3	7,674	Utah State University (1994, p. 185, table 25); pasture ET from Echo Dam station 10 miles southeast of Morgan Valley
17	Pine Forest	471	34.6	1,357	20	785	American Society of Civil Engineers (1989, p. 19, table 2) (average from Thompson [1974], Patric [1961], and Berndt [1960])
18	Pinyon-Juniper	4,591	22.5	8,602	21	8,046	American Society of Civil Engineers (1989, p. 19, table 2) (average from Gifford [1975])
19	Residential, Commercial, or Industrial areas	2,160	19.2	3,454	16.8	3,024	Brooks and others (1998, p. 8, table 1) and Wright Water Engineers (1986, table 2) (all precipitation is consumed by plants).
20	Riparian	9,022	26	19,571	17.6	13,210	American Society of Civil Engineers (1989, p. 19, table 2) (average from Schumann [1967], Ben-Asher [1981], and Sammis [1972])
21	Sagebrush	44,889	25.7	96,017	8.2	30,599	American Society of Civil Engineers (1989, p. 19, table 2) (average from Gutknecht and others [1980], Branson and others [1970], Sturges [1980], and Shown and others [1972])
22	Spruce-Fir Forest	3,424	34.6	9,882	14.9	4,251	American Society of Civil Engineers (1989, p. 20, table 2) (average from Brown and Thompson [1965])
Total/Average		**198,512**	**26.4**	**436,255**	**15.5**	**256,331**	

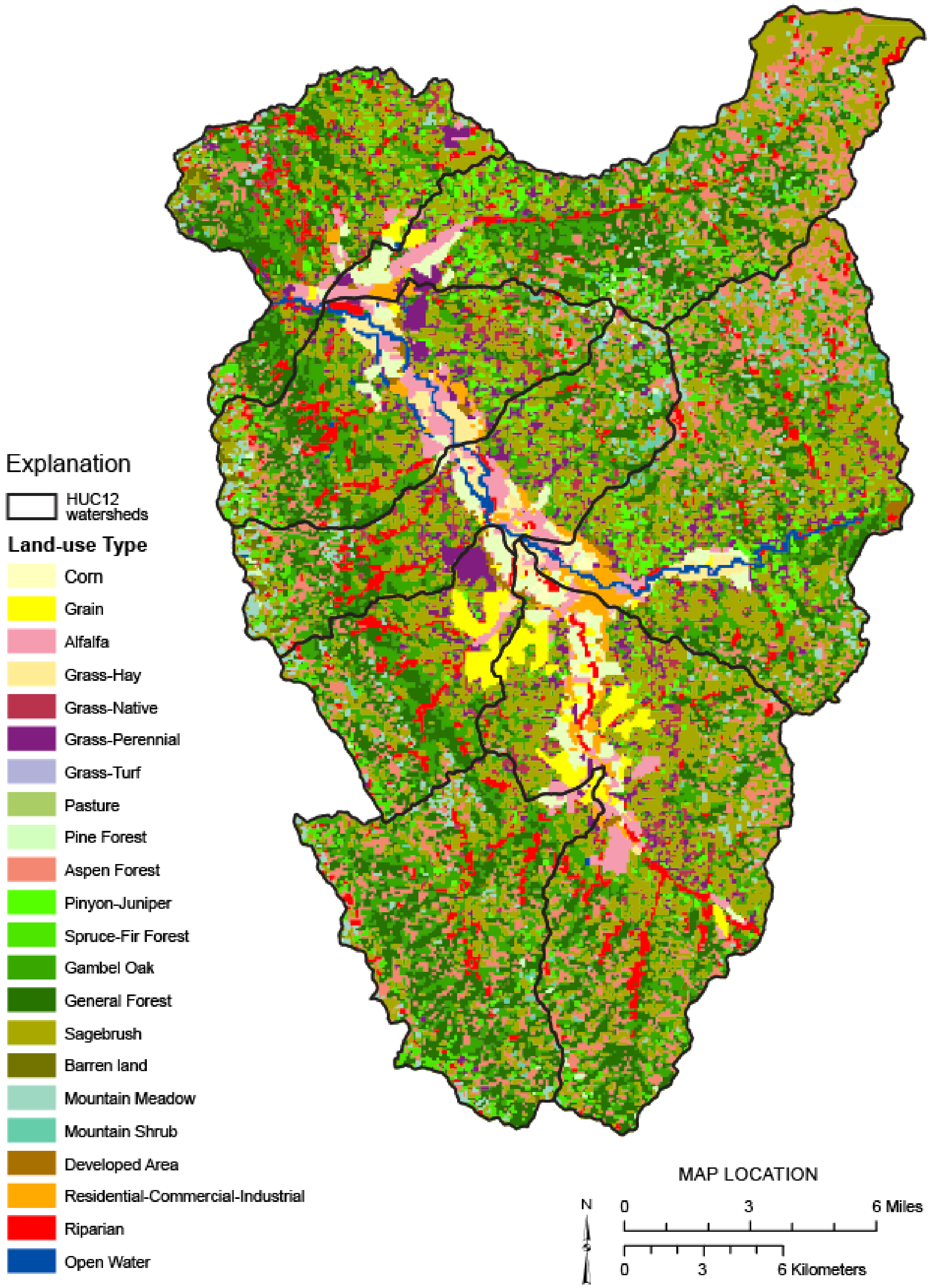


Figure 25. *Integrated land-use patterns (polygons) used for estimating evapotranspiration in Morgan Valley, Morgan County, Utah. Map integrated from GAP vegetation (Lowry and others, 2005) and Utah land-use map (Automated Geographic Reference Center, 2010). See table 2 for ET rates and volumes for all land-use patterns.*

hm^3) per year (figure 24). The average annual ET volume consumed by natural vegetation in Morgan Valley is estimated at about 228,000 acre-feet (281 hm^3) per year (figure 24). Thus the total combined average annual ET volume consumed by both irrigated agricultural land use and natural vegetation in Morgan Valley is estimated at about 256,400 acre-feet (316 hm^3) per year (figure 24), with an equivalent weighted rate of 15.5 inches (394 mm) per year.

Stream Outflow

Streamflow leaves Morgan Valley via Weber River canyon or via the Gateway canal/tunnel. The 10-year average outflow measured at the USGS Weber River streamflow station #10136500 at Gateway is about 249,000 acre-feet (307 hm^3) per year (table 2) and the water diverted to Gateway canal/tunnel is estimated at about 93,000 acre-feet (115 hm^3) per year (table 2) (Utah Division of Water Rights, 2010). The 10-year average combined outflow from the Weber River at Gateway and that portion which is transferred into Gateway canal/tunnel is about 342,000 acre-feet (422 hm^3) per year (table 2 and figure 24).

Municipal and Industrial Water Use

The current net water use for municipal and industrial purposes in Morgan Valley is about 1600 acre-feet (2 hm^3) per year (figure 24) (Utah Division of Water Resources, 2008). This water portion is included as an outflow item because it is mostly withdrawn from wells in the underlying valley-fill aquifer and was not accounted for in either evapotranspiration or streamflow. The total outflow from and within Morgan Valley drainage basin is about 600,000 acre-feet (740 hm^3) per year (figure 24).

Discussion of Water-Budget Components

The overall total inflow into and within Morgan Valley is 661,000 acre-feet per year (815 hm^3) (figure 24). The overall total outflow from Morgan Valley is 600,000 acre-feet (740 hm^3) per year (figure 24). The difference between the overall inflow and outflow is 61,000 acre-feet (75 hm^3) per year which constitutes 9.2% of the total inflow.

Although surface water and ground-water are directly connected, and we estimated the water budget for the entire integrated water system, the calculated amount of inflow does not equal outflow. The difference in inflow/outflow amounts may be explained by infiltration of recharge from perched water in the valley-fill aquifer or the deeper bedrock aquifer without flowing back to the surface. That discrepancy could be mainly attributed to estimation errors in precipitation and evapotranspiration because those variables were not verified in the field. The discrepancy could also be attributed to estimation errors for streamflow from the Weber River at Devils Slide (since it is not currently operational and it was estimated by correlation to another active station [Echo station]). Number rounding is also another source for discrepancy.

Although the integrated conceptual water budget conducted in this study is applicable to Morgan Valley because both surface water and ground water are hydraulically connected, further research is needed to understand the conceptual inter-relationship between surface water and ground-water as well as the inter-basin ground water flow. This may be achieved by constructing an updated ground-water flow model once the required water-level and well-withdrawal data are available.

WATER-QUALITY RESULTS

Ground-Water Quality Classification

To implement appropriate best-management plans for protecting the Morgan Valley valley-fill aquifer, we prepared ground-water quality classification maps based on the data we collected in 2004 for the alluvial aquifer. The Utah Ground Water Quality Protection Regulations, initially adopted in 1989, contain a provision allowing the Utah Water Quality Board to classify all or parts of aquifers as a method for maintaining ground-water quality in areas where sufficient information is available. This includes having a comprehensive understanding of the aquifer system supported by factual data for existing water quality, potential contaminant sources, and current uses of ground water.

Water-Quality Data-2004

Data collected as part of this study for the alluvial wells indicate the valley-fill aquifer yields predominantly high quality ground water. Overall ground-water chemistry is a mixed calcium-magnesium bicarbonate based on the analysis of samples obtained during 2004 (figure 26).

Total-dissolved-solids concentrations: The Utah Water Quality Board's drinking-water quality standard for TDS is 2000 mg/L for public-supply wells. The secondary drinking-water standard is 500 mg/L TDS (U.S. Environmental Protection Agency, 2010), and is primarily due to a potential unpleasant taste to the water (Bjorklund and McGreevy, 1971). Plate 6 shows the distribution of TDS in Morgan Valley's valley-fill aquifer. Based on data from ground-water samples from 66 wells and one spring (52 UGS wells, 6 UDAF wells, 8 public water-supply wells and 1 public-supply spring), TDS concentrations in the valley-fill aquifer of Morgan Valley range from 92 to 1018 mg/L, with only 1 well exceeding 1000 mg/L TDS, and have an average TDS concentration of 441 mg/L (appendix B, plate 6).

Nitrate concentrations: The drinking-water standard for nitrate is 10 mg/L (U.S. Environmental Protection Agency, 2010). More than 10 mg/L of nitrate in drinking water can result in a condition known as methoglobinemia, or "blue baby syndrome," in infants under six months (Comley, 1945), which can be life threatening without immediate medical attention (U.S. Environmental Protection Agency, 2010). This condition is characterized by a reduced ability for blood to carry oxygen. Based on ground-water data from 82 alluvial wells and one spring sampled by the UGS, UDAF, and UDW, nitrate concentrations range from less than 0.1 to 12.8 mg/L, and average 2.7 mg/L (appendix B). Three wells near Porterville and the mouth of Hardscrabble Creek yielded water exceeding the drinking-water standard for nitrate. Thirty-four percent of the alluvial wells yielded ground water exceeding nitrate concentrations of 3 mg/L.

Other constituents: Based on the data presented in appendix B, three wells exceed primary drinking-water standard of 10 μg/L for arsenic. Small amounts of arsenic can cause skin damage or circulatory system problems, and may increase the risk of cancer (U.S. Environmental Protection Agency, 2010). No alluvial wells exceeded primary or secondary drinking-water standards for any constituent except nitrate and arsenic (appendix B).

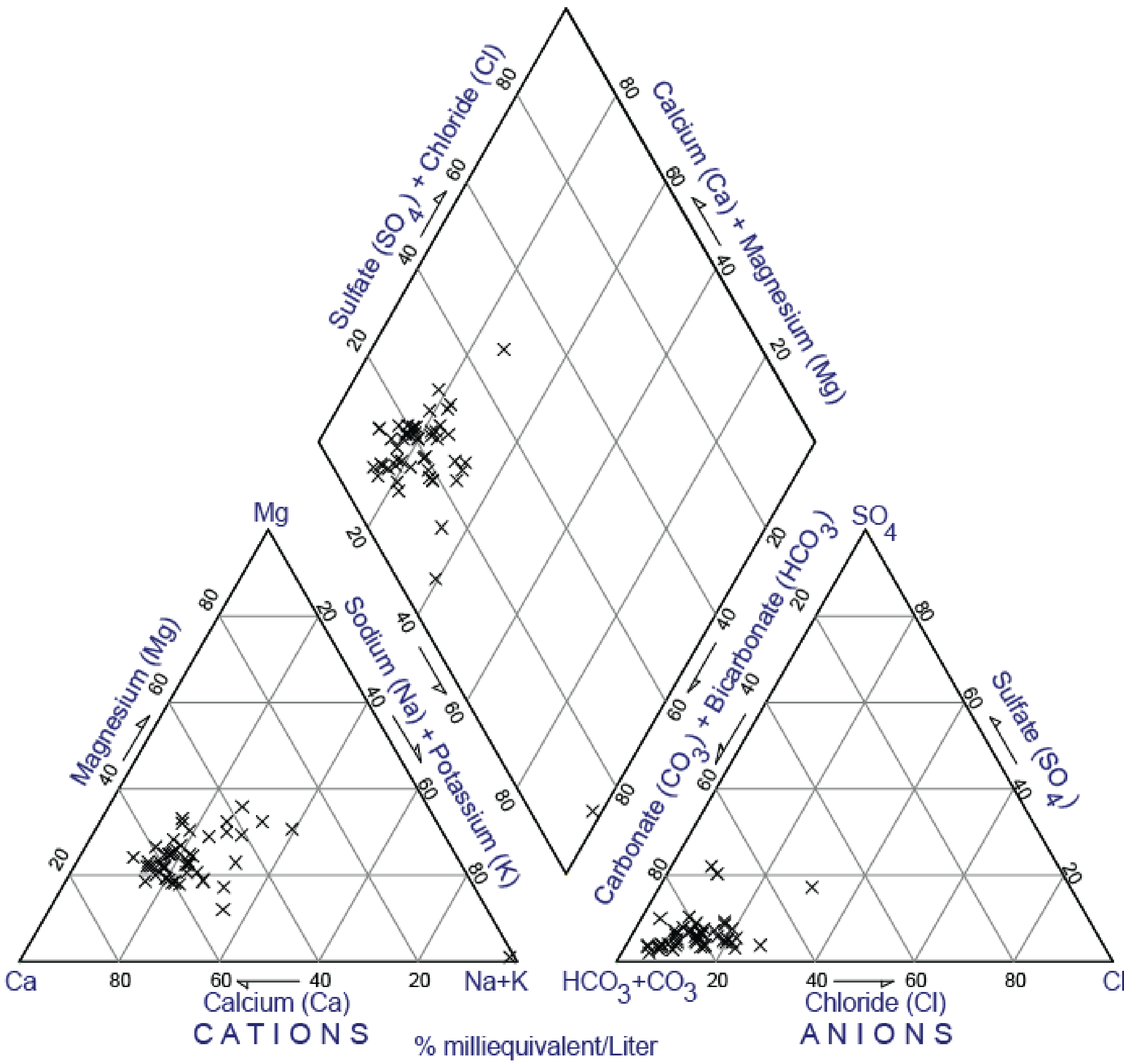


Figure 26. *Piper diagram showing chemistry type for 52 wells in Morgan Valley, Morgan County, Utah. Median water quality is calcium-magnesium bicarbonate.*

Water-Quality Data-2009

Data collected during 2009 were used to augment the study by analyzing water chemistry from wells completed in bedrock, mostly in areas on or just above the valley margins of the valley-fill aquifer, and by sampling water for environmental isotopes from both bedrock wells and previously sampled wells completed in alluvium.

Total-dissolved-solids concentrations: We sampled eight wells and two springs completed in bedrock during spring 2009. Total-dissolved-solids concentrations for these wells range from 256 to 772 mg/L (appendix B), and average 526 mg/L. Most of the wells likely penetrate the Tertiary Norwood Tuff; one likely is completed in the Weber Sandstone (quartzite) and two springs issue from the Humbug Formation (Como Spring) and from the Hyrum/Water Canyon Formation (unnamed spring).

Nitrate concentrations: During spring 2009, we sampled 10 wells completed in bedrock and resampled one high-nitrate well sampled in 2004 that was located on a dairy farm that has since been replaced by a neighborhood development that uses the well as a public-supply well. Nitrate concentrations from eight bedrock wells, one alluvial well, and one spring range from less than 0.1 to 28.4 mg/L (appendix B). The nitrate concentrations in the bedrock wells average 4.6 mg/L. The resampled alluvial well had a concentration of 9.5 mg/L. The nitrate concentration of 28.4 mg/L came from a bedrock well, which was the only site sampled in 2009 that exceeded the drinking-water standard. The nitrate in this well may be related to a small greenhouse and poultry operation on adjacent land, but we did not analyze nitrate and oxygen isotopes from this well. The average nitrate concentration for all bedrock wells excluding this anomalous high-nitrate well is 1.6 mg/L.

Other constituents: Based on the data presented in appendix B for the 10 bedrock wells sampled in 2009, one well exceeds the primary drinking-water standard of 10 μg/L for arsenic.

Uses of Ground-Water Quality Classification

Aquifer classification is a planning tool for local governments to use in making land-use management decisions. It allows local governments to use potential impacts on ground-water quality as a reason for permitting or not permitting a proposed activity or land use based on the differential protection policy. Many facilities and/or activities impact ground-water quality, but are not regulated by state or federal laws. Examples of such facilities/activities include septic systems, small scale animal feed operations, land application of animal wastes, and some industrial/manufacturing activities. Many of these facilities/activities are permitted through local land-use management programs. From this perspective, aquifer classification can be a useful tool for local governments, if they so desire, to manage their ground-water resources based on the beneficial use established by aquifer classification. Both bedrock and alluvial aquifers can be classified. We only classify the alluvial aquifer as requested by Morgan County (Wallace and Lowe, 2007); our data collected in 2009 are insufficient to classify the bedrock aquifer.

Aquifer classification as a land-use management tool has many potential applications. One example is zoning to locate industrial facilities in areas where ground-water quality is already poor. Additionally, aquifer classification can be used as a basis for determining the density of development in areas that use septic systems for wastewater disposal (for example, Wasatch County, Utah, used aquifer classification as one basis for limiting septic systems to lots larger than 5 acres [2 hm]). Aquifer classification also can be used as a basis for encouraging developers to invest in the infrastructure needed to connect a proposed subdivision onto an existing sewer line, rather than dispose of domestic wastewater using septic-tank systems. However, aquifer classification does not result in any mandatory requirement for local governments to take specific actions, such as land-use zoning restrictions, technical assessments, or monitoring.

Resulting Ground-Water Quality Classification

Under rule R317-6, Ground Water Quality Protection, December 1, 2009, Section 317-6-3, Ground Water Classes, Utah Administrative Code, Utah's ground-water quality classes are based on TDS concentrations as shown in table 1. In addition, ground water having TDS concentrations that fall within the Class IA or Class II ranges, but with one or more contaminant that exceeds drinking-water standards, is classified as Class III. Class IB ground water, called Irreplaceable ground water, is a source of water for a community public drinking-water system for which no reliable supply of comparable quality and quantity is available because of economic or institutional constraints. Ground-water protection levels for classes IA and IB, as set under Rule R317-6 Section 4, are more stringent than for other ground-water quality classes.

Morgan County petitioned the Utah Water Quality Board to classify the principal valley-fill aquifer in Morgan Valley as shown on plate 7; the Utah Water Quality Board granted the classification as described below on March 5, 2007. The classification is based on ground-water data from 66 alluvial wells and one spring presented in appendix B. Total-dissolved-solids concentrations for eight well sites (two UGS wells and six UDAF wells) were calculated from the relationship between specific conductance and TDS derived from 50 wells in Morgan Valley for which both values are known (figure 27, appendix B). Where insufficient data exist, we extrapolated ground-water quality conditions based on local geology. The classes (plate 7) are described below.

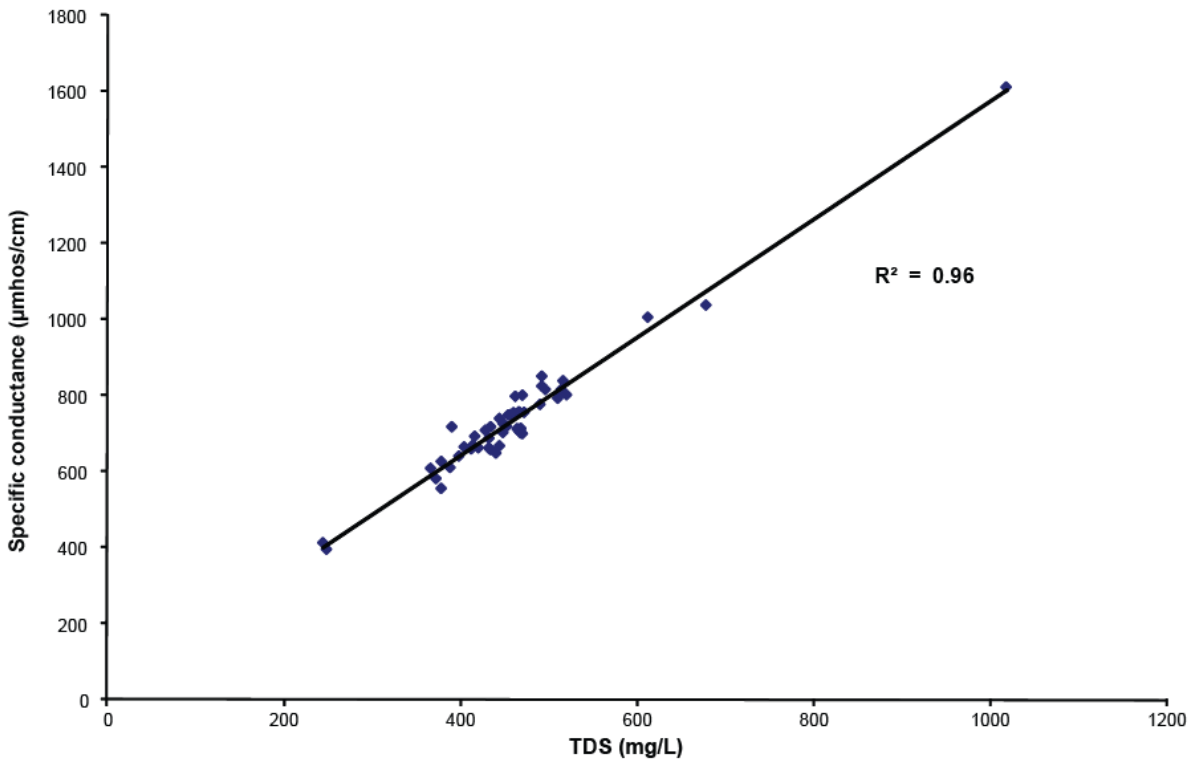


Figure 27. Specific conductance versus total-dissolved-solids concentration data for 50 wells in Morgan Valley, Morgan County, Utah. R-squared is 0.96. Based on Hem's (1985) equation for estimating TDS from specific conductance: KA=S, where K=specific conductance, S=TDS, A ranges from 0.55 to 0.96. The average A=0.63 (slope) was used to compute TDS in Morgan Valley.

Class IA- Pristine ground water: For this class, TDS concentrations in Morgan Valley range from 92 to 496 mg/L (appendix B). Class IA areas are mapped throughout most of Morgan Valley (plate 7) and cover about 98% of the total valley-fill material.

Class II- Drinking Water Quality ground water: For this class, TDS concentrations in the Morgan Valley valley-fill aquifer range from 510 to 1018 mg/L (appendix B) and cover 2% of the total valley-fill area (plate 7). Class II ground-water quality is found in the vicinity of Hardscrabble and Deep Creeks in southwestern Morgan Valley (plate 7).

Potential Contaminant Sources

Potential ground-water contaminant sources were mapped by Hansen, Allen, and Luce, Inc. (2001) and include some facilities related to mining, agriculture, industrial uses, fuel storage, and junkyard/salvage areas (appendix F, plate 8). We used potential contaminant source data by Hansen, Allen, and Luce, Inc. (2001) to identify a relationship between water quality and land-use practices. Approximately 319 potential contaminant sources were identified by them in the following categories in Morgan Valley:

(1) Mining, which includes abandoned and active gravel, phosphate, and carbonate mining operations.

(2) Agriculture, which consists of irrigated and non-irrigated farms, animal feeding operations, and cropland; active and abandoned animal feed lots, corrals, stables/barnyards; and animal wastes that are dominantly produced from feeding facilities, waste transported by runoff, and excrement on grazing or pasture land that potentially contribute nitrate.

(3) Junkyard/salvage areas that potentially contribute metals, solvents, and petroleum products.

(4) Government facility/equipment storage associated with a variety of sources such as salt storage facilities and transportation/equipment storage that may contribute metals, solvents, and petroleum.

(5) Cemeteries, nurseries, greenhouses, ball parks, and golf courses that may contribute chemical preservatives, fertilizer, and pesticides.

(6) Storage tanks that may contribute pollutants such as fuel and oil.

(7) Equipment and vehicle storage and maintenance that may contribute pollutants such as fuel and oil.

(8) Manufacturing and industrial uses that may contribute pollutants such as fuel and oil.

(9) Rural and residential homes that may contribute pollutants from septic-tank systems, fuel, household hazardous waste, equipment, and animal by-products.

(10) Remediation efforts that may contribute pollutants associated with hazardous material contamination remediation.

(11) Wastewater treatment plants and sewage lagoons which may contribute pollutants such as nitrate, fuel, and oil.

In addition to the above-described potential contaminants, septic tank soil-absorption systems in Morgan Valley are common and may potentially pollute ground water. The number of septic-tank systems in Morgan Valley is currently unknown (Mary Hazard, Weber-Morgan Health Department, personal communication, October 2004). Septic-tank systems may contribute contaminants such as nitrate and solvents. All approved water wells are also considered potential contaminant sources. There are 312 approved water wells in Morgan Valley based on Utah Division of Water Rights records, 37 of which are public-supply wells (Mark

Jensen, Division of Drinking Water, personal communication, August 2002). The location of all wells is shown on plate 7.

NITRATE SOURCES

Background

Nitrogen in the natural environment is abundant and is derived from a multitude of sources. Whole-earth abundance of nitrogen is 0.03%, with 97.76% of the total nitrogen present in rocks, 2.01% in the atmosphere, and the remainder in the hydrosphere and biosphere (Kendall, 1998). Nitrogen oxides are present in the environment and can undergo various chemical reactions that in the presence of H^+ can convert nitrogen (N) to nitrate (NO_3^-) or ammonia (NH_3). Nitrogen that is present as NH_4^+ can transform to ammonia in basic environments and subsequently can be released as NH_3 gas to the atmosphere (Canter, 1997). With increasing oxygen content, nitrification of ammonium occurs (NH_4^+ to NO_3^-). When anoxic conditions prevail, denitrification of nitrate can occur with the production of N_2 gas (Canter, 1997). Identifying the origin of nitrogen derived from single or multiple sources is difficult due to complex chemical, biological, and physical interactions that occur in the environment. Figure 28 shows the complex nature of the nitrogen cycle and the types of chemical, physical, and

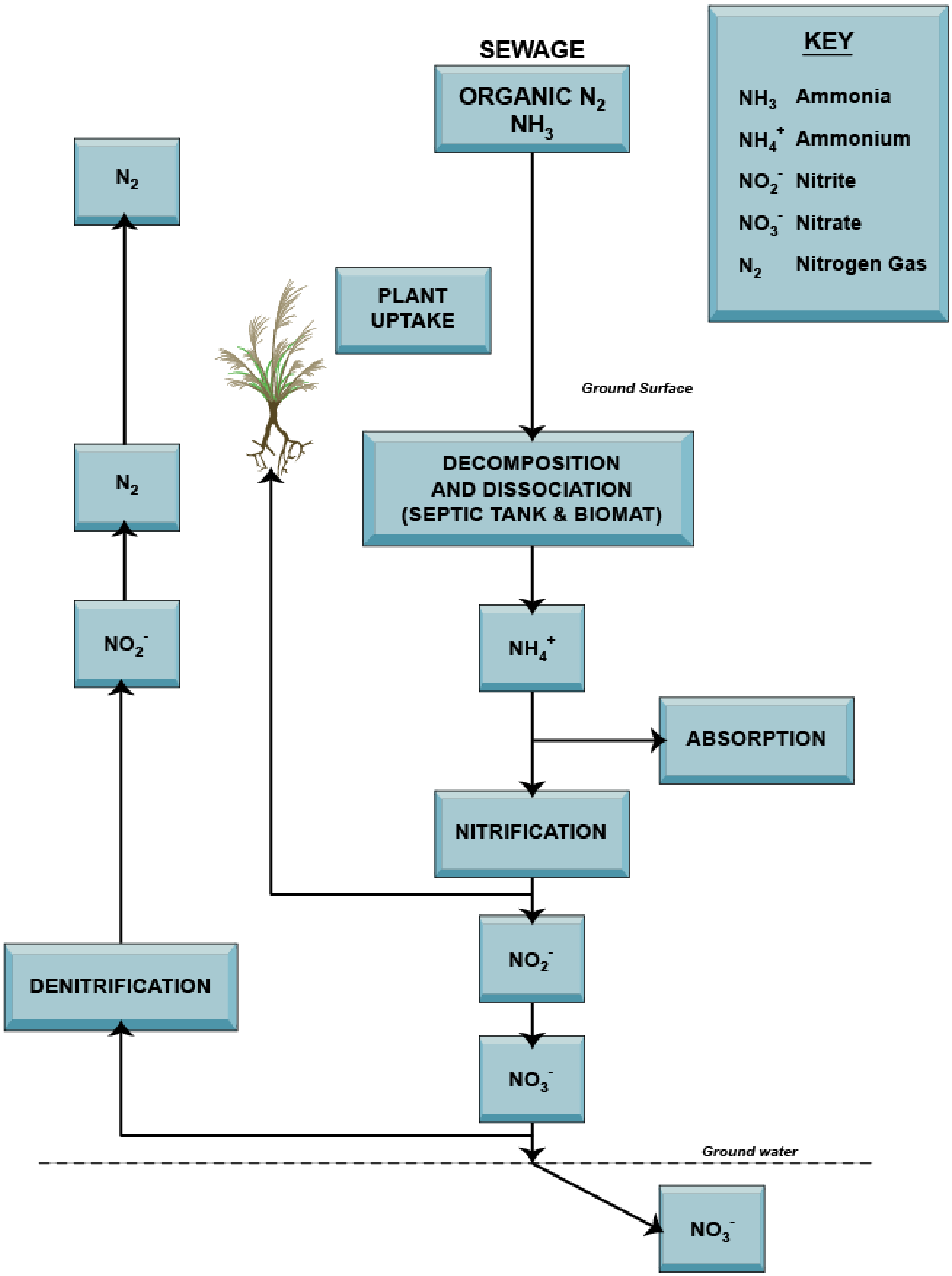


Figure 28. Diagram of the nitrogen cycle in the environment (modified from Hansen, Allen, and Luce, Inc., 1994).

bio

logical processes involved with nitrification and denitrification of septic-tank effluent. The cycle is similar for other nitrate sources. Under ideal circumstances, the analysis of nitrogen and oxygen isotopes can help determine the source of nitrogen; more commonly, the interaction of nitrogen and oxygen with other chemical and biological species obscures the true origin of the nitrate species.

Analysis of Potential Sources of Nitrate

Herein, we attempt to identify the sources of nitrate in ground water in Morgan Valley based on the data presented in this report with the caveat that processes such as mixing of different sources of water in aquifers, ammonia volatilization, denitrification, and nitrification complicate the analysis for determining a source or sources of nitrate contamination for each high-nitrate well. In addition, this report uses nitrogen and oxygen isotope data from only one sampling event; numerous sampling events examining temporal and spatial trends in isotope water chemistry is preferable in order to document and understand long-term sustainability of the ground-water resource.

Both natural and anthropogenic sources of nitrate are common. Natural sources of nitrogen can contribute, to some extent, nitrate concentrations in ground water; natural sources include atmospheric, biologic, and geologic components. Common anthropogenic sources include septic-tank systems, fertilizer, agriculture (current and historical), animal-feeding operations, and improperly sealed/constructed wells (which act as conduits for nitrate to reach ground water). Ground water having less than 0.2 mg/L nitrate is assumed to represent natural background concentrations; ground water having nitrate concentrations between 0.21 and 3.0 mg/L is considered transitional, and may or may not represent human influence (Madison and

Brunett, 1985). Ground water having concentrations exceeding 3 mg/L is typically associated with human- or animal-derived sources, but higher concentrations have also been identified with

"Geologic nitrogen" was first recognized by Boyce and others (1976) as nitrogen associated with certain geologic formations, sedimentary and inorganic in origin. The weathering of nitrogen from rock can potentially affect the chemistry of water and soil (Holloway and others, 1998). The term "geologic nitrogen" was used to describe the source of high-nitrogen soils on alluvial fans in the San Joaquin Valley of California (Sullivan and others, 1979; Strathouse and others, 1980). The contribution of weathered rock from the Diablo Range to soil nitrogen in the western San Joaquin Valley was explored by Sullivan and others (1979). The chemical state of this nitrogen includes fixed and exchangeable ammonium sorbed to clay and organic surfaces, organic matter, and natronite, a sodium nitrate salt (Sullivan and others, 1979). Holloway and others (1998) analyzed rocks in the Mokelumne River watershed in California to determine if bedrock could be a source of stream-water nitrate and reported that metasedimentary rocks containing appreciable concentrations of nitrogen contributed a significant amount of nitrate to surface waters. They concluded that nitrogen-rich rocks in the watershed, though occupying a small areal extent, had a greater influence on water quality than the areally extensive nitrogen-poor metavolcanic and plutonic rocks in the watershed.

Elevated nitrate concentrations near fault zones are another potential geologic source. Hydrothermal alteration may produce ammonium-rich minerals by replacing potassium in micas and feldspar with ammonium (Altaner and others, 1988). Ammonium-bearing alunite, a mineral indicative of acidic solutions at certain temperatures, coupled with high ammonium and low potassium in solution, is associated with hydrothermal systems in Nevada, California, Colorado, and Utah (Altaner and others, 1988). Nitrogen from these minerals, if present, could then be dissolved in ground water flowing along faults (Lowe and Wallace, 2001; Wallace, 2010). Two springs in the Morgan Valley are located on or near mapped normal faults (Como Springs and "Pit" Spring); however, nitrate concentrations for springs are below 1 mg/L).

Soil can be a source of geologic and biologic agents that contribute nitrate to ground water. Determining whether nitrate from soil is a source of ground-water nitrate in wells is complicated. Concentrations of nitrogen in soil vary widely and depend on local conditions, including climate, soil type, vegetation, presence (or absence) of animal burrowing, and land use. Recent investigations in arid/desert environments indicate residual vadose zone nitrate as a source of elevated nitrate concentrations in ground water (Stonestrom and others, 2003; Walvoord and others, 2003; Osenbrück and others, 2006). In areas where native vegetation is sparse and rainfall is low, nitrate can leach into subsoil horizons and accumulate in a subsoil reservoir. Subsequent nitrate migration can be caused by a change in recharge through a change in land use (e.g., from natural recharge on native vegetation to irrigation). The process of nitrate accumulation and migration typically spans thousands to tens of thousands of years (Stonestrom and others, 2003; Walvoord and others, 2003; Osenbrück and others, 2006; Scanlon and others, 2007). Other recent studies show that variability in nutrient enrichment (including nitrate) is based on microecological changes in environments where nutrient concentrations and types varied between species of shrubs, burrowed versus non-burrowed areas, amounts of original organic matter, vegetation spacing/density (Titus and others, 2002), as well as differences in water fluctuations, leaching rates, fertilizer application amounts, and evapotranspiration (Green and others, 2008). Green and others (2008) examined nitrogen fluxes through unsaturated zones in agricultural settings and determined that soil nitrate moves by advective transport below the root zone under conditions of high evapotranspiration and low water-table flux in areas having sandier sediments in unsaturated zones. Under these conditions, soil nitrate can reach deeper parts of the aquifer and contribute to elevated nitrate concentrations in ground water (Green and others, 2008). An interpretation that ground-water nitrate derives from soil nitrogen deserves caution due to the complexities of the processes and the mechanism by which the nitrate moves from the root zone/soil profile vertically to the water table.

Non-geologic sources of residual nitrate also exist in the vadose zone. In semiarid regions, build-up of vadose-zone nitrogen results from millennia of precipitation and evapotranspirative concentration of nitrate in the unsaturated zone (Scanlon and others, 2007). A primary source of natural nitrate in some semiarid regions is related to unsaturated zones beneath native vegetation (unfertilized). Increased recharge due to changes in land use (e.g., cultivation of formerly fallow fields) increases nutrient loading by flushing nutrients into underlying aquifers (Scanlon and others, 2007). Median nitrate concentrations in soil water beneath fertilized cropland compared to non-fertilized forests were considerably higher (18 mg/L versus 1.5 mg/L) based on a European study (Scanlon and others, 2007). Fertilizer may also be a source of residual nitrate in the vadose zone. Future sampling of soils in the vadose zone and below the water table may verify whether residual nitrate is a potential source contributing to ground water as new wells are drilled.

Nitrogen concentrations that exceed the EPA contaminant level of 10 mg/L in ground water below agricultural lands in the U.S occur in 19% of sampled wells (Green and others, 2008). Agricultural chemical application rates are generally highest on irrigated lands (Lowe and others, 2004). Differences in irrigation practices, such as conventional furrow irrigated versus center-pivot irrigated, can affect nitrate concentrations in the soil profile (Spalding and others, 2001) as can differences in fertilizer type. For example, applications of poultry manure greater than 13 metric tons per cubic hectometer can result in nitrate concentrations in ground water that greatly exceed the EPA standard of 10 mg/L (Liebhardt and others, 1979). Some studies have shown that nitrogen from applied NH_4^+ fertilizer may undergo oxidation to nitrate that occurs before transport to the water table (Green and others, 2008); this process may affect nitrate concentration in wells in the study area. The source of irrigation water can also impact the quality of ground water with respect to nitrate. Plummer and others (2000) used isotopic age data in ground water from the Eastern Snake River Plain aquifer to show that recharge from the fresher water of the Snake River diluted ground water and lowered the potential for nitrate contamination in agricultural areas.

