CHARACTERIZATION OF THE GROUNDWATER SYSTEM IN OGDEN VALLEY, WEBER COUNTY, UTAH, WITH EMPHASIS ON GROUNDWATER–SURFACE-WATER INTERACTION AND THE GROUNDWATER BUDGET

by J. Lucy Jordan, Stanley D. Smith, Paul C. Inkenbrandt, Mike Lowe, Christian L. Hardwick, Janae Wallace, Stefan M. Kirby, Jon K. King, and Ethan E. Payne

SPECIAL STUDY 165
UTAH GEOLOGICAL SURVEY
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Cover photo: *Ogden Valley and Pineview Reservoir looking southwest from near Geertsen Canyon, August 2019.*

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CHARACTERIZATION OF THE GROUNDWATER SYSTEM IN OGDEN VALLEY, WEBER COUNTY, UTAH, WITH EMPHASIS ON GROUNDWATER–SURFACE-WATER INTERACTION AND THE GROUNDWATER BUDGET

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ABSTRACT

Water resource development and concerns about wastewater disposal methods have prompted the need for a comprehensive study of the quantity and quality of Ogden Valley's groundwater. Ogden Valley is in north-central Utah about 10 miles (16 km) east of the city of Ogden. The valley is home to about 7000 residents in the communities of Huntsville, Eden, Liberty, and dispersed rural and recreational properties. The 44-square-mile (71 km^2) study area encompasses the valley and surrounding mountains and includes Causey and Pineview Reservoirs. Three major streams, the North, Middle, and South Forks of the Ogden River, and their numerous tributaries drain to Pineview Reservoir. The geologic setting along some areas of the watershed boundary creates potential for inter-basin flow of water and cross-boundary well interference in bedrock aquifers. The ridgeline defining the surface water drainage of Ogden Valley may not be the groundwater divide, and we highlight several areas where geologic conditions warrant caution in treating it as such. The groundwater system and the surface water system on the valley floor are well connected through gaining and losing reaches of streams and irrigation canals. The principal valley-fill aquifer is unconfined in the north and east parts of the valley. As groundwater flows south and west toward the outlet of the valley at Ogden Canyon water moves into either the shallow unconfined aquifer or the deeper confined part of the principal aquifer. The confining unit separating the two aquifers is composed of clayey lacustrine silt.

This report presents a new estimate of valley-fill thickness; three valley-fill cross sections; potentiometric, depth-to-water, and water-level change maps; thickness of and depth to the confining unit; a water-level trend analysis; a comprehensive analysis of the stable isotope signatures of stream, groundwater, and reservoir water; an integrated modeling of groundwater age and recharge temperature; a water balance of Pineview Reservoir; and new concepts of leakage through the confining unit, all backed by gross estimates of water-budget components, and a reevaluation of predicted water-quality degradation by future septic tanks.

We completed most fieldwork for this study in 2016. Fieldwork included collecting new gravity measurements for estimating the depth of the unconsolidated valley fill. We sampled wells, springs, and surface water for general chemistry, dissolved metals, stable and radioactive isotopes, and noble gasses. We conducted three seepage runs on streams and the Ogden Valley Canal in 2016. We measured flow in the main tributaries to Pineview Reservoir periodically over a 19-month period to create a stage-discharge relationship using our 15-minute stream stage measurements to estimate streamflow into the reservoir.

Groundwater quality in the principal valley-fill aquifer in Ogden Valley is excellent and has changed only slightly since 1997 when Lowe and Wallace (1999a, 1999b) examined and classified the valley's groundwater. The geometric mean concentration of nitrate in groundwater in the principal aquifer has increased from 0.42 mg/L in 1997 to 0.81 mg/L in 2016. Based on a mass balance model, we project that adding as few as 1540 septic tanks to the system, coupled with a change to full-time housing occupancy, could result in nitrate level in groundwater increasing by 1 mg/L on average. If minimum lot size remains at 3.0 acres, and each lot uses a septic tank, nitrate concentrations may increase to approximately 5 mg/L on average, and there is a high likelihood that some individual wells will exceed the primary drinking water standard of 10 mg/L.

This study uses a soil-water balance model to understand the interaction between unconsolidated valley-fill aquifers, bedrock aquifers, and Pineview Reservoir. We divided the valley into three sub-basins within the watershed to assess the quantity of water for groundwater–surface-water interactions in each. We estimate that in 2016, after subtracting water lost to evapotranspiration, about 158,000 acre-feet of water from precipitation was put into the system. The South Fork sub-basin had 63,000 acre-feet of input water, the North Fork sub-basin had 50,000 acre-feet, and the Middle Fork/Geertsen Creek/Spring Creek sub-basin had 46,000 acre-feet. Precipitation infiltration on the valley floor is high—24,000 acre-feet—compared to many Utah valleys, owing to high precipitation and moderate temperatures. Water supply wells for Ogden City extract more than 12,000 acre-feet of water per year from the confined aquifer, nearly five times the amount all other supply

wells combined extract. We assume the amount of inter-basin groundwater discharge leaving the watershed is very small.

The major findings of this study are:

(1) the valley fill is nearly three times deeper than previously thought;

(2) a more detailed understanding of the thickness and extent of the confining unit shows that the confining unit is relatively thin underlying the reservoir, which, because it is subjected to major downward vertical head gradient in a 2-square-mile (5 km^2) area around the Ogden City well field, is potentially leaking reservoir water to the well field;

(3) water levels in wells in most of the valley-fill aquifer have not had long-term drawdown, but the aquifer may have not reached steady state with the extraction from Ogden City's well field;

(4) streams interact with the aquifer where the water table is shallow; some sections are gaining when the water table is high but losing when the water table falls below the stream bed;

(5) the stream and canal system is net losing on an annual basis, and the Ogden Valley Canal loses nearly half its flow as seepage to the aquifer system in mid-summer;

(6) valley-fill water wells receive about half their recharge from surface recharge, which includes stream and canal seepage and precipitation infiltration, and half from mountain-block recharge;

(7) mountain-block recharge to the valley fill follows a long, slow flow path;

(8) Pineview Reservoir receives more than 31,000 acre-feet of water per year from the groundwater system, mostly from the shallow unconfined aquifer, but also partly from upward leakage through the distal edges of the confining unit; and

(9) a fraction of the water extracted from the Ogden City well field has been recharged recently; one potential source is leakage from Pineview Reservoir.

INTRODUCTION

Ogden Valley, Weber County, is in north-central Utah (figure 1) within the Wasatch Range. The valley is in the Ogden River drainage basin and is situated within a structural trough shared by Morgan Valley to the south. Ogden Valley is experiencing growth, and population trends predict an increase from 6604 people in 2010 to over 28,000 people by 2060 (Ewert, 2014, table 6). Groundwater from springs and wells provides almost all of Ogden Valley's drinking-water supply and much of the municipal water supply for the 83,000 residents of Ogden City (Governor's Office of Planning and Budget, 2012). With increased development in Ogden Valley, more wells are being drilled on the valley floor and in the surrounding mountains. The right to divert groundwater at the new well sites is often coming from applications to change the source of appropriated water from Pineview Reservoir to sites far removed from the reservoir. This movement of points of diversion necessitates a better understanding of the interconnection of the surface water and groundwater systems. Local government officials and water-resource managers need a better understanding of the relationship between geology and groundwater conditions and water-budget constraints to assess the impact of this potential growth and to better appropriate and manage water rights within the area. Potential water quality impacts from development that uses septic tank soil-absorption systems for wastewater disposal are also of concern to residents and water providers.

Purpose and Scope

The primary goals of this study are to (1) characterize the hydrogeology of the Ogden Valley drainage basin as it pertains to the occurrence and flow of groundwater, with emphasis on delineating the valley-fill aquifer thickness and determining the water-yielding characteristics of unconsolidated and fractured-rock aquifers in the study area; (2) understand the interaction between surface water and groundwater; (3) document current groundwater quality in the valley-fill aquifer; (4) develop a water budget for the drainage basin; and (5) update septic-tank system density recommendations based on the water budget. To accomplish these goals, Utah Geological Survey (UGS) personnel:

- Compiled a geologic map of Ogden Valley drainage basin, with accompanying cross section and stratigraphic columns.
- Assembled existing well data, including specific capacity and aquifer test data.
- Estimated aquifer characteristics and produced maps showing the transmissivity for the valley-fill aquifer and bedrock aquifers.
- Measured water levels in wells and constructed a potentiometric surface map for the principal valley-fill aquifer and, where possible, select fractured-rock aquifers. From these data we created depth-to-water and change-over-time maps.
- Delineated the hydrostratigraphy of valley-fill and fractured-rock units and produced three valley-fill cross sections.
- Produced an isopach map for the valley fill using new gravity data.
- Correlated well logs to model the geometry of the confining unit, from which we produced isopach and depth-to-top maps and a 3D model of the top and bottom surfaces of the confining unit.
- Collected groundwater samples and analyzed for environmental tracers and geochemistry.
- Assessed changes in water quality since the 1999 groundwater quality classification.

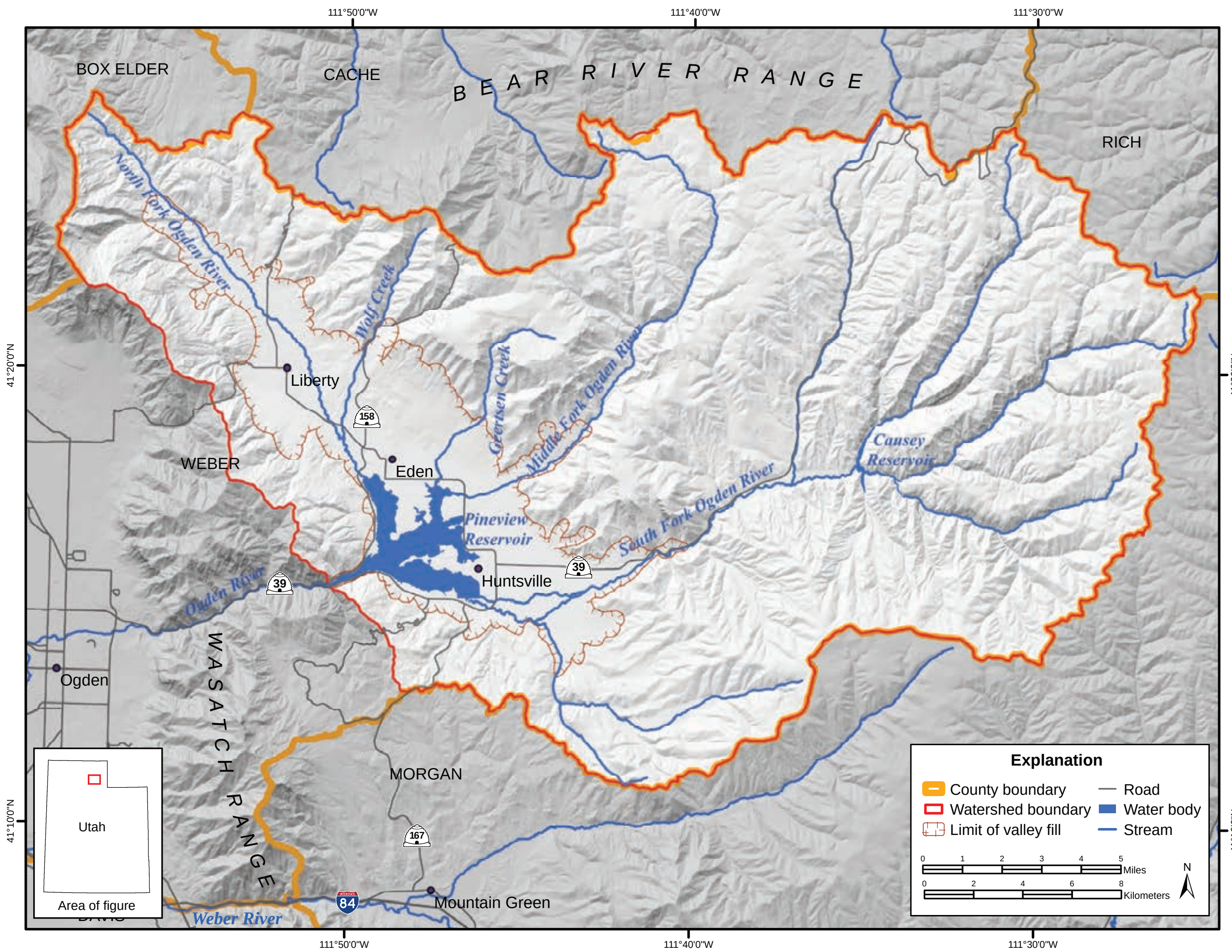


Figure 1. *Ogden Valley study area and geographic setting.*

- Drew conclusions about the groundwater system based on water chemistry type, age of groundwater, the temperature at which water is recharged, and the isotopic signature of stream water compared to groundwater.
- Developed a water balance for Pineview Reservoir, supplemented by stable isotope data.
- Produced a conceptual model of groundwater flow in Ogden Valley drainage basin.
- Developed a hydrologic water budget for Ogden Valley drainage basin, split the budget into three sub-basins, and developed a water budget for the valley-fill aquifer system.
- Calculated expected water-quality degradation based on septic-tank density.

Background Information

Location and Geography

Ogden Valley is in eastern Weber County between 41°13'15" and 41°22'30" north latitude and 111°41'15" and 111°53'45" west longitude and is about 10 miles (16 km) east of Ogden City. The valley floor is approximately 14 miles long and 3.5 miles wide (23 by 6 km), encompassing an area of 44 square miles (114 km^2) (figure 1). Ogden Valley is bounded by the Wasatch Range to the west, the Bear River Range to the northeast, Heard Mountain to the southeast, and a broad, mid-elevation topographic saddle to the south. The valley floor dips gently to the west toward the head of Ogden Canyon and ranges in elevation from approximately 4800 to 5300 feet (1460–1615 m). Several peaks in the surrounding mountains rise to more than 9500 feet (2900 m) above sea level.

The study area boundary is the surface watershed from Pineview Dam to the topographic divide surrounding Ogden Valley, an area of approximately 306 square miles (790 km^2) (figure 1). The study area covers the drainage basin formed by the South, Middle, and North Forks of the Ogden River and their tributaries. The South, Middle, and North Forks of the Ogden River enter the valley from the east, northeast, and north, respectively. These forks, other smaller streams flowing from the surrounding uplands, and valley-floor springs discharge into Pineview Reservoir. Pineview Reservoir began filling in

1937 after the completion of Pineview Dam (figure 2) (U.S. Bureau of Reclamation, 2018). The height of the dam was increased in 1957 to increase the storage capacity to 110,150 acre-feet. Water released from Pineview Reservoir flows west through the Wasatch Range via Ogden Canyon, the only surficial outlet for water in Ogden Valley. Causey Reservoir (storage capacity 7870 acre-feet), located in the canyon of the South Fork River, stores water for release during the summer months to irrigate crops in the valley (figure 1) (U.S. Bureau of Reclamation, 2018).

Ogden Valley is located in the Wasatch Hinterland section of the Middle Rocky Mountains physiographic province (Stokes, 1977). The valley is one of several “back valleys” east of the Wasatch Range including Cache Valley to the north and Morgan and Round Valleys to the south. Ogden Valley was a bay of late Pleistocene Lake Bonneville during the highest levels of the lake (Gilbert, 1890; Currey and others, 1984). As noted by Gilbert (1890), landform features in Ogden Valley related to Lake Bonneville include shorelines, the relatively flat lake-bottom, and an alluvial aggradational plain graded to the Provo shoreline level of Lake Bonneville. Other landforms in the study area are landslides and alluvial fans that pre- and post-date Lake Bonneville, and glacial cirques and moraines. Landforms that post-date Lake Bonneville include river terraces where the three forks of the Ogden River enter the valley, and alluvial fans along the valley margins at the mouths of minor drainages.

Climate

Ogden Valley has a humid continental climate, characterized by large seasonal temperature differences and moderate to high precipitation. Winters are usually cold and wet, while summers are warm and drier. The mean annual temperature at Huntsville is 45.1°F (7.3°C) (Moller and Gillies, 2008) and the mean annual temperature of the basin is slightly cooler at 43.2 ± 2.0°F (6.2 ± 1.1°C) (PRISM Climate Group, 2017a). Huntsville receives an average of 21.94 inches of precipitation annually (Moller and Gillies, 2008). Areas proximal to mountains, especially on the west side, receive a greater amount of precipitation. At Pineview Dam, only about 3 miles (5 km) southwest of Huntsville, the average annual precipitation is about 32 inches (Moller and Gillies, 2008), 48% more than at the Huntsville station. Model-estimated precipitation in the Ogden Valley drainage basin ranges from about 22 inches per year near Huntsville to nearly 68 inches per year in the mountain ranges (PRISM Climate Group, 2017a). Elevation plays a significant role in the type and amount of precipitation received by various areas of the basin (figure 3).

Population and Land Use

Ogden Valley is a rural area that has experienced periods of rapid population growth. In 1960, the population of Ogden Valley was approximately 1536 residents, with about 1000 people living outside Huntsville, the only incorporated town in the valley (Weber County Planning Commission, 1985). Between 1970 and 1980, the valley population grew by 65% to 3241 persons, with 2664 of them living outside of Huntsville (Weber County Planning Commission, 1985). Population growth slowed after 1980 and by 2010, the population of the valley was only 3653 residents (Ewert, 2014, p. 27), including Huntsville. By 2015, another period of population growth brought the population of Ogden Valley to an estimated 7138,

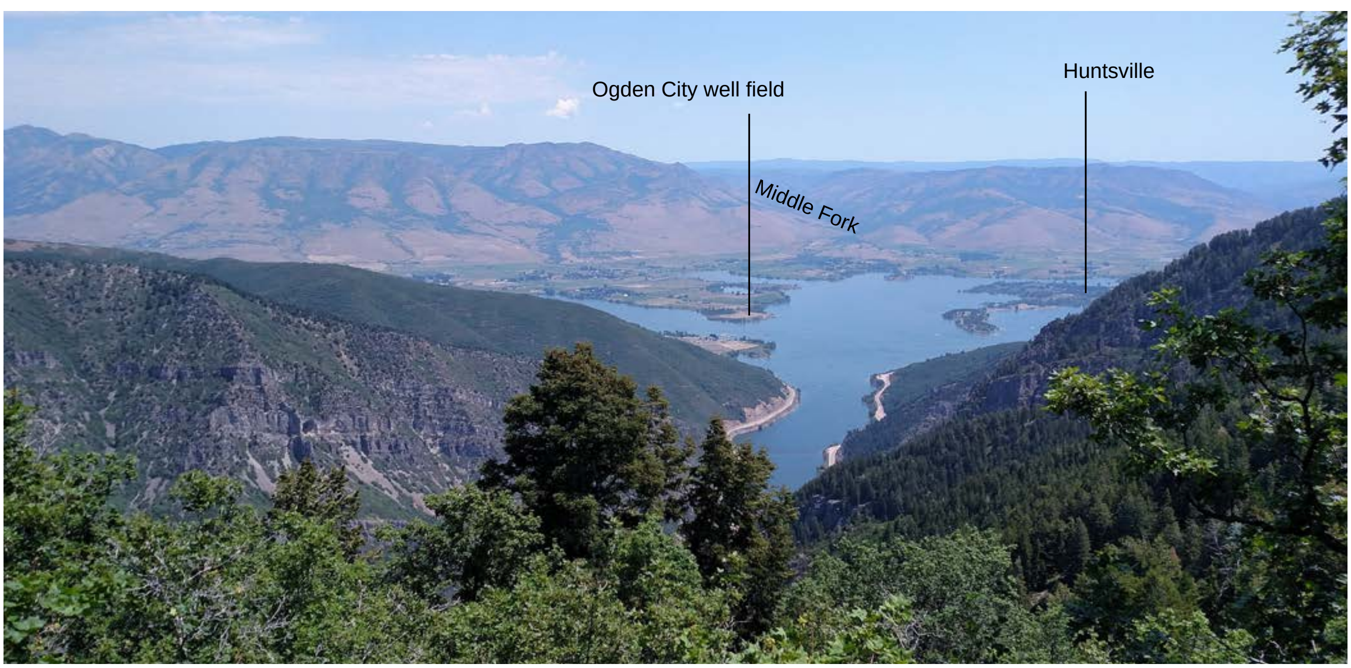


Figure 2. *Ogden Valley and Pineview Reservoir looking northeast from the south wall of Ogden Canyon. Part of Huntsville can be seen on the eastern peninsula.*

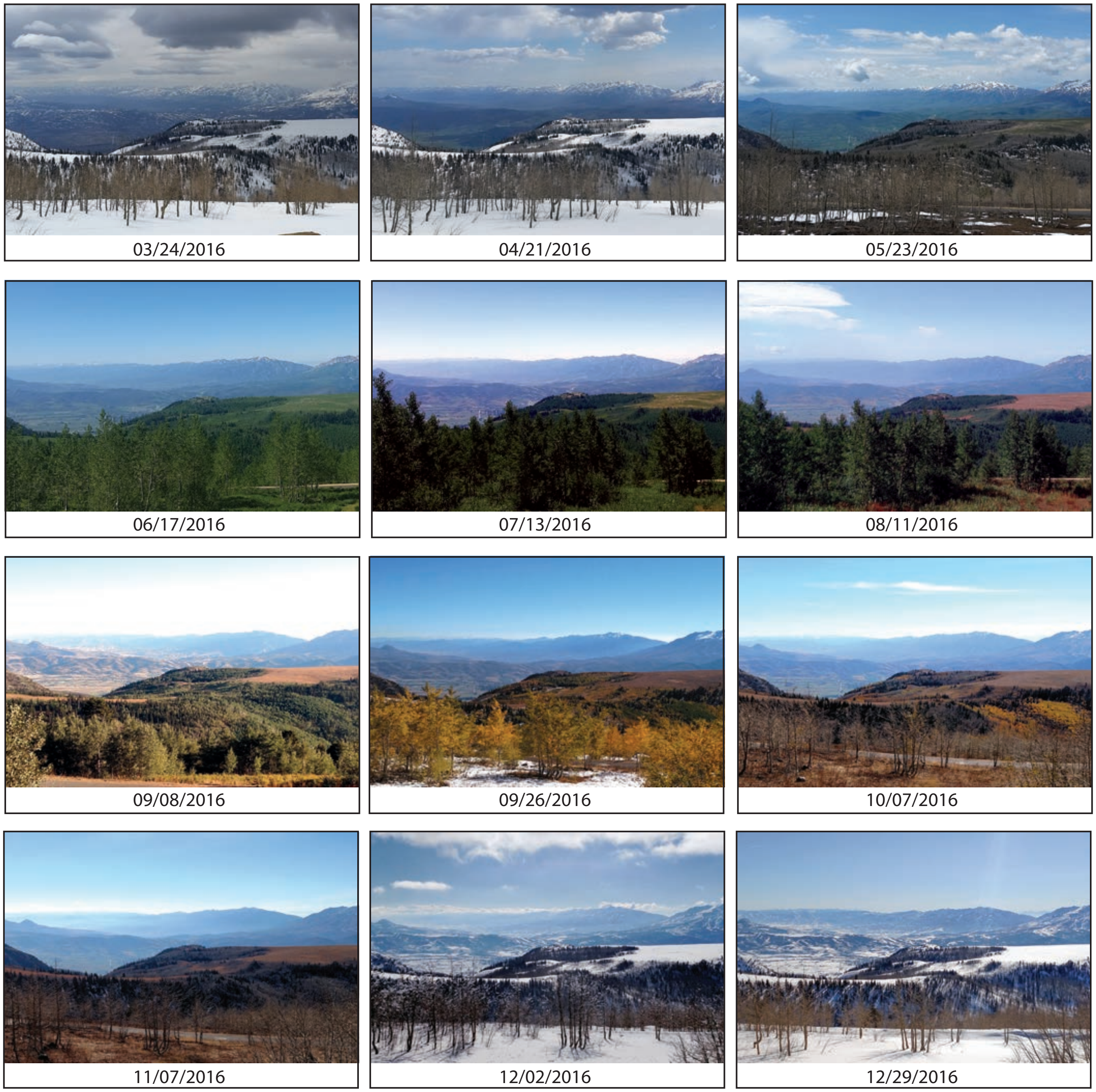


Figure 3. *Ogden Valley and the Wasatch Range as viewed from Powder Mountain Resort in the Bear River Range. Seasonal differences in temperature and precipitation can be inferred from these photos, taken at approximately four-week intervals.*

with 804 living in Huntsville (population of Ogden Valley as defined by the Ogden Valley Census County Division in U.S. Census Bureau, 2017).

A 2014 analysis estimated that approximately 24,100 dwelling units could be built in Ogden Valley under current ordinances, which is 20,500 more dwelling units than present in 2014 (Ewert, 2014, p. 9 and 27, table 6). The population in the valley could potentially increase to over 28,000 by 2060 (Ewert, 2014, table 6). The similarity between the projected number of dwelling units and population at build out is due to the valley's high vacancy rate of nearly 54%. Many of the current and future dwelling units are recreational and/or seasonal-use homes that are not occupied full time (Ewert, 2014, p. 30).

Although agriculture remains an important land-use practice in Ogden Valley, increasing residential development and recreational activities will affect future water-resource and land-use planning. In 2015, over 11,600 acres (5.9%) of land were designated as either irrigated, sub-irrigated or non-irrigated agricultural use (figure 4) (Utah Division of Water Resources, 2015). The latter includes dry farmed crops, fallow and idle

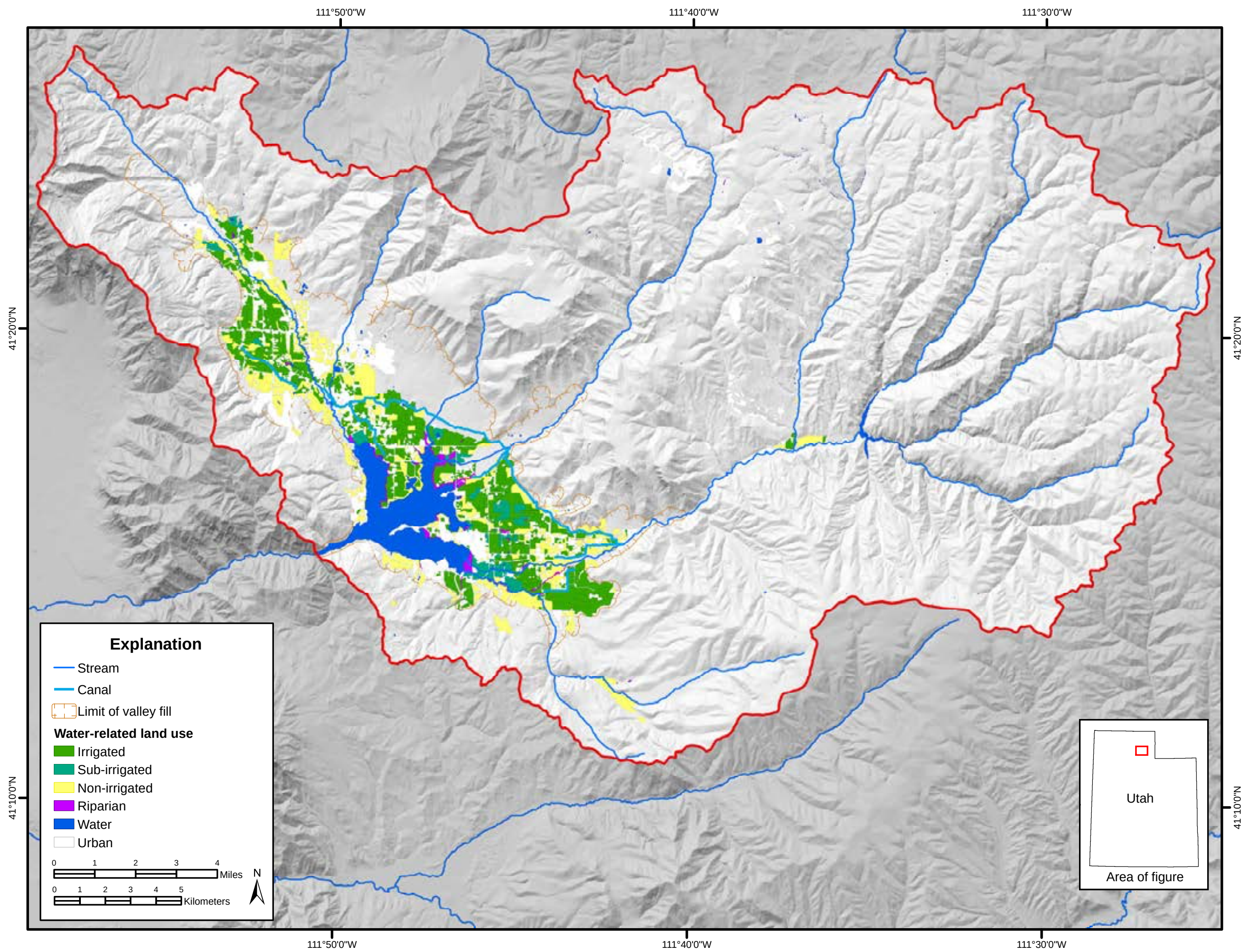


Figure 4. *Ogden Valley water-related land use and location of major canals.*

croplands, and dry land. Ninety-six percent of these agricultural lands are located within the limits of the valley fill, where they comprise 46% of the area, excluding Pineview Reservoir. Urban areas comprise 6340 acres (3.8%) of the basin. Only 73% of urban areas are located within the limits of the valley floor, where they make up 23% of the area.

Water Use and Quality

From approximately 1914 to 1934, the water supply for Ogden City came from 46 flowing artesian wells located in an area near the confluence of the three forks of the Ogden River, near the head of Ogden Canyon, known as Artesian Park (figure 5). Artesian Park is now inundated by Pineview Reservoir. In preparation for filling the reservoir, Ogden City plugged some of the wells and extended others to higher ground on what would become the peninsula between the North Fork and Middle Fork arms of the reservoir. Later, the wells were plugged and new wells drilled.

Between 1935 and 1951, the volume of water withdrawn from the Ogden City well field ranged from 9900 to 16,700 acre-feet per year (acre-ft/yr) (Thomas, 1952, p. 95). Between 1951 and 1970, the wells produced between 9400 and 18,100 acre-ft/yr (Doyuran, 1972, table 9). Groundwater withdrawal for public supply in 2004 was 9500 acre-ft/yr (Burden and others, 2005) and 12,400 acre-ft/yr in 2014 (Burden and others, 2015). Groundwater withdrawals for public supply are expected to increase as development continues in Ogden Valley. All but two of the water suppliers considered public community water systems by the Utah Division of Water Resources are expected to experience water supply deficits by 2060 (Utah Division of Water Resources, 2009, table 8). There are also more than 700 private wells in the study area, most of which are used for domestic supply.

Water quality and the potential for water-quality degradation are critical elements determining the extent and nature of future development in Ogden Valley. Although there are several community sewer systems in Ogden Valley (three lagoon systems and seven common drain fields [figure 6]), most homes (about 2970 dwellings) use septic tank soil-absorption systems for wastewater disposal (Pineview Basin Water-Quality Committee, 1998; Lowe and Wallace, 1999b; Weber-Morgan

Figure 5. *Flowing wells at Artesian Park near the head of Ogden Canyon. The wells provided water to Ogden City beginning in 1914 and were either plugged or extended to the current location of Ogden City well field before the area was inundated by Pineview Reservoir in 1937. All wells were eventually plugged and new supply wells were drilled. Photo credit: Utah State Historical Society, used with permission.*

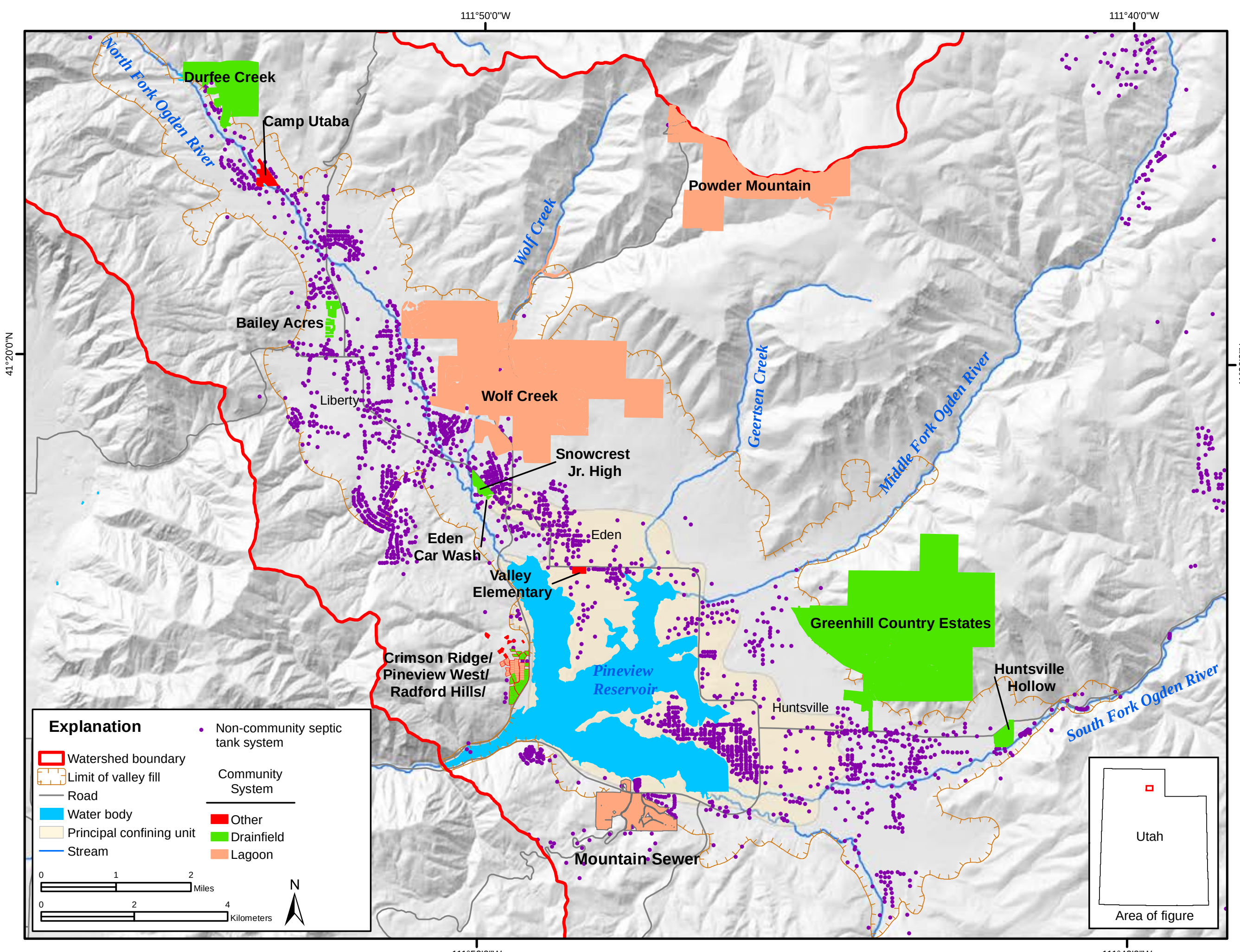


Figure 6. *Ogden Valley wastewater disposal systems in approximately 2015; data from Weber-Morgan Health Department (2017).*

Health Department, 2017). Most of these septic-tank systems are located on the valley floor (we estimate 2206 dwellings) where groundwater is vulnerable to contamination. These valley-fill deposits are also the primary aquifer. The expected growth and concomitant demand on drinking water warrants careful land-use planning and resource management to preserve the existing pristine condition of Ogden Valley's vital water resource.

Previous Work

Early investigations: Stansbury (1852) surveyed the north-central Wasatch Range in search of a new route through the Rocky Mountains. The King Survey (Hague and Emmons, 1877; King, 1878) described the Paleozoic rocks in the vicinity of Durst Mountain. Gilbert (1890) noted evidence of lake sediments and shorelines indicating that Ogden Valley was a bay during the highstand of Lake Bonneville, and described the floor of Ogden Valley as an aggradational plain graded to the Provo Shoreline stage of Lake Bonneville. Atwood (1909) conducted the first detailed survey of glaciation in the Wasatch Range. Blackwelder (1910) studied the complex thrust structure present in Ogden Canyon and described the stratigraphy of Ogden Valley.

General geology: Gilbert (1928) was the first to describe, in detail, the physiographic development of the Wasatch Range and the "back valleys" (or intermontane basins of the foreland) between it and the westernmost border with the Uinta Mountains. Gilbert (1928) concluded that these back valleys developed during uplift of the Wasatch Range as horsts, and the present cross drainages of the range are the result of antecedent structures. In some of the earliest comprehensive investigations of the north-central Wasatch area, Eardley (1933, 1944, 1952, 1955, 1959) worked out some of the complex geologic relations of the region. Stewart (1956, 1958) conducted a gravity survey of Ogden Valley. Threet (1959) and Hunt (1982) described the physiographic development of the back valleys. Hunt (1982) attributed the development of transverse canyons of the Wasatch Range to superposition by streams, which means that the Ogden River maintained its course as the Wasatch Range was uplifted. Sullivan and others (1988) studied Ogden Valley as part of a regional seismotectonic study. Royse (1993) and Peyton and others (2011) studied the Sevier thrust belt in the region and produced cross sections.

Geologic mapping in the Ogden Valley drainage basin: Lofgren (1955) produced a generalized map and discussed the Tertiary and Quaternary stratigraphy of Ogden Valley, although the names and ages of some of his units have been revised. Crittenden and others (1971) worked out the stratigraphy of the Proterozoic metasedimentary rocks around Ogden Valley. Detailed geologic mapping of Ogden Valley includes several thesis maps (Coody, 1957; Laraway, 1958; Eriksson, 1960; Doyuran, 1972; Blau, 1975; Pavlis, 1979; Rauzi, 1979). Geologic quadrangle mapping by the U.S. Geological Survey (USGS) in Ogden Valley, focusing largely on bedrock units, includes that of Mullens (1969), Crittenden (1985), Sorensen and Crittenden (1979), and Crittenden and Sorensen (1985). Parts of Ogden Valley have been mapped by Bryant (1984, 1988) and Davis (1985). Olson (1981) mapped landslides in the southern part of Ogden Valley. Soils in Ogden Valley were mapped by Carley and others (1980).

The southern part of Ogden Valley, including surficial deposits, was mapped by Coogan and King (2006) and King and others (2008). Quadrangles in the northern and eastern part of the Ogden Valley drainage basin were mapped by Coogan (2004, 2006a, 2006b); these maps also include surficial deposits. Appendix A contains an updated part of the larger Ogden 30′ x 60′ geologic map of Coogan and King (2016) and a geologic cross section derived from Coogan (1992).

Hydrogeology: Fortier (1895, 1897) noted the intimate relationship between groundwater and surface water in Ogden Valley during an investigation of seepage water and underflow of rivers in parts of Utah. The office of the Utah State Engineer studied flow of streams in 1921, stream flow/precipitation relationships in 1925, and artesian pressures in flowing wells in Ogden Valley in 1926 and 1928 (Leggette and Taylor, 1937). The U.S. Bureau of Reclamation placed boreholes near the head of Ogden Canyon at the site of Pineview Dam in 1930 (Leggette and Taylor, 1937). Leggette and Taylor (1937) conducted a detailed study of the hydrogeology and subsurface stratigraphy in Ogden Valley. Exposures of varved silt and clay in the valley bottom near the Ogden River were interpreted to be offshore sediments deposited during the highstand of Lake Bonneville (Leggette and Taylor, 1937). Overlying silt, sand, and gravel sediments were interpreted as having been deposited in a lake occupying Ogden Valley during the latter part of the Bonneville stage of Lake Bonneville (Leggette and Taylor, 1937). Leggette and Taylor (1937) identified unconfined (water table) and confined (artesian) aquifers in Ogden Valley. Thomas (1945) studied the confined aquifer in detail and noted that Ogden Valley is exceptional if not unique compared to other Utah artesian basins because of the large quantity of water available for recharge. Thomas (1952, 1953) summarized data obtained from an Ogden Valley test well (Tower Well). Lofgren (1955) studied the Tertiary and Quaternary stratigraphy in Ogden Valley and the relationship of the stratigraphy to the aquifers in Ogden Valley. Lofgren (1955) interpreted Leggette and Taylor's (1937) varved silt and clay, which forms the upper part of the confining bed for the confined aquifer, as pre-Lake Bonneville deposits derived largely from the erosion of phyllites (metamorphic rocks containing mica) in the North Fork of Ogden River drainage, and the overlying silt, sand, and gravel as Lake Bonneville lacustrine sediments. Lofgren (1955) concluded that the flat valley bottom formed during the Provo stage of Lake Bonneville when Bonneville-stage sediments were planed off and graded to the Provo-stage lake level (elevation 4800 feet or 1460 meters) at the mouth of Ogden Canyon.

Morrison, Maierle, and Preator, Inc. (1968, 1969) evaluated iron bacteria problems that developed in some of Ogden City's original artesian wells, the first of which had been drilled in 1914, which were located beneath Pineview Reservoir at the time of their study, and recommended abandonment of the old wells and drilling of the current Ogden City non-artesian well field adjacent to the reservoir. Doyuran (1972) studied the hydrogeology of Ogden Valley and provided data concerning water quality. Lowe and Miner (1990) evaluated nitrate concentrations in Ogden Valley and the possible link of nitrate to septic-tank systems. A USGS study (Avery, 1994) provided new estimates of aquifer characteristics, thickness of valley fill, streamflow measurements, a water budget, and a groundwater flow model. Lowe and Snyder (1996) and Snyder and Lowe (1998) mapped recharge and discharge areas in Ogden Valley. Lowe and Wallace (1997) and Wallace and Lowe (1998, 1999) assessed the potential impact of increasing numbers of septic tanks on water quality in Ogden Valley and provided recommendations for septic-tank system density/lot-size requirements to protect groundwater quality. The Pineview Basin Water-Quality Committee (1998) and Lowe and Wallace (1999b) evaluated wastewater disposal in Ogden Valley and its potential impact on water quality. Lowe and Wallace (1999a) mapped and classified groundwater quality in Ogden Valley.

A few dozen Drinking Water Source Protection plans for public supply wells in Ogden Valley completed since 1996 have produced valuable hydrogeologic data. King (2004) provided water budget estimates for the Powder Mountain region. Loughlin Water Associates, LLC (2013, 2015), Cascade Water Resources (2015), and Inkenbrandt and others (2016) evaluated the hydrogeology of the Powder Mountain area and the Hidden Valley well that was drilled there.

Researchers at Utah State University (USU) and the USU Water Research Laboratory under the direction of Dr. Darwin Sorensen have completed several evaluations of groundwater and surface-water conditions in Ogden Valley, focusing most of their research on Pineview Reservoir nutrient loading and the shallow unconfined aquifer. Worwood (2011), as part of an evaluation of the accuracy of Tetra Tech Inc.'s (2002) total maximum daily loading (TMDL) to Pineview Reservoir estimates, measured surface-water flows, nutrient concentrations in groundwater and surface water, and Pineview Reservoir conditions; Worwood (2011) concluded nutrients entering through the shallow unconfined aquifer represent the single greatest threat to the water quality of Pineview Reservoir. Reuben and others (2011) expanded on the work of Worwood (2011) by looking at sources of nitrogen and phosphorus loading to Pineview Reservoir and provided estimates of hydraulic conductivity and nutrient concentrations in the shallow unconfined aquifer. Carrigan (2012) examined nonpoint source pollution via tributaries to Pineview Reservoir, focusing primarily on the South Fork of Ogden River. Worwood and Sorensen (2012) augmented Worwood's (2011) work by providing a water balance and mass balance for phosphorous in Pineview Reservoir. Reuben (2013) characterized nutrient transport from the shallow unconfined aquifer to Pineview Reservoir, quantified and characterized the spatial variability of groundwater flow and nutrient loading in Ogden Valley based partly on monitoring wells installed in the shallow unconfined aquifer, and used computer modeling to estimate nitrate leaching to groundwater from cropland, lawns, and septic-system drain fields in the Ogden Valley drainage basin. Reuben and Sorensen (2014) expanded on Reuben's (2013) nitrogen leaching modeling; Reuben and Sorensen (2014) concluded that as cropland is being replaced by lawns as development occurs, nitrate concentrations in aquifers could increase in the areas undergoing development. Rumsey (2014) looked at phosphorous and nitrate concentrations in the shallow unconfined aquifers based on data from Reuben's (2013) shallow wells, and concluded that several of the wells were yielding groundwater degraded by upgradient septic-tank systems. New bathymetry of Pineview Reservoir produced by Winkelaar (2010) was used in many of these studies.

Geologic Setting

The study area is in the Cretaceous and early Tertiary-age Sevier fold and thrust belt of western North America. The thrust belt is defined by a series of easterly-directed thrust plates and related folds. Much of the Ogden Valley area lies on the Willard thrust sheet (for more details see Coogan [1992], Royse [1993], and Yonkee [1997]). The valley floor of Ogden Valley is part of a northwest-trending graben in which great thicknesses of sediment have been deposited since the early Tertiary (see Constenius [1996] for example) (appendix A). About 7000 feet (2130 m) of Tertiary rocks are exposed to the south in the Snow Basin quadrangle, and these rocks thin to the north toward Ogden Valley (King and others, 2008). About 2000 feet (600 m) of Tertiary rocks are exposed on the west side of Ogden Valley. On the east side of the valley, the Tertiary rocks are only visible in sparse, small outcrops and construction excavations.

Geologic units: Proterozoic and Paleozoic rocks, between about 1800 and 250 million years old (Ma), are exposed in the mountains around the valley (plates A-1 and A-2 in appendix A). These rocks are principally Proterozoic metamorphic rocks of the Farmington Canyon Complex (mostly gneiss and schist) and metasedimentary rocks of the Willard thrust sheet (mostly quartzite, phyllite, and argillite; see plate A-1 in appendix A). The phyllite and argillite have low permeability and are prone to mass movement. Younger Paleozoic sedimentary rocks (~540 to ~250 Ma) of the Willard thrust sheet exposed west and east of Ogden Valley are mostly dolomite and limestone, but also include sandstone and shale (plate A-1 in appendix A). Overlying these rocks in angular unconformity are the Upper Cretaceous Evanston Formation and Paleocene-Eocene Wasatch Formation (~75 to 50 Ma). These younger rocks consist of conglomerate, sandstone, and mudstone related to uplift of the older rocks during formation of the Sevier fold and thrust belt.

Much of the eastern, western, and southern margins of Ogden Valley consist of younger, less consolidated Eocene-Oligocene- and possibly Miocene-Pliocene-age rocks that were deposited between about 50 and 3 Ma. These rocks consist of claystone (altered tuff) and minor amounts of altered tuffaceous sandstone and conglomerate of the Norwood Tuff, Fowkes, and Salt Lake Formations. Coogan and King's (2016) geologic map combines some of these rocks into the Norwood Formation. Throughout this document, we use their nomenclature when referring specifically to their mapping, but we use Norwood Tuff to refer to the thick, dominantly tuffaceous sediments described in well logs to be consistent with regional stratigraphy (Hintze and Kowallis, 2009). The Norwood Tuff is largely impermeable and prone to mass movement. The tuffaceous rocks unconformably overlie older rocks and underlie younger valley-fill deposits in most areas (plate A-1 in appendix A) (see also Coogan and others, 2015).

Remnants of Pliocene and/or Pleistocene alluvial deposits are present on the east side of Ogden Valley. These early alluvial fans extend to the mountain fronts at elevations of about 6800 to 7200 feet (2070–2200 m) (King and McDonald, in preparation; Coogan and King, 2006; King and others, 2008). Thin remnants of high-level alluvial deposits consisting of quartzite boulders overlie the Norwood Formation on slopes on the east side of Ogden Valley, and similar outcrops occur on middle elevation hills south of Ogden Valley in the Snow Basin quadrangle (King and others, 2008).

Quaternary unconsolidated deposits cover most of the floor of Ogden Valley. The unconsolidated deposits consist of stream, alluvial-fan, landslide, and lacustrine sediments, and minor glacial sediments of Pleistocene and Holocene age.

Geologic history: The Precambrian Farmington Canyon Complex was metamorphosed and deformed in the late Proterozoic (see Barnett and others, 1993; Yonkee and Lowe, 2004). These rocks and Paleozoic strata were faulted and folded during the Cretaceous and Eocene as part of the Cordilleran orogeny and broad folding produced by uplift of the Wasatch anticlinorium (Yonkee and others, 1997) (see plates A-1 and A-2 in appendix A). This deformation produced low-angle to bedding-plane thrust faults, with repetition and uplift of rocks that are now the Wasatch Range, as well as associated folds, reverse faults, and normal faults (Yonkee, 1992; Yonkee and others, 1992; Yonkee, 1997; Yonkee and others, 1997). Some of the faults formed during the orogeny were reactivated during later normal-fault extension (Coogan and others, 2015; Coogan and King, 2016). Cenozoic extension began at least 40 million years ago (Ma) and possibly as early as 50 Ma (Constenius, 1996; Coogan and others, 2015). This extension produced northwest-southeast-trending normal faults that down-dropped the valley relative to the surrounding mountains, creating the Ogden Valley graben. Some offset on the normal faults is likely due to stress-relaxation and collapse of the Cordilleran fold-and-thrust belt (Constenius, 1996) during latest Eocene and Oligocene time. During this extension, about 6000 to 7000 feet (1800–2100 m) of Norwood Formation filled Morgan Valley south of Ogden Valley. The Wasatch Formation and overlying Norwood Formation were likely folded into the north-plunging Morgan Valley syncline during the Miocene; the syncline ends south of the study area (King and others, 2008; Coogan and others, 2015). Middle Miocene and younger Basin and Range faulting (Sullivan and others, 1988; McCalpin, 1993) is indicated by roughly northwest-southeast-striking normal faults that cut the Norwood Formation and Quaternary deposits (King and McDonald, in preparation; King and others, 2008; Coogan and others, 2015; Coogan and King, 2016). Extension is ongoing in the region—faults in the east Ogden Valley and North Fork fault zones cut surficial deposits, and faults in the west Ogden Valley fault zone may locally cut surficial deposits (plate A-1 in appendix A).

Deep lake cycles in the Bonneville basin and valley-fill deposits in Ogden Valley: The study area is in the hydrologically closed Lake Bonneville basin (figure 7), and water flowing into this basin leaves only by evapotranspiration. Climatic cycles in the Bonneville basin—cooler and wetter glacial/pluvial intervals coupled with warmer and drier interglacial/interpluvial intervals—have had significant impact on depositional processes in the basin (Machette and others, 1992; Oviatt and Shroder, 2016). Generally coarse-grained fluvial and alluvial sediments that fine toward the basin axis were most commonly deposited during interglacial intervals. During glacial/pluvial intervals, deltaic sediments at the mouths of major drainages and fine-grained offshore deposits underlain and overlain by coarser-grained transgressive and regressive nearshore sediments were common. Thick sequences of fine-grained offshore silt and clay were deposited during deep lake cycles, of which there were at least three during the last 200,000 years (Scott and others, 1983; Oviatt and others, 1987).

Definition of Aquifers

Previous hydrogeologic studies in the Ogden Valley drainage basin have focused primarily on the valley-fill aquifer. Groundwater in the valley occurs under perched, confined, and unconfined conditions in Quaternary unconsolidated valley fill (figure 8) (Leggette and Taylor, 1937; Thomas, 1945; Lofgren, 1955; Doyuran, 1972; Avery, 1994). In the southwestern part of Ogden Valley, lacustrine silt and clay form an extensive layer in the upper part of the valley-fill aquifer system (Leggette and Taylor, 1937; Thomas, 1945; Lofgren, 1955; Doyuran, 1972). This extensive layer creates confined conditions for underlying groundwater flow and is herein referred to as the confining unit. The valley-fill deposits below the confining unit contain sand and gravel, but also discontinuous low-permeability silt and clay lenses. The aquifer in these deposits below the confining unit is referred to as the confined aquifer, or because of its importance as a water resource, the confined principal aquifer. Away from the confining unit, groundwater in the valley fill is unconfined (Leggette and Taylor, 1937). Many wells are drilled in these deposits and they receive the bulk of recharge to the valley-fill aquifer system, so these deposits are referred

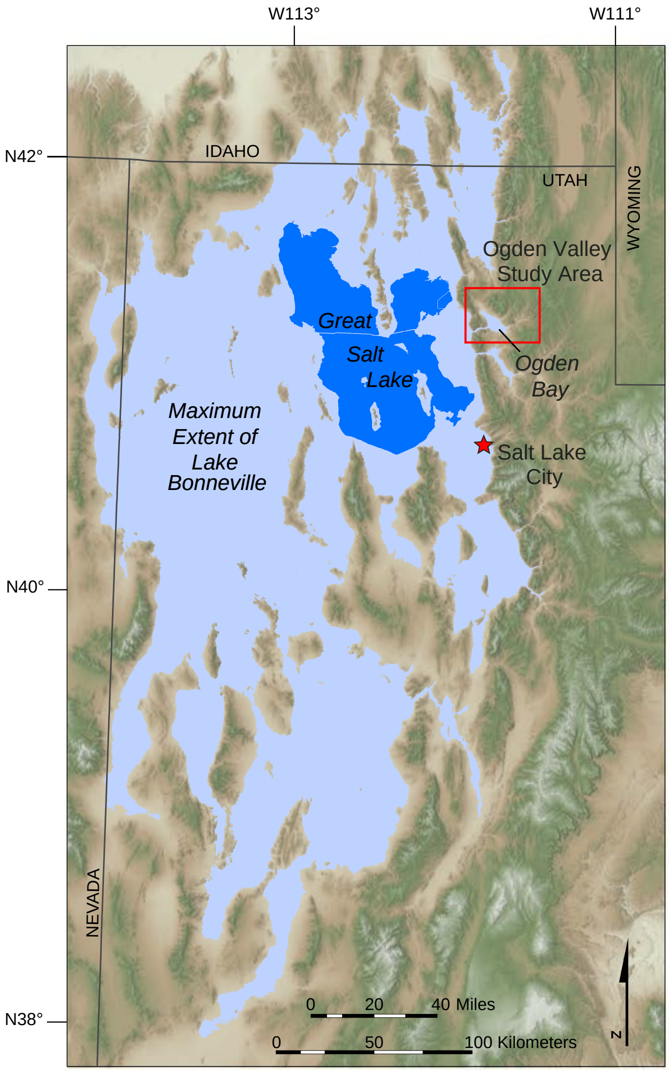


Figure 7. *Maximum extent of Lake Bonneville (after Currey and others, 1984).*

to herein as the unconfined principal aquifer. When both confined and unconfined parts of the aquifer are discussed as a whole, the aquifer is referred to as the principal aquifer (Avery, 1994; Snyder and Lowe, 1998; Lowe and Wallace, 1999a; Lowe and Wallace, 1999b). Groundwater in sediments above the confining unit is unconfined and is referred to as the shallow unconfined aquifer (Lowe and Miner, 1990). Few wells are present in this aquifer, but it plays a key role in groundwater flow to Pineview Reservoir. The shallow unconfined aquifer grades laterally to the unconfined principal aquifer. Together, the confined and unconfined parts of the principal aquifer and the shallow unconfined aquifer form the valley-fill aquifer system (Avery, 1994, p. 27).

Well and Site Numbering

Any location for which we present data in this study, whether point locations such as wells or line locations such as reaches of streams, is given a unique numerical identifier, or "hydroID." The number was sequentially generated by the mapping software and has no relation to location. We use prefixes to designate well (WL), stream (ST), spring (SP), precipitation (PRCP), snow (SNW), or reservoir (RES) locations in some tables and figures that show multiple types of sites, e.g. WL-763 is a well and SP-3672 is a spring. Locations are sometimes also referred to by identifiers given by other government agencies. The USGS and the Utah Division of Water Rights (Water Rights) use an identifier based on quadrant of the state, township, range, section, and sub-section location of the site; e.g., (A-6-1)18bad-1 is the first site in the northeast quadrant, township 6 north, range 1 east, southeast quarter of the northeast quarter of the northwest quarter of section 18. The USGS also uses a 14-digit numerical identifier based on latitude and longitude, e.g., 411544111461001.

GEOLOGY, HYDROSTRATIGRAPHY, AND THE NATURE OF AQUIFERS

Geologic Map

The geologic map, cross section, and stratigraphic columns provide the foundation for our hydrogeologic interpretations. The geologic map (plate A-1 in appendix A) is a clipped and modified portion of the Ogden 30′ x 60′ geologic map of Coogan and King (2016). The geologic cross section (plate A-2 in appendix A) is modified from Coogan (1992). Most of the surficial deposits on the map and cross section have been removed from the mountainous bedrock areas of the study area to better show geologic structure.

Delineation of Hydrostratigraphy

We grouped geologic units into three qualitative hydrostratigraphic categories that include a regional aquifer unit, a unit with mixed properties, and a regional confining unit for each of the three stratigraphic type-sections for the Ogden Valley study area. This categorization is based largely on information derived from our compiled aquifer test and specific capacity data. Aquifer units consist of coarse-grained clastic units that include unconsolidated sand and gravel of the valley fill, and sandstone, conglomerate, limestone, and dolomite rock units that yield water to wells. Confining units consist of fine-grained unconsolidated clay and silt of the valley fill, and shale, siltstone, and metamorphic-rock units that do not yield sufficient quantities of water to wells. Geologic units with multiple rock types, such as interbedded limestone and shale, and some quartzite units are classified as units having mixed properties. Water-yielding properties of unconsolidated deposits are determined by primary porosity and permeability, whereas the water-yielding properties of consolidated rocks are determined by secondary porosity and permeability resulting from fractures and dissolution features. Fracture apertures in carbonate rock can be enhanced by dissolution of the aquifer matrix. We also considered the number and distribution of wells in Ogden Valley when we delineated hydrostratigraphy.

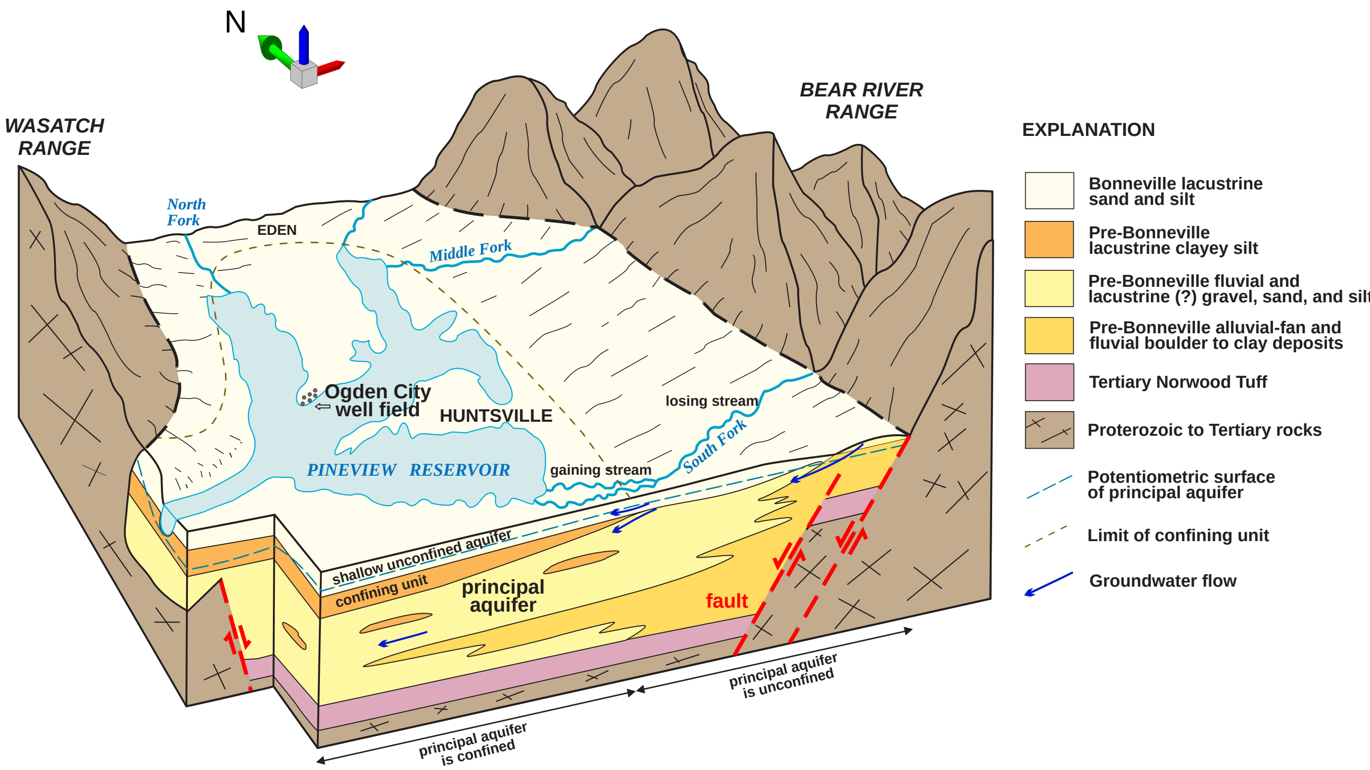


Figure 8. *Simplified block diagram of the Ogden Valley hydrogeologic system (modified from Lowe and Miner, 1990).*

Hydrostratigraphic units are presented on figure 9 and their areas of outcrop are shown on figure 10. Hydrostratigraphic units are delineated for each of the three unique stratigraphic sections that define the geologic units exposed in the study area (figure 9).

The most important aquifer group in Ogden Valley is the unconsolidated sand and gravel aquifers (QsgA). The unconsolidated sand and gravel aquifers cover about 15% of the watershed area, filling most of Ogden Valley and the bottoms of the mountain canyons (figure 10). QsgA aquifers yield water to the most wells and they occur in areas which receive recharge from streams, canals, and precipitation or applied irrigation. The confined and unconfined parts of the principal aquifer, the shallow unconfined aquifer, and any perched unconsolidated aquifers that may yield water locally to wells make up the QsgA unit.

Important bedrock aquifer units include Mesozoic and older sandstone and carbonate rock aquifers (JssA, ₱PssA, PZcaA, ЄsiA, ЄqA) from which many of the valley's large springs discharge. Many fewer wells are completed in these units than the unconsolidated aquifers because of their outcrop distribution in mountainous terrain (figure 10).

Rocks of the Cretaceous and Tertiary conglomeratic aquifer unit (KTcgA) (chiefly Cretaceous Wasatch Formation and other conglomerates) cover about 40% of the surface area of the Ogden Valley watershed, primarily in the eastern half of the study area along the upper reaches of the South Fork of the Ogden River (figure 10). Absolute thickness of this unit in the eastern half of the study area is poorly constrained. The unit overlies carbonate and siliciclastic aquifers. Although this unit is heterogeneous, its large outcrop over an area that receives a high amount of precipitation has influenced our classification as an aquifer unit.

Regionally important impermeable rocks include mostly Proterozoic siliciclastic rocks that consist of shale, mudstone, argillite, and quartzite (ZsiC) (figure 9). These rocks consist of sedimentary and low-grade metamorphic rocks that generally have very low primary permeability and, as a whole, fractures are not well enough connected to have significant regional permeability. This unit locally yields water to numerous domestic and community wells.

Within Ogden Valley, the Tertiary Norwood Formation (TvC) is classified as a confining unit based on its mineralogy, low permeability reported in drillers' logs, and its tendency to weather to clay. This unit locally yields water to a small number of wells.

Heterogeneous aquifer units (green on figure 10) may have both permeable and impermeable units within them, but because of the limited thickness of the permeable units, they do not act as important regional aquifers (figure 9). Landslide deposits occur on steep slopes and around the margins of the valley (QmmH), and heterogeneously fractured Cambrian and older quartzites (ЄZqH) are located primarily in the mountains on the east side of the North Fork drainage and high elevation in the Middle Fork drainage (figure 10).

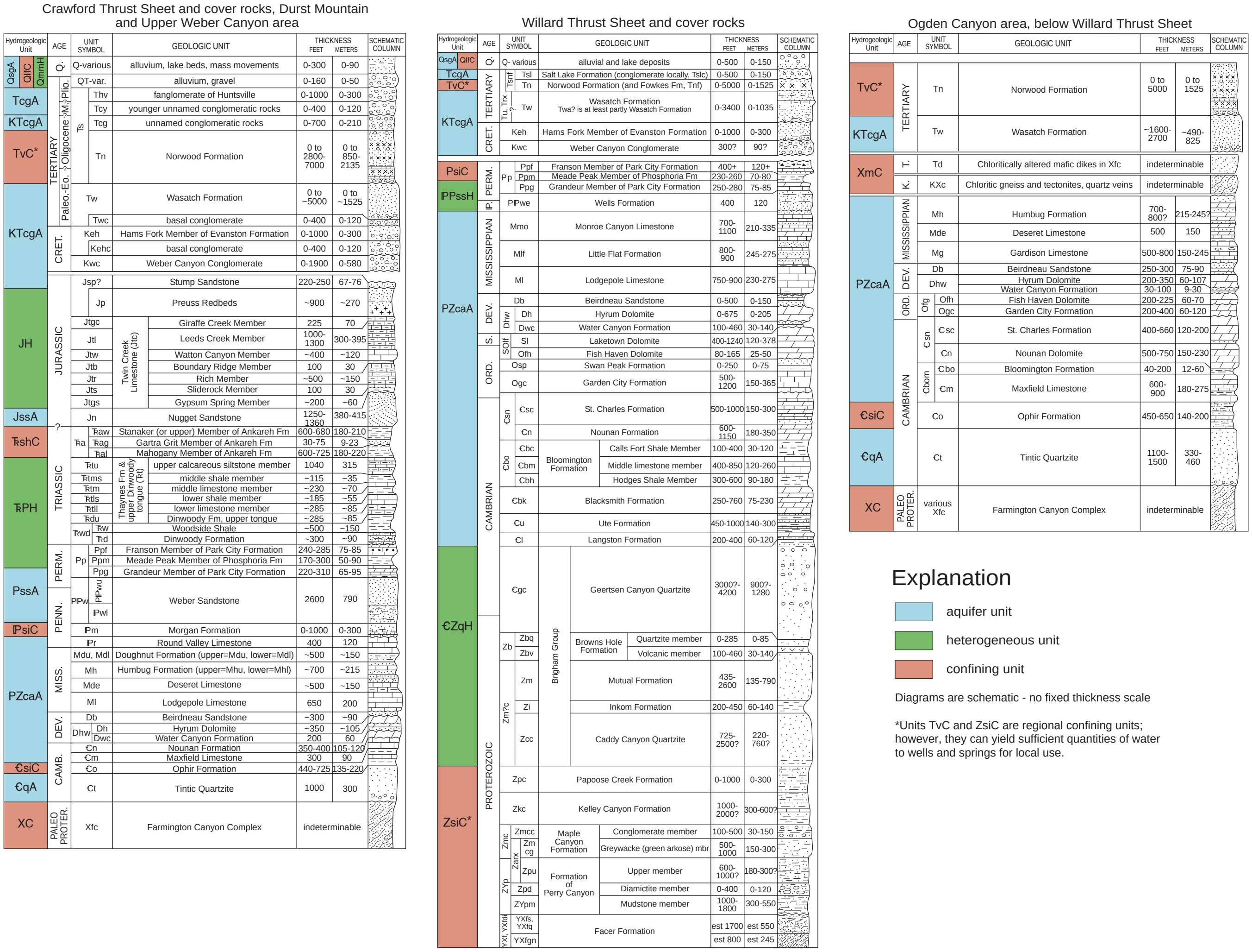


Figure 9. *Stratigraphic columns of rocks in the Ogden Valley study area. Units having similar hydrogeologic properties are grouped into aquifer, heterogeneous, and confining units. Cross sections shown on plate 1. See figure 10 for explanation of hydrogeologic unit symbols.*

Watershed Boundary Classification

We divided the watershed boundary into three broad categories of risk of inter-basin groundwater flow based on rock type from the geologic map (plate A-1 in appendix A) and assumed permeability. This methodology is necessarily simplified and is intended to provide a qualitative assessment of the potential for groundwater connection across a given part of the watershed boundary. The three categories are broadly defined as low-, moderate- and high-risk boundaries.

Low-risk boundaries consist of areas where the geologic units underlying the watershed boundary are relatively impermeable. In these areas it is unlikely that wells completed within 1000 feet (300 m) of the boundary could affect groundwater conditions on the other side of the watershed boundary. Moderate-risk boundaries consist of areas where geologic units underlying the watershed boundary are moderately permeable or the permeability is unconstrained. In these areas it is possible that wells completed within 1000 feet of the boundary could affect groundwater conditions on the other side of the watershed boundary. High-risk boundaries consist of areas where the geologic units along the watershed boundary are permeable. In these areas it is likely that wells completed within 1000 feet of the boundary will affect groundwater conditions on the other side of the watershed boundary.

Low-risk boundaries occur in the southwest corner the watershed where relatively impermeable Norwood Formation makes up much of the watershed boundary (figure 10). We classified 33% of the study area boundary as having low risk of inter-basin flow.

Moderate-risk boundaries occur along the eastern half of the watershed boundary where extensive exposures of permeable Cretaceous and Tertiary conglomeratic rocks (KTcgA) obscure the type and structure of the underlying bedded sedimentary rocks. The underlying structure may be such that pumping of the older sedimentary rocks outside the watershed near the boundary may induce groundwater flow out of the Ogden Valley basin (figure 10). We estimate 53% of the watershed boundary is at moderate risk of inter-basin flow.

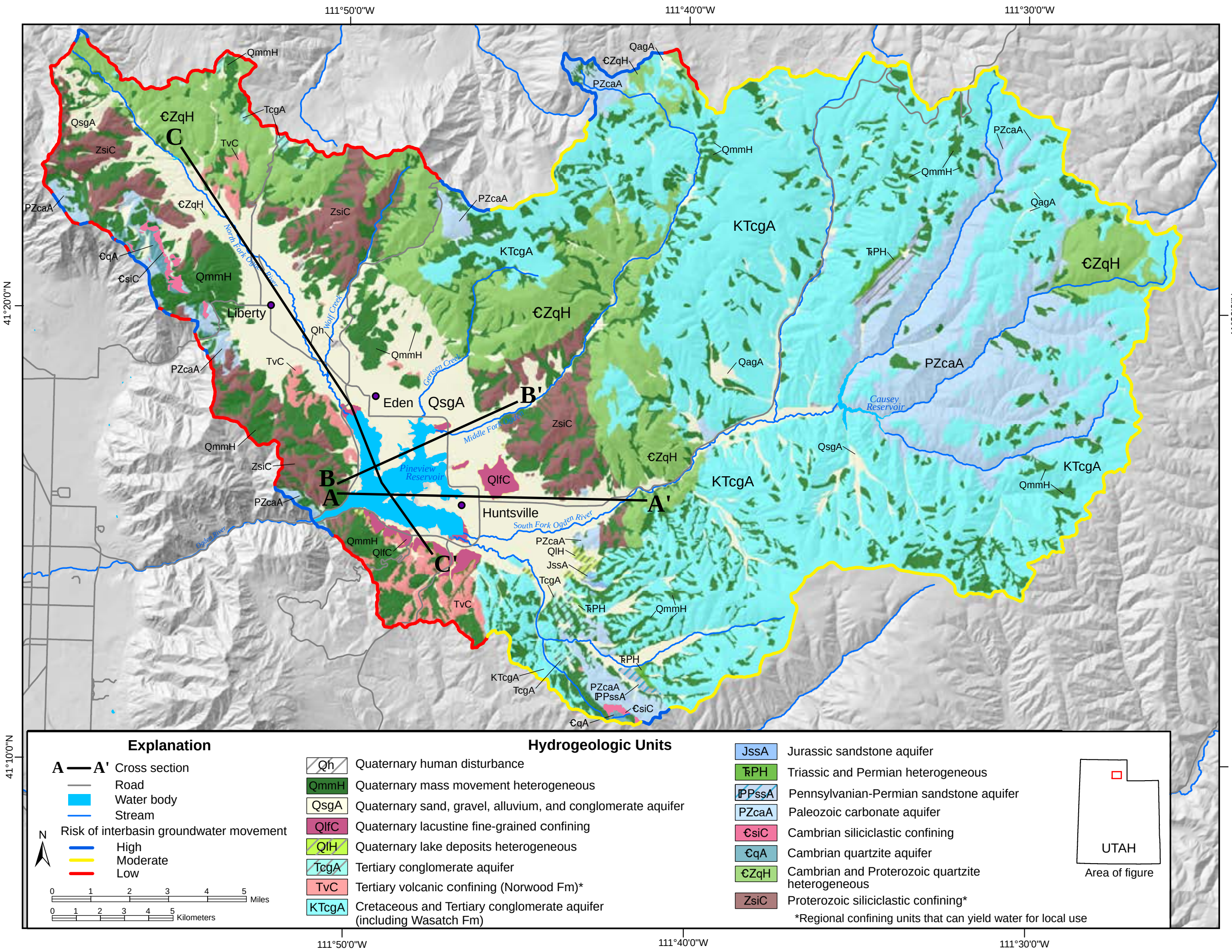


Figure 10. Distribution of hydrogeologic units in the Ogden Valley study area. Aquifer units are depicted in shades of blue, the valley-fill aquifer in tan, aquitards in shades of red, and units of mixed hydrogeologic properties in shades of green.

High-risk boundaries occur sporadically along the northern and western watershed boundary where permeable carbonate rocks straddle the boundary (figure 10). While the relative percent of the watershed boundary classified as high risk is small (14%), two high-risk areas are of immediate importance to this groundwater study. First, the bedrock on either side of Ogden Canyon at the low point of the watershed is permeable Paleozoic carbonate rocks (PZcaA) (figure 10). Groundwater discharge out of the basin may occur at this location. Second, groundwater-resource development is currently occurring and may occur in the future near high-risk areas on the ridgeline on the northern watershed boundary.

Geophysical Investigations

Gravity

We conducted a gravity survey in the study area to delineate valley-fill thickness and subsurface structures. A total of 43 new gravity stations were acquired during the 2016 field season. In gravity surveys, the working unit Gal is defined as 1 centimeter per second squared (cm/s^2). Thus, the acceleration due to gravity at the Earth's surface is 980 Gal (9.8 m/s^2). We used a Scintrex CG-5 Autograv (precision of 1 µGal, accuracy of 5 µGal) to make field measurements of gravity following the methods of Gettings and others (2008) and using an absolute gravity base station located near Salt Lake City. We established elevation control through post-processing of data collected by Trimble GeoXH GPS equipment. We observed better than 10 cm vertical accuracy for all but one station when logging for a minimum of 10 minutes. Based on the vertical gravity gradient (0.3086 mGal/m), this procedure resulted in a gravity accuracy of better than 0.03 mGal (30 µGal). We applied terrain corrections to the processed gravity data and calculated the Complete Bouguer Gravity Anomaly (CBGA) for each station using the methods outlined in Hinze and others (2005) with a reduction density of 2.67 grams per cubic centimeter (g/cm^3). UGS gravity data were merged with data from Stewart (1956) and PACES data (PACES—Pan American Center for Earth & Environmental Studies, 2012), a national gravity and magnetics data repository, to improve data coverage in the study area.

We created two-dimensional (2D) gravity models of two transects using a variable thickness sedimentary layer overlying bedrock. The gravity anomaly values along the transect were adjusted for regional effects using low-order polynomials and then modeled using the Semi-Automated Marquardt Inversion code (SAKI) of Webring (1985). The valley fill and Norwood Tuff density contrasts to bedrock are based on values from local geological information, samples, and drill logs and were held constant at -0.65 and -0.3 g/cm^3, respectively. Bedrock outcrops on the margins of the valley and lithologic information from drill logs were used as control points for the model.

Gravity data are tabulated in table B-1 in appendix B. The complete Bouguer gravity anomaly field (figure 11) shows a gravity-low anomaly on the order of 15 mGal in the southern part of Ogden Valley compared to values in the northwest part of the valley. We interpret the area of the gravity low as the area of thickest valley fill. The shape of the anomaly is trough-like, trending northwest to southeast, and the steepest gradients in the gravity field are on the west and east margins.

Two-dimensional gravity models along two transects are shown on figure 12. Line 1 extends west to east from near the Pineview Dam, through Huntsville, and up the canyon of the South Fork Ogden River. Line 1 traverses two large gradients in the gravity field, one each on the west and east sides of the valley, which we interpret as the bounding normal faults of the valley. The valley shape is asymmetric with the deepest valley fill on the east side. The valley fill gradually shallows westward until it reaches an interpreted fault plane. On the east side of the transect, the lowest point of the valley fill is estimated to be at an elevation of 800 meters (2620 ft) above mean sea level (amsl) and the lowest point of the Norwood Tuff is estimated to be at an elevation of 70 meters (230 ft) amsl.

Line 2 extends southwest to northeast from near Pineview Dam, terminating in the Middle Fork Ogden River canyon. The valley shape is approximately symmetric along line 2 with interpreted bounding faults on each end. The lowest points of valley fill and Norwood Tuff along line 2 are 950 meters (3120 ft) amsl and 220 meters (720 ft) amsl, respec-

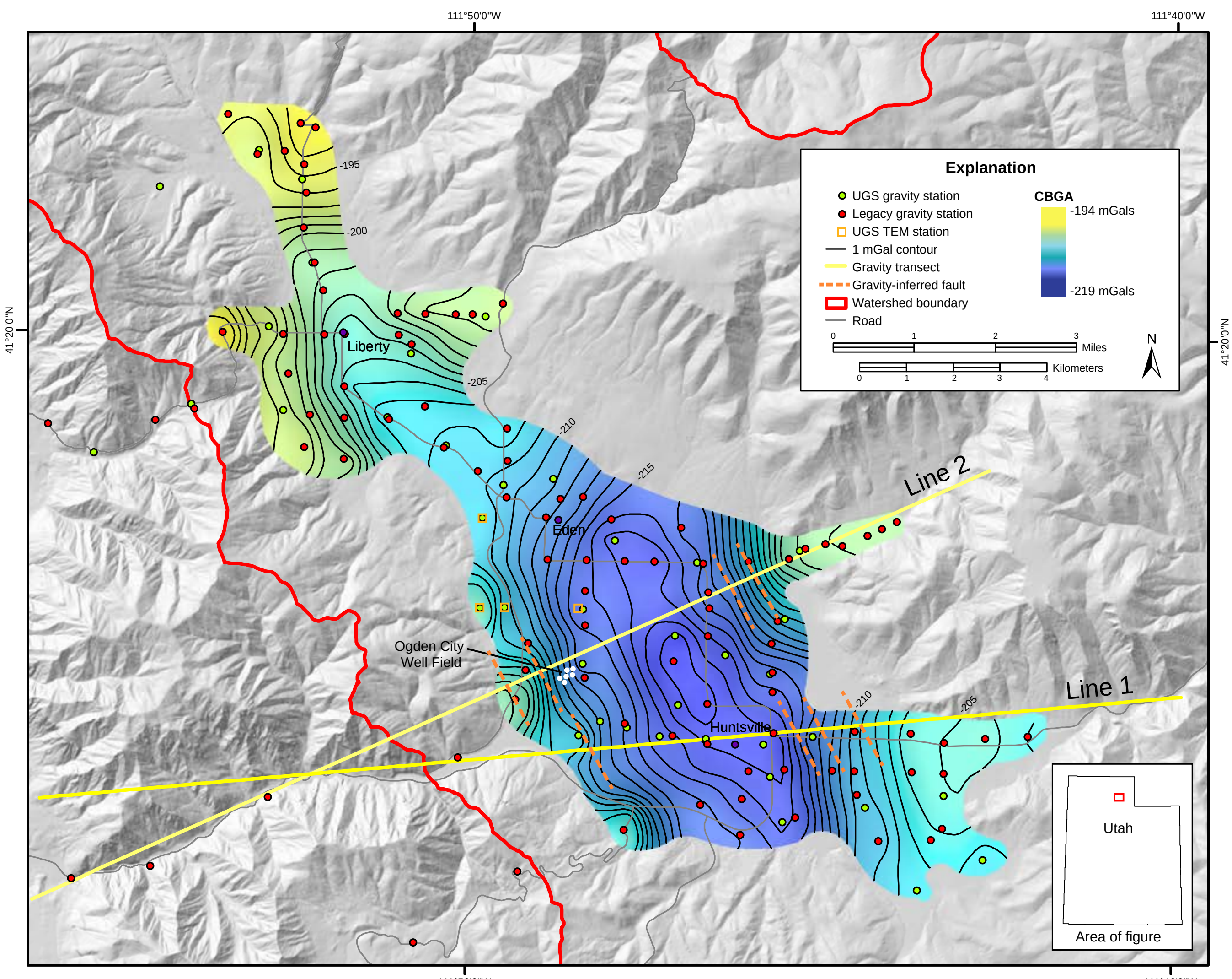


Figure 11. *Complete Bouguer gravity anomaly (CBGA) and gravity stations for Ogden Valley. Gravity transects shown on figure 12.*

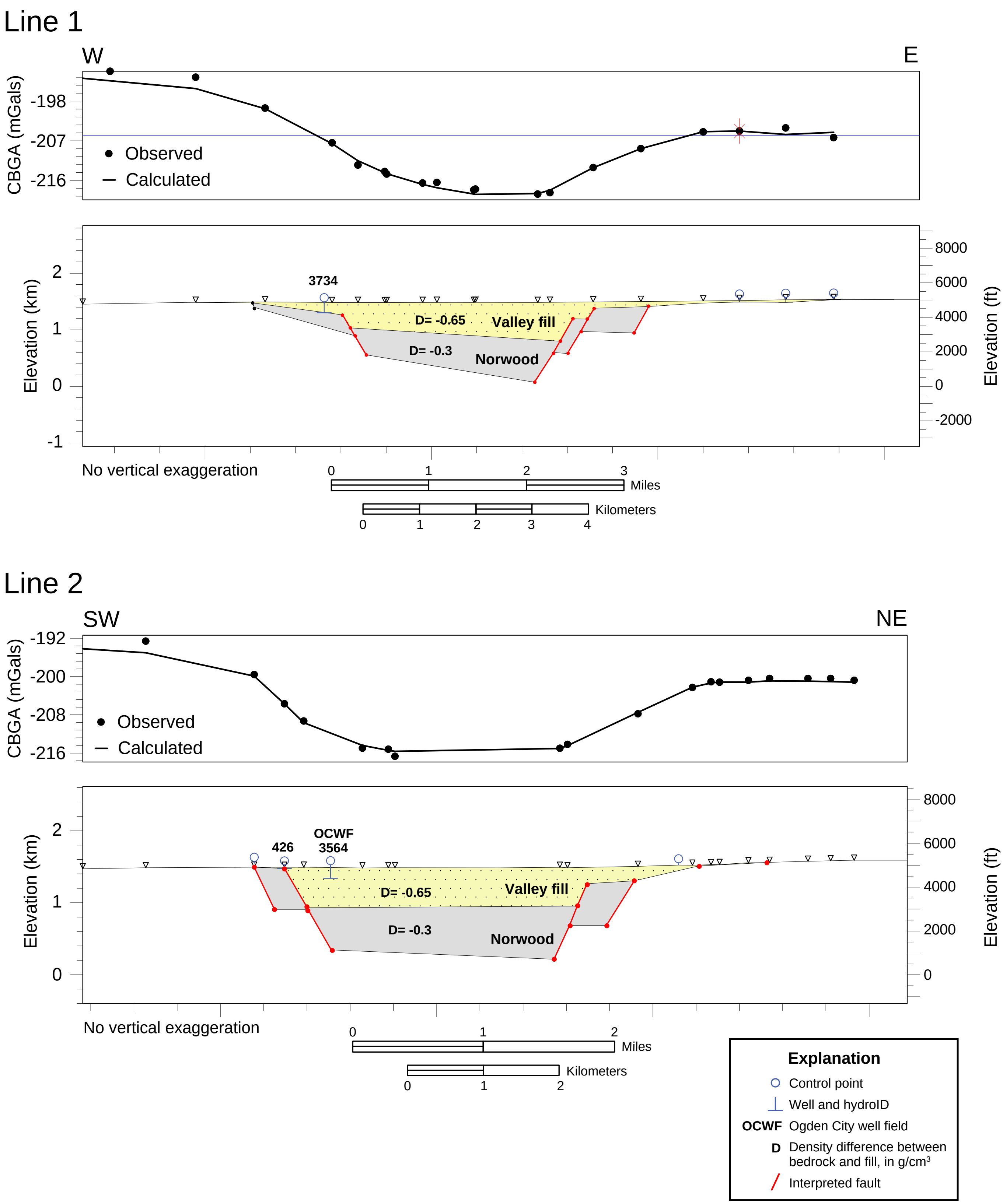


Figure 12. *Two-dimensional gravity model cross sections and interpreted subsurface geology along two transects through Ogden Valley (see figure 11 for transect locations). CBGA, complete Bouguer gravity anomaly.*

tively. Both transects display a shallow, shelf-like geometry on their eastern ends between the valley-fill margin and our interpreted fault structures.

Based on boundary effects observed during an eight-day aquifer test on an Ogden City well field well, Avery (1994) interpreted two faults on the west side of the valley, one east of the well field and one west of the well field (Avery, 1994, plate 1). Our data also support an interpretation of two faults on the west side of the valley; however, the observed gravity gradient and our modeling place both faults west of the Ogden City well field (figure 12).

Transient Electromagnetic Method

We conducted a Transient Electromagnetic Method (TEM) geophysical survey to establish resistivity baselines in the study area to better define subsurface geology and structure. TEM is an active source method that measures the attenuation signal of induced magnetic fields, which correspond to changes in the electrical properties in the subsurface. We used this data to image the shallow subsurface, which allows us to infer changes in the shallow groundwater system related to variations in groundwater salinity and aquifer characteristics across the study area. We made TEM measurements at four locations in the study area using an ABEM WalkTEM ground loop system fitted with a 40 x 40-meter transmitter antenna having high- and low-frequency receiver antenna coils capable of simultaneous recording. We made repeat measurements at specific locations to ensure data consistency and quality for the duration of the field survey period. We made two to three measurements in less than one hour at each station. All TEM stations yielded high-quality data with low signal-to-noise ratio.

After initial data processing, we created and iteratively improved one-dimensional (1D) inversion models for every station until final data fit was satisfactory and the depth of investigation (DOI) parameter had high confidence. DOI is unique for each station, relies on the physical properties of subsurface material, and indicates the maximum depth of resolution with respect to modeling. Results from models are less confident when they extend deeper than the DOI.

One-dimensional (1D) inversion models for each of the four TEM stations shown on figure 11 are presented in appendix B. Access to ideal TEM sounding locations was very limited due to private land ownership and water or vegetation barriers. TEM data were collected where we were able to locate useful sites and obtain permission from land owners. The processing and revised inversions of TEM data resulted in 1D resistivity models of each of the TEM stations. These models can be cross-correlated with downhole lithologic and resistivity logs of proximal water wells. We were unable to collect enough TEM data to accurately locate shallow subsurface structures; however, our preliminary TEM measurements and models will assist in establishing a resistivity baseline for use in future subsurface studies involving TEM.

Valley-Fill Isopach Map

We used an isopach, or thickness, map of the valley-fill sediments to determine the thickness of the valley-fill aquifer and aquifer storage capacity. An isopach map can also be used to estimate well drilling depths to various aquifer targets.

The extent of valley fill is taken from the geologic contact between consolidated units and unconsolidated sediment from the Ogden 30′ x 60′ geologic map (Coogan and King, 2016). Landslide deposits that border unconsolidated valley floor sediments were included as valley fill. Even though the Tertiary Norwood Tuff was deposited as valley fill, we include it as a bedrock unit because it is consolidated.

To constrain valley-fill thickness, we examined water well logs submitted to Water Rights. We obtained the digital forms of the well logs from Water Rights and related them to a spatial database we created in ArcMap geographic information system (GIS) software (ArcMap) (ESRI, 2017) so that lithology reported on the drillers logs could be searched spatially. In addition to well drillers' logs available on Water Rights' website, we used five other sources of lithologic logs and interpretations: (1) drinking-water source protection documents for public supply wells (appendix C), (2) the USGS National Water Information System (U.S. Geological Survey, 2016), (3) Leggette and Taylor (1937), (4) Lofgren (1955), and (5) Shaffner and others (1993). Once all logs were compiled digitally, we searched the database for lithologic descriptions of wells located on valley-fill outcrop that included the words shale, mudstone, sandstone, limestone, quartzite, quartz, tuff, conglomerate, or bedrock, and logs on which the driller checked "bedrock" as the lithology type. We reviewed each of the resulting drillers' logs with respect to supporting geophysical and geologic data to determine actual depth to bedrock. In some cases, we interpreted materials logged as unconsolidated sediments on drillers' logs as bedrock or volcanic valley-fill material (Norwood Tuff) based on subtle changes in the description or drilling characteristics.

Seventy-five wells within the extent of the valley fill are interpreted to penetrate bedrock at depths that range between 2 and 565 feet (1–170 m) (table B-2 in appendix B). Additionally, the depths of 17 moderately deep boreholes that did not penetrate bedrock were used as minimum valley-fill thicknesses. We added 208 points at land surface elevation at approximately 0.5 mile (0.8 km) increments along the limit of the valley-fill polygon. For areas away from wells that intercept bedrock, we included the elevation of the bedrock interpreted from gravity data at points along our two gravity profiles. We contoured all points using the natural neighbor interpolation algorithm in ArcMap, which produced a raster surface that honored our data points. We interpolated 36 additional points along our valley-fill cross sections (see below) and between wells and gravity cross sections and contoured them along with the hard data points to produce a smooth raster surface that depicts our interpretation of the elevation of the base of the valley fill. We subtracted the base of valley fill raster from the 10-m DEM surface elevation to produce an isopach map of the valley-fill sediments.

Valley fill in Ogden Valley, not including Tertiary volcanic sedimentary units, reaches a maximum thickness of about 2300 feet (700 m) north of Huntsville (figure 13) in a somewhat flat-bottomed, asymmetrical basin. Valley fill thins relatively rapidly on the western edge of the valley and east of Huntsville where faulting has dropped the valley floor relative to the surrounding terrain. Valley-fill thickness is not well constrained between Liberty and Eden because of lack of deep wells. Based on gravity data, the valley fill thins gradually in the North Fork arm of the valley to an estimated 500 feet (150 m) thick underlying Liberty. Relatively thin landslide deposits, which we grouped as valley-fill deposits, flank the North Fork arm east and west of Liberty.

Our estimate of valley-fill thickness is much greater than the 750 feet (210 m) of sediments given by Avery (1994, p. 7). The discrepancy may arise from our inclusion of all unconsolidated sediments as valley fill, whereas Avery did not clearly state what type of sediments he included in valley fill.

Valley-Fill Cross Sections and Stratigraphy

We created a series of cross sections to constrain lateral changes in the valley fill based on well log, geophysical, and geologic data. We used Arc Hydro Groundwater (Aquaveo, LLC, 2017), an ArcMap extension, to build three valley-fill cross sections. We chose section lines that are roughly parallel to groundwater flow based on new potentiometric contours in the South, Middle, and North Fork Ogden River arms of the valley.

To interpret the valley-fill lithology at our chosen cross section locations, we chose 44 well logs (table B-3 in appendix B) based on their proximity to section lines and quality of information contained on the logs. We also used the lithologic logs from wells to interpret lithology along section. Well drillers commonly report multiple sediment sizes through a specified depth interval, sometimes as short as a few feet. We simplified and grouped lithologies reported on well drillers' logs, which allowed us to combine the short intervals reported on logs. We designated any interval reported by the driller as containing sand, gravel, cobbles, and/or boulders as coarse-grained unconsolidated lithology, and any interval having only clay

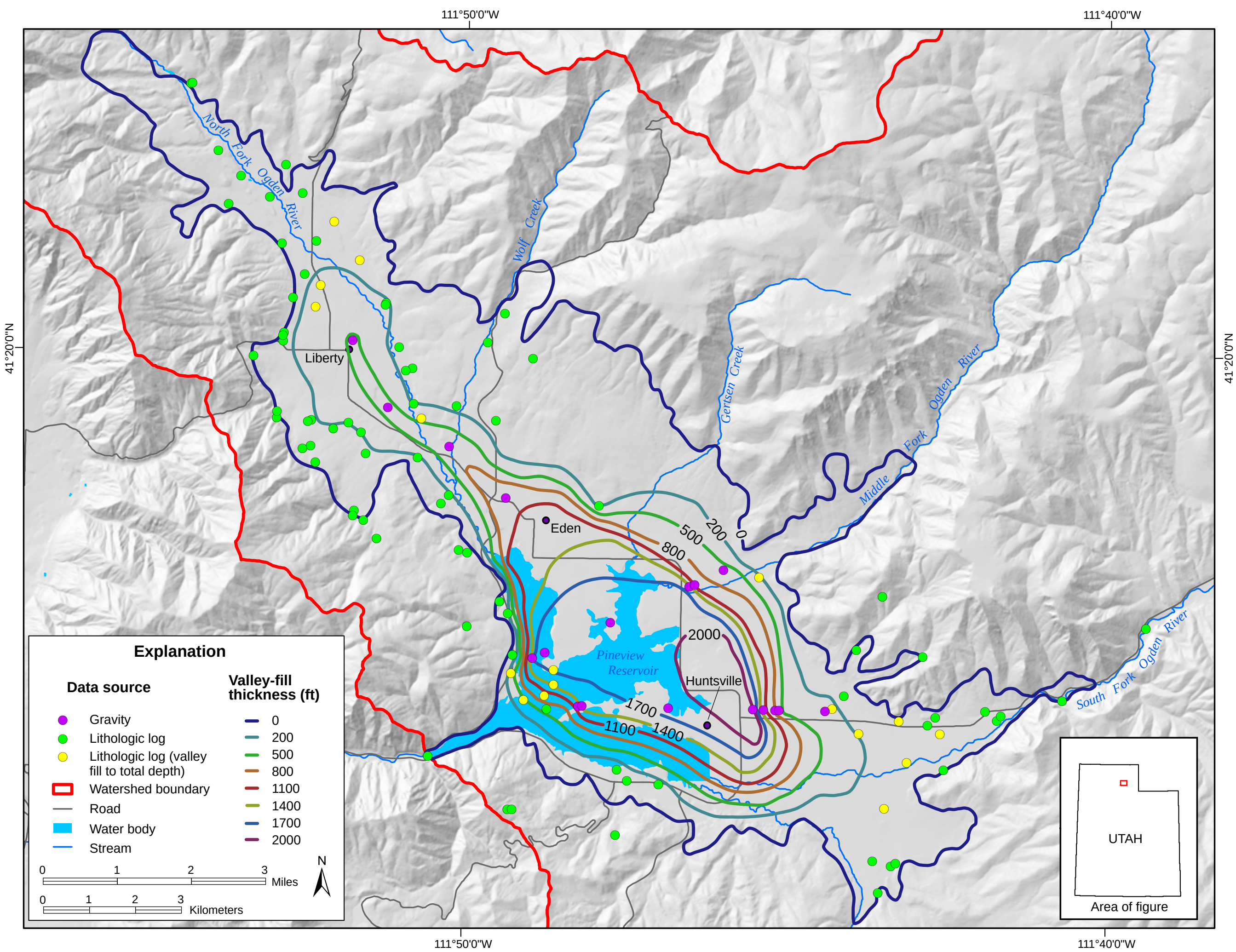


Figure 13. *Thickness of valley-fill sediments, not including Tertiary Norwood Tuff and Tertiary conglomeratic rocks.*

or silt as fine-grained unconsolidated lithology. Any unit having both fine- and coarse-grained material, we designated as mixed-grained unconsolidated lithology. We designated fine-grained units that drillers indicated had blue or green coloring as a sub-set of our fine-grained lithology group. When correlating units on our cross sections, these blue clays were correlated with other fine-grained units at similar elevation in the center of the valley underlying and near Pineview Reservoir and interpreted as the confining unit. Topsoil was prevalent and thick enough in drillers logs to call out as a separate unit, as was conglomerate, which we interpreted as having a mixture of grain sizes but dominated by coarse grain sizes, unless interpreted to indicate bedrock as described in the Valley-Fill Isopach Map section above. Parts of the cross sections below depths penetrated by wells but above the bedrock interpreted from the gravity profiles are designated as undifferentiated unconsolidated valley-fill sediment.

Cross sections show projected wells and interpreted lithology at 20 times vertical exaggeration. Additional data including the topographic profile (from the 10 m DEM), potentiometric surface (our March–April 2016 potentiometric map), the bottom of Pineview Reservoir (from a bathymetric survey by Winkelaar, 2010), and our valley-fill isopach map are also shown on cross sections. The top of the Norwood Tuff, depth to basement rocks, and the location of normal faults are based in part on the two gravity profiles. Within the framework of these projected surfaces and boreholes, we correlated the lithologic units into our interpretation of the valley-fill sediments and their relation to surrounding bedrock.

Three valley-fill cross sections (plate 1) that parallel groundwater flow (figure 10) depict the relationship of simplified lithologic units to the surrounding bedrock, the water table, and Pineview Reservoir. Thickness and depositional environments of the lithologic units on the cross sections are shown in table 1; however, we note that interpretation based on test pits (Carley and others, 1980) is a better source for topsoil thickness in Ogden Valley.

Lithologic units vary with distance from the outlet of the valley at the head of Ogden Canyon due to changing depositional environment (plate 1). Near the head of the canyon and in the proximity of Pineview Reservoir, the uppermost sediments consist chiefly of silt and sand (Leggette and Taylor, 1937; Lofgren, 1955) and some thin gravel layers (Leggette and Taylor, 1937). Drillers' logs of water wells indicate that in many locations, these silt and sand sediments are capped by varying thicknesses of clay (uppermost fine-grained unit [*fu*] on plate 1). The coarser-grained parts of this lacustrine unit are shown as the uppermost mixed-grained (*mu*) and coarse-grained (*cu*) units on plate 1. This lacustrine unit is mapped as Lake Bonneville sand (Qlsb) on the geologic map (plate A-1 in appendix A) and forms the shallow unconfined aquifer. In the lower part of the unit, sediments consist of well-sorted, well-stratified, highly permeable, nearshore Lake Bonneville lacustrine sand and gravel (Lowe and Miner, 1990). Grain sizes range from cobble to silt, but fine sand and silt make up the bulk of the deposits (Lowe and Miner, 1990). Nearshore sediments are capped by lacustrine offshore sediments deposited when the lake was at the Bonneville shoreline highstand about 18,000 years ago (Oviatt, 2015). The offshore deposits vary in thickness, have low permeability, and form hard, blocky, cliff-forming outcrops due to compaction and slight cementation by calcite and hematite (Lofgren, 1955).

Lacustrine silt and sand deposits near the outlet of the valley form the valley-fill aquifer system's confining unit (*pcu* on plate 1), which defines the areal extent of the confined aquifer. The confining unit was previously reported to be as much as 100 feet (30 m) thick in the westernmost part of Ogden Valley (Lofgren, 1955, p. 81), but thins to the north, east, and south towards the outer edge of the valley (Leggette and Taylor, 1937, plate 36; Snyder and Lowe, 1998, plate 1). The silt and clay sediments form a leaky confining layer, based on reservoir bed seepage measurements made in 1986 (Avery, 1994, p. 41). The well-stratified blue, gray, and green silts that make up the confining unit are dense and micaceous (Lofgren, 1955, p. 80 and 81). Before Pineview Reservoir filled with water, approximately 25 feet (8 m) of this unit was exposed in stream cuts near the head of Ogden Canyon (Leggette and Taylor, 1937). The extent of varved silt and clay was mapped as part of dam stability studies in the late 1980s and early 1990s (Shaffner and others, 1993) (figure 14a). The bottom of the silt confining unit is estimated to be at least 50 feet (15 m) above the bedrock channel at the head of Ogden Canyon (Leggette and Taylor, 1937), and Shaffner and others (1993) show about 90 feet (30 m) of coarser sediments between the bottom of the varved silt and clay and the bedrock channel (see cross section A-A′, figure 14b).

In our analysis of well logs to delineate the thickness and extent of the confining unit, we correlated silt and clay layers described as blue, gray, green, or sticky with surrounding fine-grained units that lacked descriptive terms. The position and thickness of *pcu* is detailed in the subsequent section.

Sediments below the confining unit (mixed grained [*mu*], coarse grained [*cu*], and fine grained [*fu*], plate 1) consist primarily of fluvial and alluvial-fan sand and gravel with some silt and clay lenses (Doyuran, 1972). Lowe and Miner (1990) suggested these sediments may be transgressive nearshore lacustrine sediments associated with the overlying offshore silts. The sediments are well sorted and permeable at the top of the sequence (Lofgren, 1955). Most wells penetrating the confined aquifer obtain water from these well-sorted sediments (Doyuran, 1972).

Mixed-grained (*mu*) and coarse-grained (*cu*) units make up the unconfined principal aquifer closer to the valley margins (east end of section A–A′, northwest end of section C–C′, and both ends of section B–B′ on plate 1). These sediments were most likely deposited in alluvial fans and streams, correlating to Qaf and Qalm, respectively, on plate A-1 in ap-

Table 1. Lithologic units on valley-fill cross sections and their depositional environments.

	Code	Lithologic unit	Lithology	Thickness (ft)	Interpreted depositional environment
Valley fill		topsoil	topsoil	0–18	soil
	cu	coarse-grained unconsolidated	sand, gravel, cobbles, and/or boulders	0–250	fluvial and alluvial fan
	mu	mixed-grained unconsolidated	any mixture of fines (clay, silt) and coarse (sand, gravel, cobbles, boulders)	0–160	fluvial, alluvial, and lacustrine nearshore
	fu	fine-grained unconsolidated	clay, silt, hardpan	0–160	distal alluvial fan and lacustrine offshore
	pcu	principal confining unit	silt, clay, usually described as blue, green, or gray	0–100	lacustrine offshore
	u	undifferentiated valley fill	lithology unknown, likely unconsolidated to semi-consolidated Quaternary and Tertiary sediments	80–1500	mixed
	c	conglomerate	conglomerate	0–50	alluvial fan?
	mm	mass movement deposits	landslide deposits	0–30	landslide and debris flow
Bedrock	Tn	Norwood Tuff	tuff and tuff conglomerate	0–2600	bedrock
		undifferentiated bedrock	undifferentiated bedrock	–	bedrock
	Zcc?	quartzite	quartzite, likely Caddy Canyon Formation	0–2300	bedrock

pendix A. The fine-grained sediments (*fu*) are most likely distal alluvial-fan deposits, perhaps having fewer deposits related to marshes and shallow lakes. Thickness of the sediments composing the unconfined aquifer was not well constrained in early studies due to lack of deep well data, but was estimated to be at least 700 feet (210 m) east of Huntsville (Avery, 1994) thinning toward the valley margins. We show the greatest thickness to be nearly 2300 feet (700 m) near Huntsville. Perched aquifers are also present in sediments where silt and clay lenses exist above the main water table (Doyuran, 1972).

Lithologic unit *c* is a conglomerate unit near the ends of the cross sections (plate 1). Well drillers often list conglomerate when drilling boulders and cobbles mixed with finer sediment. This unit is interpreted to be valley-margin alluvial-fan deposits. Lithologic unit *Qmm* is a Quaternary mass movement deposit mapped near the head of Ogden Valley on the north side of Pineview Reservoir (plate A-1 in appendix A). Lithologic unit *Tn* is the Norwood Tuff, a thick tuffaceous unit described above in the Geologic Setting section.

Undifferentiated bedrock is shown on the cross sections (plate 1) where well bores encountered consolidated bedrock, but the geologic formation was not identified in the log. Quartzite was identified in several good lithologic logs in the South Fork arm of the valley, and this bedrock unit underlies the east end of cross section A–A′ (plate 1). Based on proximity to outcrop and geologic structure, the quartzite is likely the Proterozoic Kelly Canyon or Caddy Canyon Formation, and we designate it as *Zcc?* on the cross section.

The cross sections (plate 1) show a series of faults offsetting valley fill and older deposits based on geophysical data. These faults are only approximately located and do not have surface expression in Ogden Valley.

Confining Unit Origins and Position

The confining unit plays a key role in the hydrogeologic system of Ogden Valley, and understanding its origin and relationship to the valley's aquifers is essential to understanding groundwater movement, quality, and availability for use. The confining unit's thickness is important in evaluating the potential groundwater flow through the unit given observed head gradients. Depth to the top and thickness of the unit is useful in water resource development.

Origin

Leggette and Taylor (1937) described the confining unit as a package of grayish-blue, dense, sticky clay and silt varves deposited during the highstand of Lake Bonneville. Lofgren (1955), using Leggette and Taylor's (1937) data, described this layer as a dense blanket of micaceous silt having thin, horizontal, uniform bedding indicating a lacustrine origin, and believed the cyclically bedded dark-bluish layer to consist mostly of micaceous phyllite and argillite eroded from the North Fork of the Ogden River drainage. Lofgren (1955, p. 73, 78, and 79), however, considered the confining unit to pre-date Lake Bonneville. Thus, although obviously describing the same package of sediments, Leggette and Taylor (1937) and Lofgren (1955) came to differing conclusions as to their age.

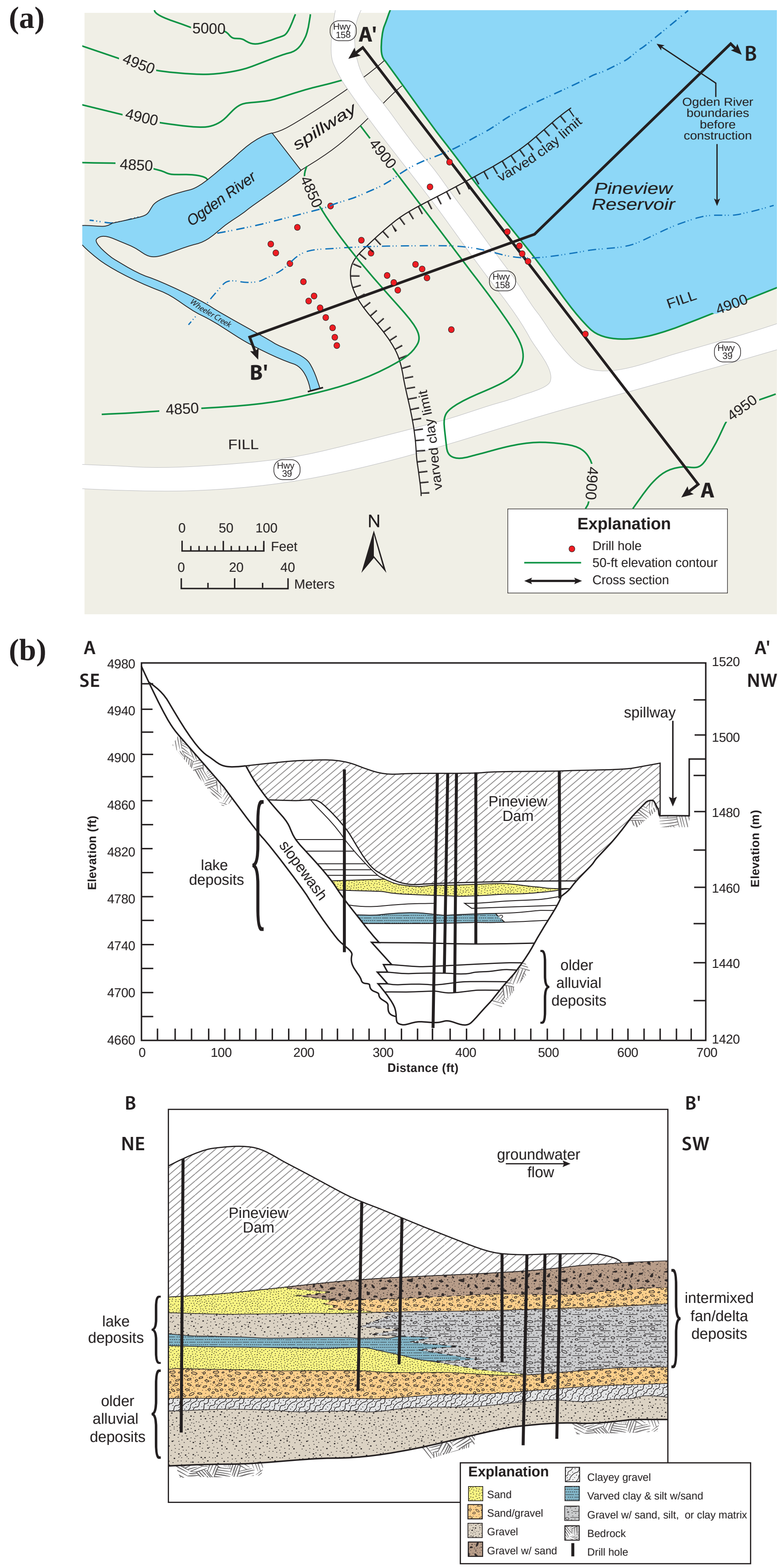


Figure 14. (a) *Plan view of Pineview Reservoir Dam and* ***(b)*** *cross sections through the dam. Modified from Shaffner and others (1993). Shaffner and others (1993) presented no vertical or horizontal scale for section B–B'.*

The Bonneville lake cycle was the most recent deep lake cycle in the Bonneville basin (figure 15, table 2). Therefore, offshore silt and clay deposited during the Bonneville lake cycle, if present, should be the uppermost of such deposits in the valley-fill sediments. The Bonneville lake cycle is unique compared to other deep-lake cycles in the Bonneville basin in that the regression from its highstand at 5092 feet (1552 m) in elevation, marked by the isostatically rebounded Bonneville shoreline at about 5150 feet (1570 m) in Ogden Valley (Lofgren, 1955), was not due entirely to climatic conditions. Around 18,000 years ago, the lake drained rapidly to the north, dropping the lake elevation to the Provo shoreline level at about 4737 feet (1444 m) (Currey and Oviatt, 1985; Oviatt, 2015; O'Connor, 2016), which was below the bottom of Ogden Bay (currently about 4825 feet [1471 m]). Because the lake drained so rapidly, we would not expect to find substantial lakeshore (medium to coarse) deposits related to regression of Lake Bonneville in Ogden Valley, and therefore we conclude that the *mu* and *cu* units above the confining unit (plate 1) must be no younger than transgressive Bonneville lake-cycle sediments. Furthermore, the discontinuous uppermost fine-grained units (*fu*) on plate 1must be deep-water deposits related to the Bonneville lake cycle due to their position as the shallowest lacustrine fine-grained deposits. Based on lidar imagery of Ogden Valley, which shows the peninsulas between the arms of Pineview Reservoir to be flat and table-like, we believe that most of the Bonneville lake cycle offshore deposits were planed off and eroded away during the fall from the Bonneville shoreline to the Provo shoreline. Lofgren (1955) came to a similar conclusion without the benefit of lidar imagery, indicating that this "remnant bench" which slopes downward in elevation from 4950 to 4915 feet (1509–1498 m) toward the outlet of Ogden Valley is graded to the Provo shoreline (elevation about 4800 feet [1460 m]) at the mouth of Ogden Canyon.

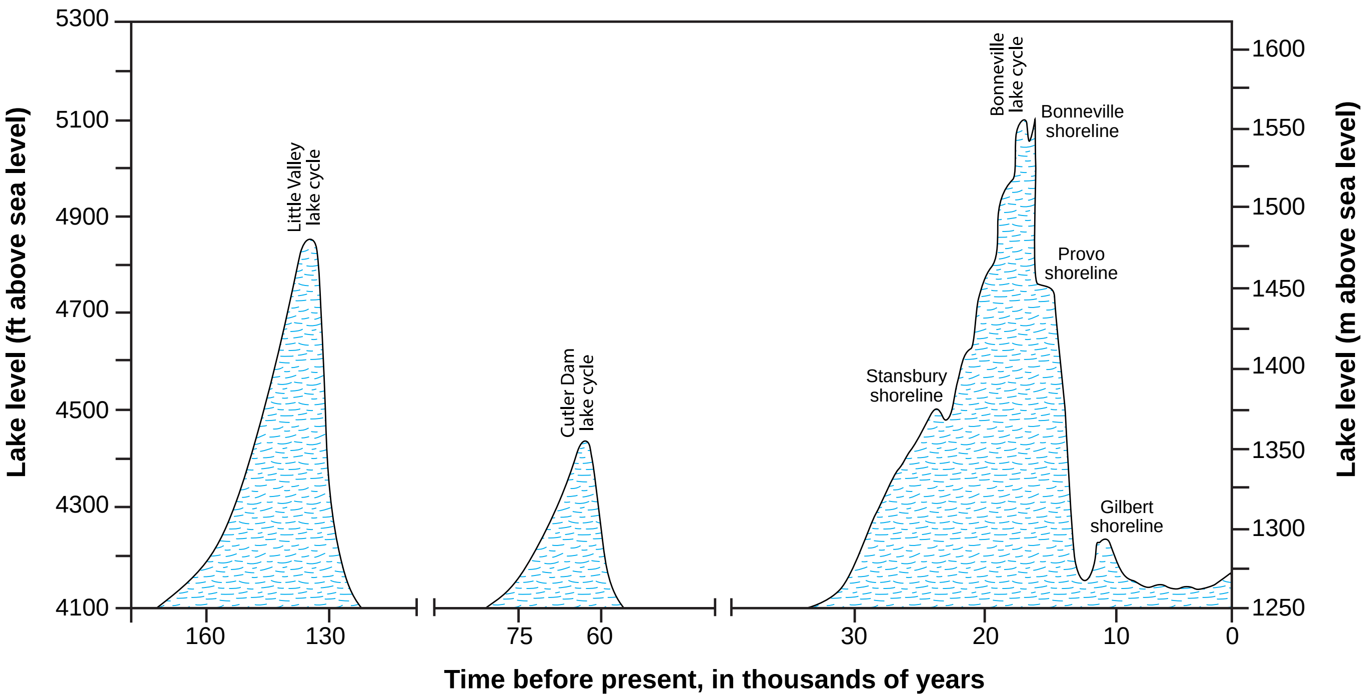


Figure 15. *Probable levels of Lake Bonneville and earlier lake cycles during the past 160,000 years (after Machette and others, 1992). The present-day elevation of the Bonneville shoreline at Huntsville is about 58 feet (18 m) higher than the Bonneville highstand due to isostatic rebound of Earth's crust.*

Table 2. *Present-day elevations of selected Bonneville basin lake shorelines.*

Older → Younger				
Little Valley Lake Cycle	Cutler Dam Lake Cycle	Bonneville Lake Cycle		
		Stansbury Shoreline	Bonneville Shoreline	Provo Shoreline
4822–5002 ft 1470–1525 m (Scott, 1988)	4395 ft 1340 m (Oviatt and others, 1987)	4418–4520 ft 1347–1378 m (Currey, 1980)	5092–5341 ft 1552–1628 m (Currey, 1982)	4738–4931 ft 1444–1503 m (Currey, 1982)

If our interpretation of the shallowest *fu*, *mu*, and *cu* units shown on plate 1 is correct, then the underlying confining unit must have been deposited during an earlier lake cycle. The next most recent lake cycle which may have had water deep enough to inundate Ogden Valley was the Little Valley lake cycle (figure 15), whose present-day shoreline elevations range from 4822 to 5002 feet (1470–1525 m) (Scott, 1988) (table 2). Our analysis of well logs shows the confining unit (*pcu*) is present at elevations of about 4750 to 4950 feet (1448–1509 m), making the Little Valley lake cycle highstand potentially deep enough to deposit most of this confining unit. (The shallowest parts of the confining unit, present in the northernmost and easternmost areas of the confining unit, may be of Lake Bonneville age, but we were unable to identify an intervening unit in the well logs.) We hesitate to use present-day shoreline elevations to speculate on the depth of water in Ogden Bay during the Little Valley lake cycle approximately 150,000 years ago because (1) evidence for the elevation of the Little Valley lake cycle highstand is sparse, and (2) tectonism, crustal depression, and isostatic rebound from Little Valley and Bonneville lake cycles have likely deformed the paleo-shorelines in a highly complex manner. Therefore, we conclude that the confining unit (*pcu*) was likely deposited during the Little Valley or earlier pluvial lake cycles, that the uppermost *mu* and *cu* units above the confining unit are likely regressive Little Valley lake cycle deposits and transgressive Bonneville lake cycle deposits perhaps mixed with fluvial and alluvial-fan deposits, and that the uppermost *fu* units are remnants of Bonneville lake cycle offshore deposits.

Position and Thickness

We created structure contour maps of the top and bottom of the confining unit, from which we calculated the thickness of the unit and the depth from the land surface to top and bottom of the unit. To construct an accurate map of the confining unit, we needed to analyze the unit in more locations than shown on our three detailed lithologic valley-fill cross sections. To accomplish this, we used Arc Hydro Groundwater (Aquaveo, LLC, 2017) to construct approximately a dozen section lines crisscrossing through approximately 150 well logs in the central part of the valley where previous researchers had identified the confining unit (Avery, 1994; Snyder and Lowe, 1998). On these section lines we correlated clay and silt units that were noted on drillers' logs as being blue, green, gray, or sticky with fine-grained units at similar elevations in nearby wells that did not have these descriptive identifiers. We defined these correlated units as the confining unit. We then used Arc Hydro Groundwater to create surfaces for the top and bottom of the confining unit by interpolating between the elevations shown on the sections using an inverse distance weighted interpolation method. The elevation of the top of the confining unit surface was higher than the elevation of the lakebed of Pineview Reservoir over much of the area of the reservoir, meaning that the confining unit had been eroded by the lower reaches of the three forks of the Ogden River before the reservoir was created in 1937. To make a surface representing the current, eroded top of the confining unit we used ArcMap to select the lower elevation of either the interpolated top of the confining unit or the elevation of the lakebed of Pineview Reservoir from Winkelaar's (2010) bathymetry study as the top of the confining unit. We derived thickness of and depths to top and bottom of the confining unit by subtracting combinations of the land surface 10 m DEM, the bathymetry, and the structure contour surfaces of the confining unit. The extent of the confining unit differs from that of previous researchers because we had additional well data on which to base our interpretation and because Snyder and Lowe (1998) mapped the confining unit only where silt and clay are greater than 20 feet (6 m) thick, whereas we mapped the unit to where it pinches out to the north and east.

The confining unit is 90 feet (30 m) thick or more on the peninsulas between the three arms of the reservoir (figure 16). At the Ogden City well field on the southern tip of the peninsula between the North Fork arm and Middle Fork arm, the confining unit is about 120 feet (40 m) thick. The confining unit is much thinner underlying the reservoir because streams have eroded the upper portion. The confining unit was exposed in the river valleys before the reservoir flooded the valleys (shown as pinkish-white color on figure 16); Leggette and Taylor (1937) likely described these exposures. East of Huntsville the confining unit is a few tens of feet thick.

The depth to the top of the confining unit is shallow (0 to 40 feet [0–12 m]) east and north of Huntsville and about 20 to 60 feet (6–18 m) over much of the rest of its extent (figure 16). The confining unit is 60 to 80 feet (18–24 m) deep south of Eden. The top of the unit is deepest where landslide and other deposits have accumulated on top of it near the mountains. The shallow unconfined aquifer occurs in the unconsolidated sediments above the confining unit. Figure 16 can be used to predict how deep a well would need to be drilled to penetrate the principal confined aquifer by adding the thickness of the confining unit to the depth to the top of the confining unit at any point on the map.

The confining unit can be visualized in three dimensions as filling the space between the two surfaces shown on figure 17. The three forks of the Ogden River eroded as much as 50 feet (15 m) of the top of the confining unit; these valleys can be seen in the area now filled by Pineview Reservoir (darker blue on figure 17). The thinnest and shallowest part of the confining unit is also the highest in elevation and occurs in the South Fork arm of the valley (darker red on figure 17). Generally, the confining unit is continuous and thins to the north and east, abutting bedrock or Norwood Tuff on parts of the south and east sides of the valley near the outlet of the valley.

Aquifer Properties Estimates

Aquifer properties describe how readily aquifers will yield water to wells. Aquifer tests, which involve pumping a well while monitoring the water-level response in the pumping well and/or nearby wells, provide good estimates of aquifer

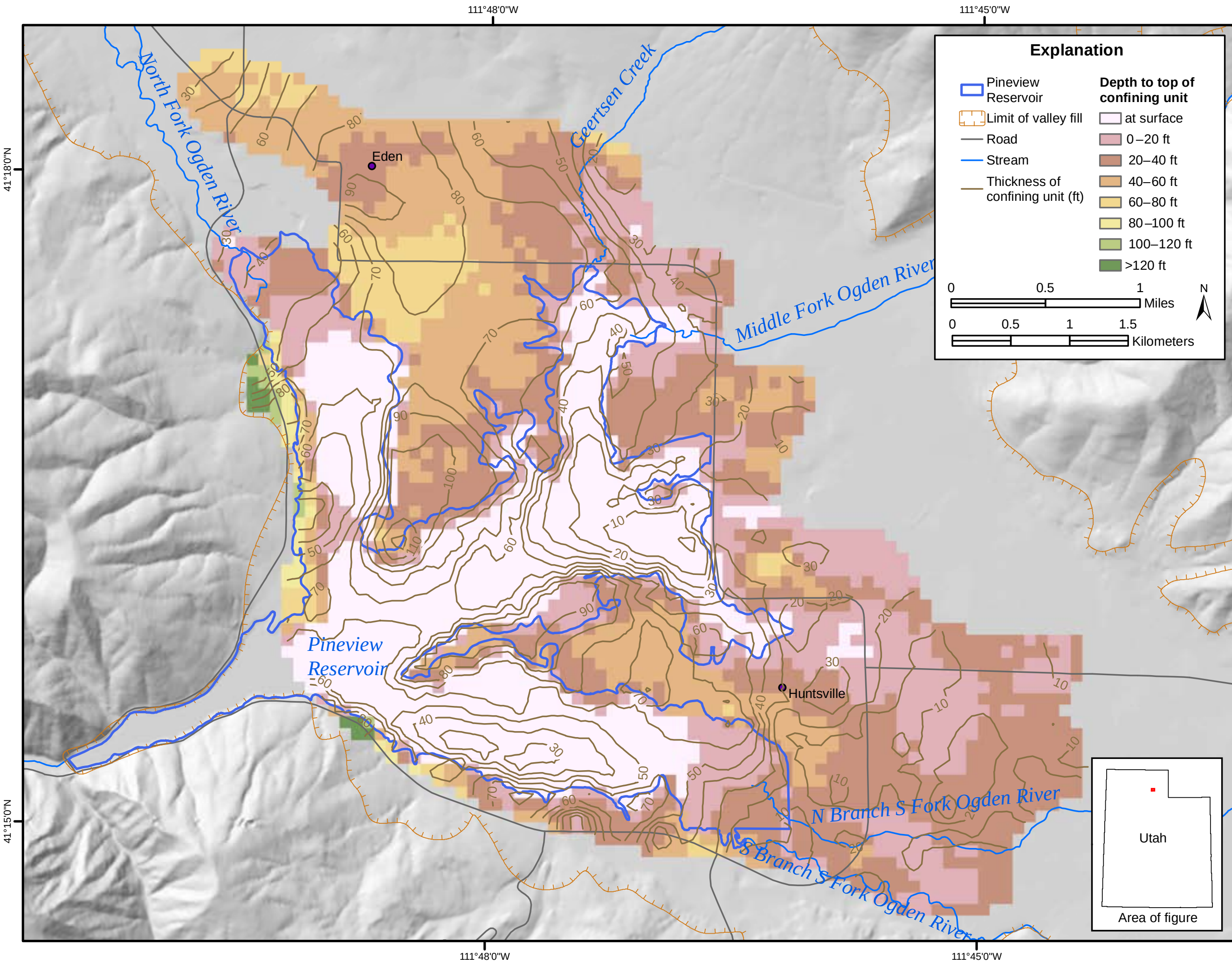


Figure 16. *Depth to the top and thickness of the confining unit.*

properties. We compiled aquifer properties that were determined by aquifer tests on public drinking water sources reported in Utah Division of Drinking Water documents (table C-1 in appendix C). Aquifer test data are not available for most domestic wells, so we used the following methods to estimate aquifer properties, including storativity, specific capacity, transmissivity, and hydraulic conductivity, for the valley-fill aquifer and selected fractured-rock aquifers from data available on water well logs.

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

2. Specific capacity (SC) is the pumping rate (Q) divided by the drawdown (s), $SC = Q/s$, in equivalent units. Specific capacity is determined by pumping a well at a known rate and observing the drawdown once it has stabilized. We assumed the available pumping and drawdown data taken from well logs represent stabilized drawdown.

3. We estimated aquifer transmissivity from specific capacity data obtained from well logs. We used the TGUESS spreadsheet algorithm of Bradbury and Rothschild (1985), which implements the Cooper-Jacob approximation of the Theis equation (Theis, 1935).

4. We estimated aquifer hydraulic conductivity by dividing transmissivity by the saturated aquifer thickness. For lack of better data, aquifer thickness was taken as the length of the well screen, perforated interval, or uncased borehole. Our hydraulic conductivity estimates are likely overestimated because true aquifer thickness is usually greater than the length of the screened interval.

Aquifer properties derived from specific capacity data are compiled in table C-2 in appendix C. We determined the summary statistics of the transmissivity values. Because transmissivity data are lognormally distributed, geometric mean represents the data better than arithmetic mean.

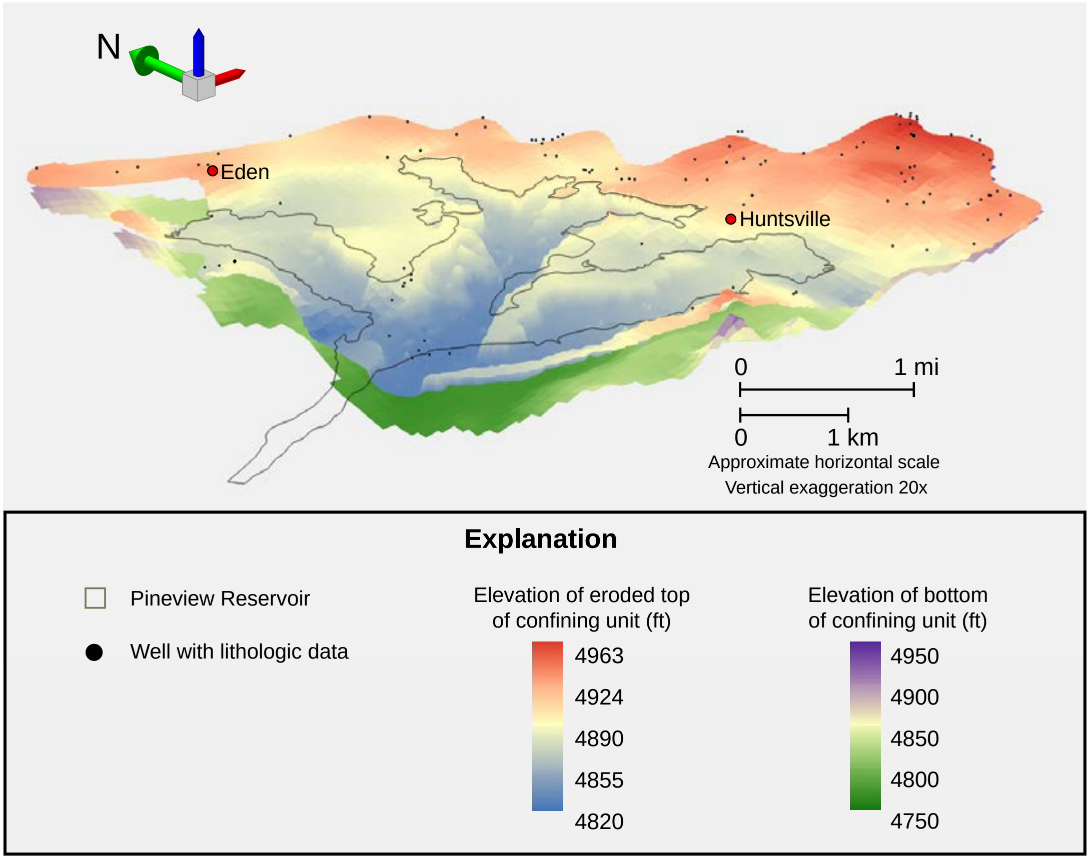


Figure 17. *Three-dimensional oblique aerial view of the position of the top and bottom surfaces of the confining unit in relation to Pineview Reservoir.*

We created a map of transmissivity by interpolating the transmissivity data using the natural neighbor interpolation technique. The kriging interpolation technique, commonly used to estimate transmissivity from well data, was not applied due to the sparse distribution and clustering of data points.

Nineteen aquifer tests were conducted in the valley for public water supplies (table C-1 in appendix C). Five aquifer tests were conducted on wells in the principal aquifer and seven tests were on wells screened to carbonate bedrock units. Data from aquifer tests were not included in summary statistics of the transmissivity values derived from specific capacity data, but many of the wells having aquifer tests also had specific capacity data available. We used the aquifer test data as a check on the accuracy of the specific capacity data.

The values obtained for the aquifer characteristics are variable and depend on logs created by well drillers and aquifer tests conducted by other scientists. Most wells in Ogden Valley are screened in aquifer units. However, where aquifer units are not present at shallow depths, wells in some areas of the valley have been screened in regional confining units or units with mixed properties. For example, in several areas of the valley, wells are screened in the Norwood Tuff, which we consider a regional confining unit, but which can yield water in sufficient quantities to supply water for homes and small subdivisions.

The transmissivity estimates from specific-capacity data and aquifer tests informed and delineated hydrostratigraphic units in the study area (see Delineation of Hydrostratigraphy section above.) We derived transmissivity from specific capacity for four of the major hydrostratigraphic units in the valley: (1) the principal aquifer (QsgA), (2) the Proterozoic siliciclastic unit (ZsiC), (3) the Tertiary volcanic and volcaniclastic unit (TvC), and (4) the Cretaceous and Tertiary conglomeratic unit (KTcgA). The principal aquifer had the highest reported transmissivities for the region, ranging from 3 to 104,000 feet squared per day (ft^2/d). Wells were subdivided into those in the confined part of the aquifer (n=45) and those in the unconfined part of the aquifer (n=147). The principal confined aquifer had the highest mean transmissivity for Ogden Valley, with a geometric mean of 220 ft^2/d (table 3). The principal unconfined aquifer had the most specific capacity data and a geometric mean transmissivity of 160 ft^2/d.

Although we generalize the Proterozoic siliciclastic and Tertiary volcanic units as regional confining units, there are enough domestic wells completed in these units to perform general analysis of transmissivity. The available well data are likely biased toward the more transmissive parts of these units because boreholes that do not yield water are not completed as wells. Although sample size of specific capacity data from Proterozoic siliciclastic (n=12) and Tertiary volcanic units (n=16) is too small for a rigorous statistical comparison, figure 18

Table 3. Transmissivity of aquifers and other hydrogeologic units in Ogden Valley.

Hydrogeologic unit	Unit symbol	Count	Min T (ft^2/d)	Max T (ft^2/d)	Median T (ft^2/d)	Mean T (ft^2/d)	Geometric mean T (ft^2/d)	Geometric mean K (ft/d)
Principal confined aquifer	QsgA	45	3	14,800	250	1100	220	30
Principal unconfined aquifer	QsgA	147	4	104,000	170	1200	160	20
Proterozoic siliciclastic	ZsiC	12	5	3100	160	600	100	3
Tertiary volcanic and volcaniclastic	TvC	16	1	3100	170	400	100	2
Cretaceous and Tertiary conglomeratic	KTcgA	34	5	2600	30	100	30	2

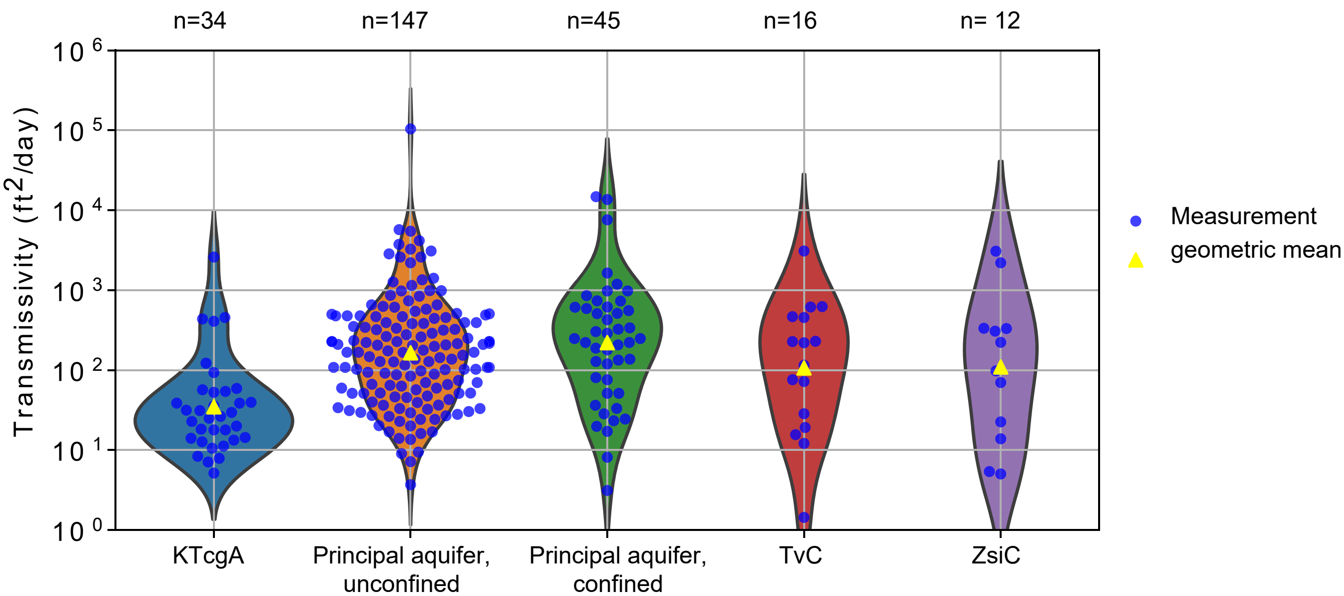


***Figure 18.** Transmissivity values for Ogden Valley aquifers.*

demonstrates that the distribution of available transmissivity is comparable to that of the principal aquifer. Geometric mean transmissivity of both units is approximately 100 ft^2/d.

The Tertiary conglomeratic unit has the lowest average transmissivity of the hydrogeologic units examined, having a geometric mean transmissivity of 30 ft^2/d. Most of the 34 available specific capacity values are less than 100 ft^2/d (figure 18). Many small domestic wells are completed in this unit high in the South Fork Ogden River drainage near Causey Reservoir in areas not underlain by other aquifers (figure 10). The Tertiary conglomeratic unit transmissivity is similar to Tertiary Wasatch and Salt Lake Formations transmissivity values measured in Cache Valley, north of Ogden Valley (Inkenbrandt and Lachmar, 2012).

Transmissivity values of confined and unconfined units were combined to produce a map of the distribution of transmissivity in the principal aquifer (figure 19). Transmissivities are highest near the western margin of the valley-fill sediments, especially near Eden and Pineview Reservoir (figure 19). Because transmissivity is a function of aquifer thickness, the transmissivity values generally correlate with valley-fill thickness (figure 13), with higher values in the deeper parts of the valley. The spatial distribution of transmissivities from aquifer test data, although sparse, generally agree with the distribution presented by the specific capacity data.

We did not investigate aquifer properties of the shallow unconfined aquifer, but Reuben (2013) performed slug tests on nine wells completed in the shallow unconfined aquifer and estimated a hydraulic conductivity range of 0.86 to 22 meters per day (2.8–72 feet per day). Low permeability of the shallow unconfined aquifer is reflected by lengthy durations (typically days) of standing water on ground surfaces following precipitation (Lowe and Miner, 1990).

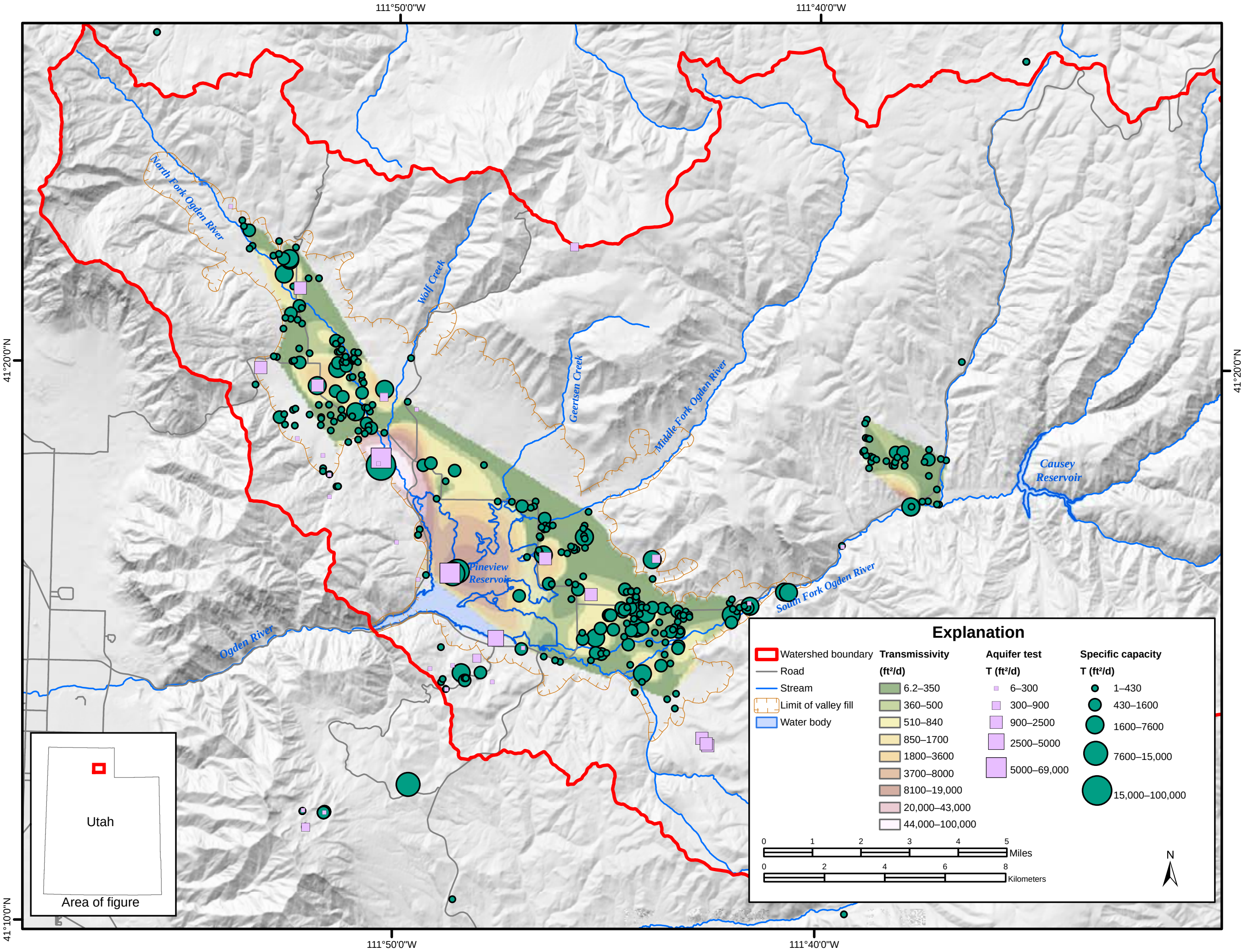


Figure 19. *Distribution of transmissivity in Ogden Valley aquifers.*

GROUNDWATER LEVELS AND STREAMFLOW

Water Levels, Potentiometric Surfaces, and Gradients Between Aquifers

Methods

To construct potentiometric surface maps, we measured the water level in 62 wells in Ogden Valley in April and May 2016 and a subset of 18 of those same wells in September 2016. We supplemented our data with several water-level measurements made by the USGS Utah Water Science Center from the National Water Information System (NWIS) database (U.S. Geological Survey, 2016). We obtained water-level measurements made by Ogden City personnel on days in which all six Ogden City well field wells were pumping. We calculated the water-level elevation at each well by subtracting the measured depth to water referenced to land surface from the land surface elevation, which was measured using a Trimble high-precision Global Positioning System (GPS) having vertical accuracy to 10 centimeters. For the 12 wells that were not accessible with the GPS, land surface elevation was extracted from a 10-meter digital elevation model (DEM) having an absolute vertical accuracy of about 3 meters; however, accuracy of the DEM is generally better than 2 meters for the types of terrain found on the floor of Ogden Valley (Gesch and others, 2014, tables 1 and 4). Locations of wells having water-level information are shown on figure 20. Location and completion information for wells in which we measured water level are given in table D-1 in appendix D and the water levels used to contour the maps are given in table D-2 in appendix D. The spring 2016 potentiometric contour map approximates the potentiometric surface in the valley as interpolated from 71 measured water levels. Fifty-one of those water levels were measured in wells completed in the principal aquifer. We extended the potentiometric surface into adjacent bedrock based on the water level in bedrock wells.

We created maps to show different features of the water-level data using ArcMap. The spring 2016 potentiometric surface map was created by interpolating the water-level points using the Topo To Raster interpolation method, converting the raster

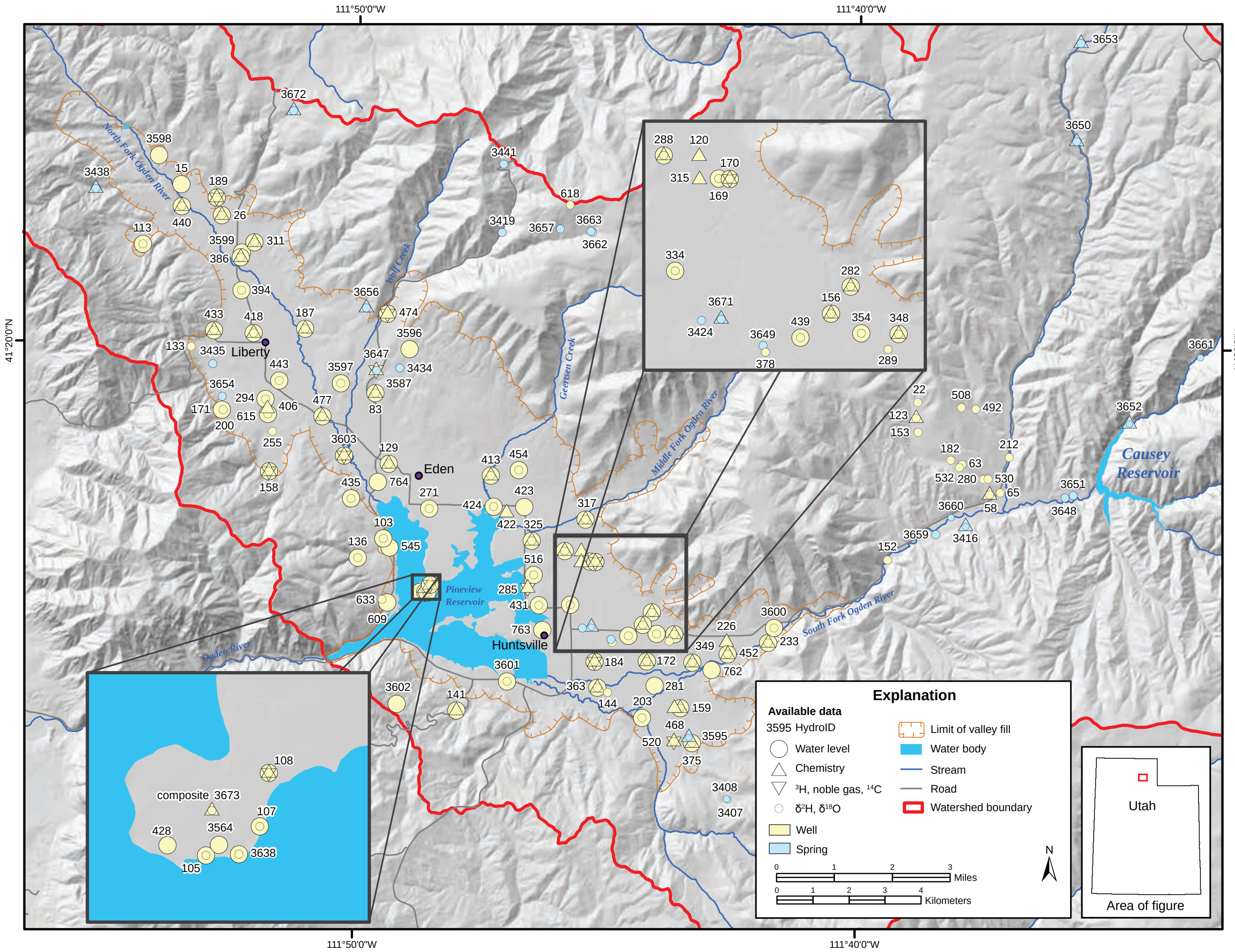


Figure 20. *Well and spring water-level measurement and sample locations.*

surface to polylines at 20- or 50-foot contour intervals, and further refining the contours manually. We then interpolated the manually refined contours back into a grid raster surface using the Topo To Raster interpolation method. We created a depth-to-water map by subtracting the 2016 potentiometric surface grid from the 10-meter DEM grid of land surface elevation using ArcMap. A map showing the change in water level from spring 2016 to fall 2016 was created by plotting the difference in water level measured at each well and contouring the values first using ArcMap and then manually refining the contours. We created a map showing the change in potentiometric level from 1985 to 2016 by (1) assigning land-surface elevations from the DEM to all well locations having 1985 or 2016 water-level data, (2) contouring water levels extracted from NWIS (U.S. Geological Survey, 2016) that were measured in May and June 1985 using 60-meter grid spacing and the Topo To Raster interpolation method, (3) contouring our 2016 water levels using the same spacing and method, and (4) subtracting the surface grid created in step 3 from the grid created in step 2. The 2016 water-level elevations and surface for the 1985 to 2016 water-level change map are not equal to the spring 2016 potentiometric surface map and elevations because we used high-accuracy GPS wellhead elevations for the latter and less accurate DEM-derived land-surface elevations for the former. Using the less accurate datum for the 1985 to 2016 change map was necessary for a representative comparison of the two data sets.

Potentiometric Surfaces

The March–April 2016 potentiometric surface (figure 21) shows that water levels are highest in the bedrock aquifers and relatively high in the valley-fill aquifer in the North Fork arm of the valley. The horizontal gradient is steepest in the mountains and the North Fork arm of the valley and less steep in the South Fork arm and in the principal aquifer surrounding Pineview Reservoir. Doyuran (1972) reported that the horizontal hydraulic gradient in the unconfined aquifer ranged from 80 feet per mile (15 m/km) near Liberty to 25 feet per mile (5 m/km) near Eden. In 2016, the horizontal gradient between Liberty and Eden was about 50 feet per mile (9 m/km), and in the South Fork arm it was about 40 feet per mile (8 m/km). The closed contours in the central part of the valley indicate a cone of depression around Ogden City's well field, which extracts water year-round.