Animal feed-lot operations and other concentrations of domestic animals are common in Morgan Valley (plate 8, appendix F). Comparing plates 8 and 9 shows some of the high nitrate areas are in the general vicinity of current or former domestic farm animal operations. Plate 8 is based on field mapping of potential contaminants performed during 2001 and represents a snapshot in time; thus, the maps do not necessarily show continual point sources of nitrate of pollution, but potential sources that may contribute nitrate to ground water.

Septic systems in residential development may be the source of nitrate contamination in some areas. Most residential developments in Morgan Valley use septic systems as a method of wastewater disposal. Septic-tank systems likely contribute nitrate to many of the samples but their locations are unknown, and assumed to be associated with domestic development. Most development is also located where irrigation is a potential source of recharge water.

Septic-tank systems are known sources of nitrate contamination. Because septic-tank systems are below ground, we were not able to map their locations on plate 8. Outside the town of Morgan, the rest of the county mainly relies on septic-tank systems that are widely spaced. Septic systems can also produce relatively high concentrations of total dissolved solids, but this is likely not the case in Morgan Valley. Ten wells having nitrate concentrations above 4 mg/L (table 4) have an average TDS concentration of 520 mg/L (appendix B), with only one well exceeding 1000 mg/L TDS. Figure 29 shows the relationship between nitrate and TDS concentrations with a correlation coefficient of 0.2, indicating a very weak relationship. Overall, wells having both low nitrate (less than 2 mg/L) and TDS concentrations are common throughout the valley (appendix B; figure 29).

Extent of Areas having High Nitrate Concentrations

In 1998, the Weber-Morgan Health Department identified 11 wells they deemed as high-nitrate concentration wells (greater than 4.6 mg/L and a range of 4.6 to 14 mg/L; appendix B, table 4) (Ray Bakker, written and verbal communication, 2004). Five of their 11 samples were in or near Hardscrabble Creek Canyon (an area, at that time, with limited development). In 2004, the UGS sampled a total of 52 wells, including 10 of the 11 originally sampled wells by the WMHD (one well was no longer available for sampling as the home was boarded up and deemed condemned). In 2009, the UGS sampled 10 bedrock wells not previously sampled, and

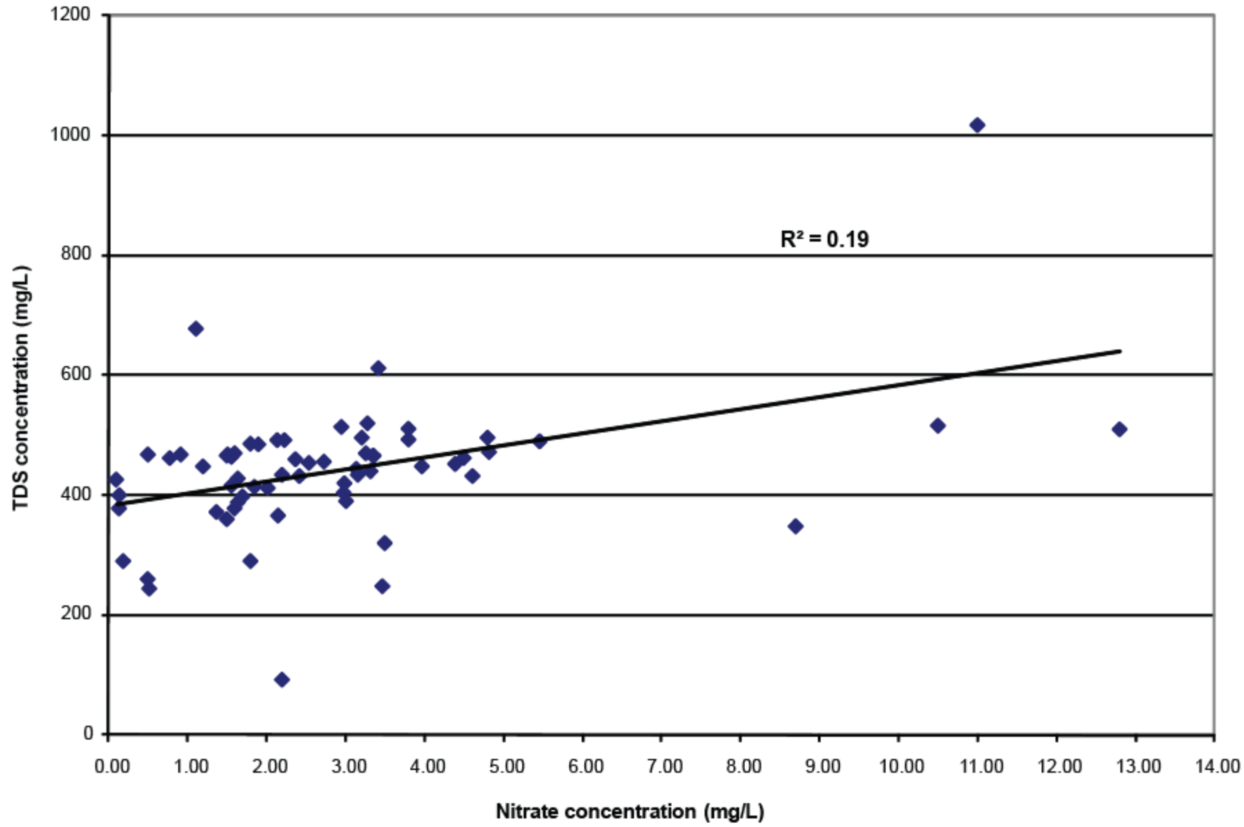


Figure 29. *Nitrate versus total-dissolved-solids concentration data for water wells in Morgan Valley, Morgan County, Utah.*

Table 4. *Nitrate concentration for wells sampled various times by various agencies in Morgan Valley, Morgan County, Utah.*

WELL ID[1]	**WELL LOCATION**	**Nitrate concentration (mg/L) Data Source**			**Sample Date**[2] **By WMHD**
		WMHD	**UGS**	**UDAF**	
1 (H)	(A-3-2) 26adb	12	4.61	-	1997
2 (H)	(A-3-2) 26bda	9.8	11	6.7	1997
3	(A-4-2) 34dbc	8	3.28	-	1998
4 (H)	(A-3-2) 26abc	6	1.11	1	1997
6	(A-3-2) 2dcb	6	7.12	-	1998
7	(A-4-2) 21cdc	5.3	3.16	3.7	1997
8 (H)	(A-3-2) 26aab	5.3	3.42	4.9	2001
9	(A-4-2) 8ccc	4.7	n/a	n/a	1999
10	(A-3-2) 14dcd	4.6	3.97	-	1997
42	(A-3-2)14dbc	-	10.5	8.5	-
44 (H)	(A-3-2) 23add	5.3	3.32	2	1997
49[+]	(A-5-1) 30cdd	5-14	8.73/ 9.5	-	1997-1999
303	(A-3-2) 1cdb	-	28.4	-	2009 (sampled by UGS only)

[1]see appendix B; “H” indicates a well in or near Hardscrabble Canyon
[2]UGS and UDAF sampled wells during spring and summer 2004
“-”not sampled
[+]this well formerly served a dairy operation that has been replaced by a subdivision, the second nitrate concentration number sampled by UGS is for a sampling date of 2009

identified one well as exceeding the 10 mg/L EPA drinking water standard for nitrate (28.4 mg/L). Plate 9 shows nitrate concentration data for all UGS wells sampled during 2004 and 2009, and also sites sampled by WMHD, UDAF, and the Utah Division of Drinking Water (appendix B). If a well was sampled more than one time, we use the most recent UGS data in lieu of older data (some of the wells we resampled that were deemed high nitrate concentration by the WMHD [greater than 4.6 mg/L] had lower nitrate concentrations; table 4).

Plate 9 shows five wells in the valley with nitrate concentrations that exceed (or have exceeded) the EPA 10 mg/L standard. Four have water with nitrate greater than 10 mg/L, and one had a concentration of 9.5 mg/L, but previously had a concentration of 14 mg/L (table 4). The latter well, located on the northeast margin of the valley fill between Mountain Green and Peterson (plate 9), is a public-supply well, downgradient from a dairy farm that recently was replaced by a subdivision. The well has had persistent, relatively high nitrate concentrations since 1997 (Ray Bakker, Weber Morgan Health Department, 2004, personal communication), and nitrate remained high in 2009. A second well in excess of EPA standards is in Hardscrabble Canyon, one of the southwestern side canyons in the valley (plate 9); here, many wells have had persistent elevated nitrate concentrations (table 4) but no apparent upgradient source of nitrogen. This area of the valley also has the highest concentrations of dissolved solids (plate 6). Two of the wells with nitrate concentrations above 10 mg/L are located about one mile (1.6 km) north of Hardscrabble Canyon along Morgan Valley Road and west of East Canyon Creek. The last site, identified in the 2009 sampling period in the southeastern part of the valley, has the highest detected nitrate concentration in the valley (28.4 mg/L).

Nitrogen and Oxygen Isotope Analysis

In 2004, we sampled the 10 wells in Morgan Valley that the Weber-Morgan Health Department showed to have nitrate concentrations exceeding 4.5 mg/L (table 4). Figure 30 shows a plot of $\delta^{18}O_{NO3}$ versus $\delta^{15}N_{NO3}$. The values and distribution of nitrogen isotopes ranged from +5.44 to +11.46‰, with a median of 7.26‰; $\delta^{18}O$ values ranged from –2.11 to +13.78‰. All of the data fall in the manure/septic-tank nitrogen field, and many plot in the area of overlap between the soil nitrogen and manure/septic-tank nitrogen (figure 30). The nitrogen in samples having values for $\delta^{15}N_{NO3}$ falling between 5 and 8.5‰ may have been derived from nitrate in soil cultivated without fertilizer (figure 30) as well as manure/septic tanks. Two samples had values for $\delta^{15}N_{NO3}$ greater than 10‰; these likely have been derived from nitrate from animal manure and/or septic-tank sources, which typically range between 10 and 25‰ (Canter, 1997). Overall, our data fall into the two fields shown in figure 30: soil nitrogen and manure/septic tank nitrogen. Field investigation confirmed the validity of a potential soil nitrogen nitrate source and animal manure nitrate source interpretation. Because most of the data for the study area do not have the high $\delta^{15}N_{NO3}$ and low $\delta^{18}O$ values characteristic of septic systems, but have values for both isotope species more characteristic of a soil-nitrogen source, the expected septic-related isotopic signatures could be obscured by dilution/mixing from recharge by lighter $\delta^{15}N_{NO3}$ water. Irrigation water may have water with the lighter isotopes associated with nitrate and ammonium

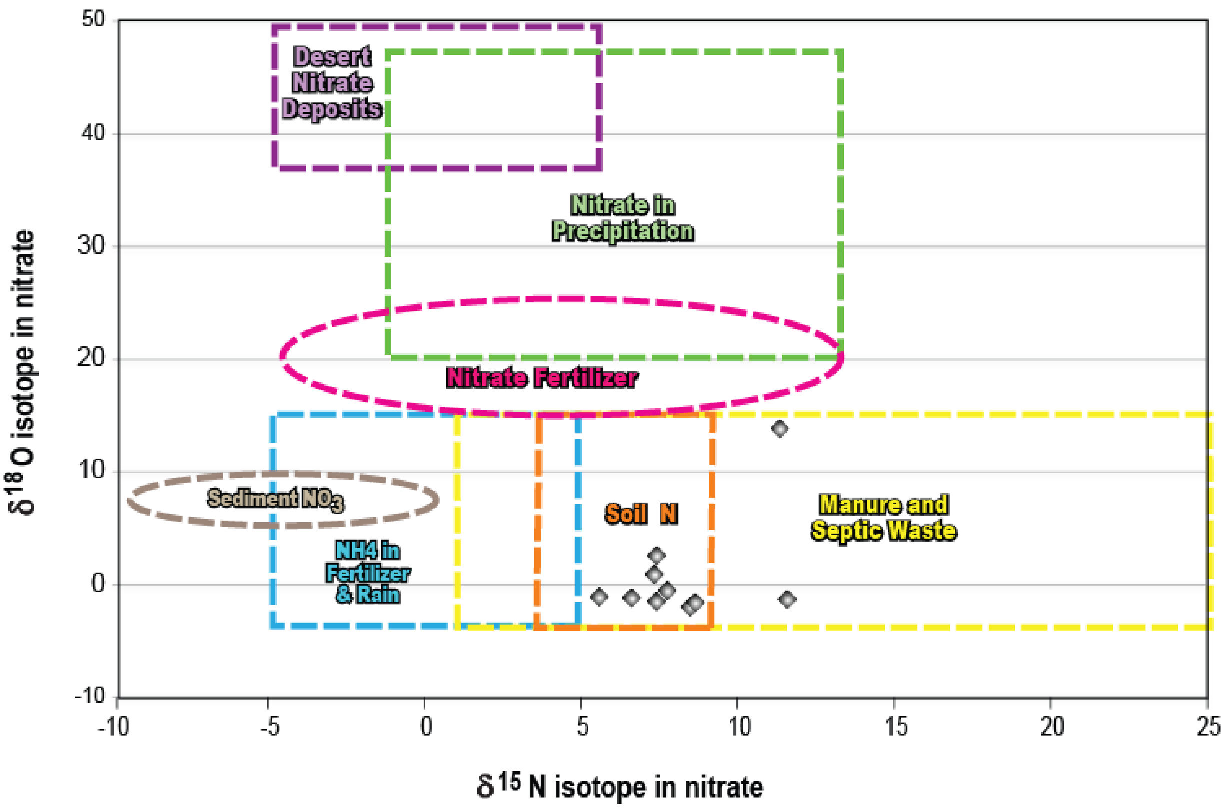


Figure 30. *Nitrogen and oxygen isotope data for 10 wells in Morgan Valley, Morgan County, Utah. Sediment NO_3 field has no corresponding $\delta^{18}O$ value (modified from Clark and Fritz, 1997).*

fertilizer. Effluent from septic-tank systems likely contributes nitrate to many of the samples; due to the overlapping nature of the data, determination of a sole source is not possible.

The nitrate concentrations in Hardscrabble Canyon have been considered anomalous and enigmatic since the late 1990s when the WMHD began sampling water from wells constructed pre-development during the planning stages of approving septic tanks for new development. Because of this, we treat this area separately from the rest of the valley. We sampled eight water wells for nitrate along relatively new development in Hardscrabble Canyon; background nitrate concentration for these wells was 3.8 mg/L, more than 1 mg/L greater than the background nitrate concentration for the entire valley. The distribution of high-nitrate concentration (greater than 4.6 mg/L) wells was sporadic. For example, wells having low nitrate concentration were both upgradient and downgradient from wells having high nitrate concentration (and homes on septic systems). Septic systems associated with residential development along Hardscrabble Canyon may have been the source of nitrate contamination since no apparent upgradient source exists; however, most development is relatively new, and some wells having high nitrate concentration obtained by UDAF and WMHD were sampled pre-development (Ray Bakker, verbal and written communication, WMHD, 2004; Mark Quilter, verbal and written communication, UDAF, 2004). The low values of both nitrogen and oxygen isotope species are likely more characteristic of a soil-nitrogen source (figure 30); if initial/present contamination is septic-related, perhaps subsequent dilution from recharge by lighter $\delta^{15}N_{NO3}$ water, more typical of recharge/precipitation $\delta^{15}N_{NO3}$ values, occurred.

Using $\delta^{15}N_{NO3}$ to determine the source/relative contributions of fertilizer and animal waste to ground water is complicated by reactions including ammonia volatilization, nitrification, denitrification, ion exchange, and plant uptake. These processes can modify the $\delta^{15}N_{NO3}$ values of nitrogen sources prior to mixing and in the resultant mixtures, causing estimations of the relative contributions of the sources of nitrate to be inaccurate (Kendall, 1998).

Denitrification is likely negligible in the study area based on the combination of high-nitrate-concentration data and overall low $\delta^{15}N$ values. The overlapping nature of the data likely reflects ground-water mixing, supported by ground-water age data presented in a subsequent section. However, in order to determine influences of other processes, such as mixing of sources of nitrate, we evaluated other chemistry data collected as part of this study. We plotted the ratio of nitrate to chloride for many wells over three different sampling intervals (figure 31) as one method to determine whether denitrification processes occurred. Nitrate and chloride behave similarly in ground water in terms of mobility, but because chloride is not affected by biological processes, the ratio of nitrate to chloride can be an indicator of nitrification/denitrification processes. A relatively constant nitrate-chloride ratio indicates nitrate leaching, whereas a decrease in nitrate-chloride ratio indicates denitrification (Canter, 1997). Based on data from 49 (water wells), we believe denitrification is negligible in Morgan Valley as most nitrate-chloride ratio values remain below 0.20, with the exception of two data points. These data were collected by different agencies at different times and not all samples were from the same wells, thus original ground-water conditions are unknown spatially and temporally. But we believe the persistent ratio for nitrate to chloride supports negligible denitrification, although the effects of mixing may alter our interpretation.

Another method for determining denitrification processes is analyzing dissolved oxygen, manganese, and iron concentration data relative to nitrate concentration data. In denitrification processes, an increase in manganese and iron is commonly coupled to a decrease in dissolved oxygen (Kendall, 1998; McQuillan, 2004). Under aerobic conditions (with dissolved oxygen available), ammonia is oxidized to nitrate. Under anaerobic (anoxic) conditions, bacteria remove oxygen from nitrate (denitrification) and from manganese and iron oxides, thereby increasing the concentration of dissolved manganese and iron in ground water (McQuillan, 2004). Figure 32

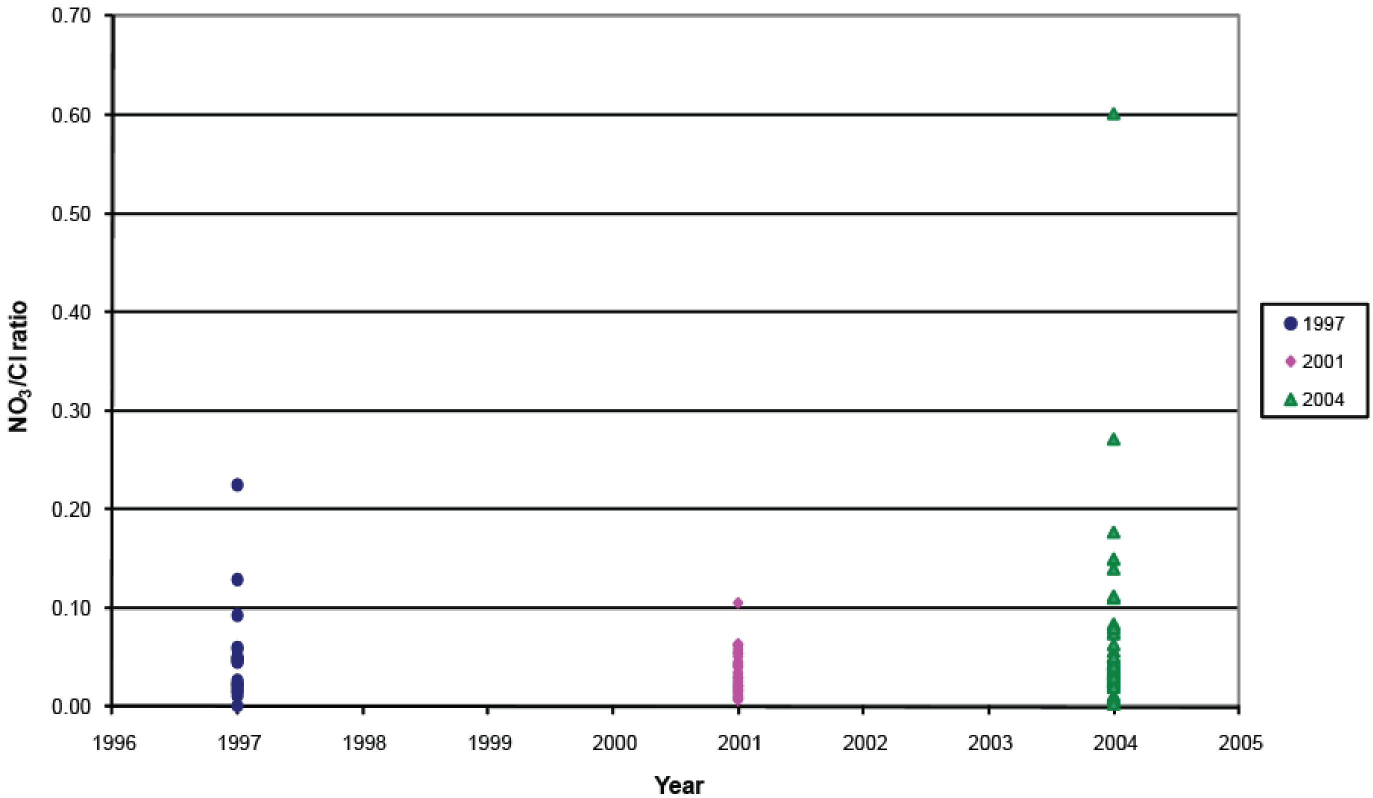


Figure 31. *Nitrate to chloride ratio data versus sampling year for water wells in Morgan Valley, Morgan County, Utah. The nearly constant nitrate to cloride ratio over time indicates negligible denitrification (except one well sampled in 2004).*

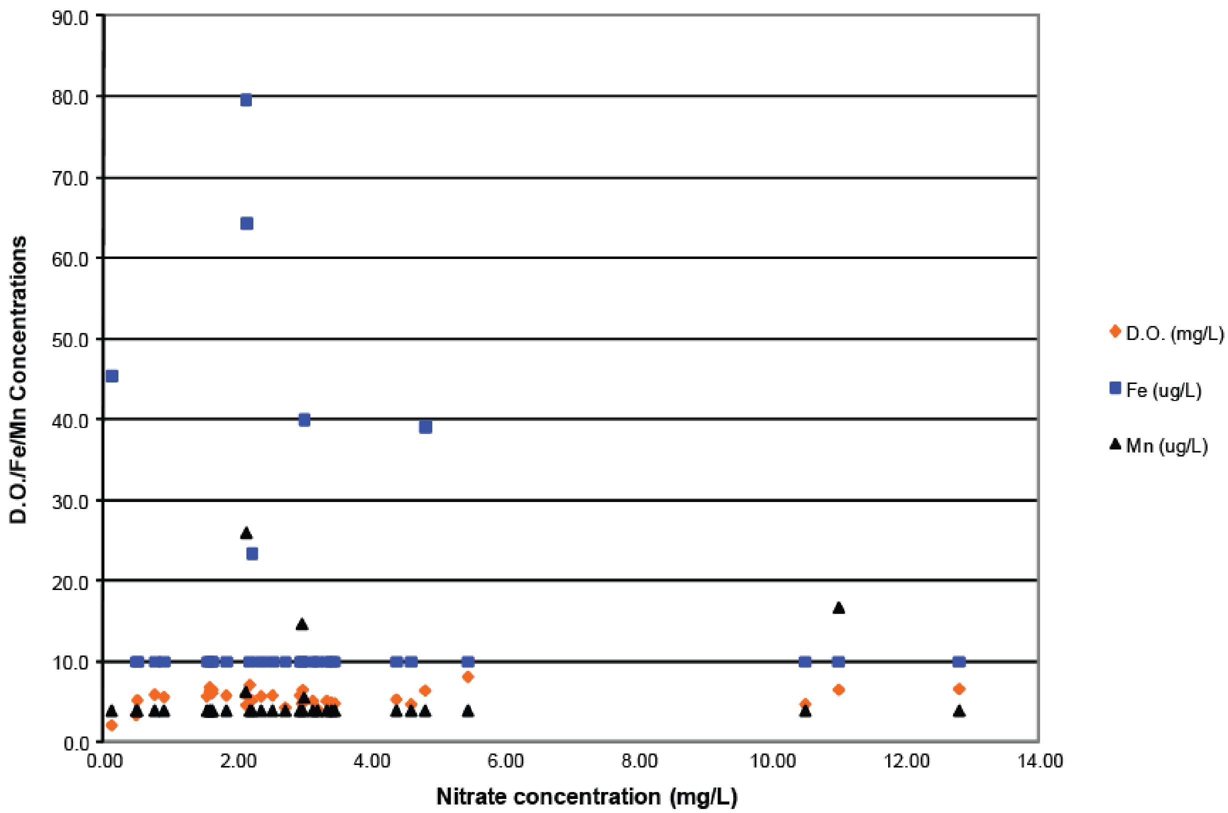


Figure 32. Nitrate concentration versus dissolved oxygen (D.O.), iron (Fe), and manganese (Mn) for water wells in Morgan Valley, Morgan County, Utah. An increase P in Fe and Mn and a decrease in D.O. compared to nitrate is indicative of denitrification; this trend is not shown by our data.

plots nitrate versus dissolved oxygen, manganese, and iron concentrations. Both manganese and dissolved oxygen concentrations remain relatively low and consistently plot at similar concentrations. Iron has a more scattered plot, but overall maintains a low concentration with no prevalent trend to indicate an increase relative to a decrease in nitrate. The data show relatively no variation in concentrations, indicating denitrification processes were not prevalent in the valley.

Denitrification is likely negligible in Morgan Valley based on the above results. We must be cautious when examining chemistry data and note that subsequent naturally occurring processes, described above, can potentially obscure data results. With future analyses of additional samples for chemical species (e.g., chloride, manganese, and dissolved oxygen, and $\delta^{15}N_{NO3}$ and $\delta^{18}O$ isotopes), we may be able to better assess the nitrate source(s) and whether denitrification occurs with time.

ENVIRONMENTAL TRACER ANALYSIS

To determine the influences of other processes on ground-water chemistry, such as mixing of recharge sources, we collected environmental tracer data (figure 33). Environmental tracers can help document the source and age of recharge water. The different types of tracers can be used in tandem to help understand ground-water flow.

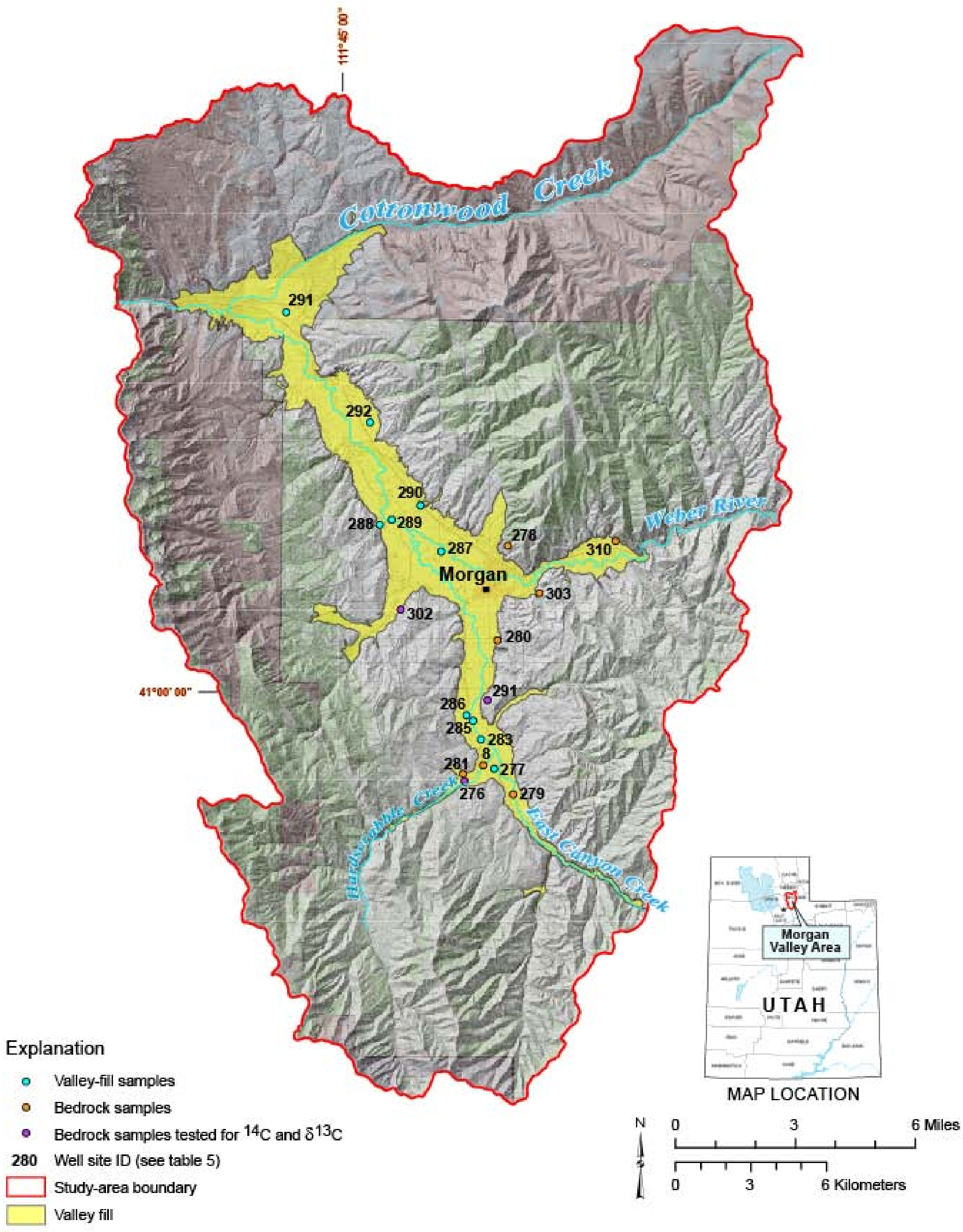


Figure 33. *Wells sampled for environmental tracers in Morgan Valley, Morgan County, Utah. All wells sampled for $\delta^{18}O$, $\delta^{2}H$, and ^{3}H. Three wells were tested for ^{14}C and $\delta^{13}C$.*

Oxygen and Deuterium Isotopes

Precipitation is the source of ground-water recharge, and, factors such as altitude, latitude, location within a continent (and proximity to a mountain range), and the amount of rainfall control isotopic composition of precipitation (Craig, 1961; Kendall and Caldwell, 1998). Heavier isotopes of oxygen and deuterium are associated with lower altitudes (on windward mountain sides), decreasing latitude, increasing distance from oceans, and smaller rainfall amounts (Gonfiantini, 1978; Faure, 1991; Kendall and Caldwell, 1998).

We sampled water from 20 wells for oxygen isotopes and deuterium (table 5). The isotopic ratios in water range from -15.2 to -16.9‰ for oxygen and -131.1 to -119.7‰ for deuterium (table 5). A plot of the oxygen and deuterium data is shown in figure 34. The global meteoric water line (GMWL) is taken from Craig (1961) and modified from Rozanski and others (1993). The local meteoric water line (LMWL) is taken from Lindon, Utah, based on analysis of 192 samples from 1999 to 2009 (Alan Mayo and David Tingey, BYU, personal communication for unpublished data, November 9, 2009). The ground-water data collected from Morgan Valley plot below both the LMWL and the GMWL, which indicates that the ground water is slightly enriched in ^{18}O relative to deuterium. Enriched samples plot below the GMWL because the slopes of each set of evaporation trend-lines plot below the GMWL and the LMWL. The greater enrichment of ^{18}O compared to deuterium in the ground water shown on figure 34 probably indicates evaporation of surface or soil water or sublimation of the snow and evaporation of surface runoff. If ground water is recharged by more heavy precipitation, then data for the ground water should plot on the meteoric water line. Samples that plot below the meteoric water line typically indicate an evaporative signature. Overall, the data from the alluvium are

Table 5. Environmental tracer data for selected water wells and springs in Morgan Valley, Morgan County, Utah.

Well ID[1]	$\delta^{18}O_{H2O}$	±σ	$\delta^{2}D$	±σ	^{3}H (TU)	±σ	$\delta^{13}C$ 0/00	±σ	^{14}C (pmC)	±σ	^{14}C Age Pearson[2]	^{14}C Age Fontes[2]	^{3}H Age[3]	Interpreted Age	Well depth (feet)
276 Green	-16.04	0.2	-122.8	1.0	5.1	0.2	-12.34	0.04	86.85	0.27	modern	modern	modern	modern	396
277 Martin	-16.19	0.2	-126.5	1.0	1.5	0.1	-	-	-	-	-	-	mixed	mixed	132
278 Pit Spring	-16.95	0.2	-130.0	1.0	3.6	0.1	-	-	-	-	-	-	mixed	mixed	-
279 Campground South	-16.26	0.2	-125.1	1.0	3.1	0.2	-	-	-	-	-	-	mixed	mixed	240-158?
280 LaBorde	-15.57	0.2	-125.7	1.0	0.3	0.1	-10.69	0.04	73.84	0.23	modern	modern	pre 1952	mixed	170
281 Moultri	-15.23	0.2	-121.8	1.0	4.3	0.2	-	-	-	-	-	-	mixed	mixed	165
282 Rees Ranch	-16.78	0.2	-129.5	1.0	3.5	0.1	-	-	-	-	-	-	mixed	mixed	210
283 Olsen	-15.32	0.2	-119.7	1.0	6.3	0.1	-	-	-	-	-	-	modern	modern	135
284 Wilson	-15.36	0.2	-120.4	1.0	5.4	0.2	-	-	-	-	-	-	modern	modern	238
286 Carter	-15.3	0.2	-120.0	1.0	6.5	0.2	-	-	-	-	-	-	modern	modern	145
287 Whimpey	-15.65	0.2	-121.6	1.0	5.2	0.2	-	-	-	-	-	-	modern	modern	120
288 Ovard	-15.42	0.2	-122.7	1.0	3.9	0.2	-	-	-	-	-	-	mixed	mixed	101
289 Bates	-15.67	0.2	-122.4	1.0	5.7	0.2	-	-	-	-	-	-	modern	modern	80-90
290 Robison	-15.37	0.2	-122.5	1.0	4.4	0.2	-	-	-	-	-	-	mixed	mixed	155
291 Wilkinson	-15.73	0.2	-121.9	1.0	3.6	0.2	-	-	-	-	-	-	mixed	mixed	192
292 Wardell	-15.53	0.2	-124.2	1.0	4.0	0.2	-	-	-	-	-	-	mixed	mixed	165
8 Thackery	-15.98	0.2	-121.8	1.0	3.9	0.1	-	-	-	-	-	-	mixed	mixed	120
310 Como Spring	-16.44	0.2	-131.1	1.0	1.4	0.1	-	-	-	-	-	-	mixed	mixed	-
302 Ecker	-15.83	0.2	-128.2	1.0	0.8	0.1	-12.38	0.04	65.75	0.21	modern	modern	pre 1952	mixed	268
303 Hawes	-15.83	0.2	-125.5	1.0	2.6	0.1	-	-	-	-	-	-	mixed	mixed	220

[1]Well ID in appendix B; [2]Carbon-age calculations by A. Mayo, BYU, written communication, 2009, using 2 different methods (Pearson and Hanshaw [1970] or Fontes and Garnier [1979]); 3Tritium ages from Clark and Fritz (1997); modern refers to less than 10 years.

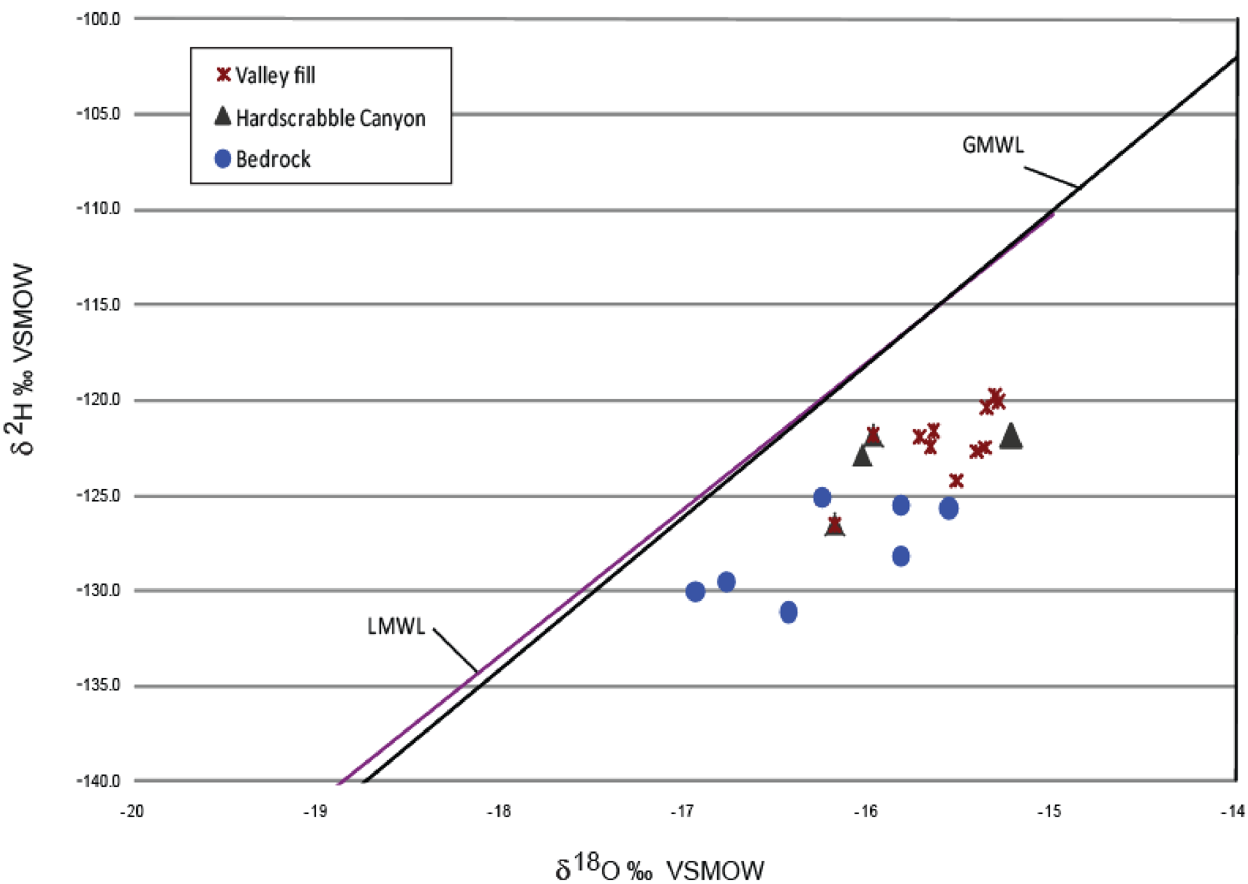


Figure 34. *Plot of oxygen versus deuterium isotopes for wells and springs in Morgan Valley, Morgan County, Utah. GMWL is the global meteoric water line (from Rozanski and others, 1993); LMWL is a local meteoric water line from Mayo and others (written communication, 2009).*

isotopically heavier (less negative) than the bedrock samples; the bedrock samples are the lightest isotopically, and the water samples from the Hardscrabble Canyon area plot between the valley-fill samples and the bedrock samples (figure 34). The lighter isotopic signature of the bedrock wells indicates a relatively cool (higher elevation?) recharge signal compared to the other samples. Overall, spring runoff is probably a significant component of recharge in the study area, so the enrichment is most likely a result of sublimation of snow and/or evaporation of water during runoff but prior to recharge.