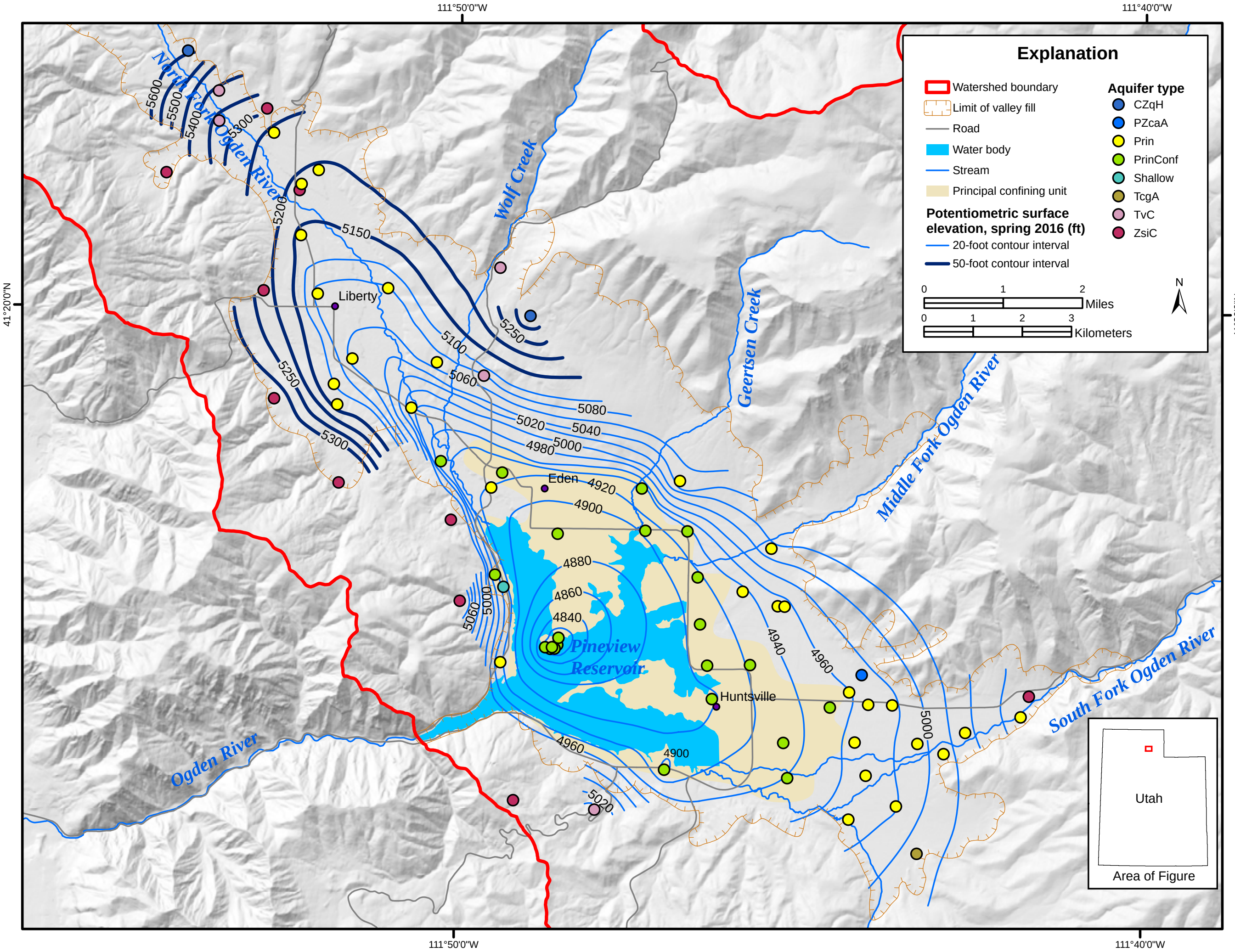


***Figure 21.** Potentiometric-surface contour map of water levels in the Ogden Valley aquifer system, March and April 2016. See figure 9 for aquifer designations.*

Depth to water in wells in the principal aquifer generally ranges from 5 to 50 feet (2–15 m). Water is usually considerably deeper in bedrock wells on valley margins or foothills (figure 22). In the unconfined principal aquifer east of Huntsville, depth to water in wells is generally between 10 and 30 feet (3–9 m), whereas near Eden and Liberty depth to water is typically 10 to 40 feet (3–12 m). Depth to water in wells at the margins of the valley and in bedrock units can be 200 feet (60 m) or more. Water levels in wells in the confined principal aquifer range from near surface level to about 40 feet (12 m) but are greater at the Ogden City well field. Depth to water in a well in the confined principal aquifer is shallower than the water-bearing stratum because the water in the confined aquifer is under pressure.

Doyuran (1972) reported that depth to the water table fluctuated seasonally as much as 30 feet (9 m). The water table is generally highest during April, May, or June (Leggette and Taylor, 1937; Thomas, 1945; Avery, 1994), and lowest in September, October, or November (Doyuran, 1972; Avery, 1994). During the study period, the level of the potentiometric surface throughout the valley generally decreased from spring to fall 2016 (figure 23). Water levels generally fell by 9 feet (3 m) or more in the North Fork arm of the valley. Two wells in the North Fork arm of the valley show greater than 25 feet (8 m) of drawdown from spring to fall 2016 (figure 23), although both wells had been pumped in the days prior to measurement, and may show residual drawdown. Summer pumping in these two bedrock wells draws down the water level more than pumping the valley-fill aquifer because bedrock has lower transmissivity and storage capacity than unconsolidated sediments.

The Ogden City well field pumps year-round, but generally about 20% more in the summer months (Utah Division of Water Rights, 2018), which created an average decline in water levels from spring to fall 2016 in the six wells of about 9 feet (3 m) (figure 23).

Water levels declined by generally less than 5 feet (2 m) in the South Fork arm of the valley. The greater thickness and extent of the principal aquifer in the South Fork arm and more recharge from losing streams likely provides more storage

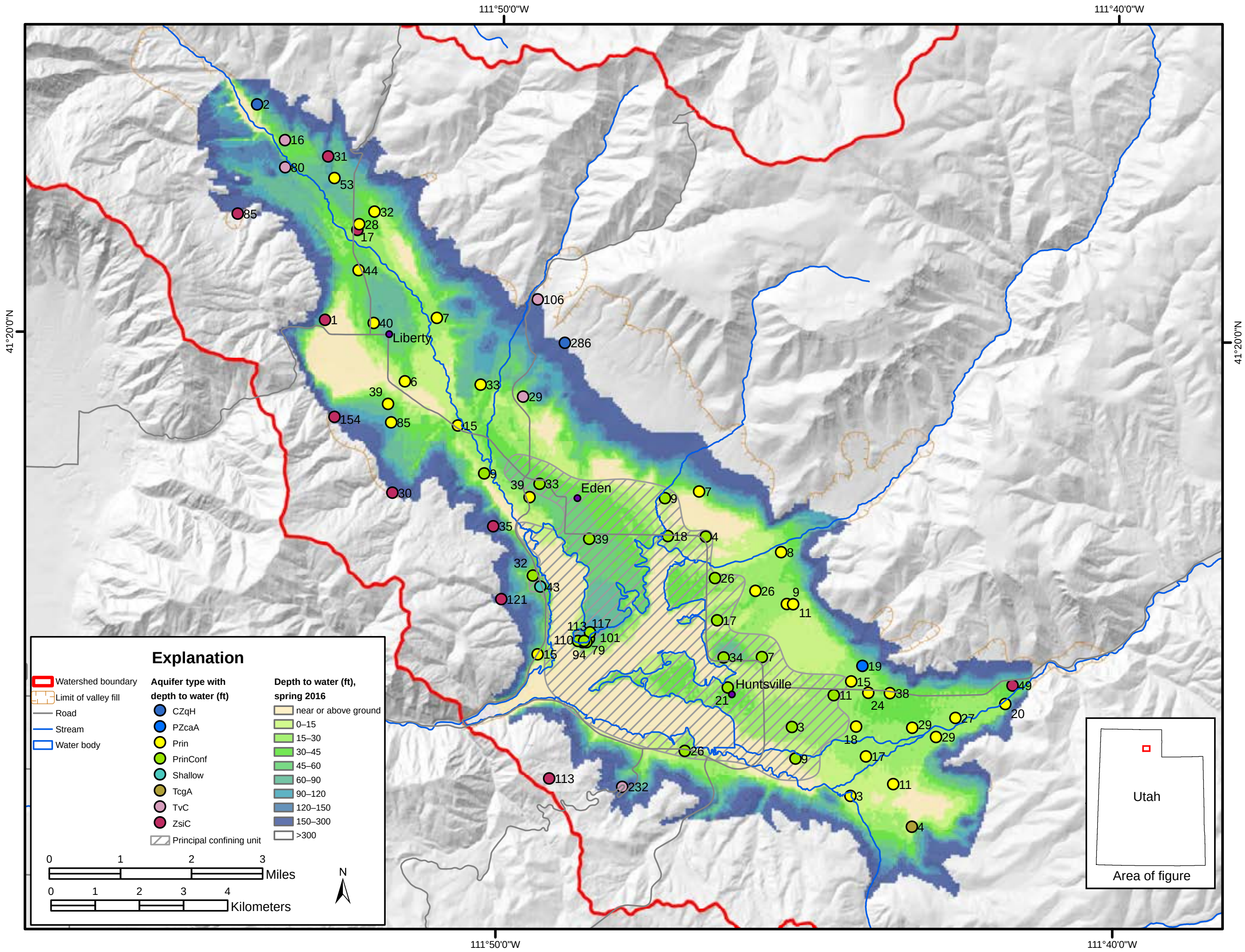


Figure 22. Depth to which water would likely rise in wells based on the spring 2016 potentiometric surface. Depth to water-bearing stratum may be deeper than depth to water. See figure 9 for aquifer designations.

capacity and stability of water levels to this area of the valley. When aquifers receive significant infiltration of unused irrigation water, water tables typically rise during the irrigation season, especially when fields are primarily flood irrigated. Water level in a well in Huntsville (WL-763) that is completed in the principal aquifer is monitored daily by the USGS, and a seasonal trend of increasing water level beginning in April or early May, peaking in June, and decreasing by September is typical (hydrograph on figure 23). In 2015, Huntsville Irrigation Company switched irrigation practices from dominantly flood type to sprinklers. Landowners in the area served by Huntsville Irrigation Company east of Huntsville reported that springs and dugouts in their fields that had typically flowed or were filled during the summer did not do so in summer 2016. The seasonal trend in the continuously monitored well in the confined aquifer did not show a marked change in 2016. This well is insulated from near-surface irrigation activities by the confining unit and is influenced by the pumping rate of the Ogden City well field, as discussed in the Gradients between Aquifers and Pineview Reservoir and Water-Level Trends sections that follow.

The long-term change in the level of the potentiometric surface of the principal aquifer was evaluated by comparing potentiometric maps of Doyuran (1972, plate 2) and Avery (1994) to our map. Prior to construction of Pineview Dam from 1934 to 1937, the pressure in the confined aquifer was sufficient to produce artesian flow in any Artesian Park wells having well-head elevations lower than 4860 feet (1481 m) (Leggette and Taylor, 1937). The average water level in the principal aquifer in March 2016 at the Ogden City well field was approximately 4812 feet (1467 m), which is a decline of nearly 50 feet (15 m). The potentiometic surface drawn by Doyuran (1972, plate 2) is about 10 to 20 feet (3–6 m) higher at the east edge of the Middle Fork arm of Pineview Reservoir than we show on our potentiometric map, indicating decline around the reservoir since 1970.

The differences between June 1985 and March–April 2016 are shown on figure 24. Water levels in many wells in Ogden Valley historically show seasonal trends whereby water level is lower in the early spring than in June by as much as 10 feet (3 m) in some wells (Thomas, 1945; Doyuran, 1972; Avery,

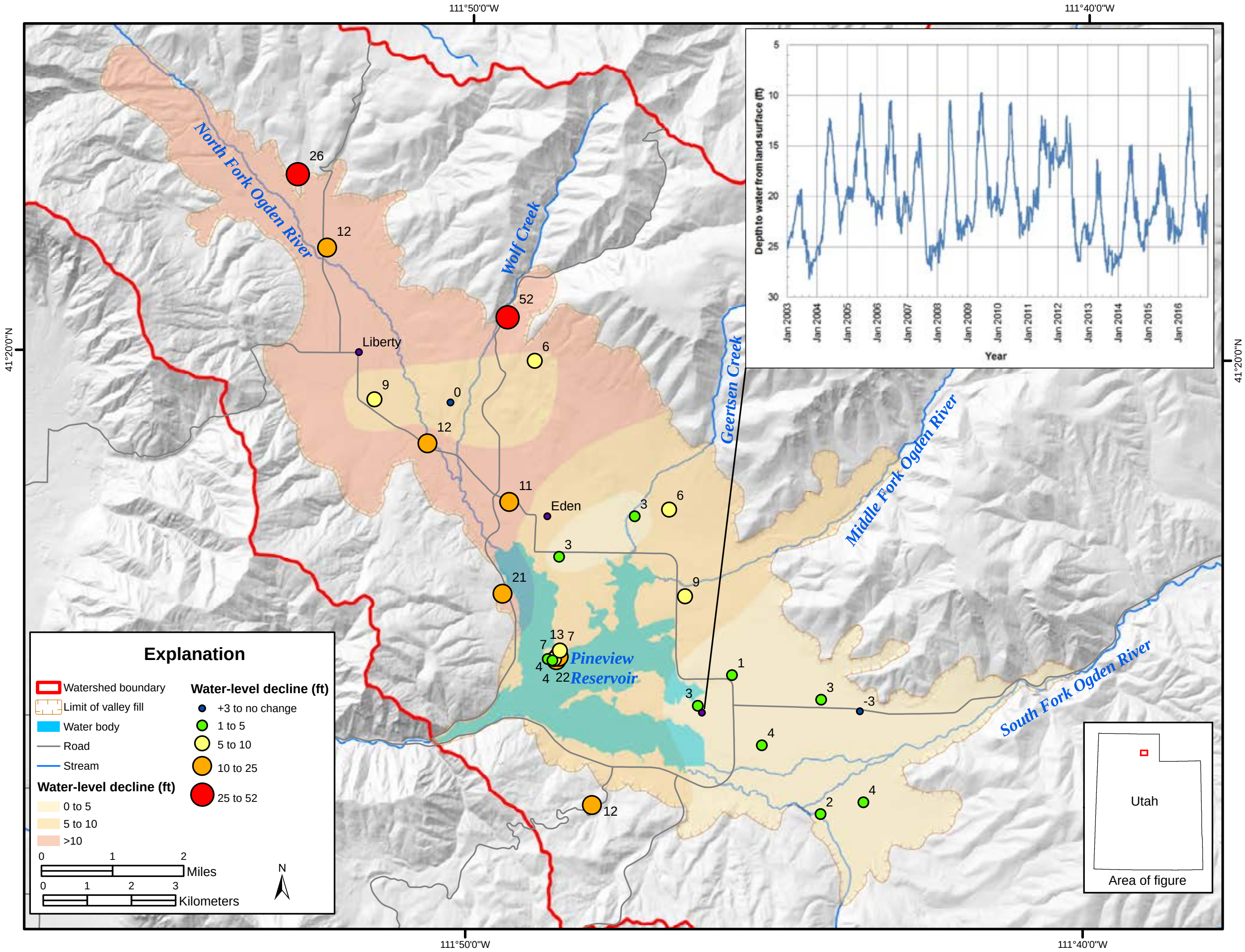


Figure 23. *Change in water-level elevation in selected wells between spring 2016 and September 2016 and a hydrograph of the Huntsville monitoring well WL-763.*

1994), which is why we do not highlight changes of ±10 feet (±3 m) on figure 24. The water levels over most of the valley were not significantly different between 1985 and 2016. An area of moderate groundwater-level decline in the South Fork arm of the valley may be a result of changing irrigation practices in this area. A larger magnitude of water-level decline in one localized area of the upper North Fork arm of the valley is based on water-level differences between different wells and should be viewed with caution. While the wells within the bullseye of decline are reported to be in the valley-fill aquifer, there may be unknown well construction or well use factors influencing the data. If the trend is reflective of water levels in the principal aquifer, the decline may be due to new well development in this area or changes in surface water management that limit aquifer recharge.

The largest magnitude and area of groundwater decline is around the Ogden City well field. Figure 24 shows that the cone of depression around the well field has deepened by up to 65 feet (20 m); however, comparison of water levels in the well field is complicated by the availability of data. Water levels used to contour the 1985 potentiometric surface were measured in wells that were not pumping, but other wells in the field had been pumping for seven months prior to measurement. The 2016 Ogden City well field water levels are pumping water levels. We estimate that water levels in pumping wells in 1985 would have been 20 to 30 feet (6–9 m) deeper than the available levels based on observation well location and the differences reported between pumping wells and non-pumping wells in the well field in 2016 (Russ Monson, Ogden City treatment plant manager, written communication February 2017). If we adjust for the differences between pumping and non-pumping water levels, the change in the cone of depression around the Ogden City well field shown on figure 24 would likely be a maximum of 30 to 40 feet (9–12 m) instead of greater than 50 feet (15 m) as shown.

Avery's (1994) potentiometric map shows a cone of depression around the wells, which has likely existed since the city began extracting water from the flowing artesian wells in the early 1900s. A hydrograph in Doyuran (1972, figure 13) of a non-pumped test well very near the well field shows the average wa-

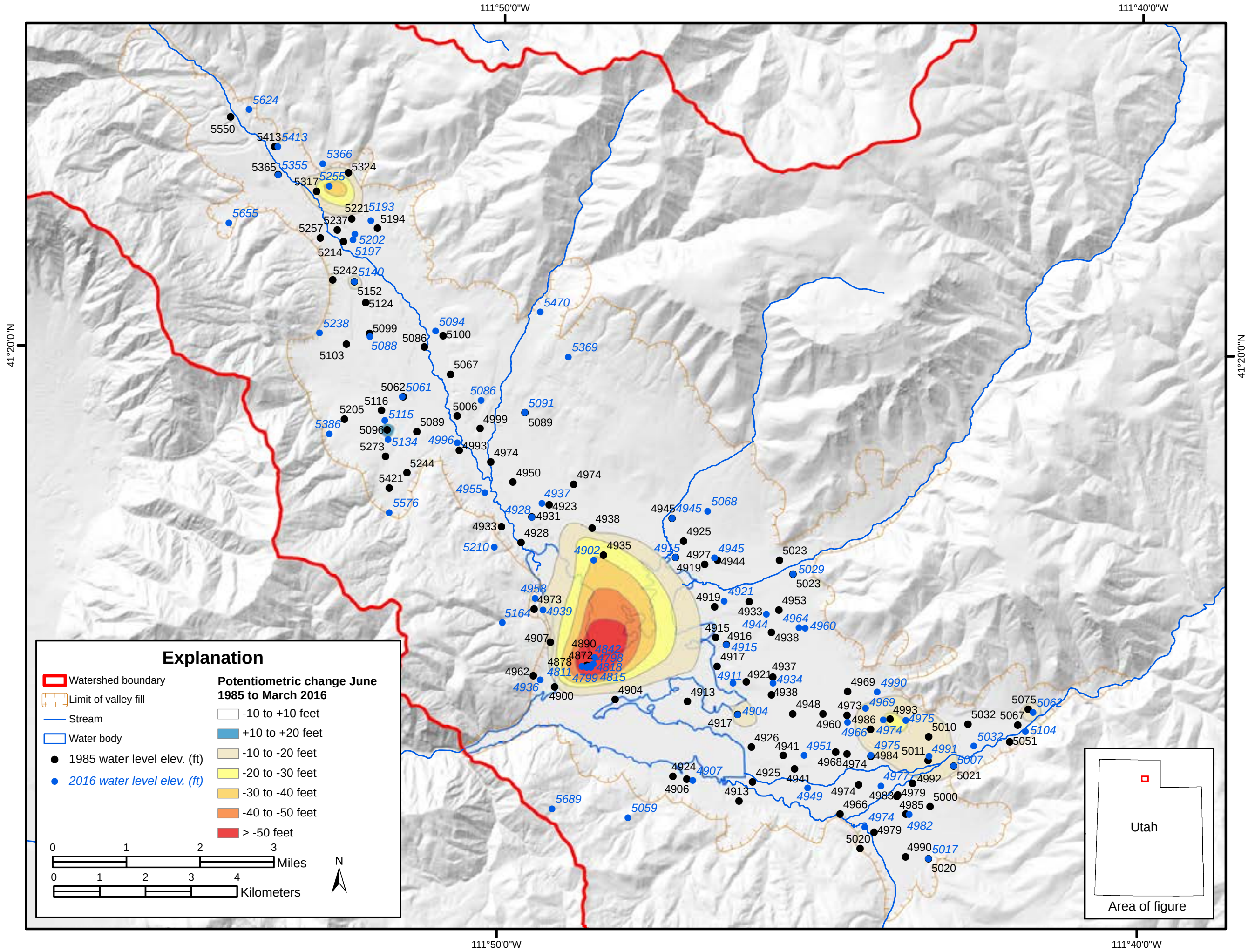


Figure 24. *Approximate change in potentiometric surface elevation from 1985 to 2016. Comparison at Ogden City well field is between water levels in monitoring wells (1986) and pumping wells (2016). Estimated actual maximum drawdown in aquifer is 30 to 40 feet (9–12 m).*

ter-level elevation was about 4866 to 4881 feet (1483–1488 m) in 1967–69, which is about 55 to 70 feet (17–21 m) higher than the average pumping level in April 2016. Again, differences in well status make direct comparison of water levels through time difficult, but some portion of the tens of feet difference is probably attributable to long-term changes in the confined aquifer. We note that annual production from the well field from 1931 to 2016 has varied from 7890 to 18,150 acre-ft per year, but the average annual production (12,165 acre-ft) has not increased over time (data from table 9 of Doyuran, 1972; Utah Division of Water Rights, 2018). From these data we conclude that the aquifer had not reached equilibrium with well field pumping in 1985, and that the cone of depression has expanded since then. Whether equilibrium had been reached by 2016 can only be determined by future water-level measurements.

Gradients between Aquifers and Pineview Reservoir

The water-table elevation in the shallow unconfined aquifer at nine locations near the shores of Pineview Reservoir in 2010 through 2011 ranged from 4912 to 4937 feet (1497–1505 m) above sea level (NGVD29 datum) and typically varied in each well by 2 to 8 feet (1–2 m) (Reuben, 2013, p. 150). During this period, the potentiometric head in the confined principal aquifer at Huntsville (WL-763) was generally between the levels seen in the two closest shallow unconfined aquifer wells (wells 4 and 8 shown on figure D-1 in appendix D) and always higher than the surface elevation of Pineview Reservoir (figure 25). There is uncertainty in our analysis because Reuben (2013) reported well cap elevations to the nearest meter, resulting in an elevation uncertainty exceeding 3 feet (1 m). Avery (1994) placed seepage meters on the lakebed of Pineview Reservoir and measured seepage coming into the reservoir, which he believed was upward seepage from the confined aquifer. Our analysis suggests that near the edge of the confining unit and distal to the Ogden City well field, the gradient between the shallow unconfined and principal confined aquifers may be upward or downward but is likely small and not conducive to inducing vertical leakage. Stronger vertical gradients between the aquifers may exist elsewhere, but lack of long-term water-level monitoring and spatially paired wells prevents further assessment. The vertical gradient is always upward from the principal confined aquifer near Huntsville to Pineview Reservoir, but this is not the case everywhere in the aquifer.

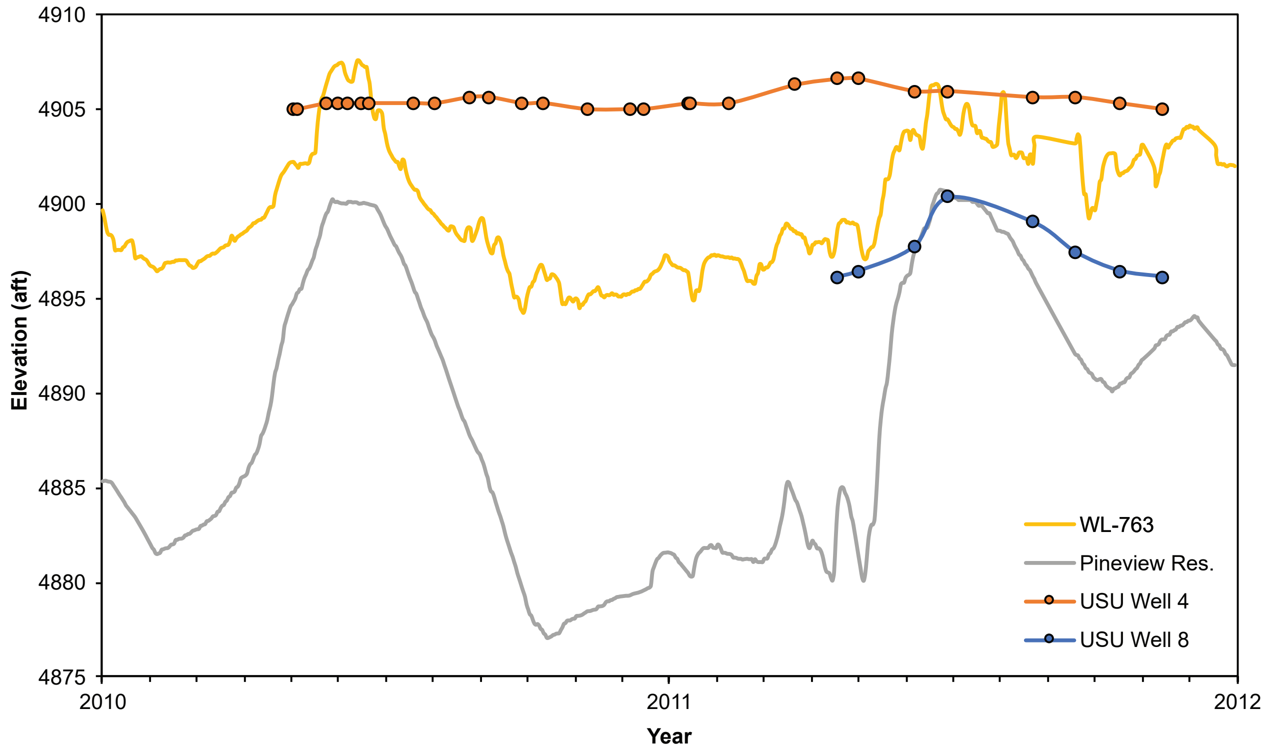


Figure 25. *Comparison of water levels in the shallow unconfined aquifer (USU wells 4 and 8), principal confined aquifer (Huntsville well WL-763), and Pineview Reservoir. Elevations referenced to NGVD29 datum. Shallow aquifer well data from Reuben (2013).*

During 2016, the pool elevation in Pineview Reservoir ranged from 4876 feet (1486 m) in January, peaking in late May at 4900 feet (1494 m) (full pool). Based on our contouring of the confining unit (figure 17) and water-level contouring (figure 21), the potentiometric level in the confined aquifer surrounding Ogden City well field is well below reservoir water level and at elevations within the confining unit (cross sections B–B′ and C–C′ on plate 1). The potentiometric surface elevation in the confined principal aquifer near the Ogden City well field in April 2016 was about 4812 feet (1497 m), providing a strong downward vertical head gradient over about 2 square miles (5 km^2) of the principal aquifer. Avery (1994) also observed downward vertical head gradients to the principal aquifer in a focused area centered around the well field in 1985. Elsewhere, his potentiometric map showed there would have been an upward vertical gradient from the principal aquifer to most areas of the reservoir during the time of his study. We reevaluated the direction of head gradient between the reservoir and the principal confined aquifer for the current study period of 2003 to 2016. Pineview Reservoir level fluctuated between 4855 and 4901 feet (1480–1495 m) above sea level during our study period and averaged about 4880 feet (1487 m). Our March-April 2016 potentiometric-surface map (figure 21) shows that a substantial portion of the confined aquifer underlying the reservoir had head levels in this range, which indicates that, depending on reservoir level, the gradient between the reservoir and the principal confined aquifer, and thus the direction of leakage, could be either up or down. Leakage is discussed in detail below.

Water-Level Trends

When Pineview Reservoir initially filled in 1937, the mass of the water loaded and compressed the confined aquifer and raised the potentiometric surface (Thomas, 1945; Doyuran, 1972). Average water-level increases in some wells were as much as 10 to 15 feet (3–5 m) (Doyuran, 1972; Avery, 1994).

Water levels have been monitored long-term in only four wells in Ogden Valley. We analyzed long-term trends in water levels using data from these four wells. To consistently interpret the year-to-year changes in water table depth, only measurements from March were used for wells having infrequent data. March was chosen because of the availability of data.

The volume of water in Pineview Reservoir and the volume of water extracted from the Ogden City well field both influence the potentiometric surface elevation of the principal confined aquifer. Well WL-763 [USGS ID 411544111461001 or (A-6-1)18bad-1] is located near the Huntsville public library and is completed in the principal confined aquifer (figure 20). The water-level elevation difference between Pineview Reservoir and the principal confined aquifer at Huntsville as measured in well WL-763 was always negative from 2010 to 2018; i.e., there is an upward gradient towards the reservoir, with a mean elevation difference of –14.2 ± 6.2 feet (–4.3 ± 1.9 m) (figure 26). Thomas (1945, 1952), Doyuran (1972), and Avery (1994) concluded that the water-level fluctuation in the confined aquifer was due to loading by water in Pineview Reservoir. We applied the Clark method (Clark, 1967)

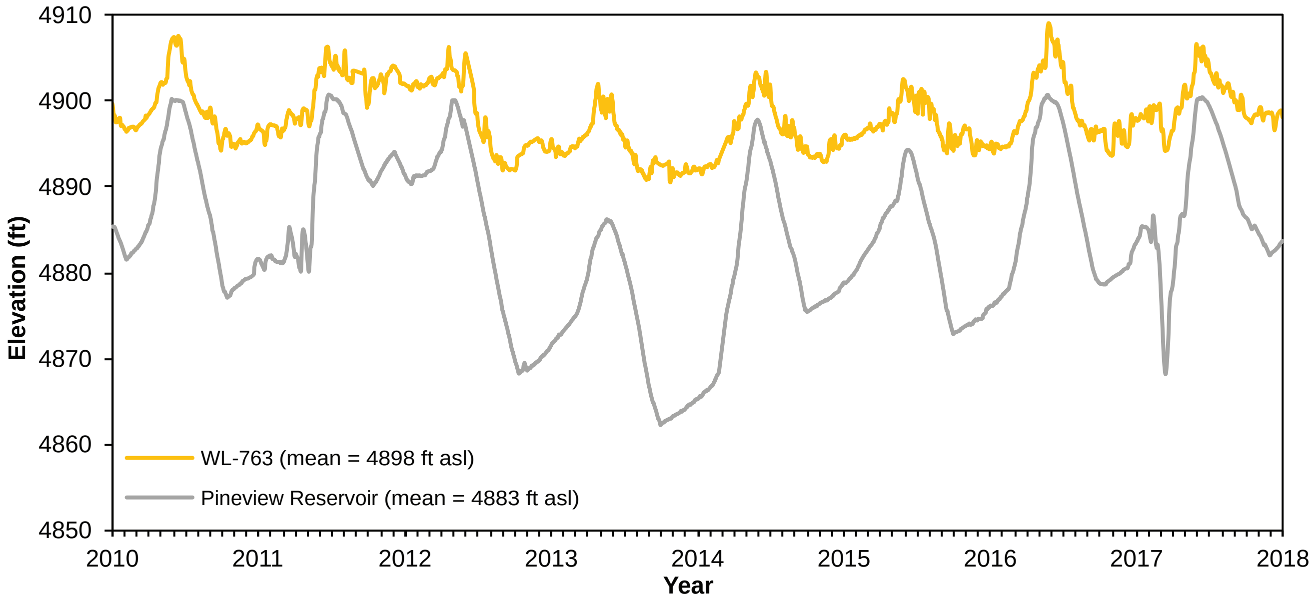


Figure 26. *Comparison of Pineview Reservoir water level and the potentiometric level in the principal confined aquifer at Huntsville (well WL-763), 2010 through 2017.*

to 2010–2018 daily water-level data to calculate a loading efficiency of 0.3744, which means that for every 1 foot (0.3 m) of water-level change in Pineview Reservoir, the potentiometric level in the Huntsville well changes by 0.37 feet (0.11 m). We then removed the effect of loading using the loading efficiency to reveal a "cleaner" long-term potentiometric level and allow us to correlate potentiometric-level fluctuations caused by other factors. With water-level fluctuation due to the weight of the water in Pineview Reservoir removed from the data, we show that daily fluctuations in potentiometric level in well WL-763 are inversely correlated with the groundwater extraction rate from the Ogden City well field (figure 27), confirming the findings of Thomas (1952) and Doyuran (1972). The strongest correlation (−0.7758) between WL-763 and the Ogden City well field is with a two-day delay between a change in pumping rate and the observed effect in WL-763. Therefore, we concur with previous researchers that changes in pressure and thus water levels in wells in the confined aquifer are induced by the weight of water in Pineview Reservoir on the aquifer matrix and by Ogden City well field extraction rate. More water in the reservoir compresses the aquifer matrix and forces water levels to rise in wells, and less pumping from the well field allows aquifer pressure to build and also causes potentiometric level in the aquifer to rise.

Water levels in the four long-term water-level monitoring wells in Ogden Valley (WL-763, WL-424, WL-762, and WL-764) are shown on figure 28. Decadal trends in water levels in WL-763 (corrected for loading from Pineview Reservoir; see Gradients between Aquifers and Pineview Reservoir section above) show a slight decline ranging between 0.26 feet (0.08 m) per year in the 1980s and 0.02 feet (0.01 m) per year in the 2010s (figure 28a). The overall trend of WL-763 is –0.05 feet (–0.02 m) per year since 1977. WL-424 shows practically no change in the overall long-term trend; however, multi-year variations exceed 6 feet (2 m) and data from the 1980s and 1990s is sparse, making the trend calculation imperfect (figure 28b). WL-762 shows the water table at approximately 14 feet (4 m) deep in 1986 (figure 28b). Levels were lower, at approximately 25 feet (8 m), in 1988 to 1999. The long-term trend for this well is –0.3 feet (–0.1 m) per year, but the more recent trend from 2001 to present is –0.13 feet (–0.04 m) per year. WL-764 has a depth to water of approximately 40 feet (12 m), which has been consistent since the start of March sampling in 1985 (figure 28b). The long-term rates of change on these four wells are small relative to yearly amplitudes that regularly exceed 10 feet (3 m). Based on these small rates of change, we conclude that there has been little long-term change in storage in the principal aquifer in the past three decades.

Discharge Measurements

Stream and canal discharge (flow) was measured for two reasons: (1) to provide the data on which we derived a stage-discharge relationship for the main streams in Ogden Valley, from which we estimated streamflow to Pineview Reservoir, and (2) to quantify the amount of water gained or lost from streams and canals.

We measured stream discharge 215 times at 121 unique locations shown on figure 29. Discharge measurement site information is given in table D-1b in appendix D. Streamflow was measured using a Hach FH950 electromagnetic current velocity meter or a Swoffer 3000 propeller-type current velocity meter at 0.6d (depth) from the water surface across stream transects (figure 30). At smaller ditches or spring brooks and through several culverts having dangerously rapid shallow flow, we measured flow using the neutral buoyant object (NBO) method through a measured channel geometry.

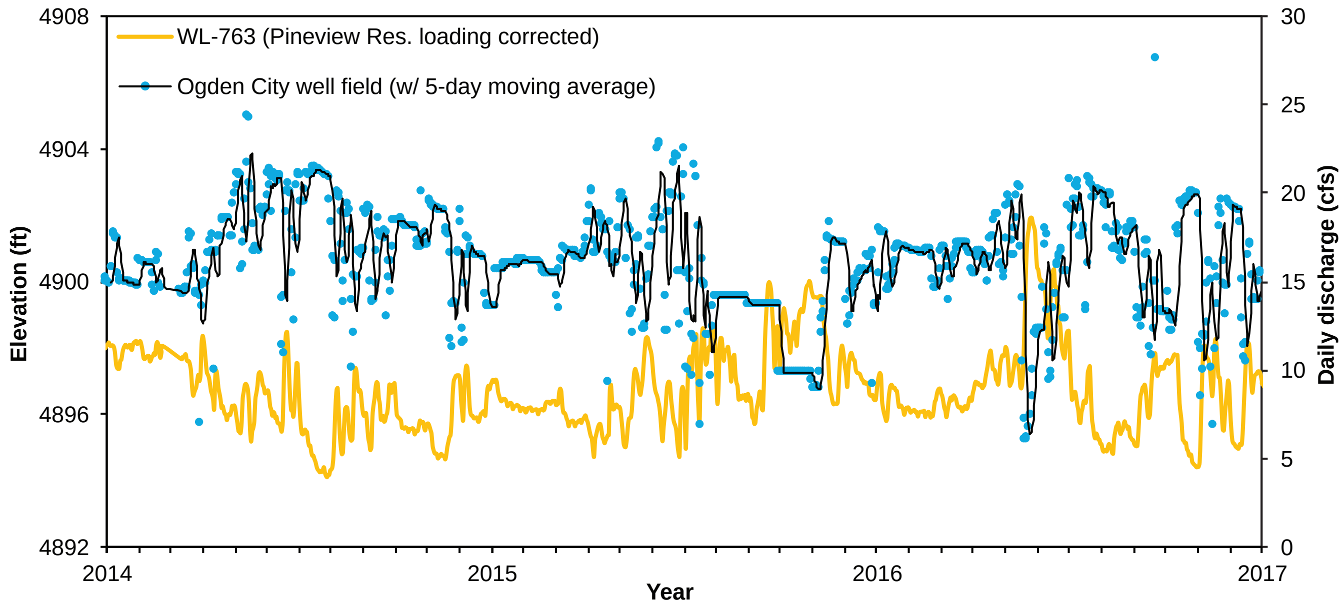


Figure 27. *Potentiometric levels in well WL-763, corrected for the loading effects from Pineview Reservoir, and daily pumping rates from the Ogden City well field, 2014 through 2016.*

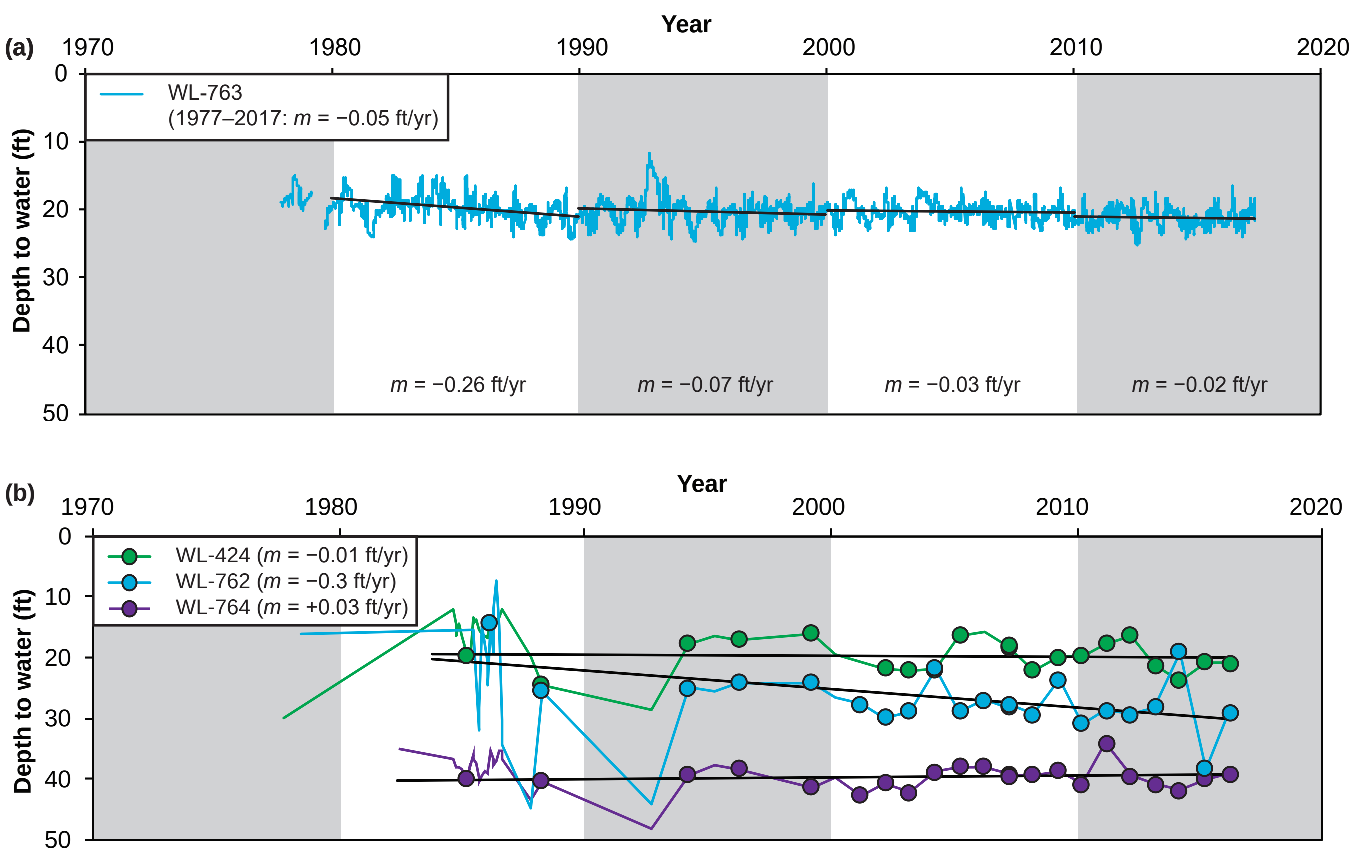


Figure 28. *Long-term trends in potentiometric levels in* ***(a)*** *Huntsville well WL-763 corrected for loading caused by Pineview Reservoir, and* ***(b)*** *other wells with long-term monitoring. All available data are plotted, but trends were calculated using March levels only (filled circles) to exclude seasonal effects.*

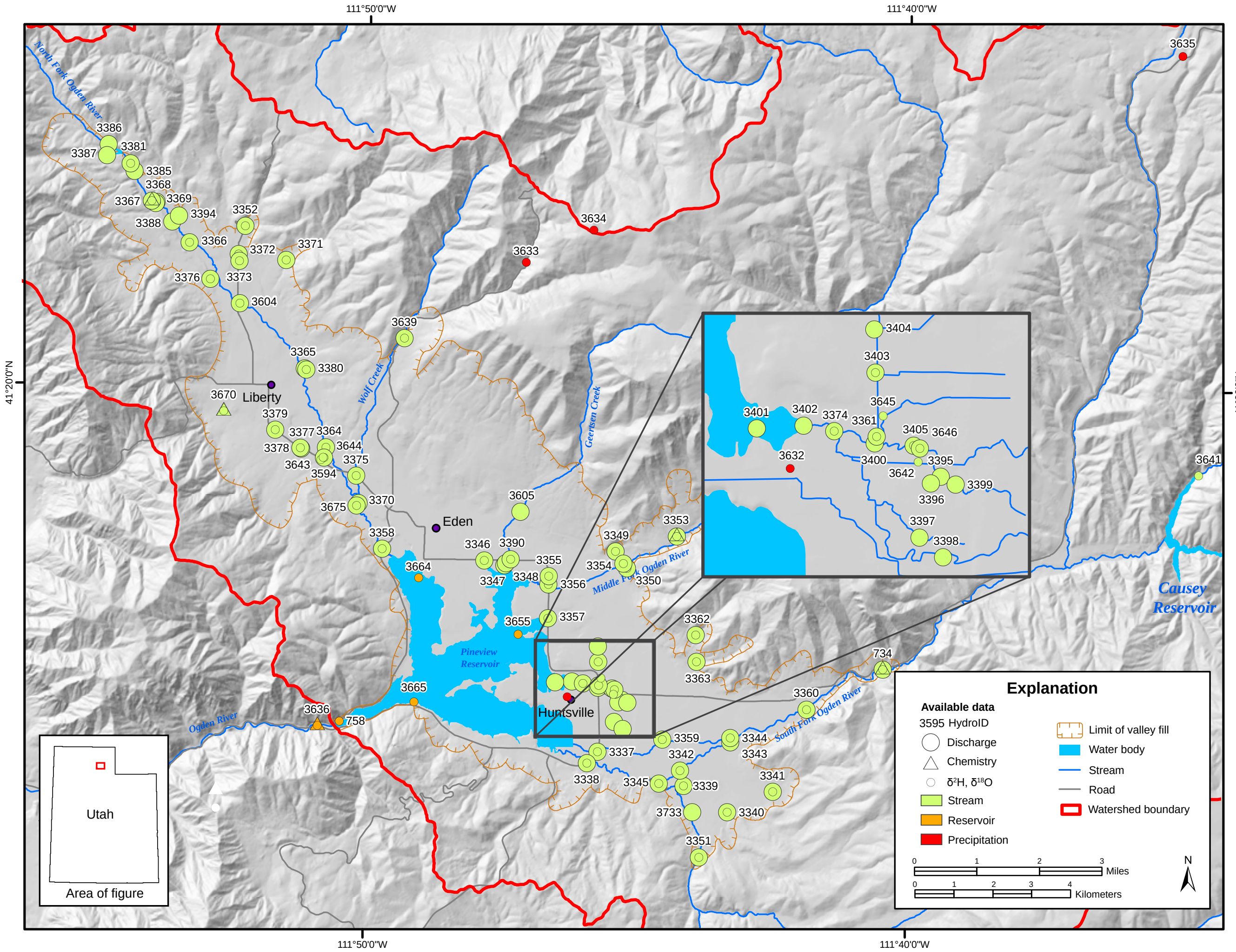


Figure 29. *Discharge measurement locations and stream, reservoir, and precipitation sample locations.*

Figure 30. *Using a current velocity meter to measure flow in the North Branch of the South Fork Ogden River.*

We observed streamflow ranging from zero to 137 cubic feet per second (cfs) during our study; the South and North Forks of Ogden River had the highest flows in spring 2016. Discharge measurements are summarized in table 4 and detailed in table D-3 in appendix D. We used our periodic discharge measurements at repeat locations to create stage-discharge relationships to quantify streamflow as part of the water budget. The methodology and results of that technique are discussed in the Streamflow subsection of the Water Budget Development section below. Time-specific discharge measurements are the basis of our seepage runs.

Stream and Canal Seepage Studies

Gaining an understanding of the extent of groundwater–surface water interaction in Ogden Valley is a key goal of this study. Streams interact with groundwater in three basic ways: streams gain water from inflow of groundwater through the streambed when the water table is higher than the streambed, streams lose water to groundwater by outflow through the stream bed when the water table is below the bottom of the streambed, or they do both, gaining in some reaches and

Table 4. *Summary of stream and canal discharge measured between August 2015 and July 2017.*

Drainage	Number of measurements	Maximum discharge (cfs)
North Fork Ogden River	55	137
Sheep Creek	10	10
Geertzen Creek	8	14
Middle Fork Ogden River	23	48
Spring Creek	28	12
South Fork Ogden River	40	132
Ogden Valley Canal	51	65

losing in other reaches (Winter and others, 1998, p. 9). If the water table rises or falls through time, losing sections can become gaining sections and vice versa.

Methods

Seepage studies using discharge measurements, coupled with geochemistry and environmental tracer analysis, form the basis of our understanding of the degree of interaction between surface water and groundwater. Seepage runs involve measuring streamflow on multiple sections of a watercourse, ideally in as short a time span as possible. We performed three seepage runs on Ogden Valley's streams and canals in 2016. The spring and fall seepage runs were performed on the natural streams from the point where the streams enter the valley to Pineview Reservoir. The Ogden Valley Canal seepage run was performed on the canal from the point where water is diverted into the canal from the South Fork Ogden River to a location near the end of the canal near Wolf Creek. We inventoried all diversions (canals, ditches) or tributaries (natural or irrigation return ditches) to or from the stream segments using detailed aerial imagery, ground survey, and interviews with irrigation users and residents before the spring and summer seepage runs. Each run was performed by two teams measuring streamflow simultaneously on a given stream segment.

We conducted the spring seepage run March 7–10, 2016, after spring thaw but before peak runoff and before irrigation season. This period was during the early part of spring runoff, and because the valley experienced a significant rain event on the evening of March 6, discharge may have varied throughout the day and from day to day at our measuring locations. The USGS continuous streamflow measurement gauge on the South Fork Ogden River showed approximately 20% decrease in flow over the four-day period but less than 5% over the period we were measuring on that stream. Similarly, the discharge of the Middle Fork River that we calculated from transducer levels shows about a 5% decrease in flow over the period we were measuring on that stream. To control for this variability, we focused our flow measurements on stream segments having approximately 2-mile (3 km) reach over a two-hour time period, so that flow measurements used to compare upstream to downstream discharge would be within about two hours of each other. We measured streamflow 51 times at locations that were selected based on suitability of the stream channel for accurate measurement and location in relation to diversions and tributaries. These streamflow measurements were used to calculate gain or loss over 23 stream reaches.

We conducted a seepage run on the Ogden Valley Canal during irrigation season on July 19, 2016. Two teams worked from the start and end of the canal, meeting in the middle, to measure or observe discharge at 45 locations. During the seepage run we noted that many of the locations at which water could be diverted from the canal were not in use on that day. Six additional measurements at established gauging stations were provided by the canal operator or irrigators. Our manual discharge measurements agreed to within 10% of the measurements by the canal operator at four locations where both data were available. We were able to calculate the gain or loss of the canal over 18 canal segments. We measured the distance of the canal and individual canal segments using GIS and aerial imagery.

We conducted the fall seepage run on the natural streams November 7–9, 2016, after surface irrigation withdrawals ceased and during a steady baseflow period. The flow was steady over this period at the South Fork Ogden River USGS gauging station. We focused our flow measurements so that we measured a particular branch of stream in as short of time as possible. We revisited each location measured in the spring seepage run. We collected 49 streamflow measurements to calculate the gain or loss over 23 stream reaches.

We calculated gains and losses for discrete reaches of the major streams and canals as the difference between the flow measured at each location and the flow measured at the location immediately upstream of that location, plus any tributary flow and minus any diversions (equation 1).

$$\text{Gain or loss} = \text{downstream flow} - (\text{upstream flow} + \text{tributary} - \text{diversion}) \quad (1)$$

Negative values indicate the stream channel lost flow between the upstream and downstream locations and positive values indicate the stream gained water from its banks between the locations. Error in the gain/loss calculation is the sum of the error values of all measurements in that calculation and is likely an overestimate of the error associated with each calculation.

Stream Seepage Study Results

During our seepage run on the valley's main streams conducted March 7–10, 2016, we observed streamflow ranging from 0.2 cfs in Cache Valley Creek at the shooting range (hydroID 3352, table D-3 in appendix D) to 96.2 cfs on the North Fork Ogden River just before it empties into Pineview Reservoir (hydroID 3358). Flow at monitoring locations proximal to the reservoir was 66 cfs in the South Branch of the South Fork Ogden River (hydroID 3338), 54 cfs in the North Branch of the South Fork (hydroID 3337), 40 cfs in the Middle Fork (hydroID 3356), 12 cfs in Spring Creek (hydroID 3374), 14 cfs in Geertsen Creek (hydroID 3347), and 0.6 to 3 cfs in in 4 smaller tributaries (table D-3 in appendix D). The sum of the measurements of these stream segments discharging into Pineview Reservoir is approximately 288 cfs.

More stream segments were gaining during the March seepage run (16 segments) than were losing (7 segments) as shown on figure 31 and table D-4a in appendix D. All measured reaches of Geertsen Creek, Middle Fork Ogden River, and Spring Creek were gaining during our March seepage run, most notably the upper reaches of the Middle Fork where the stream flows over thin alluvium that is likely saturated and the lower parts of Spring and Geertsen Creeks where they overlie the confining unit. The water table in the principal unconfined aquifer is relatively high in much of the area during runoff season, so the water table intersects the stream channels and groundwater flows into the streams (figure 22). Spring Creek and the unnamed channels near it are fed by springs discharging from the completely saturated shallow unconfined aquifer. Together, Geertsen Creek, Middle Fork Ogden River, and Spring Creek had a net gain of about 24 cfs (table 5) from the aquifer to the stream channel, which is more than a third of their combined flow as measured at the last stations before they discharge to Pineview Reservoir.

Previous studies have reported that the South Fork of the Ogden River becomes a losing stream where it enters Ogden Valley, but gains where it crosses the outer margin of the confining unit in the center of the valley, separated by an approximately 2-mile (3 km) stretch of river channel which is dry most of the year (Leggette and Taylor, 1937; Doyuran, 1972; Lowe and Miner, 1990). We found similar conditions during our study. The South Fork Ogden River was losing about 18 cfs from where it exits the South Fork Ogden River canyon to near where it crosses to the shallow unconfined aquifer, the same volume measured in 1924 by the Office of the Utah State Engineer (Leggette and Taylor, 1937). The losing reach of the South Fork flows over permeable alluvi-

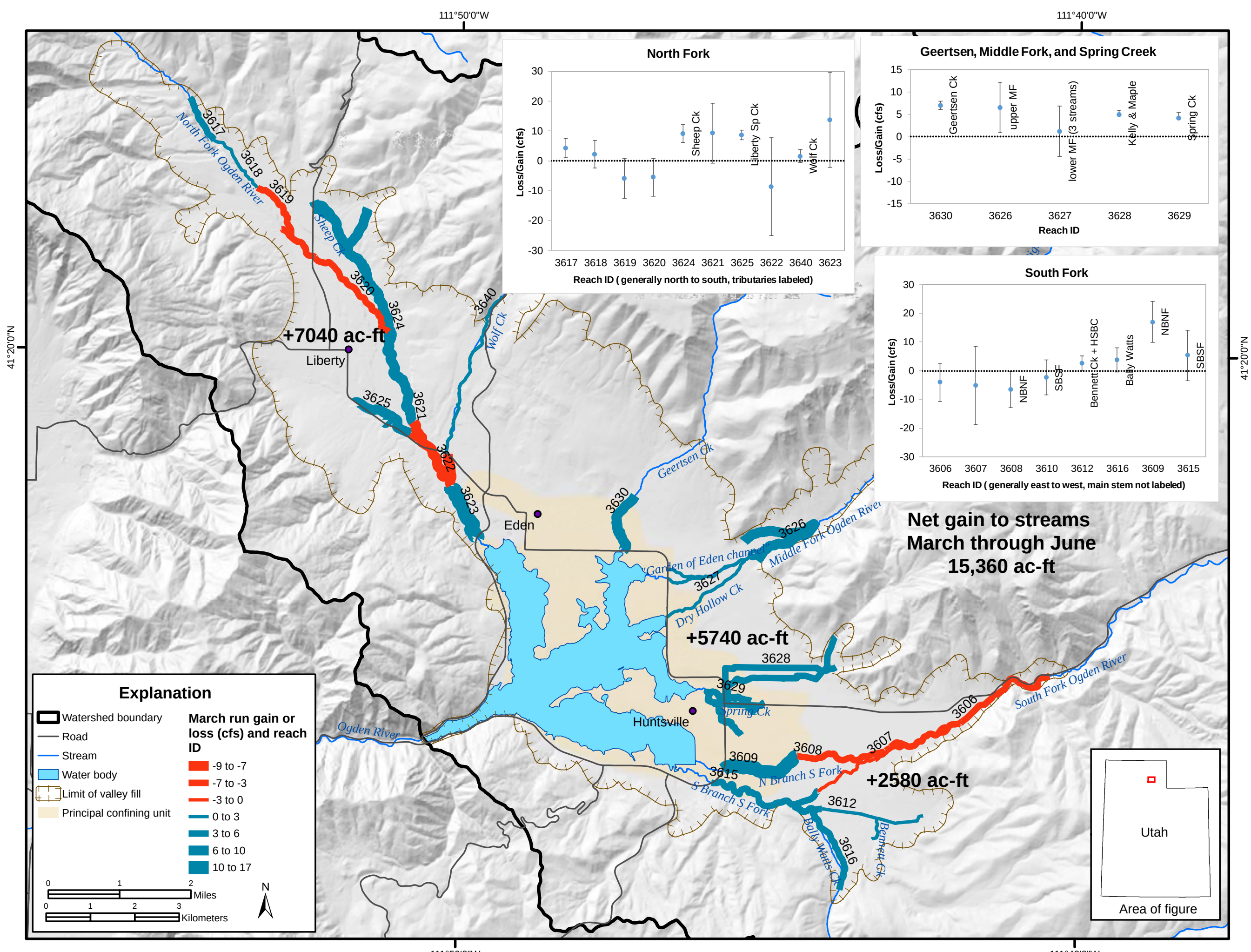


Figure 31. Gaining and losing reaches of major streams during the March 2016 seepage run and estimated net gain or loss from March through June from the North Fork, Geertsen/Middle Fork/Spring Creek, and South Fork stream networks. MF = Middle Fork, NBSF = North Branch South Fork, SBSF = South Branch South Fork, HSBC = Huntsville South Bench Canal.

Table 5. *Gains and losses during seepage runs for river drainages and Ogden Valley Canal and estimate of annual volume of water gained or lost.*

	March 2016 seepage Run			**November 2016 seepage Run**			**July 2016 canal seepage run**			Estimated annual gain or loss for drainage area (ac-ft)
	Net gain for drainage area (cfs)	% of flow gained[1]	Estimated gain Mar 1–June 30 (ac-ft)	Net gain or loss for drainage area (cfs)	% of flow gained/ lost[1]	Estimated gain or loss July 1–Feb 28 (ac-ft)	Net loss from canal (cfs)	% of flow lost[2]	Estimated loss during irrigation season (ac-ft)	
North Fork Ogden River	29	30	7040	-12	-100	-5900	-	-	-	**1140**
Middle Fork Ogden R., Geertzen Ck., Spring Ck.	24	36	5740	3	68	1560	-	-	-	**7300**
South Fork Ogden River	11	9	2580	-15	-146	-7200	-	-	-	**-4620**
Ogden Valley Canal	-	-	-	-	-	-	-18	-47	-3290	**-3290**
Net gain or loss	**63**	**22**	**15,360**	**-24**	**-154**	**-11,540**	**-18**	**-47**	**-3290**	**530**

[1] % of flow gained/lost is the sum of gains and losses in a drainage, divided by the discharge of that drainage at our measurement location most proximal to Pineview Reservoir
[2] % of flow lost is the net loss from canal divided by the discharge at the upstream end of the canal

al-fan and valley-fill deposits, and the water table is deeper than 20 feet (6 m) (figure 22). Gaining sections in the subbasin include Bally Watts and Bennett Creeks and the lower reaches of both branches of the South Fork. These reaches gained a total of about 29 cfs in March (figure 31, table D-4a in appendix D). The gaining reaches in the south part of the drainage, for example Bally Watts and Bennett Creeks, flow over thinner unconsolidated deposits and the water table is less than 5 feet (2 m) below land surface. Where the North and South Branches of the South Fork flow over the confining unit and shallow unconfined aquifer, the streams are probably intersecting the water table. The South Fork network had a net gain of 11 cfs, which is about 9% of the flow discharging to Pineview Reservoir.

The North Fork Ogden River network, including Sheep Creek and Wolf Creek, had gaining and losing reaches throughout its reach (figure 31). Gaining reaches are generally coincident with areas having depth to water less than 15 feet (5 m) below land surface and losing reaches have deeper water tables (figure 22). The network lost about 20 cfs and gained about 49 cfs for a net gain of 29 cfs, which was equal to 30% of the North Fork's discharge to the reservoir at the time of the seepage study (table 5). Overall, Ogden Valley's streams were net gaining in March 2016 by about 64 cfs (table 5).

We observed streamflow ranging from 0 to 25 cfs during our baseflow conditions seepage run, November 7–9, 2016. Eleven of the sites measured in March were dry during our fall seepage run, and only three sites, all on the South Fork Ogden River, had flow greater than 10 cfs. Total measured streamflow into Pineview Reservoir was approximately 16 cfs as measured at South Branch South Fork Ogden River (hydroID 3338) (approximately 7 cfs), North Branch South Fork (hydroID 3337) (3 cfs), Spring Creek (hydroID 3374) (4 cfs), and Middle Fork, Geertsen Creek, Dry Hollow Creek and Garden of Eden Channel (all <1 cfs) proximal to the reservoir (table D-3 in appendix D).

Roughly the same number of stream segments were gaining and losing during the November seepage run, with 11 segments gaining versus 10 segments losing (figure 32 and table D-4a in appendix D). Each drainage had both gaining and losing reaches in November except Spring Creek, which was once again gaining throughout the measured sections (figure 32). All stretches that were losing in March were also losing in November (compare figure 31 to figure 32), but several segments that were gaining in March turned to losing conditions in November, specifically Sheep Creek and Broadmouth Canyon creek, Wolf Creek, Geertsen Creek, and the upper reach of Middle Fork Ogden River. Seasonal water-table decline in these areas may be sufficient to change the condition of the stream from gaining to losing.

Geertsen Creek, Middle Fork Ogden River, and Spring Creek had a net gain of about 3 cfs (table 5) from the aquifer to the stream channel, which is about 70% of their combined flow as measured at the last stations before they discharge to Pineview Reservoir.

The South Fork Ogden River was losing about 25 cfs and gaining about 10 cfs over the same reaches that were losing and gaining in March (figure 32, table D-4a in appendix D). The South Fork network had a net loss of about 15 cfs, which is about one-and-a-half times the flow discharging to Pineview Reservoir from the South Fork network.

Segments of the North Fork Ogden River network, including Sheep Creek and Wolf Creek, were gaining or losing by ± 6 cfs, and taken as a whole, the network was net losing by about 12 cfs (figure 32). The last mile of the stream was dry, which is why table 5 shows that 100% of the streamflow in the North Fork arm of the valley was lost to the aquifer in November 2016.

Overall, Ogden Valley's streams were net losing in November 2016 by about 24 cfs (table 5). The North and South Fork Ogden River networks went from net gaining during runoff conditions to net losing during baseflow conditions, and had an estimated 12 and 15 cfs loss during the seepage run in November, respectively (figure 32). The Middle Fork Ogden River network was net gaining, as it had been in March, although to a lesser degree (3 cfs).

Ogden Valley Canal Seepage Study Results

Ogden Valley Canal had a net loss of 18 cfs on July 19, 2016 (table 5, table D-4b in appendix D). While the net gain or loss per canal segment was often within measurement error, which was calculated by summing the upstream and downstream errors and likely overestimates error, most segments were losing (figure 33, table D-4b in appendix D). Evaporation from the canal is insignificant; pan evaporation rate applied to the surface area of the canal yields a loss to evaporation of less than 0.5% of the flow.

Two locations were losing significant water. More than 4 cfs was lost from the reach between the diversion from the South Fork Ogden River to Highway 39, which flows over coarse stream alluvium that should easily accept seepage, and more than 6 cfs was lost from the reach between OVC06 and OVC07, between the South Fork and Middle Fork drainages. The underlying sediments on this second losing segment are mapped as the contact between Proterozoic metasedimentary rocks, which typically have low permeability, and Quaternary alluvium, which typically can accept leakage. Aerial imagery shows areas of green vegetation along this segment, which could indicate seeps formed from canal leakage.

Our results show one area of significant gain of over 4 cfs east of Geertsen Creek. Aerial imagery indicates a distinct line of increased green vegetation on the hillside above the canal (figure 33) where numerous springs are located on the topographic map. Our field observations during the July 19

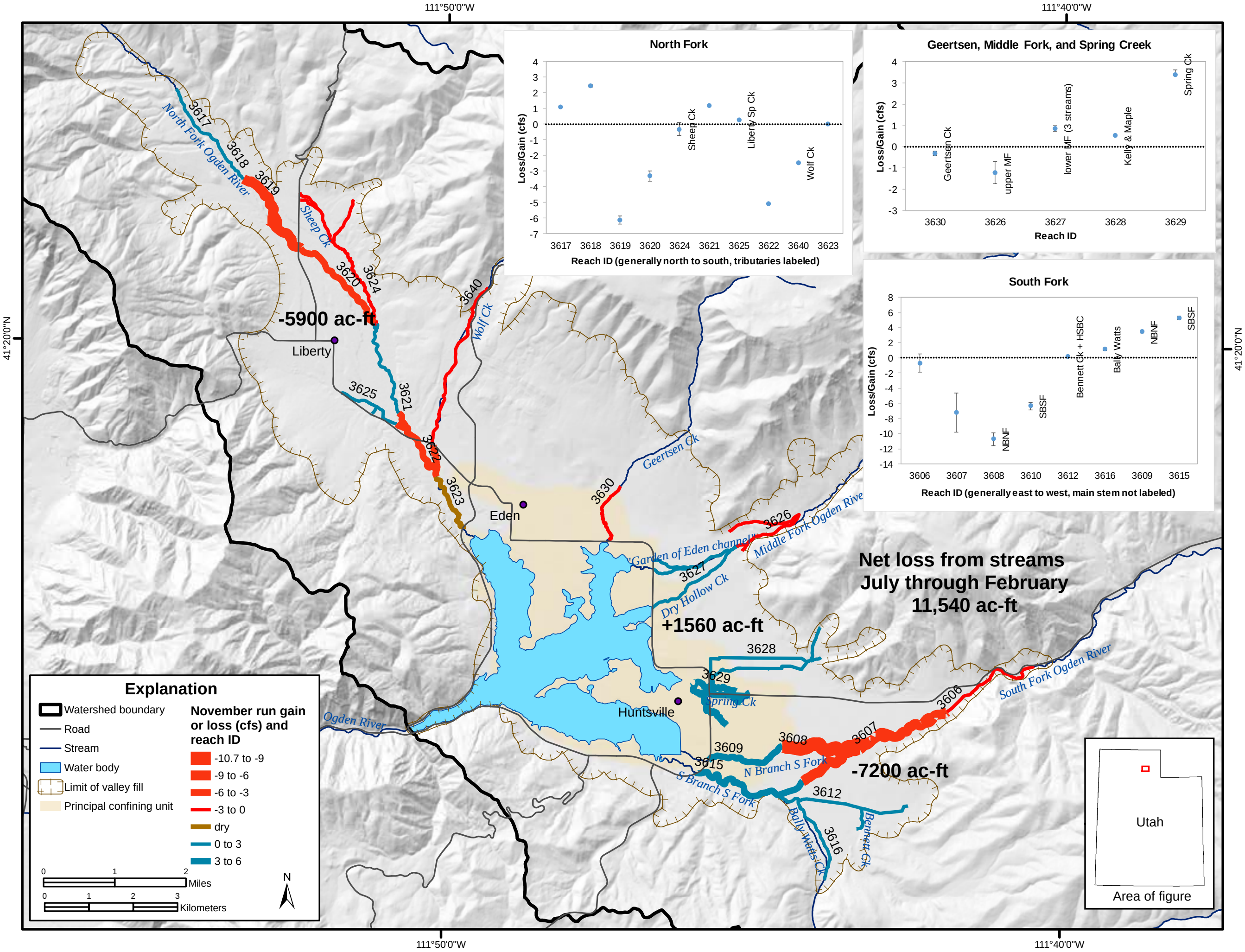


Figure 32. *Gaining and losing reaches of major streams during the November 2016 seepage run and an estimated net gain or loss from July through February from the North Fork, Geertsen/Middle Fork/Spring Creek, and South Fork stream networks. MF = Middle Fork, NBSF = North Branch South Fork, SBSF = South Branch South Fork, HSBC = Huntsville South Bench Canal.*

seepage run confirm more abundant surface water and lush vegetation in this area, but no topographic break in slope or geologic contact that provide a reason for this area to be more well-watered. The water at the surface appears to result from a high water table on the Geertsen Creek alluvial fan, which is intersecting and providing water to local springs and the Ogden Valley Canal.

CHEMISTRY OF GROUNDWATER AND SURFACE WATER

The type of geologic materials in a drainage basin and the length of time groundwater is in contact with those materials are fundamental controls on water chemistry (Winter and others, 1998, p. 22). The water chemistry from wells, springs, and streams in different locations and at different well depths, when viewed with other physical data, can help us infer flow paths and residence time of groundwater and interactions with surface water.

Water Quality Based on Previous Work

Groundwater quality in the Ogden Valley principal aquifer has previously been shown to be excellent. Avery (1994) showed that groundwater in Ogden Valley is dominantly a calcium-bicarbonate type with total dissolved solids (TDS) concentrations generally less than 350 milligrams per liter (mg/L). Lowe and Wallace (1999a) found similar results as part of a groundwater-quality classification process. Nitrate concentrations for Ogden Valley ranged from less than 0.2 to 11 mg/L nitrate as nitrogen, with a low average nitrate concentration of 0.74 mg/L (Avery, 1994; Lowe and Wallace, 1997, 1999a; Wallace and Lowe, 1999). Arsenic, iron, and lead concentrations were low to very low except one well had an arsenic concentration of 14 µg/L, which would exceeds today's maximum contaminant level (Lowe and Wallace, 1999a, table 6). The Utah Water Quality Board approved a Class 1A, Pristine groundwater-quality classification for the Ogden Valley valley-fill aquifer system (Utah Division of Water Quality, 2016), the highest quality class of water under the Utah Water Quality Board classification system (see Lowe and Wallace, 1999a).

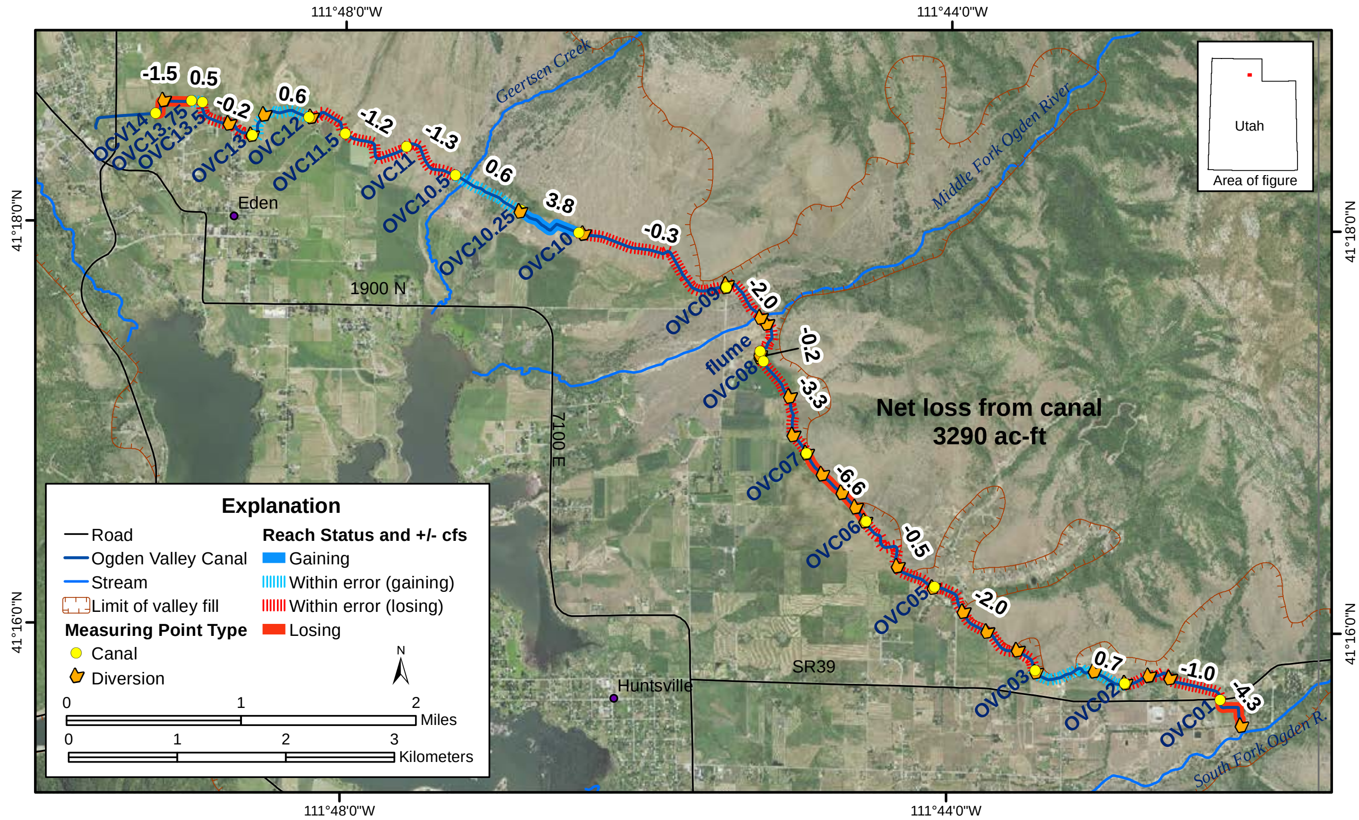


Figure 33. Gaining and losing reaches of Ogden Valley Canal, July 19, 2016.

Table 6. Radiometric tracer data and apparent mean residence times.