Tritium

We collected water samples for tritium analysis from 20 wells in Morgan Valley (figure 35, table 5); values are plotted according to sample type: bedrock versus valley-fill versus Hardscrabble Canyon samples. Tritium data provide a qualitative estimate of ground-water age, or time since ground water was recharged (Clark and Fritz, 1997). Quantitative determination of ground water ages with tritium requires multiple samples collected over a certain time period, multiple samples collected from different depths in the same well, or estimation of the initial tritium concentration prior to recharge. Additionally, mixing of recent ground water with old ground water can cause complications using quantitative methods, so using qualitative methods is the most appropriate method for this study.

Tritium concentrations measured in ground water from 20 samples range from 0.3 to 6.5 Tritium Units (TU) with a median of 3.9 TU. Tritium concentrations that have values less than 0.8 TU are categorized as pre-1952 (pre-bomb [atmospheric nuclear testing] water); values between 0.8 and 4 TU are categorized as mixed water (pre- and post-1952); values from 4 to 10 are categorized as modern water (less than 50 years old; Alan Mayo, BYU, written communication, March 17, 2010) (Clark and Fritz, 1997). The tritium values in this report have two samples that are characterized as pre-bomb water; 12 that are characterized as mixed water; and six that are characterized as modern water (table 5, figure 35). Figure 35 shows bedrock wells generally have tritium concentrations below 4 TU and valley-fill samples generally have

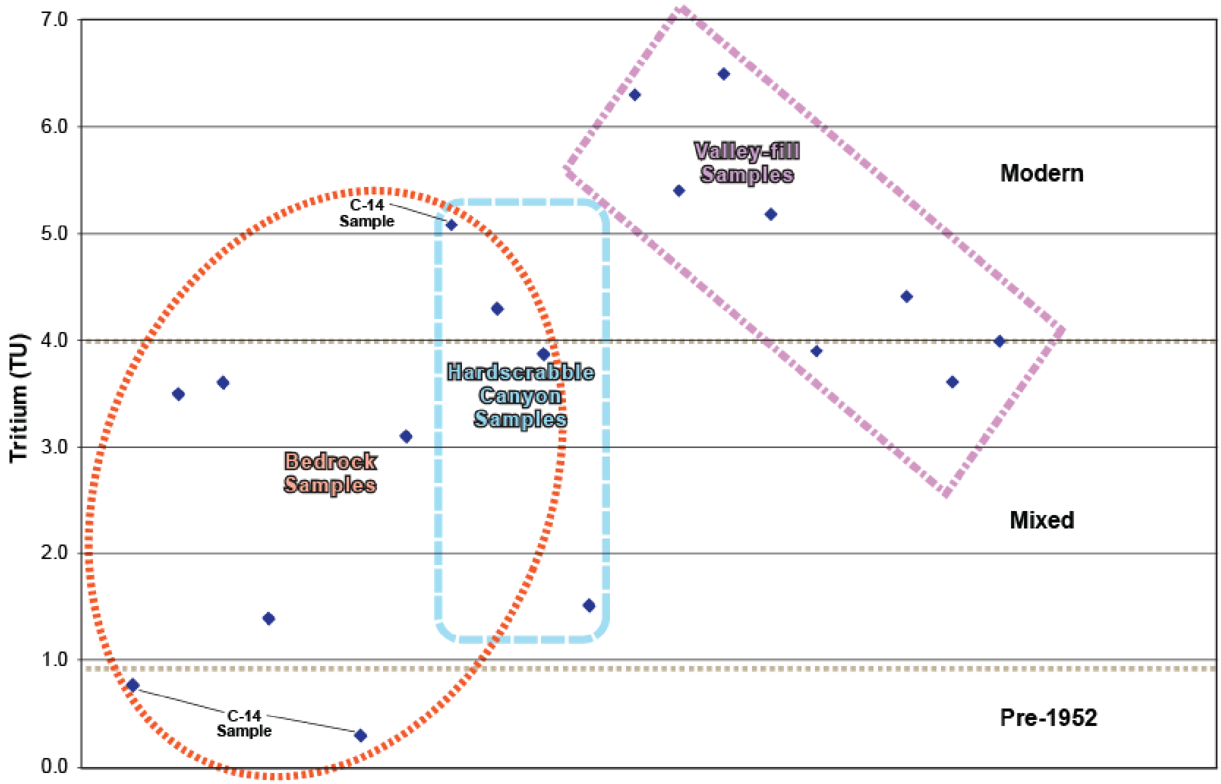


Figure 35. Plot of tritium data for 20 sample sites in Morgan Valley, Morgan County, Utah. Different shaped polygons enclose different type of samples (valley-fill, bedrock, and Hardscabble Canyon samples). The categories of pre-1952, mixed, and modern are from Clark and Fritz (1997). "Modern-age" carbon samples are also shown.

tritium concentrations that exceed 4 TU. Tritium concentrations in the wells suggest that some water in the wells was recharged on the order of 40 years ago (post-atmospheric testing) when tritium concentrations in the atmosphere were near peak levels. Some ground water in the area may be older than the estimated minimum age, but younger than pre-1952 water, due to mixing with younger, lower tritium ground water. Mixed samples may also include both young and old water (pre-1952). These data represent a pre- and post-atmospheric testing age, as well as a mixture of the two, for ground water entering the aquifer system before traveling to the well. The overall older tritium age water for the bedrock samples compared to the valley-fill samples may indicate longer residence times in the bedrock aquifer and relatively recent recharge to the valley-fill aquifer from possible recharge from the Weber River in some areas.

Carbon Isotopes

Carbon-14 is an unstable isotope having a half-life of 5730 years that allows determination of an apparent age of old ground water compared to the other environmental tracers, which provide relative dates; carbon dating can be used over a wider range from 30,000 years to modern age (less than 50 years old). We collected water samples for ^{14}C and $\delta^{13}C$ analysis from three wells in Morgan Valley (table 5). Carbon-14 concentrations measured in ground water from these wells respectively are 65.8, 73.8, and 86.9 pmC, and $\delta^{13}C$ values are -12.4, -10.7, and –12.3‰ (table 5). These values correspond to ground-water ages that are modern based on computation of the carbon isotope values according to the methods of Fontes and Garnier (1979) and Pearson and Hanshaw (1970) (Alan Mayo, BYU, written communication, February 1, 2010). Although "modern" water has no standard, it is typically considered as less than 50 years old (Alan Mayo, written communication, March 17, 2010). All of the three water samples analyzed for carbon isotopes have modern carbon-based ages.

Wells having the modern-age classification have depths of 170 (52 m), 268 (82 m), and 396 (121 m) feet deep; all are located in the southern part of the valley and have respective TDS concentrations of 664, 532, and 332 mg/L. All wells likely penetrate the Norwood Tuff and were recharged with water less than 50 years ago.

Implications of Environmental Tracer Data

Twenty wells were sampled for environmental tracer data, ten of which were sampled for nitrogen and oxygen isotopes. Because most samples analyzed for environmental tracer data (tritium and carbon) have water with a recharge-age component indicative of historical time, we believe the dominant sources of nitrate in ground water in the area are from human-related activity. Because of the lower residence times of ground water in both the alluvial and bedrock aquifers (based on the relatively recent age of ground water and overall low TDS values), the ground water in Morgan Valley is likely diluted by recent recharge water from precipitation as rain/snowfall and from the Weber River, which lowers the potential for nitrate contamination in the valley. Areas having relatively high nitrate concentration are probably localized (point-source contamination versus a pervasive non-point source). Overall environmental tracer data indicate much of the water is mixed in the study area, though bedrock samples generally have an older age component compared to the valley-fill samples and were likely recharged in higher elevation (colder temperature) regions than the bedrock samples. The bedrock samples more likely receive recharge water from precipitation from snowfall in the higher elevations and valley-fill ground water is a mixture of higher elevation recharge water and Weber River water, including canals, and associated flood-irrigation water.

SUMMARY AND CONCLUSIONS

Ground water is an important source of drinking water in Morgan Valley. We evaluated the relationship of geology to ground-water conditions, with emphasis on delineating the thickness of the valley-fill aquifer and determining the water-yielding characteristics of fractured-rock aquifers. The geology of the Wasatch Range on the west side of the Morgan Valley drainage basin consists predominantly of Precambrian metamorphic rocks of the Farmington Canyon Complex. Most of the area surrounding Morgan Valley consists of Tertiary tuffaceous rocks; Cretaceous to Tertiary conglomerate and conglomeratic sandstone with some siltstone, mudstone, and limestone; and Quaternary alluvial, colluvial, and mass-movement deposits. Precambrian crystalline basement rocks and Paleozoic and Mesozoic sedimentary rocks crop out on the north side of Upper Weber Canyon. The Morgan Valley area is in a region with complex structural features.

Primary recharge areas, commonly the uplands and coarse-grained unconsolidated deposits along valley margins, do not contain thick, continuous, fine-grained layers (confining layers) and have a downward ground-water gradient. Based on our examination of drillers' water well logs, all of Morgan Valley is primary recharge area, the most vulnerable to potential contaminants.

We provide aquifer characteristics estimates for both the valley-fill aquifer and selected fractured-rock aquifers based on existing aquifer tests, and by estimating transmissivity from specific capacity data from drillers' logs of water wells. We used information from 79 drillers' logs to estimate aquifer properties for Morgan Valley's valley-fill aquifer. Specific capacity ranges from 0.07 to 50 gallons per minute per foot (0.001-1 L/s/m) and averages 8.4 gallons per minute per foot (0.16 L/s/m), with the areas having the highest specific capacity mostly in areas having the greatest aquifer thickness. Transmissivity ranges from 6.75 to 8815 square feet per day (0.63-819 m^2/d) and averages 1340 square feet per day (125 m^2/d), with the areas having the highest transmissivity also in areas having the greatest aquifer thickness.

We used gravity data to help delineate the subsurface structure beneath Morgan Valley in order to determine the approximate thickness of the valley-fill aquifer, define the geometry of the valley fill, and locate major concealed faults. To provide sufficient gravity data in Morgan Valley for interpretation, we measured relative gravity and elevation at approximately 350 points throughout the valley. Valley-fill material is thicker in the valley center, thins toward valley margins, and is greatest near the towns of Morgan and Enterprise, where it is estimated to be greater than 600 feet (180 m).

We evaluated inflow and outflow water-budget components in Morgan Valley to develop the water budget. We used information to create a budget from climatic data, drainage patterns, land use, vegetation cover, water use, geology, soil data, and streamflow measurements. The overall total inflow into and within Morgan Valley is 661,000 acre-feet per year (815 hm^3). The overall total outflow from Morgan Valley is 600,000 acre-feet (740 hm^3) per year. Although surface water and ground water are directly connected, and we estimated the water budget for the entire integrated water system, the calculated amount of inflow does not equal outflow. The discrepancy between the amount on inflow and outflow is likely based on assumptions we used to estimate these parameters based on the best available existing data. An updated ground-water flow model is required to evaluate a more realistic ground-water flow budget, as the required data and time for creating such a model are not currently available.

Ground-water quality classification is a tool that can be used in Utah to manage potential ground-water contamination sources and protect the quality of ground-water resources. The results of the proposed ground-water quality classification for Morgan Valley indicate that the valley-fill aquifer contains mostly high-quality ground-water resources that warrant protection. Ninety-eight percent of the valley-fill area in Morgan Valley is classified as having Class IA ground water, and 2% classified as having Class II ground water, based on chemical analyses of water from 52 wells sampled during March 2004 by the Utah Geological Survey, 6 wells sampled during May 2004 by the Utah Department of Agriculture and Food, and 8 wells plus 1 spring from 1996 to 2003 for data from the Utah Division of Drinking Water (TDS range of 92 to 1018 mg/L).

We sampled 10 wells, previously sampled and having relatively high (greater than 4.5 mg/L) nitrate concentration, for nitrogen and oxygen isotopes to try to determine the source(s) of nitrate. Our data fall into two potential nitrogen-source categories: soil nitrogen and manure/septic tank nitrogen. The source of nitrate for eight of the water wells is likely derived from soil nitrogen and/or septic tank/manure (likely with most of the wells characterized by mixed sources); the nitrate source for the two other water wells located near cattle/dairy operations is likely derived from manure rather than septic-tank effluent. Other processes, such as mixing of waters, may have had an impact on nitrate concentrations, both seasonal and temporal. We evaluated two aspects of denitrification: the ratios of nitrate to chloride concentrations over time and nitrate to dissolved oxygen, iron, and manganese concentrations, and believe denitrification is negligible in Morgan Valley. Additional analyses of nitrogen and oxygen isotopes from high-nitrate concentration wells over time may help identify the ultimate source of nitrate.

We sampled 20 wells in 2009 for environmental isotopes; 10 of the wells we sampled penetrated bedrock and 10 were alluvial wells we previously sampled in 2004. We collected water from the bedrock wells and had them also analyzed for general chemistry and nutrients. Environmental tracer data for all 20 wells show most of the water is relatively modern in age, and likely recharged during historical times. Because of the lower residence times of ground water in both the alluvial and bedrock aquifers (based on the relatively recent age of ground water and overall low TDS values), the ground water in Morgan Valley is likely diluted by recent recharge water from precipitation as rain/snowfall and from the Weber River and its canals, which lowers the potential for nitrate contamination in the valley. Areas having relatively high nitrate concentration are probably localized (point-source contamination versus a pervasive non-point source).

We did not attempt to determine specific locations for siting future water-well development in the bedrock or alluvial aquifers to supply the communities' future demands. The thickest alluvial deposits in the study area are located in the central part of the valley and also in areas that yield the highest quality water. Because the fractured bedrock aquifer is mantled by up to thousands of feet of Tertiary and Quaternary sedimentary deposits in most areas, we believe the best places in the valley in terms of highest water quality and quantity to consider future water-resource development are located in the valley-fill aquifer. Water supply to future development in bedrock areas may best be sourced and pumped from the valley fill. To control potential degradation of ground-water quality in Morgan Valley, we recommend (1) applying agricultural fertilizer to the surface at rates not exceeding nitrogen uptake by crops, and (2) avoiding septic-tank system installation in areas where implementation of a public-sewer system is feasible.

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APPENDICES

APPENDIX A

UTAH AND EPA PRIMARY AND SECONDARY DRINKING-WATER STANDARDS AND ANALYTICAL METHODS

Table A1. *Utah and EPA primary and secondary drinking water-quality standards and analytical methods for some chemical constituents sampled In Morgan Valley, Morgan County, Utah.*

CHEMICAL CONSTITUENT	EPA ANALYTICAL METHOD[1]	WATER-QUALITY STANDARD (mg/L)
Nutrients:		
total nitrate/nitrite	353.2	10.0
ammonia as nitrogen	350.3	-
total phosphorous and dissolved total phosphate	365.1	-
Dissolved metals (as listed in State of Utah Public Health Laboratory online manual):		
arsenic	200.9	0.01
barium	200.7	2.0
cadmium	200.9	0.005
chromium	200.9	0.1
copper	200.7	1.3
lead	200.9	0.015
mercury	245.1	0.002
selenium	200.9	0.05
silver*	200.9	0.1
zinc*	200.7	5.0
General Chemistry: **(as listed in State of Utah Public Health Laboratory online manual)**		
total dissolved solids (TDS)	160.1	2000^{+**} or (500^{*++})
pH*	150.1	between 6.5 and 8.5

Table A1. (continued)

CHEMICAL CONSTITUENT	EPA ANALYTICAL METHOD[1]	GROUND-WATER QUALITY STANDARD (mg/L)
aluminum*	200.7	0.05 to 0.2
Calcium	200.7	-
sodium	200.7	-
boron	200.7	-
bicarbonate	406C	-
carbon dioxide	406C	-
carbonate	406C	-
chloride*	407A	250
total alkalinity	310.1	-
total hardness	314A	-
specific conductance	120.1	-
iron*	200.7	0.3
potassium	200.7	-
hydroxide	406C	-
sulfate *[++]	375.2	250
magnesium	200.7	-
manganese	200.7	0.5

Table A1. *(continued)*

CHEMICAL CONSTITUENT	EPA ANALYTICAL METHOD[1]	GROUND-WATER QUALITY STANDARD (mg/L)
aluminum*	200.7	0.05 to 0.2
Calcium	200.7	-
sodium	200.7	-
boron	200.7	-
bicarbonate	406C	-
carbon dioxide	406C	-
carbonate	406C	-
chloride*	407A	250
total alkalinity	310.1	-
total hardness	314A	-
specific conductance	120.1	-
iron*	200.7	0.3
potassium	200.7	-
hydroxide	406C	-
sulfate *[++]	375.2	250
magnesium	200.7	-
manganese	200.7	0.5

- No drinking-water quality standard exists for the chemical constituent.

*For secondary standards (exceeding these concentrations does not pose a health threat).

[+] Maximum contaminant level is reported from the Utah Administrative Code R309-200 (Utah Division of Drinking Water).

[**]For public water-supply wells, if TDS is greater than 1000 mg/L, the supplier shall satisfactorily demonstrate to the Utah Water Quality Board that no better water is available. The Board shall not allow the use of an inferior source of water if a better source of water is available.

[++]TDS and sulfate levels are given in the Primary Drinking Water Standards, R309-200. They are listed as secondary standards, excess of recommended levels cause consumer complaint.

[1] http://www.epa.gov/safewater/methods/analyticalmethods_ogwdw.html#one.

APPENDIX B

WATER-QUALITY DATA

Key to the symbols and footnotes for appendix B:

U = non-detect

a "-" indicates no data

UGS = Utah Geological Survey

UDAF = Utah Department of Agriculture and Food

WMHD = Weber-Moran Health Department

UDW = Utah Division of Drinking Water

-0.100 indicates no detection (U) above reporting level as reported by the UDAF

Note- Analysis was performed, in UDAF water samples, for the following constituents, however concentrations were less than detection limits and are not reported: Berylium, Cadmium, Cobalt, Carbonate, Chromium, Lithium, and Nickel.

*These five wells were also sampled for pesticides and organics for which results for all samples are as “U”, non-detectable.

**converted from specific conductance data

APPENDIX C

GRAVITY SURVEY STATIONS AND DATA

APPENDIX C

Gravity Data

Gravity data-collection and reduction procedures

Instrument: Scintrex CG-5, owned by UGS, and LaCoste-Romberg G-series gravimeter, borrowed from the University of Utah Department of Geology and Geophysics (stations marked with * were measured with LaCoste-Romberg).

Base Stations: For absolute gravity, University of Utah Department of Geology and Geophysics basement, 979,770.114 ± 0.002 mGal; field base station at Morgan City Hall, Morgan, Utah, gravity value established at 979,737.612. ± 0.099 mGal during study, tied to the University of Utah.

Measurement Time: 2 to 3 minutes; resulting in typical precision of 0.03 ± 0.02 mGal

Elevation and Location (UTM-NAD83): Measured using Trimble differential GPS survey equipment, with a typical vertical resolution of 1-4 cm.

Data Reduction Sequence (Geosoft Inc., 2001):

A. Instrument drift

B. Earth-tide correction

C. Latitude correction

D. Free Air Anomaly = absolute gravity (corrected for instrument drift and earth tide) – latitude correction + 0.308596 x station elevation in meters.

E. Bouguer Anomaly – $g_{ba} = g_{fa} - 0.0419088 \times [\rho h_s + (\rho_w - \rho)h_w + (\rho_i - \rho_w)h_i] + g_{curv}$, where

g_{ba} = Bouguer anomaly in milligals

g_{fa} = free air anomaly in milligals

ρ = Bouguer density of rock, assumed in this study to be 2.67 g/cm^3

ρ_w = density of water in g/cm^3

ρ_i = density of ice in g/cm^3

h_s = station elevation in meters

h_w = water depth in meters – does not apply to this study

h_i = ice depth in meters – does not apply to this study

g_{curv} = earth-curvature correction

F. Terrain correction, calculated using the algorithm of Geosoft Inc. (2001), with a 5-meter resolution digital elevation model for the local corrections and a 90-meter resolution digital elevation model for the regional corrections.

G. Complete Bouguer anomaly = g_{ba} + terrain correction

The uncertainty of individual Bouguer anomaly values from this study is likely about 0.01 to 0.20 mGal. The largest sources of uncertainty in Bouguer anomaly values are uncertainty in elevation, deviation of the Bouguer reduction density from the true density of the rocks, and inaccuracy of the terrain correction. The uncertainty due to errors in elevation is less than 0.008 mGal. A single value was used for the Bouguer reduction density for all stations, and bedrock in the study area is predominantly Proterozoic Farmington Canyon Complex, so little error among stations should result from varying bedrock density. However, the density difference between valley fill and bedrock may result in some systematic uncertainty in Bouguer anomaly values between stations above bedrock and stations above thick valley-fill deposits. Errors of up to several tenths of a milligal in the terrain correction may arise in mountainous areas with significant topography that is not accounted for by the digital elevation model used to compute the reduction.

Appendix C1. *Gravity data for Morgan Valley, Morgan County, Utah.*

Station	Elevation (m)	Gravity (mGal)	Free Air Anomaly (mGal)	Terrain Correction (mGal)	Complete Bouguer Anomaly (mGal)	Easting (NAD83)	Northing (NAD83)
1	1538.988	979737.612	-48.952	2.952	-219.63	442923.7	4542942.9
2	1541.334	979747.508	-38.707	3.993	-208.60	444055.9	4543398.6
3	1539.760	979746.340	-40.263	3.595	-210.38	443728.0	4543280.2
4	1539.657	979741.660	-44.833	3.224	-215.31	443329.5	4543107.6
5	1538.199	979736.687	-50.062	2.883	-220.72	442767.4	4542871.9
6	1539.216	979735.017	-50.798	2.945	-221.50	442892.1	4542101.4
7*	1543.098	979735.887	-49.305	2.815	-220.58	442640.2	4542817.1
8*	1542.618	979734.594	-50.653	2.717	-221.97	442370.1	4542703.6
9*	1542.595	979733.012	-52.111	2.660	-223.48	441997.5	4542544.2
10*	1542.711	979732.467	-52.513	2.749	-223.81	441681.1	4542413.0
11*	1541.901	979734.102	-51.531	2.692	-222.79	442132.5	4542908.9
12*	1541.825	979736.046	-49.824	2.831	-220.94	442495.2	4543171.1
13*	1543.041	979736.858	-48.557	2.878	-219.76	442725.4	4543070.3
14*	1543.781	979738.514	-46.747	3.003	-217.91	442977.8	4543161.4
15*	1544.401	979741.642	-43.544	3.234	-214.54	443260.4	4543302.4
16*	1545.867	979741.908	-42.504	3.243	-213.66	443430.8	4542903.0
17*	1545.162	979738.606	-45.941	3.038	-217.22	443151.2	4542803.3
18*	1543.460	979736.073	-48.851	2.824	-220.15	442735.8	4542622.3
19*	1543.564	979734.551	-50.292	2.737	-221.69	442463.3	4542563.6
20*	1543.466	979736.270	-48.525	2.859	-219.79	442840.4	4542464.7
21*	1544.935	979734.380	-49.501	2.911	-220.88	442914.9	4541892.7
22*	1550.137	979732.432	-49.128	3.024	-220.98	442995.6	4541004.7
23*	1546.475	979733.514	-49.548	2.972	-221.04	442949.1	4541465.6
24*	1556.942	979731.282	-48.170	3.104	-220.71	443156.3	4540994.4
25*	1554.689	979732.191	-48.212	3.411	-220.19	443256.8	4541309.9
26*	1547.507	979734.283	-48.665	3.609	-219.64	443229.4	4541717.3
27*	1556.682	979734.664	-45.787	3.123	-218.28	443269.7	4542131.6
28*	1547.162	979737.736	-45.930	3.129	-217.34	443258.0	4542475.9
29*	1554.352	979731.752	-48.116	3.173	-220.29	443114.3	4540518.7
30*	1559.822	979730.716	-46.938	3.283	-219.62	443131.9	4539867.8
31*	1553.555	979731.615	-47.992	2.970	-220.28	442800.7	4539892.5
32*	1553.904	979731.879	-47.645	2.820	-220.13	442447.7	4539926.8
33*	1561.344	979730.306	-46.943	2.938	-220.14	441904.7	4539956.3
34*	1551.607	979731.203	-49.530	3.269	-221.30	441951.4	4540550.2
35*	1549.699	979731.363	-50.313	2.980	-222.16	441985.4	4540989.7
36*	1544.455	979733.551	-50.622	2.721	-222.14	442499.3	4542074.0
37*	1550.971	979731.172	-50.315	2.836	-222.45	441954.3	4541241.0
38*	1549.605	979731.281	-50.957	2.844	-222.93	441928.3	4541650.0

39*	1539.355	979734.982	-52.015	2.790	-222.89	441919.1	4543628.2
40*	1539.192	979736.437	-50.805	2.961	-221.49	442144.0	4543866.7
41*	1539.889	979735.662	-50.967	2.805	-221.89	442210.7	4543373.3
42*	1541.221	979736.285	-50.015	2.885	-221.01	442387.7	4543473.1
43*	1537.236	979734.621	-53.107	2.733	-223.80	441606.7	4543725.4
44*	1537.375	979735.326	-52.589	2.847	-223.19	441740.2	4544009.8
45*	1542.768	979738.700	-47.082	3.069	-218.06	442885.4	4543419.0
46*	1542.684	979741.990	-44.016	3.320	-214.74	443129.6	4543663.2
47*	1541.735	979740.871	-45.679	3.421	-216.19	442933.4	4543975.5
48*	1544.748	979745.884	-39.617	3.889	-210.00	443527.4	4543823.5
49*	1545.450	979747.877	-37.170	4.087	-207.43	444009.0	4543525.7
50*	1549.690	979747.450	-36.081	4.468	-206.44	444616.6	4543264.1
51*	1547.636	979744.027	-39.716	3.985	-210.33	443737.2	4542747.7
52	1539.377	979737.042	-48.933	3.048	-219.55	443066.2	4542361.2
53	1540.231	979732.038	-53.384	2.885	-224.26	441862.3	4542011.2
54	1539.260	979732.518	-53.041	2.737	-223.96	442117.3	4541807.4
55	1539.594	979732.989	-52.504	2.731	-223.47	442420.3	4541851.0
56	1540.166	979732.369	-52.695	2.745	-223.71	442288.4	4541540.2
57	1572.041	979737.669	-39.307	4.444	-212.20	447010.7	4543670.0
58	1564.096	979742.781	-36.750	4.808	-208.39	446046.5	4543805.3
59	1550.355	979745.238	-38.574	5.891	-207.58	445814.4	4543858.3
60	1549.210	979745.144	-38.995	6.542	-207.23	445425.7	4543827.4
61	1548.195	979746.135	-38.370	6.225	-206.80	445415.1	4543892.9
62	1548.275	979746.246	-38.257	6.218	-206.71	445399.0	4543922.0
63	1548.107	979746.283	-38.306	6.318	-206.64	445399.4	4543964.7
64	1548.131	979745.879	-38.621	6.321	-206.95	445435.1	4543862.7
65	1550.585	979744.727	-38.509	6.439	-207.00	444940.3	4543237.8
66	1550.403	979745.246	-37.841	4.221	-208.53	444426.3	4542986.9
67	1545.634	979745.496	-39.090	3.536	-209.92	443761.0	4543026.2
68	1546.647	979739.910	-44.020	3.359	-215.15	443428.9	4542604.2
69	1562.432	979737.703	-41.289	3.566	-213.98	443559.8	4542521.0
70	1547.698	979746.260	-37.683	3.858	-208.43	444108.2	4543016.4
71	1549.323	979744.149	-39.020	4.871	-208.94	444109.7	4542678.6
72	1552.190	979745.055	-38.097	6.607	-206.60	445280.6	4543744.9
73	1544.204	979742.315	-43.766	4.082	-213.89	443180.1	4544337.1
74	1549.111	979747.008	-37.065	4.793	-207.03	444138.5	4543718.1
75	1553.581	979744.574	-38.385	4.903	-208.75	443740.5	4544050.3
76	1555.044	979742.826	-39.885	4.558	-210.76	443447.5	4544304.9
77	1542.162	979741.436	-45.352	3.863	-215.47	442942.0	4544434.2
78	1603.831	979733.018	-35.185	4.960	-211.13	443409.3	4544982.4
79	1572.523	979737.925	-39.794	4.577	-212.61	443247.1	4544803.8
80	1585.670	979726.487	-48.740	3.751	-223.85	440833.5	4546761.5
81	1565.471	979729.408	-51.862	3.740	-224.72	440593.6	4546528.4
82	1529.129	979736.095	-56.206	3.719	-225.01	440470.7	4546300.9
83	1536.172	979735.123	-54.843	3.923	-224.23	440883.3	4546096.5
84	1535.164	979735.509	-54.538	3.805	-223.93	441121.3	4545809.9

85	1544.129	979735.120	-51.927	3.602	-222.53	441495.2	4545518.4
86	1547.811	979736.722	-49.011	3.794	-219.83	442061.7	4545293.6
87	1537.019	979737.747	-51.104	3.439	-221.07	441843.0	4545032.9
88	1535.551	979736.538	-52.542	3.134	-222.65	441631.6	4544756.8
89	1535.422	979736.936	-52.035	3.116	-222.14	441791.5	4544571.2
90	1534.408	979736.507	-53.096	3.204	-223.00	441495.9	4544968.8
91	1540.246	979738.783	-48.848	3.486	-219.13	442258.1	4544752.0
92	1538.325	979738.272	-49.817	3.305	-220.06	442150.6	4544585.8
93	1536.322	979736.361	-52.030	2.967	-222.39	441869.1	4544196.1
94	1538.339	979737.799	-49.858	3.106	-220.30	442312.0	4544053.9
95	1540.487	979739.491	-47.507	3.293	-218.01	442680.6	4544055.0
96	1541.729	979740.046	-46.943	3.606	-217.27	442630.5	4544519.5
97	1535.743	979736.363	-53.029	3.372	-222.92	441468.0	4545217.4
98	1532.448	979735.701	-54.558	3.156	-224.29	441223.4	4545034.2
99	1530.684	979735.760	-55.157	3.148	-224.70	441025.2	4545176.0
100	1530.934	979735.332	-55.316	3.029	-225.01	441051.0	4544938.1
101	1529.658	979735.318	-55.762	2.992	-225.35	440838.0	4544986.9
102	1533.914	979735.235	-55.678	3.538	-225.20	440287.5	4546412.1
103	1523.745	979737.063	-56.846	3.246	-225.51	439928.6	4546239.1
104	1522.591	979737.158	-56.978	3.223	-225.54	439992.1	4546079.0
105	1524.833	979736.547	-56.698	3.167	-225.57	440218.6	4545829.5
106	1525.043	979736.184	-56.813	3.020	-225.85	440064.9	4545605.5
107	1524.404	979736.366	-56.738	2.952	-225.77	439778.6	4545495.0
108	1522.861	979736.921	-56.980	3.108	-225.69	439926.2	4545890.8
109	1521.204	979738.041	-56.797	3.294	-225.13	439796.2	4546419.9
110	1519.818	979738.545	-56.802	3.243	-225.03	439524.9	4546522.2
111	1563.854	979740.911	-39.287	5.020	-210.68	447440.6	4544529.1
112	1561.583	979742.499	-38.307	5.136	-209.33	446805.3	4544418.9
113	1563.918	979740.848	-39.115	4.659	-210.88	447474.8	4544262.0
114	1566.256	979738.819	-40.517	4.941	-212.26	447926.2	4544375.8
115	1563.871	979740.493	-39.285	4.516	-211.19	447470.4	4544015.1
116	1569.811	979738.551	-39.200	4.525	-211.76	447462.7	4543774.8
117	1567.885	979737.456	-41.311	5.316	-212.86	448515.7	4544290.4
118	1572.156	979735.972	-41.339	5.476	-213.21	448744.4	4544117.8
119	1596.606	979730.843	-38.728	4.828	-213.99	448641.5	4543876.5
120	1566.084	979738.465	-40.713	4.721	-212.66	447992.3	4544114.4
121	1567.840	979739.069	-40.145	5.912	-211.10	447661.3	4544831.9
122	1568.758	979735.331	-43.654	9.232	-211.39	448213.8	4544895.2
123	1575.127	979738.365	-38.692	6.094	-210.28	447334.3	4544949.2
124	1564.713	979740.792	-39.414	6.820	-209.11	446879.7	4544872.6
125	1562.679	979742.447	-38.169	6.761	-207.69	446426.4	4544605.0
126	1603.489	979736.009	-32.046	6.346	-206.57	446161.3	4544647.8
127	1523.235	979737.532	-56.431	3.129	-225.16	439668.9	4546112.8
128	1522.579	979737.968	-56.161	3.023	-224.92	439161.0	4546072.9
129	1521.763	979738.452	-55.804	3.038	-224.46	438801.2	4545920.6
130	1530.306	979736.937	-54.443	3.033	-224.06	438603.3	4545625.1

131	1531.122	979736.562	-54.218	3.266	-223.69	438623.6	4545194.5
132	1519.382	979739.715	-55.901	3.119	-224.21	438403.5	4546698.3
133	1523.996	979738.823	-55.199	3.123	-224.02	438328.7	4546487.6
134	1525.769	979738.827	-54.460	3.500	-223.10	438065.1	4546257.6
135	1514.666	979740.869	-56.824	3.300	-224.42	438451.1	4547469.0
136	1514.582	979741.069	-56.564	3.271	-224.18	438251.2	4547362.9
137	1511.911	979741.875	-57.034	3.351	-224.27	438070.0	4547925.0
138	1517.021	979741.118	-56.130	3.342	-223.95	437885.4	4547822.4
139	1517.346	979740.896	-55.920	3.221	-223.89	438007.0	4547410.0
140	1511.968	979743.574	-57.573	4.378	-223.79	437716.3	4550723.0
141	1526.121	979739.415	-54.221	3.441	-222.96	437717.9	4546829.0
142	1520.629	979740.009	-55.477	3.225	-223.82	437965.3	4547018.3
143	1520.823	979740.634	-55.139	3.676	-223.05	437505.4	4547451.4
144	1515.666	979741.662	-56.197	3.392	-223.81	437632.7	4548063.7
145	1515.813	979741.667	-56.516	3.423	-224.12	437486.6	4548523.3
146	1515.474	979742.012	-56.515	3.459	-224.04	437461.1	4548819.2
147	1514.877	979742.657	-56.296	3.441	-223.77	437191.7	4549121.8
148	1504.507	979744.342	-58.049	3.603	-224.20	437367.2	4549413.5
149	1524.403	979741.326	-54.466	3.315	-223.14	437074.8	4548847.3
150	1514.347	979745.201	-54.010	3.821	-221.05	436447.4	4549244.1
151	1517.881	979739.860	-56.391	3.141	-224.51	438364.1	4546911.9
152	1517.671	979739.574	-56.658	3.115	-224.78	438577.6	4546806.6
153	1528.783	979736.907	-55.973	3.884	-224.57	440098.7	4546889.8
154	1527.844	979737.262	-56.132	4.001	-224.51	439886.9	4547168.3
155	1519.767	979738.861	-56.914	3.606	-224.77	439664.8	4547032.7
156	1517.018	979739.406	-57.159	3.449	-224.87	439468.3	4546961.7
157	1516.632	979739.567	-57.245	3.446	-224.91	439331.3	4547120.7
158	1515.622	979740.208	-57.367	3.678	-224.69	439130.4	4547682.1
159	1513.474	979740.654	-57.547	3.495	-224.81	438901.7	4547638.5
160	1513.767	979740.634	-57.373	3.327	-224.84	438632.7	4547511.8
161	1514.682	979740.328	-57.238	3.265	-224.87	438662.3	4547316.5
162	1514.572	979740.314	-57.333	3.348	-224.87	438901.2	4547371.7
163	1516.695	979739.746	-57.218	3.687	-224.65	439420.6	4547332.1
164	1525.556	979738.001	-56.347	4.215	-224.25	439639.4	4547478.1
165	1533.299	979737.173	-55.100	3.834	-224.25	439316.2	4547870.1
166	1523.046	979739.509	-56.217	3.896	-224.16	438919.2	4548231.7
167	1526.496	979738.902	-56.069	3.613	-224.68	438496.4	4548618.4
168	1514.631	979741.600	-57.394	4.180	-224.10	438436.8	4549066.1
169	1518.665	979741.282	-56.935	4.749	-223.53	438532.1	4549645.4
170	1513.453	979742.798	-57.357	4.436	-223.68	438214.1	4550057.6
171	1526.564	979740.278	-55.865	4.833	-223.26	438438.8	4550097.0
172	1520.830	979741.587	-56.560	4.580	-223.57	438169.8	4550390.5
173	1512.780	979743.291	-57.463	4.293	-223.85	437842.5	4550545.4
174	1508.162	979744.862	-56.869	4.078	-222.96	437866.0	4549990.1
175	1507.886	979744.943	-56.854	3.798	-223.19	437637.1	4549967.4
176	1506.531	979745.558	-56.978	3.940	-223.02	437424.6	4550366.7