HydroID	Sample date	^{3}H (TU)	^{3}He$_{trit}$ (TU)[1]	^{4}He$_{terr}$ (×10^{-8} cm^{3} STP/g)	δ^{13}C (‰)	^{14}C (pmC)	^{3}H/^{3}He age (yr)[2]	^{14}C age (yr)[3]	Qualitative age
WL-108	5/23/16	4.85 ± 0.25	0.45	20.8	-12.5	88.74 ± 0.26	5.8 ± 23.3	modern	mixed
WL-158	5/25/16	3.94 ± 0.19	27.32	0.5	-15.2	62.41 ± 0.21	37.2 ± 1.7	modern	modern
WL-170	5/23/16	4.02 ± 0.20	53.61	755.2	-14.6	86.69 ± 0.25	59.1	modern	mixed
WL-184	5/17/16	4.75 ± 0.26	3.34	0.4	-9.6	77.05 ± 0.24	9.6 ± 2.5	modern	modern
WL-189	5/24/16	0.02 ± 0.03	-	71.9	-6.6	2.15 ± 0.03	premodern	21,800 ± 500	premodern
WL-285	5/24/16	2.61 ± 0.16	4.03	27.1	-16.2	74.01 ± 0.23	21.1 ± 26.2	modern	mixed
WL-474	5/26/16	0.04 ± 0.04	-	1.4	-16.4	34.66 ± 0.14	premodern	8200 ± 600	premodern
WL-520	5/25/16	4.88 ± 0.22	1.11	0.2	-15.7	95.33 ± 0.29	3.7 ± 3.4	modern	modern
WL-3587	5/24/16	0.04 ± 0.03	-	23.7	-12.8	43.19 ± 0.14	premodern	3300 ± 900	premodern
WL-3603	5/26/16	6.01 ± 0.23	4.30	0.6	-12.3	86.61 ± 0.26	9.7 ± 2.4	modern	modern
SP-3652	6/29/16	3.44 ± 0.15	6.88	0.3	-9.0	64.72 ± 0.21	19.7 ± 2.2	modern	modern

[1] Tritiogenic ^{3}He concentration near zero cannot be separated from terrigenic helium

[2] Uncertainty in age based on uncertainty in concentrations in ^{3}H and ^{3}He$_{terr}$; high terrigenic helium concentration prevents the calculation of uncertainty in sample WL-170

[3] Age derived from Fontes and Garnier model (Fontes and Garnier, 1979); uncertainty in age due to uncertainty in soil δ^{13}C ratio

Reuben (2013) collected samples in 2011 from nine shallow wells completed in the shallow unconfined aquifer and analyzed them for a suite of nutrients, including nitrate + nitrite nitrogen (NO_3-N + NO_2-N). Nitrate + nitrite concentrations ranged from below the detection limit to 47 mg/L (Reuben, 2013, table 18).

Methods

During spring and autumn 2016, we sampled water from 58 sites for general water chemistry and nutrient content. Of these, 43 sites were wells, 10 were springs, 4 were streams, and 1 was Pineview Reservoir (figures 20 and 29). One well having a nitrate concentration of 6.5 mg/L from a previous study was resampled and analyzed only for nitrate (WL120). Thirteen water samples from wells were also analyzed for dissolved metals. All samples were analyzed by the Utah Department of Health, Chemical and Environmental Services Division of the Utah Public Health Laboratory. Wells completed in valley fill and bedrock were selected for sampling to represent groundwater conditions throughout the valley. Wells having short perforated intervals were targeted but were not always available for sampling. Springs having relatively large discharge located in mountain recharge and valley discharge areas were selected for sampling. The stream samples were collected from the main stems of the three branches of the Ogden River near where the streams enter the valley floor, and along Liberty Spring Creek near Liberty Spring.

Water samples were collected using standard practices for water sampling (Utah Division of Water Quality, 2014). Each well had been in use on the day it was sampled and was allowed to run for at least 15 minutes prior to sample collection to purge the well of stagnant water. Wells were purged until field parameters stabilized to within 0.1 pH, 0.1°C, and 5 µS/cm conductivity per 15 seconds. Dissolved metals samples were filtered in the field within 15 minutes of sample collection. Samples were collected in lab-supplied bottles and stored on ice until delivery to the appropriate laboratory.

Important well location and completion information and an inventory of chemical analyses are given in table D-1a in appendix D. Location, common names, and summary of chemical analyses run on samples from precipitation, stream, spring, and surface-water sites is given in table D-1b in appendix D. Water-quality results for general chemistry and nutrients are given in table D-5 in appendix D. Dissolved metals content in a 13-well subset of the wells sampled for general chemistry is given in table D-6 in appendix D. We used a value of one-half the detection limit when calculating statistics that include results that were less than the laboratory method reporting limit. Charge balance of samples is generally less than ± 5% imbalance (50 samples). Of the remaining samples, five have an imbalance of less than ± 10% and one sample (SP-3672) has an imbalance of −13.3%, which is likely due to low TDS (60 mg/L) combined with a high reporting limit for sulfate (SO_4^{2-}=20 mg/L). Assuming sulfate concentration of half the reporting limit in this case lowers the charge imbalance to acceptable levels.

Chemistry of Groundwater and Surface Water in Ogden Valley

Water quality based on TDS is generally very good throughout the Ogden Valley study area (figure 34). TDS concentrations in groundwater (springs and wells) range from 28 to 1366 mg/L and average 243 mg/L. Springs have slightly better quality water (n=10, average TDS=197 mg/L) compared to wells (n=42, average TDS=255 mg/L). TDS in surface water ranged from 76 to 238 mg/L and averaged 155 mg/L in four stream samples and one Pineview Reservoir sample collected in September 2016. TDS in bedrock groundwater (n=22, average TDS=267 mg/L) is only slightly less pristine than groundwater sampled from unconsolidated valley-fill aquifers (n=28, average TDS=225 mg/L).

Piper diagrams of chemistry type (figures 35, 36, and 37) illustrated using a color scheme described by Peeters (2014) illustrate that the dominant water quality type in Ogden Valley is calcium-bicarbonate (Ca-HCO_3) with a few sites having elevated magnesium (Mg^{2+}). A few samples have elevated fractions of sodium + potassium (Na^+ + K^+) or elevated fractions of sulfate (SO_4^{2-}) or chloride (Cl^-), resulting in other water types.

Water type composition of the valley-fill aquifer is dominantly Ca-HCO_3 with apparent mixing with a Na-Cl type water. Molar fractions of cations are 0.22 to 0.74 Ca^{2+}, 0.14 to 0.29 Mg^{2+}, and 0.09 to 0.68 Na^+ + K^+. Fractions of anions are 0.35 to 0.89 HCO_3^-, 0.02 to 0.15 SO_4^{2-}, and 0.07 to 0.63 Cl^-. The Na-Cl type samples are generally located near the valley margins (WL-159 and WL-170; figure 35), suggesting this type water occurs only in discrete locations of the valley, possibly near or downgradient of hydraulically conductive fault zones. Reuben (2013, p. 44) attributed elevated electrical conductivity in a well near a major roadway in the shallow unconfined aquifer to road salt, but the wells having Na-Cl type water in our study are relatively deep and not near major roads. Wells having Na-Cl type water may be receiving significantly older groundwater that has accumulated more dissolved solids and is flowing from the mountain blocks. Only well WL-170 has groundwater age data that suggest very old water mixed with modern water (see ENVIRONMENTAL TRACERS section below). Other spatial trends are limited, but we note that well WL-315, located downgradient of well WL-170, has a composition intermediate between Na-Cl type and Ca-HCO_3 type. Furthermore, the TDS decreases from 798 to 218 mg/L between these two wells, respectively, suggesting high-salinity groundwater is diluted as it flows into the basin.

The composition of groundwater from bedrock aquifers is more diverse than other groups (figure 36). Most samples are Ca-HCO_3 type, but Na-HCO_3 type, Ca-HCO_3-SO_4 type, and

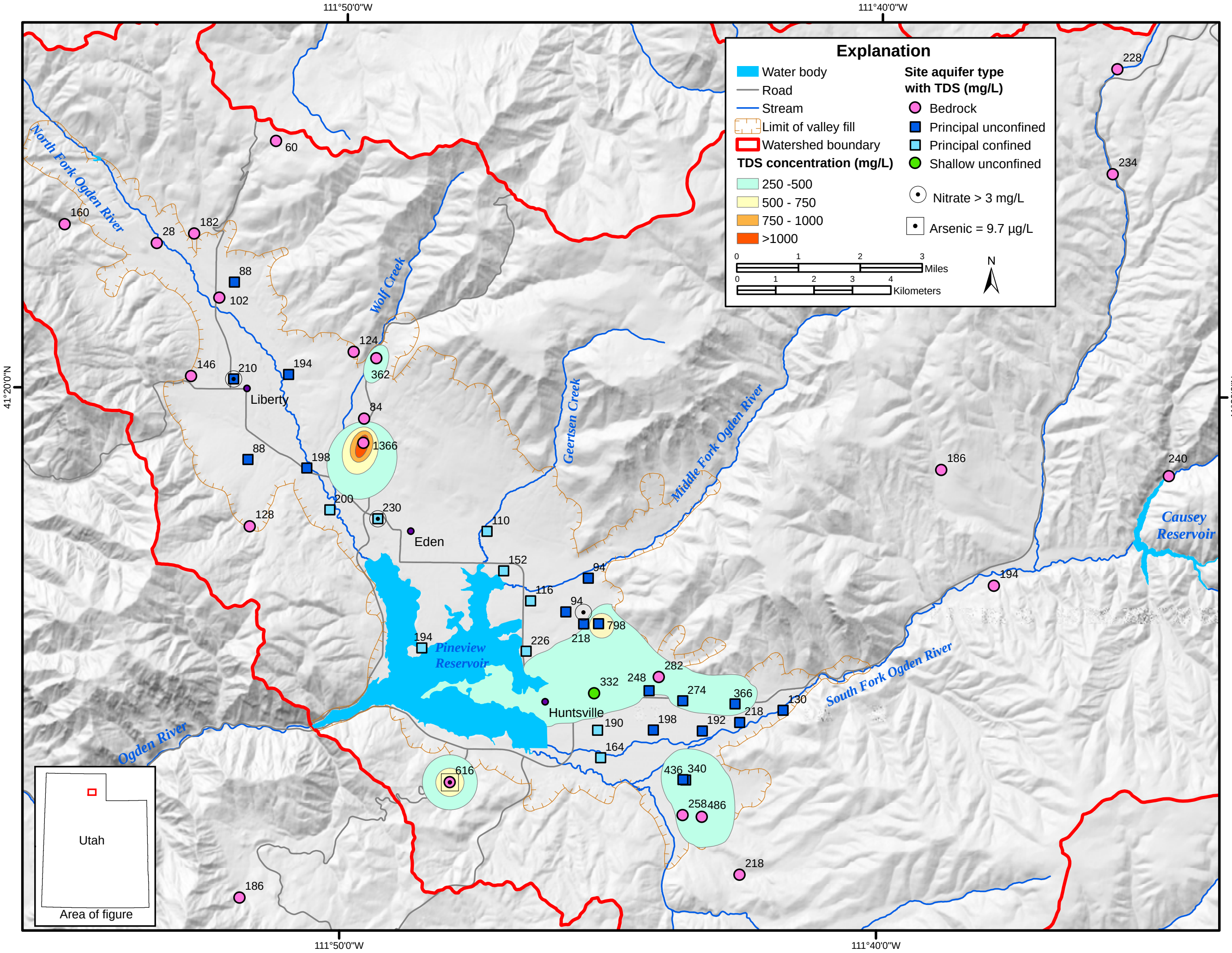


Figure 34. *TDS concentration in groundwater of Ogden Valley, and location of wells having elevated nitrate and arsenic.*

Ca-Cl type are also present. Molar fractions of cations are 0.53 to 0.69 Ca^{2+}, 0.08 to 0.38 Mg^{2+}, and 0.03 to 0.80 Na^{+} + K^{+}. Fractions of anions are 0.65 to 0.85 HCO_3^-, 0.02 to 0.49 SO_4^{2-}, and 0.3 to 0.67 Cl^-. We sampled no bedrock wells having Na-Cl type water, although we postulate that the Na-Cl samples in the valley-fill aquifer may have bedrock sources. Wells and springs located in the South Fork drainage and in conglomeratic (KTcgA) or carbonate (PZcaA) aquifer units have relatively consistent Ca-HCO_3 type compositions. Samples from the North Fork drainage, meanwhile, show greater variation in composition and in volcanic (TvC), siliciclastic (ZsiC), and quartzitic (CzqH) bedrock units. The composition of water from ZsiC is relatively consistent (Ca-CO_3 type), whereas TvC water is more variable (Na-HCO_3, Ca-Cl, and Ca-CO_3-SO_4 types).

All stream water is Ca-HCO_3 type (figure 37). Molar fractions of cations are 0.53 to 0.69 Ca^{2+}, 0.19 to 0.35 Mg^{2+}, and 0.05 to 0.12 Na^{+} + K^{+}. Fractions of anions are 0.65 to 0.85 HCO_3^-, 0.09 to 0.27 SO_4^{2-}, and 0.04 to 0.13 Cl^-. One sample with high sulfate (SP-3367) is in the North Fork drainage (figure 37) where some bedrock aquifer samples have elevated sulfate.

Chemicals of Concern

Chemicals of concern considered in this study include elevated concentrations of nitrate, major ions, and select minor metals and metalloids.

Nitrate + nitrite (NO_3^- + NO_2^-) concentrations in groundwater from wells and springs in the principal and bedrock aquifers range from 0.01 to 7.65 mg/L. We assume that nitrate + nitrite concentrations are indicative of nitrate concentrations because nitrite is completely oxidized to nitrate in typical well-oxygenated groundwater environments (Madison and Brunett, 1985). Concentrations in our data set are log-normally distributed, so we used the geometric mean (0.45 mg/L) to represent the data instead of the arithmetic mean (1.04 mg/L), the latter being skewed due to a few high nitrate concentrations. Nitrate concentration in the shallow unconfined aquifer is considerably higher than the principal and bedrock aquifers. Reuben (2013) sampled nine monitoring wells in the shallow unconfined aquifer on a roughly monthly schedule for a year and a half. He found nitrate + nitrite concentrations ranging from below detection limit to 47 mg/L (table D-7 in appendix D).

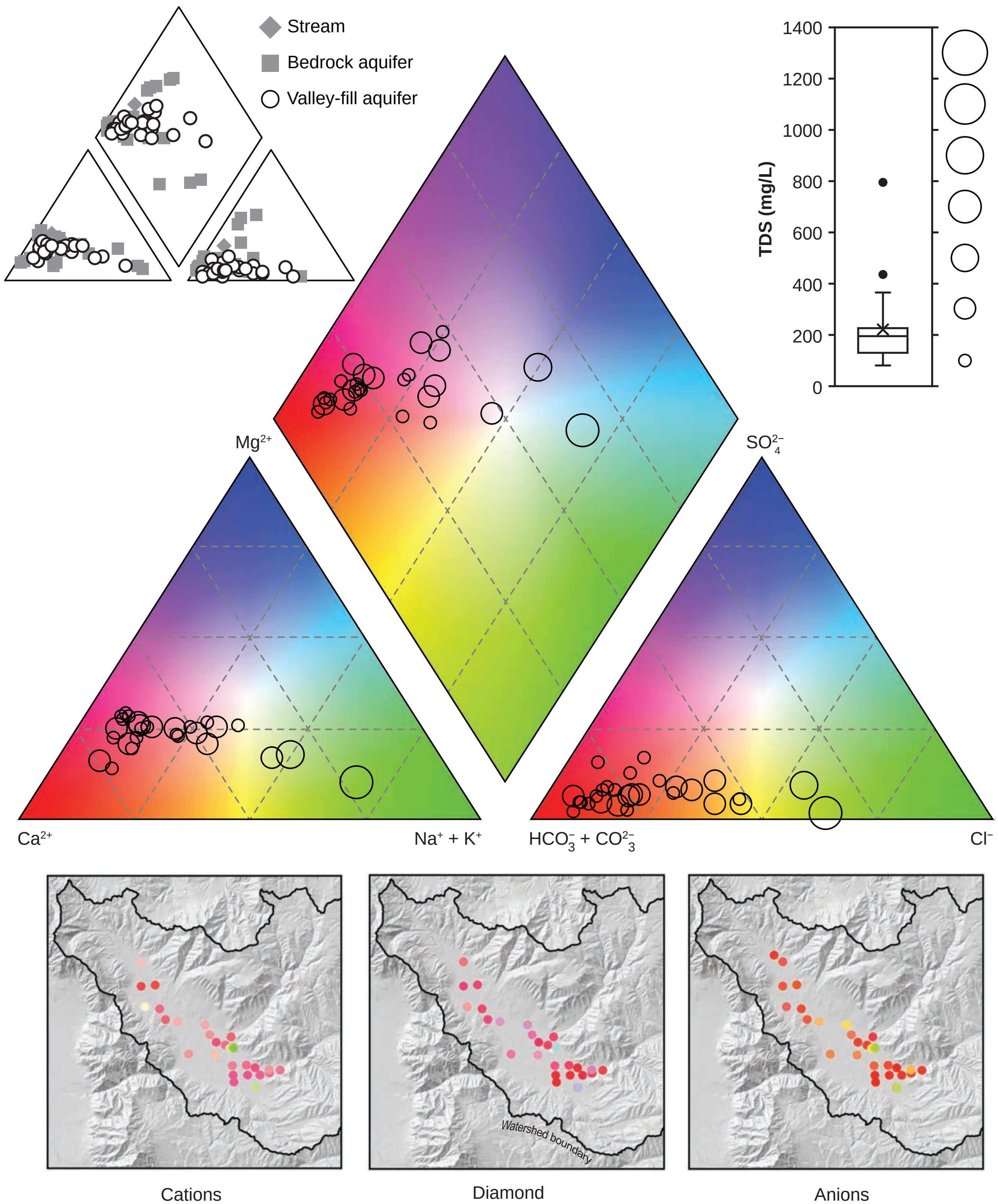


***Figure 35.** Chemical type of groundwater and location of samples from the valley-fill aquifer.*

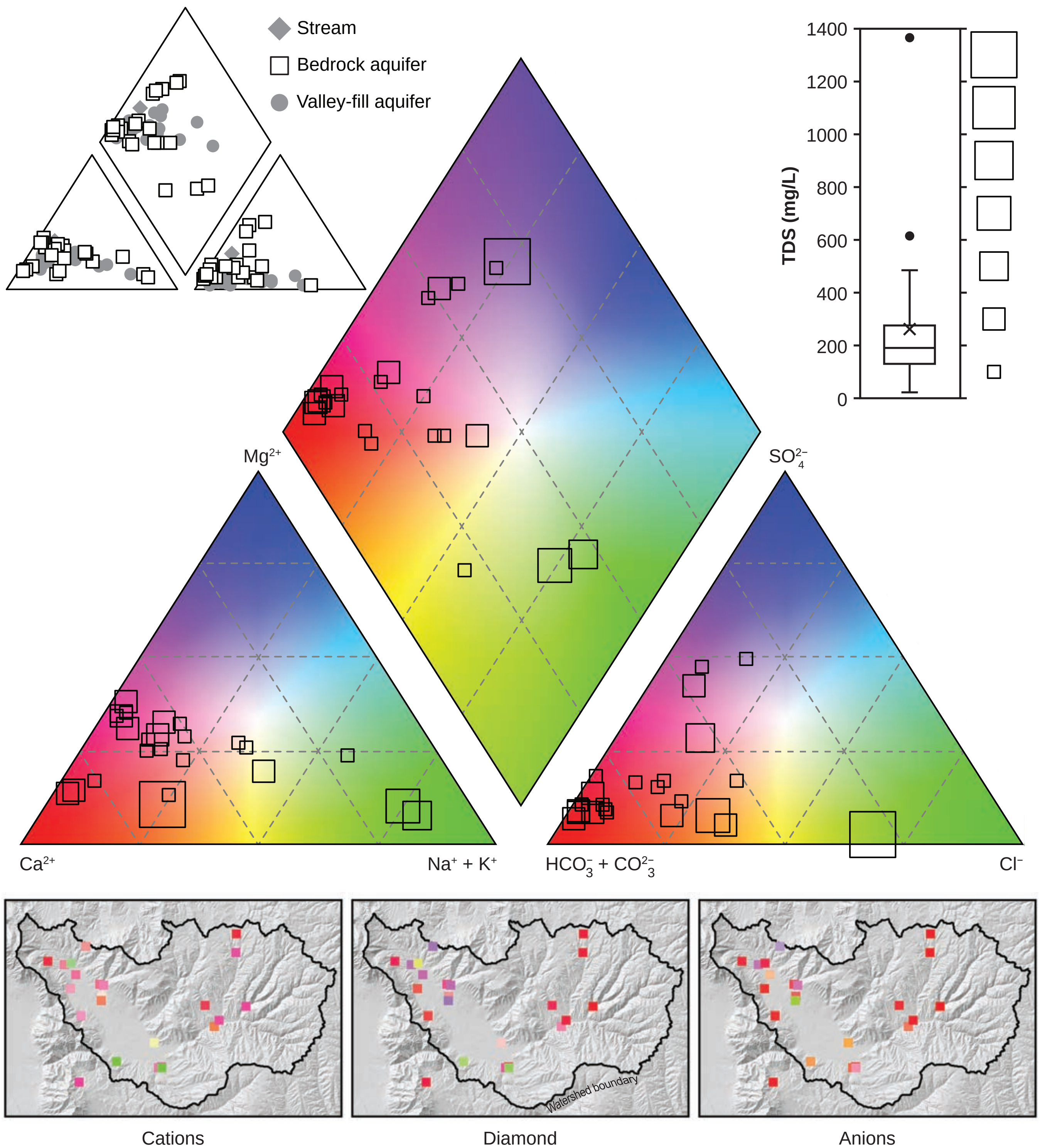


Figure 36. Chemical type of groundwater and location of samples from the bedrock aquifers.

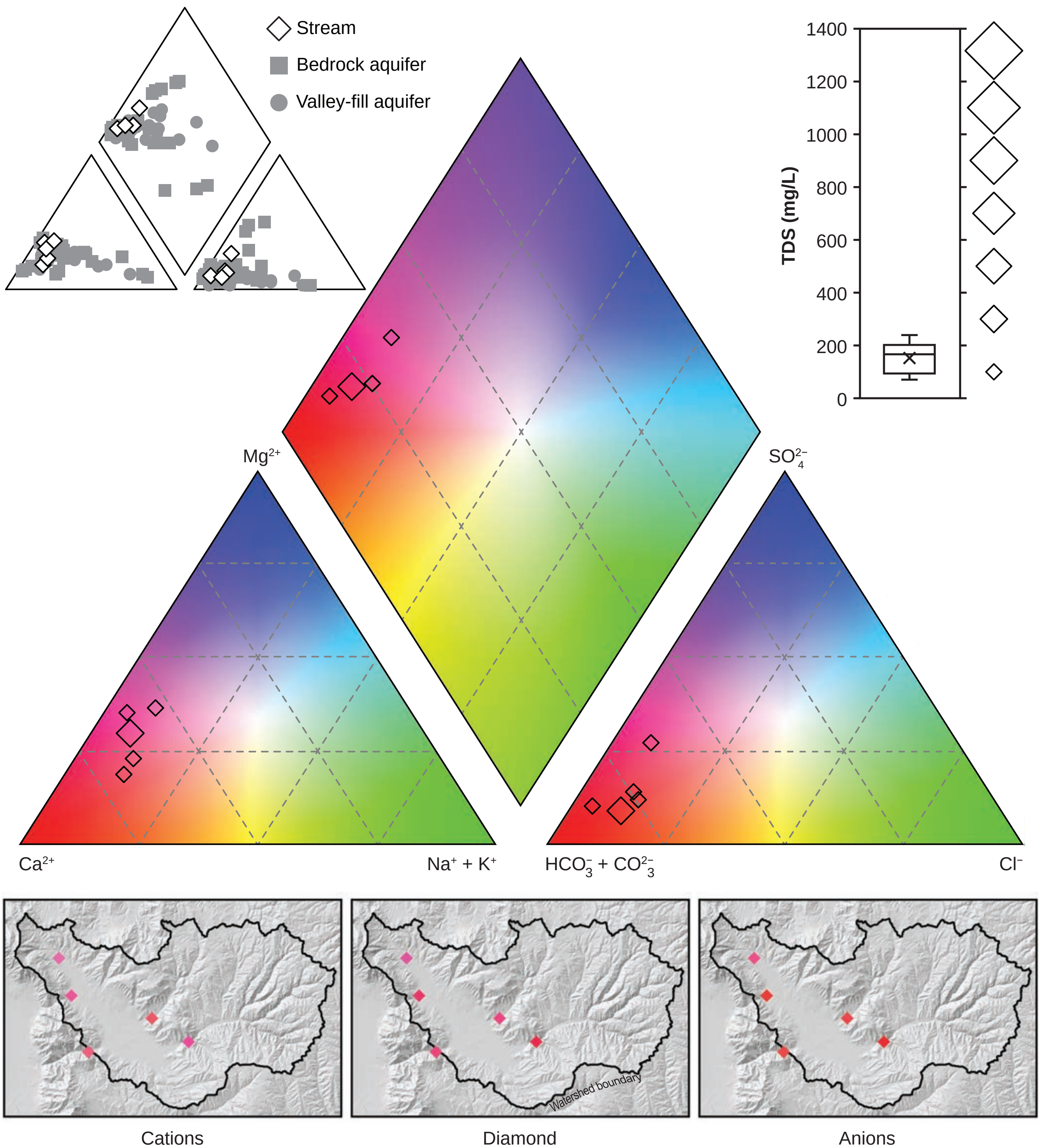


Figure 37. *Chemical type of surface water and the location of samples.*

Concentrations in each well are roughly normally distributed, but to avoid skewing the data to months having more samples, we calculated the arithmetic mean of the samples collected from the wells over the course of one year; arithmetic means in the nine wells range from 0.4 to 14.1 mg/L (table D-7 in appendix D). To quantify the average nitrate in the part of the aquifer most affected by surface nitrate sources and most active in groundwater–surface water interactions, including discharge to the reservoir, we used nitrate concentrations from a subset of available data. The geometric mean of nitrate + nitrite concentrations from 19 wells in the principal unconfined aquifer, one spring from the shallow unconfined aquifer, and the arithmetic mean from each of Reuben's (2013) nine shallow unconfined aquifer wells is 1.43 mg/L, considerably higher than the geometric mean calculated using the samples we collected from domestic and public supply wells and springs in various aquifers.

The primary drinking-water standard for nitrate is 10 mg/L nitrate as nitrogen (U.S. Environmental Protection Agency, 2016). The locations of three wells having nitrate + nitrite concentration greater than 3 mg/L are labeled on figure 34. Note that figure 34 does not include the shallow unconfined aquifer wells sampled by Rueben. Groundwater having less than 0.2 mg/L nitrate is assumed to represent natural background concentrations. Groundwater 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). Groundwater exceeding 3 mg/L nitrate is typically associated with human- or animal-derived sources, but higher concentrations have also been identified with natural sources (Green and others, 2008). Both natural and anthropogenic sources of nitrate are common in Ogden Valley.

Thirteen wells were analyzed for dissolved metals and metalloids including aluminum (Al), arsenic (As), barium (Ba), boron (B), copper (Cu), iron (Fe), lead (Pb), mercury (Hg), manganese (Mn), nickel (Ni), selenium (Se), silver (Ag), and zinc (Zn) (table D-6 in appendix D). None of these constituents exceeds primary Utah drinking water-quality standards. One well located south of Pineview Reservoir and completed in the Norwood Tuff had an arsenic concentration of 9.7 µg/L, just less than the primary drinking water (health) standard of 10 µg/L (figure 34). Arsenic is a constituent derived from some agricultural, industrial, and natural sources. Naturally occurring sources include volcanic rocks and rocks containing sulfide ores. The Norwood Tuff is a tuffaceous volcanic unit that may be the source of the arsenic, although other wells completed in the Norwood Tuff do not have elevated arsenic concentrations.

Secondary drinking water quality standards were exceeded in two wells. Well WL-83 had a chloride concentration of 402 mg/L, whereas the secondary water quality standard is 250 mg/L. Well WL-433 had an iron concentration of 1120 µg/L, whereas the secondary water quality standard is 300 µg/L. These constituents are not known to be harmful to human health but may impart an unpleasant taste or color to the water. Boron was present in one well at 1440 µg/L. Boron has no primary drinking water standard but does have a surface water-quality standard of 750 µg/L based on the Utah Division of Water Quality's criterion for Class 4 Beneficial Use Designation in the nearby Weber River.

Changes in Water Quality

In 1999, Lowe and Wallace (1999a) reported that the Ogden Valley valley-fill aquifer system contained Class 1A Pristine water quality as defined by the Utah Water Quality Board classification system. Total dissolved solids concentration in well water sampled in 1985 (data from Avery [1994]) and 1997 ranged from 42 to 402 mg/L (Lowe and Wallace, 1999a). Average background TDS concentration in the valley-fill aquifer in 1999 was 200 mg/L (Lowe and Wallace, 1999a). For the current study, which includes bedrock wells, 95% of samples have TDS concentration less than 500 mg/L; only three wells have TDS concentration above 500 mg/L. Nitrate concentration in Ogden Valley wells reported by Lowe and Wallace (1999a), which include data from Avery (1994), ranged from less than 0.2 to 11 mg/L, with an average concentration of 0.74 mg/L (Lowe and Wallace, 1997). Lowe and Wallace (1999a) reported a nitrate concentration of 6.5 mg/L from a well located in the east-central part of the valley. We resampled this well and found a lower nitrate concentration of 3.36 mg/L in 2016.

In this study we report average nitrate concentrations using the geometric mean of the analyses. Based on the log-normal distribution of the data, the geometric mean better represents the average than the arithmetic mean. In 1985, the geometric mean concentration was 0.52 mg/L for all groundwater and 0.56 mg/L for the valley-fill aquifer (Avery, 1994). In 1997, the geometric mean concentration was 0.42 mg/L for all groundwater (Lowe and Wallace, 1999a). The geometric mean nitrate concentration for all groundwater sampled for this study is 0.45 mg/L and 0.81 mg/L for the principal valley-fill aquifer. When nitrate data for the shallow unconfined aquifer (Reuben, 2013) is included, the valley-fill aquifers have a geometric mean nitrate concentration of 1.1 mg/L.

We used the t-test statistic to determine if nitrate has changed between studies. This test produces a p-value. When p-values are less than 0.05, the change is statistically significant. The 1985 concentrations (Avery, 1994) are not statistically different than those measured in 1997 (Lowe and Wallace, 1999a) (p-value = 0.35). When all groundwater samples are included, the change from 1997 to 2016 is also not statistically significant (p-value = 0.79). However, when only the principal valley-fill aquifer is considered, the change in nitrate is significant (p-value = 0.02). Adding the shallow unconfined aquifer data from Rueben (2013) to the principal valley-fill aquifer data also shows the change in nitrate has been significant (p-value = 0.00001).

The seemingly low 0.81 mg/L geometric mean nitrate concentration in the principal valley-fill aquifer disguises the likelihood of a particular well exceeding the 10.0 mg/L EPA drinking water standard for nitrate. Because nitrate concentrations are log-normally distributed, the chance that a well will exceed the EPA standard is higher than if the data were normally distributed. Using a normal distribution in the unconfined valley-fill aquifer, there is 95% certainty that a well's nitrate concentration will not exceed 6.9 mg/L, but using a log-normal distribution for this aquifer, there is 95% certainty that a well's nitrate concentration will not exceed 11.0 mg/L. Therefore, some wells will likely exceed the drinking water standard. Even when all groundwater samples from this study are considered, the log-normal 95% probability is 9.6 mg/L.

ENVIRONMENTAL TRACERS

Environmental tracers are naturally occurring or anthropogenic chemicals and isotopes that indicate groundwater sources and flow processes such as recharge conditions, residence time (i.e., age), flow rates, and mixing between sources (Kendall and Caldwell, 1998). Ideal tracers of groundwater have well-defined input sources and input histories, are inert (no reactions) or geochemically conservative (limited reactions), have transport mechanisms identical to those of water, and are detected precisely and economically. No tracer is completely ideal, and the information discerned from a single tracer usually cannot constrain the entire groundwater flow conceptualization. Therefore, the use of multiple tracers provides a more comprehensive understanding of the groundwater system.

We collected and analyzed water samples for the following stable and radioactive isotope environmental tracers: oxygen-18 ($\delta^{18}O$), deuterium ($\delta^{2}H$), and tritium (^{3}H) in water; carbon-14 (^{14}C) and carbon-13 ($\delta^{13}C$) in dissolved inorganic carbon (DIC); and dissolved noble gases including the stable isotopes of helium (^{3}He and ^{4}He) and the common stable isotopes of neon (Ne), argon (Ar), krypton (Kr) and xenon (Xe). The groundwater age tools include $^{3}H/^{3}He$, ^{14}C, and ^{4}He. The applicable age range of these tracers generally spans from less than a year to millions of years (figure 38). A total of 307 samples were analyzed for $\delta^{18}O$ and $\delta^{2}H$ and 11 samples were analyzed for ^{3}H, ^{14}C and $\delta^{13}C$, and noble gases. The purpose of each tracer is discussed below.

Stable Isotopes of Water

Method and Theory

Oxygen-18 (^{18}O) and deuterium (^{2}H) are naturally occurring stable isotopes of oxygen and hydrogen, respectively. Due to differences in mass, water molecules containing the heavier isotopes (i.e., $^{2}H^{1}HO$ and $H_2{}^{18}O$) fractionate from the molecules containing lighter isotopes (i.e., $^{1}H_2{}^{16}O$) during phase changes such as evaporation, condensation, freezing, and thawing. Values for ^{18}O and ^{2}H are expressed as isotope ratios

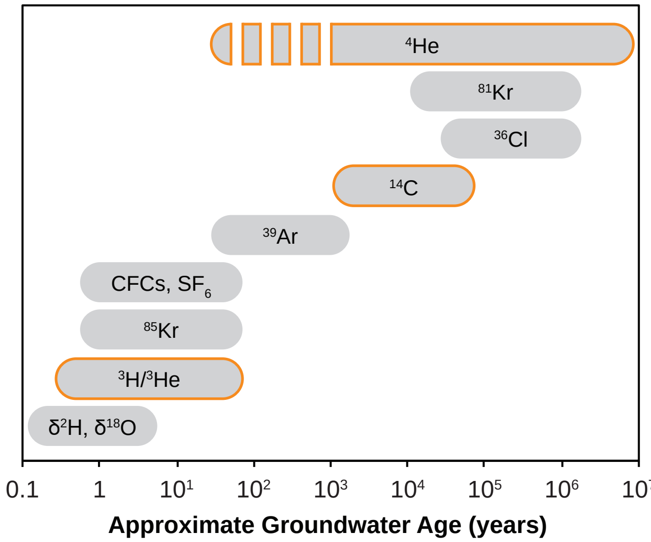


Figure 38. *Approximate groundwater ages determined from different environmental tracers; age tracers used in this study are outlined.*

(i.e., $^{18}O/^{16}O$ and $^{2}H/^{1}H$) in delta notation (δ) as per mill (‰) relative to a reference standard:

$$\delta_x = \left(\frac{R_x}{R_{standard}} - 1\right) \times 1000 \qquad (2)$$

where:

δ_x = delta notation of the sample *x* (in per mill, ‰)
R_x = isotopic atio of $^{2}H/^{1}H$ or $^{18}O/^{16}O$ in the sample (no units)
$R_{standard}$ = isotopic ratio of $^{2}H/^{1}H$ or $^{18}O/^{16}O$ in the standard (no units)

The reference standard for ^{18}O and ^{2}H is Vienna Standard Mean Ocean Water (VSMOW) (Gonfiantini, 1978). $\delta^{18}O$ and $\delta^{2}H$ in precipitation tend to fall along the global meteoric water line (GMWL; figure 39) (Craig, 1961; Rozanski and others, 1993; Clark and Fritz, 1997):

$$\delta\,^{2}H = 8\delta^{18}O + 10 \qquad (3)$$

Precipitation can have various levels of depletion depending on the event intensity, elevation, geographic origin of the air mass, distance inland, and type of precipitation (i.e., rain versus snow). In general, precipitation from higher latitudes (i.e., cooler areas), large events, high elevation, inland areas, and snow has relatively lower fractions of $\delta^{2}H$ and $\delta^{18}O$ than precipitation from lower latitudes (i.e., warmer areas), small events, low elevation, coastal areas, and rain (Clark and Fritz, 1997, chap. 2). Higher fractions of $\delta^{2}H$ and $\delta^{18}O$ are considered "enriched" and lower fractions of $\delta^{2}H$ and $\delta^{18}O$ are considered "depleted" (figure 39). Depletion due to increased elevation is observed only on the windward side of mountains and does not apply to snow (Coplen and others, 2000). In a local region, the

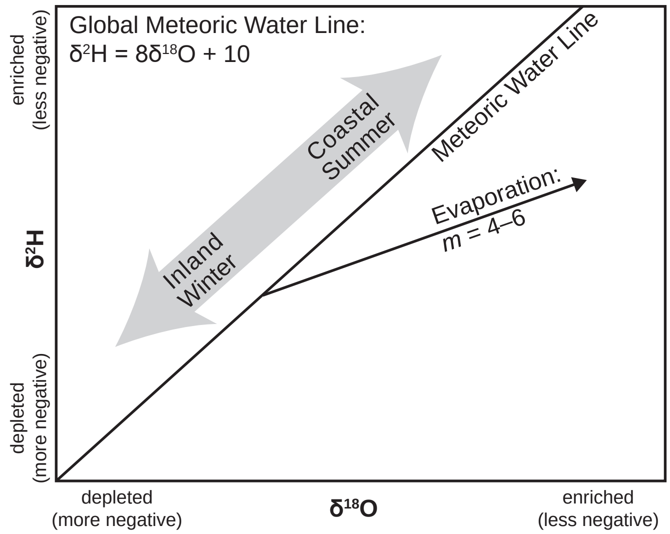


Figure 39. *Relation of oxygen-18 to deuterium in natural water, including some factors that affect relative depletion and enrichment.*

precipitation generally plots along a local meteoric water line (LMWL), which often has a different slope than the GMWL (Clark and Fritz, 1997, chap. 2).

We collected stable isotope samples of precipitation, snowpack, streams, wells, springs, and Pineview Reservoir (figures 20 and 29). Precipitation samples were collected approximately every four weeks at four locations within the Ogden Valley catchment for a total of 46 samples. Sites were chosen to represent a range of elevation and longitude within the basin. Our precipitation samplers consisted of a 2-gallon vinyl carboy connected to a funnel, which sat in a 30-gallon garbage can with the lid inverted to aid in collection of rain and snow (similar to those described by Ingraham and Taylor, 1991; Scholl and others, 1996) (figure 40). Vinyl tubing connecting the carboy and funnel was loosely knotted to create a water lock to limit evaporation. Snowpack, when present, was also collected at the four precipitation sites, for a total of 20 samples (figure 41). Precipitation and snow sample collection began January 26, 2016, and ended January 30, 2017.

Stream samples were collected from 59 sites along the major tributaries to Pineview Reservoir, including Spring Creek and the North, Middle, and South Forks of the Ogden River (figure 29). Most sampling occurred in April and November 2016; 28 sites were sampled more than once.

Groundwater samples were collected from 80 wells and 31 springs. The field parameters specific conductance, temperature, and pH were collected at the time of sampling. Sampled wells are located throughout Ogden Valley and the surrounding ranges, and springs are in the ranges and along the perimeter of the basin (figure 20). Repeat sampling was performed at 17 wells and 6 springs. Sampling occurred between April and September 2016, and most repeat samples were collected in September 2016.

Figure 40. *Precipitation collector in winter.*

Figure 41. *Snow sample collection.*

Pineview Reservoir samples were collected at four sites within the reservoir and immediately downstream in the Ogden River or at the Ogden City water treatment plant (figure 29). A total of 14 samples were collected between April 2016 and January 2017.

All stable isotope samples were filtered in the field with disposable 0.45-µm filters. Isotopic analysis of $\delta^{18}O$ and $\delta^{2}H$ was performed by cavity ring-down spectrometry at the University of Utah Stable Isotope Ratio Facility for Environmental Research (SIRFER).

Results

Stable isotope ratios from groundwater, surface water, and precipitation samples cover a wide range from −182‰ to −6‰ for $\delta^{2}H$ and −24‰ to 0‰ for $\delta^{18}O$. However, greater than 80% of sample results fall within a smaller range of −140‰ to −110‰ for $\delta^{2}H$ and −18‰ to −15‰ for $\delta^{18}O$. Clear differences in ratios are seen when samples are divided by type (figure 42). Stable isotope results are given in table D-8 in appendix D. Each type of sample is discussed in detail below.

Precipitation: Precipitation sites are shown on figure 29. The mean $\delta^{2}H$ and $\delta^{18}O$ ratios in precipitation are quite variable at −86.3 ± 39.9‰ and −11.9 ± 5.2‰, respectively (figure 43). The weighted mean was calculated using precipitation from daily PRISM grids. These weighted means range from −114.6‰ to −107.1‰ for $\delta^{2}H$ and −15.6‰ to −14.8‰ for $\delta^{18}O$. The temporal pattern of stable isotope ratios shows that summer precipitation (June to mid-September) is much more enriched than precipitation collected during the cooler months (mid-September to May; figure 44). This difference can be attributed to the source of precipitation. Winter precipitation generally comes from Pacific air masses travelling from the northwest. Summer precipitation is limited in northern Utah, but can be attributed to monsoonal flow from the south including the Gulf of California, Gulf of Mexico, and the Pacific Ocean (Gillies and Ramsey, 2009).

Precipitation collected in June to mid-September has weighted mean $\delta^{2}H$ ratios of −46.8‰ to −41.8‰ and mid-September to May precipitation has weighted mean $\delta^{2}H$ ratios of −117.9‰ to −110.9‰. The slope of a linear regression line using all precipitation is 7.4. Summer precipitation has a slope of 5.5 whereas non-summer precipitation has a slope of 8.0. Global and local meteoric water lines have slopes near 8 (Clark and Fritz, 1997, chap. 2). The lower slope of summer precipitation can be attributed to greater evaporation from raindrops when falling from clouds (Friedman and others, 2002). Alternatively, summer samples could be slightly affected by evaporation that may have occurred within the sampling apparatus. Without the means to separate the two processes, winter precipitation is assumed to be more reliable and was used to establish the LMWL.

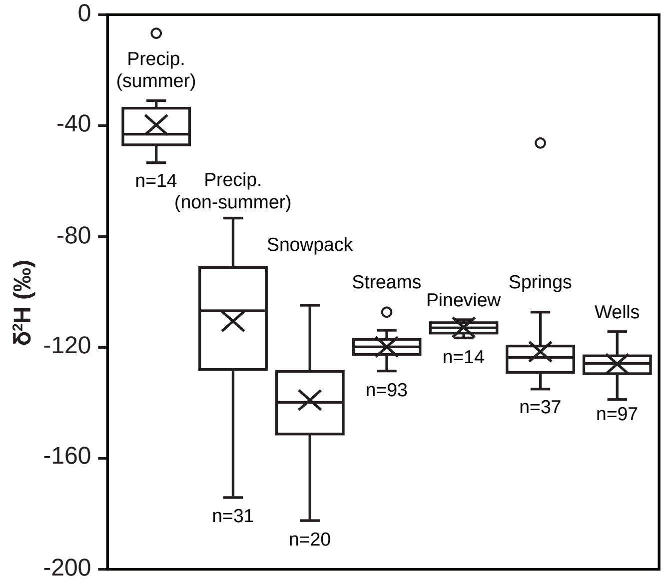


Figure 42. *Statistical comparison of $\delta^{2}H$ in Ogden Valley waters.*

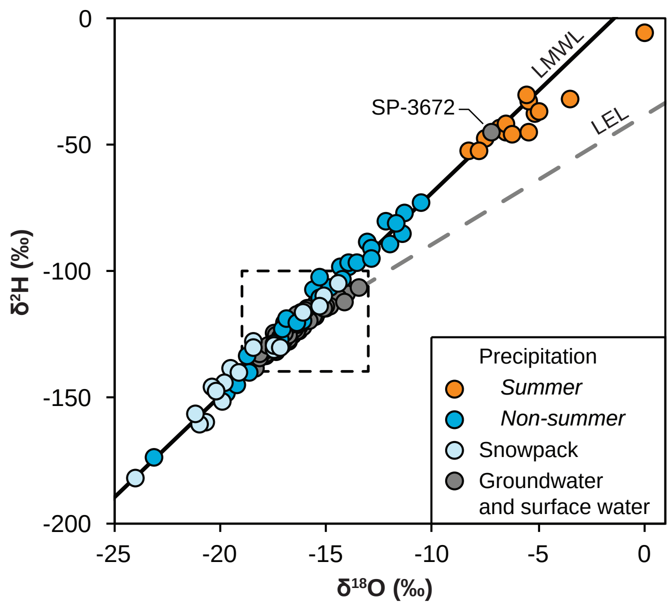


Figure 43. *Stable isotope ratios in precipitation, snowpack, groundwater, and surface water. The dashed box shows the extent of figure 45, which gives a detailed plot of groundwater and surface water ratios. LMWL = local meteoric water line, LEL = local evaporation line. See text for discussion of spring sample SP-3672.*

Collected precipitation samples do not consistently indicate a dependence on elevation, which could be because most samples were derived from snow and samplers were not specifically placed on windward slopes.

Snowpack: Composite snow samples were collected at the same locations and intervals as samples from the precipitation collectors. Snow samples were generally more depleted than precipitation samples (figure 43). The mean $\delta^{2}H$ ratio of the snowpack samples is −139.1 ± 18.8‰.

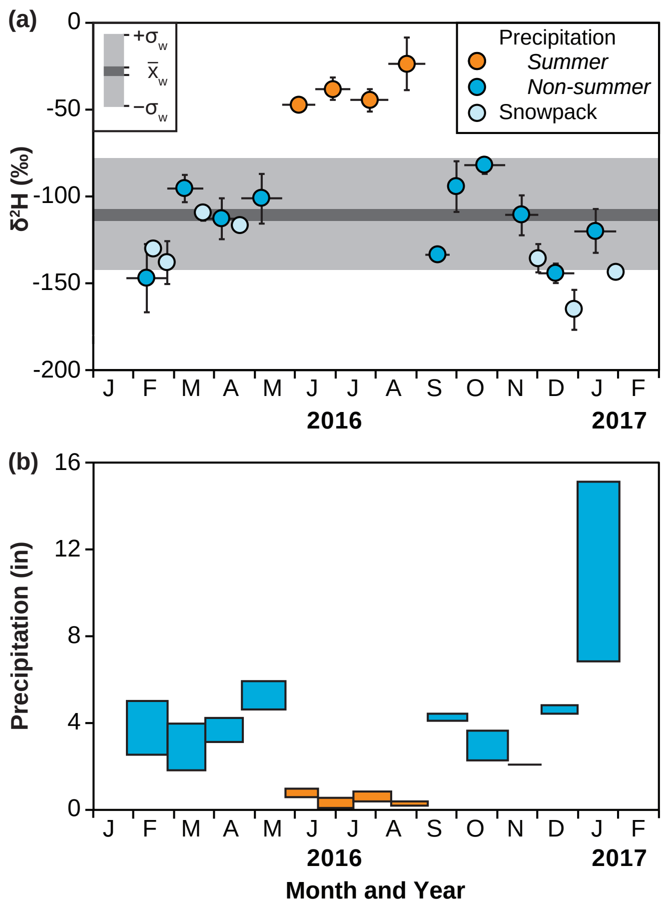


***Figure 44.** Temporal precipitation at monitoring stations. **(a)** δ^2H ratios in precipitation and snowpack, and seasonal weighted mean and standard deviation; and **(b)** ranges of precipitation amounts for each sampling period (PRISM Climate Group, 2017b).*

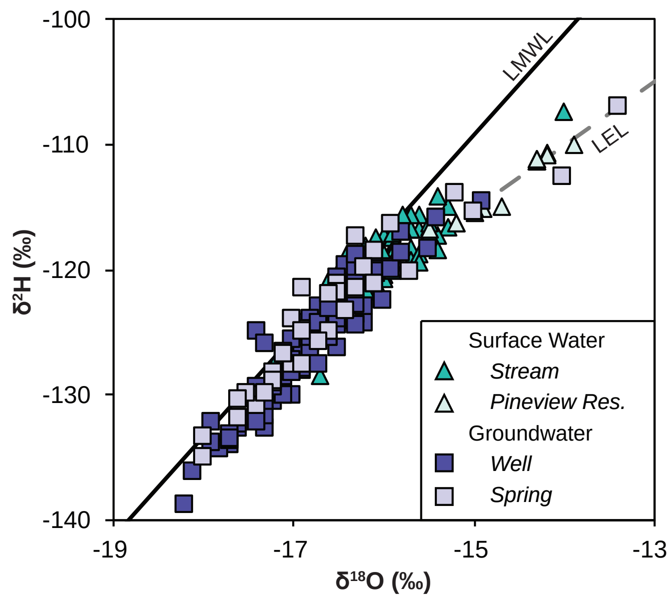


***Figure 45.** Stable isotope ratios in groundwater and surface water. LMWL = local meteoric water line, LEL = local evaporation line.*

Streams: Stream water includes all surface water samples upstream of the reservoir. The mean and standard deviation of δ^2H and $\delta^{18}O$ in stream water are −120.2 ± 3.5‰ and −16.1 ± 0.5‰, respectively (figure 45). The slope of the data, approximately 6.2, suggests evaporation, but the data are clustered on and adjacent to the LMWL, which suggests that evaporation is causing limited fractionation in most samples. The sample with the highest evaporative signal is ST-3375.

The temporal and along-reach trends were assessed for the spring and autumn sampling along the North and South Forks of the Ogden River. Due to the substantial number of individual creeks, canals, and tributaries in the Middle Fork area, we did not perform these trend analyses on that area.

Whereas the composition of the tributaries can be variable, the composition of the main rivers changed little over several miles (figure 46). A significant input of water from the valley-fill aquifer to the streams (gaining stream) should decease the stable isotope ratio in stream water. In the April–May 2016 sampling of the North Fork, a slight decrease is observed at the most-downstream sample, but this decrease could be due to inflows from Liberty Spring Creek and Wolf Creek which both have more depleted ratios (figure 46a and b). In the November 2016 sampling of the North Fork, a slight decrease is observed between the Durfee Creek and Cobble Creek inflows, but this decrease is negated after the Cobble Creek inflow (figure 46c and d). In the South Fork, the stable isotope ratios increase at the most-downstream samples of the north and south branches (figure 46e–h). Enrichment in the south branch could be due to evaporation and the inflow from Bally Watts Creek and the South Bench Canal, both of which have more enriched ratios.

The spring compositions were surprisingly more enriched than the autumn compositions. In a snow-dominated precipitation watershed like Ogden Valley, we expect runoff to be dominated by highly depleted snowmelt. However, considerable amounts of rain were recorded during the spring sampling period, which had ratios that were more enriched (δ^2H = −113‰) than the stream (δ^2H = −117‰). The composition of the stream can be explained as a mixture of snowmelt and this enriched rain. Autumn δ^2H values from the North Fork are 1.5‰ more depleted on average than spring values (figure 46a–d). These more depleted autumn values suggest groundwater input to the stream has more influence on stream composition in autumn than spring. Groundwater input is demonstrated by intermittent gaining reach status. A similar seasonal trend is seen in the South Fork, where δ^2H values in autumn were 3.7‰ more depleted than spring ratios (figure 46e–h). Here again, the spring sampling period appears to be affected by the recent spring rains and the autumn stream composition is more like groundwater. Since the upper sampled reach of the South Fork River is a losing section of the stream, the isotope composition of the stream is likely controlled by input from bedrock aquifers feeding the stream in the mountains.

Pineview Reservoir: Surface water was collected from Pineview Reservoir and from the Ogden River and the Ogden

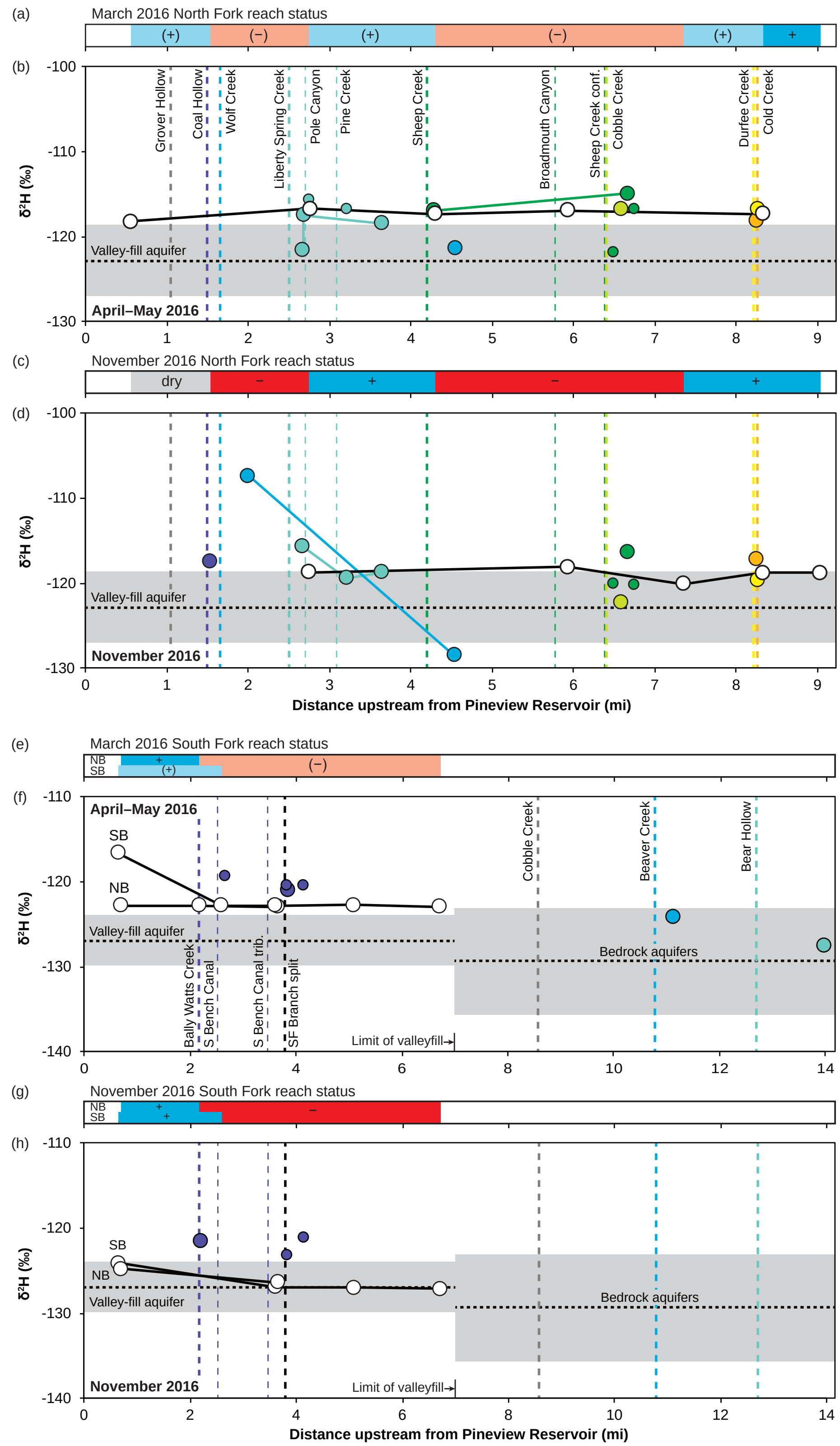


Figure 46. *δ²H and gaining or losing status in stream reaches versus distance from Pineview Reservoir. North Fork:* ***(a)*** *reach status in March 2016,* ***(b)*** *δ²H in April–May 2016,* ***(c)*** *reach status in November 2016,* ***(d)*** *δ²H in November 2016. South Fork:* ***(e)*** *reach status in March 2016,* ***(f)*** *δ²H in April–May 2016,* ***(g)*** *reach status in November 2016,* ***(h)*** *δ²H in November 2016. Thick-dashed vertical lines are locations of tributaries to the main river, thin-dashed vertical lines are locations of secondary tributaries to those primary tributaries; large colored circles are samples from the primary tributary and small colored circles are samples from the secondary tributaries; white circles are samples from the main river; black solid line connects samples from the main river and solid colored lines connect samples from the same stream or tributary and are color coded to match the dashed lines. Reach status: red = losing, blue = gaining, light red = losing within measurement error, light blue = gaining within measurement error.*

City treatment plant immediately downstream of the dam. The mean and standard deviation of δ^2H and δ^{18}O in surface water are −113.0 ± 2.4‰ and −14.6 ± 0.5‰, respectively. The best-fit regression through the data has a slope of approximately 5.0, suggesting evaporation, which is typical for a large body of surface water (figure 45). The intersection between this LEL and the LMWL has δ^2H and δ^{18}O ratios of −125.5‰ and −17.0‰, respectively. These values represent the mean weighted composition of water for the reservoir, which includes streamflow, groundwater influx, and direct input of precipitation.

Springs and wells: The mean ratio of δ^2H in springs is −123.9 ± 6.3‰ (figures 43 and 45). Two samples (SP-3666 and SP-3668) plot below the LMWL and appear enriched by evaporation. The mean ratio from wells is −126.1 ± 5.0‰ and includes the most depleted ratios, excluding precipitation and snowpack (figure 45). A single highly enriched [−45.7‰] sample at site SP-3672 is excluded from summary statistics. This sample likely represents a very localized flow path containing summer precipitation at this relatively high-elevation spring at the head of Cache Valley Creek sampled in late September.

Spatial variation and continental effects: The spatial variation in stable isotope ratios shows more depletion in the South Fork when compared to the North and Middle Forks (figure 47). This trend is seen in stream and groundwater samples. Most stream water samples from the South Fork have a δ^2H ratio between −130‰ and −120‰, whereas the other forks mostly range from −120‰ to −110‰. Most samples from bedrock aquifers in the South Fork have a ratio between −140‰ and −130‰, whereas bedrock aquifer samples from the other forks mostly range from −130‰ to −120‰. The same trend is seen in the valley-fill aquifer, but the amount of depletion is lower. In general, the stable isotope ratios in the valley-fill aquifer reflect the ratios in the adjacent bedrock aquifers, suggesting a connected system.

The depleted ratios in the South Fork drainage could be due to continental effects where precipitation becomes increasingly depleted as an air mass moves farther inland and moisture is removed (Coplen and others, 2000). Figure 48 shows δ^2H ratios versus Easting with a best-fit slope of −0.36‰ per km east (R^2 = 22.6%). This equates to approximately 17‰ decrease in δ^2H across the study area. This west-to-east trend is logical as the majority of precipitation originates as air masses in the Pacific, which move eastward to the Rocky Mountains (Gillies and Ramsey, 2009). The scatter in figure 48 could be due to transport and mixing of surface water and groundwater, or local variations in elevation and climate. Without rigorous flow modeling or groundwater ages, these factors cannot be parsed. Transport and climate likely have greater effects than elevation. Elevation effects are expected to be minimal because the majority of precipitation falls as snow, which is not fractionated with elevation (Coplen and others, 2000).

Continental fractionation effects appear to be present in precipitation and snow samples. Samplers were originally placed at Hidden Lake (PRCP-3 and SNW-3) and the Monte Cristo off-road area (PRCP-4 and SNW-4) to test this hypothesis. Based on their east-west separation of 15.5 km (9.3 mi), δ^2H at Monte Cristo should be 6‰ lower than Hidden Lake. The isotopic separation of weighted means is 7.0‰ between these two sites, which supports a continental effect.

Recharge to the valley-fill aquifer: Following examples presented by Coplen and others (2000), we divided the stable isotope data into sub-basins to determine relative contributions of recharge to the valley-fill aquifer coming from the bedrock aquifers and streams. Figure 49 shows the mean stable isotope composition of the valley-fill aquifer is a mixture of stream and bedrock aquifer water. Using a Monte Carlo approach (Huber, 1973), we calculated contributing fractions of stream and bedrock aquifer water by selecting random bedrock aquifer and stream end member compositions using the mean and standard deviation of each end member. We adjusted the relative contribution from these end members to produce a random valley-fill aquifer sample, again using the mean and standard deviation of that group. We assumed that the two fractions will always sum to 1 and discarded all invalid combinations. We excluded direct or "in-place" recharge of snowmelt and precipitation into the valley-fill aquifer from this assessment because this addition would make the results non-unique. However, we expect the isotopic composition of precipitation and snowmelt on the valley floor to be similar to that of the streams. The mean δ^2H isotopic composition of non-summer precipitation and snow from the Huntsville precipitation collection site is -122.6‰, indicating that our assumption is acceptable.

Our analysis suggests the ratio of recharge from streams or bedrock to the valley-fill aquifer varies between sub-basins (figure 49). The median stream recharge to bedrock recharge ratio in the North Fork is 0.34 stream to 0.66 bedrock, or about one-third of the water in the valley fill is recharged by stream loss and/or in-place recharge and two-thirds is from mountain-block recharge. In the Middle Fork the relative proportion of recharge source is more evenly stream/in-place and bedrock (0.54:0.46), and the South Fork is slightly more stream/in-place dominated with 0.60 stream to 0.40 bedrock recharge likely.

We assessed stable isotope composition versus depth below the potentiometric surface and distance from the valley margin (figure 50). Shallow samples, within 100 feet (30 m) of the potentiometric surface, generally match the composition of stream water for each sub-basin (figure 50). Generally, deeper wells have more depleted compositions, except the Ogden City well field, discussed below. The shallow zone of the Middle Fork sub-basin tends to have more depleted water, which has a composition more like the bedrock aquifer samples. This trend fits the hydrological setting of the Middle Fork/Geertsen Creek/Spring Creek area because many springs are present and the stable isotope ratios suggest a higher amount of discharge compared to the other forks.

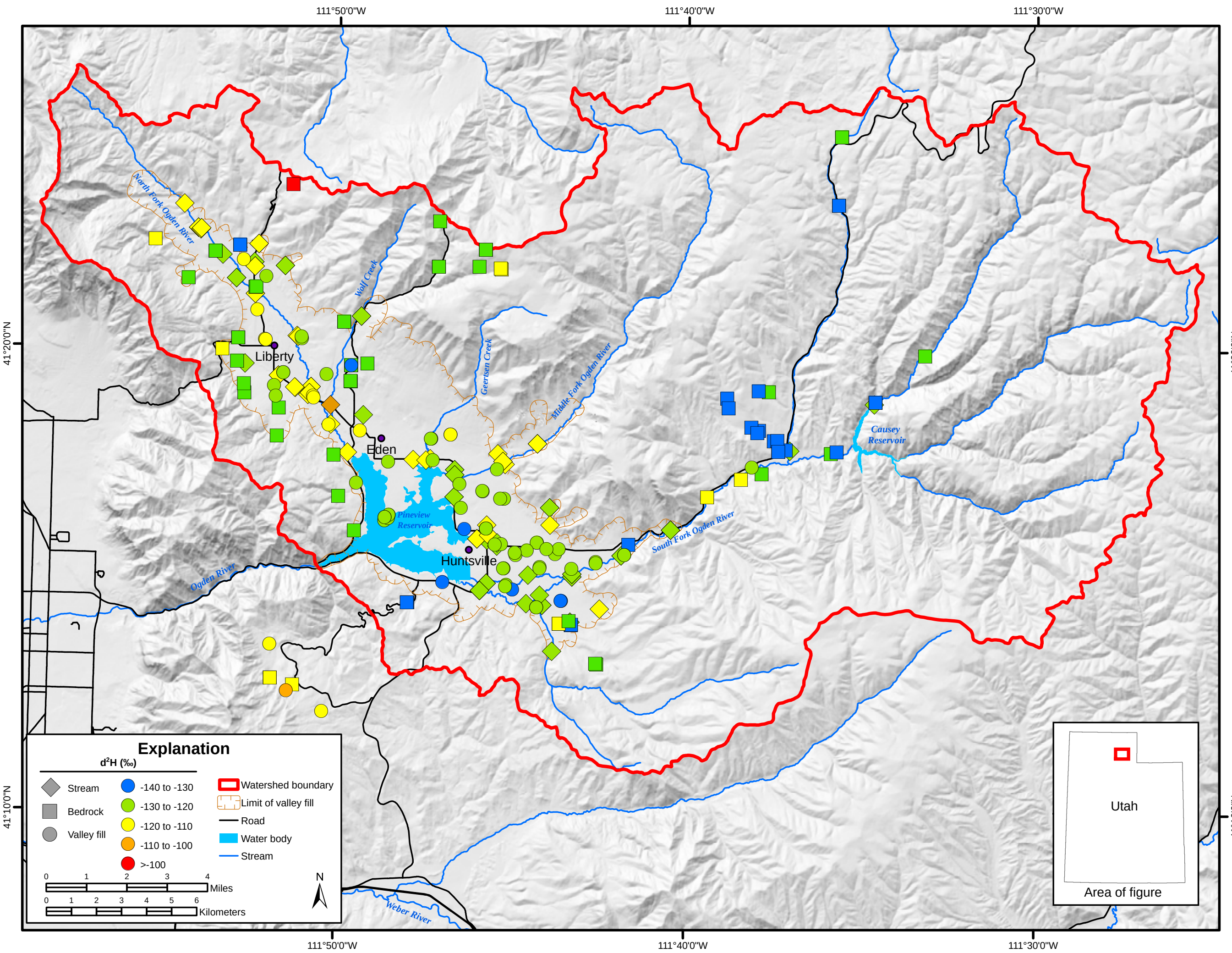


Figure 47. *Map of δ^2H in Ogden Valley streams and groundwater.*

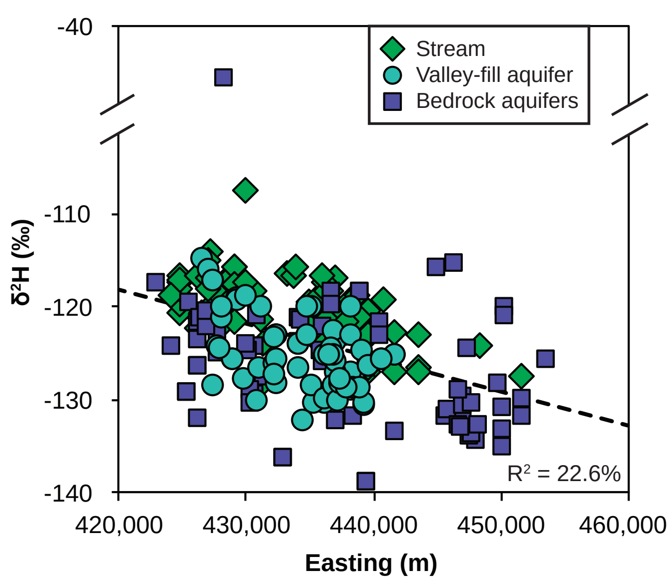


Figure 48. *δ^2H in Ogden Valley streams and groundwater versus Easting; $m = -3.64 \times 10^{-4}$ ‰/m.*

The composition of water coming from the Ogden City well field is relatively enriched compared to other deep samples, which tend to be more depleted with depth (figure 50). Enrichment suggests the well field is pulling some water from shallow depths, a hypothesis corroborated by the presence of young water, as discussed in the Noble Gases and Tritium section below.

Radiocarbon

Method and Theory

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). ^{14}C data can provide groundwater ages of 100 to tens of thousands of years (Jurgens and others, 2012). However, it is insensitive to ages outside of that range. ^{14}C data are expressed as percent modern carbon (pmC), which is relative to A.D. 1950 levels. ^{13}C is a naturally occurring stable isotope of carbon that is used to evaluate chemical reactions involving carbon (Clark and Fritz, 1997). ^{13}C is expressed using the delta notation as a ratio with ^{12}C, similar to $\delta^{18}O$ and δ^2H (see equation 2), but with the Vienna Pee Dee Belemnite (VPDB)

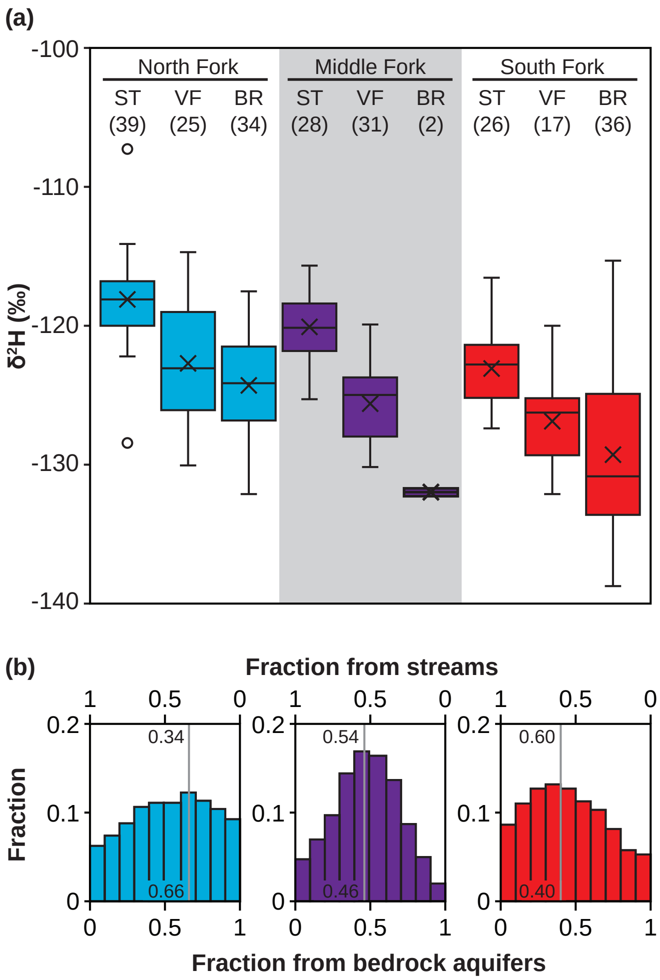


***Figure 49. (a)** Statistics of δ^2H in streams (ST), the valley-fill aquifer (VF), and the bedrock (BR) aquifers divided by sub-basin. Number of samples given in parentheses.* ***(b)** Probable contributing fractions of stream and bedrock aquifer water to the valley-fill aquifer calculated using a Monte Carlo approach (random stream and bedrock aquifer end members from each sub-basin are combined to produce a random valley-fill aquifer sample). Median fractions are given numerically in each box and shown by gray lines. Between these two sources, roughly half the valley-fill aquifer recharge comes from streams and half from the bedrock mountain block, but differences exist between sub-basins.*

as the reference standard. The $\delta^{13}C$ concentration in groundwater 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 for this study was performed by the Laboratory of Hydrogeochemistry–Brigham Young University Department of Geological Sciences in Provo, Utah.

Radiocarbon dating can be complicated by uncertainties in input concentrations, modern ratios and water-rock interactions that involve carbon. Above-ground testing of thermonuclear weapons produced elevated concentrations of ^{14}C resulting in values greater than 100 pmC in some instances. Most C and ^{14}C is incorporated into groundwater as dissolved inorganic carbon (DIC), commonly as bicarbonate, at typical groundwater pH values. DIC is readily available for chemical reactions between the aquifer material and the dissolved constituents in the water. Chemical reactions can either add or remove carbon, and knowledge of chemical reactions that occur during recharge and transport through the aquifer are necessary for estimating the initial activity of ^{14}C. Age calculations require estimates of some chemical parameters during recharge and model calculations of reactions during groundwater transport.

The calculation of ^{14}C age requires the determination of A_o, which is the initial, non-decayed ^{14}C content of the groundwater. A_o is assumed to be 100 pmC in the absence of subsurface geochemical reactions. However, the common occurrence of elevated CO_2 and carbonate minerals in the soil can render this assumption invalid. Thus, A_o is generally significantly lower than 100 and can even be lower than 50 pmC (International Atomic Energy Agency, 2013). Several models account for geochemical reactions and exchanges to calculate A_o (Ingerson and Pearson, 1964; Mook, 1972; Tamers, 1975; Fontes and Garnier, 1979). A_o was calculated in NETPATH-Win (El-Kadi and others, 2010) using the Fontes and Garnier model (Fontes and Garnier, 1979), which models the exchange and mixing of carbon and carbon isotopes between soil gas CO_2 and carbonate minerals. End members of radiocarbon and $\delta^{13}C$ were assumed to be 100 pmC and −21.8 ± 1.4‰ for soil gas CO_2 (Hart, 2009), and 0 pmC and 0‰ for carbonate minerals, respectively.

After A_o is calculated, the groundwater age is calculated by:

$$t = \tau \ln \frac{A_o}{A} \tag{4}$$

where:

t = groundwater age (years)
τ = 8267, a constant equal to ^{14}C half-life (5730 yrs) ÷ ln 2
A_o = initial ^{14}C activity (pmC)
A = measured ^{14}C activity (pmC)

When A is greater than A_o, the sample likely contains bomb-peak radiocarbon and equation 4 gives erroneous ages. These samples are considered modern or have a component of modern water mixed with pre-modern water.

Results

Radiocarbon values ranged from 2.15 to 95.33 pmC (table 6). The mean measurement uncertainty is approximately 0.22 pmC, excluding the sample from well WL-189, which had an uncertainty of 0.03 pmC. $\delta^{13}C$ ratios ranged from −16.4‰ to −6.6‰. The presence of bomb-peak radiocarbon in over half of the samples is indicated by a measured radiocarbon activity greater than the calculated initial radiocarbon activity (A_o), which we determined using Fontes and Garnier (1979) to model subsurface geochemical reactions. The presence of

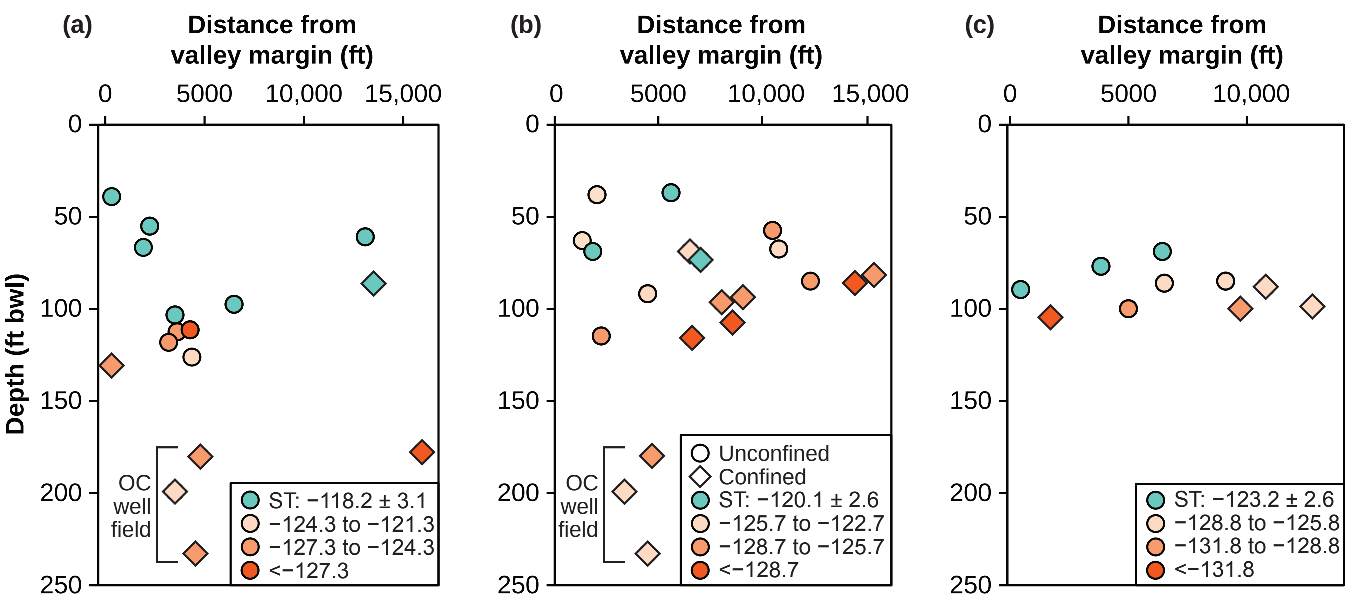


Figure 50. *δ^2H in the valley-fill aquifer relative to well depth below the water level (bwl) and distance from the valley margin for;* ***(a)*** *North Fork,* ***(b)*** *Middle Fork, and* ***(c)*** *South Fork. OC = Ogden City, ST = streams. The range of stream composition for each fork is listed in the explanation, and wells having that range are shown as blue symbols. Darker orange colors have more depleted isotope signals like bedrock aquifer samples.*

bomb-peak radiocarbon is demonstrated by comparing $\delta^{13}C$ ratios to radiocarbon. Samples without bomb-peak radiocarbon should plot left of and below the mixing line between soil gas and dead carbonate on figure 51. The addition of bomb-peak radiocarbon complicates interpretation because the atmospheric end member is unknown.

Radiocarbon ages were calculated using the Fontes and Garnier (1979) model for the three samples that contained very low concentrations of tritium, indicating the absence or negligible addition of bomb-peak radiocarbon. The radiocarbon ages for well samples WL-189, WL-474, and WL-3587 are 21,800 ± 500, 8200 ± 600 and 3300 ± 900 ^{14}C yr B.P., respectively. The uncertainty in age is due to the uncertainty of the $\delta^{13}C$ ratio in soil gas CO_2 (Hart, 2009). Using a soil radiocarbon activity of −21.8 ± 1.4‰ produced initial A_o ranging from 28 to 106 pmC in the three samples. The unfeasible A_o of 106 pmC was calculated for sample WL-474 when the soil $\delta^{13}C$ ratio input was −20.4‰. In this case we set A_o to 100 pmC for this sample.

For samples that contain a significant concentration of tritium, the NETPATH-Win models produce erroneous A_o values that are lower than the measured radiocarbon amount. A multi-tracer approach is required to model these samples, which is presented in Lumped Parameter Modeling results below.

Noble Gases and Tritium

Methods and Theory

Concentrations of dissolved noble gases in groundwater provide information concerning the physical conditions at the time of recharge and the amount of time passed since recharge.

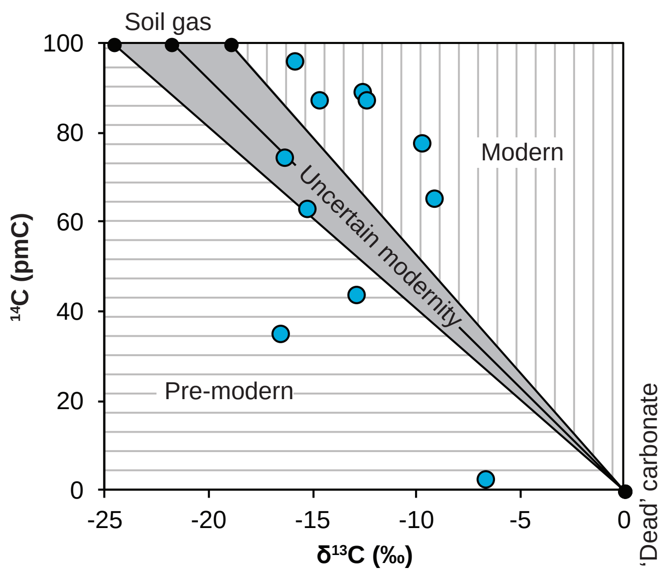


Figure 51. *Carbon isotopes in groundwater samples and simple mixing lines.*

Tritium and helium concentrations in groundwater provide useful groundwater dating tools.

Atmospheric noble gases: Noble gases (helium, neon, argon, krypton, and xenon) are chemically inert and occur in known concentrations in the atmosphere. Excluding helium, these gases generally have no significant source aside from the atmosphere. The concentrations of these gases in water are dependent on their atmospheric partial pressure (a function of elevation) and Henry's law solubilities, which are generally functions of temperature, salinity, and molecular mass (e.g., xenon is ~33 times heavier than He and at 25°C is ~12 times more soluble) (Weiss, 1971; Benson and Krause Jr., 1976; Kipfer and others, 2002). By assuming elevation (pressure) at the time of recharge, the temperature under which recharge occurred can be modeled (Aeschbach-Hertig and others, 2000).

If the water table is within a few hundred feet of the land surface, the equilibration temperature is equal to or slightly warmer than the mean annual temperature at that location. In areas of significant topographic relief, and consequently wide temperature range at which groundwater may recharge, estimates of recharge temperature can provide constraints on the spatial distribution of recharge and the potential connectivity of flow paths (Manning and Solomon, 2003). High calculated recharge temperatures may also result from gas loss (gas stripping) either in the aquifer due to flow across flow barriers (Thomas and others, 2003) or denitrification (Visser and others, 2009). Long-term climate change may also affect recharge temperatures, and groundwater recharged during the late Pleistocene may have lower calculated recharge temperatures for a given elevation (Aeschbach-Hertig and others, 2000).

Dissolved noble gas concentrations in groundwater generally exceed the concentrations expected for the atmospheric solubility. This is referred to as excess air and is caused by bubble entrapment in the porous medium when the water table rises (Heaton and Vogel, 1981). The bubbles contain atmospheric gases that are either partially or completely dissolved into groundwater, increasing the dissolved gas concentrations (Aeschbach-Hertig and others, 2000).

Noble gas recharge conditions were calculated using the Closed Equilibrium (CE) model (Aeschbach-Hertig and others, 2000). The CE model assumes that water table rise results in air entrapment within the porous medium. Fractionation occurs when the entrapped air is only partially dissolved. Additional recharge isolates the water from the atmosphere, which prevents the loss of the dissolved excess air.

In the CE forward model, dissolved noble gas concentrations are calculated from the recharge temperature (T), excess air (A_e), and fractionation (F) as well as recharge salinity and recharge elevation. In the CE inverse model, the dissolved noble gas concentrations are used to calculate T, A_e and F, given constraints on recharge salinity and recharge elevation. The inverse model is solved by minimizing the uncertainty-weighted misfit ($\sum\chi^2$) between the measured and modeled noble gas concentrations (excluding helium due to terrigenic and tritiogenic sources) while fitting the parameters T, A_e and F. Misfit was minimized using Microsoft Solver in a Microsoft Excel workbook, provided by the Dissolved and Noble Gas Laboratory at the University of Utah.

The height of the water table fluctuation can be estimated from the fractionation factor. The fractionation factor is defined as $F = v/q$, where v is the fraction of excess air that remains as free gas after equilibrium dissolution, and q is the ratio of the excess air pressure to the atmospheric pressure (Aeschbach-Hertig and others, 2000). The height of water table fluctuation (*WTF*) is estimated from q, where the excess pressure is directly related to the height of a hydrostatic column that was required to dissolve the extra gas.

Tritium/helium-3: Tritium (^3H) is a radioactive isotope of hydrogen and has a half-life of 12.3 years. The daughter of tritium decay is helium-3 (^3He), a rare and stable isotope of helium. Tritium occurs naturally in the atmosphere where it incorporates into water molecules to form $^3H^1HO$ and falls as precipitation. Because tritium is part of the water molecule, it is geochemically conservative, simplifying interpretation (Solomon and Cook, 2000).

Above-ground thermonuclear weapons testing from 1952 to 1969 added tritium to the atmosphere in amounts that far exceed the natural production rates. The amount of tritium in the atmosphere from weapons testing peaked in the early to mid-1960s and has been declining since atmospheric nuclear testing ceased. Modern concentrations in precipitation are typically between 5 and 10 tritium units (one tritium unit [TU] equals one tritiated water molecule [$^3H^1HO$] per 10^{18} molecules of ^1H_2O) (Clark and Fritz, 1997).

When isolated from the atmosphere, produced ^3He becomes dissolved and accumulates in the water. The $^3H/^3He$ ratio, after correcting for other sources of ^3He, provides the amount of time since groundwater was isolated from the atmosphere (Tolstikhin and Kamensky, 1969). The $^3H/^3He$ method can date groundwater on timescales from modern up to about 60 years before present. Water that entered the groundwater system before 1952 contains negligible tritium (<0.3 TU) and the $^3H/^3He$ method becomes insensitive. Therefore, very low tritium or the absence of tritium can indicate the absence of modern (post-1952) recharge. A mixture of waters having different $^3H/^3He$ ages can complicate interpretation.

Helium-4: Helium is predominantly composed of the isotope ^4He, with a minor component of ^3He. Helium is present in the atmosphere in low concentrations and is sparingly soluble in water. Nevertheless, atmospheric-derived helium occurs in essentially all natural water (Solomon, 2000). Groundwater that has been isolated from the atmosphere for millennia may contain orders of magnitude higher concentration of dissolved helium. This helium is derived from crustal and mantle sources and is collectively referred to as terrigenic helium. Crustal helium is produced from the radioactive decay of uranium and thorium. Uranium and thorium are present in small quantities (a few ppm) in essentially all rocks and sediments. Mantle helium is a primordial remnant from the initial formation of Earth.

Terrigenic helium concentrations are calculated by modeling the atmospheric components of helium, which includes helium from atmospheric solubility and may include helium from excess air and tritiogenic ^3He (Solomon, 2000). Any additional He in the sample that cannot be attributed to atmospheric sources can be considered terrigenic. Crustal and mantle sources can be distinguished by the $^3He/^4He$ ratio. This ratio is presented as R/R_a where R is the $^3He/^4He$ ratio of the sample and R_a is the atmospheric $^3He/^4He$ ratio of 1.38×10^{-6} (Solomon, 2000). Therefore, the R/R_a of the atmosphere is one. Crustal helium has a typical $^3He/^4He$ ratio of 2×10^{-8} (Solomon, 2000) and R/R_a of approximately 0.015 and mantle helium has $^3He/^4He$ ratios of 1.1×10^{-5} to 1.4×10^{-5} (Solomon, 2000) and R/R_a of approximately 10. The presence of tritiogenic ^3He will increase the R/R_a, which may be indistinguishable from mantle-derived helium.

Crustal ^4He concentration can be a useful tool to date old groundwater (10^3–10^6 years), including ages that exceed the range of radiocarbon (50,000 years). Crustal ^4He has also been considered a tracer of young groundwater (>10 years) in basins where helium release rates are very high (Solomon and others, 1996). The uncertainty in helium production rates, release rates, and the addition of helium that diffuses from deeper crustal sources commonly renders ^4He into a more qualitative tool. The effectiveness of ^4He as a quantitative tool generally requires calibration with another tracer, such as radiocarbon.

Sample collection and analysis: Noble gas samples were collected in copper tubes sealed with pinch-off clamps, which prevents any contact with the atmosphere (Weiss, 1968). Samples were extracted and analyzed at the Dissolved and Noble Gas Laboratory at the University of Utah. Analyses from the copper tube samplers included dissolved concentrations of all noble gases, nitrogen, and the isotopes ^3He and ^4He. Samples for tritium determination were collected in 1-liter amber glass jars with no head space. Tritium was analyzed by the ^3He ingrowth technique at the Dissolved and Noble Gas Laboratory at the University of Utah.

Results

Dissolved gas concentrations and interpretations from them are given in table 7. We used the CE model to determine recharge temperature conditions and the length of time that has passed since the sample was recharged to the groundwater from noble gas concentrations. The CE model has an excellent fit for all samples ($\sum\chi^2$ values <<1). Dissolved nitrogen did not fit the model, suggesting that nitrogen does not act conservatively in Ogden Valley groundwater system, and was excluded from the model.

Recharge temperature: Recharge temperature (T_r) ranges from 0.6° to 11.4°C. This range includes the maximum recharge temperature, which is modeled at the minimum recharge elevation (H_r), and the minimum recharge temperature, which is modeled at the maximum recharge elevation. Taking the mean temperature at each site gives a recharge temperature range of 1.4° to 10.3° ± 1.3°C. Nine of eleven samples have a mean recharge temperature less than the mean annual air temperature of Huntsville (7.3°C). The noble gas recharge temperature generally represents the mean annual ground temperature, which typically exceeds the mean annual air temperature by 1° ± 1°C (Smith and others, 1964). The mean annual ground temperature is approximately 2.5°C greater than the mean annual air temperature at Emigration Pass (Bartlett and others, 2006). Conversely, noble gas recharge temperatures from the Wasatch Range were approximately 2°C cooler than the local atmospheric lapse rate (Manning and Solomon, 2003). Assuming a +2.5°C offset, the mean annual ground temperature in Huntsville is 9.8°C. Ten of eleven samples have a mean recharge temperature less than this mean annual ground temperature. These lower recharge temperatures may indicate three processes, including combinations of (1) recharge occurring at higher elevations, (2) rapid recharge primarily occurring during cooler conditions, such as during the spring freshet, and (3) recharge during the last glacial period of the Pleistocene. Temperatures in the Wasatch Range during the last glacial maximum (~17,000 years before present [ka]) are estimated to be 6° to 7°C cooler than present (Laabs and others, 2006).

Noble gas recharge temperatures plotted versus δ^2H show a positive relation with a good correlation ($R^2 = 0.79$) (figure 52). The best-fit regression gives 2.13‰ δ^2H/°C, which is similar to the global gradient of 2.77‰ δ^2H/°C (Yurtsever and Gat, 1981). Therefore, we are comfortable extending noble gas recharge temperatures to wells on which we have stable isotope data but no noble gas data.

Excess air: Initial excess air concentration, before partial dissolution, ranges from 0.003 to 0.086 cubic centimeter at standard temperature and pressure per gram of water (cm^3 STP/g). The excess air is fractionated in all samples between 14% and 76%, and levels of fractionation tend to increase with concentration of unfractionated excess air. Measured excess air concentration ranges from 0.02 to 0.013 cm^3 STP/g (table 7).

Water table fluctuation height ranges from 0 to 18 feet (0–5 m) with a mean value of 9 feet (3 m) (table 7). This range of water table fluctuation seems to generally agree with observations, though well WL-763 has had yearly variations exceeding 25 feet (8 m). Greater fluctuations in water table elevation are expected in mountainous recharge areas due to the yearly pulse of snowmelt recharge (Manning and Caine, 2007; Inkenbrandt and others, 2016).

Terrigenic helium and ^{4}He age: In Ogden Valley, terrigenic helium ($^4He_{terr}$) concentration ranges over three orders of magnitude from 0.19×10^{-8} to 755×10^{-8}. The CE model results indicate that all samples have at least a small component of terrigenic He. The R/R_a of samples range from 0.04 to 1.71. To differentiate the sources of helium and the amount of mixing between sources, we normalized the concentration of atmospheric solubility ^4He ($^4He_{sol}$) to the total ^4He minus any excess air ($^4He_{tot} - {}^4He_{sol}$) and plotted this parameter against the $^3He/^4He$ ratio, again removing any excess air (figure 53). Most data fall along a mixing line between atmospheric solubility and a crustal source having a $^3He/^4He$ ratio of 1.2×10^{-8} ($R/R_a = 0.009$) shown by the heavy black line on figure 53. The

Table 7. Dissolved gas concentrations, isotopic ratios, and interpretation of recharge conditions.

HydroID[1]	Sample date	^{4}He ($\times10^{-8}$ cm^3 STP/g)[2]	R/R_a[3]	Ne ($\times10^{-8}$ cm^3 STP/g)[2]	Ar ($\times10^{-4}$ cm^3 STP/g)[2]	Kr ($\times10^{-8}$ cm^3 STP/g)[2]	Xe ($\times10^{-8}$ cm^3 STP/g)[2]	N_2 ($\times10^{-8}$ cm^3 STP/g)[2]	H_r (ft)[4]	T_r (°C)[5]	A_e ($\times10^{-2}$ cm^3 STP/g)[6]	*F*[7]	*q*[8]	*WTF* (ft)[9]
WL-108	5/23/16	26.8	0.24	25.7	4.10	8.97	1.27	1.44	4908–8366	4.8–7.8	2.2	0.48	1.4	15.7
WL-158	5/25/16	6.2	1.71	24.7	4.44	9.08	1.35	1.96	5587–8104	5.3–8.0	8.6	0.62	1.4	19.3
WL-170	5/23/16	761.0	0.04	26.2	4.21	9.22	1.23	1.31	4970–7480	7.6–9.8	3.8	0.53	1.4	19.0
WL-184	5/17/16	5.6	1.02	21.9	3.86	8.84	1.34	1.43	4951–7480	2.8–5.0	0.6	0.40	1.1	6.4
WL-189	5/24/16	77.6	0.08	24.8	4.32	9.86	1.49	1.77	5390–7316	0.6–2.2	1.2	0.48	1.2	10.6
WL-285	5/24/16	32.8	0.21	24.3	4.08	9.08	1.35	1.60	4928–7808	2.9–5.4	1.4	0.49	1.3	11.2
WL-474	5/26/16	9.9	0.82	35.4	4.86	9.42	1.39	2.04	5571–8858	3.2–6.0	2.7	0.28	1.7	30.4
WL-520	5/25/16	5.7	0.99	23.3	3.82	8.25	1.13	1.26	5016–7316	9.3–11.4	3.5	0.61	1.3	14.2
WL-3587	5/24/16	28.6	0.15	20.6	3.65	8.53	1.30	1.61	5233–8858	2.0–6.1	0.3	0.14	1.2	6.5
WL-3603	5/26/16	6.5	1.02	25.8	4.43	9.27	1.32	1.75	4944–8104	5.7–8.6	6.1	0.57	1.5	20.2
SP-3652	6/29/16	4.9	1.17	20.3	3.89	8.74	1.32	NR	5705–9121	2.4–5.3	4.0	0.76	1.2	8.4

[1] HydroID is the unique site identifier used in this report

[2] Nobel gas concentrations for helium (He), neon (Ne), argon (Ar), krypton (Kr), xenon (Xe), and nitrogen (N_2) given in 10^{-8} cubic centimeters at standard temperature and pressure per gram of water (cm^3STP/g)

[3] R/R_a = $^{3}He/^{4}He$ ratio of the sample relative to $^{3}He/^{4}He$ ratio of air

[4] H_r = recharge elevation. Minimum recharge elevation equal to land surface at sample site; maximum recharge elevation equal to highest elevation of potential recharge upgradient of sample site

[5] T_r = recharge temperature. Minimum recharge temperature calculated at maximum recharge elevation; maximum recharge temperature calculated at minimum recharge elevation

[6] A_e = mean excess air concentration from minimum and maximum elevations given in 10^{-2} cm^3STP/g

[7] *F* = mean gas fractionation factor from minimum and maximum elevations in percent

[8] *q* = mean ratio of excess air pressure to atmospheric pressure from minimum and maximum elevations

[9] *WTF* = mean water table fluctuation from minimum and maximum elevations

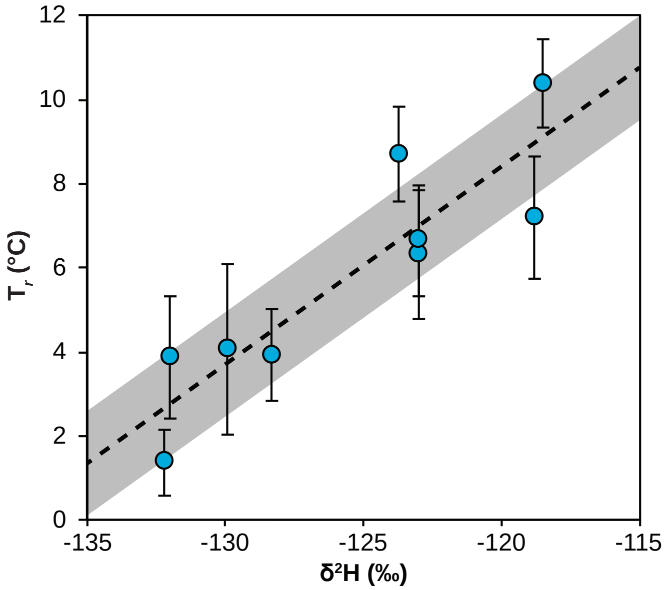


Figure 52. *Noble gas recharge temperature (T_r) versus δ^2H in groundwater and springs of Ogden Valley.*

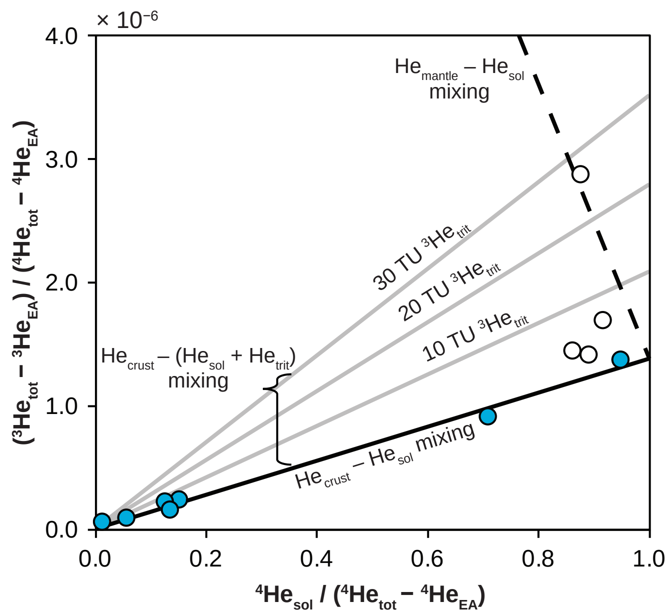


Figure 53. *Mixing sources for isotopic helium in Ogden Valley well samples. Most well samples fall along a mixing line between atmospheric solubility and a crustal source of ^4He.*

maximum crustal $^3He/^4He$ ratio indicated by our data is 6.5×10^{-8} ($R/R_a = 0.047$). A few samples plot above this mixing line and one plots along a mixing line between air equilibration and a mantle source. However, a mantle source is unlikely because these samples contain tritium and will most certainly contain tritiogenic ^3He. Therefore, we conclude these samples contain a mixture of radiogenic, tritiogenic, and atmosphere derived noble gases.

In Ogden Valley, three sites had radiocarbon amounts that are not compromised by the presence of bomb radiocarbon. Using helium production rates appropriate for young sedimentary basins (Phillips and others, 1993), well WL-474 has a helium age that agrees with the radiocarbon age. The other two samples contain higher concentrations than this production rate supports. The helium release rates need to be increased by factors of approximately 20 and 80 to fit wells WL-189 and WL-3587, respectively. This range of apparent release rates is not unrealistic and could be indicative of helium fluxes from deeper units or elevated release rates, which have been observed in other relatively young sediments (Solomon and others, 1996). The correlation between $^3H/^3He$ ages and ^4He concentrations is also weak. This scenario suggests significant mixing between modern and old groundwater sources, which is addressed below in Lumped Parameter Modeling.

Tritium/helium-3 ages: Dating using $^3H/^3He$ requires the separation of ^3He sources, which include the atmosphere (solubility equilibrium and excess air), terrigenic sources (crustal and mantle), and decayed tritium (tritiogenic). We determined the atmospheric component by modeling the concentrations of the other noble gases and the terrigenic component by modeling the normalized concentration of ^4He and the $^3He/^4He$ ratio that excludes excess air (figure 53).

Tritium/helium-3 age of analyzed samples ranges from premodern (>60 years) to less than a decade (table 6). All samples contain detectable amounts of tritium, but three samples contain less than 0.1 TU. These three low-tritium samples have undetectable levels of tritiogenic helium-3, suggesting the water at these sites predominantly recharged before the 1950s. $^3H/^3He$ ages in the other samples are modern, having recharge ages of 3.7 to 59 years. The uncertainty of $^3H/^3He$ age depends on the amount of terrigenic helium and the uncertainty in the terrigenic $^3H/^3He$ ratio. Samples having low terrigenic helium have small age uncertainty averaging ± 2.5 years. Samples having high terrigenic helium have large age uncertainty that exceeds 20 years or cannot be calculated with the statistical model.

WL-108, one of the wells in the Ogden City well field, had a relatively high level of tritium and a calculated $^3H/^3He$ age of 5.8 ± 23.3 years (table 6). The presence of this much tritium is an indicator that modern recharge is reaching the well.

Lumped Parameter Modeling

Method and Theory

The interpretation of groundwater age can be complicated because a groundwater sample usually contains a mixture of groundwater having a range of recharge ages. Long well screens, well completion in multiple aquifers, and mixing within an aquifer result in a distribution of ages rather than a single age. We assessed the mixture of different groundwater ages using lumped parameter models, which assign tracer concentration to models of idealized groundwater flow. For this study we used the USGS's program TracerLPM, which runs in MS Excel (Jurgens and others, 2012), to model available age-tracer data (^{3}H, $^{3}He_{trit}$, ^{4}He, and ^{14}C). The choice of flow model depends on conceptualization of the aquifer geometry, groundwater flow, and the location and geometry of the sampled well or spring. Models are more robust when constrained with multiple tracers. A brief description of these models is given below and thorough details of each model are described by Jurgens and others (2012).

The piston-flow model (PFM) assumes that no mixing occurs in the aquifer and that the sample contains water of a single age. This model may be appropriate for wells with very short screened intervals and wells completed in confined aquifers that are located far from a small recharge zone. The simplest exponential model is the exponential mixing model (EMM), which assumes that no mixing occurs in the aquifer, the aquifer is unconfined, and that the well has a long screened interval that spans the thickness of the aquifer. The sampled water contains an exponential distribution of ages starting at 0 years and approaching infinitely old. Similar to the EMM is the partial exponential model (PEM) which has the assumptions of the EMM except the well screen does not span the entire aquifer thickness, resulting in an age gap. A third exponential model is the exponential piston-flow model (EPM), which assumes an unconfined zone that receives recharge followed by a confined zone. The well screen spans the aquifer thickness and is in the confined zone. The age distribution in the sample is exponential, but a fraction of young water is excluded. The dispersion model (DM) accounts for dispersive mixing within the aquifer. This model can be used to represent a range of aquifer-well configurations. In addition to these models, it is possible to model binary mixtures of different models (binary mixing model [BMM]). Well completion in multiple aquifers, high pumping rates, or very heterogeneous aquifers can yield samples with binary mixtures. For example, a well completed in an unconfined aquifer and a confined aquifer may produce samples with a binary mixture of young water with an exponential age distribution (EMM) and old water with a single age (PFM).

The tritium input for Ogden Valley was estimated from precipitation records in Albuquerque, which is the nearest station with a long tritium record. The Albuquerque record needs to be adjusted to account for higher levels of atmospheric tritium at higher latitudes (Clark and Fritz, 1997, chap. 7). The Albuquerque record was adjusted to Ogden Valley by multiplying by 1.33 through trial and error to fit the observed tritium concentrations in groundwater. The ^{14}C input is the Northern Hemisphere, Zone 1, as is appropriate for the latitude of Ogden Valley (Hua and Barbetti, 2004; Reimer and others, 2009).

Results

Groundwater samples collected from Ogden Valley wells and springs contain a distribution of ages, as indicated by the presence of terrigenic ^{4}He, an indicator of old groundwater, in all samples including those that contain high concentrations of tritium, an indicator of young groundwater.

Most samples were best modeled as binary mixtures between a younger component fitting the EMM or PEM and an older component fitting the PFM (table 8). One sample, well WL-3603 was not a binary mixture and fit the EMM. The mean age of the young component was 2 to 81 years for samples containing significant amounts of tritium and 112 to 170 years for samples having very small concentrations of tritium. The mean age of the old component was on the order of 10^3 to 10^7 years. Examples of age distributions are shown on figure 54.

All age tracers (^{3}H, $^{3}He_{trit}$, ^{14}C, and ^{4}He) were used to constrain the model parameters when possible. Exceptions include the samples with low tritium and subsequently high ^{4}He because $^{3}He_{trit}$ could not be calculated. Also, ^{4}He was excluded from well WL-3603 because the helium concentration could not be explained with the EMM model. The relative errors for the models were 0.3% to 2.6%.

The modeled mean age of the old component was generally controlled by the helium concentration. Because we could only estimate the helium production rate for Ogden Valley, the absolute age of this component is qualitative. Therefore, more relevant age distributions bin the data into ages of 0 to 50, greater than 50, and greater than 100 years. Groundwater recharged within the last 50 years is assumed to be local recharge, which likely recharged into the valley-fill aquifers. Groundwater recharged before the last 100 years is likely recharged far from the collection point. This water may have recharged into the mountain block and has since flowed into the valley aquifers. Groundwater having ages between 50 and 100 years is not indicative of either short or long flow paths. The mean fraction of modern water in our samples is 0.49, but samples spanned the entire range from no modern water to no pre-modern water (table 8). The mean fraction of pre-modern water is 0.41, but samples spanned from no pre-modern water to nearly all (0.97) pre-modern.

Our choice of age bins is subjective and has not been constrained by a flow model. However, binning does appear to differentiate water recharged at high elevation. Figure 55 shows the noble gas recharge temperature versus the fraction of groundwater having a residence time longer than 1000 years. The general trend shows that the modeled recharge temperature decreases with an increasing fraction of old groundwater, which, because of its long residence time, we assume recharged in the uplands of the basin. The correlation is marginal, which could be explained by the general simplicity of this approach. Particle tracking within a three-dimensional groundwater flow model that is calibrated to groundwater age could further constrain this model. This result suggests that at least 40% of sampled groundwater is recharged in the mountain block and moved by subsurface flow into the basin aquifers.

Table 8. *Groundwater age results from TracerLPM (Jurgens and others, 2012).*

			For BMMs only				Sample fraction				
HydroID	Model[1]	Mean age (yr)[2]	Mean age of 1st model component (yr)	PEM parameter[3]	Mixing fraction of 1st model component	Mean age of 2nd model component (yr)	<50 yr	>50yr	>100 yr	Tracers used in optimization	Relative error (%)
WL-108	BMM-EMM-PFM	119,000	2.1	NA	0.68	370,000	0.68	0.32	0.32	$^{3}H,^{3}He_{trit},^{14}C,^{4}He$	0.5
WL-158	BMM-EMM-PFM	3050	19.1	NA	0.59	7460	0.55	0.45	0.41	$^{3}H,^{3}He_{trit},^{14}C,^{4}He$	2.2
WL-170	BMM-EMM-PFM	4,300,000[5]	112.0	NA	0.81	23,000,000[5]	0.29	0.71	0.52	$^{3}H,^{3}He_{trit},^{14}C,^{4}He$	2.6
WL-184	BMM-EMM-PFM	2780	6.4	NA	0.78	12,700	0.78	0.22	0.22	$^{3}H,^{3}He_{trit},^{14}C,^{4}He$	1.0
WL-189	BMM-PEM-PFM	412,000	122.6	1.6	0.07	444,000	0.00	1.00	0.97	$^{3}H,^{14}C,^{4}He$	0.5
WL-285	BMM-PEM-PFM	155,000	16.1	11.8	0.63	414,000	0.62	0.38	0.38	$^{3}H,^{3}He_{trit},^{14}C,^{4}He$	0.7
WL-474[4]	BMM-PEM-PFM	14,600	170.0	0.7	0.29	20,500	0.00	1.00	0.91	$^{3}H,^{14}C,^{4}He$	1.2
WL-520	BMM-PEM-PFM	1280	2.5	20.0	0.88	10,600	0.88	0.12	0.12	$^{3}H,^{3}He_{trit},^{14}C,^{4}He$	0.3
WL-3587	BMM-PFM-PFM	135,000	81.2	NA	0.70	444,000	0.00	1.00	0.30	$^{3}H,^{14}C,^{4}He$	0.3
WL-3603	EMM	7	NA	NA	NA	NA	1.00	0.00	0.00	$^{3}H,^{3}He_{trit},^{14}C$	0.5
SP-3652	BMM-EMM-PFM	1970	9.5	NA	0.58	4,680	0.58	0.42	0.42	$^{3}H,^{3}He_{trit},^{14}C,^{4}He$	0.5
Mean							0.49		0.42		

[1]BMM = binary mixing model; EMM = exponential mixing model; PFM = piston flow model; PEM = partial exponential model

[2]Includes any travel time in the unsaturated zone; unsaturated zone travel time is zero for all samples except WL-520, which is 4 yr

[3]Ratio of screened interval to un-screened interval within saturated zone

[4]Required low helium release rate to match ^{4}He measurement

[5]Unrealistically large modelled age qualitatively indicates very old water

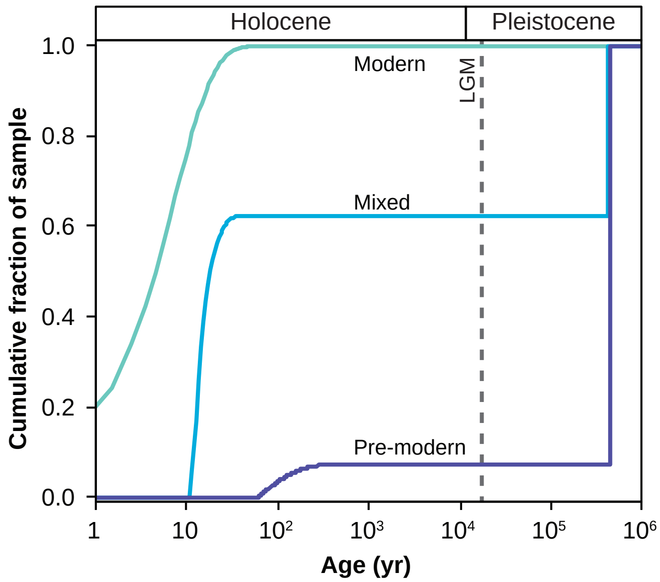


***Figure 54.** Examples of modeled groundwater age distributions from TracerLPM (Jurgens and others, 2012).*

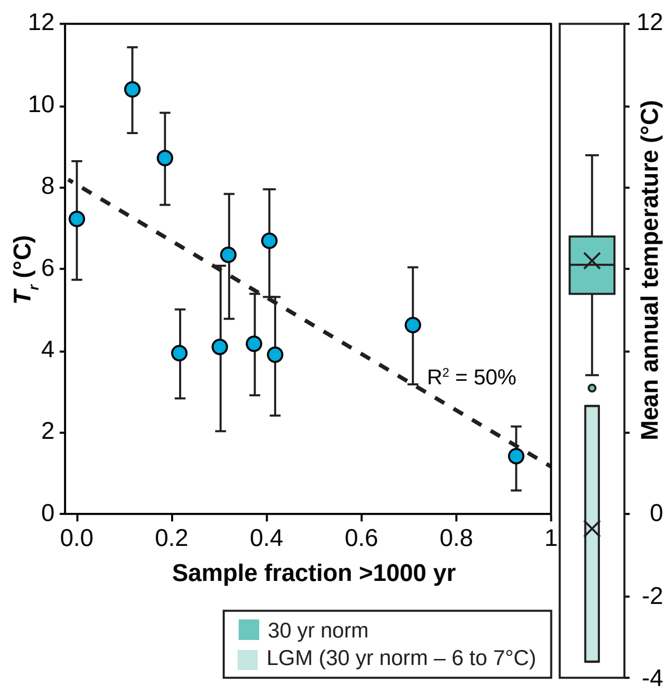


***Figure 55.** Noble gas recharge temperature (T_r) versus the fraction of groundwater samples having residence time exceeding 1000 years. LGM = last glacial maximum.*

PINEVIEW RESERVOIR VOLUMETRIC AND ISOTOPIC MASS BALANCE

Pineview Reservoir is a major component of the Ogden Valley surface water and groundwater systems because of its size and position at the end of the Ogden Valley flow system. Groundwater inflow to the reservoir is an important quantity in the groundwater budget and one of the most difficult water budget components to measure or estimate. We created a mass balance model using quantified or estimated inputs and outputs and solved for the net groundwater input. We enhanced and constrained the model by characterizing the stable isotope ratios of each source and sink.

Method

The hydrological budget of Pineview Reservoir can be conceptualized by considering all known inputs and outputs and maintaining a water mass balance. The change in volumetric reservoir storage is the difference between the volume of input and the volume of output. Sources of input include upstream inflow, groundwater inflow, and precipitation. Sources of output include releases from the dam, groundwater outflow, and evaporation. The volumetric mass balance is described by:

$$\Delta L = I_L + P_L \pm G_L - D_L - E_L \qquad (5)$$

where:

ΔL = change in lake or reservoir volume (acre-ft)
I = stream inflow (acre-ft)
P = precipitation (acre-ft)
G = groundwater (acre-ft)
D = release from dam (acre-ft)
E = evaporation (acre-ft)
and subscript $_L$ denotes the component to or from the lake/reservoir.

The reservoir volume, discharge, inflow, and evaporation are reported daily (U.S. Bureau of Reclamation, 2017). We used our estimates of stream inflow (see Streamflow in WATER BUDGET section below) and evaporation, and published daily measurements of precipitation and pan evaporation at Pineview Dam (Utah Climate Center, 2017a, 2017b) in the model. The volumes of precipitation and evaporation from the reservoir are proportional to the surface area of the reservoir. We related the surface area to the reservoir storage using recent bathymetric data (Winkelaar, 2010). We assumed evaporation from the reservoir to be 77% of pan evaporation and avoided more complicated relations (e.g., Kohler and others, 1955; Linacre, 1994). We assumed that evaporation is zero when the reservoir is iced over. Observations by the Utah Division of Wildlife Resources suggest Pineview Reservoir was completely iced over during January through mid-March 2016, so we assumed evaporation as zero for January and February and 50% for March.

Water volume released from the dam includes discharge to the Ogden River and deliveries to the Pineview Water Systems pipeline in Ogden Canyon and the Ogden City water treatment plant below the dam. A monthly summary of Pineview Reservoir discharge from the U.S. Bureau of Reclamation (2017) is given in table E-1 in appendix E. We checked the U.S. Bureau of Reclamation data against Pineview Reservoir discharge provided by the Pineview Water Systems manager (Mike Scott, written communication, February 28, 2017).

The only unknown parameters are groundwater inflow and outflow. The net input of groundwater is the deficit of the other volumes required to maintain the measured reservoir volume.

We used stable isotopes of water to further constrain and check the water balance including groundwater inflow and outflow. The stable isotope ratios in the reservoir are a function of the stable isotope ratios and volumes of the inputs and outputs. This relation is represented as:

$$L\delta_L = I_L\delta_I + P_L\delta_P + G_{in,L}\delta_{in,G} - G_{out,L}\delta_{out,G} - D_L\delta_D - E_L\delta_E \quad (6)$$

where:
L = lake or reservoir volume (acre-ft)
δ_x = isotopic ratio of component x (‰)
G_{in} = groundwater inflow (acre-ft)
G_{out} = groundwater outflow (acre-ft)
and $I, P, D, E,$ and $_L$ are as defined in equation 5, and the subscripts $_{I,\ P,\ G,\ D,}$ and $_E$ denote stream input, precipitation, groundwater, dam release, and evaporate, respectively.

We assume the reservoir is isotopically well mixed and any outflow has the isotopic ratio of the reservoir. The reservoir is known to seasonally stratify and turnover (Peterson and others, 1990), but noticeable effects from this are not observed in the isotopic data. The well-mixed assumption is also justified as stable isotope ratios are very similar in samples collected from the reservoir, water treatment plant, and Ogden River. With this assumption, equation 6 simplifies to:

$$L\delta_L = I_L\delta_I + P_L\delta_P + G_{in,L}\delta_{in,G} - (G_{out,L} + D_L)\delta_L - E_L\delta_E \quad (7)$$

The isotopic ratio in surface water inflow is the mean of stream water collected immediately upstream of Pineview Reservoir. The isotopic ratio of modeled inflowing groundwater is the mean of all groundwater samples from Ogden Valley (stable isotope ratios in the shallow unconfined and principal confined aquifers are similar and therefore relative inputs cannot be parsed with this method). The isotopic ratio in precipitation is the monthly average from precipitation collected in Huntsville.

Model details are described briefly here and more complete details are provided by Gibson and others (2008). The Pineview Reservoir area has a seasonal climate, which requires more complex modeling than non-seasonal environments. The calculation δ_E requires the calculation of the isotopic ratio in atmospheric moisture (δ_A). Atmospheric moisture is assumed to be in equilibrium with δ_P. For seasonal climates, δ_P is weighted to the annual evaporation flux (figure 56). Other evaporation flux-weighted parameters were weighted monthly and include temperature, humidity, and the equilibrium isotopic separation between liquid and vapor; the latter is a function of temperature. The evaporation flux-weighted temperature was up to approximately 2°C higher than the mean temperature. Flux-weighted humidity changed insignificantly.

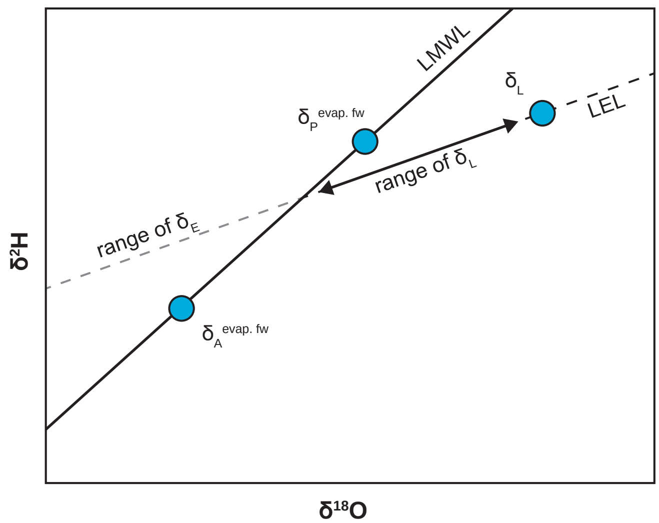


Figure 56. *Relation of isotopic end members used to calculate the isotopic ratios in evaporated lake water (modified after Gibson and others, 2008). LMWL = local meteoric water line; LEL = local evaporation line; isotopic ratios in evaporate (δ_E), evaporation flux-weighted precipitation ($\delta_P^{evap.fw}$), evaporation flux-weighted atmospheric moisture ($\delta_A^{evap.fw}$), and residual liquid in lake or reservoir (δ_L).*

We solved equation 7 for δ_L. Groundwater was added to the modeled reservoir volume to match the observed reservoir volume. However, some days had stream inflow that increased reservoir volume beyond what was measured. As a result, groundwater would need to be subtracted to compensate. To avoid this condition, groundwater was added constantly in 20-day increments. If stream inflow was excessive for a 20-day increment, no groundwater was added. This resulted in approximately 4000 acre-feet of excess water in the reservoir by the year's end. Additional groundwater inflow and outflow, in equal quantity, were required to match the stable isotope ratio of the reservoir and outflow. The initial isotopic ratio of the reservoir and groundwater flows were optimized to minimize the misfit between observed and modeled isotopic ratios of both δ^2H and δ^{18}O, while matching the reported reservoir volumes. Boundary limits of the initial isotopic ratio were not required as the optimized values were within the standard deviation of isotopic ratios measured in the reservoir. Modeled ratios of δ_E plotted near, but not on the local evaporation line (LEL). To match δ^2H and δ^{18}O ratios in the reservoir, the $\delta_E{}^2$H ratio was adjusted by up to 10% to eliminate the misfit with the LEL. Stable isotope ratios used in the model are shown in figure 57.

Results

When only volumes are considered in the model (equation 5), the calendar year 2016 inputs to Pineview Reservoir are 6648 acre-feet of precipitation (33.6 inches; 4% of input), 114,000 acre-feet of streamflow (74% of input) (table D-9 in appendix D), and 31,300 acre-feet of groundwater (22% of input). The 2016 outputs are 6710 acre-feet of evaporation (34.3 inches; 5% of output) and 125,000 acre-feet of dam outflow (95% of

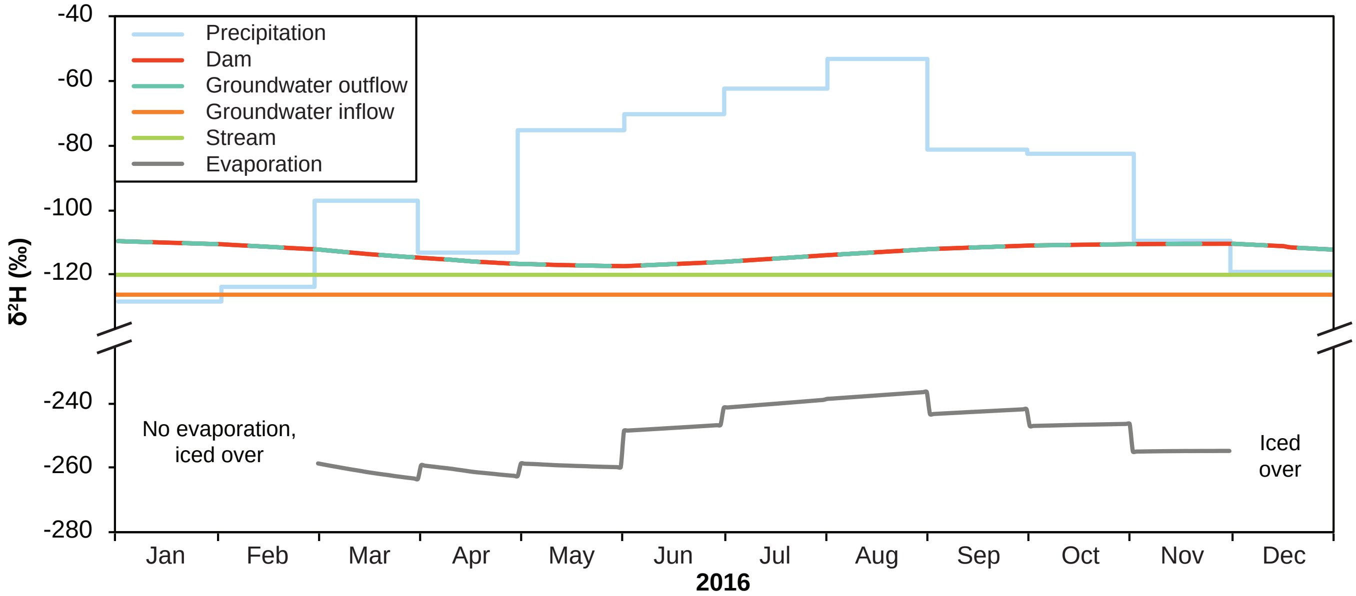


Figure 57. *Modeled stable isotope ratios for reservoir inputs and outputs used in the volumetric mass balance and stable isotope reservoir model.*

output). Groundwater input is a net volume because we could not measure groundwater inflows and outflows, and the net groundwater flux is estimated as the deficit of inflow compared to outflow to maintain mass balance.

Approximately half of stream and groundwater input (51% and 49%, respectively) in 2016 occurred between April and May, which coincides with the spring runoff. Input during this period was further increased by high precipitation (31% of yearly input). Most of the dam output occurred between May and July (58%), and most evaporation occurred from June to August (57%).

When the volumes from the mass balance model are applied to the stable isotope model (equation 7), the model generally fits the data, but the effects of evaporation are too great, and the model overestimates the evaporative enrichment observed from September to November. By increasing groundwater input and adding flow out to groundwater, evaporative enrichment is limited, and the model fit is good (figure 58). The amount of reservoir water needed to discharge to the groundwater system to attain a good fit is 2700 acre-ft/yr, which increases groundwater inflow to the reservoir to 34,000 acre-ft/yr. All other inputs and outputs remain as above and are shown as daily volumes in and out of the reservoir on figure 59. Our modeled stable isotope ratios of the reservoir water fits the values we measured in 2016 in reservoir samples reasonably well (figure 60).

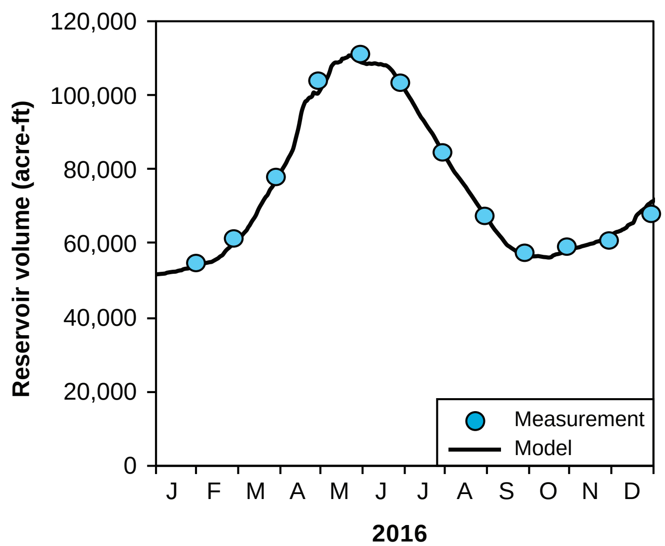


Figure 58. *Modeled reservoir volume fits well to measured values when stable isotopes are used to refine the unknown groundwater input and output volumes in the reservoir mass balance model.*

Model Sensitivity and Assumptions

The accuracy of this model is dependent on the conceptualization and correctly identifying the isotopic composition of end members (figure 57). The isotopic ratios of streams, groundwater, and precipitation are all well constrained by our analysis of dozens of samples. The volume of evaporate and the isotopic ratios of evaporate and atmospheric moisture have the greatest uncertainty because these values cannot be directly measured. Furthermore, while evaporation only accounts for a few percent of the water output, the highly depleted stable isotope ratio in the evaporate strongly affects the ratio in the reservoir. The calculation of δ_E depends on the temperature, humidity, and evaporation flux-weighted precipitation. Increasing the temperature by 2°C decreases the groundwater outflow by 4%. Increasing the humidity by 5% increases the groundwater outflow by 12%. Decreasing evaporation by 2% decreases groundwater outflow by 86%. The volume of precipitation and stream input also alters the required groundwater outflow. Increasing monthly precipitation by 5% increases

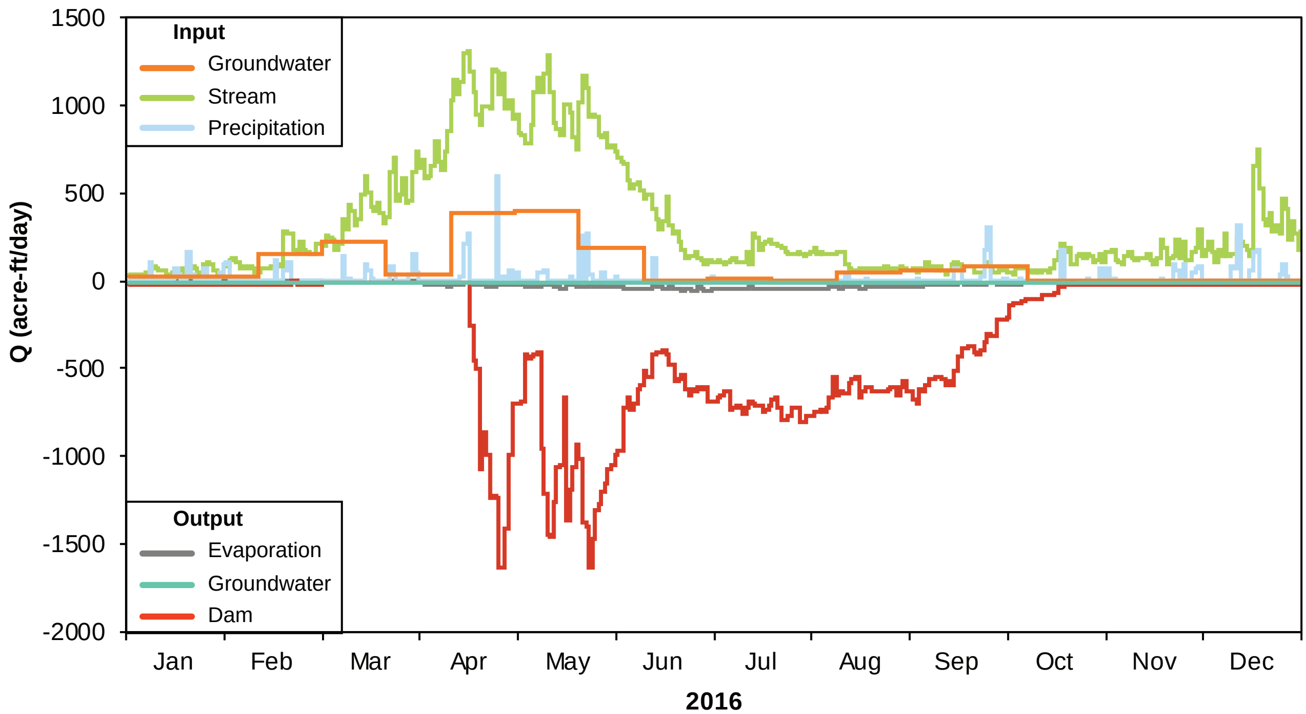


Figure 59. *Daily volumetric reservoir flux (Q) components. Stream and precipitation input and evaporation and dam release output are measured or estimated, and groundwater input and output are modeled using a volumetric and isotopic mass balance.*

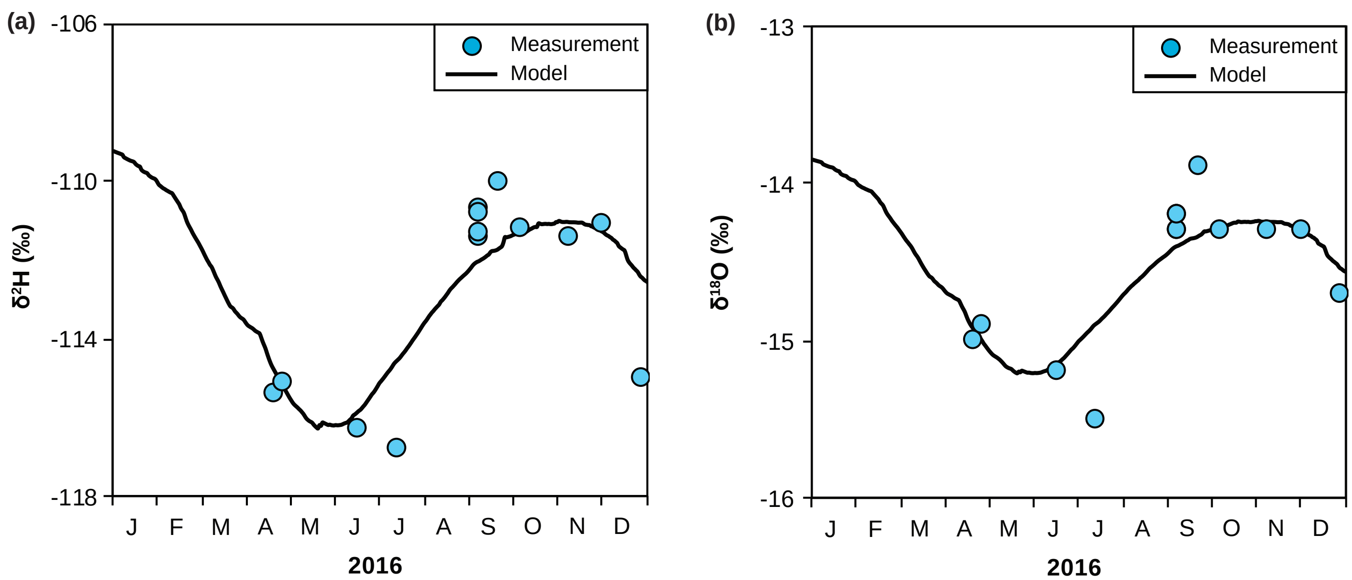


Figure 60. *Measured and modeled stable isotope ratios for Pineview Reservoir;* ***(a)*** *δ^2H and* ***(b)*** *δ^{18}O.*

groundwater outflow by 18%. Increasing stream flow by 5% increases groundwater outflow by 4%. Altering the composition of groundwater has a large effect on the groundwater outflow. Increasing δ^2H and δ^{18}O by 1‰ and 0.2‰, respectively, increases groundwater outflow by 61%. Decreasing δ^2H and δ^{18}O by the same amounts decreases groundwater outflow by 54%. Clearly, a more accurate estimate of groundwater outflow requires greater constraint on evaporative processes, but because the model suggests groundwater outflow from the reservoir (2% of total outflow) is an insignificant component of the overall budget, further constraint is not warranted.

We have no way of directly measuring groundwater outflow. Avery (1994) suggested that flow from the reservoir to groundwater could be occurring, but had no evidence and assumed the amount may be negligible, so ignored it in his water balance. Potentiometric data presented in the Gradients between Aquifers and Pineview Reservoir section above shows that a downward gradient from the reservoir to the confined aquifer is present over part of the bottom of the reservoir, providing one path for groundwater outflow. A second avenue for groundwater outflow is seepage of reservoir water under Pineview Dam to the alluvial deposits in Ogden Canyon.

Another model assumption is that the reservoir is well mixed. Previous studies have shown that the lake is well mixed through most of the season; however, thermal stratification exists from late June to August (Peterson and others, 1990; Tetra Tech Inc., 2002). This period of stratification could be affecting the model if dam and groundwater outflow have isotopic ratios that differ from the well-mixed reservoir. However, other isotopic lake studies assume well-mixed bodies of water (Brooks and others, 2014).

Comparison to Other Models

Annual Pineview Reservoir water budget estimates of Reuben and others (2011) include surface water inflow of 138,000 acre-feet and groundwater inflow of 2800 acre-feet (2008–2011 average). The total inflow of Reuben and others (2011) is similar to this study, but surface water inflow is 27% higher than our estimate and thus groundwater inflow is significantly lower (by 91%) than our estimate. Reuben and others (2011) estimated groundwater discharge to the reservoir using a Darcy flow calculation with hydraulic conductivity values derived from slug tests in piezometers in the shallow unconfined aquifer and measured the hydraulic gradient between the piezometers and Pineview Reservoir. We suggest Reuben and others' (2011) estimate of groundwater discharge to the reservoir is too low because their hydraulic conductivities may not be spatially representative (only 1 liter of water was bailed for the slug tests, which limits the zone of investigation to immediately outside the well casing) and higher flow zones, such as those underlying and adjacent to stream beds, were likely inadequately represented. Furthermore, Reuben and others' (2011) stream gauging occurred weekly to monthly, conditions permitting, and yearly totals could be incorrect due to interpolation between these points. Also, Reuben and others' (2011) estimate, which was for the shallow unconfined aquifer discharge to Pineview Reservoir, did not consider the possibility of leakage from the confined aquifer up through the confining unit.

Leakage from Pineview Reservoir to the Confined Aquifer

Our model results estimate that 2700 acre-feet of reservoir water is lost to the groundwater system per year. Comparison of the 2016 potentiometric surface (figure 21) with the range of reservoir water level elevation (4855 to 4901 feet [1480–1494 m] during our study period) indicates that the reservoir level can be lower or higher than the potentiometric head in the confined aquifer depending on how full the reservoir is and proximity to the Ogden City well field. The balance between reservoir level and potentiometric head in the principal aquifer creates upward or downward vertical gradient between the two, but the gradient is always downward in the Ogden City well field cone of depression. Downward leakage when and where reservoir level is higher than the head in the principal aquifer could occur via two pathways: (1) through the confining unit and (2) through abandoned wells. Previous studies have considered the confining unit either negligibly permeable (Leggette and Taylor, 1937) or significantly leaky (Avery, 1994). Thomas (1945) supposed that downward leakage could be occurring through the thinner and more interbedded edge of the confining unit. Core-scale permeability testing reported in Leggette and Taylor (1937) was below the limits of the method (<0.013 ft/d). Seepage studies of Avery (1994) are more representative of formation-scale permeability and gave comparable permeability at 0.01 to 0.04 ft/d, which is typical of silts. Based on this assessment, differences in the reservoir stage relative to the potentiometric surface of the confined aquifer will lead to leakage. This leakage will buffer the water-level differences between the two systems. In addition to leakage through the porous medium of the confining unit, leakage could be occurring at abandoned wells that are submerged below Pineview Reservoir. At least 51 wells were drilled in the Artesian Park area near the former confluence of the North and Middle Forks. Several of these wells were abandoned before the reservoir was filled and others were abandoned in the 1970s due to bacteria problems (Doyuran, 1972). The state of most wells at abandonment is unknown and decades of further decay may have deteriorated plugs or caps. These wells may now be a conduit between Pineview Reservoir and the confined aquifer.

Environmental tracers provide some clues to the interactions between the confined aquifer and surface water. The first piece of evidence is the presence of tritium in water from the Ogden City well field (WL-108 had 4.85 ± 0.25 tritium units), which undoubtedly indicates significant amounts of modern water are reaching the confined aquifer. The second piece of evidence is the presence of elevated nitrate concentrations in this well. The measured concentration of 1.43 mg/L is greater than the geometric mean nitrate in Ogden Valley groundwater excluding the shallow unconfined aquifer (0.807 mg/L). The third piece of evidence is in the stable isotopes of water. Ratios of δ^2H are greater than other deep groundwater found in the confined aquifer (figure 50). That is, the stable isotopes signature suggests recharge to this well comes from shallower recharge sources than the deep bedrock recharge expected given the depth of the Ogden City wells. The 2016 extraction from the well field is roughly 12,000 acre-ft/yr. The reservoir water balance stable isotope model gives a leakage of approximately 2700 acre-ft/yr. Therefore, this amount of leakage could account for the fraction of Ogden City well water coming from a source other than the confined aquifer. However, while these lines of evidence suggest the source of water to the Ogden City well field is not solely the confined aquifer, the general chemistry and isotopic composition does not clearly show mixing of reservoir water with water of the confined aquifer. Concentrations of major ions in the one Ogden City well sample (WL-108, table D-5 in appendix D) are not consistently intermediate between the concentrations of major ions in the reservoir water sample (RES-3636, table D-5 in appendix D) and an average of concentrations of major ions from principal aquifer wells. Similarly, the stable isotope signature of water from the well field does not show an evaporative signature like that in the reservoir. Another source for young, elevated-nitrate, less-depleted water is groundwater from beyond the limits of the confining unit but near enough to the well field to have a relatively short (i.e., quick) flow path. The primary candidate for this pathway is the area west of the reservoir.

Seepage from Pineview Reservoir under Pineview Dam

Another pathway for the 2700 acre-feet of water from Pineview Reservoir to exit to groundwater is in the alluvium under the dam. About 100 feet (30 m) of unconsolidated sediments fill Ogden Canyon under Pineview Dam (figure 14b). Beneath the dam and above the varved silt and clay, which is an extension of the confining unit, there are roughly 40+ feet (12+ m) of sediments that are a potential conduit for leakage from Pineview Reservoir (Leggette and Taylor, 1937; Shaffner and others, 1993). Underlying the cutoff channel of the dam, steel sheet piles were driven to bedrock to prevent any leakage. Doyuran (1972) claimed that the sheet piles completely stopped seepage, but the U.S. Bureau of Reclamation stated that the sheet piles were ineffective at changing pore pressures downstream (i.e., did not decrease downstream seepage; [U.S. Bureau of Reclamation, 2008, p. 100]). We calculated a range of possible flow in the sediments above the confining unit beneath the dam using a Darcy flow approach and the following: (1) we assumed the sheet piles were completely ineffective, (2) hydraulic conductivity is 50 to 100 feet per day (Avery, 1994), (3) horizontal hydraulic gradient is 70 feet over 1000 feet (20m/300m) (approximate difference between average reservoir level and the elevation of Ogden River below Pine-view Dam over the approximate distance between the upstream and downstream toes of the dam), and (4) cross sectional area of 11,500 square feet (1070 m^2) (from figure 14). By our calculation, 300 to 700 acre-ft/yr of water from Pineview Reservoir could be leaking through the alluvium beneath the base of the dam and the confining unit in Ogden Canyon. If sheet piles are effective, the discharge would be smaller. Our estimate of seepage below the dam is very small compared to the other sources and sinks and is only a fraction of the amount our reservoir water balance suggests is occurring.

DISCUSSION

Conceptual Model of Groundwater Flow

The study area boundary, which is the surface drainage divide for the Ogden River above Pineview Dam, provides a good approximation of the limits of the groundwater basin. However, we recognize that some localized sections of the boundary may not represent the true groundwater divide. Ogden Valley is surrounded by bedrock deformed into complex structures. The deep, older bedrock in the southeast part of the study area is covered by a mantle of Cretaceous and Tertiary conglomeratic rocks (KTcgA). Precipitation recharge can percolate through high-permeability areas in this unit, but once in the underlying Paleozoic rocks (CZqH, ƦPH), geologic structure may divert groundwater flow out of the study area. Several areas of the boundary of the surface watershed are underlain by carbonate rocks (PZcaA) known to have karst permeability, as well as permeable rocks tilted at an attitude that may channel infiltrated precipitation out of the surface watershed. Furthermore, the zone of influence of pumping water-supply wells located near the surface drainage divide may extend through the divide, especially in areas we have classified as having high likelihood of inter-basin flow. In this study, we assumed the surface water divide was the groundwater divide but recognize that localized geologic constraints may influence recharge and groundwater extraction that occurs close to some areas of the divide.

Recharge from precipitation to the bedrock surrounding the valley flows either toward springs and streams to become surface flow or through the bedrock into the valley-fill aquifers in Ogden Valley. The geologic setting of Ogden Valley may limit mountain-block recharge to the valley fill due to the extent of impermeable bedrock units. The northern mountains contain important aquifer units interspersed with heterogeneous and confining units, complicating groundwater flow from the mountains to the valley. The Cretaceous and Tertiary conglomeratic aquifer (KTcgA) covering much of the surface of the high-elevation parts of the South Fork Ogden River watershed is of only moderate transmissivity. Water that does penetrate the cover rocks may encounter a variety of hydrogeologic units, some that are permeable and some that are impermeable. Lying between the unconsolidated valley fill and the mountain block in all but the North Fork arm of the valley, the Tertiary Norwood Tuff (TvC) may limit transmission of groundwater from permeable bedrock units to permeable valley fill, forcing the mountains to maintain higher water levels, spring discharge, and baseflow to streams. The position of the Norwood Tuff is a contributing factor to the dominance of surface water on the hydrogeologic system. Even though the unconsolidated valley-fill sediments are up to about 2300 feet (700 m) thick in the deepest part of the basin, environmental tracer data show that the upper few hundred feet of the aquifer is where much of the groundwater flow and groundwater–surface-water interaction is taking place. Older water occurs in deeper parts of the aquifer.

The principal aquifer is much thicker than reported in previous studies of Ogden Valley. From our new gravity data, we show that the unconsolidated valley fill is up to about 2300 feet (700 m) thick at its deepest point near Huntsville (figure 13). The bottom of the confining unit at this location is only about 50 feet (15 m) deep, leaving a thick package of unconsolidated sediment to transmit and store water (figures 16 and 17). Since no wells penetrate deeper than 600 feet (180 m) in the valley fill, the nature of these sediments is unknown, and porosity is almost certainly lower than it is near the surface because of compaction by the weight of overlying sediments and water in Pineview Reservoir. Our environmental tracer data show that deep wells are producing water that was recharged thousands of years ago (figures 51, 54, and 55), which suggests groundwater flow through the deep parts of the basin is much slower, or flow paths are longer, than in shallow parts. Still, this thick package of sediment is a large reservoir for groundwater, and groundwater storage in the valley fill is potentially very high. Water levels in most valley-fill wells show no long-term decline (figures 24 and 28), despite increasing development, which is further evidence of adequate storage. However, the cone of depression around the Ogden City well field has expanded despite no overall average increase in extraction, indicating that the system may not have reached equilibrium yet and the well field may be extracting groundwater from storage.

Groundwater flows in the principal aquifer from the margins of the valley toward Pineview Reservoir, perpendicular to potentiometric contours (figure 21). The principal unconfined aquifer receives recharge primarily from seepage from streams entering Ogden Valley, seepage from irrigation canals, unconsumed irrigation water applied to the land surface, and infiltration from precipitation. As groundwater flows in the principal unconfined aquifer toward Pineview Reservoir, it encounters the outer edge of the silt and clay confining unit. Because the water table is above the elevation of the edge of this confining unit, water from the top of the principal unconfined aquifer moves into the shallow unconfined aquifer and deeper flow becomes confined in the principal aquifer (figure 61) (Leggette and Taylor, 1937; Thomas, 1945). The water flowing into the shallow unconfined aquifer has been termed "rejected recharge" (Thomas, 1945; Doyuran, 1972; Avery, 1994) and the amount depends on the amount of available storage in the confined principal aquifer (Leggette and Taylor, 1937). The amount of water entering the confined principal aquifer is likely equal to the sum of well withdrawal from the confined aquifer, upward leakage to Pineview Reservoir, and subsurface discharge out of the valley (if any).

Groundwater flows toward the reservoir in the shallow unconfined aquifer. Recharge to the shallow unconfined aquifer is primarily from horizontal groundwater flow from the unconfined aquifer beyond the outer margin of the confining unit and downward movement of seepage from streams, infiltration from precipitation, irrigation, and septic-tank leachate (Reuben and others, 2011; Reuben, 2013; Reuben and Sorensen, 2014). Before Pineview Reservoir was constructed, springs and seeps discharged from the shallow unconfined aquifer in stream valleys incised into the confining unit (Leggette and Taylor, 1937, p. 136). Now, some water discharges to springs that flow to Spring Creek and to gaining sections of the lower parts of stream reaches (figure 61). Most groundwater that is not discharged to surface water eventually discharges to the reservoir (Doyuran, 1972; Avery, 1994).

Downward leakage from the shallow unconfined aquifer to the confined principal aquifer is possible. Earlier studies of Ogden Valley's groundwater system (Doyuran, 1972; Avery, 1994) indicated the vertical gradient between the shallow unconfined aquifer and the confined principal aquifer was likely upward, and that leakage was negligible in most areas because of the confining unit's low permeability (Leggette and Taylor, 1937). Using water levels from wells constructed in 2009 in the shallow unconfined aquifer, we show that the gradient between the aquifers is now likely dynamic, changing direction with seasonal head changes in the aquifers. Leakage between the shallow unconfined aquifer and the principal confined aquifer is more likely at the edge of the confining unit where the unit's relative thinness and silty composition provide a potential pathway for leakage between the confined principal and shallow unconfined aquifers. However, the gradient in these areas is also likely small, which provides little drive for leakage.

Avery (1994) recognized downward head gradient from Pineview Reservoir to the central area of the cone of depression around the Ogden City well field. We suspect that the cone of depression has expanded and deepened around the well field to the point that head in the principal confined aquifer is lower than the reservoir water level over a large area at least part of most years and especially when the reservoir is full or nearly full, providing a strong gradient for downward leakage (figure 61). Sets of nested piezometers or paired wells in the shallow unconfined and confined principal aquifer are needed to quantify extent of the cone of depression with more certainty. In summary, leakage through the confining unit can be up or down depending on location and the dynamics of reservoir and aquifer water levels.

Groundwater flow is confined by the confining unit in the southwest part of the valley. Movement of groundwater in the confined aquifer is generally toward the south, southwest, and west toward the head of Ogden Canyon (Leggette and Taylor, 1937). The confining unit is up to 120 feet (40 m) thick at its maximum thickness near the Ogden City well field but pinches out to the north and east. The confining unit is as thin as 10 feet (3 m) under parts of the reservoir because streams have eroded into the top of the unit (figures 16 and 17). At the junction between the three arms of the reservoir, where the well field's cone of depression is deepest and head gradient is always downward between the reservoir and the principal confined aquifer, the confining unit is about 60 feet (20 m) thick. Groundwater flow in the principal confined aquifer ultimately flows to the Ogden City well field (Doyuran, 1972; Avery, 1994), which is shown to be a sink on potentiometric maps (figure 21) (Avery, 1994, figure 11). Tritium and slightly elevated nitrate in the well field strongly suggest the well field is extracting some modern water. The source of this modern water could be (1) reservoir water leakage through the confining unit (60 feet [20 m] thick) or through deteriorated abandoned well casings, (2) shallow unconfined aquifer leakage through the confining unit when and where gradient is downward, or (3) bedrock recharge directly west of the well field. Our volumetric–stable-isotope reservoir model suggests the reservoir is losing water to groundwater; therefore, we favor the pathway of leakage through the confining unit and/or through abandoned well casings.