177	1504.165	979746.496	-57.166	4.018	-222.86	437170.8	4550860.3
178	1502.117	979747.601	-57.017	4.060	-222.44	436799.4	4551264.5
179	1509.528	979744.253	-56.782	3.858	-223.24	437806.0	4549650.1
180	1515.626	979742.095	-56.391	3.749	-223.64	438248.7	4548819.6
181	1511.878	979743.138	-56.731	3.785	-223.53	438099.0	4549100.4
182	1509.916	979743.775	-56.869	3.752	-223.48	437936.2	4549312.9
183	1509.734	979743.810	-56.848	3.658	-223.53	437755.5	4549261.7
184	1508.740	979744.421	-56.488	3.615	-223.10	437472.4	4549195.7
185	1509.803	979744.022	-56.342	3.592	-223.10	437508.0	4548927.3
186	1510.802	979743.326	-56.739	3.574	-223.63	437782.3	4548936.3
187	1508.257	979744.488	-56.768	3.656	-223.29	437465.5	4549440.9
188	1507.050	979744.999	-56.880	3.735	-223.19	437480.4	4549751.3
189	1519.061	979743.366	-55.924	4.292	-223.02	437361.0	4551136.5
190	1516.100	979744.514	-56.041	4.364	-222.73	436964.6	4551574.2
191	1511.666	979747.415	-54.751	3.614	-221.69	435995.7	4551883.1
192	1496.764	979751.955	-54.955	3.887	-219.95	435725.1	4552067.1
193	1496.234	979753.136	-53.611	3.759	-218.68	435466.0	4551664.5
194	1494.916	979753.259	-54.270	3.752	-219.20	435523.6	4552129.1
195	1492.028	979753.898	-54.917	3.896	-219.37	435523.9	4552617.3
196	1496.586	979754.125	-52.504	3.770	-217.60	435263.2	4551653.5
197	1496.769	979756.944	-49.654	3.983	-214.56	434832.3	4551689.7
198	1509.036	979755.247	-47.766	3.957	-214.07	434694.4	4551940.0
199	1518.587	979754.657	-46.336	3.468	-214.20	434451.8	4553089.8
200	1495.186	979758.116	-50.212	3.529	-215.39	434680.3	4553229.0
201	1489.433	979757.795	-52.100	3.597	-216.56	434890.4	4552968.8
202	1490.605	979756.256	-53.142	3.662	-217.67	435149.3	4552799.0
203	1530.869	979739.512	-56.533	4.751	-224.50	437271.7	4551631.0
204	1500.103	979751.378	-55.443	4.042	-220.66	435432.3	4553235.2
205	1493.458	979754.318	-54.968	3.539	-219.94	435281.3	4553750.6
206	1520.599	979749.330	-52.099	3.169	-220.49	435472.0	4554390.1
207	1480.451	979759.280	-53.912	3.482	-217.48	434795.8	4553621.2
208	1479.557	979759.967	-53.408	3.496	-216.86	434661.7	4553507.0
209	1481.199	979757.984	-54.700	3.570	-218.27	434964.4	4553275.0
210	1496.458	979756.484	-52.230	3.223	-217.86	434862.8	4554191.8
211	1497.613	979755.374	-53.196	3.220	-218.96	435132.6	4554451.9
212	1492.152	979752.902	-54.896	3.695	-219.57	435398.8	4551406.1
213	1504.952	979751.077	-52.492	3.732	-218.56	435375.1	4551060.1
214	1499.881	979753.535	-51.692	3.802	-217.12	435177.7	4551178.8
215	1505.664	979749.936	-53.200	3.933	-219.15	435524.2	4550795.7
216	1508.372	979747.317	-54.557	4.036	-220.71	435927.9	4550263.4
217	1513.995	979745.858	-53.858	4.018	-220.66	436108.9	4549738.5
218	1512.066	979745.191	-54.763	3.888	-221.48	436399.9	4549294.0
219	1503.083	979748.948	-54.887	3.813	-220.67	435801.0	4550672.4
220	1492.057	979749.758	-57.585	3.688	-222.25	436134.2	4550799.9
221	1493.144	979748.426	-58.533	3.693	-223.32	436452.4	4550737.2
222	1494.887	979749.016	-57.113	3.769	-222.02	436179.7	4550377.2

223	1509.169	979745.138	-55.817	3.672	-222.42	436584.6	4549424.1
224	1499.425	979746.768	-57.277	3.659	-222.80	436652.2	4549526.0
225	1499.250	979746.004	-58.028	3.594	-223.60	436908.0	4549440.9
226	1497.800	979745.969	-58.816	3.600	-224.22	436961.6	4549819.4
227	1576.150	979733.378	-46.290	3.031	-221.06	436406.6	4548661.0
228	1494.553	979758.284	-51.203	3.184	-216.66	434554.5	4554424.2
229	1486.196	979762.478	-49.725	3.207	-214.22	434073.4	4554598.3
230	1491.760	979758.637	-51.891	3.127	-217.09	434685.2	4554644.5
231	1495.935	979756.213	-53.038	3.187	-218.64	435059.7	4554654.1
232	1498.940	979754.821	-53.598	3.332	-219.39	435313.8	4554770.7
233	1503.493	979753.921	-53.316	3.333	-219.62	435471.1	4555046.3
234	1502.230	979755.324	-52.437	3.065	-218.87	435148.9	4555215.1
235	1498.268	979758.003	-50.775	3.049	-216.78	434757.7	4554963.5
236	1513.616	979753.389	-51.112	3.079	-218.81	435546.9	4555525.7
237	1522.041	979752.460	-49.767	3.052	-218.44	435730.3	4555926.6
238	1522.696	979751.710	-50.242	3.089	-218.95	435857.0	4555836.2
239	1542.443	979748.996	-47.395	3.197	-218.21	436488.3	4556489.9
240	1542.873	979747.461	-48.648	3.309	-219.40	436613.3	4556303.9
241	1485.797	979765.653	-46.936	3.275	-211.31	433746.2	4554925.6
242	1500.030	979760.232	-48.009	3.171	-214.09	434162.1	4554976.7
243	1500.870	979762.078	-46.263	3.101	-212.51	433841.7	4555425.7
244	1501.653	979759.843	-48.239	2.987	-214.69	434275.1	4555399.8
245	1498.895	979761.569	-47.223	3.059	-213.29	433999.6	4555227.3
246	1480.656	979769.422	-44.770	3.464	-208.38	433154.5	4554952.1
247	1477.872	979771.919	-43.180	3.701	-206.24	432807.8	4555014.3
248	1477.502	979776.349	-38.755	4.669	-200.81	431740.7	4554889.2
249	1474.434	979774.949	-40.927	4.283	-203.02	432175.6	4554669.2
250	1473.598	979775.174	-40.812	4.415	-202.68	432141.7	4554486.4
251	1478.182	979773.980	-40.936	4.140	-203.59	432309.7	4554911.6
252	1538.605	979733.710	-53.300	2.658	-224.22	441545.0	4543359.2
253	1530.478	979734.216	-56.244	2.771	-226.14	440389.2	4544537.3
254	1529.873	979734.555	-56.295	2.844	-226.05	440501.4	4544788.2
255	1528.890	979735.006	-56.267	2.924	-225.83	440574.5	4544935.3
256	1527.928	979735.037	-56.489	2.850	-226.02	440229.5	4544884.2
257	1527.126	979735.224	-56.589	2.835	-226.05	440054.8	4544933.8
258	1525.053	979735.979	-56.681	2.880	-225.86	439807.5	4545192.6
259	1528.761	979735.054	-56.031	2.778	-225.73	439840.0	4544659.1
260	1526.746	979735.640	-56.255	2.822	-225.68	439692.2	4544893.8
261	1524.503	979735.381	-57.379	2.906	-226.47	440212.1	4545102.1
262	1528.269	979734.475	-56.755	2.792	-226.39	440522.2	4544645.5
263	1530.551	979734.542	-55.948	2.865	-225.76	440932.6	4544597.1
264	1530.519	979733.984	-56.221	2.739	-226.16	440739.2	4544232.2
265	1531.685	979734.148	-55.595	2.772	-225.63	441052.3	4544104.6
266	1531.430	979734.329	-55.710	2.826	-225.66	441019.6	4544373.6
267	1533.451	979734.568	-54.605	2.797	-224.81	441424.3	4544070.9
268	1533.649	979734.188	-54.778	2.739	-225.06	441368.2	4543889.5

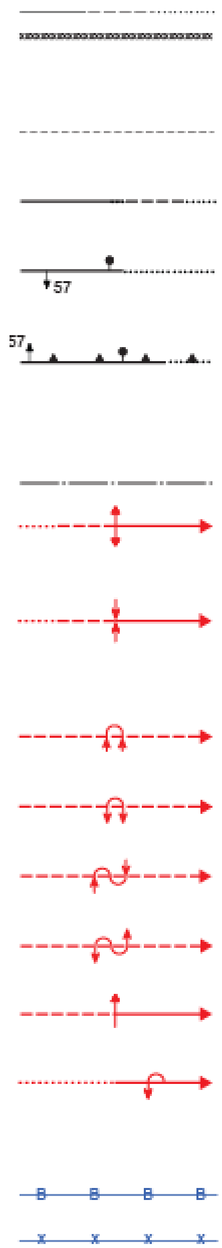
269	1534.608	979733.540	-54.897	2.664	-225.37	441289.3	4543602.1
270	1537.915	979734.431	-52.627	2.700	-223.43	441993.4	4543152.7
271	1537.824	979733.462	-53.433	2.643	-224.28	441744.6	4542916.6
272	1538.040	979732.681	-53.959	2.744	-224.73	441174.3	4542687.5
273	1537.279	979733.035	-53.989	2.638	-224.78	441374.2	4542871.3
274	1539.955	979732.064	-54.056	2.864	-224.93	440631.7	4542781.3
275	1534.144	979733.236	-54.915	2.705	-225.29	440635.6	4543075.6
276	1534.402	979733.192	-55.101	2.628	-225.58	440922.1	4543348.1
277	1534.348	979733.289	-55.138	2.641	-225.60	441070.8	4543492.3
278	1534.432	979733.553	-54.538	2.862	-224.79	440181.8	4543114.6
279	1535.739	979733.734	-54.054	2.720	-224.59	439862.5	4543241.3
280	1554.070	979735.939	-44.974	3.079	-217.21	438961.2	4541739.2
281	1544.438	979734.659	-49.756	3.071	-220.92	439420.6	4542391.2
282	1532.039	979733.541	-55.718	2.633	-225.93	440435.4	4543645.2
283	1531.386	979733.611	-56.035	2.672	-226.13	440674.3	4543872.9
284	1533.032	979733.532	-55.232	2.655	-225.53	440206.9	4543414.1
285	1535.214	979733.662	-54.235	2.760	-224.68	440032.0	4543175.0
286	1535.358	979734.010	-54.004	2.761	-224.46	439624.7	4543377.2
287	1530.629	979735.761	-54.061	2.972	-223.78	439189.0	4543813.4
288	1527.534	979735.017	-56.233	2.736	-225.84	439770.2	4544395.3
289	1529.337	979734.759	-55.791	2.723	-225.61	439615.1	4544217.7
290	1530.180	979734.969	-55.158	2.773	-225.02	439402.5	4544018.5
291	1533.433	979735.370	-53.954	2.992	-223.96	438963.0	4544270.5
292	1527.321	979735.741	-55.630	2.841	-225.10	439183.1	4544468.4
293	1566.375	979729.682	-45.478	2.856	-219.32	441959.0	4539291.0
294	1557.547	979731.486	-46.142	3.025	-218.83	442120.6	4538971.5
295	1557.050	979731.689	-46.059	3.080	-218.63	442656.5	4538927.5
296	1556.681	979731.994	-45.887	2.913	-218.59	442398.5	4538952.6
297	1575.541	979727.853	-44.225	2.761	-219.19	442038.3	4538976.1
298	1575.029	979728.226	-44.159	2.867	-218.96	441802.4	4539163.5
299	1575.519	979728.326	-43.398	2.822	-218.30	442122.1	4538527.9
300	1581.084	979727.285	-42.707	2.998	-218.06	441668.5	4538514.7
301	1574.099	979728.669	-43.476	2.789	-218.25	441895.5	4538510.0
302	1573.089	979729.460	-42.676	2.853	-217.28	441969.9	4538111.5
303	1562.058	979731.314	-44.301	2.966	-217.55	442142.1	4538202.9
304	1574.874	979729.475	-41.913	2.821	-216.75	442004.7	4537866.4
305	1578.476	979728.541	-41.774	2.976	-216.86	441722.4	4537917.2
306	1576.728	979728.994	-41.860	2.909	-216.81	442196.9	4537912.5
307	1583.812	979728.353	-39.830	2.776	-215.71	442194.2	4537311.2
308	1637.377	979718.878	-32.470	2.746	-214.39	441642.5	4536938.0
309	1586.155	979728.155	-39.217	3.041	-215.10	441882.4	4537205.1
310	1575.781	979730.641	-39.657	2.957	-214.46	442727.8	4536856.2
311	1594.139	979727.377	-36.817	2.850	-213.78	442646.6	4536314.8
312	1606.294	979725.739	-34.396	2.722	-212.85	442526.2	4535932.0
313	1644.103	979726.344	-21.439	3.013	-203.85	441350.2	4535093.2
314	1623.618	979726.968	-27.517	2.772	-207.87	441866.9	4535561.8

315	1614.687	979729.407	-27.476	3.238	-206.36	441865.0	4535117.7
316	1614.447	979725.728	-31.680	2.722	-211.05	442297.4	4535673.1
317	1606.459	979729.505	-29.999	3.162	-208.04	442267.2	4535215.8
318	1574.733	979732.062	-38.252	3.138	-212.75	443262.0	4536471.3
319	1599.218	979727.779	-33.536	3.498	-210.42	443753.5	4534679.4
320	1586.982	979730.100	-35.043	3.872	-210.18	444009.4	4534742.0
321	1586.197	979730.353	-35.547	3.430	-211.04	443418.2	4535384.6
322	1579.765	979731.497	-36.761	3.247	-211.72	443386.7	4535846.8
323	1553.276	979732.953	-47.172	2.940	-219.46	442827.0	4540429.1
324	1567.232	979730.713	-43.871	3.273	-217.40	442852.6	4538899.2
325	1567.645	979730.177	-44.599	3.652	-217.79	443105.2	4539292.0
326	1572.328	979731.306	-40.822	3.145	-215.05	442709.1	4537804.6
327	1589.061	979727.722	-39.429	2.977	-215.70	442761.9	4538035.0
328	1577.017	979730.842	-39.591	2.994	-214.49	442925.3	4537494.9
329	1583.773	979730.329	-38.038	3.102	-213.59	443156.8	4537516.8
330	1588.908	979730.558	-36.083	3.429	-211.88	443369.0	4537340.9
331	1573.701	979732.327	-38.748	3.044	-213.23	442929.5	4537021.8
332	1574.705	979732.018	-38.605	3.071	-213.17	443076.7	4536845.4
333	1597.543	979726.156	-45.669	4.976	-220.89	441137.2	4547084.5
334	1616.817	979727.947	-36.794	4.013	-215.14	442692.9	4545663.3

APPENDIX D

DESCRIPTION OF GEOLOGIC UNITS

GEOLOGIC SYMBOLS



Contact, dashed where Xfcm-Xfc contact approximately located, dotted where concealed, and x-ed where gradational (in Xfc and Twc-Tw contact)

Marker bed mapped in Tw in Bybee Knoll quadrangle

Fault, dashed where approximately located, dotted where concealed, sense of movement unknown

Normal fault, bar and ball on downthrown side, dotted where concealed; arrow and number indicate photogrammetric dip on fault

Thrust fault, teeth on upper plate, dotted where concealed; arrow and number indicate photogrammetric dip on fault; bar and ball indicates later normal fault offset

Lineament, fold axis or fault, but offset uncertain

Antiform hinge-zone trace, dashed where approximately located, dotted where concealed, arrow shows plunge

Synform hinge-zone trace, dashed where approximately located (very approximate for broad syncline in Tertiary units and unit Keh), dotted where concealed, arrow shows plunge

Overturned synform hinge-zone trace, dashed because approximately located

Overturned antiform hinge-zone trace, dashed because approximately located

Inverted anticline hinge-zone trace, arrow shows plunge, dashed because approximately located

Inverted syncline hinge-zone trace, arrow shows plunge, dashed because approximately located

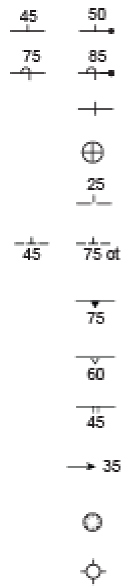
Monocline (flexure), dashed where approximately located, arrow shows plunge

Overturned monocline, dotted where concealed

Lake Bonneville shoreline, dashed where approximately located

Bonneville (about 5180 feet [1579 m])

transgressional (prominent at about 5060 feet [1542 m])



Strike and dip of bedding

Upright (top known from bedding indicators on right)

Overturned (top known from bedding indicators on right)

Vertical

Horizontal

Approximate, upright

Photogrammetric, upright on left; overturned on right (ot suffix on dip angle)

Strike and dip of foliation (high grade)

Strike and dip of cataclastic foliation

Strike and dip of cleavage (low grade)

Lineation, with plunge angle

Sinkhole

Borehole, with name (East Canyon)

Thin Quaternary unit over another unit (for example Ql/Tcg)
Qm/Qa4 in Weber Canyon near Devils Slide

Landslide with nearly intact rotated blocks of unit in parentheses; for example Qms(Tn); queried (Qms?, Qmso?) where blocks may be in place.

APPENDIX D

MAP UNIT DESCRIPTIONS

QUATERNARY

Alluvial Deposits

Qal Stream alluvium (Holocene) - Sand, silt, clay, and gravel in channels, flood plains, and terraces 10 or less feet (3 m) above the Ogden and Weber Rivers and larger tributaries like Cottonwood, East Canyon, and Lost Creeks; locally includes muddy, organic overbank and oxbow lake deposits; composition depends on source area, so typically contains many quartzite cobbles recycled from the Wasatch Formation; 0 to 20 feet (0-6 m) thick.

Qat2, Qatp

Stream-terrace deposits (Holocene and Pleistocene) - Sand, silt, clay, and gravel in terraces above flood plains, mostly along the Weber River and Cottonwood Creek; lower terraces (Qat2) are mostly Holocene in age and are typically about 20 feet (6 m) above adjacent floodplains; 0 to at least 20 feet (0-6+ m) thick. Higher terraces (Qatp) are graded to the Provo and slightly lower shorelines of Lake Bonneville (at and less than ~4820 feet [1470 m] in area), and with Qap form a “bench” at about 4900 feet (1494 m) along the Weber River in Morgan Valley and similar “bench” along South Fork of Ogden River; the Qatp terraces are typically about 25 to 30 feet (8-9 m) above Weber River and up to 40 feet above the South Fork of the Ogden River.

Qaf, Qafy, Qafp, Qafb, Qafo, Qafoe

Alluvial-fan deposits (Holocene and Pleistocene) - Mostly sand, silt, and gravel that is poorly bedded and poorly sorted; includes debris flows, particularly in drainages and at drainage mouths (fan heads); where possible subdivided into relative ages, indicated by letter suffixes; Qaf with no suffix used where age uncertain or for composite fans where portions of fans with different ages cannot be shown separately at map scale; generally less than 60 feet (18 m) thick. Younger alluvial-fans (Qafy) are active and impinge on present-day drainages, like the Weber River and Cottonwood Creek, and are younger than regressional shorelines of Lake Bonneville (mostly Holocene in age). Lake Bonneville-age alluvial-fans are inactive and locally dissected; fans labeled Qafp and Qafb are graded to the Provo (and slightly lower) and Bonneville shorelines of late Pleistocene Lake Bonneville, respectively. Older alluvial-fan deposits (Qafo) are inactive and at least locally dissected; these fans are above and typically incised/eroded at the Bonneville shoreline; above the Bonneville shoreline, unit Qafo is topographically higher than fans graded to the Bonneville shoreline (Qafb), and are typically dissected. Eroded old alluvial-fan deposits (Qafoe) are fan remnants located above and apparently older than pre-Lake Bonneville older alluvial deposits (Qafo, Qao); and are less bouldery and lower relative to high-level alluvium (for example QTa, QTaf).

Qa, Qay, Qap, Qab, Qa3, Qaoe

Alluvium (Holocene and Pleistocene) - Sand, silt, clay, and gravel in stream and alluvial-fan deposits; composition depends on source area; deposits lack fan shape and are distinguished from terraces (Qat) based on upper surface sloping toward adjacent drainage, or are shown where areas of fans and terraces are too small to show separately at map scale; where possible subdivided into relative ages, indicated by number and letter suffixes; Qa with no suffix used where age uncertain or alluvium of different ages can not be shown separately at map scale; generally 0 to 20 feet (0-6 m) thick. Younger alluvium (Qay) post-dates upper Pleistocene Lake Bonneville and is likely mostly Holocene in age. Lake Bonneville-age alluvium appears graded to the Provo and/or Bonneville shoreline and Qa3 is used where age uncertain or alluvium of different ages can not be shown separately at map scale; alluvium when labeled Qap and Qab is graded to the Provo (and slightly lower) and Bonneville shorelines of Lake Bonneville, respectively. A prominent surface ("bench") is present on Qap at about 4900 feet (1494 m) along the South Fork of the Ogden River and along the Weber River in Morgan Valley. Older alluvium (Qao) is above and likely older than the Bonneville shoreline and is above adjacent Lake Bonneville alluvium. Eroded old alluvium (Qaoe) is also located above the Bonneville shoreline and apparently above, and older than, pre-Lake Bonneville older alluvium (Qao and Qafo).

Lacustrine Deposits

Qlm Young lacustrine and marsh deposits (Holocene) - Present in marshy area near Maples recreation area, Snow Basin quadrangle, where lake(s) may have formed due to landslide damming; likely less than 20 feet (6 m) thick.

Ql Lake Bonneville deposits, undivided (upper Pleistocene) - Includes silt, clay, sand, and cobbly gravel in variable proportions; mapped where grain size is mixed, deposits of different materials cannot be shown separately at map scale, or surface weathering obscures grain size and deposits are not exposed; thickness uncertain.

Qlg Lake Bonneville gravel (upper Pleistocene) - Mostly interbedded gravel and sand deposited along beaches and slightly offshore; mostly mapped below the Bonneville shoreline on the southwest margin of the map area; includes Bonneville-level bar and transgressive beach deposits on Strawberry Creek fan-delta; likely less than 20 feet (6 m) thick.

Qls Lake Bonneville sand (upper Pleistocene) - Mostly sand with some silt and gravel deposited nearshore in Morgan Valley; typically unstratified and lack of bedding in “bench” east of Mountain Green is the only reason the bench is not mapped as deltaic deposits; typically less than 20 feet (6 m) thick, but thicker in “bench” east of Mountain Green.

Qlf Lake Bonneville fine-grained deposits (upper Pleistocene) - Mostly silt, clay, and fine sand (typically eroded from shallow Norwood Formation) in Ogden and Morgan Valleys; deposited near- and off-shore in lake. Red laminated claystone at least 30 feet (9 m) thick on Frontier Drive in Snow Basin quadrangle (thickness from Rogers, 1986, borehole 1), despite no nearby red bedrock, like the Wasatch Formation; these data indicate red clay or "shale" in boreholes in Morgan Valley may not be Wasatch Formation bedrock. Other deeper water fine-grained deposits overlie older shoreline and delta gravels (Qlf/Qdlg) at the mouths of several drainages along Weber River; the gravels were deposited above the Provo shoreline during transgression of Lake Bonneville to the Bonneville shoreline and are similar to unit Qdlb, but contain more gravel.

Qdlb Lake Bonneville deltaic and lacustrine deposits, undivided (upper Pleistocene) - Mostly sand, silty sand, and gravelly sand deposited near shore; mapped where poor exposures preclude separation; deposited as the lake transgressed to and was at the Bonneville shoreline in Ogden Valley and in Morgan Valley, where it is more gravel rich and cobbly; zero to at least 40 feet (12 m) thick.

Glacial Deposits

Qg Glacial deposits, undivided (Holocene and upper and middle Pleistocene) - Till and outwash of various ages mapped on Durst Mountain and the Wasatch Mountains; till is non-stratified, poorly sorted clay, silt, sand, and gravel, to boulder size that is typically in ground, recessional, and lateral moraines; outwash is stratified and variably sorted, but better sorted and bedded than till due to alluvial reworking, and is mapped directly downslope from other glacial deposits where it can be separated from alluvium (Qa); glacial deposits locally include rock glaciers; 0 to at least 100 feet (0-30 m) thick; mostly Pinedale-age. On Durst Mountain, unlike in the Wasatch Mountains to the west, no sign of younger glacial deposits upslope. Queried glacial deposits (Qg?) may be older (likely Bull Lake age, ~130,000 to 150,000 years old), and have well-developed soil and subdued moraine morphology. Other possible glacial features are pimple mounds on Herd Mountain in Durst Mountain and Bybee Knoll quadrangles and possible stone stripes (solifluction) in unit Qcg.

Qgy Younger glacial deposits (Holocene and upper Pleistocene) - Mostly Pinedale-age (~15,000 to 30,000 years old, upper Pleistocene) till and outwash; end moraines are vegetated and have poorly developed soil and moderate to sharp moraine morphology; upslope these younger units include vegetated recessional deposits from glacial stillstands and/or minor advances (deglacial pauses) about 13,000 to 14,000 years ago; in cirques include Holocene deposits with very poorly developed soil and sharp, mostly non-vegetated moraines; in some cirques, like Strawberry Bowl, Snow Basin quadrangle, unit Qgy includes un-vegetated, angular, cobble- to boulder-sized debris with little matrix in pro-talus ramparts and rock glacier deposits (inactive, no ice matrix) with lobate crests; these rocky deposits may be as young as Little Ice Age (A.D. 1500 to 1800).

Qgo Older glacial deposits (middle? Pleistocene) - Till and outwash mapped down drainage from and locally laterally above Pinedale (Qgy) deposits; moraines vegetated with well-developed soil and subdued moraine morphology; probably Bull Lake age; 0 to 150? feet (0-45? m) thick. Deposits in Maples area, Snow Basin quadrangle, are much farther from cirques than any other deposits and might be older than Bull Lake glaciation.

Mass-Movement Deposits

Qms, Qmso

Landslide deposits (Holocene and Pleistocene) - Poorly sorted clay- to boulder-sized material; includes slide, slump, and flow deposits; generally characterized by hummocky topography, main and internal scarps, and chaotic bedding in displaced blocks; composition depends on local sources; morphology becomes more subdued with time and amount of water in deposits; thickness highly variable. Qmso mapped when deposits likely emplaced before Lake Bonneville transgression, and typically mapped where rumpled morphology that is characteristic of mass movements has been diminished and/or younger surficial deposits cover or cut Qmso. These older deposits are as unstable as other landslide deposits, and are easily reactivated with the addition of water, be it irrigation or septic-tank drain fields. Locally, unit involved in landslide is shown in parentheses where a nearly intact block is visible. On northwest margin of Durst Mountain, Qmso(Ts) block was emplaced before Qao, making it middle Pleistocene. Qms queried (?) where bedrock block may be in place.

Qmc Landslide and colluvial deposits, undivided (Holocene and Pleistocene) - Mapped where landslide deposits are difficult to distinguish from colluvium (slopewash and soil creep) and where mapping separate, small, intermingled areas of landslide and colluvial deposits is not possible at map scale; locally includes talus; typically mapped where landslides are thin ("shallow"); also mapped where the blocky or rumpled morphology that is characteristic of landslides has been diminished ("smoothed") by slopewash and soil creep; composition depends on local sources; 0 to 40 feet (0-12 m) thick. These deposits are as unstable as other landslide units (Qms, Qmso).

Qmt Talus (Holocene and Pleistocene) - Angular debris at the base of and on steep slopes; only larger debris fields can be shown at map scale and include pro-talus ramparts and colluvium locally; also includes rock-glacier deposits too small to show separately at map scale; grades laterally into Qct; shown mostly in Wasatch Mountains; 0 to 30 feet (0-9 m) thick.

Qct Colluvium and talus (Holocene and Pleistocene) - Angular debris at the base of and on steep, typically vegetated slopes; shown mostly in cirques in the Wasatch Mountains; 0 to 30 feet (0-9 m) thick.

Qc Colluvium (Holocene and Pleistocene) - Includes material moved by slopewash and soil creep; composition depends on local sources; generally 6 to 20 feet (2-6 m) thick; not shown where less than 6 feet (2 m) thick.

Qcg Gravelly colluvial deposits (Holocene and Pleistocene) - Present downslope from gravel-rich deposits of various ages (for example units Keh, Tcg, Thv, QTaf, QTa, Qafoe and Qaoe, and Qafo and Qao) but mostly mapped downslope from Thv on west side of Durst and Elk Mountains; typically differentiated from colluvium and residual gravel (Qc, Qng) by prominent stripes trending downhill on aerial photographs; stripes are concentrations of gravel up to boulder size; stone stripes are prominent on Durst Mountain in the southeastern Snow Basin quadrangle; generally 6 to 20 feet (2-6 m) thick; some deposits previously included in Huntsville fanglomerate (see Thv).

Mixed Deposits

Qac Alluvium and colluvium (Holocene and Pleistocene) - Includes stream and fan alluvium, colluvium, and, locally, mass-movement deposits too small to show at map scale; 0 to 20 feet (0-6 m) thick.

Qla Lake Bonneville deposits and alluvial deposits, undivided (Holocene and uppermost Pleistocene) - Mostly poorly sorted and poorly bedded sand, silt, and clay, with some gravel; mapped where Lake Bonneville deposits are reworked by later stream action or covered by stream wash, and where lake deposits are thin and overlie older alluvial deposits; deposits typically eroded from shallow Norwood Formation; mostly mapped near Bonneville shoreline; thickness uncertain.

Qng Colluvial and residual gravel deposits (Holocene and Pleistocene?) - Gravel of uncertain origin, but probably mostly colluvium and residuum; poorly sorted pebble to boulder gravel in a matrix of silt and sand; mostly gravel-armored surfaces that are gently to steeply dipping; present near high-level fans (QTaf) near head of Strawberry Creek and south of Weber River; also near QTaf north of Morgan; generally 6 to 20 feet (2-6 m) thick.

Qfd, Qfdb, Qfdp

Lake Bonneville alluvial-fan and delta deposits, undivided (upper Pleistocene) - Cobbly gravel, sand, silt, and clay deposited above (subaerial) and in Lake Bonneville (subaqueous); typically mapped where shorelines are obscure, so that line cannot be drawn between fan and delta; typically better sorted delta and lake deposits over poorly sorted alluvial-fan deposits. Qfdb mapped above the Provo shoreline and deposited as lake transgressed to and was at the Bonneville shoreline; prominent along Deep Creek in the Morgan quadrangle, Bally Watts Creek in Durst Mountain quadrangle, and up Dalton and Deep Creeks in the Peterson quadrangle; also present in Durst Mountain quadrangle in Quarry Hollow and along Cottonwood Creek upstream from Qdlb. Qfdp mapped below/near the Provo shoreline and best developed near head of Weber Canyon, with likely Bonneville-level deposits, along Strawberry Creek in the Snow Basin quadrangle;

Qfdp also present in Weber Canyon; 0 to at least 40 feet (0-12+ m) thick.

Qmg Mass-movement and glacial deposits, undivided (Holocene and Pleistocene) - Mapped where glacial deposits lack typical moraine morphology, and appear to have failed or moved down slope; also mapped in upper Strawberry Bowl, Snow Basin quadrangle where glacial deposits have lost their distinct morphology and the contacts between them and colluvium and talus in the cirques cannot be mapped; likely less than 30 feet (9 m) thick.

Qmtr Talus and rock glaciers, with some colluvium (Holocene and Pleistocene) - Angular debris at the base of and on steep slopes and lobate mounds at the base of talus slopes in cirques in Snow Basin quadrangle; mounds called pro-talus ramparts by some workers and rock glaciers by others; 0 to 30 feet (0-9 m) thick.

Human Deposits

Qh Human disturbance (Historical) - Obscures original deposits by cover or removal; mostly fill along railroad and highway grades, cement plant operations, and some large gravel pits.

QUATERNARY AND TERTIARY

QTa High-level alluvium (lower Pleistocene and/or Pliocene) - Gravel, sand, silt, and clay above other stream-terrace and alluvial-fan deposits; at least locally gravel-armored and poorly sorted; located above Qaoe, so older; estimate 30 to 70 feet (9-20 m) thick in Morgan Valley; queried near Henefer where age uncertain.

QTaf High-level alluvial-fan deposits (lower Pleistocene and/or Pliocene) - Gravel, sand, silt, and clay above other stream-terrace and alluvial-fan deposits (including QTa); typically more bouldery than other alluvium; at least locally gravel-armored and poorly sorted; forms little dissected fan south of Weber River, and fan-head remnants north of Weber River near head of Strawberry Creek and on northwest flank of Durst Mountain; estimate 30 to 160 feet (9-50 m) thick. Upper surfaces of these high-level deposits, with some high-level alluvium (QTa) in Morgan Valley, appear to be the Weber Valley surface of Eardley (1944); however, high-level alluvial fans (QTaf) extend to the mountain front at elevations of about 6800 to 7200 feet (2070-2195 m), rather than to the mountain ridgelines as suggested by Eardley (1944).

In East Canyon graben, the high-level fans are red gravel, sand, silt, and clay eroded from red conglomeratic Wasatch Formation (Tw) and Weber Canyon Conglomerate (Kwc), as well as sandy Preuss Redbeds (Jp, Jsp?); these red bedrock units, at least locally, shallowly underlie the red fans, making fan contacts difficult to map; overlain downslope by unit Qafo and upslope locally includes small younger (likely Holocene) alluvial-fans (Qafy); estimate about 240 feet (75 m) thick; mapped as Wasatch Formation by Bryant (1990).

TERTIARY

Ts Tertiary strata, undivided - Used for mostly concealed outcrops with characteristics of Tcg and Thv west of Elk Mountain, and where multiple or uncertain Tertiary map units are under Quaternary deposits, for example Qgo/Ts near Snow Basin or are in landslide blocks, Qms(Ts) and Qmso(Ts).

Thv Fanglomerate of Huntsville (Pliocene? and Miocene) - Typically dark-weathering, poorly to moderately consolidated, pebble to boulder gravel in brown to reddish brown silt and sand; gravel and matrix reflect source of Wasatch Formation as well as Paleozoic and Precambrian rocks exposed on Durst Mountain (see Coogan and King, 2006, for details); unconformably overlies conglomeratic strata (Tcy and Tcg) with negligible to noticeable angular unconformity and locally a change to larger clast quartzite conglomerate; in graben in Durst Mountain may include strata that are age-equivalent to units Tcy and/or Tcg; estimate 40 to 1000 feet (12-300 m) thick on west flank of Durst and Elk Mountains (Coogan and King, 2006); queried where identification uncertain on west side of Durst Mountain.

Tcy Younger unnamed Tertiary conglomeratic rocks (Miocene?) - Rounded, pebble- to boulder-sized, quartzite-clast conglomerate with gray, tan, or reddish matrix and some mudstone, siltstone, and sandstone; since lithologically like unit Tcg, Tcy-Tcg contact based on change in dip across angular unconformity (5-10^{o} vs >10^{o} in Morgan quadrangle) and more regular bedding in Tcy; angular unconformity becomes less distinct to north and unit Tcy apparently pinches out and is not present north of Sheep Herd Creek (Thv "rests" on Tcg) (see Coogan and King, 2006), so queried near Sheep Herd Creek and to south of lineament (fault?) in Big Hollow; estimate 200 to 400 feet (60-120 m) thick in Durst Mountain quadrangle (Coogan and King, 2006). Previously included in Huntsville fanglomerate (see Thv), but mapped Tcy-Thv contact (lithologic change and unconformity) is more distinct than Tcy-Tcg contact (unconformity with no consistent lithologic change).

Tc Unnamed conglomerate of Salt Lake City salient - (Miocene?) - Light-brown to light-gray, variably cemented, pebble to cobble conglomerate and sandstone; clasts generally subrounded to sub-angular limestone and quartzite, but contains Farmington Canyon complex clasts near exposures of the complex; maximum thickness >1600 feet (500 m) (Bryant, 1990). Age likely based on basin-and-range normal fault contact with Paleozoic and Farmington Canyon complex rocks; underlies even younger conglomerate and overlies likely Norwood Tuff with marked angular unconformity, yet appears to be lateral equivalent of Keetley Volcanic rocks (see Van Horn, 1981; Van Horn and Crittenden, 1987); Tc therefore occupies stratigraphic interval of units Tcy and Tcg near Morgan.

Tcg Unnamed Tertiary conglomeratic rocks (Oligocene?) - Characterized by rounded, cobble- to boulder-sized, quartzite-clast conglomerate with pebbles and less than 10 percent to more than 50 percent gray, tan, or reddish mudstone matrix; quartzite clasts are recycled Wasatch Formation clasts; interbedded with tan, gray, and reddish-brown pebble-bearing mudstone to sandstone and some claystone (altered tuff); most beds poorly indurated and poorly exposed; some non-conglomeratic beds in Tcg look like the gray upper Norwood Formation (Tn) and are locally tuffaceous; mudstone likely constitutes the matrix of the conglomeratic beds; some Tcg conglomerate beds have carbonate and chert clasts (like Norwood), rare altered tuff clasts from Norwood Formation, or mostly angular carbonate and/or Tintic quartzite clasts (see Coogan and King, 2006); an estimated 500 feet (150 m) thick in aggregate and thickens north of Cottonwood Creek and to south in Morgan quadrangle to possibly 3000 feet (900 m) thick, though faulting or folding (lineament on map) may make this estimate too large; previously included in Huntsville fanglomerate (see Thv). Tcg is queried at several sites in the map area where identification is uncertain.