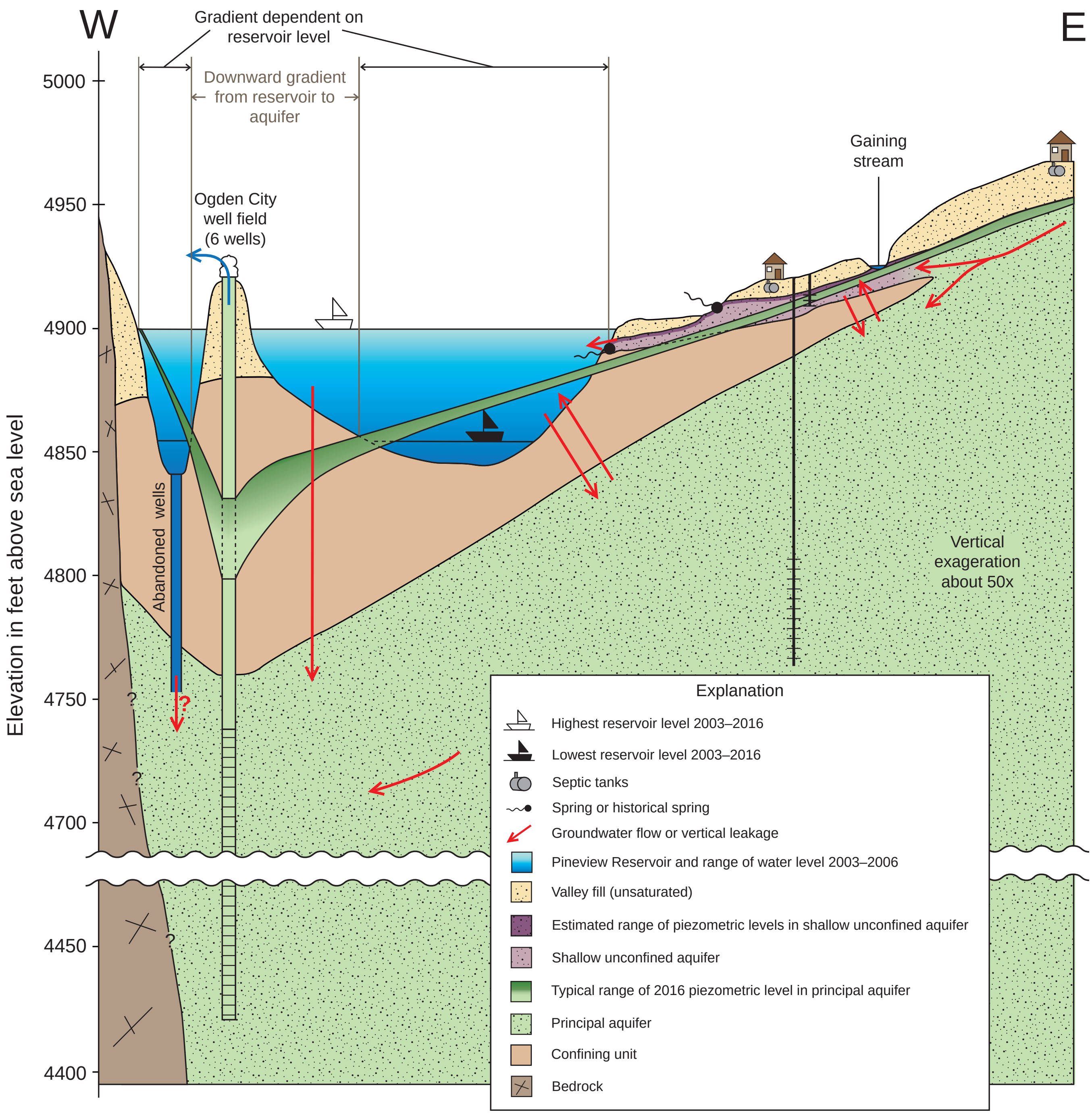


Figure 61. *Schematic cross section through Pineview Reservoir and the valley-fill aquifer system showing possible relationships between reservoir and potentiometric levels and likely pathways for groundwater flow and leakage through the confining unit.*

Surface water plays a key role in the groundwater system of Ogden Valley. Losing streams and canals recharge the unconfined principal aquifer when and where the water table is below the bottom of the streambed, especially during baseflow conditions and overlying the unconfined principal aquifer near the South Fork Ogden River and the upper and lower parts of the North Fork Ogden River arm of the valley (figures 31 and 32). Conversely, streams are gaining in areas having a shallow water table, especially during runoff season when the aquifer is recharged by in-place recharge on the valley floor. This interchange of groundwater and surface water is apparent in the environmental isotope data. Stable isotopes of water indicate that groundwater in the principal aquifer is a mix of water from the bedrock aquifers and streams (figure 49). The ratio varies between forks, but the average is nearly half from surface water and/or in-place recharge of precipitation through the valley floor and half from groundwater flow through the mountain block. Separating the water out by depth shows that the more isotopically enriched water that resembles stream water is shallow while the more depleted water that resembles bedrock aquifer water is deeper (figure 50). Recharge temperatures from dissolved noble gases, which inversely correlate with δ^2H values, indicate that deeper water was recharged at lower temperatures that could occur at higher elevations and/or during the last glacial maximum. Age-dating tracers show a diverse range of conditions. Five samples are predominantly modern (recharged after about 1950), three samples are predominantly pre-modern, and three samples are a mix of modern and pre-modern. A groundwater system dominated by modern water suggests active recharge and inherent susceptibility to contamination from urban, agricultural, and industrial sources. A system dominated by pre-modern water suggests that groundwater recharge is inactive or has a long residence time and/or flow path; these systems are generally less vulnerable to surface-based contamination sources. In a surface-water-dominated groundwater system such as Ogden Valley, we expect the principal unconfined aquifer, shallow unconfined aquifer, and shallow bedrock aquifers to contain young water. Similarly, we expect the confined principal aquifer to contain old water and be protected from contamination. However, modern concentrations of tritium in the Ogden City well field suggest that water is entering the well field within a few years of having recharged the aquifer. The source of the young water in the well field was not definitively constrained in this study, but likely sources include leakage through the confining unit that underlies the unconfined aquifer and Pineview Reservoir and leakage through the casings of abandoned wells in the former Artesian Park.

Composition of Ogden Valley Groundwater

The groundwater we sampled for this study has generally very good water quality throughout, with average TDS values around 240 mg/L (figure 34). Dominant chemistry is calcium bicarbonate, though a few samples have elevated sodium or chloride (figures 35, 36, and 37). The principal aquifer has consistently high-quality water, although some wells around the valley margins in the Middle Fork area have marginal quality water. We measured more diverse groundwater quality in the bedrock aquifers, especially in the North Fork where rocks are older and more geologically diverse. Still, groundwater sourced from bedrock had an average TDS only slightly higher than valley-fill aquifers—267 mg/L and 225 mg/L, respectively. No wells had constituents that were above primary drinking water standards.

Nitrate concentration in the 50 wells and springs sampled for this study ranged from 0.01 to 7.65 mg/L (figure 34), with a geometric mean of 0.45 mg/L, which is similar to the geometric mean of 0.42 mg/L we calculated from data used by Lowe and Wallace (1997) when groundwater in Ogden Valley was classified as Pristine by the Utah Water Quality Board (Lowe and Wallace [1997] used an arithmetic mean of 0.97 mg/L in the classification). Because few, if any, supply wells are completed in the shallow unconfined aquifer, our sampling did not capture the degraded water quality previous researchers had sampled. In 2010 and 2011, nitrate + nitrite concentrations in the shallow unconfined aquifer ranged from below detection to 47 mg/L (table D-7 in appendix D) (Reuben, 2013). Nitrate in wells in Ogden Valley is likely associated with anthropogenic sources, either septic-tank effluent or fertilizer, or both. Reuben and Sorensen (2014) concluded from their NLEAP-GIS modeling that mean annual NO_3-N (from fertilizer) leaching rates from lawns were generally higher than from croplands, and that as development occurs and cropland is replaced by lawns, nitrate concentrations in aquifers could increase. While we are uncomfortable with a number of the assumptions Reuben and Sorensen (2014) were forced to make in their modeling effort (such as using silage corn modeling parameters for lawns because turf grass was not a choice available in the modeling software), we have no data to contradict their conclusion. Rumsey (2014), however, used nitrogen and oxygen isotope analyses and other water chemistry results (for example, boron concentrations) to show that nitrate (and phosphorous) contamination from septic-tank effluent is occurring in Ogden Valley. Recent work in nitrate source detection has focused on detection of anthropogenic substances such as household chemicals, food additives, and pharmaceuticals as tracers of septic tank leachate (for example, Oppenheimer and others, 2011; Snider and others, 2017). We suggest future samples from the shallow unconfined aquifer monitoring wells be analyzed for anthropogenic markers.

Groundwater–Surface-Water Interaction in Valley-Fill Aquifers

Our chemistry and streamflow analyses show that there is a high degree of interaction among surface water in streams, precipitation falling on the valley floor, and the upper few hundred feet of groundwater in the principal aquifer.

Stable isotopes of water provide important constraints on the location and amount of surface water and groundwater interaction. Rain is more isotopically depleted the farther inland it travels on northern Utah's prevailing westerly storm track, and these continental effects are evident between the North and Middle Forks compared to the South Fork (figure 47). Stable isotope ratios are about 10‰ more depleted in stream and bedrock samples in the South Fork sub-basin and somewhat less depleted in valley-fill samples than samples from the North and Middle Fork. In general, the stable isotope ratios in the valley-fill aquifer reflect the ratios in the adjacent bedrock aquifers within each sub-basin. We used these differences and similarities to estimate the ratio of recharge to the principal aquifer from bedrock versus streams and/or in-place recharge in each sub-basin (figure 49). Valley-fill wells in the North Fork sub-basin receive, on average, less stream and in-place recharge than bedrock recharge. Conversely, wells in the South Fork sub-basin receive more steam and in-place recharge than bedrock recharge. The valley fill in the Middle Fork shows nearly equal recharge between the two end members. Our seepage studies corroborate this difference; streams gain more water in the North Fork sub-basin than they lose, supporting a system that receives slightly more bedrock recharge, and streams and canals lose more water in the South

Fork sub-basin than they gain, supporting a system that receives slightly more surface-water recharge (table 5).

The potentiometric surface of the principal aquifer generally increases in the spring, peaks in the summer, and declines in the fall. Our seepage runs on Ogden Valley's streams and SWAT modeling show that during spring runoff, losing streams and surface infiltration of precipitation raise the water table in some locations in the principal unconfined and shallow unconfined aquifers enough to intersect stream channels. Because the aquifers are at capacity, they discharge more water to streams than they receive from them. During baseflow conditions in late summer though winter, slight water table decline allows more water to be lost from the streams.

The presence of stream-composition water in the principal aquifer suggests active recharge. A relatively homogeneous stable isotope and major ion chemistry composition of stream water within a sub-basin, even in reaches that are gaining, suggests the water gained in the stream channels through the streambed was previously stream water that recharged the principal and shallow unconfined aquifers farther upstream.

Overall, the interchange between surface water and the valley-fill aquifer system was slightly net losing to groundwater in 2016. The North and Middle Fork sub-basins had approximately 8400 acre-feet net gain to streams, but that amount was nearly balanced by net loss from the South Fork and the Ogden Valley Canal (table 5). An additional 4000 acre-feet of estimated canal loss from the valley's extensive network of irrigation canals, several of the larger of which are in the South Fork sub-basin valley-fill area, tips the balance to net losing overall.

WATER BUDGET

Water Budget Development

We estimated a water budget for the Ogden Valley drainage basin for water years 2004 to 2016 (water year 2004 is from October 1, 2003, to September 30, 2004) by quantifying annual inflow and outflow. The primary inflow component of the water balance is precipitation, and the three main known outflow components are evapotranspiration, Ogden City well field pumping, and Pineview Reservoir discharge. Groundwater discharge through alluvium and shallow bedrock of Ogden Canyon may be a fourth, likely small, outflow component (Avery, 1994). For any year that these inflow and outflow components do not balance, we assumed that groundwater was put into or taken out of storage in the aquifers to balance the overall water budget. We evaluated these components for the whole basin and individual sub-basins drained by the North, Middle, and South Forks of the Ogden River.

Within the larger drainage basin water budget, we examined components of the aquifer system. Inflow components are in-place recharge from precipitation, recharge from runoff infiltration (losing streams), infiltration of unconsumed irrigation water, and infiltration of septic-system leachate. Outflow components are discharge to springs and gaining streams, groundwater discharge to Pineview Reservoir, and well pumpage. Aquifers can lose water directly to evaporation, but our methods produced estimates of gross evapotranspiration only.

Utah Basin Model Development and Data Sources

The Utah Basin Model (UBM) was the primary means for checking the large water budget components of this study. The UGS created the UBM based on the methods of the USGS Basin Characterization Method (BCM), which has been applied to most of the western portion of Utah (Flint and others, 2004; Flint and Flint, 2007; Heilweil and Brooks, 2011; Thorne and others, 2012). The USGS did not publish results from the BCM for Ogden Valley. The UBM uses a monthly water-soil balance to determine evapotranspiration, runoff, recharge, and soil water. The UBM method correlates well with the BCM where both methods have been applied. Further statewide calibration of the UBM is necessary for a complete proof of concept for this model.

Evapotranspiration data: We based evapotranspiration estimates on MODIS 16 rasters (Mu and others, 2011, 2013). MODIS 16 is a 500-meter-square absolute and potential evapotranspiration grid derived from NASAs Moderate Resolution Imaging Spectroradiometer (MODIS) satellite input and the modified Penman-Monteith algorithm (Mu and others, 2013; Running and others, 2018). The algorithm uses land cover classifications determined by the International Geosphere-Biosphere Programme Data and Information System (IGBP-DIS) that include cropland, grassland, open shrubland, and forests. We downloaded the MOD16 ET 8-day raster data from 2001 to 2014 as tiles from the online data pool, courtesy of the NASA Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota (https://lpdaac.usgs.gov/tools/data-pool/). We re-projected the tiles to Albers Conic Equal Area (USGS) projection, and mosaiced the tiles into consistent monthly data. We scaled the evapotranspiration and potential evapotranspiration layers so the rasters would be in units of meters of water. MODIS 16 masks all water bodies, resulting in "holes" in the rasters. We filled the holes using focal statistics interpolation of the values around the margins of the holes. In the case of Pineview Reservoir, the ET values at the shores of the reservoir represent wetlands and lowland vegetation. The raster grids were then used to calculate areal evapotranspiration for the study area.

Snow data: We based our estimate of snowmelt and rain on Snow Data Assimilation System (SNODAS) data (National Operational Hydrologic Remote Sensing Center, 2004). These data were created using a combination of remotely sensed snow cover gridded with ground control stations that include Snowpack Telemetry (SNOTEL) stations. SNODAS data are provided in a daily format available from September 2003 to present. We scaled the daily data by the appropriate scaling factors, then summed the daily data into monthly data, and projected the monthly rasters into Abers Conic Equal Area.

Soils data: Soil properties used in the UBM are taken from the U.S. Department of Agriculture State Soil Geographic (STATSGO2) data (Natural Resources Conservation Service, 2016). Soils data from STATSGO2 are provided as polygons separated by the Mapping Unit Identifier, which is the unique identifier to connect each polygon to the associated tables in the STATSGO2 database. We used a weighted average to summarize the soil properties for a given Mapping Unit Identifier and then output values for soil thickness (depth to bedrock restrictive layer in meters), bulk density (in g/cm^3), field capacity (in percent), and wilting point (in percent). From the STATSGO2 output we derived values in meters of water for total soil water, wilting point, and field capacity. Total soil water is calculated as the soil thickness multiplied by porosity. Porosity (percent) is calculated as:

$$100 \times \frac{1-\rho_b}{\rho_p} \tag{8}$$

where:
ρ_b = bulk density (g/cm^3)
ρ_p = particle density (2.65 g/cm^3)

Where valley fill was predominant, we used a modified soil thickness of 6 meters, following the conceptualization of Flint and Flint (2007), to accommodate for the additional thickness of the unconsolidated material. We converted values of field capacity and wilting point from percentages to meters of water by multiplying total soil water by field capacity and wilting point. The total soil water, field capacity, and wilting point grids were then rasterized to match the grid dimension of the inputs for precipitation, snowmelt, and potential evapotranspiration.

Geologic properties data: Geologic permeability is required for the UBM calculation of runoff and recharge. We based the geologic unit in a given area on the digital geologic map of Utah (Hintze and others, 2000). For each geologic unit a value of permeability in meters per month was assigned following the assumed unit permeabilities presented in Heilweil and Brooks (2011, table A3-1). The geologic permeabilities were then rasterized to match the grid dimension of the inputs for precipitation, snowmelt, and potential evapotranspiration.

Soil-water balance: The UBM is a decision tree-based soil-water balance model that uses a series of nested if-then statements to determine how water is apportioned through the soil system, and calculates the amount of recharge or runoff that may occur in a given month. The UBM integrates spatial data from ArcMap with programming written in Python (van Rossum, 2017), and follows the logic and soil water budget accounting used by the BCM as presented by Flint and others (2004), Flint and Flint (2007), Heilweil and Brooks (2011), and Thorne and others (2012). Monthly precipitation as rain and snowmelt and potential evapotranspiration are the variable inputs to the model. Static input to the model includes soil property grids of total soil water, field capacity, wilting point, and geologic permeability. The monthly precipitation, snowmelt, and evapotranspiration grids' inputs are summed with the estimate of existing soil moisture from the previous month's calculation to yield a monthly available soil-water volume. For the first model iteration, soil water was set to field capacity. For each subsequent iteration, water is routed to runoff, recharge, or actual evapotranspiration via four nested if-then statements (figure 62) based on the amount of available soil water calculated for a given month.

If total available water, for a given month, is greater than total soil water, water is directed to groundwater recharge as limited by vertical hydraulic conductivity between the soil and the aquifer. Water beyond the limit of infiltration to the aquifer is directed to runoff, the next month's soil moisture, and actual evapotranspiration. When the soil moisture is greater than wilting point, actual evapotranspiration is equivalent to potential evapotranspiration.

If the available water, for a given month, is greater than field capacity and less than total soil water, but it is limited by hydraulic conductivity from entering the aquifer, it becomes runoff. Recharge is the amount of available water greater than the field capacity up to the limit of hydraulic conductivity.

If the available water, for a given month, is between field capacity and wilting point, it becomes actual evapotranspiration up to the value of potential evapotranspiration. Available water greater than potential evapotranspiration is retained as the following month's soil moisture. Potential evapotranspiration may become actual evapotranspiration for available water values up to the wilting point.

If available water, for a given month, is less than wilting point, no water is available for actual evapotranspiration, runoff, or recharge, and all available water is carried forward to the next month's soil moisture.

We applied the model to data from January 2004 to December 2014. The resulting rasters were averaged to determine the monthly and yearly average soil water, actual evapotranspiration, runoff, and recharge.

SWAT Model

We used a soil-water balance model, Soil and Water Assessment Tool (SWAT) (Arnold and others, 2012) (figure 63), to understand how hydrologic and hydrogeologic aspects of the Ogden Valley system relate to each other. We used this model as a check on other methods of budget calculation. Because of its compatibility and ease of application, we implemented ArcSWAT 2012.10.19, an ArcMap extension (Dile and others,

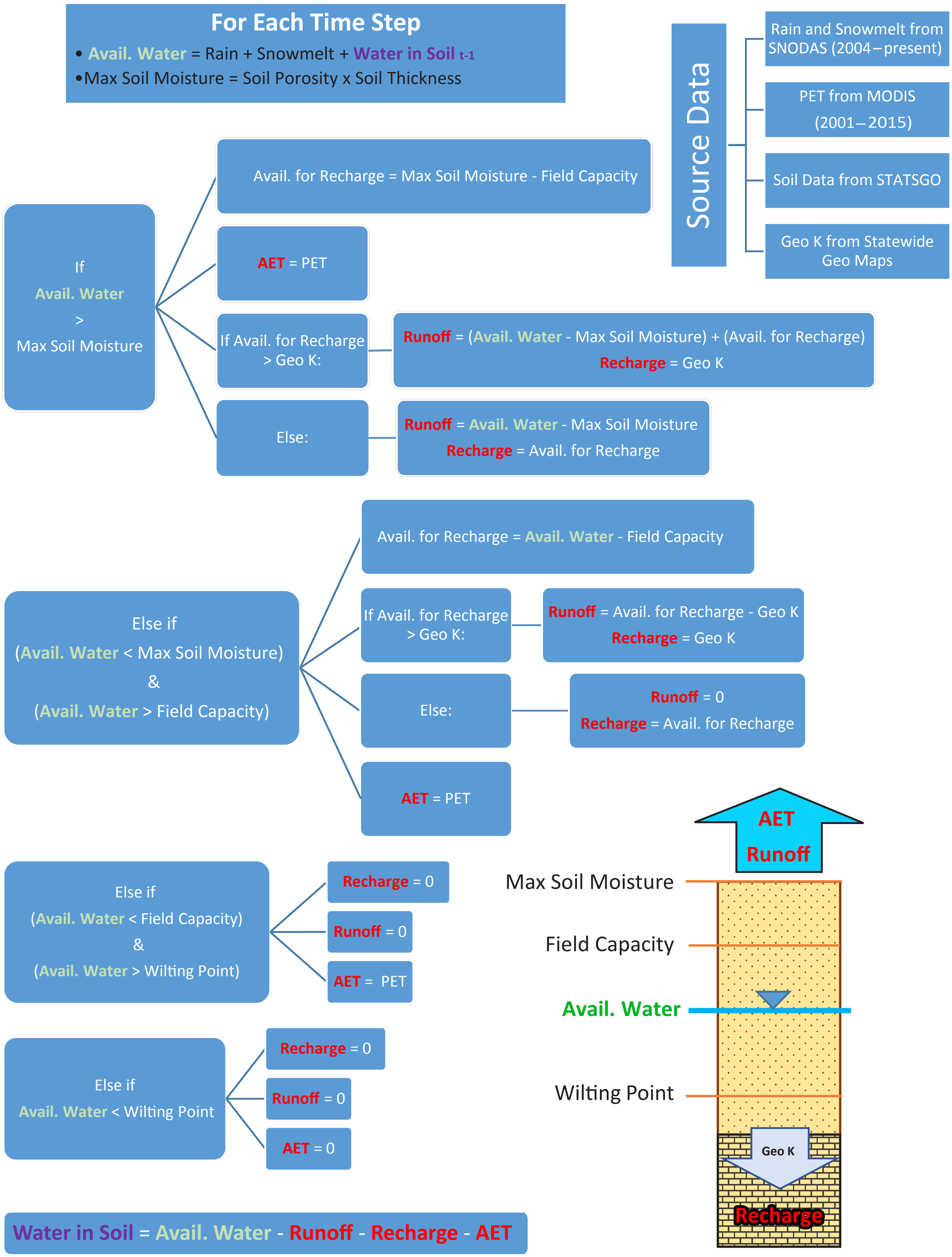
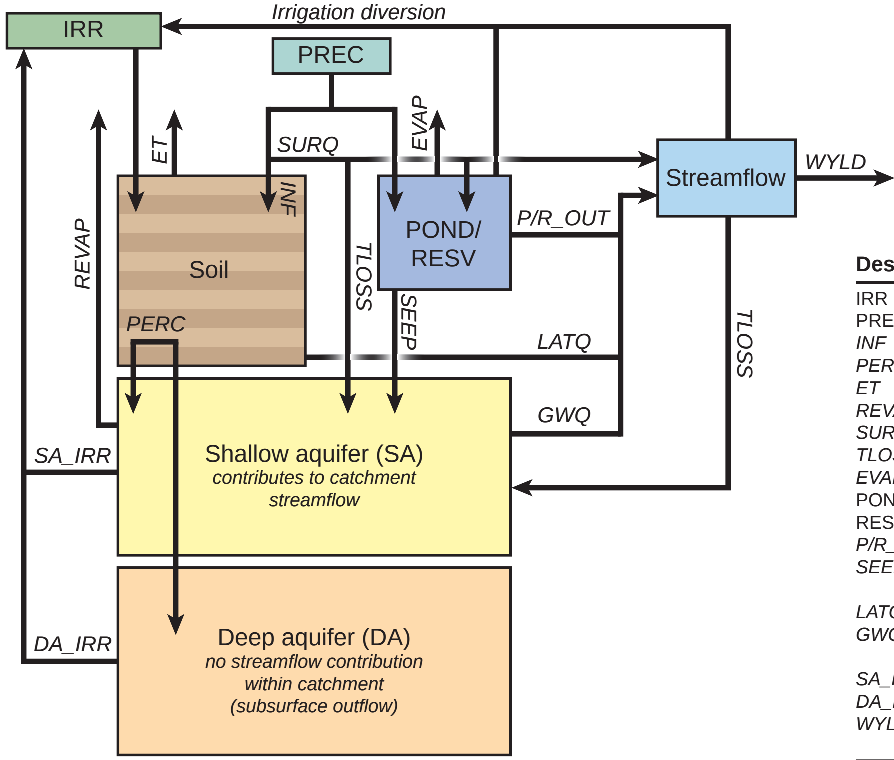


Figure 62. *Utah Basin Model (UBM) conceptual flow chart. AET = actual evapotranspiration, PET = potential evapotranspiration, Geo K = geologic hydraulic conductivity.*



Description of exchanges and reservoirs

IRR	= Irrigation
PREC	= Precipitation (includes rain and snowmelt)
INF	= Infiltration to soil
PERC	= Percolation to shallow and deep aquifers
ET	= Evapotranspiration from soil
REVAP	= Evapotranspiration from shallow aquifer
SURQ	= Surface runoff
TLOSS	= Transmission losses to shallow aquifer
EVAP	= Evaporation from ponds and reservoirs
POND	= Off-stream surface water impoundment
RESV	= In-stream surface water impoundment
P/R_OUT	= Outflow from ponds and reservoirs
SEEP	= Seepage from ponds and reservoirs into shallow aquifer
LATQ	= Lateral flow in soil contributing to streamflow
GWQ	= Lateral flow in shallow aquifer contributing to streamflow
SA_IRR	= Irrigation water taken from shallow aquifer
DA_IRR	= Irrigation water taken from deep aquifer
WYLD	= Water yield (*WYLD = SURQ + LATQ + GWQ – TLOSS – other losses)*

Figure 63. *Soil and Water Assessment Tool (SWAT) model output conceptual flow chart.*

2016). The SWAT model requires a digital elevation model or delineated watershed, weather station data, soil properties from SSURGO or STATSGO, and land use data. Other input data, such as water chemistry data, are optional for this model and were not used for this study.

We used high-resolution SSURGO soils data and land use data from the 2011 National Land Cover Database (NLCD) (Homer and others, 2015). SSURGO data is provided by the same agency as STASTGO, but has higher spatial resolution and, conversely, sparser coverage than STATSGO data (Natural Resources Conservation Service, 2016). Because of the continuity of the precipitation and temperature data, and the complete spatial coverage, we used time series PRISM data to generate weather data (PRISM Climate Group, 2017a).

The model requires user input to segregate the modeled area into hydrologic response units (HRU). For our model runs, generated HRUs had minimum areas of 10 hectares (24.7 acres). Each HRU designation was based on a unique combination of soil type, slope, and land use within each sub-basin (Neitsch and others, 2011). We used three slope grades, 0–10%, 10–30%, and >30%, to delineate slope zones. We defined five different elevation bands, which allows the model to accurately model the distribution of snow.

SWAT also allows for the input of other parameters to account for factors that may influence the water budget. The model includes a water exported parameter, to which we designated the monthly volumes of water extracted by the Ogden City well field. We also entered daily reservoir volume and release for Causey and Pineview Reservoirs (U.S. Bureau of Reclamation, 2017).

The model timeframe is from 2000 to 2017, with a five-year warm-up period and daily timesteps. The warm-up period allows the model to stabilize prior to providing saved output information.

We used SWAT-CUP to attempt to calibrate the model. We included 12 parameters and calibrated to the U.S. Bureau of Reclamation reported reservoir volume in Pineview and Causey Reservoirs and discharge on the Ogden River below Pineview Reservoir. We conducted 100 iterations of the model and chose the parameters from the model run having the highest R^2 value using the measured data. We input the best-fit parameters back into the ArcSWAT interface and reran the model to generate spatial data from the calibrated model.

Remotely Sensed Data

We compiled remotely sensed PRISM precipitation data and MODIS16 evapotranspiration estimates to check the inputs and outputs of the hydrologic models. PRISM data are elevation-corrected interpolations of weather station and radar data (PRISM Climate Group, 2017b). Monthly PRISM data are provided as continuous raster grids, having a cell size of 4 kilometers square. PRISM 30-year averages are available at 800-meter-square resolution. The 4-kilometer cells of the monthly PRISM data did not fall evenly into the individual watershed units (HUCs), which caused error in our estimate of precipitation in each HUC. To increase accuracy of HUC precipitation estimates, we split the 4-kilometer cells across HUC boundaries and down-sampled the PRISM data to 250-meter-square cells, using a cubic convolution technique in ArcMap. Validation studies (Bishop and Beier, 2013; Daly and others, 2017) indicate that PRISM data are highly accurate, even at 4-kilometer grid resolution, showing errors of 2% for annual basin averages.

MODIS16 data are provided as monthly averages of evapotranspiration from 2004 and 2014 and eight-day evapotranspiration from 2002 to present. The MODIS16 data are validated with sparse evapotranspiration tower measurements. The reported uncertainty for MODIS16 evapotranspiration estimates is 10% to 30%, with the mean absolute bias of 24%. We used the monthly data when available and aggregated the eight-day MODIS16 data to monthly data for 2015 and 2016.

Streamflow

We estimated streamflow of the major tributaries to Pineview Reservoir (North Fork Ogden River, Middle Fork Ogden River, Spring Creek, North Branch South Fork Ogden River, and South Branch South Fork Ogden River) by monitoring the water level in the stream channel at 15-minute intervals at locations proximal to the reservoir and using our periodic discharge measurements to create a stage-discharge relationship for each location. We deployed pressure transducers in each stream channel where it passes under the highway around Pineview Reservoir and at an 8-foot Parshall flume on Spring Creek beginning in August 2015 or March 2016 depending on the site and removed them in March 2017.

We processed the stream transducer data to estimate the hourly discharge of the major tributaries. We used Solinst Levelogger Edge non-vented pressure transducers that gauge absolute (water + air) pressure. Atmospheric pressure must be subtracted from non-vented transducer readings to correctly measure the pressure exerted by a column of water above the transducer. We downloaded hourly barometric pressure data from MesoWest stations C8844 (Huntsville) and E8702 (Eden). We used two stations because each station had gaps in the hourly record. Using linear regression, we combined the time series of the two data sets, filling gaps in the Huntsville dataset with the regression-adjusted Eden dataset. Air pressure varies with elevation and the Huntsville climate station is at a different elevation from each of the stream stations. To adjust for this constant offset in pressure, we performed windowed linear regression between each stream transducer dataset to the gap-filled Huntsville dataset. In the regression, three-day segments of data were examined in each window over the entire duration. We retained the regression results where slope was greater than 0.9, which represented a near one-to-one relationship between the barometer and the transducer, and then averaged the y-intercepts of those data, which represent the elevation offset between the barometer and the stream stations. We subtracted the elevation offset and the barometric pressure from each stream dataset.

After removing barometric pressure, the adjusted measurements indicate water pressure above the transducer. However, without absolute manual measurements of the stream stage, these data only represent the "relative stage" of the stream (relative changes of the water level in the stream). The relative stage measurements in the transducers have obvious jumps or "tares" when the transducers were periodically moved to download data or when high stream flow moved the weighted casing housing the transducer. The obvious jumps were visible in the data as sudden offsets of more than 0.25 feet between hourly measurements. We manually adjusted and removed these offsets in the data, aligning the data where the obvious jumps occurred.

For each tributary, we matched the manual discharge measurement to the closest in time relative stage measurement. We plotted the manual discharge values against the relative stage measurements in a scatter plot and fit a power function to the points. The power function is in the form of (Braca, 2008):

$$Q = C(x + A)^B \tag{9}$$

where:
Q = stream discharge
A, B, C = fitting coefficients
x = absolute stage of the stream

This equation assumes steady, uniform flow in a rectangular channel and does not accommodate for hysteresis. However, we chose this equation because of limited manual data and the ease of its application. Once we fit the power equation to data from each tributary, we applied the equation to the relative stage data to produce estimates of stream discharge.

We processed the resulting discharge data to estimate baseflow (groundwater contribution) to the streamflow. For baseflow separation estimates, we applied a recursive digital filter following the techniques applied by Eckhardt (2005), using an alpha value of 0.98 and a base flow index of 0.7. See Eckhardt (2005) and Inkenbrandt (2017) for details regarding this technique.

Well and Spring Water Usage

We tabulated annual water use data from 2003 to 2016 using data supplied voluntarily by public water suppliers through the Utah Water Use Program (Utah Division of Water Rights, 2018). The Utah Division of Water Resources conducts detailed studies every four years on municipal and industrial water use by community water systems that detail the type of use (potable, secondary, indoor, outdoor, and others) (Utah

Division of Water Resources, 2003, 2009, 2010, 2014). The municipal and industrial use studies provide a framework in which to interpret and verify the annual Water Use Program data for the years 2003, 2005, and 2010. Some systems did not report water use some years. In these cases, we applied the average of the years before and after the missing years. In several instances, we contacted the public or private water suppliers directly to gather additional data.

For suppliers who did not report data to the Utah Water Use Program, we estimated usage from domestic wells and springs and other small water systems by analysis of the Water Rights points of diversion as of July 7, 2015. From this data, we selected valid water rights on underground and spring sources that were not represented in the Water Use Program data. We assumed the larger of these small systems, defined by us as having a water right greater than 12 acre-ft/yr, were using two-thirds the value of the water right and the smaller systems were using their full right. The total value from 2015 was scaled to population growth for other years. Valid water rights on wells that were abandoned before Pineview Reservoir filled were excluded.

Seepage Runs

Seepage runs are one way to quantify the amount of streamflow that is being lost to or gained from the groundwater system. However, a seepage run is designed to understand the nature of the watercourse at one point in time. We used the results of our spring and fall seepage runs on the stream system and our July canal seepage run to estimate the volume of water gained or lost throughout the year.

We extrapolated the volume gained by or lost from the stream or canal segments to all of 2016. We analyzed the hydrograph of the daily average flow for 2000–2014 recorded at the USGS gauging station on the South Fork Ogden River (station 10137500) to determine when runoff and baseflow dominate the system. The spring seepage measurements are assumed to represent runoff conditions and the fall measurements are assumed to represent baseflow. These results are applied for runoff and baseflow periods defined by long-term hydrographs. The inflection points on the 14-year-average graph indicate runoff dominates the hydrograph for the South Fork Ogden River on average from March 1 to July 1. We applied the gain or loss in cfs determined for each stream segment in the March seepage run to 122 days of the year (March 1 to June 30) and the gain or loss in the November seepage run to the remaining 243 days of the year. For the canal, we multiplied percentage of loss determined for the canal on the day we conducted the seepage run to the volume of water diverted through the canal in 2016 (Panter, 2015). An alternate method to calculate seepage is to scale the point-in-time values from our seepage runs to the flow we estimated using our stage-discharge relationships in each stream branch or the reported daily flow in the canal. We did not use this method because the gain or loss is controlled more by the hydraulic conductivity of the stream or canal bed than the volume of flow in the channel.

Infiltration of Unconsumed Irrigation

The maximum amount of seepage from agricultural and residential irrigation is assumed to be the difference between net delive red irrigation water and calculated irrigation requirements. Most water is delivered via canal, and the maximum amount of seepage can be calculated as follows:

$$I = D_g - (T_s + T_e + D_u + C) \tag{10}$$

where:

I =	volume infiltrated
D_g =	gross volume diverted
T_s =	seepage during transmission
T_e =	evaporation during transmission
D_u =	unused diverted water that returns to Pineview Reservoir
C =	consumed irrigation water

Water delivered for irrigation includes water distributed by agricultural irrigation companies (e.g., Wolf Creek Irrigation Company) and culinary water suppliers that provide secondary use water (e.g., Huntsville Town Water System). Agricultural irrigation is primarily from stream diversions, which then enter canals and pipelines. Due to transmission losses and unused diversions, the amount of water applied to fields can be significantly less than the amount diverted. Based on the estimates of Avery (1994), 10% is unused. Evaporation during transmission is insignificant and was calculated to be less than 0.5%. We measured seepage losses in the Ogden Valley Canal as stated above and estimated seepage in other canals. We estimated consumption of applied irrigation using water-related land use data (Utah Division of Water Resources, 2015) and irrigation consumption estimates for Ogden Valley (Utah Division of Water Rights, 1994), which we modified for monthly deviations in temperature and precipitation (Panter, 2016).

We calculated water use efficiencies for urban areas but deemed them unreliable because multiple sources (e.g., delivered secondary use water, delivered potable water, and personal well water) are used to irrigate. We assumed the amount of groundwater recharge resulting from urban irrigation to be small relative to agricultural irrigation recharge. Furthermore, a recent study found that secondary-use water is often underreported in Utah (Bowen Collins & Associates and Hansen Allen & Luce Inc., 2018).

Septic-Tank Drain-Field Seepage

We estimated the volume of groundwater recharge from septic-tank drain-field leachate by multiplying the population using septic tanks by per capita indoor water use. Ogden Valley has high seasonal population variability because people use second homes, cabins, and resort lodging on a part-time basis. To account for seasonal use, we used the number of developed parcels derived from GIS data provided by Weber-Morgan Health Department (2017) and assumptions of household occupancy to estimate a range recharge volume.

Water Budget Results

The main components of the water budget for the groundwater system in the Ogden Valley drainage basin for water years 2004 through 2016 are summarized in table 9. In estimating recharge to the system, we assumed that the surface-water drainage boundary is a groundwater divide, which precludes groundwater inflow from adjacent hydrologic basins. Therefore, the only primary input to the system is precipitation. Water can leave the system by four means: evapotranspiration, discharge from Pineview Reservoir, groundwater extraction through the Ogden City well field, and potentially, groundwater discharge beneath Pineview Dam through alluvium in Ogden Canyon or shallow bedrock flow near Ogden Canyon.

SWAT and UBM Model Calibration and Limitations

To better understand the interplay between water budget components, we applied two different hydrologic models to the watershed, SWAT and UBM. The SWAT model is more complex than the UBM and requires significantly more input. For this study, the UBM was not calibrated but provided average discharge values comparable to the measured discharge from Pineview Reservoir.

The SWAT model was calibrated to the South Fork Ogden River near the Huntsville USGS gauging station and the total discharge from Pineview Reservoir. Calibration was achieved by allowing variation in seepage from Pineview and Causey Reservoirs. A relatively good calibration was achieved, but the modeled discharge is less attenuated than observed discharge—discharge increases more sharply after precipitation or melt events relative to observed data. The SWAT model also retained too much water in the system, which can be explained by an erroneously high precipitation estimate, erroneously low evapotranspiration estimate, a pathway for water leaving the system that the model does not account for, or a combination of these factors. The spatial distribution of precipitation, soil water, evaporation, and the routing of water through the soil and shallow groundwater appear to adhere to our conceptual model of the hydrologic system. However, values presented should be regarded with large margins of error.

Precipitation

We relied on PRISM data for estimates of precipitation entering the Ogden Valley watershed. Based on the SNODAS data, snow makes up 60% of the precipitation that falls in the Ogden Valley watershed. Differences between SNODAS and PRISM water volume estimates are likely due to differences in raster resolution and how the snow-water-equivalence (SWE) is determined for each dataset. PRISM reported higher estimates of precipitation than the SNODAS data, but we prefer to use the PRISM data because it is derived using elevation-corrected interpolations from radar and weather station data. Annual precipitation for the water years 2004 to 2016 ranged from 394,000 to 800,000 acre-feet (table 9).

Discharge

Evapotranspiration: We chose scaled MODIS data to represent evapotranspiration (ET) in the Ogden Valley watershed. SWAT modeling indicated that evapotranspiration was too low relative to precipitation to produce the discharge observed at Pineview Reservoir. We increased the MODIS ET by 19% to balance the average inputs and outputs of the system. The adjusted ET was similar to the average estimated by the UBM through 2014. UBM data did not extend to 2016. MODIS data were deemed most appropriate because the estimates were more direct than those provided by the SWAT and UBM approaches.

The annual ET from water year 2004 to 2016 varied from 340,000 to 410,000 acre-feet, which is less variation than observed in the incoming precipitation (table 9). ET is positively correlated with precipitation. ET accounts for 70% of the water leaving the watershed (figure 64). Most ET occurs from heavily forested mountainous areas and agricultural areas on the valley floor. The foothills along the eastern margin of the valley have relatively low ET rates due to steep slopes that are conducive to runoff and coarse-grained soils that promote infiltration.

Average annual ET from Pineview Reservoir, interpolated based on MODIS values surrounding the reservoir, was about 2800 acre-ft per year. When compared to our 2016 estimate of 6710 acre-feet as described in the PINEVIEW RESERVOIR VOLUMETRIC AND ISOTOPIC MASS BALANCE section, this is an underestimate of ET from the open water of the reservoir. The difference relative to the total basin ET is insignificant.

Surface water discharge: The only surface water discharge from the study area is water exiting Pineview Reservoir, which includes water released through the Pineview Dam as surface flow to the Ogden River, water taken through a pipe to the Ogden City water treatment plant, water sent down Ogden Canyon through Pineview Water Systems' pipeline, and reservoir spillage. Pineview Reservoir discharge for water years 2004 to 2016 ranged from 71,100 acre-feet in 2004 to 357,200 acre-feet in 2011 (table 9). Monthly discharge is tabulated in table E-1 in appendix E.

Ogden City well field discharge: Water pumped from the six closely-spaced wells comprising the Ogden City well field on the peninsula between the North Fork and Middle Fork arms of Pineview Reservoir is removed from Ogden Valley's hydrologic system. The well field provides culinary water to a

Table 9. Basin-wide water budget for the Ogden Valley drainage basin, water years 2004 to 2016, in acre-feet.

Budget component	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Range	Average
					INPUT									acre-ft/yr	acre-ft/yr
Precipitation	511,000	679,000	668,000	430,000	502,000	602,000	451,000	800,000	399,000	394,000	562,000	447,000	537,000	394,000–800,000	537,000
					OUTPUT										
Evapotranspiration	365,000	388,000	380,000	341,000	348,000	393,000	379,000	410,000	349,000	358,000	376,000	366,000	386,000	341,000–410,000	372,000
Pineview Reservoir discharge	71,080	234,200	260,370	115,500	129,540	170,540	107,970	357,250	142,210	74,380	88,280	79,740	124,740	71,080–357,250	150,000
Ogden City well field	9140	10,760	10,990	11,610	11,320	10,880	11,850	12,240	12,190	10,940	11,900	11,610	11,150	9140–12,240	11,300
Groundwater discharge out	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400
Total discharge	**445,620**	**633,360**	**651,760**	**468,510**	**489,260**	**574,820**	**499,220**	**779,890**	**503,800**	**443,720**	**476,580**	**457,750**	**522,290**	**443,720–779,890**	**534,000**
					CHANGE IN STORAGE										
Pineview Reservoir	36,330	7540	(5960)	(25,560)	15,880	18,560	(8930)	27,290	(44,700)	(12,120)	22,160	(4970)	11,320	-44,700–+36,330	3000
Soil and ground-water	28,900	38,200	22,700	(13,000)	(3100)	8800	(39,000)	(7000)	(60,400)	(38,300)	63,500	(4900)	3600	-60,400–+63,500	0
Total change in storage	**65,230**	**45,740**	**16,740**	**-38,560**	**12,780**	**27,360**	**-47,930**	**20,290**	**-105,100**	**-50,420**	**85,660**	**-9870**	**14,920**	**-105,100–85,660**	**3000**

Values may not sum due to rounding

Pineview Reservoir discharge includes all surface water discharge from the reservoir (i.e., Pineview Water Systems' pipeline, Ogden City treatment plant, discharge to Ogden River, and reservoir spillage)

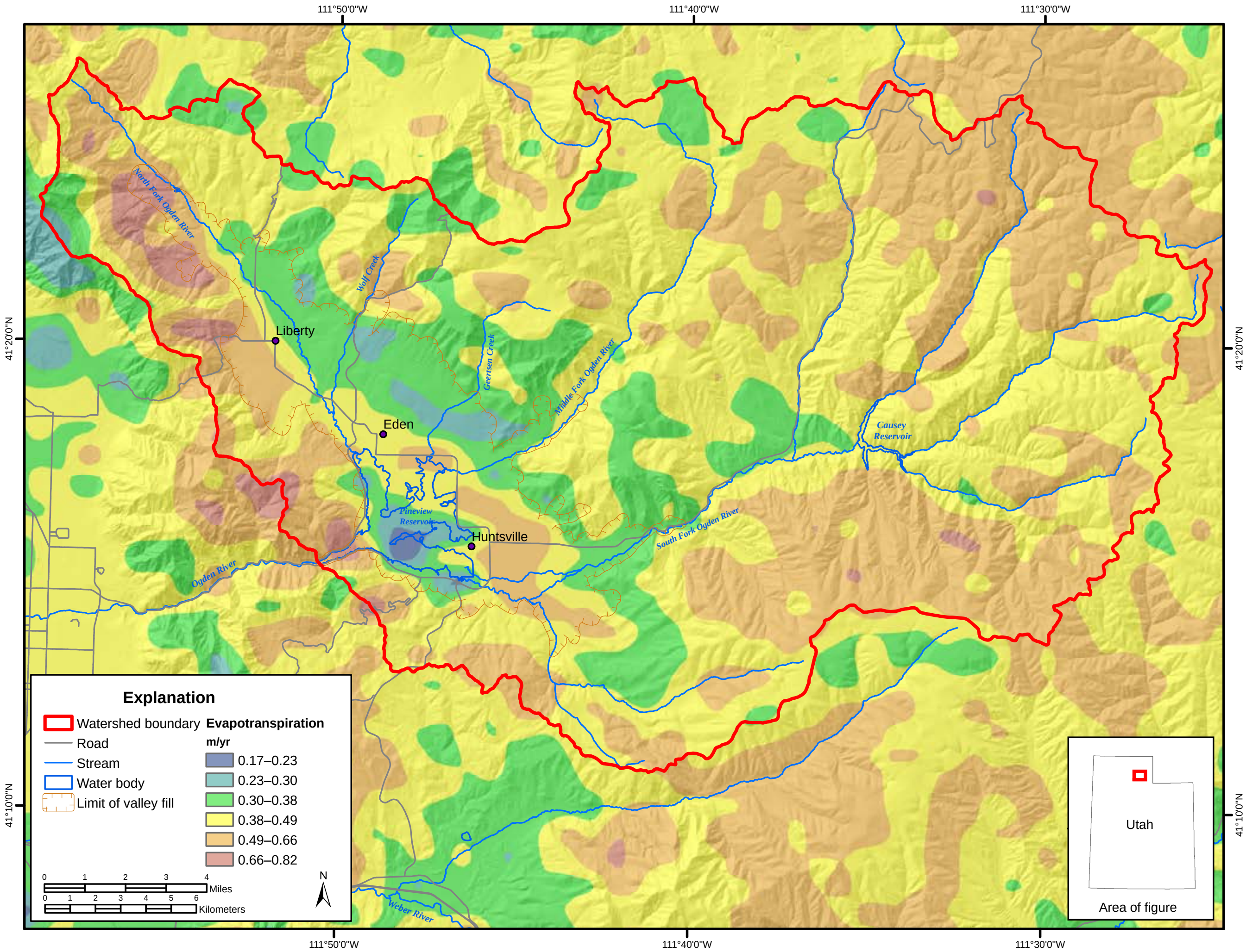


Figure 64. *Distribution of relative evapotranspiration (ET) from averaged MODIS data.*

water treatment plant below Pineview Dam before the water is delivered to users in Ogden City. Under normal operation, the well field pumps continually throughout the year and about 20% higher during summer months. Since 2003, the well field has pumped an average of 11,300 acre-feet per water year (table 9), which is similar to historical production. Between 1931 and 2016, annual well production ranged from 7890 to 18,150 acre-feet and averaged 12,165 acre-feet (data from table 9 of Doyuran, 1972; Utah Division of Water Rights, 2018), with a period from about 1942 to 1968 having annual total withdrawal on the higher end of that range (15,300 acre-ft).

Groundwater discharge through Ogden Canyon: The isotope mass balance of Pineview Reservoir suggests that water could be flowing out of the reservoir to groundwater. The likely flow paths include downward leakage through the confining unit and into the confined aquifer, or under the dam and down Ogden Canyon. Groundwater samples from the confined aquifer (Ogden City well field) do not clearly contain water with an evaporative stable isotope signature that matches the water in Pineview Reservoir, but there exists a strong downward vertical gradient from the reservoir to the confined aquifer (see the Gradients between Aquifers and Pineview Reservoir section), and this pathway cannot be excluded. A Darcy flow calculation for seepage from the reservoir under the dam (discussed in the Seepage from Pineview Reservoir under Pineview Dam section) was 300 to 700 acre-ft/yr.

Previous studies have not conclusively identified or negated the presence of groundwater flowing beneath the dam (Doyuran, 1972; U.S. Bureau of Reclamation, 2008), although Shaffner and others (1993) documented that the 80+ feet (20+ m) of sediments below the varved clay and silt were part of the confined aquifer. Ogden River in Ogden Canyon has generally gaining conditions, and Leggett and Taylor (1937) thought discharge to the river was from the confined aquifer. We estimated groundwater flow through the sediments *below* the varved clay and silt using the same approach we used to estimate seepage from the reservoir through the sediments *above* the varved clay and silt (i.e., a Darcy calculation). Using similar assumptions (sheet piles are ineffective, same hydraulic conductivity, same gradient due to lack of better data, and a cross sectional area of 13,800 square feet (1300 m^2) (from figure 14b), we estimate groundwater discharge from the confined aquifer through the Ogden Canyon alluvium may be 400 to 800 acre-ft/yr. Our estimate is smaller than Leggett and Taylor's (1937) estimated maximum discharge from the confined aquifer through Ogden Canyon of 5 cfs (3600 acre-ft/yr). The volume of seepage is small in comparison to the controlled loss from the dam, and the water budget is not greatly affected by the addition or omission of this sink.

We included 400 acre-ft/yr of possible groundwater discharge out of the basin through the cross sectional area of the unconsolidated sediments under the dam in our water budget (table 9).

Change in Storage

We delineate two categories of storage in our water budget: (1) Pineview Reservoir storage, and (2) soil and groundwater storage. The U.S. Bureau of Reclamation (2017) controls and tracks reservoir storage (table 9). We calculated groundwater and soil-water change in storage in our basin-wide water balance as the difference between input and output less the change in reservoir storage. Groundwater and soil-water change in storage estimates vary significantly over time, having a range of ± 60,000 acre-feet per water year or up to about 10% of the total input and output (table 9). A significant portion of each year's change in storage is from Pineview Reservoir, and the change in groundwater storage is generally correlative with the change in reservoir storage. Despite significant fluctuations, the average change in groundwater storage from 2004 to 2016 (table 9) is close to zero. Based on the available hydrograph data (figure 28) and comparison of potentiometric surfaces (figure 24), most areas of the valley have not experienced a change in storage, with the exception of the cone of depression around the Ogden City well field. The Ogden City well field may be extracting water from storage in the central part of the principal aquifer.

The change in storage during 1985 estimated by Avery (1994) is in line with the variability in our study. Water added to storage in 1985, a wet hydrologic year, was 8900 acre-feet in the unconfined part of the principal aquifer, 8.5 acre-feet in the confined part of the principal aquifer, and 4600 acre-feet in the shallow unconfined aquifer (Avery, 1994).

Distribution of Water Budget Components Between Sub-Basins

The geology and geography of Ogden Valley create a potential for significant differences in recharge and discharge components within and between the sub-basins of the watershed. Here, we present a discussion and approximate water budget for each of the main sub-basins in Ogden Valley: the North Fork Ogden River drainage, the Middle Fork Ogden River drainage (in which we combine Middle Fork Ogden River with Geertsen Creek, Dry Hollow Creek, and Spring Creek), and the South Fork Ogden River drainage (table 10). We also break out Pineview Reservoir (PR) as a sub-watershed because the reservoir is a main point of water accounting in this system, as stream gauging data are most available at points where rivers and creeks flow into the reservoir. No distinction is made between the areas underlain by bedrock versus valley fill in this discussion.

Input water distribution between sub-basins: We define the amount of input water for each sub-basin as the difference between precipitation falling on the land surface and ET in that sub-basin. Input water becomes either recharge within the sub-basin or is transmitted out of the sub-basin via runoff.

The North Fork sub-basin has the highest total annual precipitation (including snow) per acre of our three sub-basins. For example, 2016 precipitation in the North Fork was 41 inches, whereas the Middle Fork and South Fork received 39 and 34 inches of precipitation, respectively. Although the South Fork receives the least amount of precipitation per unit area, it makes up 60% of the total area of the watershed so about half of the total volume of precipitation coming into the Ogden Valley watershed in 2016 fell in the South Fork drainage (table 10). The balance of the 2016 precipitation fell on the Middle and North Forks somewhat equally.

The distribution of evapotranspiration is similarly proportional to the surface area of each sub-basin; about 60% of the total basin ET occurs from the South Fork sub-basin. Area-adjusted ET rates are relatively consistent across the watershed, ranging from 1.6 to 2 feet (0.5–0.6m) per year.

Avery (1994) estimated 182.25 cfs (132,070 acre-ft/yr) of recharge to the Ogden Valley valley-fill aquifer in 1985. We estimate about 157,750 acre-feet of input water in 2016 (table 10). Because the South Fork sub-basin is the largest sub-basin by area, and consequently receives the largest amount of precipitation, the amount of input water in the sub-basin is about 25% more than is available in the North or Middle Fork sub-basins.

Streamflow: We measured a total combined streamflow of 112,300 acre-feet flowing into Pineview Reservoir from the three sub-basins in 2016 (table D-9 in appendix D). Due to its relative area, South Fork contributed 50% (56,600 acre-ft) of the total 2016 flow into the reservoir. North and Middle Forks contributed 30% and 20% of streamflow, respectively. In 2016, 125,100 acre-feet of water was removed from Pineview Reservoir as surface flow and diversions.

Overall, the South Fork sub-basin has more than double the amount of streamflow compared to the Middle Fork sub-basin and 40% more than the North Fork sub-basin. The relative drainage area of each sub-basin is the primary reason for these differences.

Based on estimated baseflow derived from the Eckhardt (2005) hydrograph separation method, baseflow makes up about 60% of the water flowing in Ogden Valley streams, except for North Fork and Spring Creek for which baseflow

Table 10. *Water budget by sub-basin, including Pineview Reservoir, calendar year 2016, in acre-feet.*

Budget component	NF	MF	SF	PR	Total
		INPUTS			
Input water (precip-ET)	49,800	45,500	62,500	(50)	157,750
Precipitation	*129,500*	*116,000*	*292,900*	*6650*	*545,050*
Evapotranspiration	*(79,700)*	*(70,500)*	*(230,400)*	*(6700)*	*(387,300)*
Streamflow	0	0	0	112,300	112,300
Groundwater inflow	0	0	0	34,000	34,000
Canal interchange	0	6950	0	–	6950
Total	49,800	52,450	62,500	146,250	311,000
		OUTPUTS			
Streamflow (baseflow + runoff)	32,600	23,100	56,600	125,100	237,400
Baseflow to streams	*22,300*	*14,200*	*33,700*	–	*70,200*
Runoff	*10,300*	*8900*	*22,900*	–	*42,100*
Groundwater flow to reservoir or reservoir flow to groundwater	12,400	14,800	6800	2700	36,700
Ogden City well field	4250	5050	2350	–	11,650
Canal diversion	0	0	6950	–	6950
Total	49,250	42,950	72,700	127,800	292,700
Sub-basin interchange and ground-water change in storage	550	9500	(10,200)	–	(150)
Change in storage	–	–	–	18,500	18,500

Values may not sum due to rounding

NF= North Fork, MF = Middle Fork, Geertsen, and Spring Creek, SF = South Fork, PR = Pineview Reservoir

makes up about 70% of the total flow (table 10). The baseflow estimate includes water contributed by gaining sections of the streams and by discrete springs flowing into the streams. Baseflow contribution to Spring Creek is relatively consistent, likely controlled by the springs at the source of the creek. The relative fractions of baseflow are like those estimated via isotopes (figure 49), where the North Fork has the highest relative fraction of water from bedrock aquifers. Most of the surface flow of Wolf Creek in the North Fork comes from large springs, which could help explain the larger proportion of baseflow observed in the North Fork drainage (Inkenbrandt and others, 2016). Baseflow accounted for 70,200 acre-feet of the 2016 streamflow into the Pineview Reservoir.

Our baseflow estimate using hydrograph separation is higher than estimated by our seepage studies because hydrograph separation takes the entire watershed into account, whereas our seepage studies attempt to quantify the baseflow entering the streams only on the valley floor through gaining sections of the stream.

These estimates of baseflow compare reasonably to values from the upper Colorado River system immediately east of the Ogden Valley watershed (Rumsey and others, 2015), although 70% is on the high side of reported values. Rumsey and others (2015) concluded that there is generally higher baseflow yield in higher elevation watersheds having a large percentage of precipitation as snow.

Water in the streams originates as surface runoff, soil water, and shallow groundwater. The sum of these, minus any losses, is the water yield. Unlike recharge, SWAT does not specify the spatial distribution of discharge. Therefore, this water discharges in topographically low areas where streams generally exist. Geology and hydraulic head do not control the patterns of discharge in the SWAT model. Water yield was spatially summed using the DEM and the Hydrology tools in ArcMap. We calculated and normalized the gain for each reach to the length of each reach. Segments with high gain per distance are indicative of areas having high recharge and lateral flow. The location of these high-gain sections are not limited to areas with the highest water yield, but instead are probably related to segments that have relatively large catchment areas.

Groundwater flow to Pineview Reservoir and Ogden City well field: Our volumetric and isotopic mass balance model of Pineview Reservoir suggests the 2016 groundwater input is 31,000 to 34,000 acre-feet. The lower estimate assumes that groundwater does not seep into the underlying aquifer and the isotopic data were ignored. The upper estimate reflects a larger inflow of groundwater to match the isotopic signature, which resulted in the requirement of groundwater seepage to maintain a volumetric balance. We used a sub-basin water balance to divide the 34,000 acre-feet among three sub-basins. The contribution of groundwater from each sub-basin cannot be estimated using isotopes because the input signals from each fork are similar. We split groundwater contributions using the relative area of valley fill in each sub-basin based on the relative role that in-place valley-floor precipitation recharge and unused irrigation seepage have in the valley-fill water budget. The Middle Fork/Geertsen Creek/ Spring Creek sub-basin accounts for 44% of the valley-fill area and thus 14,800 acre-feet of groundwater discharge to the reservoir. The North and South Forks account for 37% and 20% of the valley-fill area and thus 12,400 acre-feet and 6800 acre-feet of groundwater discharge, respectively (table 10).

We proportioned the amount of water leaving the watershed through extraction by the Ogden City well field in the same manner as we did for groundwater flow to the reservoir (i.e., proportional to valley-fill area).

At first, the distribution of groundwater flow into Pineview Reservoir and the Ogden City well field seems at odds with the proportion of input water between the three sub-basins. Due to its size, the South Fork drainage basin has much more input water and streamflow than the North or Middle Fork sub-basins (table 10). The reason greater input water does not equate to more groundwater flow to the reservoir from the South Fork drainage is because we used the surface water divide to partition groundwater flow. Groundwater from the South Fork makes up part of the south extension of the Middle Fork sub-basin, as discussed below.

Inter-basin interchange and change in storage: Our break-out of water budget components into sub-basins (table 10) is useful for understanding the different influences of geography and geology on the hydrogeologic system. Constraining input and output in each sub-basin to the best of our ability results in surplus or deficit in each sub-basin shown as inter-basin interchange and groundwater change in storage on table 10.

We grouped Spring Creek into the Middle Fork drainage, but most of the water in Spring Creek is sourced from springs discharging from the shallow unconfined aquifer, which receives recharge in part from the South Fork Ogden River and the principal aquifer in the South Fork drainage (Avery, 1994). Part of the deficit in the South Fork and surplus in the Middle Fork is created from this transfer of groundwater from the South Fork groundwater to Middle Fork groundwater and surface water.

Adding to the imbalance between the South Fork and Middle Fork sub-basins is the diversion of 6950 acre-feet of water out of the South Fork Ogden River via the Ogden Valley Canal (Panter, 2016). Most of this water is applied to fields in the Middle Fork/Geertsen/Spring Creek sub-basin, which contributes to additional recharge to the valley-fill aquifer in these areas (table 10).

In-Place Recharge

In the SWAT model, water that percolates into the soil can either become lateral flow through the soil (LATQ) or recharge to the aquifer ("in-place recharge"). Land-surface slope and soil type partially control the division into these two components. LATQ exceeds recharge on steep slopes and through low-permeability soils. LATQ and recharge vary year to year, which is largely an effect of variations in precipitation. Between 2010 and 2016, the highest precipitation, recharge, and LATQ occurred in 2011 and the lowest precipitation, recharge, and LATQ occurred in 2013. Areas the SWAT model predicted had significant in-place recharge in 2016 include the northern margins of the basin in broad elevated areas such as the mountains between the Middle Fork and South Fork sub-basins (figure 65). Recharge is also high on the alluvial deposits between the North and Middle Fork sub-basins. Conversely, LATQ is high on all steeply sloped surfaces, with higher values found in the North and Middle Forks where precipitation is higher. Neither recharge nor LATQ dominate the soil-water balance in the South Fork drainage, which may be due to soil types. Very little water becomes surface runoff. In the SWAT model, 5% of water that recharges the aquifer ("shallow aquifer" in SWAT terms) is transmitted to a groundwater reservoir that does not interact with streams or soils ("the deep aquifer" in SWAT terms). Water in the deep aquifer ultimately leaves the basin as subsurface discharge, though SWAT does not explicitly consider the routing of this water.

Our modeling shows that most in-place recharge occurs beyond the valley fill. The valley accounts for 14% of the area of the Ogden Valley watershed and only 7% of in-place recharge. However, because SWAT is a soil water-balance model and does not explicitly consider the hydraulics of a groundwater flow system, it does not account for lower permeability in areas underlain by bedrock. In-place recharge outside the valley fill becomes baseflow to streams, spring discharge in the mountains, or mountain-block recharge to the valley fill.

Groundwater–Surface-Water Interchange in the Valley-Fill Aquifer

We estimated 2016 calendar year components of input and output from the valley-fill aquifer to conceptualize the interchange of water between groundwater and surface water (table 11) and how a change in one component may influence other components. To constrain the components we used our hydrologic models, seepage runs, and compilation of available data. We report large margins of error on components that have poor constraint.

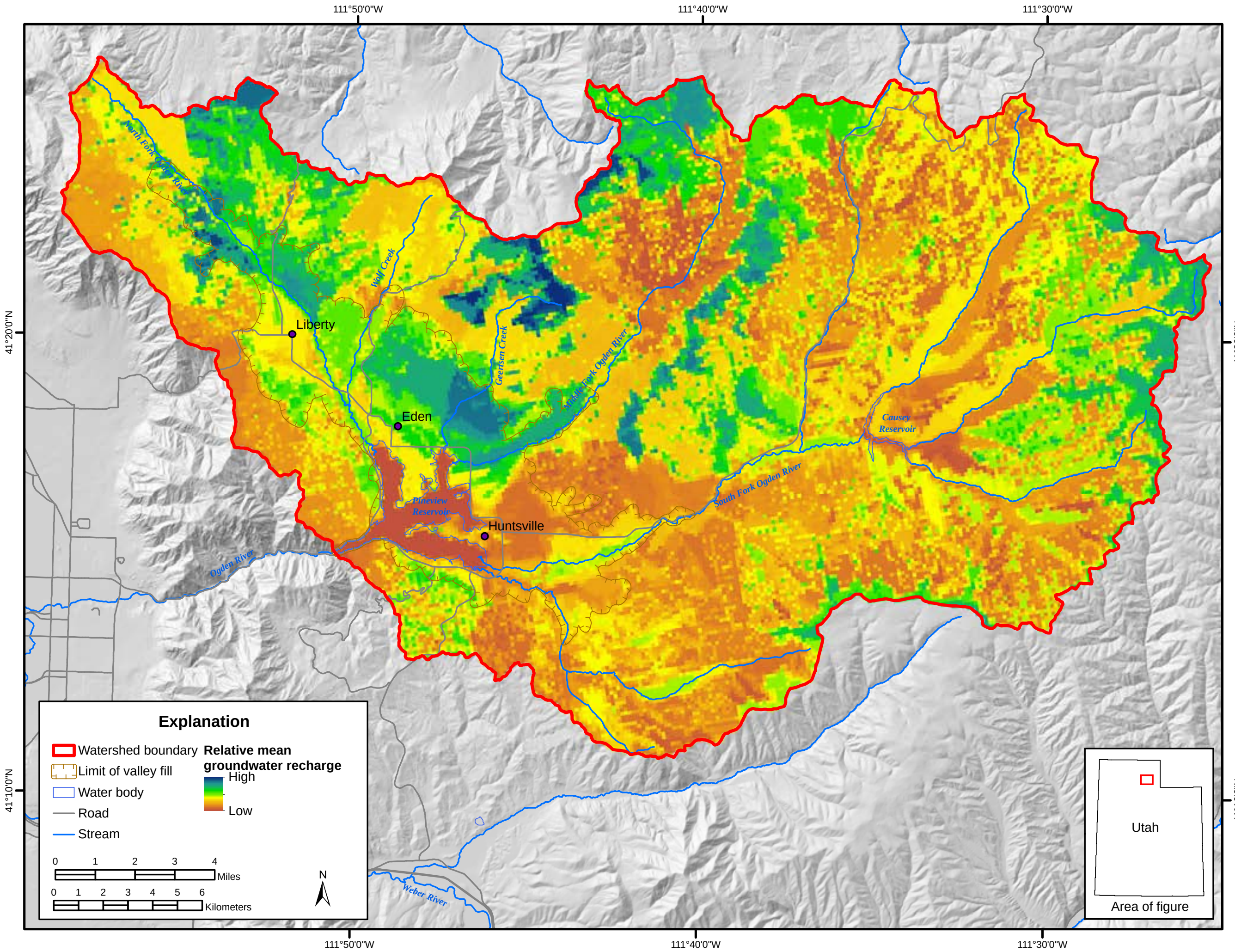


Figure 65. *Relative distribution of recharge generated by the SWAT model for the Ogden Valley watershed.*

Recharge to the Valley-Fill Aquifer

In-place recharge: In-place recharge is the volume of water from precipitation falling on the valley floor that reaches the water table. In-place recharge must be less than the amount of input water (precipitation − evapotranspiration) for the valley fill (40,000 acre-ft/yr) and likely more than the amount estimated by the UBM (4000 acre-ft/yr), which used SNODAS data, which we think is too low, as the input for precipitation. We relied on in-place recharge estimated by the SWAT model because the distribution of in-place recharge more closely matched the distribution of precipitation and soil properties than output from the UBM. We caution that the SWAT model may overestimate in-place recharge because there was insufficient evapotranspiration in the model to produce the volume of water observed exiting the watershed. Based on the SWAT model, 24,000 acre-feet of water infiltrated into the valley-fill aquifer as in-place recharge in 2016 (table 11). Much of the valley-fill aquifer recharge is occurring in the Middle and North Fork areas of the valley, which are underlain by permeable soils and have higher precipitation (figure 65).

Losing streams and canals: The North Fork and South Fork of the Ogden River were losing 12 and 15 cfs, respectively, during baseflow conditions in November 2016 (table 5). Extrapolating those losses to the baseflow period July through February, the North and South Fork Ogden River networks contributed an estimated 5900 and 7200 acre-ft/yr of recharge to the aquifer, respectively (figure 32), for a total of about 13,000 acre-ft/yr (table 11).

The Ogden Valley Canal, which flows for 9 miles (15 km) over mostly coarse alluvial-fan sediments, lost approximately 18 cfs, or 47% of its flow during our July seepage run. We estimate the total loss for the irrigation year by applying the percent loss during our seepage run to the volume of water diverted in 2016 (6936 acre-feet [Panter, 2016]), for a loss of approximately 3290 acre-feet during the 2016 irrigation season (figure 33, tables 5 and 11).

Because seepage was not measured on the other canals or pipelines, and other canals flow over more diverse sediment types and in areas of shallow water table, a more conservative 20% loss was applied to these systems. Water delivered

Table 11. Groundwater–surface-water interchanges for the valley-fill aquifer, calendar year 2016, in acre-feet per year.

Budget component	Total	Constraint
RECHARGE		
In-place recharge	24,000	±16,000
Losing streams	13,000	± 4000
Ogden Valley Canal seepage	3300	± 1000
Other canal seepage	4000	± 1000
Unused irrigation seepage	4700	+ 2700, –300
Septic-tank seepage	350	± 100
Mountain-block recharge	17,760	± 16,000
Probable inputs into groundwater	**67,110**	
DISCHARGE		
Evapotranspiration From GW	2300	± 1000
Baseflow to streams and springs	16,920	± 1000
Ogden City well field	11,650	± 50
Other wells	1890	± 100
Groundwater discharge to Pineview Reservoir	33,950	± 3000
Groundwater outflow through Ogden Canyon alluvium	400	± 1000
Probable outputs to surface water	**67,110**	
Change in storage	0	

Values may not sum due to rounding

for irrigation to all Ogden Valley canals in 2016 totaled about 26,900 acre-feet (Panter, 2016), leaving about 20,000 acre-feet for systems other than the Ogden Valley Canal. At 20% loss, approximately 4000 acre-feet of canal water is expected to recharge the valley-fill aquifer system from other canals (table 11). Therefore, the system-wide canal seepage was approximately 7300 acre-feet in 2016, which equates to an average seepage loss of 27% from all Ogden Valley canals.

Unused irrigation seepage: Water delivered for irrigation totaled 26,900 acre-feet (Panter, 2016). Subtracting 7300 acre-feet lost from the canals as seepage and 12% unused diversion (return to streams or reservoir), we estimate 17,200 acre-feet of water was applied to irrigated land in Ogden Valley.

Irrigated agricultural land, documented in 2015, totals 6342 acres in Ogden Valley, which is 3.2% of the basin (Utah Division of Water Resources, 2015). Based on consumptive use estimates (Utah Division of Water Rights, 1994) and monthly temperature and precipitation departures from normal, an average 23.7 inches of irrigation water was required to meet crop demand on the 6342 acres, totaling 12,520 acre-feet of irrigation water necessary. A volume of 17,200 acre-feet of water applied to 6342 acres equates to watering efficiency of approximately 70% or an average of 2.7 feet of water applied per acre. Seventy percent efficiency in Ogden Valley is good, considering typical watering efficiencies for flood- and sprinkler-irrigated lands are 40% to 80% and 55% to 95%, respectively (Stewart and Howell, 2003). Irrigated lands in Ogden Valley are 29% flood irrigated and 71% sprinkler irrigated (Utah Division of Water Resources, 2015).

We assumed excess applied irrigation water that is not consumed by crops becomes recharge. We estimate that 4700 acre-feet of the 17,200 acre-feet applied to land seeped to the valley fill in 2016 (table 11).

Diversion, consumption, and seepage were estimated for other years having land use estimates and are shown on figure 66. Seepage from urban irrigation is not considered here due to uncertainty in irrigation sources. However, we expect it to be small relative to agricultural irrigation seepage.

Septic-tank drain-field seepage: We provide a range of the volume of groundwater recharge from septic-tank seepage depending on the population using septic tanks. Considering the 2015 estimated population of Ogden Valley (7138 persons) (U.S. Census Bureau, 2017) and average per capita indoor water use (60 gallons [Utah Division of Water Resources, 2010, equation 5, p. 16]), the maximum recharge is 480 acre-ft/yr. This calculation ignores homes serviced by wastewater systems other than septic systems, such as sewage lagoons, and does not account for part-time residents or seasonal use lodging.

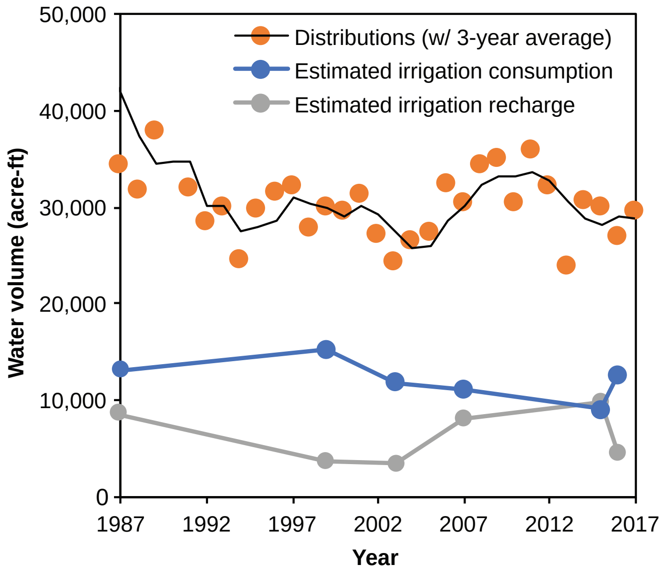


Figure 66. *Irrigation diversions and estimated water consumption and seepage from 1987 to 2016. Sources: distribution volume records from Utah Division of Water Rights (2016) and irrigation consumption calculated from Utah Division of Water Rights (1994).*

More accurate calculations account for the number of dwellings in the watershed serviced by septic tanks (2970) (Weber-Morgan Health Department, 2017) and the average number of people per household (pph). With a census population of 7138 residents in 4110 developed parcels in the watershed, the average pph is 1.7. If 2970 septic tanks are servicing 1.7 pph, 5158 people use septic tanks and contribute 347 acre-feet of septic-system leachate as groundwater recharge per year.

As a method to account for seasonal use we assumed full-time residences are occupied by an average of 3.0 people per household, the typical Weber County average (U.S. Census Bureau, 2017), and that the remaining existing homes are second homes (4110 parcels – [7138 population ÷ 3 pph] = 1731 second homes) occupied at 50% capacity. The addition of 3 pph in 1731 second homes 50% of the time increases the mean effective total population to 9734 people, or 2.4 people per household. This yields 7128 people using septic tanks (2970 tanks x 2.4 pph) and 479 acre-ft/yr of septic system recharge.

As an upper bound on septic-tank recharge we took the number of septic tanks and assumed they were occupied full time by the county average household size. If there are 2970 septic tanks (Weber-Morgan Health Department, 2017) used full time (3.0 pph), there are 8910 people using septic tanks and 599 acre-ft/yr of septic recharge.