Tn Norwood Tuff/Formation (lower Oligocene and upper Eocene) - Typically light-gray to light-brown, altered tuff (claystone), tuffaceous siltstone, sandstone, and conglomerate; locally colored light shades of red and green; variable calcareous cement and zeolitization, but more common to north, so extensive unaltered tuff near Morgan; near type area in Porterville quadrangle, has cut-and-fill structures (fluvial) and includes volcanic-clast conglomerate, and local limestone and silica-cemented rocks; upper Norwood Formation, as exposed on west margin of Durst Mountain (see Coogan and King, 2006), is gray, granule to small pebble conglomerate, with chert and carbonate clasts, as well as claystone and fine- to coarse-grained sandstone that is interbedded with overlying more conglomeratic unit (Tcg); Norwood is at least 7000 feet (2135 m) thick to the north near the Morgan County line (King and others, 2008) and thins to the south to about 5000 feet (1525 m) thick north of Morgan; only about 1500-foot (460 m) thickness is exposed in type area, Norwood Canyon. Tn queried where interbedded with conglomerate (might be Tcg) on east side of Weber River northeast of Morgan. Overall an aquitard due to high clay content from alteration.

Norwood Formation in the East Canyon graben includes more tuff and volcanic-rock clasts, and is transitional between more distal sedimentary strata in Morgan Valley and more proximal volcano apron deposits to south near Park City (included in Keetley Volcanics). The stratigraphy of similar volcaniclastic rocks (Tn and Tkb of Bryant, 1990) on the Salt Lake City salient, southwest corner of map area, has not been worked out.

Tkc Keetley Volcanics conglomerate (Oligocene and Eocene?) - Pebble to boulder conglomerate and sandstone with clasts and grains of nearby Mesozoic rocks and clasts of some upper Paleozoic rocks; contains some volcanic-clast sedimentary conglomerates, as well as a few tuff beds and lahars (volcanic-clast breccias); estimate up to 300 to 650 feet (90-200 m) thick; on south flank of Uinta Mountains, similar sedimentary-rock conglomerates are typically in the lower part of the Keetley Volcanic rocks; shown as Toc by Bryant (1990).

Tw Wasatch Formation (Eocene and uppermost Paleocene) - Typically red to reddish brown sandstone, siltstone, mudstone, and conglomerate; locally contains pale reddish gray algal limestone; clasts usually rounded quartzite; lighter shades of red, yellow/tan, and light gray more common in uppermost Wasatch near Morgan and along Cottonwood Creek; basal conglomerate contains locally derived clasts where contact with underlying Paleozoic rocks is exposed nearby and is less likely to be red; Wasatch knobs north of Cottonwood Creek are reddish to light-gray to brownish-gray variably cemented conglomeratic rocks; queried Wasatch is in fault slivers on west side of Morgan Valley, where unit may be red-stained Quaternary deposits, and on Durst Mountain where the unit might be Evanston Formation; total thickness about 5000 to 6000 feet (1500-1800 m) south of Weber River, Morgan and Devils Slide quadrangles, and about one-fifth as thick to west next to Wasatch Mountains; likely up to about 2600 feet (800 m) thick near Herd Mountain; thickness varies locally due to considerable relief on basal erosional surface, may be as much as 300 to 400 feet (90-120 m) of relief in north part of Bybee Knoll quadrangle. Contains numerous small seasonal springs that indicate small, local, perched aquifers.

An apparent angular unconformity is present in the upper Wasatch Formation near Bybee Knoll, because dips on the capping Wasatch are nearly flat lying while older Wasatch strata dip greater than 3 degrees. This angular unconformity is shown as a marker bed on geologic map and cross section A-A', because numerous springs seem to indicate a perched water table above this unconformity.

Twc Basal conglomerate, Wasatch Formation - Red-orange- and tan-weathering, cobble conglomerate (Coogan, 2004a,b); mainly comprised by quartzite clasts (DeCelles, 1994); mapped separately from Tw where it forms prominent cliffs west of Lost Creek at the base of the Wasatch Formation; 0 to 400 feet (120 m) thick (Coogan, 2004a,b). Includes Twc unit of Bryant (1990), though he describes it as overlying less conglomeratic parts of the Wasatch Formation.

CRETACEOUS

Keh Hams Fork Member of Evanston Formation (Upper Cretaceous-Maastrichtian/Campanian) - Light-gray, brownish-gray, and tan sandstone, conglomeratic sandstone, and quartzite- and chert-pebble conglomerate, and variegated gray, greenish-gray, and red mudstone; member coarsens downward to gray and brownish-gray, cobble conglomerate containing dominantly quartzite clasts (Coogan, 2006a,b; Coogan and King, 2006); where possible basal conglomerate is mapped separately (Kehc); Hams Fork Member up to about 1000 feet (300 m) thick northeast of Durst Mountain (Coogan and

King, 2006), about 700 to 800 feet (210-240 m) thick near Devils Slide, including basal conglomerate, and is up to about 600 feet (180 m) thick just north of Bybee Knoll quadrangle; regionally, unconformably truncated and locally absent beneath Wasatch Formation; unconformably overlies various Mesozoic and Paleozoic rocks, in particular the Hams Fork overlies the Weber Canyon Conglomerate with angular unconformity just north of Bybee Knoll quadrangle and near Devils Slide; overlies Willard thrust sheet in northeast part of map area.

Kehc Basal conglomerate of Hams Fork Member (Upper Cretaceous) -Tan and gray, cobble to boulder conglomerate with minor interbedded gray, carbonaceous mudstone; conglomerate contains rare Precambrian schist and gneiss clasts (DeCelles, 1994); about 200 to 400 feet (60-120 m) thick west of East Canyon graben near Devils Slide. Mann (1974) measured about 950 feet (290 m) of covered strata with Precambrian schist boulder float northwest of East Canyon Reservoir, but called it Wasatch Formation.

Kew Undivided basal conglomerate of Hams Fork Member of Evanston Formation and Weber Canyon Conglomerate - Mapped along East Canyon fault zone where Bryant (1990) did not separate these two conglomerates and showed them as Echo Canyon Conglomerate (his Ke).

Kwc Weber Canyon Conglomerate (Upper Cretaceous) - Red, gray, and tan, boulder to cobble conglomerate with minor sandstone and mudstone interbeds; cliff forming; exposures continue south of Devils Slide along East Canyon fault (included in Echo Canyon Conglomerate, Ke, by Bryant, 1990); at least 1900 feet (580 m) thick near Devils Slide (after DeCelles, 1994). Unconformably overlies older units.

Weber Canyon Conglomerate may be present in subsurface beneath Herd Mountain, but if so, its overall lithology and clast composition are like exposures to the north along the Right Fork of South Ogden River (see Coogan, 2006a,b) rather than like that near Devils Slide or to southeast in Lost Creek drainage (see Coogan, 2004a,b). Exposures north of Herd Mountain are tan and gray conglomerate, mainly composed of clasts from a paleo-topographic ridge developed on the Lodgepole Limestone in the Causey Dam quadrangle. Only the upper ~300 feet (90 m) of Weber Canyon Conglomerate are exposed along the South Ogden River (Coogan, 2006a,b).

Kf Frontier Formation (Upper Cretaceous-Coniacian?/Turonian/Cenomanian) - Not exposed in map area, but present in subsurface near East Canyon graben (as Kfo and Kfl); subdivided into members by Hale (1960, 1962) and mapped as three members by Bryant (1990).

Kfo Oyster Ridge Sandstone - Subsurface unit shown on east end of cross-section C-C' (see also Bryant, 1990, cross-section C-C'). Light-yellow- to orange-gray, fine-grained, calcareous sandstone with local pebble layers and disarticulated pelecypod shells; thins northward in the Henefer area from 260 to 140 feet (80-43 m).

Kfl Lower members - Subsurface unit shown on east end of cross-section C-C' (see also Bryant, 1990, cross-section C-C'); about 3200 feet thick near Henefer and at least 4600 feet thick near Coalville (after Hale, 1960)

Kk Kelvin Formation (Lower Cretaceous-Albian/Aptian) - Best exposed east of Henefer, outside map area. Upper part mainly light-gray, tan, and light-reddish-gray, coarse-grained to pebbly sandstone; interbedded with gray, tan, and minor red and gray-green mudstone and siltstone; up to 2300 feet (700 m) thick (Eardley, 1944). Lower third dominantly red and tan mudstone and siltstone; contains thin, discontinuous beds of nodular, blue-gray and lavender, micritic limestone (Morrison of some workers); gray and red, coarse-grained to pebbly sandstone with reddish-gray, chert-pebble conglomerate toward base; up to 700 feet (210 m) thickness exposed (Eardley, 1944). Total Kelvin thickness near Henefer at least 5700 feet (1740 m), with base not exposed (Coogan, unpublished); estimate about 3000 feet (900 m) thickness penetrated in Richins well in East Canyon graben (adjusted for dip but eroded at top) and Bryant (1990) showed about 3500 feet (1070 m) in subsurface.

KXc Chloritic gneiss, cataclasite, mylonite, and phyllonite (Cretaceous and[?] Proterozoic) - Dark- to gray-green, variably fractured and altered rock in shear and fracture zones, and in diffuse altered zones associated with quartz pods; contains variable amounts of fine-grained, recrystallized chlorite, muscovite, and epidote (Yonkee, 1992; Yonkee and others, 1997); locally includes quartz veins (see Bryant, 1988, p. 5-6, 8; and in part his unit Afq); some linear zones of this unit mapped as faults by Bryant (1988); produced by mostly Cretaceous deformation and greenschist-facies alteration that overprints various Farmington Canyon complex protoliths (Yonkee and Lowe, 2004).

JURASSIC - Likely present in subsurface in an east-dipping homocline between southern Morgan Valley and East Canyon graben, as well as in East Canyon graben, possibly in an antiform (see Bryant, 1990, cross-section C-C'). The homocline is likely similar to that exposed near Devils Slide.

Jsp? Stump Sandstone and Preuss Redbeds, undivided (Upper and Middle Jurassic) - Poorly exposed with much of the material being reddish soil with no bedding; may be residual deposits above salt welt in East Canyon graben, hence the query on Wasatch Formation (Tw?/Jsp?); Stump and Preuss combined are about 1000 feet (300 m) thick to northeast (Coogan, 2004b). These units are aquitards. Stump is mostly reddish and greenish shale and calcareous sandstone; about 220 feet (67 m) thick to southeast near Peoa (Pipiringos and Imlay, 1979).

Jp Preuss Redbeds (Middle Jurassic) - Reddish sandstone, siltstone, and shale; poorly exposed near East Canyon fault; basal halite and lesser anhydrite in subsurface (unit Jps); about 900 feet (270 m) thick to northeast (Coogan, 2004b), and 1196 feet (365 m) thick to southeast near Peoa (Thomas and Krueger, 1946); subsurface thickness in East Canyon area about 900 to 1250 feet (275-380 m) [likely including Stump], with 0 to 700 feet (210 m) (Gulf Richins well) and possibly as much as 6000 to 7500 feet (1800-2300 m) of saline strata penetrated in Amoco Franklin Canyon well, but bed dips uncertain (Lamerson, 1982, p. 325; Utah DOGM website); see Yonkee and others (1997, figure 28) for complex interpretation of Franklin Canyon well.

Jtc Twin Creek Limestone (Middle Jurassic) - Mostly gray, shaly limestone, with some shale; well exposed in east-dipping homocline near Devils Slide, and >2722 feet (825 m) thick (Imlay, 1967); member thicknesses from Imlay (1967, p. 11, 13); descriptions and some thicknesses are from Coogan (2004b) to northeast in Lost Creek drainage. Subsurface extent north of Weber River uncertain (see Yonkee and others, 1997, figure 28). Boundary Ridge member aquitard separates Twin Creek Limestone into upper and lower aquifers, with porosity and permeability developed due to fracture cleavage. Some members are gas and oil reservoirs to the east near Utah-Wyoming border, due to cleavage permeability (see for example Yellow Creek field in Bruce, 1988).

Jtgl Giraffe Creek and Leeds Creek Members - Giraffe Creek is a gray, calcareous sandstone and lime grainstone that forms ridges; incompletely exposed at Devils Slide (Imlay, 1967) and thrust truncated; complete thickness about 225 feet (70 m) (Coogan, 2004b). Leeds Creek is a light-gray, clay-rich micritic limestone with tan silt partings that forms barren scree-covered slopes and locally exhibits bedding-normal pencil cleavage; 1289 feet (393 m) thick at Devils Slide (Imlay, 1967).

Jtw Watton Canyon Member - Dark-gray, lime micrite and wackestone and minor oolitic packstone that forms prominent ridges and locally exhibits bedding-normal stylolitic, spaced cleavage; 380 feet (115 m) thick at Devils Slide (Imlay, 1967).

Jtb Boundary Ridge Member - Gray, very thick bedded, ridge-forming, oolitic, lime grainstone to wackestone beds in middle and upper part that separate red and purple siltstone and gray, silty limestone beds in middle and lower part; about 100 feet (30 m) thick at Devils Slide (Imlay, 1967).

Jtrs Rich and Sliderock Members, undivided -

Rich Member - Light-gray, clay-rich, micritic limestone in upper part, and gray, lime wackestone in lower part; locally exhibits bedding-normal pencil cleavage; forms barren scree-covered slopes; 540 feet (165 m) thick at Devils Slide (Imlay, 1967).

Sliderock Member - Dark-gray, very thick bedded, lime wackestone in upper part and dark-gray, pelecypod and crinoid grainstone in lower part; forms small ridges; 100 feet (30 m) thick at Devils Slide (Imlay, 1967).

Jtgs Gypsum Spring Member - Red siltstone and sandstone, and gray, vuggy dolomite, with anhydrite in subsurface; up to 208 feet (65 m) thick at Devils Slide (Imlay, 1967).

Aquitard that separates lower Twin Creek aquifer from underlying Nugget Sandstone aquifer.

Jn Nugget Sandstone (Lower Jurassic) - Pale-, orangish- to pinkish-gray to locally white, well-cemented, cross-bedded, quartz sandstone; 1100 feet (335 m) thick to northeast at Toone Canyon, Lost Creek Dam quadrangle (Coogan, 2004b). Incompletely exposed near Quarry Hollow, Durst Mountain quadrangle (Coogan and King, 2006); subsurface extent between these exposures and Weber River is uncertain. High permeability in oil and gas fields to east near Utah-Wyoming border make this a target aquifer (see for example Lindquist, 1988; Sercombe, 1989).

TRIASSIC - Thickness estimates from Devils Slide quadrangle. Subsurface extent north of Weber River uncertain, but some units are exposed north of Elk Mountain (see Coogan and King, 2006). Likely present in east-dipping homocline in subsurface between southern Morgan Valley and East Canyon graben, as well as in East Canyon graben, possibly in an antiform (see Bryant, 1990). The homocline is likely similar to that exposed near Devils Slide.

TRa Ankareh Formation and other units, undivided (Triassic) - Upper Ankareh (Wood Shale Tongue) is bright-orange-red shale, siltstone, and sandstone (after Coogan, 2004a) that is an estimated 600 to 680 feet (180-210 m) near Devils Slide. Basal Ankareh (Lanes Tongue) is a purple and brownish-red shale, siltstone, and sandstone (after Coogan, 2004a) that is an estimated 600 to 725 feet (180-220 m) near Devils Slide. At Devils Slide, the middle unit is a thin, about 30 to 76 feet (9-23 m) thick, gritty sandstone (Shinarump of Scott, 1954, and Schick, 1955) or possibly a locally conglomeratic sandstone (Gartra Grit of Smith, 1969; Higham Grit of Coogan, 2004a). Total thickness estimated as ~1400 feet (425 m) near Devils Slide. TRa is an aquitard that separates Nugget Sandstone aquifer from Thaynes Formation mixed aquifer and aquitard.

TRt Thaynes Formation (Lower Triassic) - Regionally composed of brownish-gray and gray, calcareous siltstone to shale and silty limestone in upper and lower part, separated by resistant, gray, limestone ridge (see Kummel, 1954); mapped as undivided unit near Bennett Creek (see Coogan and King, 2006); regionally 1835 feet (560 m) thick in Lost Creek drainage (supercedes Coogan, 2004a), with the same thickness estimated near Devils Slide (not including upper tongue of Dinwoody). Some members are aquifers and others are aquitards, with the lower Thaynes limestone member and upper tongue of the Dinwoody Formation being the best aquifers.

Member descriptions from Lost Creek drainage (after Coogan, 2004a):

TRtu Upper calcareous siltstone member - Brownish-gray, thin-bedded, calcareous siltstone and thin-bedded, gray, fossiliferous limestone; an estimated 1040 feet (315 m) thick.

TRto Older members of Thaynes Formation and upper tongue of Dinwoody Formation, undivided - Cross section only.

TRtms Middle shale member - Gray, thin-bedded, calcareous, silty shale; an estimated 230 feet (70 m) thick.

TRtml Middle limestone member - Gray, very thick to medium-bedded, fossiliferous limestone; forms prominent ridge; an estimated 175 feet (50 m) thick.

TRtls Lower shale member - Gray to brownish-gray, thin-bedded, calcareous siltstone to silty shale; an estimated 140 feet (45 m) thick; lower half is likely reddish sandy siltstone of Decker Tongue of Ankareh Formation.

TRtd Lower limestone member of Thaynes Formation and upper tongue of Dinwoody Formation - Gray to grayish-brown, thick- to thin-bedded, fossiliferous limestone with *Meekoceras* ammonite zone at base of Thaynes underlain by less resistant, silty limestone and calcareous siltstone of upper tongue of Dinwoody Formation; an estimated 500 feet (150 m) thick.

TRwd Woodside Shale and Dinwoody Formation undivided - Cross section only.

TRw Woodside Shale (Lower Triassic) - Dark-red, sandy shale and siltstone, with some sandstone; an estimated 500 feet (150 m) thick near Devils Slide. This unit forms an aquitard between the overlying Thaynes and upper Dinwoody tongue limestone aquifer and underlying units.

TRd Dinwoody Formation (Lower Triassic) - Greenish-gray and tan, calcareous siltstone and silty limestone; an estimated 300 feet (90 m) thick near Devils Slide but contact with underlying Park City Formation uncertain. The main Dinwoody Formation acts as an aquitard and aquifer depending on the carbonate content and fracturing and overlies the upper Park City fractured aquifer.

PERMIAN - Exposed north of Weber River and east of Elk Mountain (Coogan and King, 2006), so likely present in subsurface beneath Wasatch Formation east of Elk and Durst Mountains. Also likely present in subsurface in: southern Morgan Valley; between southern Morgan Valley and East Canyon graben in an east-dipping homocline, like that exposed to the north near Devils Slide; and in subsurface in East Canyon graben, possibly in an antiform (see Bryant, 1990).

Pp Park City and Phosphoria Formations, undivided - Mostly gray, cherty limestone and calcareous to dolomitic sandstone, with lesser shale, dark-colored phosphatic shale and siltstone, and dark-colored bedded chert; total thickness near Sheep Herd Creek 675 feet (205 m) (Schell and Moore, 1970); total thickness near Devils Slide reported as 857 feet (260 m), but lower two units likely faulted (Cheney and others, 1953; Cheney, 1957), see also Williams (1943). Bryant (1990) showed unit as 1800 feet (600 m) thick on his cross section, but it is likely one-third that amount. Consists of: Franson Member of Park City and Rex Chert Member of Phosphoria, potential aquifer if fractured; the middle Meade Peak Phosphatic Shale Member of Phosphoria, likely an aquitard; and lower Grandeur Member of Park City, likely part of the Weber and Morgan mostly sandstone aquifer.

PERMIAN AND PENNSYLVANIAN - Exposed north of Weber River and east of Elk Mountain (Coogan and King, 2006), so likely present in subsurface beneath Wasatch Formation east of Elk and Durst Mountains. Also likely present in subsurface in: southern Morgan Valley; between southern Morgan Valley and East Canyon graben in an east-dipping homocline, like that exposed to the north near Morgan; and in subsurface in East Canyon graben, possibly in an antiform (see Bryant, 1990, IPw).

PIPw Weber Sandstone (Lower Permian and Pennsylvanian) - Gray, indurated, quartzose sandstone with dolomite and siltstone in lower part; reportedly 2500 to 3123 feet (760-952 m) thick near Morgan (Eardley, 1944; Bissell and Childs, 1958 [2260 feet Weber + 381 feet "Park City"]; Mullens and Laraway, 1973)(see also Williams, 1943), but reported thicknesses were likely measured across a back thrust.

PENNSYLVANIAN - Likely present in subsurface in southern Morgan Valley, and between southern Morgan Valley and East Canyon graben in an east-dipping homocline (see Bryant, 1990), like that exposed to the north near Morgan.

IPm Morgan Formation (Pennsylvanian) - Sandstone, siltstone, and limestone that grade northward into lower part of Weber Sandstone, "pinching" out to north (see Coogan and King, 2006) and reportedly not present to southwest near Salt Lake City (Bryant, 1990), but see unit IPr below; thrust faulted "into" Weber Sandstone rather than intertongued; queried on leading edge of west-directed back thrust where carbonate-bearing strata identified as Morgan might be in the lower Weber; 0 to 1000 feet (0-300 m) thick in Morgan area (Eardley, 1944; Bissell and Childs, 1958; Mullens and Laraway, 1973)(see also Williams, 1943).

IPr Round Valley Limestone (Pennsylvanian and possibly Mississippian) - Mostly light-gray, fine-grained limestone with regular bedding; about 375 to 400 feet (115-120 m) thick near Morgan (Crittenden, 1959; Mullens and Laraway, 1973). Bryant (1990) showed this unit as ~424 feet (130 m) thick on his map and ~700 feet (200 m) thick in his cross-section, but described it as ~1000 feet (300 m) thick and containing more clastic material; therefore his IPr unit may or may not contain Morgan Formation strata. Forms part of the lower Morgan, Round Valley, and upper Doughnut carbonate aquifer that is separated from the Mississippian carbonate aquifer by the lower Doughnut shale (Mdl) aquitard.

MISSISSIPPIAN - Likely present in subsurface in southern Morgan Valley, and at greater depths between southern Morgan Valley and East Canyon graben in an east-dipping homocline (see Bryant, 1990), like that exposed to the north near Morgan, though some unit names are different to southwest. Thickness estimates on Durst Mountain from Coogan and King (2006).

Mdo Doughnut Formation, undivided (Upper Mississippian) - Where possible divided into informal members of different lithologies.

Mdu Upper member - Limestone and siltstone; about 300 feet (90 m) thick on Durst Mountain (Crittenden, 1959; Mullens and Laraway, 1973; Coogan and King, 2006).

Mdl Lower, shale member - Siltstone, black shale, and limestone; typically poorly exposed and less resistant than adjacent map units; an estimated 200 feet (60 m) thick on Durst Mountain; shale may only be 33 to 100 feet (10-30 m) thick to southwest (see Bryant, 1990). Aquitard.

Mh Humbug Formation (Upper Mississippian) - Tan- to reddish- weathering, interbedded calcareous to dolomitic, quartzose sandstone, and sandy limestone and dolomite; lower part contains more sandstone and is less resistant than upper part; estimate total thickness as 700 feet (215 m) on Durst Mountain. Map unit likely contains about 300 feet (90 m) of Deseret Limestone in Snow Basin quadrangle, and elsewhere contact with Deseret may not be consistent. Regionally Humbug, Deseret, and Lodgepole Formations contain karst (see for example White, 1979) and are a Mississippian carbonate aquifer; the only indication of such karst (springs or sinkholes) in study area are Como Springs, issuing from the lower Humbug Formation; recharge area for Como Springs is uncertain.

Mde Deseret Limestone (Mississippian) - Limestone, dolomite, and sandstone, with dark, less-resistant, shaly, phosphatic strata at base (Delle Phosphatic Shale Member); about 500 feet (150 m) thick in Morgan quadrangle (Mullens and Laraway, 1973) and estimated on Durst Mountain.

Ml Lodgepole Limestone (Lower Mississippian) - Gray, fossiliferous limestone and lesser dolomitic limestone, locally cherty; estimate thickness as 650 feet (200 m) on Durst Mountain; called Gardison Limestone to west in Ogden Canyon area (Sorensen and Crittenden, 1972; Yonkee and Lowe, 2004; King and others, 2008). To southwest near Salt Lake City, this unit is shown as Gardison Limestone (Mg) by Bryant (1990). Sinkhole fill mapped in the Gardison and underlying Pinyon Peak Limestone by Van Horn and Crittenden (1987).

DEVONIAN - Descriptions and thicknesses for Beirdneau, Hyrum, and Water Canyon Formations on Durst Mountain are from Coogan and King (2006). Similar Devonian rocks are likely present in subsurface in southern Morgan Valley, but unit names, ages, and exact rock types change to southwest (see Bryant, 1990; and Pinyon Peak and Stansbury units below), so Dx has been used on cross section C-C'. With the exception of the Ophir Formation (an aquitard), Devonian and Cambrian strata are a mixed sandstone and carbonate aquifer.

Dp Pinyon Peak Limestone - Pale tan to gray, thin-bedded nodular limestone containing gray shale interbeds; overlies Stansbury Formation near Salt Lake City; reportedly 165 to 200 feet (50-60 m) thick, but shown as 300 feet (90 m) thick in cross section (see Bryant, 1990); mostly younger than Beirdneau Sandstone.

Ds Stansbury Formation - Light-gray to yellowish-gray, calcareous sandstone and siltstone, and silty limestone; some reddish shale; basal pale-gray to white laminated dolomite, dark-gray dolomite, and quartzite bed; unconformably overlies Maxfield(?) Formation since older Devonian, Silurian, and Ordovician rocks missing; reportedly ~500 feet (150 m) thick, but shown as 300 feet (90 m) thick in cross section (see Bryant, 1990); roughly the same age as the Beirdneau Sandstone and contains similar rock types.

Db Beirdneau Sandstone - Reddish-tan to tan to yellowish-gray, calcareous sandstone and siltstone, some silty to sandy dolomite and limestone, and lesser intraformational (flat-pebble) conglomerate; less resistant than adjacent map units; estimated thickness ~200 to 300 feet (60-90 m) on Durst Mountain; in Ogden Canyon area, likely 250 to 300 feet (75-90 m) thick (see Sorensen and Crittenden, 1972, 1974). Contact with Hyrum Dolomite does not appear to be mapped at consistent horizon.

Dhw Hyrum and Water Canyon Formations, undivided - Subdivided where possible into:

Dh Hyrum Dolomite - Brownish-gray and gray dolomite and minor limestone; more resistant at top and bottom with center of less resistant beds that grade laterally into reddish, dirty carbonate like the Beirdneau Sandstone; estimated thickness 250 to 450 feet (75-140 m) on Durst Mountain; about 200 to 350 feet (60-107 m) thick near Ogden Canyon (after Sorensen and Crittenden, 1972, 1974; Yonkee and Lowe, 2004); unconformably overlies Water Canyon Formation.

Dwc Water Canyon Formation - Light-yellow-gray to medium-gray, interbedded calcareous sandstone and silty to sandy dolomite and limestone, with sandstone below carbonate; less resistant than underlying and overlying units; estimate 200 feet (60 m) thick on Durst Mountain; 30 to 100 feet (9-30 m) thick in Ogden Canyon area (Yonkee and Lowe, 2004), and about 100 to 150 feet (30-45 m) thick to northeast on leading edge of Willard thrust sheet (Coogan, 2006a,b).

SILURIAN and ORDOVICIAN - Missing on Durst Mountain, along with all or most(?) of St. Charles Formation equivalent strata (uppermost Cambrian), due to thinning over Tooele arch and/or Stansbury uplift (see Hintze, 1959 and Rigby, 1959, respectively). Note that about 15 miles (25 km) to the northwest in Ogden Canyon, 1000 feet (300 m) of Ordovician and upper Cambrian strata are present (Fish Haven, Garden City, and St. Charles Formations), as is part of the Bloomington Formation between the Nounan and Maxfield Formations. The Nounan and Maxfield are also thicker in Ogden Canyon, though the Ophir and Tintic are about the same thickness (see Yonkee and Lowe, 2004). To southwest near Salt Lake City, Silurian and Ordovician rocks, and the Cambrian St. Charles, Nounan, and Bloomington Formations are reportedly missing (Bryant, 1990).

ORDOVICIAN

Ofg Fish Haven and Garden City Formations - Mapped near Ogden Canyon.

Fish Haven Dolomite - Medium- to dark-gray, cliff-forming dolomite; likely 200 to 225 feet (60-70 m) thick (see Sorensen and Crittenden, 1972, 1974); unconformably overlies Garden City with Swan Peak Quartzite missing, an effect of the Ordovician Tooele arch (see Hintze, 1959).

Ogc Garden City Formation - Pale-gray to buff-weathering, ledge- and slope-forming dolomite, silty dolomite and limestone, and minor siltstone; about 200 to 400 feet (60-120 m) thick (Yonkee and Lowe, 2004).

ORDOVICIAN AND CAMBRIAN

Csb St. Charles, Nounan, and Bloomington Formations, undivided - Mapped near Ogden Canyon; Nounan Formation mapped separately on Durst Mountain where St. Charles and Bloomington Formations are missing.

St. Charles Formation - Light- to medium-gray, cliff-forming dolomite; 400 to 660 feet (120-200 m) thick in Ogden Canyon area (after Rigo, 1968; Sorensen and Crittenden, 1972, 1974).

CAMBRIAN - Units below Bloomington Formation are likely present in subsurface in southern Morgan Valley (see Bryant, 1990). However, units may not be directly comparable; Bryant's (1990) Ophir may only be the lower shale member of the Ophir as mapped to the north. Overall units are thinner on Durst Mountain than in Wasatch Mountains.

Cn Nounan Formation (Upper and Middle Cambrian) - Medium-gray, typically thick-bedded, cliff-forming dolomite and some limestone; estimate 350 to 400 feet (105-120 m) thick (see Coogan and King, 2006) on Durst Mountain; about 500 to 750 feet (150-230 m) thick in Ogden Canyon area (Yonkee and Lowe, 2004).

Bloomington Formation - Not mapped separately. Brown-weathering, gray to olive-gray, silty argillite interlayered with gray- to yellowish- and orangish-gray-weathering, thin- to medium-bedded, silty limestone, flat-pebble conglomerate, nodular limestone, and wavy-bedded (ribbon) limestone; slope-forming; lithologically similar to Calls Fort (upper) and Hodges (lower) Shale Members of Bloomington Formation (King and others, 2008); apparent thicknesses of 40 to 200 feet (10-60 m)(after Sorensen and Crittenden, 1972; Yonkee and Lowe, 2004).

Cm Maxfield Limestone (Middle Cambrian) - From top down includes dolomite, limestone, argillaceous to silty limestone and calcareous siltstone and argillite, and basal limestone with argillaceous interval; about 600 to 900 feet (180-270 m) thick in Wasatch Mountains (Rigo, 1968; after Yonkee and Lowe, 2004) but only 300 feet (90 m) thick on Durst

Mountain (Coogan and King, 2006). Cambrian limestone of Mullens and Laraway (1973) includes Maxfield and upper two members of Ophir Formation. Because he reported a thickness of 1180 feet (360 m) and showed ~1400 feet (425 m) on his cross section, the Maxfield of Bryant (1990) may include upper members of the Ophir Formation and/or the Nounan Formation. The Maxfield contains a sinkhole, indicating karst formation, in both the Snow Basin and Durst Mountain quadrangles.

Co Ophir Formation, undivided (Middle Cambrian) - Consists of upper and lower brown-weathering, slope-forming (rarely exposed), gray to olive-gray, variably calcareous and micaceous to silty argillite to slate with intercalated gray, silty limestone beds; middle ledge-forming, gray, micritic limestone. Highly deformed in most outcrops causing highly variable apparent thicknesses, but estimate at least 440 to 725 feet (135-220 m) thick on Durst Mountain (Coogan and King, 2006); about 300 to 660 feet (90-200 m) thick in Wasatch Mountains (Sorensen and Crittenden, 1972; Yonkee and Lowe, 2004). Ophir of Eardley (1944) and Mullens and Laraway (1973) is only the lower argillite member. Ophir of Bryant (1990) may or may not include upper members because he reported a thickness of about 200 feet (60 m) but showed a cross-section thickness of 400 feet (120 m). Upper Ophir contains a sinkhole in Durst Mountain quadrangle, but overall an aquitard separating the overlying Devonian and Cambrian mixed aquifer from the Cambrian Tintic Quartzite, which contains water only where extensively fractured.

Ct Tintic Quartzite (Middle and (?)Lower Cambrian) - Tan-weathering, cliff-forming, very well-cemented quartzite, with lenses and beds of quartz-pebble conglomerate, and lesser thin argillite layers; argillite more abundant at top and quartz-pebble conglomerate increases downward; greenish to purplish to tan, arkosic sandstone, conglomerate, and micaceous argillite at base that is 50 to 200 feet (15-60 m) thick (see for example Yonkee and Lowe, 2004) and derived from unconformably underlying Farmington Canyon Complex; about 1100 to 1500 feet (335-450 m) thick in Wasatch Mountains (Sorensen and Crittenden, 1972; Yonkee and Lowe, 2004; King and others, 2008) and 800 to 1000 feet (245-300 m) thick on Durst Mountain (after Eardley, 1944; Mullens and Laraway, 1973). Highly fractured along fault zone on west side of Elk Mountain and Durst Mountain (east side of Morgan Valley) and knob on Durst Mountain-Snow Basin quadrangles boundary. Due to cementation, this quartzite contains water only where extensively fractured.

PROTEROZOIC

Xfc Farmington Canyon Complex, undivided (Paleoproterozoic) - Granitic and migmatitic gneiss with quartz-rich gneiss and biotite-rich schist, and lesser meta-gabbro, amphibolite, and meta-ultramafic rock; includes small mafic and pegmatitic pods and dikes; queried where identification uncertain. Barnett and others (1993) reported the various isotopic ages of the Complex and concluded it was Paleoproterozoic (about 1700 Ma) in age. More detailed information on the Complex is available in Bryant (1988) and

Yonkee and Lowe (2004). The Farmington Canyon Complex is locally an aquifer where extensively fractured, but is typically altered to clays that inhibit permeability and porosity. Undivided unit of micaceous schistose and gneissic rocks mapped on Durst Mountain and in Wasatch Mountains, roughly south of Farmington Canyon; where possible divided into:

Xfcq Quartzite, schist, and gneiss - Mapped by Bryant (1988, 1990) as separate unit mostly in gradational contact with undivided Farmington Canyon Complex (Xfc), except on east margin of Xfcq, as quartzite content decreases; quartzite dominates much of Xfcq and is white to light greenish-gray layers as much as 30 feet (10 m) thick; quartzite composed of interlocking, recrystallized quartz grains and some light-green muscovite (Bryant, 1988).

Xfcm Migmatitic gneiss - Medium- to light-pink-gray, strongly foliated and layered (migmatitic) quartzo-feldspathic rock with widespread garnet and biotite; cut by variably deformed pegmatite dikes; unit also contains widespread amphibolite bodies, granitic gneiss pods, and some thin layers of sillimanite-bearing, biotite-rich schist; contact with granitic gneiss is gradational (after Yonkee and Lowe, 2004) and migmatitic gneiss seems to be interlayered with granitic gneiss (King and others, 2008); queried where identification uncertain. Contact between migmatitic gneiss and undivided Farmington Canyon complex (Xfc) on this map is south of Bryant's (1988, 1990) contact and is based on change in weathering from less resistant to north to more resistant with lighter colored ribs (strongly foliated) to south.

Xfcb Biotite-rich schist - Medium-gray to dark-brown, strongly foliated, biotite-rich schist with widespread garnet and sillimanite; displays alternating biotite-rich and quartz-feldspar-rich bands; cut by variably deformed, garnet-bearing pegmatite dikes; schist also contains some thin layers of amphibolite, quartz-rich gneiss, and granitic gneiss; gradational contacts with migmatitic gneiss (after Yonkee and Lowe, 2004).

Xfcg Granitic gneiss - Light- to pink-gray, moderately to strongly foliated, fine- to medium-crystalline, hornblende-bearing, quartzo-feldspathic rock with minor orthopyroxene; cut by variably deformed, light-colored, pegmatite dikes; also contains widespread, small pods of amphibolite; contact with migmatitic gneiss is gradational (after Yonkee and Lowe, 2004) and seems to be interlayered with migmatitic gneiss (King and others, 2008).

WILLARD THRUST SHEET

Present in the northeast part of map area, mostly in subsurface (see cross section A-A’); partly exposed in map area in Durst Mountain quadrangle (units Zm, Zi, Zcc, Zkc) and Snow Basin quadrangle (unit ZYp) and better exposed to north in Browns Hole, Causey Dam, and Horse Ridge quadrangles. Lithologic information on these thrust sheet exposures is summarized in figure 10.

The thrust sheet is folded into a broad synform with a hinge roughly west of Herd Mountain and likely plunging to the north; this would funnel water to the north, out of the study area. Called Causey syncline by Yonkee (1997), but the synform roughly aligns with the Beaver Creek Syncline, previously named by Mullens (1969). As mapped by Mullens (1969) the synform is complicated by numerous small folds and faults. Because these exposed structures may not extend as far south as the study area and the cross section A-A' is generalized, no such minor structures are shown on A-A'.

The Willard thrust sheet likely ramps upward to the south into the study area because mapping by Coogan (2006a,b) shows that it ramps upward to the south along its leading edge from the Proterozoic quartzites in the Dairy Ridge quadrangle to the Cambrian carbonate rocks in the Horse Ridge quadrangle (Coogan, 2006a,b). The synform appears to plunge to the north, because units as young as Permian are exposed to the north in the Causey Dam quadrangle (see Mullens, 1969) and units that young will not fit in the syncline in subsurface to the south in the study area (see following discussion). Strata as young as the Mississippian Lodgepole Limestone may be present in the syncline in the map area north of cross-section A-A', because the Lodgepole is exposed nearby (see Mullens, 1969; Coogan and King, 2001). The Kelley Canyon Formation (Zkc), older than the oldest Proterozoic quartzite (Zcc), is exposed on the west side of the thrust sheet in the Durst Mountain quadrangle, so it is likely present in subsurface north of cross-section A-A'. Based on exposures in the Horse Ridge quadrangle (see Coogan, 2006a,b), a splay of the Willard thrust may be present on the eastern edge of the Willard thrust. This splay is shown on cross-section A-A’ as containing Mississippian through Silurian strata (unit MDS).

Exactly which units are present in subsurface below the Evanston (Keh) and Wasatch (Tw) Formations in the study area on the folded thrust sheet is uncertain. At cross-section A-A’ only Cambrian and Proterozoic quartzite strata (CZq) may be present. Alternatively, rocks as young as Mississippian might be present in the study area. In subsurface in the study area, there should be less than ~6500 feet (2000 m) of Cambrian and Proterozoic quartzite strata in the syncline (mostly Geertsen Canyon, Mutual, and Caddy Canyon quartzites), with Proterozoic (unit Zkc) below quartzite strata faulted out (see Yonkee, 1997, figure 17; Yonkee and others, 1997, figure 28 unit CZ). These CZ strata are likely less than 5000 feet (1500 m) thick on the leading edge of the Willard thrust sheet (see Coogan, 2006a,b).

In addition to the CZ strata, cross section A-A’ shows some Ordovician and Cambrian (OCc) strata in the syncline and a dip between 45 and 50 degrees. With the lower (45 degree) dip, only 0 to 1500 feet (0-450 m) of space is available in the upper part of the syncline in subsurface in the study area at cross-section A-A’. In which case only Cambrian and Proterozoic quartzite (CZq) strata is in the syncline or, at most, the Blacksmith and older Cambrian formations would fit in the available subsurface space.

James C. Coogan, a co-author in Yonkee and others (1997), produced an unpublished, larger (1:100,000 scale) version of their figure 28, which crosses the study area and presents an alternative subsurface interpretation. This cross section shows almost 4000 feet (1200 m) of M-O-D-C (Mississippian through Cambrian, mostly carbonate) unit, with about 10,000 feet (3000 m) of underlying CZ quartzite, and no overlying Permian and Pennsylvanian strata. So if the CZ unit is only about 6000 feet (1800 m) thick, there is room for at least 7000 feet (2100 m) of M-C strata. This would enable most of the Mississippian, Little Flat (Mlf) and older, and all the Devonian strata, as well as the Silurian and older strata to fit in the available subsurface space in the syncline. Therefore, the Mississippian and older units, as exposed to the north, are summarized in the lithologic column. Although it is unlikely that strata as young as Permian and Pennsylvanian, and Mississippian Monroe Canyon Limestone (Mmc) are present on the concealed folded Willard thrust sheet in the map area, they are included in figure 10, because their unique characteristics should be easily identifiable in reverse-circulation cuttings.

CAMBRIAN Shown as unit Cc in subsurface this report; see figures 9 and 10 for formations.

PROTEROZOIC - Several units exposed in map area in Durst Mountain quadrangle. In subsurface included in unit CZq. Inkom Formation may be missing and other units likely thinner (compare Coogan, 2006a,b, to Crittenden and others, 1971).

Browns Hole Formation (upper Proterozoic) - Not exposed in map area; just to north brownish to purplish red (hematitic), mostly volcanic sandstone with some argillite;

characteristic volcanic material decreases to south so only traces near South Fork of Ogden River, Browns Hole quadrangle; 20 to 200 feet (6-60 m) thick to east on Willard thrust sheet (Coogan, 2006a,b), and 180 to 460 feet (55-140 m) thick near Huntsville (Crittenden and others, 1971).

Zm Mutual Formation (upper Proterozoic) - Grayish-red, pink, tan, light-gray and purplish, thick- to very thick bedded, quartzite with pebble conglomerate and argillite lenses, locally arkosic [feldspathic] (Crittenden and others, 1971); reportedly 435 to 1200 feet (130-370 m) thick in Browns Hole quadrangle (Crittenden, 1972) but thinnest near South Fork Ogden River and also at least as thin to northeast on Willard thrust sheet (see Coogan, 2006a,b).

Zi Inkom Formation (upper Proterozoic) - Near South Fork of Ogden River, mostly micaceous and red, argillite to psammite (meta-sandstone over meta-siltstone); about half as thick as near Huntsville with gray-green lower part mostly missing; 360 to 450 feet (110-140 m) total thickness near Huntsville (Crittenden and others, 1971); not present to east on Willard thrust sheet (see Coogan, 2006a,b).

Zcc Caddy Canyon Quartzite (upper Proterozoic) - Mostly vitreous, almost white, cliff-forming quartzite; lower contact with Kelley Canyon is gradational with brownish quartzite beds and argillite over a few tens of to 200 feet; 1500 feet (460 m) thick near South Fork of Ogden River and thickening to north (Crittenden and others, 1971);

appears to thin to northeast on Willard thrust sheet where undivided Mutual-Caddy Canyon quartzite (Zmc) is about 1000 feet (300 m) thick (see Coogan, 2006a,b).

Zkc Kelley Canyon Formation (upper Proterozoic) - Gray to olive-gray argillite to phyllite, with rare meta-carbonate; contains much interbedded quartzite grading into overlying Caddy Canyon Quartzite near Huntsville; reportedly has basal thin (10 foot) bed of tan-weathering dolomite overlain by variegated argillite and locally thin beds of greenish fine-grained sandstone; 2000 feet (610 m) thick near Huntsville (Crittenden and others, 1971, figure 7) and may thin to east on Willard thrust sheet (see Coogan, 2006a,b). Underlain by heterolithic Maple Canyon Formation in Huntsville quadrangle (see Crittenden and others, 1971; Crittenden, 1972; Sorensen and Crittenden, 1979), but Maple Canyon Formation likely not present in map area.

ZYp Formation of Perry Canyon (upper and possibly middle Proterozoic) - Only exposed in Snow Basin quadrangle and may not extend in subsurface into study area. Slate to micaceous argillite and meta-sandstone to meta-gritstone to meta-diamictite; typically non-resistant and tan weathering such that gray to green to dark-gray fresh color is seldom seen (see Crittenden and Sorensen, 1985); previously mapped as graywacke member of Maple Canyon Formation, with 1500 feet (460 m) thickness reported in Huntsville quadrangle by Sorensen and Crittenden (1979); in Snow Basin area includes phyllite that weathers to impermeable clay that is prone to landsliding; likely less than 2000 feet (600 m) thick.

APPENDIX E

AQUIFER PROPERTIES DATA

Table E1. *Summary of drillers' log data and estimated aquifer properties for the valley-fill aquifer in Morgan Valley, Utah County, Utah.*

Table E1. *Summary of drillers' log data and estimated aquifer properties for the valley-fill aquifer in Morgan Valley, Utah County, Utah.*

Well Location Data						*Well Field Data*										
Label_ID	WIN	X	Y	Well elevation	Well_PLSID	Well depth	Well diameter	Drilling date	Water level at drilling	Depth to Water at drilling	Well Test method	Pumping rate	Test duration	Draw down	Water depth intake
		NAD27_m	NAD27_m	feet		feet	inch		feet	feet		gpm	hours	feet	feet
1	4820	433023	4554678	4881	N 700 W 500 E4 26 5N 1E SL B&M	72	6	10/03/1983	4869	12	Bail	14.8	1	15	67
2	4946	435149	4553811	4910	N 600 E 1250 SW 30 5N 2E SL B&M	137	6	03/21/1994	4901	9	Pump	30.1	36	60	78
3	14584	435363	4554546	4944	N 350 E 1930 W4 30 5N 2E SL B&M	155	6	02/04/1997	4934	9	Bail	23.8	1	3	85
4	7185	435632	4550832	4900	N 1893 W 381 S4 06 4N 2E SL B&M	109	12	07/25/1967	4898	3	Pump	317.0	6	43	92
5	33516	435714	4555758	4990	S 4025 W 1840 NE 19 5N 2E SL B&M	189	8	01/00/1973	4974	16	Pump	60.0	2	25	105
6	11794	436531	4548966	4999	N 739 E 350 SW 08 4N 2E SL B&M	135	4	05/27/1996	4964	35	Bail	20.2	1	15	105
7	26213	437234	4551395	5003	N 3380 E 2700 SW 05 4N 2E SL B&M	200	6	11/12/2002	4917	86	Pump	49.8	1	19	154
8	14106	437236	4551236	4974	N 2860 E 2705 SW 05 4N 2E SL B&M	174	6	10/15/1996	4914	60	Bail	17.1	1	19	152
9	19639	437355	4550895	4964	S 800 W 2320 E4 05 4N 2E SL B&M	181	6	07/15/1999	4907	57	Pump	44.9	2	5	170
10	10411	437371	4547858	5013	N 2456 W 2075 SE 17 4N 2E SL B&M	170	6	09/15/1986	4971	42	Bail	25.1	1	15	161
11	22406	437531	4550683	4950	N 1128 W 1705 SE 05 4N 2E SL B&M	174	8	08/08/2000	4904	46	Pump	140.0	2	22	164
12	16437	437719	4550687	4956	N 1100 E 1600 S4 05 4N 2E SL B&M	150	6	10/01/1997	4913	43	Bail	22.0	1	15	142
13	18305	437980	4546341	4999	N 100 W 60 E4 20 4N 2E SL B&M	158	4	11/23/1998	4973	26	Pump	35.0	1.5	75	108
14	14704	438135	4546417	4993	N 350 E 450 W4 21 4N 2E SL B&M	164	6	04/25/1997	4971	22	Bail	20.2	1	5	157
15	12137	438204	4549928	4967	S 1350 E 500 NW 09 4N 2E SL B&M	165	6	06/29/1996	4933	34	Bail	60.1	1	10	160
16	2901	438219	4550354	5018	N 50 E 550 SW 04 4N 2E SL B&M	150	4	07/07/1993	4948	70	Bail	14.8	1	15	131
17	26602	438356	4548777	4964	N 140 W 1556 S4 09 4N 2E SL B&M	110	6	02/13/2003	4931	33	Pump	79.9	1.5	22	108
18	1660	438412	4543793	5156	S 280 E 1175 N4 33 4N 2E SL B&M	108	6	12/02/1992	5141	15	Pump	35.0	2	60	104
19	6423	438422	4545855	5025	N 1130 E 1410 SW 21 4N 2E SL B&M	81	6	06/09/1994	5005	20	Bail	39.9	1	2	75
20	145	438462	4545743	5035	N 760 E 1540 SW 21 4N 2E SL B&M	109	6	03/17/1992	5000	35	Pump	44.9	3	50	104
21	9618	438498	4549149	4984	N 1350 E 1575 SW 09 4N 2E SL B&M	151	6	08/03/1995	4946	38	Pump	35.0	3	12	141
22	16051	438554	4545525	5003	N 47 E 1843 SW 21 4N 2E SL B&M	100	6	07/25/1997	4979	24	Bail	39.9	1	10	97
23	1664	438706	4545579	5007	N 222 E 2340 SW 21 4N 2E SL B&M	82	6	03/30/1992	4806	201	Bail	14.8	1	18	75
24	1962	438744	4544719	5035	N 2756 W 86 S4 28 4N 2E SL B&M	50	6	01/28/1993	5008	27	Pump	49.8	2	1	35
25	5941	439149	4545778	4986	N 915 W 1361 SE 21 4N 2E SL B&M	80	6	04/22/1994	4982	4	Pump	39.9	1	9	76
26	16657	439203	4547678	4977	N 1970 W 1300 SE 16 4N 2E SL B&M	110	6	12/1/1997	4963	14	Bail	22.0	1	6	106
27	22065	439259	4545895	4987	S 1292 W 1058 E4 21 4N 2E SL B&M	90	6	06/12/2000	4983	4	Pump	60.1	2.5	15	86
28	430951	439286	4545847	4986	N 1141 W 912 SE 21 4N 2E SL B&M	107.5	6	01/09/2008	4980	6	Bail	60.0	1	16	96
29	17141	439393	4543506	5036	S 1200 W 580 E4 33 4N 2E SL B&M	101	6	03/20/1998	5017	19	Pump	35.0	1	1	95
30	23643	439468	4547608	5069	N 1740 W 430 SE 16 4N 2E SL B&M	160	6	09/09/1987	5004	65	Bail	20.2	1	30	152
31	1681	439599	4543123	5059	N 200 E 109 W4 34 4N 2E SL B&M	68	4	5/15/1992	5031	28	Bail	39.9	2	3	39
32	19475	439672	4543382	5036	N 1050 E 350 SW 34 4N 2E SL B&M	116	6	06/09/1999	5016	20	Bail	44.9	1	4	108
33	23604	439717	4545874	4990	N 1230 E 500 SW 22 4N 2E SL B&M	118	6	07/20/1987	4982	8	Bail	30.1	1	2	105
34	8911	439938	4543120	5039	N 190 E 1223 W4 34 4N 2E SL B&M	49	6	05/05/1995	5014	25	Pump	39.9	2	1	34
35	9203	439973	4542613	5121	N 1180 E 1350 SW 34 4N 2E SL B&M	247	6	06/26/1995	5037	84	Pump	22.0	3	102	222
36	5809	440051	4543043	5039	N 2620 W 1042 S4 34 4N 2E SL B&M	40	6	03/28/1994	5015	24	Pump	39.9	1	1	34
37	10651	440052	4546871	5043	S 690 W 1161 N4 22 4N 2E SL B&M	204	6	09/10/1995	4997	46	Bail	25.1	6	35	156
38	23603	440110	4542939	5043	N 2250 E 1800 SW 34 4N 2E SL B&M	111	6	10/01/1987	5023	20	Bail	25.1	1	10	101
39	211	440183	4546394	5003	N 369 W 3353 E4 22 4N 2E SL B&M	91	6	05/04/1992	4976	27	Pump	39.9	1	10	88
40	8478	440248	4546620	5062	S 1515 W 520 N4 22 4N 2E SL B&M	73	6	03/03/1995	5022	40	Bail	44.9	1	8	69

Drillers' well logs were taken from Utah Division of Water Rights Website; http://www.waterrights.utah.gov/wellinfo/wellsearch.asp

*Sy is integrated from Johnson (1967) and Ss is integrated from Domenico (1972). Aquifer Storativity (S) was estimated based on the formula S=Sy+Ss*b ; where Sy is the average specific yield, Ss is the average specific storage, and b is the saturated screen length.*

Transmissivity was estimated using TGUESS Algorithm adopted by Bradbury and Rothschild (1985) which is a Cooper-Jacob approximation of the Theis equation

Table E1. (Continued).

Well Location Data						*Well Field Data*									
Label_ID	**WIN**	**X**	**Y**	**Well elevation**	**Well_PLSID**	**Well depth**	**Well diameter**	**Drilling date**	**Water level at drilling**	**Depth to Water at drilling**	**Well Test method**	**Pumping rate**	**Test duration**	**Draw down**	**Water depth intake**
		NAD27_m	NAD27_m	feet		feet	inch		feet	feet		gpm	hours	feet	feet
41	826	440319	4545564	5003	N 250 W 200 S4 22 4N 2E SL B&M	74	6	08/12/1992	4999	4	Pump	75.0	3	20.6	69
42	14388	440490	4542646	5043	N 1320 E 400 S4 34 4N 2E SL B&M	117	6	11/11/1996	5015	28	Bail	44.9	1	5	100
43	17666	440878	4544336	5023	N 1580 W 1020 SE 27 4N 2E SL B&M	155	6	07/01/1998	4988	35	Bail	22.0	1	21	145
44	7526	440887	4544078	5023	N 735 W 990 SE 27 4N 2E SL B&M	81	6	10/20/1994	5016	7	Bail	60.1	1	5	76
45	23023	440956	4542608	5046	N 1225 W 720 SE 34 4N 2E SL B&M	130	6	11/13/2000	5031	15	Bail	39.9	1	5	120
46	10021	440969	4543915	5023	N 200 W 720 SE 27 4N 2E SL B&M	91	6	08/21/1995	5023	0	Pump	35.0	2	10	85
47	431381	441045	4545845	5041	N 1208 W 498 SE 22 4N 2E SL B&M	126	4.5	05/21/2008	4998	43	Bail	50.0	1	3	95
48	35333	441082	4545850	5061	N 1225 W 375 SE 22 4N 2E SL B&M	126	4.5	04/13/2006	5020	41	Bail	50.0	1	3	87
49	8787	441092	4543896	5023	N 138 W 317 SE 27 4N 2E SL B&M	90	6	04/20/1995	5012	11	Pump	38.2	2	9	85
50	8572	441188	4543931	5026	N 250 0 SE 27 4N 2E SL B&M	120	6	03/1 /1995	5017	9	Bail	30.1	1	3	115
51	8338	441249	4544007	5023	N 500 E 200 SW 26 4N 2E SL B&M	120	6	03/1 /1995	5009	14	Bail	25.1	1	3	115
52	24228	441298	4543329	5039	N 3590 E 400 SE 34 4N 2E SL B&M	140	6	09/17/2001	5027	12	Bail	9.9	1	20	110
53	24984	441766	4542352	5056	N 383 E 1937 SW 35 4N 2E SL B&M	121	8	04/01/2002	5030	26	Pump	60.1	2	3	98
54	25358	441909	4534645	5376	S 3690 W 2740 NE 26 3N 2E SL B&M	75.5	6	03/07/2002	5325	51	Pump	25.1	1	20	40
55	1989	441939	4541926	5069	S 1000 W 150 N4 02 3N 2E SL B&M	142	6	03/09/1993	5031	38	Pump	14.8	2.5	80	137
56	30020	441946	4543424	5045	S 1412 E 2485 NW 35 4N 2E SL B&M	200	16	10/15/2004	5027	18	Pump	1500.0	12	65	153
57	12395	442017	4537564	5177	N 500 E 200 S4 14 3N 2E SL B&M	116	6	07/23/1996	5145	32	Bail	44.9	1	70	96
58	23549	442046	4542231	5059	0 E 200 N4 02 3N 2E SL B&M	102	6	07/1/1987	5040	19	Bail	25.1	1	6	99
59	17240	442147	4538332	5171	S 2249 E 3243 NW 14 3N 2E SL B&M	118	6	04/30/1998	5116	55	Bail	39.9	1	1	80
60	15662	442432	4539717	5095	N 2295 W 1088 SE 11 3N 2E SL B&M	115	6	07/15/1997	5081	14	Bail	20.2	1	20	107
61	20141	442472	4536936	5190	S 1550 W 900 NE 23 3N 2E SL B&M	128	6	09/20/1999	5143	47	Bail	48.0	1	8	95
62	595	442660	4536272	5241	N 1650 W 275 SE 23 3N 2E SL B&M	205	4	07/28/1992	5152	89	Pump	30.0	3	66	128
63	14681	442683	4536745	5187	N 3200 W 200 SE 23 3N 2E SL B&M	135	6	01/15/1997	5132	55	Bail	17.1	1	4	105
64	17016	442688	4536151	5240	N 980 W 340 SE 23 3N 2E SL B&M	127	6	03/15/1998	5165	75	Bail	22.0	1	5	105
65	17933	442718	4542897	5059	N 2200 W 250 S4 35 4N 2E SL B&M	120	8	09/01/1998	5045	14	Bail	25.1	1	2	110
66	16219	442799	4535731	5269	S 128 E 183 NW 25 3N 2E SL B&M	132	6	09/01/1997	5217	52	Bail	25.1	1	20	102
67	8319	442952	4536790	5148	N 660 E 680 W4 24 3N 2E SL B&M	115	6	02/10/1995	5136	12	Pump	42.2	1	5	75
68	8039	442972	4537378	5240	S 100 W 1867 N4 24 3N 2E SL B&M	51	6	12/28/1994	5209	31	Bail	39.9	1	1	48
69	6858	443031	4537282	5163	S 400 E 950 NW 24 3N 2E SL B&M	71	6	07/31/1994	5138	25	Pump	43.1	1	1	61
70	430240	443077	4540848	5081	N 707 E 1015 SW 01 3N 2E SL B&M	130	8	07/19/2007	5060	21	Bail	10.0	1	40	115
71	7837	443170	4541190	5082	N 1830 E 1300 SW 01 3N 2E SL B&M	91	6	12/02/1994	5064	18	Bail	60.1	1	4	88
72	2671	443251	4541525	5092	S 2300 E 1500 NW 01 3N 2E SL B&M	91	6	04/08/1993	5068	24	Pump	39.9	2	2	80
73	2000	443273	4541592	5082	S 2080 E 1570 NW 01 3N 2E SL B&M	105	6	03/16/1993	5066	16	Bail	31.9	2	5	100
74	18699	443347	4536014	5174	N 780 W 680 S4 24 3N 2E SL B&M	118	6	03/18/1999	5150	24	Bail	44.9	1	5	98
75	1532	444044	4534446	5202	N 924 W 959 SE 25 3N 2E SL B&M	240	4	10/23/1992	5179	23	Bail	17.9	1	240	160
76	26335	444162	4534431	5213	N 875 W 570 NE 36 3N 2E SL B&M	158	6	12/20/2002	5179	34	Pump	22.0	1.5	6	80
77	11660	444306	4533573	5294	N 700 W 70 E4 36 3N 2E SL B&M	105	4	04/30/1996	5260	34	Bail	13.9	1	4	100
78	432600	448160	4544640	5140	N 48 E 1718 W4 28 4N 3E SL B&M	90	6	03/27/2009	5115	25	Bail	50.0	1	15	80
79	33611	448666	4530256	5491	S 347 W 465 NE 09 2N 3E SL B&M	104	8	05/15/2005	5481	10	Pump	89.0	24	30	88

Drillers' well logs were taken from Utah Division of Water Rights Website; http://www.waterrights.utah.gov/wellinfo/wellsearch.asp

*Sy is integrated from Johnson (1967) and Ss is integrated from Domenico (1972). Aquifer Storativity (S) was estimated based on the formula S=Sy+Ss*b ; where Sy is the average specific yield, Ss is the average specific storage, and b is the saturated screen length.*

Transmissivity was estimated using TGUESS Algorithm adopted by Bradbury and Rothschild (1985) which is a Cooper-Jacob approximation of the Theis equation

Table E1. (Continued).

Well Location Data — *Derived aquifer parameter values based on water intake lithology* — *Estimated Aquifer Properties*

Label_ID	WIN	X	Y	Well elevation	Well_PLSID	Aquifer	Aquifer intake lithology	Depth to screen top	Depth to screen bottom	Aquifer thickness	Specific storage (Ss)	Specific yield (Sy)	Storativity (S)	Specific capacity (Sc)	Tguess Transmissivity (T)	Hydraulic Conductivity (K)
		NAD27_m	NAD27_m	feet				feet	feet	feet	1/ft			gpm/ft	sq ft/d	ft/day
1	4820	433023	4554678	4881	N 700 W 500 E4 26 5N 1E SL B&M	Valley fill	SAND AND GRAVEL	67	72	5	0.000161	0.25	0.250322	0.99	96.1	19.23
2	4946	435149	4553811	4910	N 600 E 1250 SW 30 5N 2E SL B&M	Valley fill	GRAVEL	78	137	59	0.000328	0.25	0.256234	0.50	74.1	1.26
3	14584	435363	4554546	4944	N 350 E 1930 W4 30 5N 2E SL B&M	Valley fill	GRAVEL AND CLAY	75	150	75	0.000161	0.05	0.062861	7.93	1251.8	16.69
4	7185	435632	4550832	4900	N 1893 W 381 S4 06 4N 2E SL B&M	Valley fill	GRAVEL	92	101	9	0.000328	0.25	0.256234	7.37	1028.6	114.29
5	33516	435714	4555758	4990	S 4025 W 1840 NE 19 5N 2E SL B&M	Valley fill	GRAVEL AND SAND	105	187	41	0.000328	0.25	0.256234	2.40	275.9	6.73
6	11794	436531	4548966	4999	N 739 E 350 SW 08 4N 2E SL B&M	Valley fill	CLAY LENS OF GROUND-WATER	105	135	30	0.003018	0.03	0.120551	1.35	175.3	5.84
7	26213	437234	4551395	5003	N 3380 E 2700 SW 05 4N 2E SL B&M	Valley fill	CLAY,SAND,GRAVEL	154	200	46	0.000161	0.16	0.167395	2.62	319.8	6.95
8	14106	437236	4551236	4974	N 2860 E 2705 SW 05 4N 2E SL B&M	Valley fill	CLAY,SAND,GRAVEL	152	174	22	0.000161	0.16	0.163537	0.90	92.8	4.22
9	19639	437355	4550895	4964	S 800 W 2320 E4 05 4N 2E SL B&M	Valley fill	SAND,GRAVEL	170	179	9	0.000161	0.25	0.251447	8.98	1330.3	147.81
10	10411	437371	4547858	5013	N 2456 W 2075 SE 17 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	161	168	7	0.000161	0.25	0.251125	1.68	179.0	25.58
11	22406	437531	4550683	4950	N 1128 W 1705 SE 05 4N 2E SL B&M	Valley fill	SAND,GRAVEL,COBBLES	164	174	10	0.000161	0.25	0.251608	6.37	842.4	84.24
12	16437	437719	4550687	4956	N 1100 E 1600 S4 05 4N 2E SL B&M	Valley fill	SILT	142	150	8	0.003018	0.18	0.204147	1.46	158.4	19.80
13	18305	437980	4546341	4999	N 100 W 60 E4 20 4N 2E SL B&M	Valley fill	CLAY, SAND, AND GRAVEL	108	158	50	0.000161	0.16	0.168038	0.47	52.7	1.05
14	14704	438135	4546417	4993	N 350 E 450 W4 21 4N 2E SL B&M	Valley fill	GRAVEL,CLAY	157	161	4	0.000161	0.05	0.050643	4.04	606.2	151.54
15	12137	438204	4549928	4967	S 1350 E 500 NW 09 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	160	165	5	0.000161	0.25	0.250804	6.01	778.1	155.62
16	2901	438219	4550354	5018	N 50 E 550 SW 04 4N 2E SL B&M	Valley fill	GRAVEL	131	150	19	0.000328	0.25	0.256234	0.99	110.0	5.79
17	26602	438356	4548777	4964	N 140 W 1556 S4 09 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	108	109	1	0.000161	0.25	0.250161	3.63	463.7	463.72
18	1660	438412	4543793	5156	S 280 E 1175 N4 33 4N 2E SL B&M	Valley fill	CLAY, SAND, AND GRAVEL	104	107	3	0.000161	0.16	0.160482	0.58	63.2	21.06
19	6423	438422	4545855	5025	N 1130 E 1410 SW 21 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	75	80	5	0.000161	0.25	0.250804	19.95	2993.7	598.75
20	145	438462	4545743	5035	N 760 E 1540 SW 21 4N 2E SL B&M	Valley fill	CLAY,SAND,GRAVEL	104	109	5	0.000161	0.16	0.160804	0.90	110.5	22.10
21	9618	438498	4549149	4984	N 1350 E 1575 SW 09 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	141	151	10	0.000161	0.25	0.251608	2.92	396.2	39.62
22	16051	438554	4545525	5003	N 47 E 1843 SW 21 4N 2E SL B&M	Valley fill	SILT,SAND,GRAVEL	96	100	4	0.000161	0.21	0.210643	3.99	500.5	125.12
23	1664	438706	4545579	5007	N 222 E 2340 SW 21 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	75	82	7	0.000161	0.25	0.251125	0.82	77.3	11.05
24	1962	438744	4544719	5035	N 2756 W 86 S4 28 4N 2E SL B&M	Valley fill	SAND, GRAVEL, AND COBBLES	35	45	10	0.000161	0.25	0.251608	49.77	8815.0	881.50
25	5941	439149	4545778	4986	N 915 W 1361 SE 21 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	76	78	2	0.000161	0.25	0.250322	4.44	550.9	275.45
26	16657	439203	4547678	4977	N 1970 W 1300 SE 16 4N 2E SL B&M	Valley fill	SILT,SAND	106	109	3	0.003018	0.18	0.189055	3.67	460.7	153.56
27	22065	439259	4545895	4987	S 1292 W 1058 E4 21 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	86	90	4	0.000161	0.25	0.250643	4.01	554.2	138.56
28	430951	439286	4545847	4986	N 1141 W 912 SE 21 4N 2E SL B&M	Valley fill	FINE SAND	96	106	10	0.000427	0.21	0.214265	3.75	464.6	46.46
29	17141	439393	4543506	5036	S 1200 W 580 E4 33 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	95	101	6	0.000161	0.25	0.250965	35.01	5588.0	931.34
30	23643	439468	4547608	5069	N 1740 W 430 SE 16 4N 2E SL B&M	Valley fill	GRAVEL	152	160	8	0.000328	0.25	0.252625	0.67	60.7	7.59
31	1681	439599	4543123	5059	N 200 E 109 W4 34 4N 2E SL B&M	Valley fill	CLAY,SAND,GRAVEL	38	68	30	0.000161	0.16	0.164823	13.32	2339.8	77.99
32	19475	439672	4543382	5036	N 1050 E 350 SW 34 4N 2E SL B&M	Valley fill	SAND,CLAY,GRAVEL	108	116	8	0.000161	0.16	0.161286	11.22	1657.8	207.23
33	23604	439717	4545874	4990	N 1230 E 500 SW 22 4N 2E SL B&M	Valley fill	GRAVEL	105	118	13	0.000328	0.25	0.254265	15.04	2179.6	167.66
34	8911	439938	4543120	5039	N 190 E 1223 W4 34 4N 2E SL B&M	Valley fill	SAND,GRAVEL, CLAY	34	49	15	0.003018	0.16	0.205276	19.97	6600.0	440.00
35	9203	439973	4542613	5121	N 1180 E 1350 SW 34 4N 2E SL B&M	Valley fill	CLAY,SAND,GRAVEL	222	247	25	0.000161	0.16	0.164019	0.22	21.0	0.84
36	5809	440051	4543043	5039	N 2620 W 1042 S4 34 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	34	39	5	0.000161	0.25	0.250804	39.95	6464.9	1292.98
37	10651	440052	4546871	5043	S 690 W 1161 N4 22 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	156	204	48	0.000161	0.25	0.257717	0.72	88.4	1.84
38	23603	440110	4542939	5043	N 2250 E 1800 SW 34 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	101	111	10	0.000161	0.25	0.251608	2.51	286.6	28.66
39	211	440183	4546394	5003	N 369 W 3353 E4 22 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	88	89	1	0.000161	0.25	0.250161	3.99	488.5	488.49
40	8478	440248	4546620	5062	S 1515 W 520 N4 22 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	69	72	3	0.000161	0.25	0.250482	5.61	719.2	239.74

Drillers' well logs were taken from Utah Division of Water Rights Website; http://www.waterrights.utah.gov/wellinfo/wellsearch.asp

*Sy is integrated from Johnson (1967) and Ss is integrated from Domenico (1972). Aquifer Storativity (S) was estimated based on the formula S=Sy+Ss*b ; where Sy is the average specific yield, Ss is the average specific storage, and b is the saturated screen length.*

Transmissivity was estimated using TGUESS Algorithm adopted by Bradbury and Rothschild (1985) which is a Cooper-Jacob approximation of the Theis equation

Table E1. (Continued).

Well Location Data — *Derived aquifer parameter values based on water intake lithology* — *Estimated Aquifer Properties*

Label_ID	WIN	X	Y	Well elevation	Well_PLSID	Aquifer	Aquifer intake lithology	Depth to screen top	Depth to screen bottom	Aquifer thickness	Specific storage (Ss)	Specific yield (Sy)	Storativity (S)	Specific capacity (Sc)	Tguess Transmissivity (T)	Hydraulic Conductivity (K)
		NAD27_m	NAD27_m	feet				feet	feet	feet	1/ft			gpm/ft	sq ft/d	ft/day
1	4820	433023	4554678	4881	N 700 W 500 E4 26 5N 1E SL B&M	Valley fill	SAND AND GRAVEL	67	72	5	0.000161	0.25	0.250322	0.99	96.1	19.23
2	4946	435149	4553811	4910	N 600 E 1250 SW 30 5N 2E SL B&M	Valley fill	GRAVEL	78	137	59	0.000328	0.25	0.256234	0.50	74.1	1.26
3	14584	435363	4554546	4944	N 350 E 1930 W4 30 5N 2E SL B&M	Valley fill	GRAVEL AND CLAY	75	150	75	0.000161	0.05	0.062861	7.93	1251.8	16.69
4	7185	435632	4550832	4900	N 1893 W 381 S4 06 4N 2E SL B&M	Valley fill	GRAVEL	92	101	9	0.000328	0.25	0.256234	7.37	1028.6	114.29
5	33516	435714	4555758	4990	S 4025 W 1840 NE 19 5N 2E SL B&M	Valley fill	GRAVEL AND SAND	105	187	41	0.000328	0.25	0.256234	2.40	275.9	6.73
6	11794	436531	4548966	4999	N 739 E 350 SW 08 4N 2E SL B&M	Valley fill	CLAY LENS OF GROUND-WATER	105	135	30	0.003018	0.03	0.120551	1.35	175.3	5.84
7	26213	437234	4551395	5003	N 3380 E 2700 SW 05 4N 2E SL B&M	Valley fill	CLAY,SAND,GRAVEL	154	200	46	0.000161	0.16	0.167395	2.62	319.8	6.95
8	14106	437236	4551236	4974	N 2860 E 2705 SW 05 4N 2E SL B&M	Valley fill	CLAY,SAND,GRAVEL	152	174	22	0.000161	0.16	0.163537	0.90	92.8	4.22
9	19639	437355	4550895	4964	S 800 W 2320 E4 05 4N 2E SL B&M	Valley fill	SAND,GRAVEL	170	179	9	0.000161	0.25	0.251447	8.98	1330.3	147.81
10	10411	437371	4547858	5013	N 2456 W 2075 SE 17 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	161	168	7	0.000161	0.25	0.251125	1.68	179.0	25.58
11	22406	437531	4550683	4950	N 1128 W 1705 SE 05 4N 2E SL B&M	Valley fill	SAND,GRAVEL,COBBLES	164	174	10	0.000161	0.25	0.251608	6.37	842.4	84.24
12	16437	437719	4550687	4956	N 1100 E 1600 S4 05 4N 2E SL B&M	Valley fill	SILT	142	150	8	0.003018	0.18	0.204147	1.46	158.4	19.80
13	18305	437980	4546341	4999	N 100 W 60 E4 20 4N 2E SL B&M	Valley fill	CLAY, SAND, AND GRAVEL	108	158	50	0.000161	0.16	0.168038	0.47	52.7	1.05
14	14704	438135	4546417	4993	N 350 E 450 W4 21 4N 2E SL B&M	Valley fill	GRAVEL,CLAY	157	161	4	0.000161	0.05	0.050643	4.04	606.2	151.54
15	12137	438204	4549928	4967	S 1350 E 500 NW 09 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	160	165	5	0.000161	0.25	0.250804	6.01	778.1	155.62
16	2901	438219	4550354	5018	N 50 E 550 SW 04 4N 2E SL B&M	Valley fill	GRAVEL	131	150	19	0.000328	0.25	0.256234	0.99	110.0	5.79
17	26602	438356	4548777	4964	N 140 W 1556 S4 09 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	108	109	1	0.000161	0.25	0.250161	3.63	463.7	463.72
18	1660	438412	4543793	5156	S 280 E 1175 N4 33 4N 2E SL B&M	Valley fill	CLAY, SAND, AND GRAVEL	104	107	3	0.000161	0.16	0.160482	0.58	63.2	21.06
19	6423	438422	4545855	5025	N 1130 E 1410 SW 21 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	75	80	5	0.000161	0.25	0.250804	19.95	2993.7	598.75
20	145	438462	4545743	5035	N 760 E 1540 SW 21 4N 2E SL B&M	Valley fill	CLAY,SAND,GRAVEL	104	109	5	0.000161	0.16	0.160804	0.90	110.5	22.10
21	9618	438498	4549149	4984	N 1350 E 1575 SW 09 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	141	151	10	0.000161	0.25	0.251608	2.92	396.2	39.62
22	16051	438554	4545525	5003	N 47 E 1843 SW 21 4N 2E SL B&M	Valley fill	SILT,SAND,GRAVEL	96	100	4	0.000161	0.21	0.210643	3.99	500.5	125.12
23	1664	438706	4545579	5007	N 222 E 2340 SW 21 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	75	82	7	0.000161	0.25	0.251125	0.82	77.3	11.05
24	1962	438744	4544719	5035	N 2756 W 86 S4 28 4N 2E SL B&M	Valley fill	SAND, GRAVEL, AND COBBLES	35	45	10	0.000161	0.25	0.251608	49.77	8815.0	881.50
25	5941	439149	4545778	4986	N 915 W 1361 SE 21 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	76	78	2	0.000161	0.25	0.250322	4.44	550.9	275.45
26	16657	439203	4547678	4977	N 1970 W 1300 SE 16 4N 2E SL B&M	Valley fill	SILT,SAND	106	109	3	0.003018	0.18	0.189055	3.67	460.7	153.56
27	22065	439259	4545895	4987	S 1292 W 1058 E4 21 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	86	90	4	0.000161	0.25	0.250643	4.01	554.2	138.56
28	430951	439286	4545847	4986	N 1141 W 912 SE 21 4N 2E SL B&M	Valley fill	FINE SAND	96	106	10	0.000427	0.21	0.214265	3.75	464.6	46.46
29	17141	439393	4543506	5036	S 1200 W 580 E4 33 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	95	101	6	0.000161	0.25	0.250965	35.01	5588.0	931.34
30	23643	439468	4547608	5069	N 1740 W 430 SE 16 4N 2E SL B&M	Valley fill	GRAVEL	152	160	8	0.000328	0.25	0.252625	0.67	60.7	7.59
31	1681	439599	4543123	5059	N 200 E 109 W4 34 4N 2E SL B&M	Valley fill	CLAY,SAND,GRAVEL	38	68	30	0.000161	0.16	0.164823	13.32	2339.8	77.99
32	19475	439672	4543382	5036	N 1050 E 350 SW 34 4N 2E SL B&M	Valley fill	SAND,CLAY,GRAVEL	108	116	8	0.000161	0.16	0.161286	11.22	1657.8	207.23
33	23604	439717	4545874	4990	N 1230 E 500 SW 22 4N 2E SL B&M	Valley fill	GRAVEL	105	118	13	0.000328	0.25	0.254265	15.04	2179.6	167.66
34	8911	439938	4543120	5039	N 190 E 1223 W4 34 4N 2E SL B&M	Valley fill	SAND,GRAVEL, CLAY	34	49	15	0.003018	0.16	0.205276	19.97	6600.0	440.00
35	9203	439973	4542613	5121	N 1180 E 1350 SW 34 4N 2E SL B&M	Valley fill	CLAY,SAND,GRAVEL	222	247	25	0.000161	0.16	0.164019	0.22	21.0	0.84
36	5809	440051	4543043	5039	N 2620 W 1042 S4 34 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	34	39	5	0.000161	0.25	0.250804	39.95	6464.9	1292.98
37	10651	440052	4546871	5043	S 690 W 1161 N4 22 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	156	204	48	0.000161	0.25	0.257717	0.72	88.4	1.84
38	23603	440110	4542939	5043	N 2250 E 1800 SW 34 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	101	111	10	0.000161	0.25	0.251608	2.51	286.6	28.66
39	211	440183	4546394	5003	N 369 W 3353 E4 22 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	88	89	1	0.000161	0.25	0.250161	3.99	488.5	488.49
40	8478	440248	4546620	5062	S 1515 W 520 N4 22 4N 2E SL B&M	Valley fill	SAND AND GRAVEL	69	72	3	0.000161	0.25	0.250482	5.61	719.2	239.74