GIS analysis of the location of developed parcels not on lagoon wastewater treatment systems (Weber-Morgan Health Department, 2017) shows 2206 septic tanks overlying the valley-fill aquifer. With people per household numbers of 1.7, 2.4 and 3.0 as above, the populations are 3750, 5294, and 6618, respectively. Septic-system recharge volumes to the valley-fill aquifer are 252, 356, and 445 acre-ft/yr, respectively.

In summary, groundwater recharge by septic-system leachate estimates range from 250 to 600 acre-ft/yr, but we estimate recharge is more likely in the 250 to 450 acre-ft/yr range.

Mountain-block recharge: Mountain-block recharge is the least constrained value in our recharge estimates. There is no way to directly measure the volume entering the valley-fill aquifer in the subsurface from bedrock. Darcy flow estimates rely on very sparse hydraulic conductivity estimates. To estimate mountain-block recharge to the valley fill, we attributed as much recharge as was needed to balance the valley-fill water budget in 2016. We used our stable isotope analysis of the relative proportions of surface or in-place recharge versus mountain-block type water found in wells as a gross check on the values. To balance the valley-fill inflow and outflow, 18,000 acre-feet of mountain-block recharge was needed in 2016 (table 11). It may be incorrect to assume the valley-fill aquifer water budget for calendar year 2016 is balanced because our estimate for the change in basin-wide groundwater and soil-water storage for the 2016 water year is 3600 acre-feet (table 9). However, the change in storage is small relative to the overall budget.

Discharge from the Valley-Fill Aquifer

Evapotranspiration from the groundwater system: ET directly from groundwater (as opposed to from the surface or vadose zone) occurs through plants transpiring water they take up from the water table or capillary fringe. Evaporation from bare ground occurs if the water table or capillary fringe is near the surface. This ET primarily occurs in areas of wetland vegetation, including the margins of Pineview Reservoir and riparian areas where the groundwater table is shallow and within the reach of plant roots (figure 64). SWAT estimates that evapotranspiration from shallow groundwater within the valley-fill area, labeled as the variable REVAP in SWAT, is about 2000 acre-ft/yr. The National Wetlands Inventory reports 1146 acres of wetlands in the valley, which includes riverine (223 acres), shrub (183 acres), and emergent (740 acres) wetlands areas (U.S. Fish and Wildlife Service, 2016), yielding an average ET rate of 1.74 feet (0.53 m) per year. For comparison, Doyuran (1972, p. 70) used ET rates ranging from 1.46 to 2.32 feet (0.45–0.71 m) per year for crops, pasture, and lawns in his study of Ogden Valley. Kirby and others (in preparation) have found slightly higher rates in a drier, lower elevation Utah basin of 4.0 feet (1.2 m) per year for emergent, 1.2 feet (0.4 m) per year for shrub, and 3.0 feet (0.9 m) for riparian wetlands. Using these higher rates, our estimate of ET from groundwater would be approximately 3900 acre-ft/yr. Our estimate of 2000 acre-ft/yr of ET from groundwater for wetter, higher Ogden Valley is reasonable, given that Ogden Valley has lower ET rates and more soil and vadose zone water is available.

Studies in the western U.S. have shown that phreatophytes, especially greasewood, can utilize groundwater from water tables as deep as 30 feet (9 m) below surface when precipitation does not meet plant needs (Moreo and others, 2007). Ogden Valley has no significant area of these types of phreatophytes, but it does have approximately 800 acres of subirrigated grass hay and pasture and 1200 acres of dry land or dry farmed where the water table is less than 30 feet deep. The rooting depth of most pasture grasses grown on dry land or under irrigation in Utah is commonly 2 to 3 feet (0.6–1 m) (USDA-ARS-Forage and Range Research Lab, undated). Alfalfa commonly has roots extending 7 to 10 feet (2–3 m) below ground but, depending on soil characteristics and water availability, tap roots may extend to 20 feet (6 m) or more (Weaver, 1926). Ogden Valley has about 400 acres of dry alfalfa growing in areas where the water table is more than 30 feet (9 m) deep, so little ET from groundwater is expected in those areas. Ogden Valley has about 3200 acres of irrigated alfalfa, about 10% to 20% of which is being cultivated on land where the water table is less than 10 feet (3 m) deep. Alfalfa in Ogden Valley uses between 20 and 30 inches (50–80 cm) of water to meet its growing requirement, based on experimental stations at higher elevation Woodruff and similar elevation Santaquin (Hill and others, 2011). Given that crops which may have roots extending to the water table are also under irrigation in Ogden Valley, we assume that the roots have not developed to depths that use groundwater to meet plant needs.

Gaining streams: Ogden Valley's streams were net gaining in March 2016 by about 63 cfs (table 5). Extrapolating this value to the period March 1 to June 30 when the hydrologic system is under runoff conditions, we estimated that the aquifer is yielding roughly 15,400 acre-feet to the surface water system, with the largest contribution in the North Fork drainage (7040 acre-ft) followed by the Middle Fork (5740 acre-ft) and the South Fork (2580 acre-ft). The Middle Fork system continued to gain about 1500 acre-feet throughout the remainder of the year (table 5). Springs feeding Spring Creek are accounted for in the seepage runs. Throughout 2016, Ogden Valley's streams were receiving about 17,000 acre-feet as baseflow from valley-fill aquifers (table 11). Note that baseflow to streams in table 10 is much larger than baseflow to streams in table 11 because the former includes baseflow from the mountain block, which we do not include in our valley-fill water budget.

Well and spring discharge: The largest source of well discharge from the groundwater system in Ogden Valley is the Ogden City well field. Under normal operation, the well field pumps continually throughout the year and about 20% more during summer months. Since 2003, pumping at the well field has averaged 11,300 acre-ft/yr (table E-2 in appendix E).

Other large and moderate producing wells are owned or operated by public and private water suppliers to provide water for towns, unincorporated communities, and resorts for indoor and outdoor use. Reported use for these wells ranged from 400 to 730 acre-feet for the years 2003–2016 (table E-2 in appendix E). Most of the community wells are producing water from bedrock aquifers, but about 160 acre-feet of water was reportedly produced from wells in the valley fill in 2016.

Few irrigation wells are in use in Ogden Valley, but many domestic wells serve individual homes or groups of homes. We estimated discharge from domestic wells and wells not reported to the Water Use Program (Utah Division of Water Rights, 2018) by applying either the full water right for small domestic water rights or a fraction of the water right for larger rights. In 2015, there were over 1100 valid water rights in the watershed. Scaled to population, we estimate domestic and other wells produced 1600 to 2100 acre-ft/yr from 2003 to 2016 (table E-2 in appendix E). Excluding domestic wells outside the valley fill, we estimate about 1730 acre-feet of water was produced from domestic wells in the principal aquifer in 2016. Adding water production data from the wells reported in the Water Use Program, we estimate that wells other than the Ogden City well field produced approximately 1900 acre-feet from the principal aquifer in 2016 (table 11).

Another way to estimate water use is by per capita use. Weber County residents used an estimated 105 gallons of water per person per day in 2010 (Utah Division of Water Resources, 2014). The 2015 population of Ogden Valley was 7138 people (U.S. Census Bureau, 2017); however, we estimate an additional 2726 people may spend part of their time in Ogden Valley based on the number of homes or developed parcels (Weber-Morgan Health Department, 2017). By this method, we estimate residential water use by full-time residents and part-time visitors to Ogden Valley, many of which are on domestic wells, may total 1200 acre-ft/yr.

Ogden Valley has high seasonal population variability because people use second homes, cabins, and resort lodging on a part-time basis. The added seasonal population increases the mean population above the census-derived population. Septic loading analysis was performed assuming two population scenarios.

Numerous large and small springs discharge groundwater in the Ogden Valley watershed. Avery (1994) estimated basin-wide spring discharge to be at least 24,000 acre-ft/yr in the mid-1980s, with over half of the flow coming from Causey Spring near Causey Reservoir. Many springs have been developed for use in Ogden Valley. Spring water used for culinary supply from Water Use Program data (Utah Division of Water Rights, 2018) is between 900 and 3100 acre-ft/yr in Ogden Valley from 2003 to 2016 (table E-2 in appendix E). Although several large springs are located on unconsolidated sediments around the perimeter of the valley, their source is likely bedrock aquifers (Avery, 1994, p. 26). The only significant springs that get their water from valley-fill sediments are the springs that feed Spring Creek, which we account for in our seepage run analysis.

Groundwater discharge to Pineview Reservoir: We estimated groundwater discharge to Pineview Reservoir using a mass balance approach as discussed in the PINEVIEW RESERVOIR VOLUMETRIC AND ISOTOPIC MASS BALANCE section. Discharge to Pineview Reservoir in 2016 from all parts of the valley-fill aquifer system (shallow unconfined aquifer and principal confined aquifer) was between 31,000 and 34,000 acre-feet.

Groundwater outflow exiting the basin: Using a simple Darcy flow calculation, we estimated flow in the alluvium under the dam is between 400 and 700 acre-ft/yr. However, sheet piles under the dam may limit this flow to zero, and our Darcy calculation is not well constrained due to lack of accurate hydraulic conductivity and gradient information.

Comparison to Previous Studies

Budget details from the 1985 USGS groundwater study (Avery, 1994) differ from those calculated for this study (figure 67). Avery (1994) conducted many of the measurements in 1985, one of the wettest years recorded in Utah (Natural Resources Conservation Service, 2017); discharge from Pineview Reservoir was nearly twice that reported for 2016 (U.S. Bureau of Reclamation, 2017). Avery's (1994) budget focused on the valley-fill groundwater budget, and he briefly considered precipitation and evapotranspiration in the South Fork sub-basin. Our our table 11 is most analogous to what Avery (1994, table 10) reported, although the time intervals and units are different.

Avery (1994) had good estimates of well withdrawal; however, he did not have model-based estimates of groundwater recharge, precipitation, or evapotranspiration. While he reported historical stream gage data from the USGS and conducted limited seepage runs and made discrete discharge measurements, he was not able to estimate streamflow accurately with his limited number of discharge measurements. We now have more sophisticated methods of estimating precipitation and recharge. We also conducted seepage studies during baseflow, early spring runoff, and during the height of the irrigation season, and we related monthly streamflow measurements to 15-minute river stage measurements to more accurately estimate streamflow.

Both studies attribute a substantial portion of recharge to the valley-fill aquifer system to mountain-block recharge—38% "subsurface inflow" in Avery (1994) and 26% mountain-block recharge in our study. Mountain-block recharge in both studies is very poorly constrained due to limited knowledge of the hydraulic gradient and transmissive properties of the bedrock adjacent to the valley-fill aquifer.

Recharge components of the water budgets differ significantly in the proportion of recharge attributed to losing streams. Avery (1994) attributed one-third of valley-fill groundwater recharge to losing streams, whereas we estimate about 19%. Avery (1994) did not explicitly define how he calculated stream loss, and 1985 was a year of very high streamflow, so his estimate may be higher than ours because of different methods and a wetter than average year.

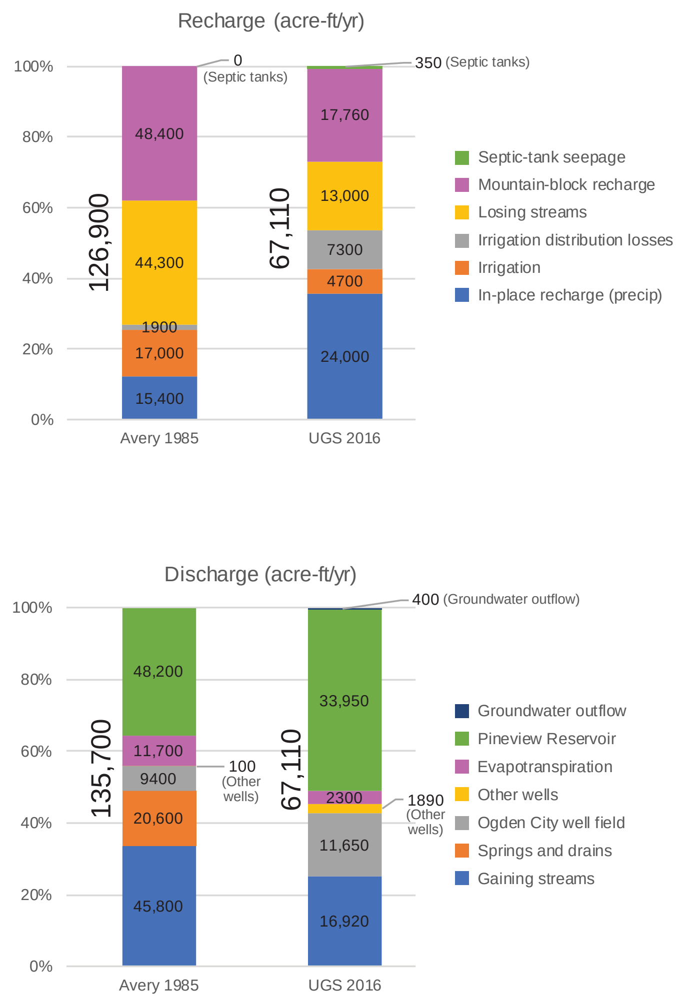


Figure 67. *Comparison of Avery's (1994) water budget to the budget derived from this study (table 11).*

Another significant difference in recharge components is the proportion attributed to precipitation infiltration, or what we term in-place recharge. Avery (1994) estimated in-place recharge was 12% of his budget due to only allowing recharge after 1.5 inches (3.8 cm) of precipitation had fallen, and we estimate in-place recharge is more than a third of the recharge to the valley fill using a soil-water balance computer model (SWAT).

Components of groundwater discharge from the valley-fill aquifer are different between the two studies in several categories. The largest discrepancy is between the proportion attributed to gaining streams. From our seepage studies, we estimate 25% of discharge from the valley-fill aquifer is to gaining streams, in which we include the springs feeding Spring Creek. Avery (1994) tallied 34% of his discharge budget to gaining streams and an additional 15% to springs and drains. Again, the method used to estimate stream gain is not explicit in Avery's (1994) report, but it appears he was using a combination of streamflow measurements done in 1985 and baseflow separation of older data, whereas we used only our two stream-seepage studies. Our estimate of baseflow to streams (shown in table 10) is much larger (70,000 ac-ft/yr) than our valley-fill gaining stream estimate (shown in table 11), but our baseflow (and likely Avery's) includes baseflow from the mountain block, which we are not including in our valley-fill water budget. It appears 15% of Avery's (1994) discharge budget attributed to springs and drains includes all springs, even though he explicitly states that most if not all the springs in Ogden Valley are discharging from bedrock aquifers (Avery, 1994, p. 26). Our budget of discharge from the valley-fill aquifer only includes springs from the valley fill (i.e., the springs feeding Spring Creek, which are accounted for in stream gain in the Middle Fork sub-basin).

Another major difference in the discharge budget was in groundwater discharge to Pineview Reservoir. Avery (1994) listed 36% or 48,000 acre-feet of groundwater discharge from the valley-fill aquifer system was by seepage to Pineview Reservoir upward from the principal aquifer through the confining unit, which he derived from seepage rates measured at three seepage meters on the lake bed. In contrast, we derived our estimate of groundwater discharge to the reservoir using a stable-isotope enhanced reservoir water balance, and we conclude that in 2016, about 34,000 acre-feet discharged to the reservoir, or about 51% of our discharge budget. Our estimate reflects discharge from the shallow unconfined aquifer to the reservoir and leakage up through the confining unit. Clearly, Avery (1994) estimated much higher seepage through the lakebed, which we believe to be in error. Avery (1994) applied his measured seepage rate over the entire area of the reservoir, including the area having downward gradient due to the cone of depression around the Ogden City well field, and we believe some of the seepage he measured could be from the shallow unconfined aquifer based on the locations of his seepage meters.

Our better estimation methods and corroboration using environmental tracers lead us to conclude that our water budget for the valley-fill aquifer more closely approximates the recharge and discharge components of the aquifer in a normal year.

Water Supply

Our water budget shows that the Ogden Valley watershed has been in a generally balanced state since 2003. Wet years in which water is put into storage, both in the groundwater reservoir and Pineview Reservoir, balance dry years (table 9). However, we stress that several of the water budget components are very difficult to quantify, and therefore, we used the general lack of long-term water level decline in four monitored wells to assess that the system is in relative balance. Water-level data from near the Ogden City well field suggest that the central part of the principal aquifer is running a deficit of recharge to discharge.

We show that input water was 20% to 30% greater in the South Fork Ogden River sub-basin in 2016 than in the Middle Fork and North Fork sub-basins, and that water was exported from the South Fork sub-basin mostly to the Middle Fork sub-basin through canal diversion and as discharge to Spring Creek and the valley fill between the South Fork and Middle Fork rivers (table 10). The latter is mostly a result of grouping the Spring Creek area with the Middle Fork. The "excess" input water in the South Fork sub-basin is sourced from precipitation on the larger drainage basin and appears to be fully utilized as diversion for irrigation to the Ogden Valley Canal.

SEPTIC TANK DENSITY AND WATER-QUALITY DEGRADATION

Local government officials have formally documented the valley-fill aquifer's current pristine quality through groundwater-quality classification (Lowe and Wallace, 1999a), and have enacted lot-density requirements based on a previous septic-tank system density/water-quality degradation study (Wallace and Lowe, 1998). However, local government officials continue to express concern about the potential impact that development may have on groundwater quality, particularly development that uses septic-tank soil-absorption systems for wastewater disposal, and desire updated septic-tank density recommendations based on the water budget developed as part of this study to protect water quality.

The Mass Balance Method

The purpose of septic-tank density analyses is to provide recommended conventional septic-tank-system densities to local planning and development organizations. We used a mass-balance approach to evaluate potential water-quality degradation from septic tanks. The mass-balance approach uses nitrate as the constituent of interest because it is a common pollutant associated with septic-tank systems and because it is easy to detect and analyze. Nitrate in drinking water also poses a health risk to humans, especially infants. Infants consuming water or milk containing more than 10 mg/L of nitrate are susceptible to a condition known as methemoglobinemia, or "blue baby syndrome" (Comly, 1945), which can be life threatening without immediate medical attention (U.S. Environmental Protection Agency, 2015).

In the mass-balance approach, we add the nitrogen mass from the projected additional conventional septic tanks to the current nitrogen mass and then dilute it with the amount of groundwater flow available for mixing plus the water added by the septic-tank systems themselves. The water available for mixing is groundwater flow in the upper few hundred feet of the principal unconfined aquifer, which becomes flow in the shallow unconfined aquifer and upper part of the principal confined aquifer. The best estimate of this flow volume is from our volumetric and isotopic mass balance of Pineview Reservoir. This volume includes recharge from existing septic tanks.

We used the following equation to determine the projected nitrate concentration resulting from additional conventional septic tanks, and thus to determine how many conventional septic-tank systems can be added before exceeding a designated target nitrate concentration:

$$N_P = \frac{(ST_T - ST_C) \times Q_{ST} \times N_L + N_A \times (Q_M + ST_T \times Q_{ST})}{ST_T \times Q_{ST} + Q_M} \quad (11)$$

where:

N_P = projected nitrate concentration in groundwater (mg/L)

N_A = ambient nitrate concentration for the aquifer (mg/L)

N_L = estimated average nitrate concentration from each septic tank (mg/L)

ST_T = total number of septic tanks in the system (variable, unitless)

ST_C = current number of septic tanks (constant, unitless)

Q_{ST} = flow from each septic tank in liters per second (L/s)

Q_M = groundwater flow computed from the groundwater budget (L/s)

To determine a recommended septic-tank system density, we divided the domain area (in this case, valley floor) acreage by the total number of septic tanks (ST_T) that could exist at the projected nitrate concentration (N_P):

$$\text{Tank Density} = \frac{\text{(Domain acreage)}}{ST_T} \quad (12)$$

where ST_T is defined above.

We provide this recommendation for the valley-fill aquifer as a whole to provide a comparison to the previous septic-tank density/water-quality degradation analysis for Ogden Valley (Wallace and Lowe, 1998; Wallace and Lowe, 1999).

Results

Wallace and Lowe (1998) determined that if 1 mg/L additional nitrate was acceptable in the Ogden Valley principal aquifer, the groundwater system could accommodate 9500 septic-tank systems. We repeated the calculations of Wallace and Lowe (1998) using updated septic tank numbers, population data, groundwater flow volumes, and valley area. The latter was corrected by subtracting the area of Pineview Reservoir from the area of the valley fill. For this analysis, we only considered housing units built within the limits of the valley-fill aquifer and ignored housing units that are serviced by sewage lagoons. Furthermore, we only considered groundwater that flows from the unconfined principal aquifer to Pineview Reservoir, either through the shallow unconfined aquifer or as leakage up through the confining unit, as we consider this to be the primary path for groundwater in the upper few hundred feet of the unconfined principal aquifer and shallow unconfined aquifer where septic leachate is focused.

Ogden Valley has many second homes, cabins, and resort lodging that is occupied only part of the time. Seasonal population added to the census-derived population increases the mean population. Septic loading analysis was performed assuming two population scenarios. The first scenario ignores impacts of seasonal residency on groundwater nitrate and assumes the total 2015 population of 7138 people (U.S. Census Bureau, 2017) is disbursed on 4110 developed parcels (Weber-Morgan Health Department, 2017), which equates to 1.7 people per household (pph). The second scenario assumes full-time residences are occupied by an average of 3.0 people per household, the typical Weber County average (U.S. Census Bureau, 2017), and that the remaining existing homes are second homes (4110 parcels – [7138 population ÷ 3 pph] = 1731 second homes), which are occupied at 50% capacity. The addition of 3 pph in 1731 second homes 50% of the time, increases the mean effective total population to 9734 people, or 2.4 people per household.

We limited our septic-tank density analysis to the valley-fill aquifer. GIS analysis of the location of developed parcels not on lagoon wastewater treatment systems shows 2206 septic tanks overlying the valley-fill aquifer. Using 1.7 and 2.4 pph values, the mean valley population on septic tanks is 3750 or 5294 people, respectively.

We calculated the amount of nitrogen added by septic tanks by multiplying the volume of effluent by the amount of nitrogen contributed. Each person contributes 60 gallons of effluent per day (Utah Division of Water Resources, 2010), and that effluent from a conventional septic-tank system has an estimated nitrogen concentration of 64 mg/L. The latter value is based on (1) an average nitrogen loading of 17 grams of nitrogen per capita per day (Kaplan, 1988), and (2) an assumed retainment of 15% of the nitrogen in the septic tank (to be later removed during pumping) (Andreoli and others, 1979); this number is similar to Bauman and Schafer's (1985) nitrogen concentration in septic-tank effluent of 62 ± 21 mg/L based on the averaged means from 20 previous studies. Using these values, a typical single-family septic-tank system in Ogden Valley serving an average of 1.7 to 2.4 occupants discharges 102 to 144 gallons (386–545 L) of effluent per day containing 25 to 35 grams of nitrogen.

Groundwater flow available for mixing is the major control on nitrate concentration in aquifers when using the mass-balance approach (Lowe and Wallace, 1999b). We consider the volume of groundwater flowing in the upper few hundred feet of the unconfined aquifers, where septic leachate is focused, to be equivalent to the volume that we estimate discharges to Pineview Reservoir using the volumetric and isotopic mass balance we performed on Pineview Reservoir (see PINEVIEW RESERVOIR VOLUMETRIC AND ISOTOPIC MASS BALANCE section).

Figure 68 is a plot of projected nitrate concentration versus number of septic-tank systems located in valley fill in Ogden

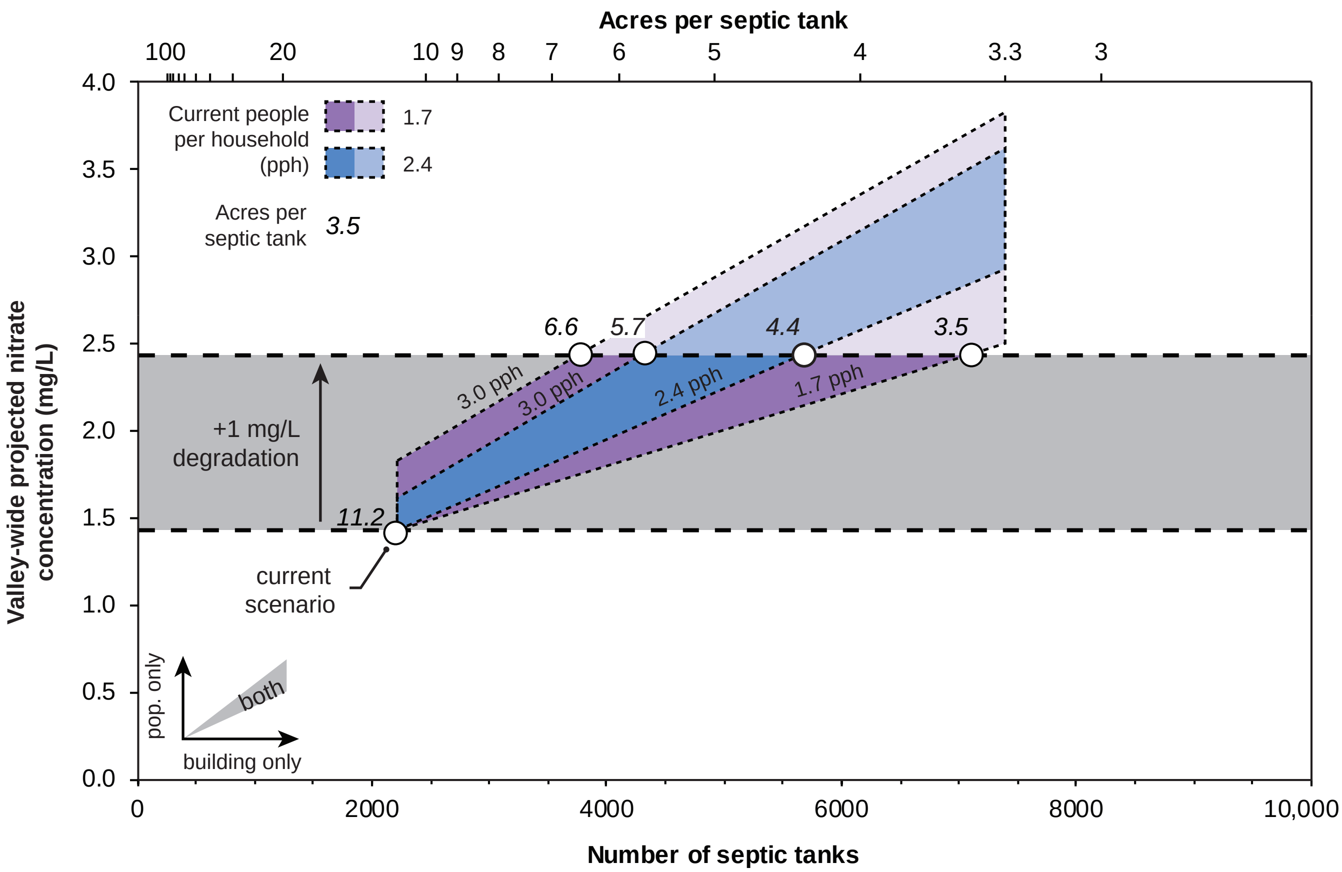


Figure 68. *Current and projected nitrate concentration versus number of septic-tank systems in Ogden Valley. The gray shaded area denotes an increase of 0–1 mg/L nitrate; the colored areas show the range of mean nitrate concentrations in groundwater given a range of population, growth, and groundwater flow scenarios. Simplified to show the largest range calculated from a range of groundwater flux input values.*

Valley. The present-day ambient nitrate concentration for the unconfined valley-fill aquifers is 1.43 mg/L nitrate as nitrogen (note: this average includes data for the shallow unconfined aquifer as reported by Reuben [2013] along with data collected as part of our study). The Ogden Valley floor (excluding Pineview Reservoir) has an area of 24,614 acres, so the existing average septic-system density is 11.2 acres per system. Based on our analyses, estimated groundwater flow available for mixing in the valley-fill aquifer is 31,000 to 34,000 acre-ft/yr, which includes the current septic-system discharge of 250 to 350 acre-ft/yr. Higher septic-system discharge is expected to be coupled with future population growth, which is included in the model. We present several growth scenarios that allow 1 mg/L of degradation over the 2016 mean concentration. Allowable water-quality degradation of 1 mg/L nitrate in the scenarios presented below is for discussion only; our data can be used to make land-use decisions for any level of water-quality degradation.

In the first scenario, we assume the current nitrate concentrations are attributed to a population of 1.7 people per household and ignore contribution from part-time occupancy. In this scenario, an additional 4471 to 4858 conventional septic-tank systems could be added while adding 1 mg/L nitrate, which results in an average housing density of 3.5 to 3.7 acres per dwelling (figure 68). However, a shift to full occupancy of all valley-fill homes at this point would increase nitrate by an additional 1.1 mg/L. An approach that is more protective of groundwater is to model nitrate concentrations by assuming existing homes quickly fill to Weber County's more typical 3.0 people per household, which increases nitrate by 0.3 mg/L. Adding 1539 to 1759 new homes occupied at 3.0 people per household at this point brings nitrate to 2.43 mg/L. The resulting housing density is 6.2 to 6.6 acres per dwelling unit.

We modeled a more likely scenario using an average household size of 2.4 people, which accounts for 50% occupancy of seasonal-use residences. If development continues at this rate of occupancy, an additional 3166 to 3441 conventional septic-tank systems could be added while adding 1 mg/L nitrate. The average housing density under this scenario is 4.4 to 4.6 acres per dwelling unit (figure 68). However, a shift to year-round residency of valley-fill homes at this point would increase nitrate by an additional 0.4 mg/L. Again, the more protective approach is to model nitrate concentrations by first increasing people per household to 3.0, without any new home construction, which would increase nitrate by 0.2 mg/L. If new homes are built at this point, and occupied at 3.0 people per household, only 2075 to 2294 new homes can be constructed, resulting in an average density of 5.7 to 5.8 acres per dwelling unit.

If the 1999 lot size recommendation (3 acres per lot, which equates to 3.33 acres per lot when right of ways are included) is not changed, and each lot is permitted to have a conventional septic-tank system, nitrate concentrations will increase to approximately 3.6 to 3.9 mg/L, depending on residency. We did not consider agricultural contributions to groundwater nitrate in our approach, and new septic input may be partially negated by decrease in agricultural nitrate input as land use changes from agriculture to residential. Nitrate contribution to groundwater from future development could also be lessened by a requirement that new systems use advanced nitrogen removal technology. Advanced systems may decrease the amount of total nitrogen in effluent by more than 50% compared to the 64 mg/L value we used in this analysis (Lancellotti and others, 2017).

We emphasize that the current average nitrate concentration in the principal and shallow unconfined aquifers is markedly higher than those reported in the 1998 assessment of the principal aquifer (Wallace and Lowe, 1998). Mean nitrate in groundwater in the mid-1990s was reported as 0.74 mg/L (geometric mean 0.42 mg/L) with approximately 2300 septic tanks (Wallace and Lowe, 1998). So, the present nitrate concentration in unconfined aquifers (1.43 mg/L) has nearly exceeded the 1 mg/L degradation target.

In the 1998 study, Wallace and Lowe (1998) predicted the number of septic tanks systems in the valley could be allowed to reach 9500 tanks before the 1 mg/L additional nitrate degradation limit was exceeded, which equated to an average lot size of 3.3 acres. The differences in this study compared to the 1998 study are: (1) smaller area of valley fill calculated by subtracting the area of the reservoir from the valley-fill area, (2) fewer initial septic tanks because we based the current number of septic tanks on the number of developed parcels on valley fill, whereas the 1998 study used the total number of septic systems in the study area provided by the county health department, (3) lower estimate of groundwater flow, and (4) higher initial nitrate concentrations due to inclusion of results from shallow unconfined aquifer monitoring wells. The apparent decrease in the number of septic tanks that can be added, from 7200 additional tanks recommended in the 1998 study, to only 1539 to 4858 additional tanks in this study, is mostly due to the much smaller groundwater flux available for mixing—43 cfs in 2016 compared to 166 cfs in 1998. Our new lower flux volume is more appropriate for this analysis because it represents the flux occurring in the upper few hundred feet of aquifer, where mixing is likely to occur. Also, assumptions about population in this study are more conservative.

The 2016 geometric mean nitrate concentration in the principal valley-fill aquifer is 0.807 mg/L, and, because nitrate concentrations in wells are log-normally distributed, there is a 95% certainty that a well's nitrate concentration will not exceed 11.0 mg/L. This means that some wells will exceed the EPA drinking water standard of 10 mg/L, and as mean concentration increases with the addition of septic tanks, the probability of encountering high nitrate concentrations also increases.

FUTURE WATER RESOURCE IMPACTS AND DEVELOPMENT

Water Supply

Quadrupling the population of Ogden Valley from 2015's roughly 7000 people to 28,000 people at full build-out will require development of Ogden Valley's water resources. We estimate agricultural diversions in Ogden Valley are nearly 27,000 acre-ft/yr and irrigation efficiency is about 70%. Increasing efficiency to the likely maximum of 80% on flood irrigated acres and 95% on sprinkler irrigated acres (Stewart and Howell, 2003) could free up a few thousand more acre-feet of water to be used by existing water right holders. At full build-out, land used for agriculture would be developed, essentially eliminating agricultural irrigation from the budget, but adding more domestic and commercial use. We estimate a full build-out population of 28,000 people would require approximately 1880 acre-ft/yr for indoor water use (at 60 gallons per capita per day) (Utah Division of Water Resources, 2010) and 4200 acre-ft/yr for outdoor water use (at 134 gpcd) (Utah Division of Water Resources, 2010). However, this estimate of outdoor water use would only be sufficient to water between 2130 and 4260 acres (at between 50% and 100% efficiency and 11.85 inches irrigation per year [Utah Division of Water Rights, 1994]), which is low compared to the land area likely occupied by the projected 24,000 dwellings at full build-out. Calculating outdoor water by use by using the number of dwellings and the Weber County average of 3 persons per household, outdoor water use may be expected to increase to 10,900 acre-ft/yr, which could irrigate 5500 to 11,000 acres (at between 50% and 100% efficiency and 11.85 inches irrigation per year [Utah Division of Water Rights, 1994]). This value, in addition to 1880 acre-ft/yr indoor usage, is less than 50% of what is currently diverted for agricultural irrigation. Based on our analysis, meeting water demand of higher population is possible in Ogden Valley by shifting water use from agriculture to urban uses; however, water storage and waste-water treatment systems would need to be added, and land and water management practices may need to change to meet demand and assure water quality.

With new development using septic tanks as wastewater disposal, indoor water use is mostly recycled back into the groundwater system as poorer quality groundwater recharge. New development using lagoons or sewage treatment plants will result in a loss of water to evaporation or discharge as surface water, respectively. Outdoor water use for new development in areas that are not currently irrigated or forested will result in loss of more water to ET. However, forested mountain regions currently contribute the majority of ET loss, so new development may not actually increase ET in these areas.

Future development of groundwater resources in any of the sub-basins would likely result in less discharge of groundwater to gaining sections of streams and reduced groundwater discharge to Pineview Reservoir. Shallow water in the valley-fill aquifer is generally recharged locally, likely focused along rivers, major creeks, and canals. Deeper valley-fill groundwater is recharged higher in the mountain block. Pumping groundwater from the mountain block lowers the local water table, reducing the hydraulic gradient, and thus recharge, to the valley. Drawdown of the water table per unit volume pumped is more in bedrock aquifers than in the principal valley-fill aquifer due to substantially lower storage in bedrock aquifers. Mountain-block pumping will also likely affect mountain spring discharge and baseflow to mountain streams (Inkenbrandt and others, 2016). Increased pumping from the principal valley-fill aquifer will lower the potentiometric surface, which will increase the seasonal capacity for recharge from losing streams and canals in the unconfined principal aquifer. Recharge from the unconfined principal aquifer to the shallow unconfined aquifer could decrease if the water table drops, and the composition of recharge to the confined principal aquifer will become more like surface and precipitation sources. Hydrologic systems dominated by younger surface water and precipitation recharge are more susceptible to contamination.

Ogden Valley's extensive network of canals, especially the Ogden Valley Canal, are a significant source of recharge to the valley-fill aquifer system. Attempts to limit leakage from the Ogden Valley Canal will likely have minimal effect on water quality but negative impact on local water tables.

If water tables in the valley-fill aquifers decline significantly either from increased pumping or decreased recharge from streamflow, canals, or mountain-block recharge due to water resource development in the mountains and foothills, groundwater discharge to gaining sections of streams will decrease, which in turn will reduce streamflow to the reservoir. ET will decrease, although we estimate this volume to already be low (2300 acre-feet in 2016, table 11), resulting in some water saved.

Effect of Adding Septic Systems

At maximum build-out, at least 10,000 dwelling units could occupy the valley-fill area of Ogden City (Ewert, 2014). This number of units does not adhere to 3-acre-minimum lot sizes because some subdivisions have previously agreed-on building densities. Instead, the average dwelling units per acre at maximum build-out is between 1.9 and 2.3 (Forest Valley Zone and Agricultural Valley Zone, respectively) (see Ewert, 2014). Many of these subdivisions may choose community sewer options and therefore will have minimal contributions to the nitrate issues.

The fate of septic effluent from upland housing developments is less certain than valley-floor build-out. The flow paths from mountain septic systems could result in discharge of septic leachate to streams, which ultimately flow into Pineview Reservoir or recharge the valley-fill aquifer. Alternatively, the septic effluent may flow in the subsurface to the valley-fill aquifer. With these different scenarios, it is difficult to predict the impacts on the valley-fill aquifer. Future population predictions can be used to calculate the yearly nitrate loads from septic systems. In 2060 the population is predicted to be 28,106, which equates to 163 tons of nitrate produced yearly.

While larger lots limit the number of septic tanks, their non-centralized aspect also requires the use of septic tanks instead of community wastewater systems. Small lot sizes are more suited to lagoons or municipal wastewater treatment plants. Higher density developments using lagoon systems are already present in Ogden Valley and have largely avoided contributing to the nitrate problem while still meeting housing needs. Large lot sizes developed with septic systems will be costlier to convert to sewer if the nitrate problem forces the use of community sewer systems in the future.

SUMMARY

Ogden Valley is a well-watered valley in northern Utah. The area is home to more than 7000 people and has a temporary population of perhaps 7000 more who enjoy seasonal and recreational opportunities in Ogden Valley's mountains (mountain resorts, summer homes, National Forest lands) and water reservoirs (Pineview and Causey Reservoirs). The population of the valley could increase to more than 28,000 at full build-out under current zoning by 2060 if population grows at recent rates.

The goals of this study were to characterize the hydrogeology of Ogden Valley in more detail than previous studies, specifically using new geologic and geophysical data, water chemistry data, environmental chemistry tracers, stream flow, and water levels to understand the interaction between streams, canals, bedrock and valley-fill aquifers, and Pineview Reservoir. We analyzed three sub-basins within the watershed using environmental tracers and water budgets to help water managers understand how changes in water use within the basin may impact other users.

Current land use on the valley floor, which makes up 14% of the study area, is about half agriculture and half residential. The mountains are primarily forested, although residential and commercial development makes up a small fraction of land use in the mountains.

Community wells, developed springs, and domestic wells supply most of the valley's estimated potable water demand of 4000 to 6000 acre-ft/yr, which includes some outdoor water use. About 17,200 acre-feet of water is used to irrigate crops. The Ogden City well field, located on a peninsula in Pineview Reservoir, extracted between 10,200 and 12,400 acre-feet of water per year from the principal confined aquifer for export out of the valley from 2003–2016. Between 59,000 and 349,000 acre-feet of water exited the valley as either surface flow in Ogden River or through a water supply conduit down

Ogden Canyon during that period. Municipal and domestic waste-water treatment is by individual septic tanks, community septic-tank systems, or lagoons.

New data collected for this study includes 43 gravity measurements; 80 water levels in wells; 215 stream flow and canal flow measurements; river stage measurements at 5 locations proximal to Pineview Reservoir at 15-minute intervals for approximately 19 months; 58 general water chemistry samples from wells, springs, streams, and Pineview Reservoir; 13 samples from wells for dissolved metals; 307 samples from wells, springs, and streams for stable isotopes; and 11 samples from wells for radioactive isotopes and noble gases.

Groups of geologic units having similar hydrogeologic properties are classified as aquifers (unconsolidated valley fill, carbonates, conglomerates), aquitards (tuff, shale, unfractured quartzite, metamorphic rocks) and mixed hydrogeologic properties (landslides, interbedded sedimentary rocks). The principal aquifer in Ogden Valley is the unconsolidated valley-fill aquifer, which is unconfined on the valley margins and confined in the center of the valley. Other important aquifers occur in fractured and karstic carbonate rocks. We classified the Tertiary Norwood Tuff and Proterozoic quartzite as aquitards.

Ogden Valley is bounded on the west and east by normal faults. Complex structural relations relating to the Willard thrust sheet juxtapose low-permeability metamorphic Farmington Canyon Complex and metasedimentary rocks with younger Paleozoic dolomite and limestone aquifers. Much of the east half of the mountains surrounding Ogden Valley is covered by Tertiary conglomerate overlying older rocks. Tertiary volcanic rocks (tuff) and volcaniclastic conglomerates probably underlie most of the unconsolidated valley-fill sediments. The unconsolidated sediments consist of stream, alluvial-fan, landslide, and lacustrine deposits, and minor glacial deposits of Pleistocene and Holocene age.

Using new gravity data, we show the unconsolidated valley-fill sediments above the Norwood Tuff are up to 2300 feet (700 m) thick, considerably deeper than previous studies reported, which provides a large storage reservoir for groundwater. The basin is asymmetric and deepest near Huntsville. We approximately located a set of normal faults under Pineview Reservoir and another set east and north of Huntsville based on 2D modeling of the gravity data. We correlated well logs to define the extent of a silt and clay confining unit and show that the unit is up to 120 feet (40 m) thick near the Ogden City well field, but much thinner underlying Pineview Reservoir because of erosion by streams; the unit thins to zero to the north and east. We suggest that the confining unit was deposited during the Little Valley lake cycle rather than the Bonneville highstand of Lake Bonneville as other researchers have proposed. Important unconsolidated aquifer units (medium to coarse Quaternary sand and gravel) above and beyond the edge of the confining unit are Lake Bonneville sand, stream alluvium and flood deposits, and alluvial-fan deposits. Most supply wells penetrate either the confined or unconfined part of the principal aquifer, which have geometric mean transmissivity values of 220 and 160 ft^2/d, respectively. Two units we classify as aquitards or confining units, because of their spatial distribution in areas where domestic wells are needed, have been developed for water supply and have geometric mean transmissivity lower than the principal aquifer. Other carbonate aquifer units have not been tapped extensively, but generally may have transmissivity values lower than the principal aquifer. Bedrock units, because of their lower porosity and permeability, generally have lower storage capacity than unconsolidated aquifers, which reduces their functionality as municipal supply aquifers.

Our potentiometric surface for March–April 2016 shows a sink in the center of the valley induced by pumping from the Ogden City well field that likely has existed since the wells first began producing water in the early 1900s. While the potentiometric head in the confined aquifer was above the bottom of the confining unit, a 2-square-mile (5 km^2) area centered around the Ogden City well field had/has a strong, perpetual downward vertical gradient from the reservoir to the confined aquifer. Elsewhere, the vertical gradient between the confined aquifer and the shallow unconfined aquifer/Pineview Reservoir may be dynamic and change between upward (leakage to the shallow aquifer or reservoir) and downward (leakage from the shallow unconfined aquifer and reservoir to the principal confined aquifer).

The level of the potentiometric surface throughout the valley generally decreased from spring to fall 2016, most notably in bedrock wells in the North Fork arm of the valley. Long-term water-level change since 1985 is not outside the variability expected of a dynamic surface-water dominated system, except one isolated area in the North Fork arm of the valley and near the Ogden City well field where the potentiometric surface is tens of feet lower than it was in 1986. An area of moderate water-level decline east of Huntsville is probably a result of changing from flood irrigation to sprinkler irrigation.

We observed streamflow ranging from 0.2 to 96 cfs during our seepage run on the valley's streams in March 2016, which was at the start of the spring runoff. More stream segments were gaining during the March seepage run than were losing, and overall, Ogden Valley's streams were net gaining by 64 cfs. We extrapolated the conditions measured in March 2016 to the normal runoff period to show that the aquifer is yielding roughly 15,400 acre-feet to the surface water system, with the largest contribution in the North Fork drainage (7040 acre-ft) followed by the Middle Fork (5740 acre-ft) and the South Fork (2580 acre-ft). Notable gaining reaches in March, which signal groundwater discharge to streams, were the upper reaches of the Middle Fork where the stream flows over thin alluvium that is likely saturated, and the lower parts of Spring and Geertsen Creeks where they overlie the confining unit. The South Fork Ogden River was losing heavily (18 cfs) in the few miles downstream from its canyon where it flows over permeable valley-fill deposits having water table deeper than 20 feet (6 m). Conversely, the lower branches of the South Fork were gaining heavily. Gaining reaches are generally coincident with areas having depth to water less than 15 feet (5 m) below land surface and losing reaches have a deeper water table. Streamflow during our November baseflow seepage run was a fraction of the flow during March, and several segments that were gaining in March were losing in November, likely because the few feet of seasonal water-table decline in these areas is sufficient to change the condition of the stream from gaining to losing. Overall, Ogden Valley's streams were net losing in November 2016 by about 24 cfs, which was roughly 11,500 acre-feet extrapolated to the entire baseflow period. The Middle Fork Ogden River network was net gaining, as it had been in March, but the North and South Fork Ogden River networks went from net gaining during runoff conditions to net losing during baseflow conditions.

The Ogden Valley Canal had a net loss of 18 cfs on July 19, 2016, which is 47% of flow at the start of the canal. The reach at the beginning of the canal between the diversion from the South Fork Ogden River to Highway 39 was losing 4 cfs and another reach between the South Fork and Middle Fork drainages was losing 6 cfs. A stretch of canal east of Geertsen Creek was gaining about 4 cfs. In 2016, roughly 6900 acre-feet of water was let down the canal for irrigation, so we estimate that the canal lost approximately 3300 acre-feet during the 2016 irrigation season. The canal is a significant source of recharge to the valley-fill aquifer system. Attempts to limit leakage from the canal will likely have an impact on local water tables and recharge.

Analysis of environmental tracers provided unique insight into the hydrogeologic system of Ogden Valley. There was enough distinction between the stable isotopes of water in summer and winter precipitation, groundwater, surface water, and continental effects on precipitation for us to show the connection between streams and groundwater and contribution of mountain-block recharge. The large number of stable isotope samples proved to be important in parsing out statistically significant differences in the types of water.

The stable isotope composition of the North Fork and South Fork changed little over several miles, despite those same reaches gaining water from the groundwater system. We conclude from this that there is a dynamic interchange of groundwater and surface water in the aquifer proximal to the rivers, indicating the stream zone is dominated by surface water. Conversely, we show the mean stable isotope composition of the valley-fill aquifer as sampled at wells is a mixture of stream and bedrock aquifer water, though shallower wells are more like stream water than deeper wells. Based on the difference between stream and bedrock ratios and between waters from the three sub-basins of the valley (North Fork, Middle/Geertzen/Spring Creek, and South Fork) we estimate that mountain-block recharge overall makes up about half of the water extracted at valley-fill wells, though there are slight differences in the contributions in each sub-basin. The South Fork sub-basin appears to have a higher fraction of stream recharge than bedrock recharge, as supported by our seepage run finding of annual net loss from streams in the South Fork as opposed to net gain in the other two sub-basins. Noble gases, tritium, and radiocarbon data help us understand when and at what temperature recharge took place, which we correlate to length of flow path and recharge elevation. Lumped parameter modeling of these data show that about 40% of water accessed by valley-fill wells is mountain-block recharge, which generally concurs with seepage run and stable isotope findings.

We used multiple methods of investigation, including head gradients, chemistry, and a volumetric water balance, to determine the extent of interaction between Pineview Reservoir and the confined aquifer. Our stable-isotope enhanced water balance of Pineview Reservoir suggests that there must have been at least 2700 acre-feet of reservoir water moving to the confined aquifer in 2016. An area of at least 2 square miles (5 km^2) having a strong downward vertical head gradient is around the Ogden City well field, and the area could likely be much larger depending on the difference between changing reservoir level and changing seasonal water level in the principal confined aquifer. The presence of tritium and elevated nitrate in the Ogden City well is convincing evidence that recent groundwater recharge is entering the confined aquifer, yet stable isotopes do not reflect reservoir influence. Without more information, we are unable to positively identify and quantify the interaction between Pineview Reservoir and the confined aquifer, but we find it highly likely that a few thousand acre-feet of reservoir water is leaking to the confined aquifer through the confining unit and/or through deteriorated abandoned wells submerged in the reservoir. The west side of Pineview Reservoir is another possible source for rapid recharge to the principal aquifer.

We created a basin-wide water balance for the watershed study area for 2004–2016. Input (precipitation) and output (ET, surface discharge, and well field export) each average approximately 535,000 acre-ft/yr. The water available to interact with streams and the aquifer (precipitation minus ET) is much smaller—we estimate about 158,000 acre-feet in 2016. The largest sub-basin, South Fork, had the largest amount of input water in 2016 (63,000 acre-ft) as compared to the North Fork (50,000 acre-ft) and Middle Fork/Geertsen Creek/Spring Creek (46,000 acre-ft) sub-basins. The distribution of in-place recharge (precipitation infiltration) shown by our soil-water balance model is highest in the northern margins of the basin in broad, elevated areas such as the ridgeline between the Middle Fork and South Fork sub-basins. Recharge is also high on the alluvial deposits between the North and Middle Fork sub-basins, although because of the volume of precipitation and amount of surface area, in-place recharge on the valley floor accounts for only 24,000 acre-feet or 7% of total in-place recharge. We estimate Pineview Reservoir accepted 112,000 acre-feet of streamflow, based on our stream discharge measurements and stage-discharge relationship, and 34,000 acre-feet of groundwater inflow. Streamflow (baseflow and runoff combined) is larger in the South Fork sub-basin (57,000 acre-ft/yr) compared to the other areas (23,000 to 33,000 acre-ft) due to the size of the watershed. Our estimate of how much groundwater discharge from each sub-basin enters Pineview Reservoir or the Ogden City well field is mostly a result of how we delineated the valley-fill aquifer system, and should be taken as a gross approximation. We assume the amount of groundwater discharge leaving the watershed is very small based on the small cross-sectional area available in the Ogden River alluvium below Pineview Dam, but recognize that the geologic setting in some localized areas of the watershed boundary creates potential for inter-basin flow of water.

Within the valley-fill aquifer system, the largest component of recharge in 2016 was in-place recharge of precipitation on the valley floor (24,000 acre-feet), followed by losing streams and canals (20,000 acre-feet), and mountain-block recharge (18,000 acre-feet). Although nearly all residents use septic tanks for wastewater disposal, recharge from the leach fields is a small component of the valley-fill aquifer budget. These water budget estimates are consistent with the findings from environmental isotopes indicating streams/canals and mountain-block recharge play roughly equal parts in recharging the valley-fill aquifer system.

Within the valley-fill aquifer system, the largest component of discharge in 2016 was groundwater discharge to Pineview Reservoir (34,000 acre-feet), followed by baseflow to streams and springs (17,000 acre-feet), and pumpage from the Ogden City well field (12,000 acre-feet). ET from the groundwater, pumpage from other wells, and possible groundwater outflow through alluvium of Ogden Canyon are small components of the budget.

Water use has increased slowly but steadily and appears to have had negligible effect on the overall budget and water levels in most of the principal aquifer. However, careful analysis of available data indicates that the principal aquifer surrounding the Ogden City well field was not in equilibrium with the extraction rate as of 1985. We hypothesize that development of water resources in any of the sub-basins would likely result in less discharge of groundwater to gaining sections of streams and reduced groundwater discharge to Pineview Reservoir. If the water table is lowered far enough by increased pumping in the bedrock or principal aquifers, groundwater may not be able to flow to the shallow unconfined aquifer, and the principal confined aquifer would take all the flow from the unconfined principal aquifer, including water at the top of the water table that is degraded by septic-tank leachate. Because transmissivity and storage capacity of bedrock aquifers are lower on average than valley-fill aquifers, new supply wells in bedrock aquifers have the potential to negatively impact water levels in the mountain block, affecting mountain spring discharge and baseflow of mountain streams.

Based on the 2016 sampling campaign, water quality in Ogden Valley groundwater is generally excellent and is classified as dilute calcium-bicarbonate type water with an average TDS concentration of 243 mg/L. Isolated locations of sodium-chloride type water found on the margins of the valley may be older groundwater that has accumulated more dissolved solids flowing from the mountain blocks. One well had arsenic concentration near the drinking water quality standard and several wells exceeded secondary water quality standards. Bedrock water quality is more diverse than valley-fill water quality. Nitrate concentration in samples from water supply wells and springs ranged from 0.01 to 7.65 mg/L and the geometric mean is only 0.45 mg/L, but the shallow unconfined aquifer has much poorer water quality with nitrate + nitrite up to 47 mg/L (Reuben, 2013). Including data from the shallow unconfined aquifer, the geometric mean nitrate + nitrite concentration of all valley-fill aquifers is 1.06 mg/L and is 1.43 mg/L for just the unconfined portion of the principal aquifer and shallow unconfined aquifer (the most active groundwater reservoir).

We updated the mass-balance approach used by Wallace and Lowe (1998, 1999) to project groundwater nitrate concentration given an increase in septic tanks. Using two different population growth scenarios, one assuming full-time residency and the other assuming high seasonal occupation, approximately 1540 to 4860 conventional septic tanks, respectively, could be added before geometric mean nitrate concentration increases by 1 mg/L. Adding 1540 septic tanks to the valley (full-time residency) produces an average septic-tank density of 6.6 acres per system and adding 4860 septic tanks equates to an average density of 3.5 acres per system. Requiring new systems to use advanced nitrate removal technology is an approach managers could chose to meet desired water-quality degradation limits while keeping the current 3 acres per system lot size. We note that current average nitrate concentrations in the principal and shallow unconfined aquifers are markedly higher than those found in the 1998 assessment of the principal aquifer (Wallace and Lowe, 1998), and that degradation has nearly exceeded the 1 mg/L degradation target modeled in 1998. Furthermore, we stress that allowing a degradation of 1 mg/L to the mean nitrate concentration will increase the probability that nitrate concentration in individual wells may surpass the allowable safe drinking water standard.

While Ogden Valley is still only sparsely inhabited, development pressures and water management choices have resulted in some degradation of water resources. Water in the valley is plentiful due to high precipitation and moderate evapotranspiration. However, reliance on septic systems has contributed to locally high nitrate concentrations in both the principal aquifer and the shallow unconfined aquifer, potentially jeopardizing the Pristine water-quality classification. With some fraction of the Ogden City well field extraction being modern recharge, as shown by tritium and slightly elevated nitrate, the risk of contamination from surface sources is greater than is typical for wells in confined aquifers. Water resource managers should be vigilant in protecting the quality of Ogden Valley's groundwater resources as population and use grows.

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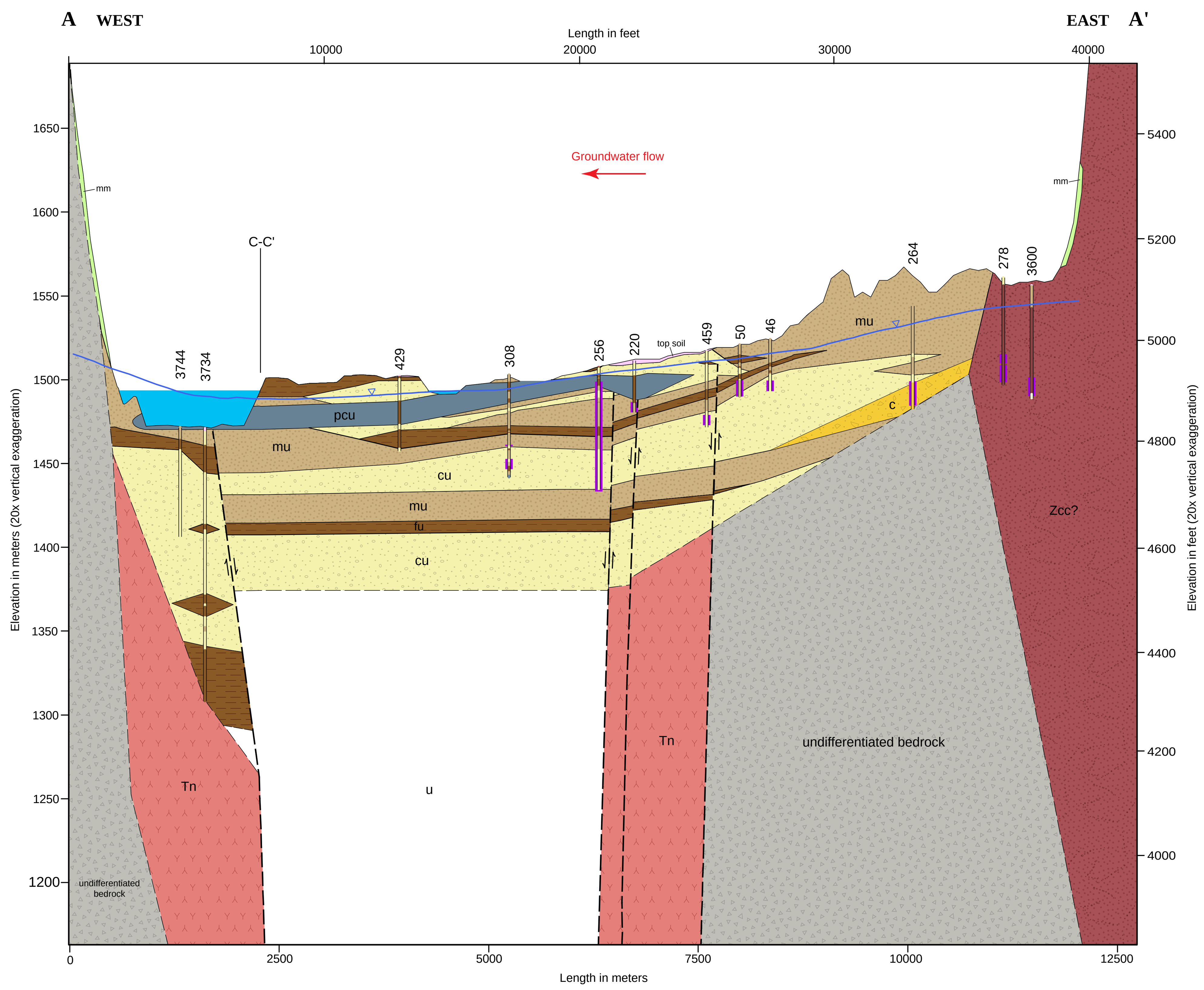
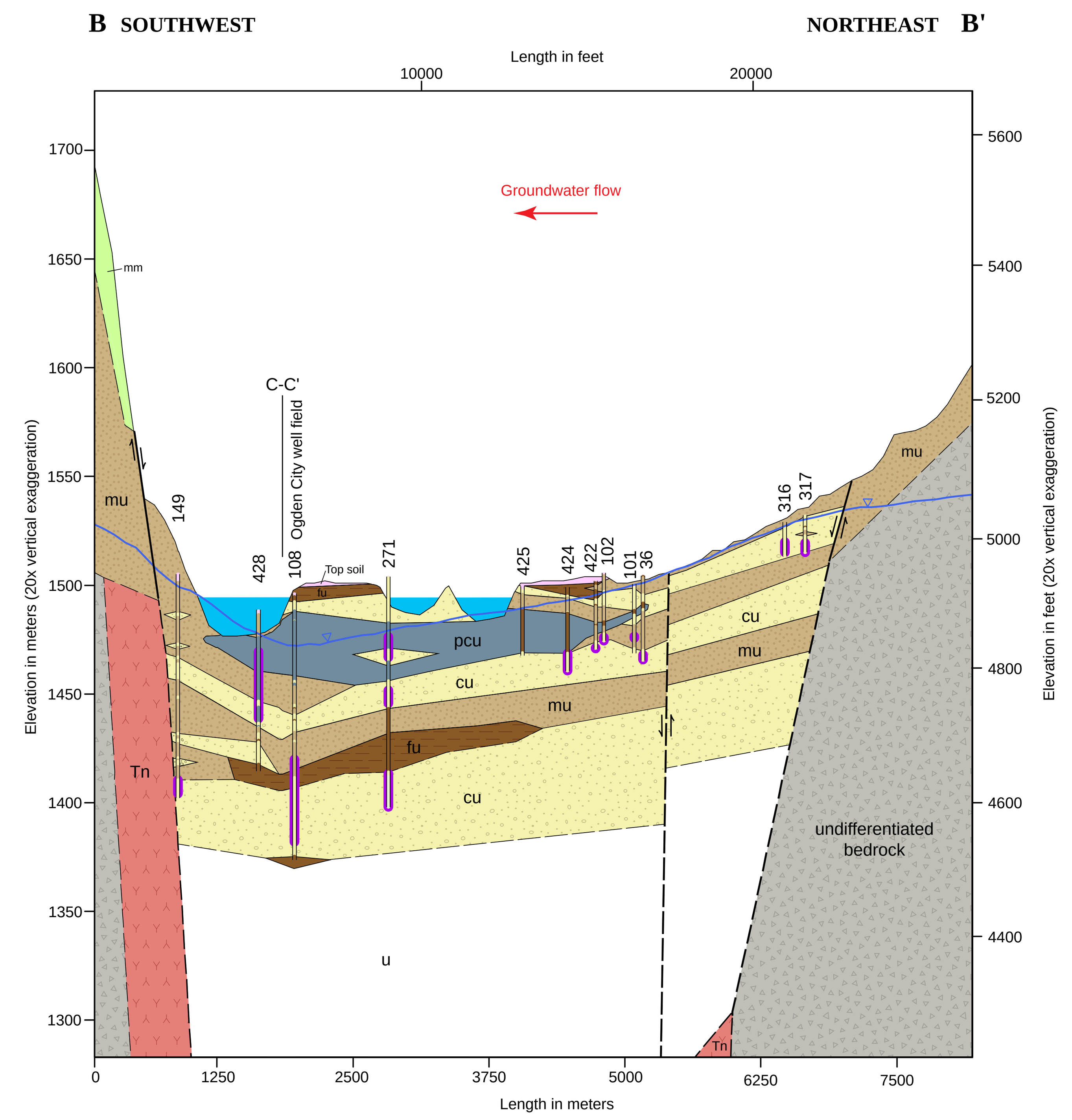
VALLEY-FILL CROSS SECTIONS THROUGH OGDEN VALLEY

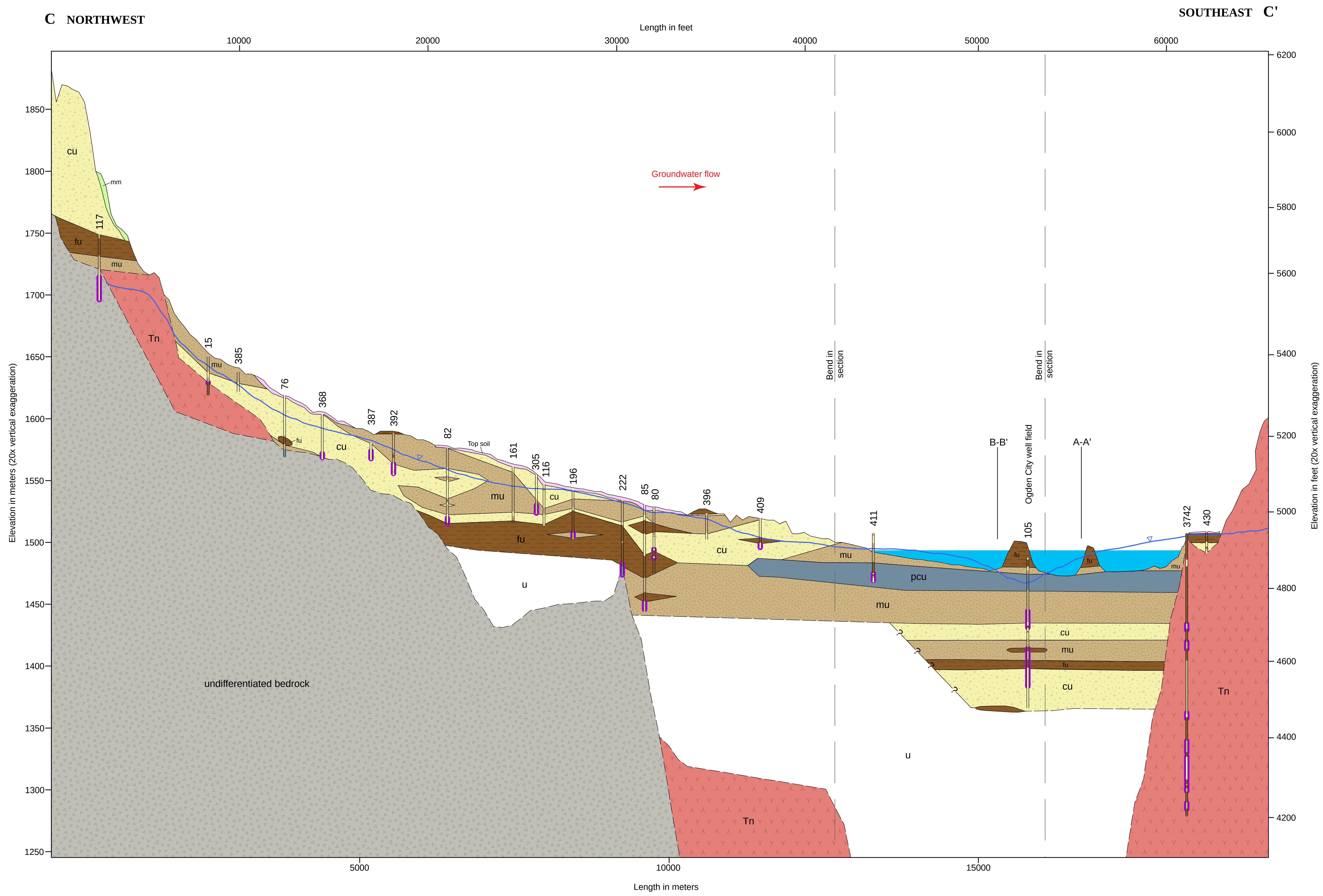
A WEST — **EAST A'**

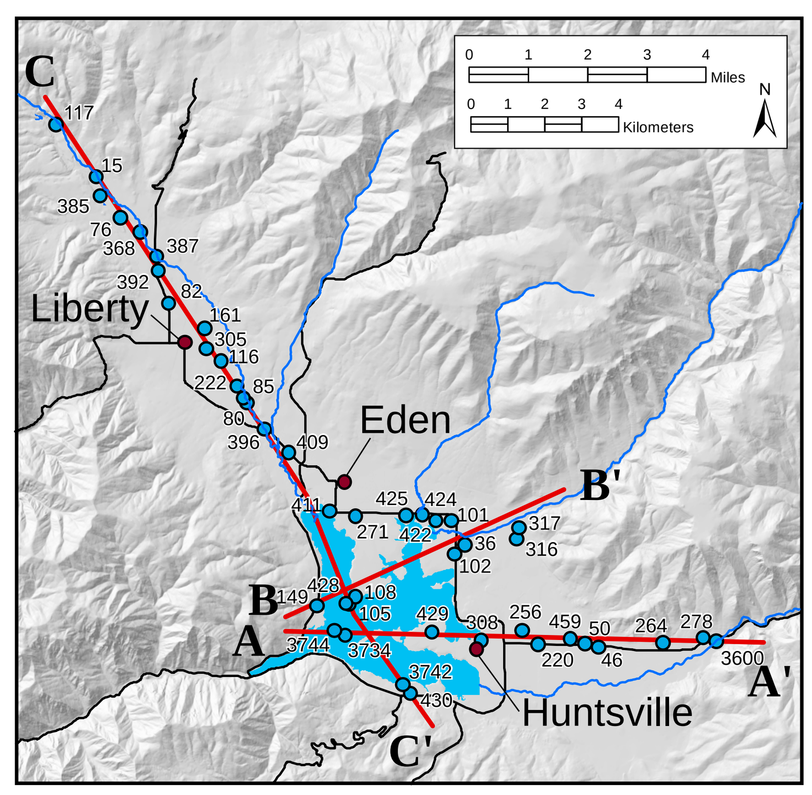


B SOUTHWEST — **NORTHEAST B'**



C NORTHWEST — **SOUTHEAST C'**





CROSS SECTION LOCATION MAP

UTAH
Area of figure

Lithologic Units
Dashed boundary indicates limit of interpreted extent

Valley Fill

- Top soil
- cu — Coarse-grained unconsolidated
- mu — Mixed-grained unconsolidated
- c — Conglomerate
- fu — Fine-grained unconsolidated
- pcu — Principal confining unit of fine-grained, unconsolidated fill
- u — Undifferentiated valley fill
- mm — Mass movement deposit

Bedrock Units

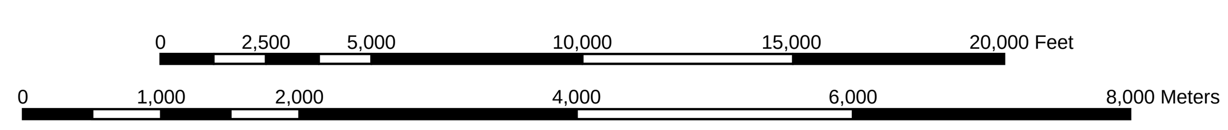
- Tn — Norwood Tuff
- Zcc? — Quartzite (likely Proterozoic Caddy Canyon Fm.)
- Undifferentiated bedrock

Symbols

- Pineview Reservoir
- 2016 potentiometric surface
- Fault with arrows showing relative displacement

Wells - projected at actual elevation onto section lines

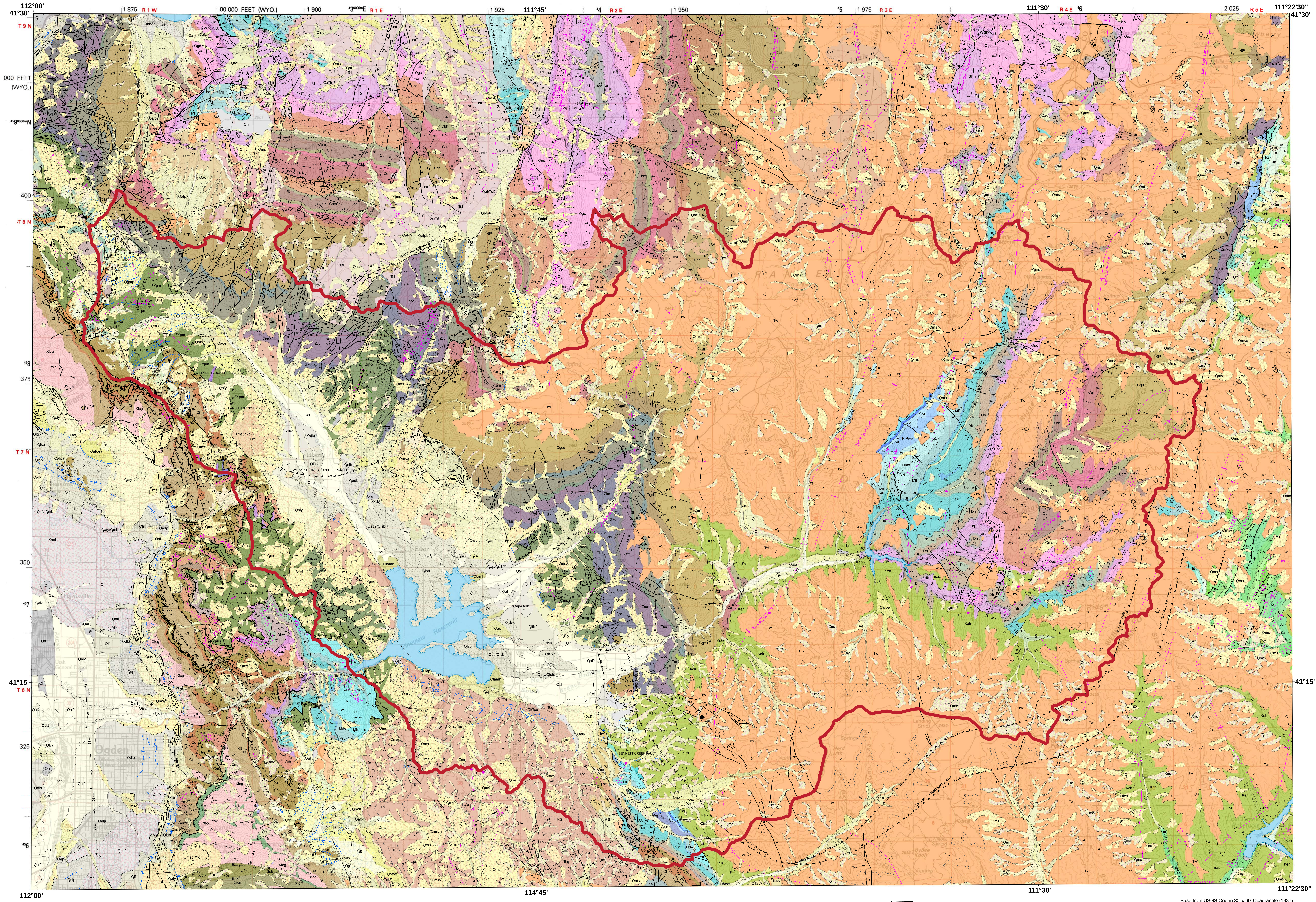
- 85 — Well ID
- Borehole lithology by color
- Perforated or screened interval



APPENDICES

UTAH GEOLOGICAL SURVEY
a division of
Utah Department of Natural Resources

Plate A-1
Utah Geological Survey Special Study 165
Characterization of the Groundwater System in Ogden Valley, Weber County, Utah



APPROXIMATE MEAN DECLINATION, 2018

SCALE 1:62,500

1 0.5 0 1 2 3 4 Miles

2 1 0 2 4 Kilometers

UTAH

MAP LOCATION

Base from USGS Ogden 30' x 60' Quadrangle (1987)
Geologic map excerpted and modified from the interim geologic map of the Ogden 30 x 60-minute quadrangle (Coogan and King, 2016).
Projection: UTM Zone 12
Datum: NAD 1927
Spheroid: Clarke 1866

GEOLOGIC MAP OF THE OGDEN VALLEY HYDROGEOLOGIC STUDY AREA

Geologic Map Symbols

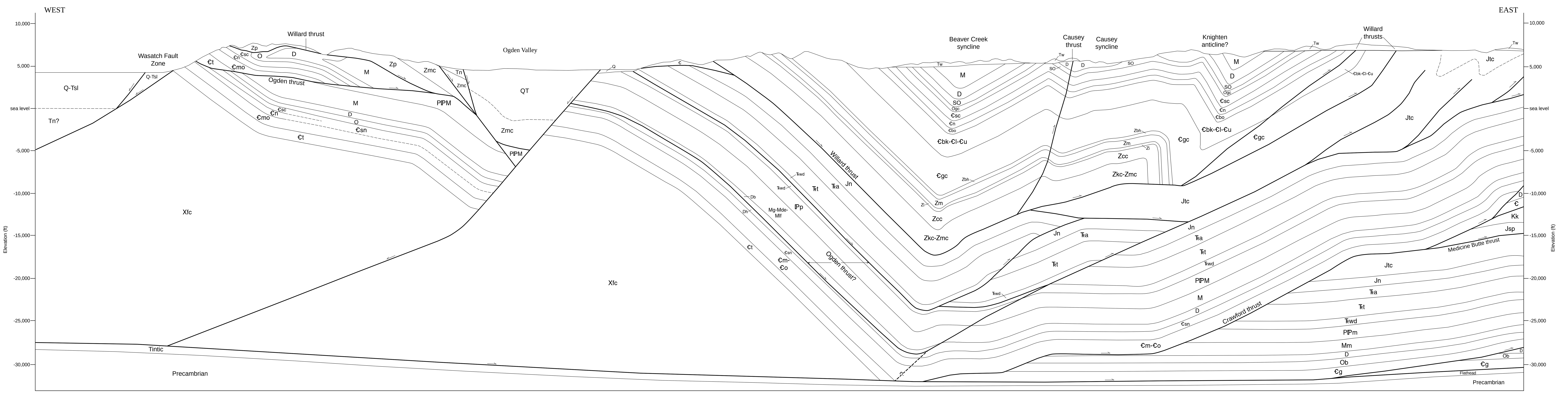
Boundary, map
Boundary, water, reservoir
Boundary, study area
Cirque headwall
Contact, well located
Contact, approximately located
Contact, approximately located, queried
Contact, concealed
Contact, concealed, queried
Contact, scratch, used where map units combined
Arete, ice-carved bedrock ridge
Beach ridge
Older moraine crest, asymmetrical
Older moraine crest, symmetry unknown
Moraine crest, asymmetrical
Moraine crest, symmetry unknown
Sinkhole extent
Detachment fault, well located
Detachment fault, approximately located, queried
Detachment fault, concealed
Normal fault, concealed, inferred from gravity data
Fault, gravity slide, well located
Fault, gravity slide, approximately located, queried
Fault, gravity slide, concealed
Fault, gravity slide, concealed, queried
Normal fault, well located
Normal fault, approximately located
Normal fault, approximately located, queried
Normal fault, concealed
Normal fault, concealed, queried

Thrust fault, well located
Thrust fault, approximately located
Thrust fault, approximately located, queried
Thrust fault, concealed
Thrust fault, concealed, queried
Older thrust fault, well located
Older thrust fault, concealed
Thrust fault with later normal offset, well located
Thrust fault with later normal offset, approximately located
Thrust fault with later normal offset, concealed
Fault, uncertain sense of movement, well located
Fault, uncertain sense of movement, approximately located
Fault, uncertain sense of movement, approximately located, queried
Fault, uncertain sense of movement, concealed
Fault, uncertain sense of movement, concealed, queried
Scarp, landslide
Bonneville shoreline, well located
Bonneville shoreline, approximately located
Provo shoreline, well located
Lake Bonneville regressional shoreline, well located
Lake Bonneville regressional shoreline, approximately located
Lake Bonneville transgressional shoreline, well located
Lake Bonneville transgressional shoreline, approximately located
Shoreline, uncertain, well located
Marker bed, Cambrian & older, well located
Marker bed, Cambrian & older, approximately located
Marker bed, Tertiary, well located
Marker bed, Tertiary, approximately located

Anticline, overturned, well located
Anticline, overturned, approximately located
Anticline, overturned, concealed
Anticline, upright, well located
Anticline, upright, approximately located
Anticline, upright, concealed
Monocline, antiformal bend, approximately located
Monocline, antiformal bend, concealed
Monocline, well located
Monocline, approximately located
Monocline, concealed
Monocline, synformal bend, approximately located
Monocline, synformal bend, concealed
Antiformal syncline, well located
Antiformal syncline, approximately located
Antiformal syncline, concealed
Syncline, overturned, well located
Syncline, overturned, approximately located
Syncline, overturned, concealed
Syncline, upright, well located
Syncline, upright, approximately located
Syncline, upright, approximately located, queried
Syncline, upright, concealed
Syncline, upright, concealed, queried
Lineament - contact, fold trace, or fault (offset uncertain)

Bedding, horizontal
Bedding, strike & dip, upright, approximate
Bedding, strike & dip, upright
Bedding, strike & dip, inclined, approximate, photo-interpreted
Bedding, strike & dip, upright, photogrammetric (3-point)
Bedding, strike & dip, overturned
Bedding, strike & dip, overturned, photogrammetric (3-point)
Bedding, strike & dip, overturned, top known
Bedding, strike & dip, upright, top known
Bedding, strike & dip, vertical
Cleavage, strike & dip, inclined
Cleavage, strike & dip, inclined, photogrammetric (3-point)
Water well
Normal fault ball & bar
Fault dip with dip number
Fault dip with dip number, photogrammetric (3-point)
Minor anticline, upright, field mapped
Minor anticline, overturned
Minor antiform, upright
Minor syncline, upright, field measured
Minor syncline, overturned
Minor synform, upright
Fold trace plunge arrow
Foliation, high grade, strike & dip, inclined
Joint, strike & dip, inclined
Planar feature, strike & dip, inclined photogrammetric (3-point)
Zircon U-Pb isotopic sample, see Table 5
Other isotopic sample, see text
Palynology sample, see Appendix & Table 6
Sinkhole
Select spring

DIAGRAMMATIC GEOLOGIC CROSS SECTION THROUGH OGDEN VALLEY, WEBER COUNTY, UTAH
Modified from Coogan (1992a)
Crosssection located at approximately 41°15' north on Plate A-1



APPENDIX A

GEOLOGIC MAP AND CROSS SECTION OF THE OGDEN VALLEY HYDROGEOLOGIC STUDY AREA

The geologic map of the Ogden Valley hydrogeologic study area shown on plates A-1 and A-2 is excerpted and modified from the interim geologic map of the Ogden 30 x 60-minute quadrangle, Utah and Wyoming, authored by J.C. Coogan and J.K. King and published in 2016 as Utah Geological Survey Open-File Report 653 (Coogan and King, 2016). The open-file report makes information available to the public that may not conform to UGS technical, editorial, or policy standards. Minor updates to the open-file report, made by King, are represented on plates A-1 and A-2 and in the following descriptions. The geologic cross section on plate A-2 is modified from J.C. Coogan's doctoral dissertation (Coogan, 1992a) by King.