Drillers' well logs were taken from Utah Division of Water Rights Website; http://www.waterrights.utah.gov/wellinfo/wellsearch.asp

*Sy is integrated from Johnson (1967) and Ss is integrated from Domenico (1972). Aquifer Storativity (S) was estimated based on the formula S=Sy+Ss*b ; where Sy is the average specific yield, Ss is the average specific storage, and b is the saturated screen length.*

Transmissivity was estimated using TGUESS Algorithm adopted by Bradbury and Rothschild (1985) which is a Cooper-Jacob approximation of the Theis equation

Label_ID	WIN	Public Land Survey ID	Name	X	Y	Elevation	Well Depth	Drilling Date	Well Diameter	Depth to water at drilling	Water level at drilling	Well Test Method	Pumping Rate	Well Test Duration	Drawdown
				NAD27-m	NAD27-m	feet	feet		inch	feet	feet		gpm	hours	feet
1	12198	N 700 W 300 S4 14 4N 3E SL B&M	JALCOBA Limited Partnership	451,710	4,547,218	5,509	126	7/15/1996	8	11	5,498	Pump	25	50	10
2	17476	S 740 E 350 W4 31 3N 3E SL B&M	Cheryl Davies Sanders Family Protection Trust	444,434	4,533,134	5,312	600	6/4/1998	8	25	5,287	Pump	25	10	540
3	18500	N 3342 W 1446 S4 27 5N 1E SL B&M	W. Leonard and Cheryl E. Skidmore	430,315	4,554,714	4,993	318	4/18/1999	6	27	4,966	Pump	10	19	150
4	23668	N 74 E 262 SW 25 3N 2E SL B&M	Tyler Pettit	442,799	4,534,171	5,607	355	6/21/2001	6	42	5,565	Bail	20	1	355
5	29874	S 200 W 3000 E4 25 4N 3E SL B&M	Powder Hollow Ranch LLC	453,062	4,544,470	6,821	340	7/23/2004	5	158	6,663	Pump	2.5	36	35
6	428164	N 496 E 1108 NE 27 4N 3E SL B&M	Dewey W. Taggart	451,155	4,545,545	5,390	90	8/31/1964	6	55	5,335	Pump	15	3	16
7	431574	S 628 W 2353 NE 08 5N 1E SL B&M	Snowbasin Resort Company	427,705	4,559,996	8,222	1,840	10/10/2008	10	88	8,134	Pump	100	93	500
8	24298	S 200 E 3200 NW 23 3N 2E SL B&M	Porterville Ward LDS Church	442,039	4,537,311	5,184	175	12/21/1978	6	62	5,122	Pump	20	24	1
9	2148	S 1820 E 1125 NW 25 5N 1E SL B&M	Robert N. and Melinda M. Newhouse	433,525	4,554,713	4,882	500	3/25/1993	6	22	4,860	Pump	15	5	3
10	23314	S 194 E 1916 W4 27 5N 1E SL B&M	Jeremy E. and Jill Mello	430,545	4,554,441	4,925	200	3/14/2001	6	121	4,804	Bail	10	10	5
11	23266	S 493 E 2116 NW 28 4N 2E SL B&M	LDS Church Milton Ward Water System	438,637	4,545,361	5,020	177	2/5/2001	6	25	7,268	Pump Test	19	30	60.0
12	15007	S 950 E 1950 NW 27 5N 1E SL B&M	Monte Verde Well	430,569	4,555,008	5,085	430	4/30/1969	8	43	5,043	Pump Test	65	24	8.2
13	7185	N 1893 W 381 S4 06 4N 2E SL B&M	Peterson Pipeline Irrigation Company Well#1	435,469	4,550,954	4,902	109	8/30/1994	8	5	4,897	Pump Test	283	5.5	27.0
14	30020	S 1412 E 2485 NW 35 4N 2E SL B&M	Morgan City Road Island Well	441,946	4,543,424	5,046	200	10/15/2004	6	19	5,027	Pump Test	1500	8.3	63.8

Label_ID	WIN	Data Source	Estimation Method for Transmissivity	Water Depth Intake	Screen Top	Screen Bottom	Aquifer Thickness	Target Aquifer	Target Aquifer Lithology	Specific Storage	Specific Yield	Storativity	Specific Capacity	Transmissivity	Hydraulic Conductivity
				feet	feet	feet	feet			1/feet			gpm/feet	square feet/day	feet/day
1	12198	Driller's log data	Tguess algorithm spreadsheet which was developed by Bradbury and Rothschild (1985) using the Cooper-Jacob approximation of Theis equation.	100	100	125	25	Dinwoody Formation	CLAY	0.003018	0.02	0.095	2.51	472	19
2	17476	Driller's log data		575	575	600	25	Wasatch Formation	CLAY	0.003018	0.02	0.095	0.05	4.2	0.17
3	18500	Driller's log data		148	148	308	160	Wasatch Formation	CLAY, GRAVEL	0.000160761	0.05	0.076	0.07	8.1	0.05
4	23668	Driller's log data		195	195	355	160	Norwood Formation	CLAY AND SAND	0.000161	0.07	0.096	0.06	3.5	0.02
5	29874	Driller's log data		280	280	300	20	Twin Creek Limestone	HARD SHALE	0.003018	0.18	0.240	0.07	8.7	0.43
6	428164	Driller's log data		80	80	90	10	Weber Quartzite	SAND AND CLAY	0.003018	0.16	0.190	0.94	113	11
7	431574	Driller's log data		1220	1220	1820	600	Tintic Quartzite	TINTIC QUARTZ	0.000119	0.02	0.091	0.20	30	0.05
8	24298	Driller's log data			140	175	35	Norwood Formation	HARD SHALE	0.003018	0.18	0.286	20.0	4,026	115
9	2148	Driller's log data		400	400	500	100	Norwood Formation	CLAY	0.003018	0.02	0.322	4.94	738	7.4
10	23314	Driller's log data		122	122	200	78	Wasatch Formation	SAND AND GRAVEL	0.000161	0.25	0.263	1.97	294	3.8
11	23266	Pump test data from DWSP	Gardner Engineering, 2001; Groundwater and wells (Driscoll, 1986, Eqn 9.7 p 221)	125	125	175	50	Norwood Formation	CLAY, GRAVEL	0.000160761	0.05	0.058	0.39	64	1.3
12	15007	Pump test data from DWSP	Bishop, C.E., 2001; Moench (1984) for fractured bedrock confined aquifer	400	400	430	30	Wasatch Formation	SAND AND GRAVEL	0.000161	0.25	0.255	2.17	1,055	35
13	7185	Pump test data from DWSP	Schick International Inc. and Mountain Land Development Services LLC., 2007; Moench (1984) for fractured bedrock confined aquifer	92	92	101	9	Norwood Formation	HARD SHALE	0.003018	0.18	0.207	31.4	1,430	159
14	30020	Pump test data from DWSP	Jones and Associates Consulting Engineers, 2006; Moench (1984) for fractured bedrock confined aquifer	160	160	200	40	Wasatch Formation (Valley fill?)	SAND AND GRAVEL	0.000161	0.25	0.256	37.5	8,250	206

Drillers' well logs were taken from Utah Division of Water Rights Website (http://www.waterrights.utah.gov/wellinfo/wellsearch.asp); Pump test data and estimated aquifer properties were taken from unpublished reports on drinking water source protection plans from the Utah Division of Drinking Water.
*Sy is integrated from Johnson (1967) and Ss is integrated from Domenico (1972). Aquifer Storativity (S) was estimated based on the formula S=Sy+Ss*b ; where Sy is the average specific yield, Ss is the average specific storage, and b is the saturated screen length.*

Table E2. *Summary of drillers' log and aquifer-test data and estimated aquifer properties for fractured-rock aquifers in Morgan Valley, Utah County, Utah.*

Label_ID	WIN	Public Land Survey ID	Name	X	Y	Elevation	Well Depth	Drilling Date	Well Diameter	Depth to water at drilling	Water level at drilling	Well Test Method	Pumping Rate	Well Test Duration	Drawdown
				NAD27-m	NAD27-m	feet	feet		inch	feet	feet		gpm	hours	feet
1	**12198**	N 700 W 300 S4 14 4N 3E SL B&M	JALCOBA Limited Partnership	451,710	4,547,218	5,509	126	7/15/1996	8	11	5,498	Pump	25	50	10
2	**17476**	S 740 E 350 W4 31 3N 3E SL B&M	Cheryl Davies Sanders Family Protection Trust	444,434	4,533,134	5,312	600	6/4/1998	8	25	5,287	Pump	25	10	540
3	**18500**	N 3342 W 1446 S4 27 5N 1E SL B&M	W. Leonard and Cheryl E. Skidmore	430,315	4,554,714	4,993	318	4/18/1999	6	27	4,966	Pump	10	19	150
4	**23668**	N 74 E 262 SW 25 3N 2E SL B&M	Tyler Pettit	442,799	4,534,171	5,607	355	6/21/2001	6	42	5,565	Bail	20	1	355
5	**29874**	S 200 W 3000 E4 25 4N 3E SL B&M	Powder Hollow Ranch LLC	453,062	4,544,470	6,821	340	7/23/2004	5	158	6,663	Pump	2.5	36	35
6	**428164**	N 496 E 1108 NE 27 4N 3E SL B&M	Dewey W. Taggart	451,155	4,545,545	5,390	90	8/31/1964	6	55	5,335	Pump	15	3	16
7	**431574**	S 628 W 2353 NE 08 5N 1E SL B&M	Snowbasin Resort Company	427,705	4,559,996	8,222	1,840	10/10/2008	10	88	8,134	Pump	100	93	500
8	**24298**	S 200 E 3200 NW 23 3N 2E SL B&M	Porterville Ward LDS Church	442,039	4,537,311	5,184	175	12/21/1978	6	62	5,122	Pump	20	24	1
9	**2148**	S 1820 E 1125 NW 25 5N 1E SL B&M	Robert N. and Melinda M. Newhouse	433,525	4,554,713	4,882	500	3/25/1993	6	22	4,860	Pump	15	5	3
10	**23314**	S 194 E 1916 W4 27 5N 1E SL B&M	Jeremy E. and Jill Melle	430,545	4,554,441	4,925	200	3/14/2001	6	121	4,804	Bail	10	10	5
11	**23266**	S 493 E 2116 NW 28 4N 2E SL B&M	LDS Church Milton Ward Water System	438,637	4,545,361	5,020	177	2/5/2001	6	25	7,268	Pump Test	19	30	60.0
12	**15007**	S 950 E 1950 NW 27 5N 1E SL B&M	Monte Verde Well	430,569	4,555,008	5,085	430	4/30/1969	8	43	5,043	Pump Test	65	24	8.2
13	**7185**	N 1893 W 381 S4 06 4N 2E SL B&M	Peterson Pipeline Irrigation Company Well#1	435,469	4,550,954	4,902	109	8/30/1994	8	5	4,897	Pump Test	283	5.5	27.0
14	**30020**	S 1412 E 2485 NW 35 4N 2E SL B&M	Morgan City Road Island Well	441,946	4,543,424	5,046	200	10/15/2004	6	19	5,027	Pump Test	1500	8.3	63.8

Label_ID	WIN	Data Source	Estimation Method for Transmissivity	Water Depth Intake	Screen Top	Screen Bottom	Aquifer Thickness	Target Aquifer	Target Aquifer Lithology	Specific Storage	Specific Yield	Storativity	Specific Capacity	Transmissivity	Hydraulic Conductivity
				feet	feet	feet	feet			1/feet			gpm/feet	square feet/day	feet/day
1	**12198**	Driller's log data	Tguess algorithm spreadsheet which was developed by Bradbury and Rothschild (1985) using the Cooper-Jacob approximation of Theis equation.	100	100	125	25	Dinwoody Formation	CLAY	0.003018	0.02	**0.095**	**2.51**	**472**	**19**
2	**17476**	Driller's log data		575	575	600	25	Wasatch Formation	CLAY	0.003018	0.02	**0.095**	**0.05**	**4.2**	**0.17**
3	**18500**	Driller's log data		148	148	308	160	Wasatch Formation	CLAY, GRAVEL	0.00016076	0.05	**0.076**	**0.07**	**8.1**	**0.05**
4	**23668**	Driller's log data		195	195	355	160	Norwood Formation	CLAY AND SAND	0.000161	0.07	**0.096**	**0.06**	**3.5**	**0.02**
5	**29874**	Driller's log data		280	280	300	20	Twin Creek Limestone	HARD SHALE	0.003018	0.18	**0.240**	**0.07**	**8.7**	**0.43**
6	**428164**	Driller's log data		80	80	90	10	Weber Quartzite	SAND AND CLAY	0.003018	0.16	**0.190**	**0.94**	**113**	**11**
7	**431574**	Driller's log data		1220	1220	1820	600	Tintic Quartzite	TINTIC QUARTZ	0.000119	0.02	**0.091**	**0.20**	**30**	**0.05**
8	**24298**	Driller's log data			140	175	35	Norwood Formation	HARD SHALE	0.003018	0.18	**0.286**	**20.0**	**4,026**	**115**
9	**2148**	Driller's log data		400	400	500	100	Norwood Formation	CLAY	0.003018	0.02	**0.322**	**4.94**	**738**	**7.4**
10	**23314**	Driller's log data		122	122	200	78	Wasatch Formation	SAND AND GRAVEL	0.000161	0.25	**0.263**	**1.97**	**294**	**3.8**
11	**23266**	Pump test data from DWSP	Gardner Engineering, 2001; Groundwater and wells (Driscoll, 1986, Eqn 9.7 p 221)	125	125	175	50	Norwood Formation	CLAY, GRAVEL	0.00016076	0.05	**0.058**	**0.39**	**64**	**1.3**
12	**15007**	Pump test data from DWSP	Bishop, C.E., 2001; Moench (1984) for fractured bedrock confined aquifer	400	400	430	30	Wasatch Formation	SAND AND GRAVEL	0.000161	0.25	**0.255**	**2.17**	**1,055**	**35**
13	**7185**	Pump test data from DWSP	Schick International Inc. and Mountain Land Development Services LLC., 2007; Moench (1984) for fractured bedrock confined aquifer	92	92	101	9	Norwood Formation	HARD SHALE	0.003018	0.18	**0.207**	**31.4**	**1,430**	**159**
14	**30020**	Pump test data from DWSP	Jones and Associates Consulting Engineers, 2006; Moench (1984) for fractured bedrock confined aquifer	160	160	200	40	Wasatch Formation (Valley fill?)	SAND AND GRAVEL	0.000161	0.25	**0.256**	**37.5**	**8,250**	**206**

Drillers' well logs were taken from Utah Division of Water Rights Website (http://www.waterrights.utah.gov/wellinfo/wellsearch.asp); Pump test data and estimated aquifer properties were taken from unpublished reports on drinking water source protection plans from the Utah Division of Drinking Water.

*Sy is integrated from Johnson (1967) and Ss is integrated from Domenico (1972). Aquifer Storativity (S) was estimated based on the formula S=Sy+Ss*b ; where Sy is the average specific yield, Ss is the average specific storage, and b is the saturated screen length.*

APPENDIX F

POTENTIAL CONTAMINANT SOURCES

Key to the symbols and footnotes for appendix F:

UST/LUST = Underground Storage Tank/ Leaking Underground Storage Tank

RCRIS = Resource Conservation and Recovery Information System

Equip = Equipment

Mnfg = Manufacturing

HHW = Household Hazardous Waste

PCS ID*	MAP ID	LOCATION NAME/DESCRIPTION	POTENTIAL CONTAMINANT TYPE	POLLUTANT
1-1	1	CONSTRUCTION COMPANY	RCRIS**	Unknown qty of Haz. Mat'ls (RCRA)
1-10	12	MORGAN MINE	Mining	Conduit to aquifer; potential dumping.
1-12	17	GRAVEL PIT IN TWN 5N RNG 1E SEC 25	Mining	Conduit to aquifer; potential dumping.
1-121	99	11 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-122	100	Home with Fuel Storage	Fuel Storer	Fuel Storage
1-123	101	11 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-124	102	Petroleum - Gas Station	UST/LUST	UST (gasoline), 8 to 10 >1000 gal ASTs (diesel)
1-125	103	Valley Metals	UST/LUST	Fuel Storage, equip maint, UST
1-126	104	Industrial fuel storage	Fuel Storer	above ground fuel storage - 2 1,000 gal tanks
1-127	105	Welding	Commercial	waste fluids
1-128	106	Automotive - Lube Center	Equip/Vehicle Maintenance	Auto maintenance - waste fluids
1-129	107	Machine shop	Equip/Vehicle Maintenance	Vehicle maintenance - waste fluids
1-13	24	UT HWYS PIT NO 15003	Mining	Conduit to aquifer; potential dumping.
1-130	108	Car Dealership - Service Center	UST/LUST	LUST, auto maint - waste fluids
1-131	109	Petroleum - Gas Station	UST/LUST	UST (gasoline), 8 to 10 >1000 gal ASTs (diesel)
1-132	110	Lube and Tire Center	Equip/Vehicle Maintenance	Auto maint - waste fluids - Used Oil Tank (ab)
1-133	111	Motors/car lot	Equip/Vehicle Maintenance	Auto maintenance - waste fluids
1-134	112	Gas Station	UST/LUST	UST (gasoline & diesel)
1-135	113	Railroad - Morgan Yard	UST/LUST	UST
1-136	114	Morgan City & County Garbage Dump	Junkyard/salvage	Garbage Dump/Landfill
1-137	115	Morgan County Road Supt	UST/LUST	LUST
1-138	116	Food Mart Gas Station	UST/LUST	Former UST (gasoline) -out of business
1-139	117	Service Gas Station	UST/LUST	LUST (gasoline)
1-14	25	UT HWYS PIT NO 15004	Mining	Conduit to aquifer; potential dumping.

1-140	118	School District - Bus Garage	UST/LUST	LUST (gasoline or diesel)
1-141	119	High School, Middle School, & Elementary	Large Lawn	fertilizers, pesticides, herbicides`
1-142	120	School District - Maintenance Shed	Equip/Vehicle Maintenance	bus maintenance
1-143	121	Morgan City Shop	UST/LUST	LUST
1-144	122	High School, Middle School, & Elementary	Large Lawn	fertilizers, pesticides, herbicides`
1-145	123	Fuel storage and Residence	Fuel Storer	Fuel Storage
1-146	124	Substation	Substation	transformer fluids
1-147	125	Gravel Pit Operation	Mining	gravel pit, fuel storage, equip maint
1-148	126	6 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-149	127	6 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-15	26	UT HWYS PIT NO 15005	Mining	Conduit to aquifer; potential dumping.
1-150	128	5 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-151	129	5 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-152	130	Golf Course	Large Lawn	fuel, herbicides, fertilizers, equip maint, HHW, septic
1-153	131	2 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-154	132	Restaurant & Roost	Commercial	Camping, fuel storage, equip maint
1-155	134	4 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-156	135	4 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-157	136	7 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-158	137	7 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-159	138	11 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-16	27	UT HWYS PIT NO 15007	Mining	Conduit to aquifer; potential dumping.
1-160	141	11 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-161	142	11 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-162	143	14 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-163	145	7 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals

1-164	146	10 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-165	147	15 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-166	148	30 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-167	149	Barn Area	Barn Area	Fuel Storage, equip maint
1-168	152	10 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-169	153	4 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-17	30	UT HWYS PIT NO 15019	Mining	Conduit to aquifer; potential dumping.
1-170	154	9 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-171	155	13 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-172	156	13 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-173	157	Water Conservancy District w/ 2 Hom	Rural Homes	diesel fuel storage, HHW, septics, equip maint
1-174	158	9 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-175	159	6 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-176	160	27 Homes	Residential Area	HHW, fuel, animals
1-177	161	27 Homes	Residential Area	HHW, fuel, animals
1-178	162	Trout Farm & 1 home	Fish Hatchery	Unknown Chemicals, HHW
1-179	163	2 Rural Homes	Rural Homes	fuel, HHW, equipment, animals
1-18	31	UTAH NO 15022	Mining	Conduit to aquifer; potential dumping.
1-180	164	Subdivision (>15 Homes)	Residential Area	HHW, animals, fuels
1-181	165	West Subdivision (>15 Homes)	Residential Area	HHW, animals, fuels
1-182	166	Residential Subd (>25 Homes)	Residential Area	HHW, animals, fuels
1-183	167	Wastewater Treatment Facility	Wastewater/sewer	Sewage treatment chemicals and sewage discharge
1-184	168	15 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-185	169	15 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-186	170	8 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-187	171	Quick Stop - gas station	UST/LUST	UST (gasoline), auto maintenance, possible LUST
1-188	172	12 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-189	173	12 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-190	174	9 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals

1-191	175	Campfire area	Camping	camping
1-192	176	6 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-193	177	9 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-194	178	Car Wash/Beauty Salon	Commercial	auto cleaning detergents and wastes
1-195	179	Barn with Storage Sheds	Barn Area	scrap piles, fuel storage, equip. maint, waste oil
1-196	180	>40 Rural Homes in Peterson Town	Rural Homes	Septic, fuel, HHW, equipment, animals
1-197	181	Barn Area	Barn Area	equip maint, fuel storage
1-198	182	Barn	Barn Area	equip maint, fuel storage
1-199	183	14 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-2	6	Firearms Manufacturing Company	Remediation	Haz. Mat'l contamination remediation
1-20	32	UT HWYS GRAVEL PIT 15034	Mining	Conduit to aquifer; potential dumping.
1-200	184	14 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-201	185	5 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-202	186	5 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-203	187	7 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-204	188	7 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-205	189	Barn Area for farm	Barn Area	equip maint, fuel storage
1-206	190	3 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-207	191	3 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-208	192	12 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-209	193	12 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-21	33	UT HWYS GRAVEL PIT 15037	Mining	Conduit to aquifer; potential dumping.
1-210	194	4 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-211	195	4 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-212	196	10 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-213	197	10 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-214	198	12 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-215	199	12 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-216	200	15 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals

1-217	201	15 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-218	202	16 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-219	203	16 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-22	35	UNKNOWN GRAVEL PIT	Mining	Conduit to aquifer; potential dumping.
1-220	204	3 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-221	205	3 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-222	206	Barn Area	Barn Area	Fuel Storage, equip maint
1-223	207	16 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-224	208	Barn Area	Barn Area	Fuel Storage, equip maint
1-225	209	Firearms Manufacturing Company	UST/LUST	unknown-USTs
1-227	210	commercial INC.	UST/LUST	unknown-USTs
1-228	211	COUNTY ROAD SUPT.	UST/LUST	unknown-USTs
1-229	212	BUS GARAGE	UST/LUST	unknown-USTs
1-23	36	UT HWYS PIT NO 29047	Mining	Conduit to aquifer; potential dumping.
1-230	213	UDOT STA. # 126	UST/LUST	unknown-USTs
1-231	214	SERVICE station	UST/LUST	unknown-USTs
1-232	215	MORGAN YARD	UST/LUST	unknown-USTs
1-233	216	FARM PARTNERSHIP	UST/LUST	unknown-USTs
1-234	217	CITY SHOP	UST/LUST	unknown-USTs
1-235	218	SERVICE station	UST/LUST	unknown-USTs
1-236	219	PARKSIDE	UST/LUST	unknown-USTs
1-237	220	service station STOP	UST/LUST	unknown-USTs
1-238	221	car dealer	UST/LUST	unknown-USTs
1-239	222	CONSTRUCTION	UST/LUST	unknown-USTs
1-24	37	16 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-240	223	TOWING	UST/LUST	unknown-USTs
1-246	224	Firearms COMPANY	UST/LUST	unknown-USTs
1-248	225	Commercial INC.	UST/LUST	unknown-USTs
1-249	226	COUNTY ROAD SUPT.	UST/LUST	unknown-USTs

1-25	38	Barn Area	Barn Area	Fuel Storage, equip maint
1-250	227	BUS GARAGE	UST/LUST	unknown-USTs
1-251	228	UDOT STA. # 126	UST/LUST	unknown-USTs
1-252	229	SERVICE station	UST/LUST	unknown-USTs
1-253	230	MORGAN YARD	UST/LUST	unknown-USTs
1-254	231	FARM PARTNERSHIP	UST/LUST	unknown-USTs
1-255	232	CITY SHOP	UST/LUST	unknown-USTs
1-256	233	SERVICE station	UST/LUST	unknown-USTs
1-257	234	PARKSIDE	UST/LUST	unknown-USTs
1-258	235	service station STOP	UST/LUST	unknown-USTs
1-259	236	car dealer	UST/LUST	unknown-USTs
1-26	40	7 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-260	237	CONSTRUCTION	UST/LUST	unknown-USTs
1-261	238	TOWING	UST/LUST	unknown-USTs
1-267	239	service station STOP	UST/LUST	unknown-USTs
1-268	240	PETERSON YARD	UST/LUST	unknown-USTs
1-269	241	gas #43029	UST/LUST	unknown-USTs
1-27	41	7 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-270	242	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-271	243	Homes & Farms	AFO	Animal Feeding Operation, Septic, HHW, fuel, equip
1-272	244	Animal Farm	AFO	Animal Feeding Operation, fuel, HHW, septics, equip
1-273	245	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-274	246	Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-275	247	Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-276	248	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-277	249	Animal Farm	AFO	Animal Feeding Operation, fuel, HHW, septic, equip
1-278	250	Elk Farm	AFO	Animal Feeding Operation, fuel, HHW, septic, equip

1-279	251	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-28	42	15 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-280	252	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-281	253	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-282	254	Farm	AFO	Animal Feeding Operation, fuel, HHW, septic, equip
1-283	255	Farm	AFO	Animal Feeding Operation, fuel, HHW, septic, equip
1-284	256	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-285	257	Animal Farm	AFO	Animal Feeding Operation, fuel, HHW, septic, equip
1-286	258	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-287	259	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-288	260	Dairy	AFO	Animal Feeding Operation, fuel storage, equip maint
1-289	261	Animal Farm	AFO	Animal Feeding Operation
1-29	43	11 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-290	262	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-291	263	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-292	264	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-293	265	Farm	AFO	Animal Feeding Operation, fuel, HHW, septics, equip
1-294	266	Farm	AFO	Animal Feeding Operation, fuel, HHW, equip
1-295	267	Animal Farm	AFO	Animal Feeding Operation, fuel, HHW, septics, equip
1-296	268	Family Farm/Ranch	AFO	Animal Feeding Operation, fuel, HHW, equip
1-297	269	Farm	AFO	Animal Feeding Operation, HHW
1-298	270	Farm	AFO	Animal Feeding Operation, fuel, HHW, equip
1-299	271	Animal Farm	AFO	Animal Feeding Operation, fuel, HHW, equip
1-3	7	MOUNTAIN GREEN LAGOON EFFLUENT	Wastewater/sewer	Treated sewage (or other) outfall.
1-30	44	11 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-300	272	Animal Farm	AFO	Animal Feeding Operation, fuel, HHW, septics, equip

1-307	273	Herefords	AFO	Animal Feeding Operation, fuel, fert, pest, herb
1-308	274	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-309	275	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-31	45	10 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-310	276	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-311	277	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-312	278	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-313	279	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-314	280	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-315	281	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-316	282	County Fairgrounds	AFO	Livestock Pens - Animal Feeding Operation
1-317	283	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-318	284	Ranch	AFO	Animal Feeding Operation, fuel storage, equip maint
1-319	285	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-32	46	17 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-320	286	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-321	287	Animal Farm	AFO	Animal Feeding Operation, fuel storage
1-322	288	Animal Farm	AFO	Animal Feeding Operation, fuel storage
1-323	289	1 Rural Home	AFO	Animal Feeding Operation, Septic, HHW, fuel, equip
1-324	290	Horse Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-325	291	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-326	292	Cattle Farm	AFO	Animal Feeding Operation, fuel, equip, herbicides
1-327	293	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-328	295	Sheep Farm (25-50 sheep)	AFO	Animal Feeding Operation
1-329	296	Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-33	47	6 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-330	297	Animal Farm	AFO	Animal Feeding Operation
1-331	298	Sheep Farm	AFO	Animal Feeding Operation, fuel, HHW, septics,

				equip
1-332	299	Sheep Farm	AFO	Animal Feeding Operation, fuel, HHW, septics, equip
1-333	300	Animal Farm	AFO	Animal Feeding Operation
1-334	301	Animal Farm	AFO	Animal Feeding Operation
1-335	302	Limousin - Farm	AFO	Animal Feeding Operation
1-336	303	Machine/ Farm	AFO	machine shop, Animal Feeding Op, fuel, equipment
1-337	304	Farms	AFO	Animal Feeding Operation, fuel storage, equip maint
1-338	305	LL Ranch - Horse Training Facility	AFO	Animal Feeding Operation, fuel storage, equip maint
1-339	306	Deer Farm	AFO	Animal Feeding Operation, septic
1-34	48	6 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-340	307	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-341	308	Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-342	309	3 Barns	AFO	Animal Feeding Operation, fuel storage, equip maint
1-343	310	Animal Farm	AFO	Animal Feeding Operation, Septic, HHW, fuel
1-344	311	Animal Farm	AFO	Animal Feeding Operation, Septic, HHW, fuel, equip
1-345	312	Barn Area for Animals	AFO	Animal Feeding Operation, fuel storage, equip maint
1-346	313	1 Rural Home	AFO	Animal Feeding Operation, Septic, HHW, fuel
1-347	314	1 Rural Home	AFO	Animal Feeding Operation, Septic, HHW, fuel
1-348	315	Ranch	AFO	Animal Feeding Operation, fuel storage, equip maint
1-349	316	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-35	49	17 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-350	317	Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-351	318	Sheep Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
1-352	319	Ranch	AFO	Animal Feeding Operation, fuel storage, equip maint
1-36	50	24 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-37	51	15 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-38	52	Fuel storers and Residence	Fuel Storer	500 gal fuel storage

1-39	53	6 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-4	8	MORGAN LAGOONS	Wastewater/sewer	Treated sewage (or other) outfall.
1-40	54	10 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-41	55	16 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-42	56	16 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-43	57	Personal business Residence	Rural Homes	Septic, fuel, HHW, equipment, animals
1-44	58	5 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-45	59	12 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-46	60	11 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-47	61	30 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-48	62	30 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-49	63	15 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-50	64	Home with Fuel Storage	Fuel Storer	Fuel Storage
1-51	65	16 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-52	67	9 Rural Homes	Rural Homes	HHW, animals, fuel, equip
1-53	70	12 Rural Homes	Rural Homes	HHW, animals, fuel, equip
1-54	71	UDOT Station #1426	UST/LUST	Heavy equip maint, fuel storage, deicing chemicals,
1-55	74	Sewage Disposal Ponds	Wastewater/sewer	sewage outfall and overflow
1-56	77	8 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-57	79	26 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
1-58	80	Construction, Co.	Mining	borrow pit, fuel storage, equip maint
1-59	81	UDOT Rest Area	Camping	pit toilet
1-60	82	Barn Area	Barn Area	equip maint, fuel storage
1-61	83	Gas Station	UST/LUST	UST (gasoline & diesel)
1-62	84	2 Homes	Rural Homes	HHW, Septic, fuel
1-63	85	Gravel Companies	Mining	gravel pit, fuel, equip maint
1-64	86	Gravel Companies	Mining	gravel pit, fuel, equip maint
1-65	87	Gravel Companies	Mining	gravel pit, fuel, equip maint

1-66	88	Mountain Green Residential & Commercial Areas	Residential Area	HHW, res & com streets, animals, veh maint
1-67	89	Plumbing	Commercial	equip maint
1-68	90	Products International	Mnfg & Industrial	equip maint, unknown chemicals
1-69	91	Heating & Air Conditioning	Commercial	equip maint
1-70	92	Manufacturing Co.	Mnfg & Industrial	unknown chemicals, equip maint, fuel
1-71	93	Shed w/ unknown ownership	Equip/Vehicle Maintenance	equip maint, fuel storage
1-72	94	Alliance industry	Mnfg & Industrial	unknown chemicals, equip maint, fuel
1-73	95	Airport Hangers	Equip/Vehicle Maintenance	airplane maint, fuel storage
1-74	96	Firearms Manufacturing Company	Mnfg & Industrial	unknown chemicals, equip maint, fuel
1-75	97	Firearms Manufacturing Company	Mnfg & Industrial	unknown chemicals, equip maint, fuel
1-76	98	Snow Basin Sewage Lagoons	Wastewater/sewer	Potential discharge of sewage
1-9	9	WEST MINE	Mining	Conduit to aquifer; potential dumping.
4-1	2	Firearms Manufacturing Company	RCRIS**	Unknown qty of Haz. Mat'ls (RCRA)
4-120	39	14 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
4-121	66	16 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
4-122	68	9 Rural Homes	Rural Homes	HHW, animals, fuel, equip
4-123	69	10 Rural Homes	Rural Homes	HHW, animals, fuel, equip
4-124	72	13 Rural Homes	Rural Homes	HHW, animals, fuel, equip
4-125	73	13 Rural Homes	Rural Homes	HHW, animals, fuel, equip
4-126	75	11 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
4-127	76	11 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
4-128	78	9 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
4-13	4	PRATTS PASS	RCRIS**	Unknown qty of Haz. Mat'ls (RCRA)
4-14	5	ENTERPRISE	RCRIS**	Unknown qty of Haz. Mat'ls (RCRA)
4-161	133	14 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
4-162	139	11 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals

4-163	140	12 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
4-164	144	14 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
4-165	150	30 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
4-166	151	10 Rural Homes	Rural Homes	Septic, fuel, HHW, equipment, animals
4-24	10	GEM MINE	Mining	Conduit to aquifer; potential dumping.
4-25	11	MORGAN- PROPERTY	Mining	Conduit to aquifer; potential dumping.
4-26	13	HILL MINE	Mining	Conduit to aquifer; potential dumping.
4-27	14	GEM	Mining	Conduit to aquifer; potential dumping.
4-28	15	PHOSPHATE LOCALITY	Mining	Conduit to aquifer; potential dumping.
4-29	16	PHOSPHATE DEPOSIT	Mining	Conduit to aquifer; potential dumping.
4-290	294	Large Animal Farm	AFO	Animal Feeding Operation, fuel storage, equip maint
4-30	18	GRAVEL PIT IN TWN 4N RNG 2E SEC 26	Mining	Conduit to aquifer; potential dumping.
4-31	19	COAL PROSPECT	Mining	Conduit to aquifer; potential dumping.
4-32	20	COPPER PROSPECT	Mining	Conduit to aquifer; potential dumping.
4-34	21	RANCH ADIT	Mining	Conduit to aquifer; potential dumping.
4-37	22	TUNNELAND MINE PROSPECT	Mining	Conduit to aquifer; potential dumping.
4-38	23	UNKNOWN CLAIM	Mining	Conduit to aquifer; potential dumping.
4-39	28	UT HWYS PIT NO 15009	Mining	Conduit to aquifer; potential dumping.
4-40	29	UT HWYS PIT NO 15012	Mining	Conduit to aquifer; potential dumping.
4-41	34	UNKNOWN PROSPECT	Mining	Conduit to aquifer; potential dumping
4-6	3	INC/SLIDE PLT	RCRIS**	Unknown qty of Haz. Mat'ls (RCRA)

* Identification number assigned by Hansen, Allen, and Luce, Inc. (2001)

** Resource Conservation and Recovery Information System

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Plate 1
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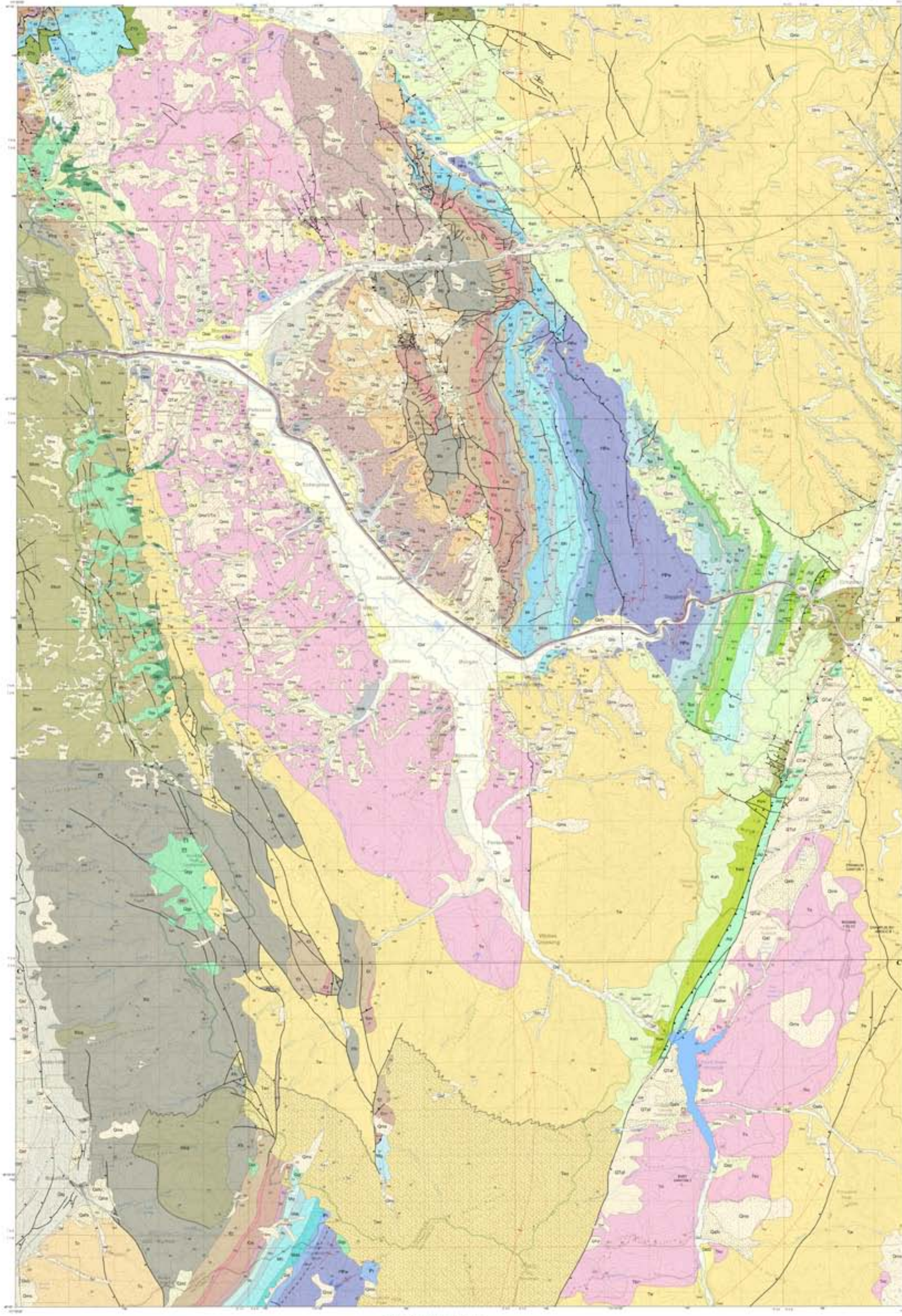
Hydrogeology of Morgan Valley, Morgan County, Utah



See Appendix D for unit descriptions and symbols

SCALE 1:50,000

CONTOUR INTERVAL 100 FEET

APPROXIMATE MEAN DECLINATION

PLATE 1.
GEOLOGIC MAP OF THE MORGAN VALLEY AREA, MORGAN, WEBER, SALT LAKE, DAVIS AND SUMMIT COUNTIES, UTAH

COMPILED BY JON K. KING

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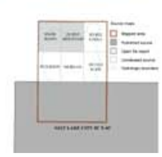

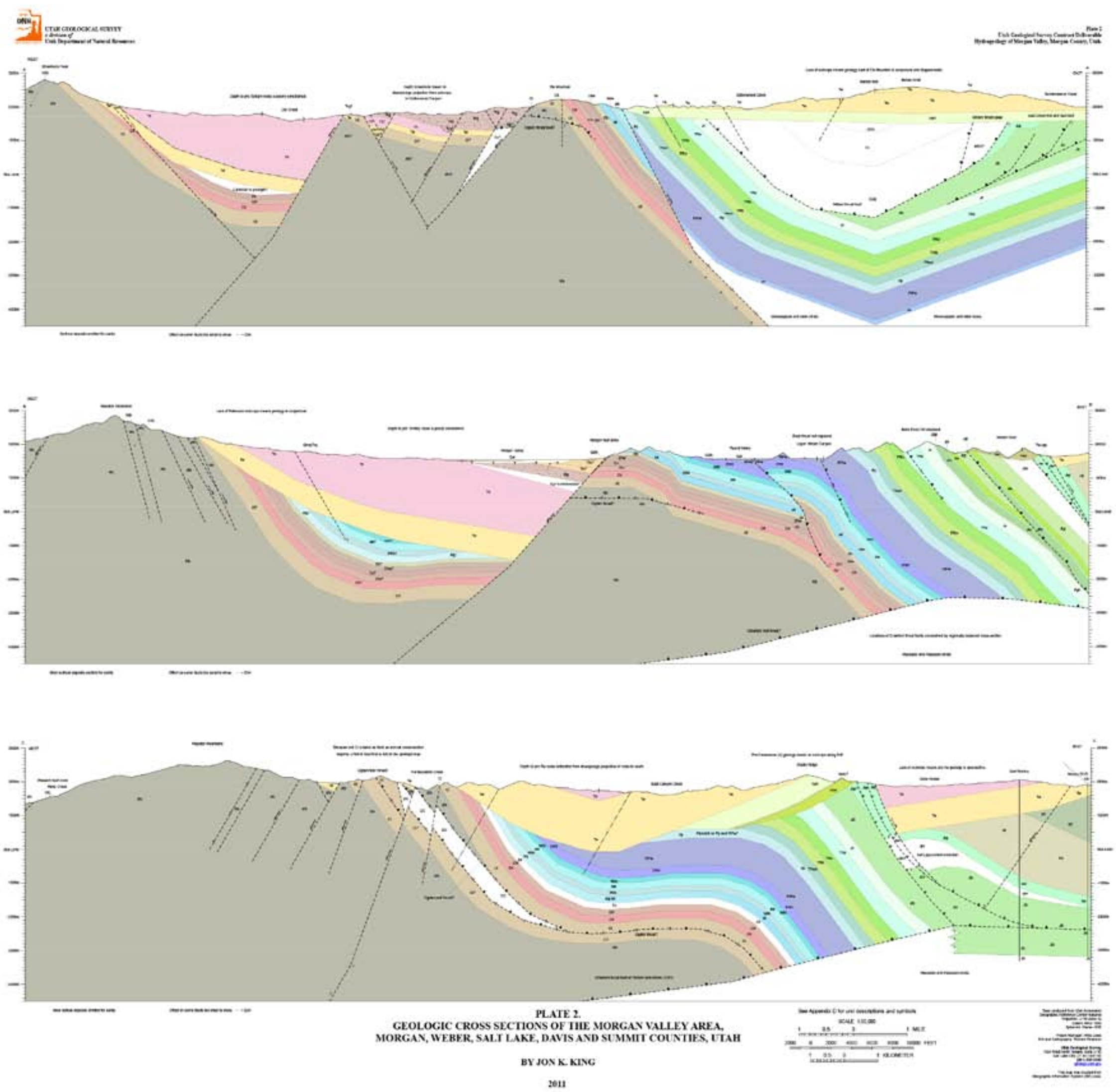
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Plate 2
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Hydrogeology of Morgan Valley, Morgan County, Utah
PLATE 2.
GEOLOGIC CROSS SECTIONS OF THE MORGAN VALLEY AREA,
MORGAN, WEBER, SALT LAKE, DAVIS AND SUMMIT COUNTIES, UTAH
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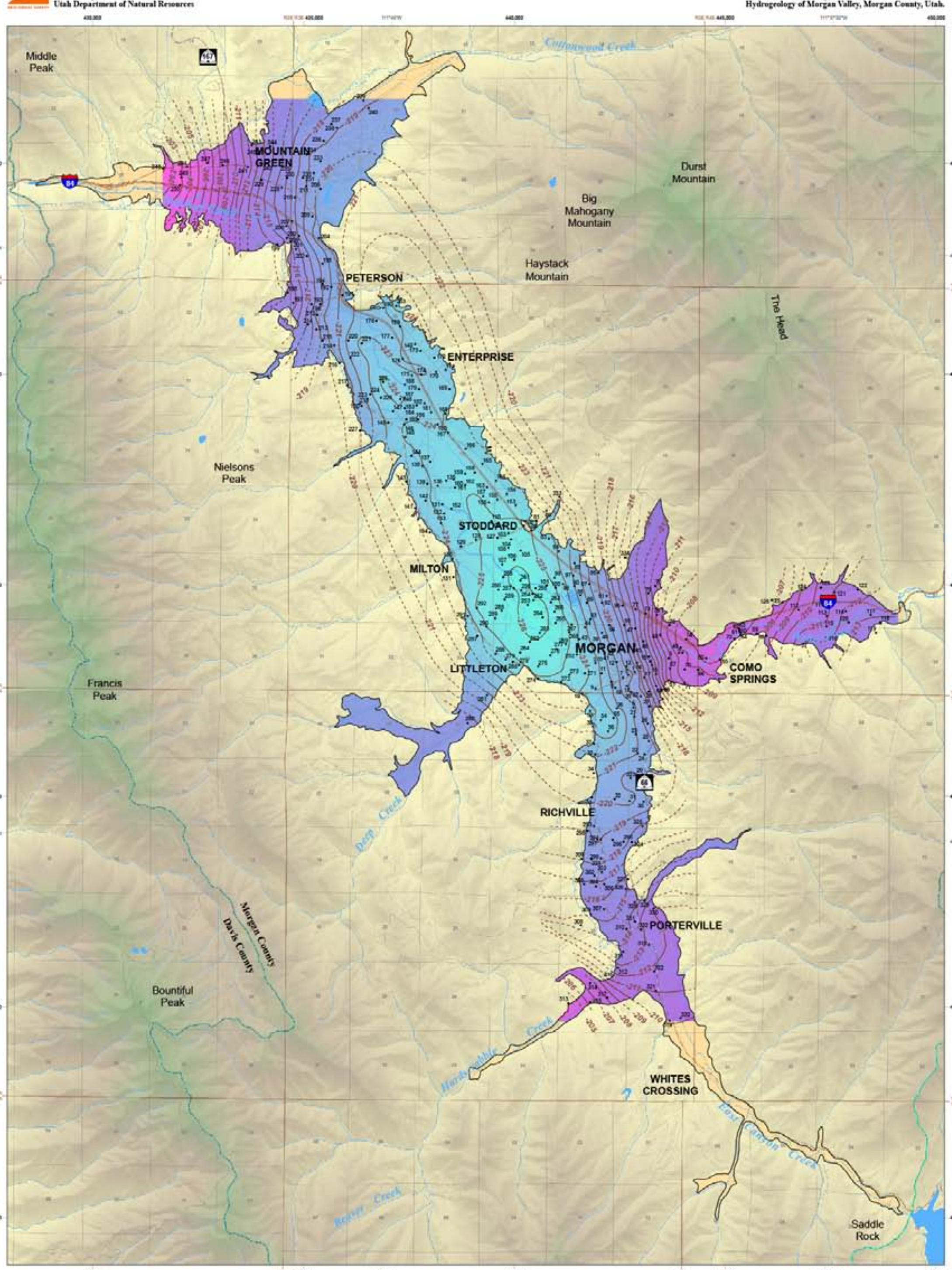

PLATE 3.
CONTOURED COMPLETE BOUGUER ANOMALY, MORGAN VALLEY, UTAH

by Janae Wallace, Mike Lowe, Jon King, Walid Sabbah, and Kevin Thomas

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Explanation

Bouguer value (mGal)
-200.8
-213.0
-226.5
Gravity station location
77• See Table C1 for data by station ID

Bouguer contour
Contour interval 1.0 mGal
— Valley fill
- - Bedrock (inferred)
— Morgan Valley drainage basin boundary
Valley fill (no data)
Bedrock

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1 0.5 0 1 MILES
1 0.5 0 1 2 3 KILOMETERS
SCALE 1:62,500

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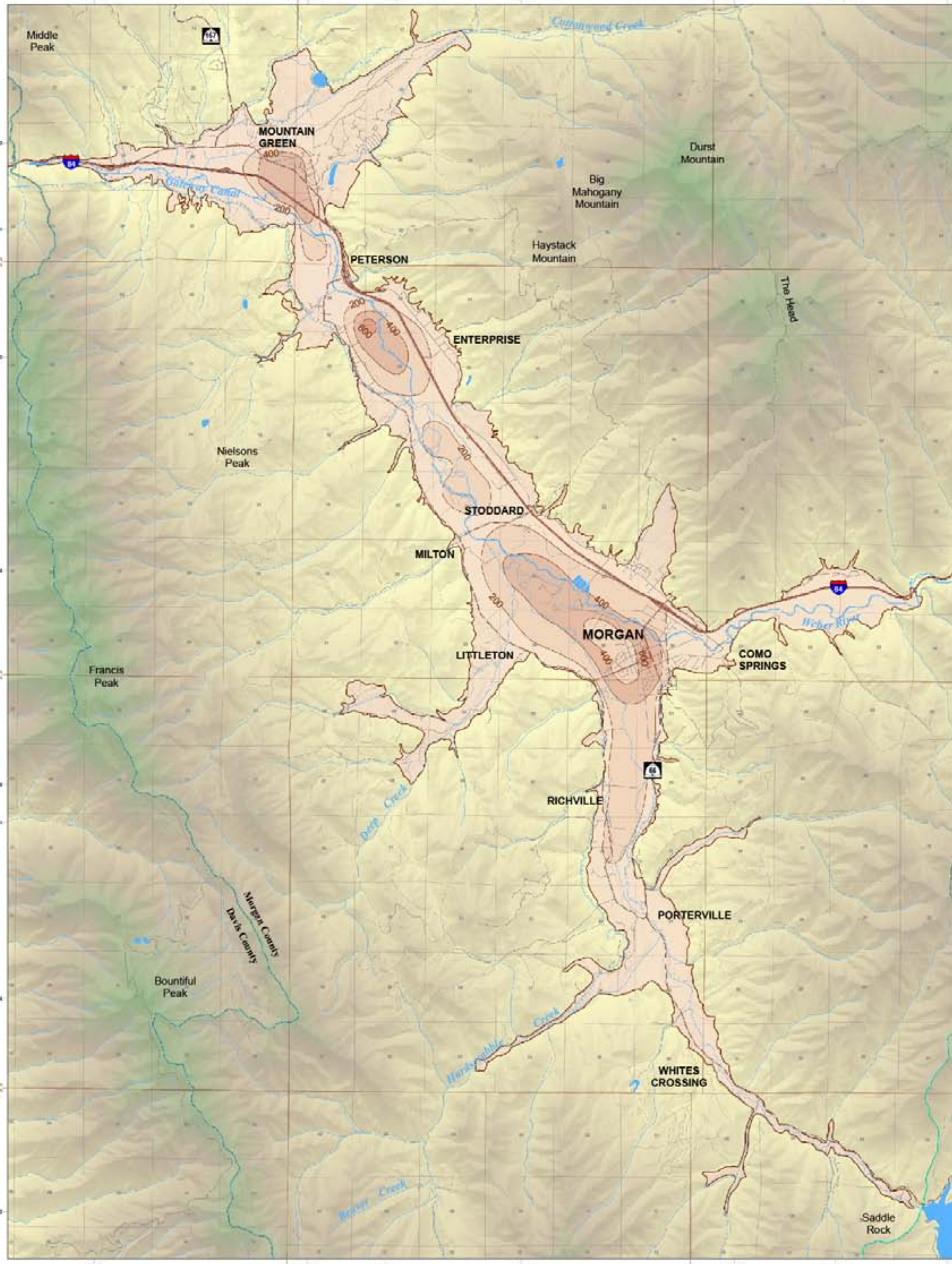

Explanation

Depth to bedrock in feet

- < 200
- 200 - 400
- 401 - 600
- > 600
- Valley-fill boundary
- Morgan Valley drainage basin boundary
- Bedrock

PLATE 4.

SCHEMATIC ISOPACH OF UNCONSOLIDATED VALLEY-FILL DEPOSITS BASED ON INTERPRETATION OF GRAVITY DATA, MORGAN VALLEY, UTAH

by Janae Wallace, Mike Lowe, Jon King, Walid Sabbah, and Kevin Thomas

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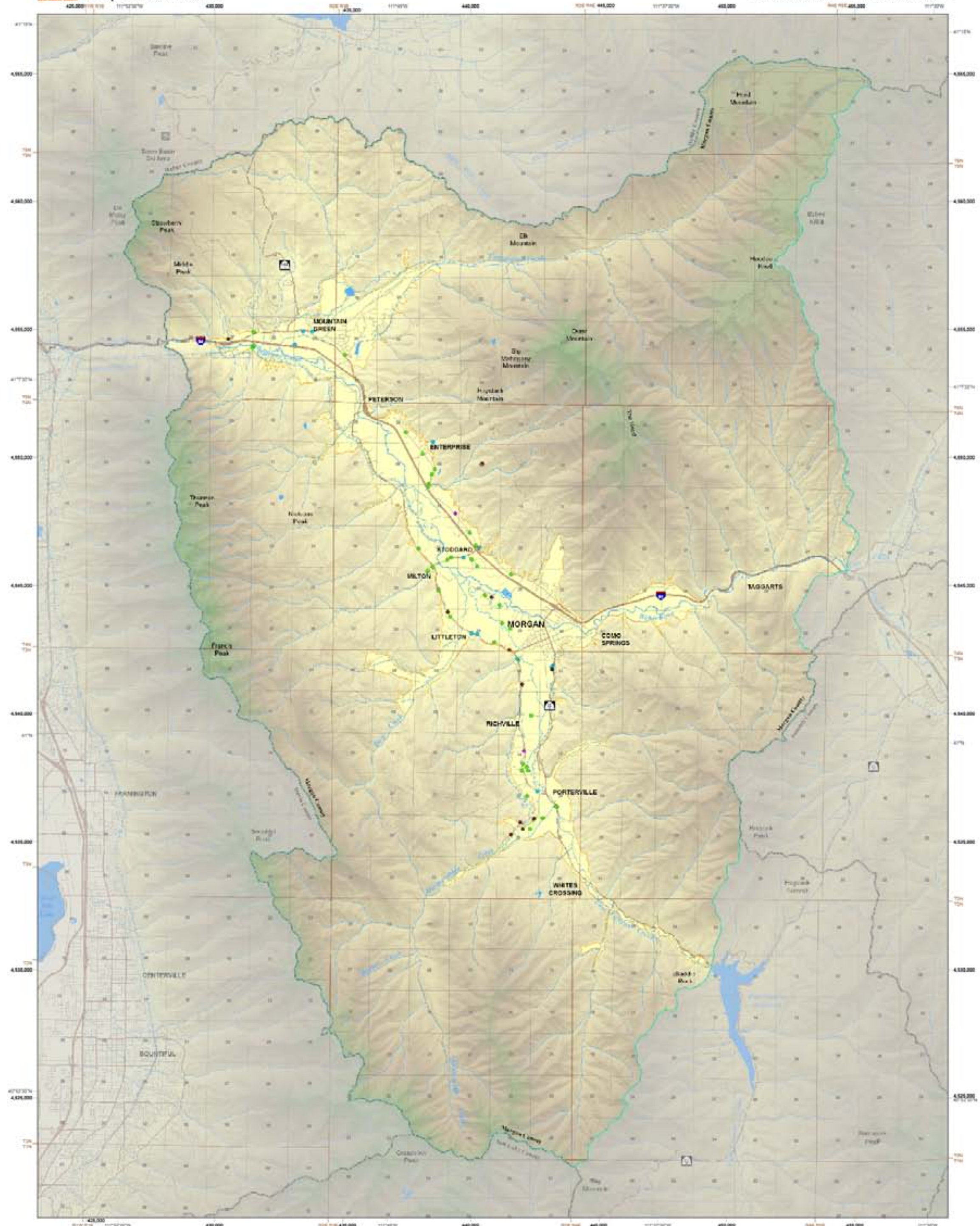
Hydrogeology of Morgan Valley, Morgan County, Utah.



Explanation

Well characteristics

- Bedrock well
- Primary recharge well
- Secondary recharge well
- Discharge well

- Valley fill - primary recharge
- Bedrock - primary recharge
- Morgan Valley drainage basin

- Stream or river
- Canal or aquaduct
- Water body

PLATE 5.
RECHARGE AREA, MORGAN VALLEY, UTAH

by Janae Wallace, Mike Lowe, Jon King, Walid Sabbah, and Kevin Thomas

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N

1 0.5 0 1 2 MILES

1 0.5 0 1 2 3 4 5 KILOMETERS

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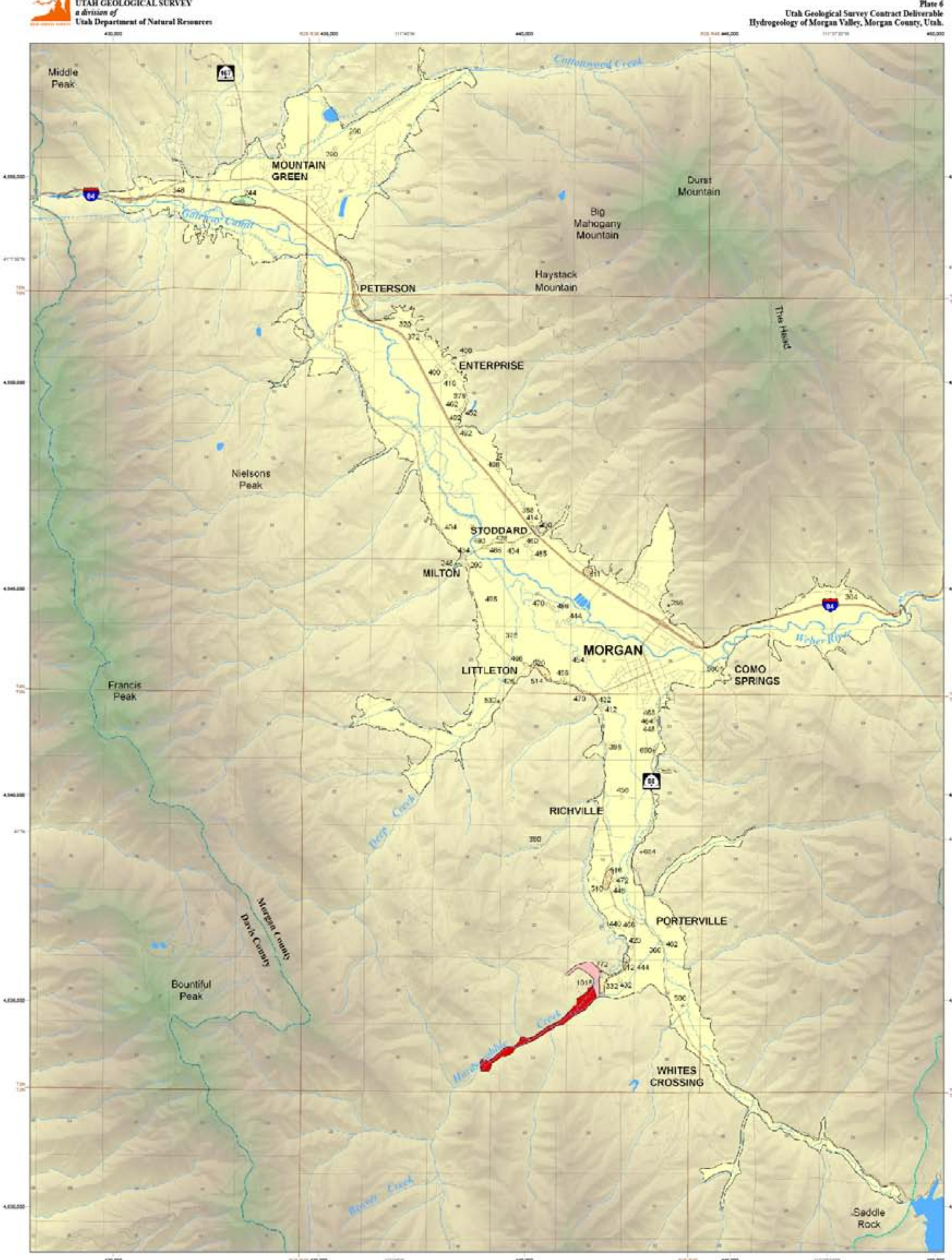

PLATE 6.
TOTAL-DISSOLVED-SOLIDS CONCENTRATIONS FOR THE VALLEY-FILL AQUIFER, MORGAN VALLEY, UTAH

by Janae Wallace, Mike Lowe, Jon King, Walid Sabbah, and Kevin Thomas

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Explanation

Total-Dissolved-Solids Sample Location
- 0 - 250 mg/L
- 251 - 500 mg/L
- 501 - 750 mg/L
- 751 - 1000 mg/L
- 1001 - 1250 mg/L
- Denotes well completed in bedrock

Total-Dissolved-Solids Concentration
- 0 - 250 mg/L
- 251 - 500 mg/L
- 501 - 750 mg/L
- 751 - 1000 mg/L
- 1001 - 2000 mg/L
- Bedrock (not analyzed)

- Stream or river
- Canal or aquaduct
- Water body
- Morgan Valley drainage basin boundary

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1 0.5 0 1 2 3 KILOMETERS
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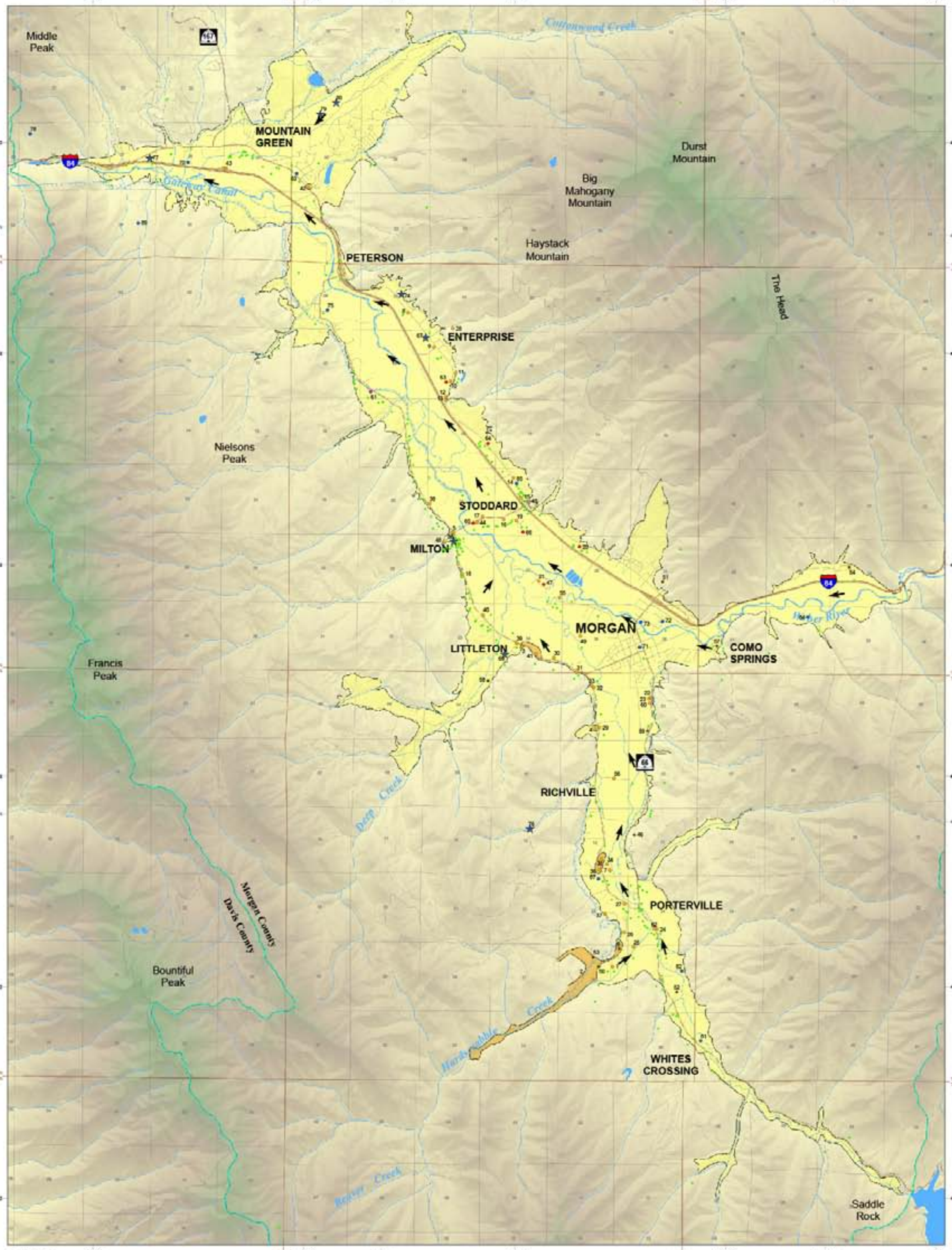
Hydrogeology of Morgan Valley, Morgan County, Utah.



Explanation

Ground-water quality sample location and well ID. Color denotes agency responsible for sampling (see appendix B for chemistry data).

- Utah Geological Survey
- Utah Division of Water Quality
- Utah Department of Agriculture and Food
- Weber-Morgan Health Department
- Halo denotes TDS calculated from specific conductance
- Solid center denotes well competed in bedrock (not used to classify valley-fill aquifer)
- Star denotes a public-supply well
- Perfected water well (DWRi data)

Ground-water quality classification*

- Class IA, Pristine Quality (0-500 mg/L)
- Class II, Drinking Water Quality (500-3000 mg/L)
- Bedrock (not analyzed)
- Morgan Valley drainage basin boundary
- Ground-water flow direction

*From Wallace and Lowe, 2007

PLATE 7.
GROUND-WATER QUALITY CLASSIFICATION FOR THE VALLEY-FILL AQUIFER, MORGAN VALLEY, UTAH

by Janae Wallace, Mike Lowe, Jon King, Walid Sabbah, and Kevin Thomas

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1 0.5 0 1 2 3 KILOMETERS

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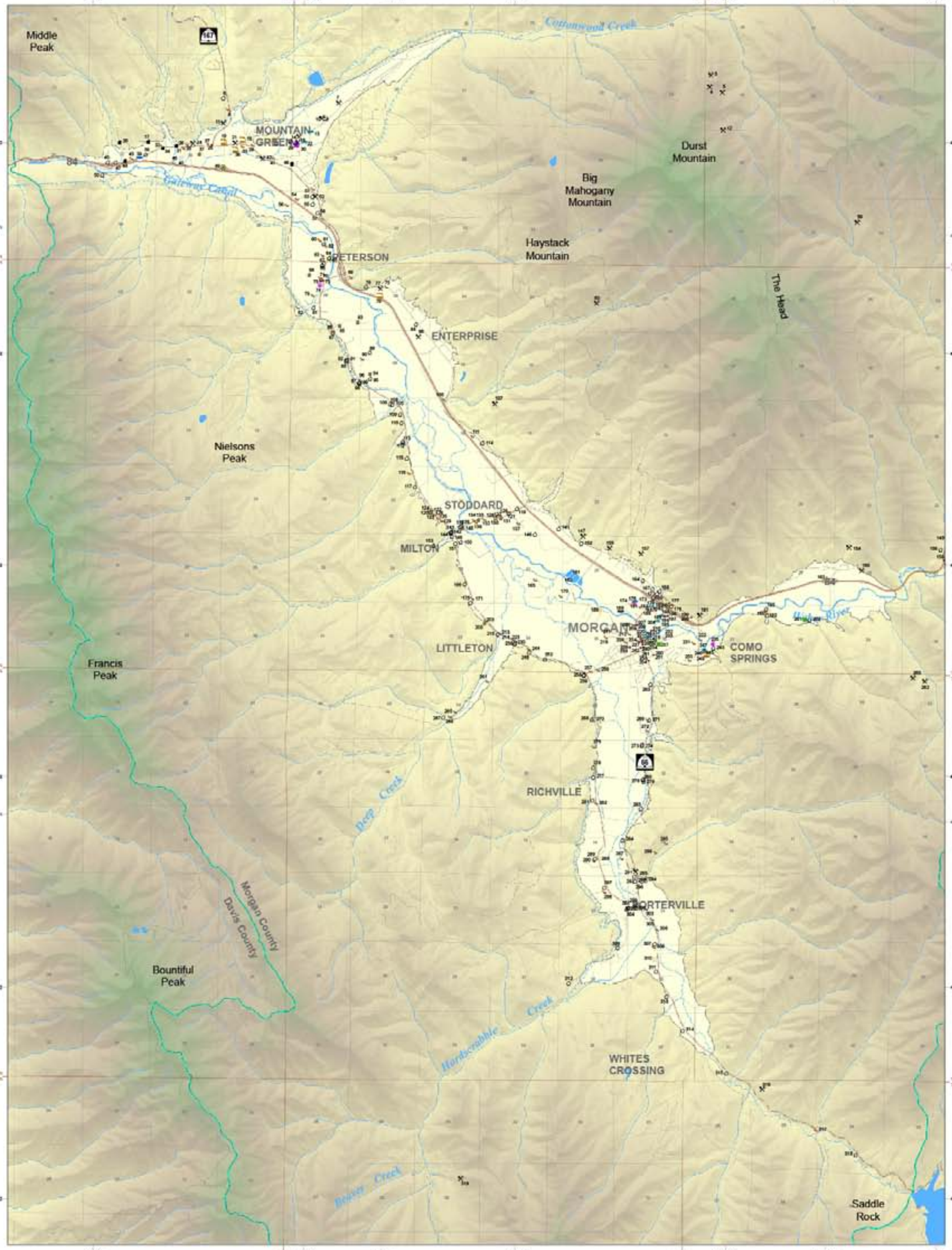

PLATE 8.
POTENTIAL CONTAMINANT SOURCES, MORGAN VALLEY, UTAH

by Janae Wallace, Mike Lowe, Jon King, Walid Sabbah, and Kevin Thomas

2011

Explanation

Potential Contaminant Sources*

- AFO
- Barn area
- Camping
- Commercial
- Equip/vehicle maintenance
- Fish hatchery
- Fuel storer
- Industry & manufacturing
- Junkyard/salvage
- Large lawn
- Mining
- RCRIS
- Remediation
- Residential area
- Rural home
- Substation
- UST/LUST
- Wastewater/sewer
- Valley fill
- Morgan Valley drainage basin boundary

*See Appendix F for description by site ID

1 0.5 0 1 MILES

1 0.5 0 1 2 3 KILOMETERS

SCALE 1:62,500

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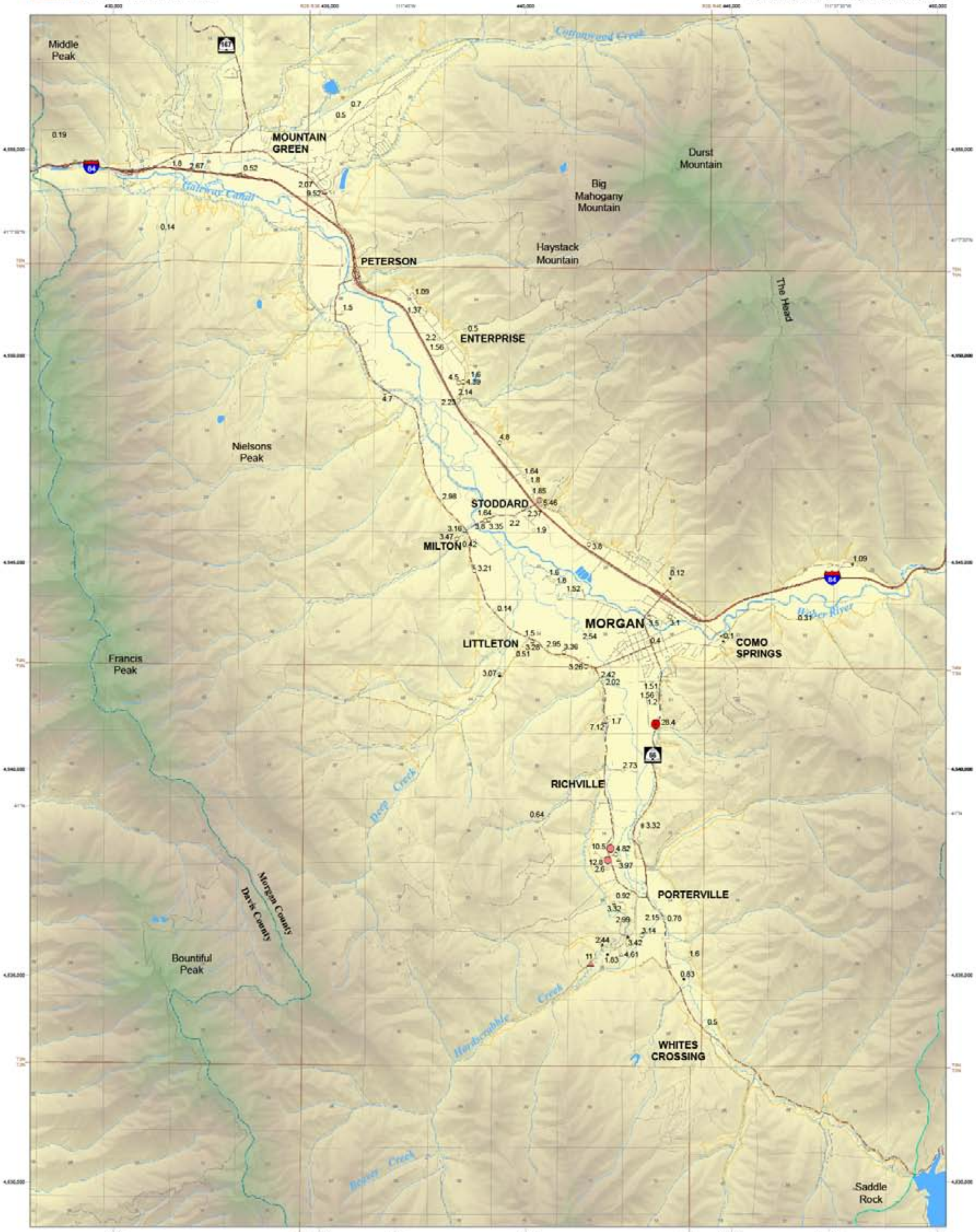

PLATE 9.
NITRATE CONCENTRATION AND LOCATION OF NITROGEN AND OXYGEN ISOTOPE SAMPLES, MORGAN VALLEY, UTAH

by Janae Wallace, Mike Lowe, Jon King, Walid Sabbah, and Kevin Thomas

2011

Explanation

Sample location

- 0.1 - 3.0 mg/L
- 3.1 - 5.0 mg/L
- 5.1 - 10.0 mg/L
- 10.1 - 15.0 mg/L
- 15.1 - 30.0 mg/L
- Valley fill
- Morgan Valley drainage basin boundary

• Solid center denotes well completed in bedrock

△ denotes $\delta^{15}N$ and $\delta^{18}O$ sample ○ denotes only $\delta^{15}N$ sample

N

1 0.5 0 1 MILES

1 0.5 0 1 2 3 KILOMETERS

SCALE 1:62,500

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