Description of Map Units for the Geologic Map of the Ogden Valley Hydrogeologic Study Area

The following descriptions are based on the pamphlet that accompanies the geologic map of Coogan and King (2016), and as such, not all units described in this document are on plate A-1. Units are queried where classification is uncertain.

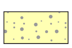
SURFICIAL DEPOSITS

Unconsolidated Material

QUATERNARY

Alluvial Deposits

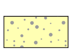
Where possible, alluvial deposits have been subdivided into relative ages, indicated by number and letter suffixes. These alluvial units are listed and described separately. The relative ages of the units, including terraces and fans, are in part based on deposit heights above present adjacent drainages in Morgan and Round Valleys, and this subdivision apparently works in and is applied in Ogden and Lost Creek Valleys and above the North, Middle, and South Forks of Ogden River (see tables 1 and 2 in Coogan and King, 2016). Despite the proximity to Lake Bonneville, alluvial deposits along and near Box Elder Creek in the northwest corner of the map area (Mantua quadrangle) seem to be slightly higher than age comparable deposits in Ogden Valley (see Coogan and King, 2016).



Qa, Qa?

Alluvium, undivided (Holocene and Pleistocene) – Sand, silt, clay, and gravel in stream and alluvial-fan sediments deposited near Lake Bonneville during the late Pleistocene; composition depends on source area; variably sorted; variably consolidated; deposits lack fan shape of Qaf and are distinguished from terraces (Qat) based on upper surface sloping toward adjacent streams from sides of drainage, or are shown where fans and terraces are too small to show separately at map scale; Qa with no suffix used where age uncertain or alluvium of different ages cannot be shown separately at map scale; Qa queried where relative age uncertain (see following paragraph); generally 6 to 20 feet (2–6 m) thick.

Units Qa2, Qay, Qap, Qab, Qapb, Qao, and Qaoe are described below; their relative age is queried where uncertain, generally due to height not fitting into ranges and/or typical order of surfaces contradicts height-derived age (see Coogan and King, 2016).



Qa2, Qa2?, Qay

Younger alluvium (mostly Holocene) – Like undivided alluvium, with Qay at, to slightly, above present drainages, unconsolidated, and not incised by active drainages; likely mostly Holocene in age and post-dates late Pleistocene Provo shoreline of Lake Bonneville; height above present drainages is low and is within certain limits, with suffix 1 (not present on this map) being the youngest and being at to slightly (<10 feet [3 m]) above drainages and suffix 2 being slightly higher and older, with y suffix where ages 1 and 2 cannot be separated; generally 6 to 20 feet (2–6 m) thick.

Qap, Qap?, Qab, Qab?,

Qapb

Lake Bonneville-age alluvium (upper Pleistocene) – Like undivided alluvium but height above present drainages appears to be related to shorelines of Lake Bonneville and is within certain limits, and unconsolidated to weakly consolidated; alluvium labeled Qap and Qab is related to Provo (and slightly lower) and Bonneville shorelines of Lake Bonneville (at ~4800 to 4840 feet [1463–1475 m] and 5180 feet [1580 m] in Ogden Valley), respectively; Qapb is used where more exact age cannot be determined, or where alluvium of different ages cannot be shown separately at map scale; Qap is up to about 50 feet (15 m) thick, with Qapb and Qab, at least locally up to 40 and 90 feet (12 and 27 m) thick, respectively. Queried where classification or relative age uncertain.

A prominent surface ("bench") is present on Qap and Qatp at about 4900 feet (1494 m) elevation and about 25 to 40 feet (8–12 m) above the South Fork Ogden River.

Qao, Qao?

Older alluvium (mostly upper Pleistocene) – Sand, silt, clay, and gravel above and likely older than the Bonneville shoreline; mapped on surfaces above Lake Bonneville-age alluvium (Qap, Qab, Qapb); composition depends on source area; at least locally up to 110 feet (34 m) thick.

Older alluvium is likely older than Lake Bonneville and the same age as Qafo, so likely Bull Lake age, 95,000 to 130,000 years old (see Chadwick and others, 1997, and Phillips and others, 1997); older alluvium (Qao, Qafo, Qato) may encompass an upper (pre-Bull Lake) and lower (Bull Lake) alluvial surface that is present in Ogden Valley but is not easily recognized in Morgan Valley (see Coogan and King, 2016).

Qaoe, Qaoe?

Older eroded alluvium (middle and lower Pleistocene) – Eroded alluvium located above Bonneville shoreline (at 5180 feet [1580 m] in Ogden Valley) with upper surfaces apparently above and older than adjacent pre-Lake Bonneville alluvium (Qao and Qafo); mostly sand, silt, and gravel in stream and alluvial-fan deposits; composition depends on source area; typically about 10 to 60 feet (3–20 m) thick.

Mapped on benches about 80 to 100 feet (24–30 m) above Cottonwood Creek in the Durst Mountain quadrangle, because deposits are higher than adjacent Qafo, though height above adjacent drainages is similar to Qao and Qafo (table 1 in Coogan and King, 2016) and deposits may be slightly older generation of older alluvium (see Qao above).

Unit Qaoe age estimated as older than 730 ka (>780 ka, Bassinot and others, 1994), based on reversed paleomagnetism in deposits west of the Weber River in the Morgan quadrangle (see Sullivan and others, 1988). But the sample site is one of the highest remnants of Qaoe and may be unit QTay. If this high remnant is QTay, it is greater than 780 ka, and Qaoe and Qafoe may be related to the Pokes Point lake cycle (Marine Oxygen Isotope Stage 12 by Oviatt and others, 1999) (pre-Illinoian B continental glaciation, >300 ka) and/or be pre-Pokes Point (Marine Oxygen Isotope Stage 16, "Nebraskan" continental glaciation, >500 ka) (see table A-1). The age(s) of units Qaoe and Qafoe may be refined if a Lava Creek B and/or Bishop ash were found in them (see table A-1).

Qal, Qal1, Qal2, Qal2?

Stream alluvium and flood-plain deposits (Holocene and uppermost Pleistocene) – Sand, silt, clay, and gravel in channels, flood plains, and terraces typically less than 16 feet (5 m) above river and stream level; moderately sorted; unconsolidated; along the same drainage Qal2 is lower than Qat2 and has likely been subject to flooding, at least prior to dam building; present in broad plains along the Ogden River and larger tributaries like Cottonwood and Lost Creeks, along Box Elder Creek, and in narrower plains of larger tributary streams; locally includes muddy, organic overbank and oxbow lake deposits; composition depends on source area, so in back valleys typically contains many quartzite cobbles recycled from the Wasatch Formation; mostly Holocene, but deposited after regression of Lake Bonneville from the late Pleistocene Provo shoreline; 6 to 20 feet (2–6 m) thick; greater thicknesses (>50 feet [15 m]) are reported in the map area (Utah Division of Water Rights, 2016), but likely include Lake Bonneville and older Pleistocene deposits (see Coogan and King, 2016).

Suffixes 1 and 2 indicate ages where they can be separated, with 1 including active channels and 2 including low terraces 10 to 20 feet (3–6 m) above the Ogden River and the South Fork Ogden River that may have been in the flood plain prior to damming of these waterways.

Qalp?

Lake Bonneville regression-age stream alluvium (upper Pleistocene?) – Pebble and cobble gravel, gravelly sand and silty sand, with minor clay in channel incised into Lake Bonneville deltaic and lacustrine deposits (Qldb) in Ogden Valley; queried because age uncertain; thickness uncertain.

Qat, Qat2, Qaty,

Qatp, Qatp?, Qatpb,

Qato

Stream-terrace alluvium (Holocene and Pleistocene) – Sand, silt, clay, and gravel in terraces above flood plains deposited near Lake Bonneville during the late Pleistocene; moderately sorted; variably consolidated; upper surfaces slope gently downstream; locally includes thin and small mass-movement and alluvial-fan deposits; where possible, subdivided into relative ages, indicated by number and letter suffixes, with 2 being the lowest/youngest terraces, typically about 10 to 20 feet (3–6 m) above adjacent flood plains; Qat with no suffix used where age unknown or age subdivisions of terraces cannot be shown separately at map scale; 6 to at least 20 feet (2–6+ m) thick, with Qatp 50 to 80 feet (15–24 m) thick in Mantua Valley.

Terraces labeled Qat2 are post-Lake Bonneville and are likely mostly Holocene in age. A terrace labeled Qaty is up to 20 feet (6 m) above the South Fork Ogden River, but may be related to the Provo or regressional shorelines. Terraces labeled Qatp are likely related to the Provo and slightly lower shorelines of Lake Bonneville (at and less than ~4820 feet [1470 m] in area), and with Qap form “benches” at about 4900 feet (1494 m) along the South Fork Ogden River. Qato terraces pre-date Lake Bonneville. Relative age queried (Qatp?) where age is uncertain, generally due to height not fitting into ranges in Coogan and King (2016) and/or typical order of surfaces contradicts height-derived age.

Qaf, Qaf?

Alluvial-fan deposits, undivided (Holocene and Pleistocene) – Mostly sand, silt, and gravel that is poorly bedded and poorly sorted deposited near Lake Bonneville during the late Pleistocene; variably consolidated; includes debris flows, particularly in drainages and at drainage mouths (fan heads); generally less than 60 feet (18 m) thick; in subsurface, about 100 to 150 feet (30–45 m) thick in Mantua Valley beneath Qac (see Coogan and King, 2016). Qaf with no suffix used where age uncertain or for composite fans where portions of fans with multiple ages cannot be shown separately at map scale; toes of some fans have been removed by human disturbances, so their age cannot be determined. Qaf queried where relative age uncertain, generally due to height not fitting into ranges in Coogan and King (2016) and/or typical order of surfaces contradicts height-derived age (see following paragraphs).

Subdivided alluvial fans (Qaf1, Qaf2, Qafy, Qafp, Qafpb, Qafb, Qafo, Qafoe) are listed and described separately below. Their relative ages are queried where the age is uncertain, generally due to the height not fitting into the ranges in Coogan and King (2016) and/or the typical order of surfaces contradicts height-derived age.

Qaf1, Qaf2, Qaf2?, Qafy,

Qafy?

Younger alluvial-fan deposits (Holocene and uppermost Pleistocene) – Like undivided alluvial fans, but all of these fans are unconsolidated and should be considered active; height above present drainages is low and is within certain limits; generally less than 40 feet (12 m) thick; fans are shown as Qafy where Qaf1 and Qaf2 cannot be separated, and all contain well-rounded recycled Lake Bonneville gravel.

Qaf1 fans are active because they impinge on and deflect present-day drainages. Qaf2 fans appear to underlie Qaf1 fans but may be active. Qafy fans are active, impinge on present-day floodplains, divert active streams, overlie low terraces, and/or cap alluvial deposits (Qap) related to the Provo and regressive shorelines. Therefore, Qafy fans are younger than the Provo shoreline and likely mostly Holocene in age but may be as old as latest Pleistocene and may be partly older than Qaf1 fans.

Qafp, Qafp?, Qafb, Qafb?, Qafpb, Qafpb?

Lake Bonneville-age alluvial-fan deposits (upper Pleistocene) – Like undivided alluvial fans, but height above present drainages appears to be related to shorelines of Lake Bonneville and is within certain limits (see table 1 in Coogan and King, 2016); these fans are inactive, unconsolidated to weakly consolidated, and locally dissected; fans labeled Qafp and Qafb are related to the Provo (and slightly lower) and Bonneville shorelines of late Pleistocene Lake Bonneville, respectively, while unit Qafpb is used where fans may be related to the Provo or Bonneville shoreline (for example Qafpb is ~40 feet [12 m] above Lost Creek Valley), or where fans of different ages cannot be shown separately at map scale; Qafp fans typically contain well-rounded, recycled Lake Bonneville gravel and sand and are moderately well sorted; generally 10 to less than 60 feet (3–18 m) thick. Fans labeled Qafpb? are above the Bonneville shoreline and might be Qafo; see the note under Qao about two possible ages of older alluvium (Qao, Qato, and Qafo).

Qafo, Qafo?

Older alluvial-fan deposits (mostly upper Pleistocene) – Incised and at least locally dissected fans of mostly sand, silt, and gravel that is poorly bedded and poorly sorted; includes debris flows, particularly in drainages and at drainage mouths (fan heads); older fans are typically above the Bonneville shoreline, with an eroded bench at the shoreline; upstream and above the Bonneville shoreline, unit Qafo is topographically higher than fans related to the Bonneville shoreline (Qafb), and is typically dissected; generally less than 60 feet (18 m) thick. In Mantua Valley, exposed thickness up to about 100 feet (30 m), but water wells were still in gravelly to bouldery valley fill at depths of 505 and 467 feet (154 and 142 m), respectively, and red coloration that may indicate Wasatch Formation bedrock was not noted (see Bjorklund and McGreevy, 1973, p. 16).

Amino-acid age estimates presented in Sullivan and Nelson (1992) imply unit Qafo in Morgan Valley (south of map area) considerably predates Lake Bonneville and is middle Pleistocene in age (≥400 ka). However, the Bonneville shoreline is obscure on this fan, and soil-carbonate age estimates (>70–100 ka) and other amino-acid age estimates (~98–155 ka) in Sullivan and others (1988) imply these older fans are related to Bull Lake glaciation (95,000 to 130,000 years old; see Chadwick and others, 1997; Phillips and others, 1997). As noted under Qao, Qafo deposits may contain two ages (levels) of alluvial surfaces that are not easily recognized in Morgan Valley but are recognized along the North and South Forks of Ogden River and in Lost Creek Valley.

Qafoe, Qafoe?

Older eroded alluvial-fan deposits (middle and lower Pleistocene) – Typically eroded fan remnants located above and apparently older than pre-Lake Bonneville older alluvial deposits (Qafo, Qao); contains mostly sand, silt, and gravel that is poorly bedded and poorly sorted; less bouldery and lower relative to high-level alluvium (QTa, QTay, QTao, QTaf); 6 to 60 feet, or more (2–18+ m) thick. Unit likely same age as Qaoe (Marine Oxygen Isotope Stage 12 and/or 16; middle Pleistocene), but possibly greater than the 780 ka paleomagnetic reversal (see table A-1) and early Pleistocene in age. Queried in Mantua Valley, and above Middle and North Forks of Ogden River, because as high as QTay in Morgan Valley (see Coogan and King, 2016). Queried in North Ogden quadrangle on Pleasant View salient because not very eroded and may be unit Qafo; also compare mapping of af5 of Personius (1990) to afo of Nelson and Personius (1993).

Qafoe–QTaf

Older eroded fan and/or pediment-mantle deposits (middle or lower Pleistocene) – Gravel, sand, silt, and clay in alluvium and colluvium that cap surfaces that are partly correlative with the pre-Lake Bonneville McKenzie Flat geomorphic surface of Williams (1948) (see McCalpin, 1989); north of map area in Paradise quadrangle, McCalpin (1989) described this unit (his afo) as a relatively thin discontinuous veneer, less than 33 feet (10 m) thick, forming dissected surfaces on a pediment "cut" on Tertiary Salt Lake Formation; Mullens and Izett (1964) described the deposits as quartzite conglomerate (to boulder size) resting with angular unconformity on Salt Lake Formation conglomerate; mapping indicates the surface edges are about 100 to 400 feet (30–120 m) above adjacent drainages.

McKenzie Flat is along the axis of a broad open syncline in the underlying Salt Lake Formation with eroded remnants of these deposits dipping west from the East Cache fault zone to McKenzie Flat, with dips that are nearly the same as bedding in the underlying Salt Lake Formation in the east limb of the syncline. This implies the west-dipping surfaces are capped by residual deposits rather than being tilted fan deposits, and the flat may have the same origin. Alternatively, the flat and limb deposits have two different origins, fan and lag/residual, respectively. Fans on McKenzie Flat could be middle Pleistocene (McCalpin, 1989; see also Sullivan and Nelson, 1992) (Little Valley or Pokes Point lake cycle) and/or early Pleistocene (after Sullivan and others, 1988) in age; although the lower heights above the adjacent drainages fit this middle and early Pleistocene age (Qafoe), the upper limit is in the range of Quaternary-Pliocene fans (QTaf) (see table 1 in Coogan and King, 2016).

The Precambrian (Neoproterozoic) and Cambrian quartzite boulders could be recycled from the Salt Lake Formation conglomerate, the Wasatch Formation, or be from quartzite exposures to the south in the James Peak quadrangle. The latter implies transport to the north into lower parts of Cache Valley. When the boulders were transported is more problematic, since they could be a lag from the underlying Salt Lake Formation rather than being transported during Pleistocene fan deposition.

Another gravel-armored surface (flat and possible fan remnant), the Hyrum Bench of Ezell (1953), is present on the Salt Lake Formation in the northwest part of the James Peak quadrangle (separated into Qafoe and QTa on the Ogden Valley map) and southwest part of the Paradise quadrangle. This Hyrum Bench surface is at a slightly higher altitude than the surface on McKenzie Flat (~5800–6000 feet [1770–1830 m] versus ~5400–5600 feet [1650–1710 m]) but may be related because several normal faults mapped between the two flats in the James Peak quadrangle may offset the surfaces (see map). These altitude differences are relatively small and Williams (1958) stated the two surfaces were co-extensive, reasoning they were parts of a larger surface.

Glacial deposits

Qg, Qg?, Qgm, Qgm?,

Qga, Qga?

Glacial till and outwash, undivided age (Holocene and upper and middle? Pleistocene) – Qg is undivided glacial deposits (till and outwash) of various ages; till is non-stratified, poorly sorted clay, silt, sand, and gravel, to boulder size; Qgm is moraines of unknown age that are mapped where distinct shapes of end, recessional and lateral moraines are visible; outwash (Qga) is stratified and variably sorted, but better sorted and bedded than till due to alluvial reworking; Qga is mapped directly downslope from other glacial deposits where it is thick enough to obscure older deposits and bedrock, and where it can be separated from ground moraine (mapped as Qg) and alluvium (mapped as Qa_); locally include mass-movement (Qms, Qmt, Qct) and rock glacier deposits that are too small to show separately at map scale; 6 to 150 feet (2–45 m) thick. Undivided because age uncertain or where deposits with multiple ages cannot be shown separately at map scale; queried where interpretation as glacial deposits is uncertain. Glacial deposits are prone to slope failures.

Qgy, Qgy?, Qgmy?

Younger glacial till and outwash (Holocene) – Mapped in cirques as undivided (Qgy) and distinct moraines or protalus deposits (hence query on Qgmy); moraines are mapped where distinct shapes of end and lateral moraines and, locally, recessional moraines are visible; include 8000- to 10,000-year-old and possibly middle Holocene (~5000 years old) deposits with very poorly developed soil and sharp, mostly non-vegetated moraines; ages modified from Madsen and Currey (1979); includes un-vegetated, angular, cobble- to boulder-size debris with little matrix in protalus 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); Qgy queried where age uncertain; Pinedale glacial deposits (Qgp, Qgmp, Qgap) are downslope from younger deposits; estimate 6 to 60 feet (2–18 m) thick. Glacial deposits are prone to slope failures because they are clay rich.

Qgp, Qgmp,

Qgmp?,

Qgap

Pinedale glacial till and outwash (upper Pleistocene) – Pinedale-age (~12,000 to 30,000 years old) (Gosse and others, 1995; Phillips and others, 1997) deposits mapped as undivided (Qgp), distinct moraines (Qgmp), and outwash (Qgap); moraines are mapped where distinct shapes of end, recessional, and lateral moraines are visible; mapped moraines have poorly developed soil and moderate to sharp moraine morphology (estimate 19,000 years old); upslope these units include partially vegetated recessional deposits from glacial stillstands and/or minor advances (deglacial pauses) about 12,000 to 15,000 years ago; ages modified from Madsen and Currey (1979); Qgmp queried where age uncertain; estimate 6 to 100 feet (2–30 m) thick; older glacial deposits (Qgo, Qgmo, Qgao) are downslope from Pinedale moraine. Glacial deposits are prone to slope failures because they are clay rich.

Qgo, Qgo?, Qgmo, Qgmo?,

Qgao, Qgao?

Older glacial till and outwash (upper and middle? Pleistocene) – Mapped down-drainage from and locally laterally above Pinedale deposits as undivided (Qgo), till in distinct vegetated moraines (Qgmo), and outwash (Qgao); see sub-unit differences under undivided glacial units (Qg, Qgm, Qga); mapped moraines have well-developed soil and subdued moraine morphology; may have two Bull Lake moraines and deposits, or Bull Lake and pre-Bull Lake deposits; Bull Lake age about 95,000 to 130,000 years old (see Chadwick and others, 1997; Phillips and others, 1997); Qgo queried where material may not be glacial deposits; Qgmo queried where age uncertain; Qgao queried where age uncertain or material may not be glacial outwash; estimate 6 to 160 feet (6–50 m) thick and even thicker, at least 200 feet (60 m) thick, along Cutler Creek (Mantua quadrangle). Glacial deposits are prone to slope failures because they are clay rich.

Some glacial deposits are much farther from cirques than any other deposits and are potential pre-Bull Lake glacial deposits. These deposits are above Cutler Creek and the upper reaches of the North Fork Ogden River (Mantua quadrangle), and in the Maples area (Snow Basin quadrangle). The pre-Bull Lake deposits may be related to pre-Illinoian continental glaciation (>300 ka) (Pokes Point lake cycle >271 ka, see Balch and others, 2005; or most likely ~450 ka, Marine Oxygen Isotope Stage 12, see Oviatt and others, 1999), or be some pre-Pokes Point glaciation (possibly "Nebraskan" continental glaciation, >500 ka; or Sacagawea Ridge age, ~600 ka, see Chadwick and others, 1997; Phillips and others, 1997) (see table A-1).

Mass-movement deposits

Qmdf, Qmdf?

Debris- and mud-flow deposits (Holocene and upper and middle? Pleistocene) – Very poorly sorted, clay- to boulder-size material in unstratified deposits characterized by rubbly surface and debris-flow levees with channels, lobes, and mounding; variably vegetated; in drainages typically form mounds, an indication of more viscous Qmdf, rather than being flat like unit Qac; Qmdf queried where may not be mostly debris- and mud-flow deposits; many debris flows cannot be shown separately from alluvial fans at map scale; 0 to 40 feet (0–12 m) thick. Age(s) uncertain; deposits in drainages likely post-date the Provo shoreline of Lake Bonneville, while deposits above drainages are likely as old as Bull Lake glaciation but could pre-date Bull Lake glaciation and be middle Pleistocene.

Qms, Qms?, Qmsy, Qmsy?,

Qmso, Qmso?

Landslide deposits (Holocene and upper and middle? Pleistocene) – Poorly sorted clay- to boulder-size material; includes slides, slumps, and locally flows and floods; 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 material during emplacement; Qms may be in contact with Qms when landslides are different/distinct; thickness highly variable, up to about 20 to 30 feet (6–9 m) for smaller slides, and 80 to 100 feet (25–30 m) thick for larger landslides. Qmsy and Qmso queried where relative age uncertain; Qms queried where classification uncertain. Numerous landslides are too small to show at map scale and more detailed maps shown in the index to geologic mapping in Coogan and King (2016) should be examined.

Qms without a suffix is mapped where the age is uncertain (though likely Holocene and/or late Pleistocene), where portions of slide complexes have different ages but cannot be shown separately at map scale, or where boundaries between slides of different ages are not distinct. Estimated time of emplacement is indicated by relative-age letter suffixes with: Qmsy mapped where landslides deflect streams or failures are in Lake Bonneville deposits, and scarps are variably vegetated; Qmso typically mapped where deposits are "perched" above present drainages, rumpled morphology typical of mass movements has been diminished, and/or younger surficial deposits cover or cut Qmso. Lower perched Qmso deposits are at Qao heights above drainages (95 ka and older) and the higher perched deposits may correlate with high level alluvium (QTa_) (likely older than 780 ka) (see Coogan and King, 2016). Suffixes y and o indicate probable Holocene and Pleistocene ages, respectively, with all Qmso likely emplaced before Lake Bonneville transgression. These older deposits are as unstable as other slides, and are easily reactivated with the addition of water, be it irrigation or septic tank drain fields.

Qms(QTaf), Qms(QTms), Qms(rx), Qms(Tu), Qms(Trx), Qms(Tsl), Qms(Tcg), Qms(Ts), Qms(Tn), Qms(Tnf), Qms(Tn/Tw), Qms(Tw), Qms(Keh), Qms(Mg), Qms(Ml), Qms(Dwc), Qms(Sl), Qms(Cbm), Qms(Cm), Qms(Ct), Qms(Ct?), Qms(Zcc), Qms(Zkc), Qms(Zrx), Qms(Zmc), Qms(Zmcc), Qms(ZYp), Qms(Zpu), Qms(ZYpm), Qms(YXf), Qms(Xfc), Qms(Xfcg), Qms(Xfcg?)

Qms?(Qlf), Qms?(Qafoe?), Qms?(QTaf), Qms?(QTaf/Tw), Qms?(QTms), Qms?(rx), Qms?(Thv), Qms?(Tsnf), Qms?(Tu), Qms?(Tsl), Qms?(Tcg), Qms?(Tcg?), Qms?(Ts), Qms?(Tn), Qms?(Tw), Qms?(Keh), Qms?(PIPw), Qms?(Mh), Qms?(Ogc), Qms?(Cn), Qms?(Cbo), Qms?(Cm), Qms?(Co), Qms?(Ct), Qms?(Cgc), Qms?(Zm), Qms?(Zcc), Qms?(Zpc), Qms?(Zkc), Qms?(Zrx), Qms?(Zmc), Qms?(Zmcc), Qms?(ZYp), Qms?(Zpu), Qms?(Zpu?), Qms?(Zpd?), Qms?(ZYpm), Qms?(YXf), Qms?(YXfq), Qms?(YXfs), Qms?(Xfc), Qms?(Xfcg)

Qmso(QTcg?), Qmso(Ts), Qmso(Tn), Qmso(Keh), Qmso(Xfc)

Qmso?(Qafoe), Qmso?(QTcg?), Qmso?(Ts), Qmso?(Tcg), Qmso?(Tn), Qmso?(Xfc)

Block landslide and possible block landslide deposits (Holocene and upper and middle? Pleistocene) – Mapped where nearly intact block is visible in landslide (mostly block slide) with stratal strikes and dips that are different from nearby in-place bedrock; unit involved in landslide shown in parentheses, for example Qms(Tw), and composition depends on bedrock unit; rx shown where bedrock unit in block not known or multiple units are in the block, with Zrx shown where the units are Neoproterozoic; see surficial deposits or rock unit in parentheses for descriptions of blocks; thickness highly variable, up to about 20 to 30 feet (6–9 m) for smaller slides, and cross sections show larger blocks are about 150 feet (45 m) thick. Relative ages are like those for other landslide deposits (Qms, Qmso).

Qms and Qmso queried (Qms?, Qmso?) where bedrock block may be in place, that is stratal strikes and dips in queried block are about the same as nearby in-place bedrock.

Qml, Qml?

Lateral-spread deposits (Holocene and upper Pleistocene?) – Clay, silt, and fine-grained sand, with minor gravel deposited mostly offshore in Lake Bonneville (unit Qlf) and later emplaced by lateral spreading due to liquefaction during earthquake ground shaking; largely poorly drained, possibly due to shallow groundwater; contain minor younger alluvial and marsh deposits and possibly lacustrine deposits; "break-away" scarps located upslope and at least locally cut foreshore Lake Bonneville (Qlg, Qls, Qlsp) and deltaic (Qdp) deposits, incorporating these coarser materials into lateral-spread deposits; lobate toes of spreads typically higher than surrounding topography; contain hummocks, ridges, swales, and irregular depressions; unstratified to tilted strata to highly contorted bedding visible in excavations like the Ogden area brick plant pit (see for examples Miller, 1980; Harty and Lowe, 2003); thickness highly variable. Queried where may not be part of lateral spread.

Age uncertain as younger alluvial fans deposited on the lateral spreads appear to be related to the regression from the Provo shoreline of Lake Bonneville (see Personius, 1990) as well as appear to post-date Lake Bonneville (Nelson and Personius, 1993; see also Harty and Lowe, 2003). On 1937 aerial photographs, several lateral spreads of different ages appear to be present, because different lobes are visible and some spread margins appear to impinge on older spreads.

Qm

Mass-movement deposits, undivided (Holocene and Pleistocene) – Poorly sorted to unsorted clay- to boulder-size material; includes landslides (slides, slumps, and flows), colluvium, talus, and alluvium that is mostly composed of debris-flow deposits; mapped where several mass-movement processes may contribute to deposits or where mapping separate, small, intermingled areas of different kinds of mass movements is not possible at map scale; the larger debris-flow component in Qm is difference between Qm and Qmc; composition depends on local sources; 0 to 40 feet (12 m) thick.

Qmc

Landslide and colluvial deposits, undivided (Holocene and Pleistocene) – Poorly sorted to unsorted clay- to boulder-size material; 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 and debris flow and flood deposits; 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; 6 to 40 feet (2–12 m) thick. These deposits are as unstable as other landslide units (Qms, Qmsy, Qmso).

Qmt

Talus (Holocene and Pleistocene) – Unsorted clay- to boulder-size angular debris (scree) at the base of and on steep mostly unvegetated slopes; only larger debris fields can be shown at map scale and includes smaller rockfall deposits; locally includes pro-talus ramparts and minor colluvium; also includes rock-glacier deposits too small to show separately at map scale; grades laterally into Qct; 0 to 30 feet (0–9 m) thick.

Qmrf

Rock-fall deposits (Holocene and Pleistocene) – Unsorted, angular pebble- to block to small house-size carbonate-rock debris at north edge of Dairy Ridge quadrangle and in Mantua quadrangle (section 38, T. 8 N., R. 1 W.); cliff-face sources distinct; only largest debris fields can be shown at map scale; may be from one or multiple events; thickness uncertain.

Qct

Colluvium and talus, undivided (Holocene and Pleistocene) – Unsorted clay- to boulder-size angular debris (scree) at the base of and on steep, typically partly vegetated slopes; shown mostly on steep slopes of resistant bedrock units; 6 to 30 feet (2–9 m) thick.

Qc

Colluvium (Holocene and Pleistocene) – Unsorted clay- to boulder-size material; includes material moved by slopewash and soil creep; composition depends on local sources; as shown generally 10 to 20 feet (3–6 m) thick; not shown where less than 10 feet (3 m) thick.

Lacustrine deposits

Qly, Qly?

Younger lacustrine deposits (Holocene) – Fine-grained material and locally marsh deposits in lakes outside the Great Salt Lake basin; includes deposits in karst sinks near Mantua and near Maples recreation area (Snow Basin quadrangle); queried where may be mostly marsh deposits; some material may not be younger than Lake Bonneville; likely less than 20 feet (6 m) thick.

Ql, Ql?

Lake Bonneville deposits, undivided (upper Pleistocene) – 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 in scarps or construction cuts; thickness uncertain.

Qlf, Qlf?, Qlfb, Qlfb?

Fine-grained lacustrine deposits (Holocene and upper Pleistocene) – Mostly silt, clay, and fine-grained sand deposited near- and off-shore in Lake Bonneville; typically mapped as Qlf below the Provo shoreline (P) because older transgressive (Qlfb) deposits are indistinguishable from younger regressive deposits; mapped as Qlfb above the Provo shoreline because these deposits can only be related to the Bonneville shoreline (B) and transgression; grades upslope with more sand into Qls or Qlsp; typically eroded from shallow Norwood Formation in Ogden Valley and at least 12 feet (4 m) thick in an excavation near Mountain Green in Morgan Valley. Qlf and Qlfb queried where grain size is uncertain.

Qls, Qls?, Qlsp, Qlsb, Qlsb?

Lake Bonneville sand (upper Pleistocene) – Mostly sand with some silt and gravel deposited nearshore below and near the Provo shoreline (Qlsp) and between the Provo and Bonneville shorelines (Qlsb); Qls mapped downslope from slope break below Provo shoreline beach deposits where thin Lake Bonneville regressional sand may overlie transgressional sand; grades downslope into unit Qlf with decreasing sand content and laterally with more gravel into units Qdlp, Qdlb, and upslope with more gravel into unit Qlgb; Qls and Qlsb queried where grain size or unit identification uncertain; may be as much as 75 feet (25 m) thick, and thickest near Ogden; typically less than 20 feet (6 m) thick in Morgan Valley and suspect about the same thickness in Ogden Valley; may include small deltas and deltas that lack typical delta shape.

Qlg, Qlg?, Qlgp, Qlgb, Qlgb?

Lake Bonneville gravel and sand (upper Pleistocene) – Mostly interbedded pebble and cobble gravel and sand deposited along beaches and slightly offshore; varies from clast supported to only rare gravel clasts in a matrix of sand and silt; grades downslope and, locally, laterally into finer grained deposits (Qls, Qlsp, Qlsb); mapped as Qlg downslope from topographic slope break of Provo and regressive beaches (Qlgp) because gravel and sand may be related to Lake Bonneville transgression on this gentler slope; also mapped as Qlg where Provo shoreline not distinct or relationships to shorelines uncertain; Qlg and Qlgb queried where grain size or unit identification uncertain; up to about 100 feet (30 m) thick in gravel pits but less than 20 feet (6 m) thick on most valley slopes. Constructional landforms (beach ridges, bars, and spits) and transgressive (t) shorelines limited in Ogden Valley map area.

Qlgp is mapped in beaches near and below the erosional bench at the Provo shoreline (P); gravel typically subrounded to rounded, but locally along bedrock mountain fronts marked by a carbonate-cemented, poorly sorted, angular pebble to boulder gravel in a sandy matrix.

Qlgb is mapped in beaches mostly just downslope from Bonneville shoreline (B), typically an eroded bench, and above Provo shoreline; deposited during transgression to and occupation of the Bonneville shoreline; clasts typically subrounded to rounded but contains subangular to angular clasts on steep bedrock mountain fronts; mountain front Bonneville shoreline benches covered by locally mappable (> 6 feet [2 m] thick) colluvium and talus (Qmt, Qc, Qct).

Deltaic deposits

Lake Bonneville deltaic deposits (upper Pleistocene) – Pebble and cobble gravel in a matrix of sand and minor silt; interbedded with thin sand beds; moderately to well sorted within beds; clast to matrix supported; deposited as foreset beds with dips of 30 to 35 degrees; distinct foresets allow separation from mixed lacustrine deposits (Qdlp, Qdlb).

Qdp

Provo-shoreline and regressive deltaic deposits – Present at mouth of North Ogden Canyon and north of the mouth of Ogden Canyon below the Provo shoreline; clasts typically subrounded to rounded; much of Qdp material may have been redeposited from Bonneville-shoreline lacustrine and alluvial deposits during and soon after Bonneville flood; may be as much as 100 feet (30 m) thick at mouth of Ogden Canyon. These deltaic deposits are prone to slope failures on steep slopes because they are not cohesive (lack clay).

Qdb

Transgressive and Bonneville-shoreline deltaic and lacustrine deposits – Only mapped separately on slope between Qafb and Qlgb just below the Bonneville shoreline in Mantua Valley; subangular to subrounded clasts; thickness not known.

Mixed lacustrine deposits

Qdlp

Provo-shoreline and regressive deltaic and lacustrine deposits (upper Pleistocene) – Mostly sand, silty sand, and gravelly sand deposited near shore in Lake Bonneville; extensive below Provo shoreline between Ogden and Weber Rivers along the Wasatch front; related to the Provo and slightly lower regressional shorelines; regressive (r) shorelines on the Qdlp deposits indicate lake reworking of deltaic deposits (Qdp or Qadp) and a mixed origin; may be as much as 100 feet (30 m) thick. These deposits are prone to slope failures on steep slopes because they are not cohesive (lack clay).

Qdlb, Qdlb?

Transgressive and Bonneville-shoreline deltaic and lacustrine deposits (upper Pleistocene) – Mostly sand, silty sand, and gravelly sand deposited near shore in Lake Bonneville; related to transgression to and occupation of the Bonneville shoreline with lacustrine deposits covering deltaic deposits; near mouth of Coldwater Canyon (North Ogden quadrangle) contain more cobbles and overall more gravel; 0 to at least 40 feet (12 m) thick in Ogden Valley. These deposits are prone to slope failures on steep slopes because they are not cohesive (lack clay).

Qadp, Qadp?

Provo-shoreline and regressive alluvial and deltaic deposits (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 alluvial fan and delta; mapped below/near the Provo shoreline and related to the Provo and slightly lower regressional shorelines; deposits prominent east of Brigham City (Mantua quadrangle) and at mouth of North Ogden Canyon; deposited as delta foreset beds with dips of 30 to 35 degrees that allow separation from mixed lacustrine deposits (Qdlp); deltaic deposits at least 40 feet (12 m) thick and contain subrounded to well-rounded pebble and cobble gravel in a matrix of sand and silt with interbeds of sand and silt; capped by gently dipping alluvial-fan and stream topset beds that are less than 16 feet (5 m) thick, are poorly to moderately sorted, silty to sandy, subangular to well-rounded pebble and cobble gravel, and contain subangular to angular clasts in a matrix of sand and silt with interbeds of sand and silt (see units lpd and alp of Personius, 1990).

The Provo shoreline fan-delta sediments were eroded from Bonneville-shoreline lacustrine and alluvial deposits, contain 20 to 70 percent rounded recycled Lake Bonneville clasts (Personius, 1990), and were redeposited during and soon after the Bonneville flood, which occurred during the drop of Lake Bonneville to the Provo shoreline. The Qadp unit probably includes Provo-stillstand deltaic deposits, sub-Provo-stillstand (regressional) alluvial-fan and lacustrine-deltaic deposits that contain abundant reworked materials from the Provo-shoreline delta, and locally overlying alluvial-fan deposits. Personius (1990) noted that deposits at the mouth of Box Elder Canyon are a fan-delta. A fan-delta is built when an alluvial fan enters a lake or ocean, and includes both the fan and the delta.

Qadb, Qadb?

Transgressive and Bonneville-shoreline alluvial and deltaic deposits (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 alluvial fan and delta; include rounded to subangular clasts in a matrix of sand and silt with interbeds of sand and silt; mapped above the Provo shoreline and deposited as lake transgressed to and was at the Bonneville shoreline; typically better sorted delta and lake deposits over poorly sorted alluvial-fan deposits; 0 to at least 40 feet (0–12+ m) thick. Note that the Bonneville-shoreline fan-delta unit (Qadb) is typically higher than the related alluvial units (Qab, Qafb) (see Coogan and King, 2016). A fan-delta is built when an alluvial fan enters a lake or ocean and includes both the fan and the delta.

Qla, Qla?

Lake Bonneville lacustrine deposits and post- and pre-Lake Bonneville alluvial deposits, undivided (Holocene and upper? 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 thin stream and fan deposits, and where lake deposits are thin and overlie older alluvial deposits; unit queried where may be dominantly alluvium; deposits typically eroded from shallow Norwood Formation; mostly mapped near Bonneville shoreline; thickness uncertain.

Qlamh

Lacustrine, marsh, and alluvial deposits, undivided (Historical) – Sand, silt, and clay mapped where streams enter Pineview Reservoir, and reservoir levels fluctuate such that lacustrine, marsh, and alluvial deposits are intermixed; thickness uncertain.

Spring deposits

Qsm

Spring deposits (Holocene and upper Pleistocene?) – Wet, fine-grained, organic-rich sediment associated with springs, ponds, seeps, and wetlands; mapped below Bonneville shoreline in Ogden Valley and below Provo shoreline in North Ogden quadrangle; at least 5 feet (1.5 m) thick.

Qst

Spring travertine (Holocene and Pleistocene) – Hard, vesicular to compact carbonate mapped downstream from Causey Spring (Causey Dam quadrangle); likely at least as old as Pleistocene; up to 60 feet (18 m) thick. Source of spring apparently is fault contact between the Little Flat and Monroe Canyon Formations. Causey Spring may be related to karst in Monte Cristo Range north of the study area.

Mixed deposits

Qac

Alluvium and colluvium (Holocene and Pleistocene) – Unsorted to variably sorted gravel, sand, silt, and clay in variable proportions; includes stream and fan alluvium, colluvium, and, locally, mass-movement deposits too small to show at map scale; typically mapped along smaller drainages that lack flat bottoms; 6 to 20 feet (2–6 m) thick.

Qcg

Gravelly colluvial deposits (Holocene and Pleistocene) – Gravelly materials present downslope from gravel-rich rock and deposits of various ages (for example units Keh, Tw, Tcg, Thv, QTaf, QTa, Qafoe, Qaoe, Qafo, and Qa); may contain residual deposits; 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; generally 6 to 20 feet (2–6 m) thick.

Qmg, Qmg?

Mass-movement and glacial deposits, undivided (Holocene and Pleistocene) – Unsorted and unstratified clay, silt, sand, and gravel; 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, but may be thicker in Mantua, James Peak, North Ogden, and Huntsville quadrangles.

Uncertain

Qng

Colluvial and residual gravel deposits (Holocene and Pleistocene) – Poorly sorted pebble to boulder gravel in a matrix of silt and sand; gravel of uncertain origin, but probably includes colluvium and residuum, and at least locally glacial deposits (for example near Powder Mountain) and alluvium; mostly gravel-armored deposits on and near alluvial and colluvial deposits like units Qcg, QTay?, QTao?, and QTaf; locally on gravel-rich bedrock (Thv, Tcg, Tw, and Keh) and Paleozoic quartzite (Cgcu and Ct); typically have gently dipping upper surface; present on Elk Mountain, and near high-level fans (QTaf) near head of Strawberry Creek (Snow Basin quadrangle); generally 6 to 20 feet (2–6 m) thick.

Human disturbances

Qh, Qh?

Human disturbances (Historical) – Mapped disturbances obscure original deposits or rocks by cover or removal; only larger disturbances that pre-date the 1984 aerial photographs used to map the Ogden 30 x 60-minute quadrangle are shown; includes engineered fill, particularly along Interstate Highway 84, the Union Pacific Railroad, and larger dams, as well as aggregate operations, gravel pits, sewage-treatment facilities, brick plant and clay pit, Defense Depot Ogden (Browning U.S. Army Reserve Center), and low dams along several creeks.

QUATERNARY AND TERTIARY

The change in the Quaternary-Tertiary boundary favored by Europeans from about 1.8 Ma, roughly the top of the Olduvai normal paleomagnetism subchron, to about 2.6 Ma, roughly the top of the normal paleomagnetism marking the top of the Gauss chron (Gibbard and Cohen, 2008), does not affect mapping and labeling of the following unconsolidated units because Coogan and King (2016) did not have any paleomagnetic data. However, carving nearly a million years out of the episodically shrinking Pliocene means rocks Coogan and King (2016) have listed as Pliocene, like the fanglomerate of Huntsville (Thv) and various Salt Lake Formation units (Tslc, Tsl, Tsnf), may be Quaternary even though they are consolidated (rock). Coogan and King (2016) chose to keep rocks (consolidated and/or lithified) as Tertiary and unconsolidated deposits as Quaternary and Quaternary/Tertiary to emphasize their hydrologic, erosional and geotechnical differences.

QTa, QTa?, QTay?, QTao, QTao?

High-level alluvium (lower Pleistocene and/or Pliocene) – Gravel, sand, silt, and clay above other stream-terrace and alluvial-fan deposits; typically more bouldery than lower alluvium (including units Qafoe and Qaoe); at least locally gravel-armored and poorly sorted; where possible, divided into younger (y) and older (o) based on height of deposits above drainages (see table 1 in Coogan and King, 2016) and elevation difference of more than 150 feet (45 m) on adjacent deposits; but heights above drainages overlap and appear to decrease up slope; estimate 240 feet (75 m) thick along Lost Creek and Box Elder Creek but only 10 to 80 feet (3–24 m) thick south of map area in Morgan Valley.

Various QTa units are queried where relative age is uncertain due to overlap and wide range in heights above drainages (see tables 1 and 2 in Coogan and King, 2016).

QTa along Box Elder Creek is about 240 to 300 feet (75–90 m) above the present creek and upper surface altitudes (5800 to 6000 feet [1770–1830 m]) are about those of the McKenzie Flat surface (mapped as Qafoe–QTaf).

Deposits in Eden Pass (North Ogden divide) are at elevations of up to about 6400 feet (1950 m) and were noted by Eardley (1944, p. 886), who suggested they were probably related to the Weber Valley surface.

High-level alluvium is likely 780 ka or older based on paleomagnetic reversal in Qaoe (see Coogan and King, 2016) and location above Qaoe. The age(s) of these deposits and unit QTaf may be refined if a Lava Creek B, Bishop, Mesa Falls, and/or Huckleberry Ridge ash were found in them (see table A-1).

QTaf, 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 QTao); typically more bouldery than alluvium lower than QTay (including units Qafoe and Qaoe); at least locally gravel-armored and poorly sorted (see for example Eardley, 1944, p. 874); forms fan-head remnants near head of Strawberry Creek (Snow Basin quadrangle) and less-eroded fans in Morgan Valley south of the map area; queried where may be unit QTa; estimate 30 to 200 feet (9–60 m) thick.

Upper surfaces of these high-level alluvial fans, with some high-level alluvium (QTa) in Morgan Valley, appear to be the Weber Valley surface of Eardley (1944), though Coogan and King's (2016) high-level alluvial fans (QTaf) extend to the mountain front at elevations of about 6800 to 8000 feet (2070–2440 m), rather than to the mountain ridgelines as suggested by Eardley (1944). A bench on the Tintic Quartzite at about 8200 feet (2500 m) below the bowls (cirques) in the Snow Basin quadrangle may be another example of this surface (King and McDonald, 2017). Thin remnants of high-level alluvial deposits (QTao, QTaf) (boulder lags with unmappable extents) are present on some ridges in the Snow Basin and Peterson quadrangles.

Since release of the Snow Basin quadrangle open-file report (King and others, 2008), the stacked deposits (Qgo/Tw, Qgo/Tn/Tw) in the Maples area have been reinterpreted as alluvial-fan deposits, most likely unit QTaf.

In Coogan and King (2016), QTaf is shown as two varieties (ages?) of fans because several eroded fans are lower (above adjacent drainages and down slope) and may be the upstream equivalents of unit QTay.

QTms(ZYp)

Quaternary and/or Tertiary mega-landslide (Pleistocene and/or Pliocene) – Jumbled mass of formation of Perry Canyon (ZYp) with blocks of rock from North Ogden divide klippe out of stratigraphic position and "floating" in muddy Perry Canyon; mostly mapped as ZYpm and ZYpg by Crittenden and Sorensen (1985b); inconsistent and divergent attitudes shown by Crittenden and Sorensen (1985b) also support mass movement; north margin of landslide uncertain due to overturned dips in adjacent ZYpm outcrop; mass seems to have slid down Willard thrust fault plane; estimate up to about 700 feet (210 m) thick. Younger landslides, including Qms(QTms) and Qms?(QTms) are mapped on this mass, indicating continued instability.

QTcg, QTcg?

Gravelly colluvial deposits (Pleistocene and/or Pliocene) – Unconsolidated, poorly sorted pebble to cobble to boulder clasts in light-colored gravelly silt and sand matrix that weathers to an indistinct soil; mapped on east side of Ogden Valley; no tuff noticed in soil but thin Norwood Formation may be present in subsurface; rounded quartzite and Paleozoic carbonate clasts are like those upslope in the gravel-rich Wasatch Formation, but matrix not reddish like material typically derived from Wasatch Formation; angular clasts appear to be from underlying Geertsen Canyon Quartzite; unlike younger colluvial gravels (Qcg), stone stripes, which trend downhill, are not present or visible on aerial photographs; generally 6 to 20 feet (2–6 m) thick, but may be as much as 80 feet (25 m) thick. Some QTcg deposits previously shown as Pliocene(?) (Huntsville) fanglomerate (see Lofgren, 1955, in particular figure 19). QTcg queried where material may be units QTng or QTaf.

STACKED UNITS

Numerous stacked units are on this map. This is partly a result of the compromise between showing surficial deposits and bedrock on the same map. By stacked, Coogan and King (2016) meant a thin covering of one unit over another, which is shown by the upper map unit (listed first) then a slash and then the underlying unit (for example Qa/Tfb). The upper unit is typically a surficial deposit and the lower unit is rock (Q_/rx), but exceptions are present. Coogan and King (2016) mapped the stacked units where it was important to show both units as they have potential geologic hazards and/or economic value (for example landslides or landslide-prone and impermeable clayey bedrock units, and sand and gravel). The upper unit is typically at least 6 to 10 feet (2–3 m) thick and conceals but does not obscure the lower unit. These thicknesses were chosen because a building foundation would penetrate a thinner upper unit, particularly colluvium (Qc), making it a small factor in construction. Coogan and King (2016) did not map most of the colluvium as it is thinner than 6 to 10 feet (2–3 m) and they could tell what is underneath. The Ogden Valley map is simplified from more detailed geologic mapping (see index to geologic mapping, figure 1, in Coogan and King, 2016) to show bedrock by removing most of the surficial deposits that are less than 6 to 10 feet (2–3 m). The exceptions to this simplification are where the thin deposits obscure the geologic details of faulting, lithologies, and age relationships. The underlying unit in the stack has been identified based on exposures at the edges of the stacked unit and exposure windows (gaps) or excavations in the cover, and materials in the cover that came from the underlying unit. The gaps cannot be shown separately at the map scale (1:62,500), whereas on more detailed maps (1:24,000 scale), the stacked units may be shown as separate areas.

Qh/Qml, Qh/Qml?, Qh?/Qml, Qaf1/Qml, Qafy/Qml, Qafy?/Qml,

Qms/Qml,

Ql/Qmc,

Ql/Qms,

Qapb/Qmso, Ql/Qmso, Qlf/Qmso, Qlfb/Qmso, Qlsb/Qmso, Qlsb/Qmso?, Qlgb/Qmso, Qcg/Qmso

Surficial deposits over mass-movement deposits – These units were mapped because they inform the map user about underlying potential geologic hazards.

Qmc/Qatp,

Qmc/Qlg,

Qmc/Tn,

Qmc/Tsnf?

Mass-movement deposits over surficial deposits and bedrock – These units were mapped because they inform the map user about overlying potential geologic hazards.

Qaf/Tsnf, Qafp?/Tsnf, Qafo?/Tsnf, Qcg/Tsnf, Qcg/Tsnf?, Qac/Tsnf,

Qc/Trx, Qac/Trx, Qafpb/Trx?, Qng/Ts, QTaf/Ts,

Qac/Tsl, Qaf/Tsl, Qaf/Tsl?, Qafo/Tsl,

Ql/Tcg,

Ql/Tn,Ql/Tn?, Qlf/Tn, Qls?/Tn, Qlsb/Tn, Qlsb/Tn?, Qac/Tn, Qaf/Tn?, QTaf/Tn,

Qaf/Tnf,

Qng/Tw, Qng/Tw?, Qg/Tw?, QTaf/Tw, QTao/Tw,

Qc/Keh?,

Qdlb/Zarx, Ql/Zarx, Ql/Zmcg?, Qgo?/ZYpm

Surficial deposits over bedrock – The units were mapped because they inform the map user about potential geologic hazards due to the underlying landslide-prone and impermeable clayey bedrock.

Qc/Kwc?,

Qc/Csn?,

Qng/Cgcu,

Qafoe?/rx, Qgo?/rx

Qg?/Mh,

Colluvial, uncertain, and queried surficial deposits over bedrock – These units were mapped because they show where Coogan and King (2016) were uncertain about which underlying unit is present (underlying unit queried or rx), and where the origin of the overlying unit is uncertain.

Thv/Ct,

Thv/Xfc,

Tsl/Tnf,

Tslc/Mlf,

Tn/Tw,

Twa?/Cgc

Bedrock over bedrock – Thin, typically easily weathered bedrock over other bedrock, which means the overlying "bedrock" may actually be surficial deposits; also units Thv, Tsl, Tslc, Tn, Tnf, Tw, and Twa are at least locally landslide prone and impermeable.

Qaf1/Qlmf, Qlsb/Qac,

Qa2/Qafp?, Qac/Qafp?, Qafp/Qdlb,

Qafy/Qap, Qafy/Qap?,

Qafy/Qlsb, Qaty/Qlsb, Qay/Qlsb, Qatp/Qlsb, Qafp/Qlsb, Qap/Qlsb, Qap?/Qlsb,

Qlsb/Qafo?, Qafm/Qafo?,

Qafy/Qdlb, Qay/Qdlb, Qap/Qdlb, Qap/Qdlb?, Qap?/Qdlb, Qlsp/Qdlb, Qlf/Qdlb,

Qlf/Qdb,

Qafo?/Qafoe?

Qafp/Qadb,

Surficial deposits over surficial deposits – These units were mapped because they inform the map user about stratigraphic age-relation details seen in the field that went into the "Surficial Deposit" correlation charts in Coogan and King (2016).

Qh/Qac,

Qh/Qlg, Qh/Qlg?,

Human disturbances over surficial deposits – These units were mapped because they inform the map user that the area is disturbed and materials at the surface may not reflect the deposits encountered in a foundation excavation.

WILLARD THRUST SHEET COVER ROCKS

Strata that are younger than and overlie the Willard thrust sheet.

TERTIARY

Tu, Tu?

Tertiary Formations, undivided – Poorly exposed calcareous conglomerate, calcareous sandstone, siltstone, claystone, and oncolitic limestone in uncertain proportions; at least locally tuffaceous; unit has characteristics of Salt Lake, Norwood-Fowkes, and Wasatch Formations (see each unit for descriptions, in particular unit Twl); mapped east of Cache Valley in Pole Creek graben, east of McKenzie Mountain, because oncolitic (stromatolitic in older reports) limestone on west side of Cache Valley is in Norwood-Fowkes equivalent strata or the Wasatch(?) Formation (see Smith, 1997; Oaks and others, 1999) (see also descriptions of Tnf and Twa?), and Rauzi (1979) mapped these Pole Creek rocks as Salt Lake Formation; about 500 feet (150 m) thick (Rauzi, 1979). Unit queried where may be Paleozoic bedrock.

Locally the upper part of the Pole Creek graben fill is regularly bedded and conglomeratic like unit Tcy near Elk and Durst Mountains (see Coogan and King, 2006) and locally a basal contact can be mapped. If this interpretation is correct the upper Pole Creek graben fill is likely Salt Lake Formation and the underlying strata are Norwood-Fowkes equivalent rocks (unit Tnf).

Trx, Trx?

Tertiary rocks, undivided – Red-weathering, non-conglomeratic rocks that dip about 16 degrees (between typical Tsnf and Tw dips); located in saddles between Sink Hole valley and Devils Gate Valley near Salt Lake Formation strata overlying Norwood and Fowkes Formation strata (Tsl/Tnf); though red like Wasatch Formation (Tw) and nearby rocks are mapped as Twa?, the red may be material eroded from the Wasatch Formation that was incorporated into Tsnf and/or be terra rossa since several sink holes are nearby and one saddle has off-white patches (tuffaceous?); queried, shown as Trx?, where may be terra rossa.

Thv?

Fanglomerate of Huntsville area(?) (Pliocene and/or Miocene) – Brown to reddish-brown weathering sand, silt, and gravel (pebbles to boulders) on flat area near 7313-foot (2230 m) elevation hill on eastern margin of Mantua quadrangle; queried due to uncertain origin; located on Rendezvous Peak erosion surface of Williams (1948), so uncertain age (compare Williams, 1948 to 1958); similar patches on topographic highs to north and south are mapped as Salt Lake Formation conglomerate (Tslc); reddish color may be from erosion of Wasatch Formation and/or terra rossa development on underlying karstic carbonate rocks; may be post- or late-Salt Lake Formation age, like Thv on Elk and Durst Mountains.

Tslc, Tslc?

Salt Lake Formation conglomerate (Pliocene and Miocene) – Non-red-matrix conglomeratic tuffaceous strata, with quartzite clasts, likely from the Geertsen Canyon, Mutual, and Caddy Canyon Formations, and off-white to pinkish-gray to brownish-gray matrix; variably bedded and bouldery; weathers to colluvial deposits that inflate apparent outcrop size and dip; along Box Elder-Cache County line and southeast of Clay Valley, Tslc bouldery, overlies tuffaceous strata (Tsl/Tnf), and dips <10 degrees, which supports it being upper part of Salt Lake Formation; elsewhere unit Tslc directly overlies Paleozoic rocks without any underlying tuffaceous strata and the only age indication is bedding dips of <10 degrees and non-red coloration like the Salt Lake Formation; up to about 200 feet (60 m) thick between Clay Valley and Sink Hole valley, and along Box Elder-Cache County line.

The Salt Lake Formation conglomerate should contain clasts that are not quartzites (see units Tnf and Twa?), and as presently mapped may include rocks as old as the Fowkes Formation and deposits as young as Pleistocene. For example, Tslc is red locally at its base and in thin skiffs on Paleozoic rocks such that this red material may be pre-Salt Lake Formation terra rossa. Brown coloration, in particular on Rendezvous Peak, and flat dips, at least locally, may indicate post- or late-Salt Lake Formation age (hence queried Tslc on map), like the revised Huntsville conglomerate on Elk and Durst Mountains (see Thv description).

If described correctly by Ezell (1953, part of his Tb unit), clasts in Tslc were recycled from eroded Wasatch Formation rocks. His picture (plate 3) of fractured clasts on Rendezvous Peak shows clasts that are strikingly like typical fractured Wasatch Formation clasts. Ezell's (1953) Tertiary boulder unit (Tb) is similar to the Huntsville fanglomerate (see Coogan and King, 2006), in that what he mapped is actually several Quaternary deposits, including colluvium and residuum, Pliocene(?) to Eocene ash-bearing rocks, and the Wasatch Formation. Ezell (1953) noted that his boulder deposits were on the Rendezvous Peak erosional surface of Williams (1948, p. 1160).

On McKenzie Mountain, east of Cache Valley, similar variably fractured cobbly and bouldery deposits were noted by Mullens and Izett (1964) and Rauzi (1979, p. 41–44), but they did not describe any reddish or tuffaceous matrix or reddish patina on the boulders. Rauzi (1979) considered the boulders to be Tertiary remnants, likely because they look like clasts in the Wasatch Formation. Mullens and Izett (1964) stated their high-level boulders were probably deposited on the Rendezvous Peak erosion surface, which they and Williams (1948) reported as preserved along the hills south and west of the Paradise quadrangle. However, Coogan and King (2016) reported little evidence of a widespread Rendezvous Peak erosion surface.

Coogan's mapping of Tslc would place the erosional planing of the Rendezvous Peak surface prior to deposition of the conglomerate in the upper part of the Salt Lake Formation. The Salt Lake Formation in southern Cache Valley is 10.5 Ma to 4.4 or 5.1 Ma (see data in Oaks and others, 1999). If post-Salt Lake Formation in age, the surface and boulder deposits would be younger than 4.4 to 5.1 Ma and older than middle (McCalpin, 1989; see also Sullivan and Nelson, 1992) and/or early Pleistocene (after Sullivan and others, 1988), the age of the McKenzie Flat surface. This would be a QT unit in UGS terminology, though it may be Thv.

Tsl, Tsl?

Salt Lake Formation (Pliocene and Miocene) – Grayish-white tuff, tuffaceous siltstone and sandstone, altered tuff/claystone, and conglomerate, with local limestone; poor exposures, lack of persistent beds, and probable structural complications prohibit measuring the thickness and recognizing less-resistant lithologies (like altered tuff/claystone and tuffaceous sandstone); about 450 feet (140 m) exposed in James Peak quadrangle east of Davenport Creek. The Salt Lake Formation is prone to slope failures because it is clay rich and therefore it also has limited porosity and permeability (an aquitard).

North of the map area in Cache Valley, Williams (1962) described his upper conglomerate and sandstone unit of the Salt Lake Formation (entire Salt Lake Formation on map) as predominantly conglomerate, with generally rounded pebbles and cobbles in a matrix of calcium carbonate and tuffaceous sand, and lesser interbedded tuffaceous sandstone, tuffaceous marl and compact limestone bearing ostracods, imprints of grass roots, and many impressions of a small clam. Williams (1962) described this unit west of the Little Bear River as 1000 to 2000 feet (300–600 m) thick. Williams' (1962) lower tuff unit of his Salt Lake Formation in Cache Valley is likely Coogan and King's (2016) Norwood-Fowkes equivalent strata (see Tnf below).

Also to the north of the map area, but east of the Little Bear River, Mullens and Izett (1964) described Salt Lake Formation exposures as mainly conglomerate that contained a large proportion of rocks (did they mean clasts?) derived from formations older than those exposed nearby in the Paradise quadrangle. Yet, Williams (1962) described the pebbles and cobbles from the same area as chert, sandstone, calcareous sandstone, and limestone mostly from Carboniferous formations that are exposed nearby. The implication is clasts are Cambrian and Neoproterozoic quartzite (older than strata nearby), like the boulder deposits on McKenzie Flat, as well as Mississippian and Pennsylvanian rocks from just east of the East Cache fault zone. Coogan and King (2006) described similar differences in Tertiary conglomeratic strata in another depositional basin to the south near Elk and Durst Mountains, Utah; there the non-quartzite clasts, dominant in older conglomerate beds, were from local Paleozoic strata, and the quartzite clasts, dominant in younger conglomerate beds, were recycled from erosion of the Wasatch Formation (Coogan and King, 2006).

North of the map area in the southern Cache Valley, the Salt Lake Formation is Pliocene in age based on fossil data (see summary in McClellen, 1977), and Pliocene and Miocene based on chemical correlations with isotopically dated tuffs (4.4–10.5 Ma; see Smith, 1997; Oaks and others, 1999). On the map, unit Tsl may include some Oligocene-Eocene Norwood Formation strata. Tsl queried where it may be older tuffaceous rocks of the Norwood-Fowkes Formation (Tnf).

Tsnf, Tsnf?

Salt Lake, Norwood, and Fowkes Formations, undivided (Pliocene-Eocene?) – Pale-gray to greenish, altered tuff (claystone), altered tuffaceous siltstone and sandstone; tuff extensively altered to zeolites and bentonite (smectite and mixed layer clays); extensive alteration implies these strata are Norwood-Fowkes Formation (Tnf) or atypical altered Salt Lake Formation (Tsl) deposited in a lake or closed basin; mostly mapped in Devils Gate Valley, a closed basin with extensive colluvial cover and limited small outcrops, and with topographic relief great enough that pre-Salt Lake strata may be exposed in drainages; poorly exposed, with best exposures in landslide scarps; locally bedded, with near-horizontal to about 5 degree dips (like Salt Lake Formation); exposed thickness up to about 160 feet (50 m); Oaks and others (1999, figure 7) showed about 3000 feet (900 m) of Tsnf west of the Little Bear River in Cache Valley in their measured section (5a, 5b) nearest the map area. These undivided strata lap onto considerable paleotopography of the underlying queried Wasatch Formation (Twa?), and have a somewhat consistent fill line (or shoreline?) at an elevation of about 6500 feet (1980 m) in Devils Gate Valley. Unit Tsnf is only queried where it is in a stacked unit, because it might be unit Twa?. This combined unit (Tsnf) is prone to slope failures due to high clay content and is an aquitard.

Coogan and King (2016) also mapped unit Tsnf rather than thin Tsl over Tnf (symbolized as Tsl/Tnf) where no bedding dips were found, stratal dips are intermediate between the shallower dips in Tsl and the steeper dips in Tnf, and between less gently dipping Tsl and Tnf strata on both sides of the southern Cache Valley where the angular unconformity between these units is not mappable and Tsnf strata may be in either unit.

Coogan and King (2016) mapped unit Tsl/Tnf where the contact between Pliocene and late Miocene Salt Lake Formation (Tsl) and underlying Oligocene and Eocene Norwood Formation should be present but is not visible, despite an age gap of 20 to 40 million years and an angular unconformity; the Norwood contact with underlying Eocene Fowkes Formation equivalent strata is also not visible. North of the map area in the Mount Pisgah quadrangle, Salt Lake Formation rocks appear to lap onto (unconformably overlie) Paleozoic rocks, and may conceal (onlap) both the Norwood-Fowkes strata and redbeds tentatively correlated with the Wasatch Formation. The Norwood-Fowkes strata also appear to lap onto (overlie with angular unconformity) Paleozoic rocks and conceal the Wasatch Formation.

Tn, Tn?

Norwood Formation (lower Oligocene and upper Eocene) – Typically light-gray to light-brown altered tuff (claystone), altered tuffaceous siltstone and sandstone, and conglomerate; unaltered tuff, present in type section south of Morgan, is rare; locally colored light shades of red and green; variable calcareous cement and zeolitization; involved in numerous landslides of various sizes due to high clay content and is an aquitard; estimate 2000 feet (600 m) thick in exposures on west side of Ogden Valley (based on bedding dip, outcrop width, and topography). Norwood Formation queried where poor exposures may actually be surficial deposits. For detailed Norwood Formation information see description under heading “Sub-Willard Thrust - Ogden Canyon Area” since most of this unit is in and near OgdenValley and covers the Willard thrust, Ogden Canyon, and Elk and Durst Mountains areas.

Tnf, Tnf?

Norwood and Fowkes Formation equivalent strata, undivided (Oligocene? and Eocene) – Light-colored, altered tuffaceous fine-grained rocks (claystone and mudstone) with at least local conglomerate, limestone, and sandstone as exposed in southern Cache Valley; extensive altered tuff (claystone), tuff, and tuffaceous sandstone higher in section may or may not be in these equivalent strata (see Tsl notes above); estimate 600 to 1250 feet (180–380 m) thick; about 500 feet (150 m) exposed below angular unconformity in James Peak quadrangle east of Davenport Creek. When the angular unconformity between Tsl and Tnf is not visible the strata have been mapped as Salt Lake Formation over Norwood and Fowkes equivalent strata (Tsl/Tnf). Unit Tnf queried where it may be tuffaceous Salt Lake Formation (Tsl). This combined unit (Tnf) is prone to slope failures due to high clay content and is an aquitard.

North of the map area, Williams (1962) showed his tuff unit (Norwood-Fowkes strata of Coogan and King, 2016) as an irregular band next to Paleozoic rocks on the west side of Cache Valley, and described these strata as 1200 feet (360 m) of earthy gray tuff (actually altered, so claystone or mudstone), with two distinctive limestone beds near the base and a minor amount of pebble conglomerate. He described the upper limestone as stromatolitic (oncolitic, see Adamson, 1955, figure 11). Smith (1997) placed these limestones in her Norwood-Fowkes strata (Tfnx), while Oaks and others (1999) placed them in their Wasatch Formation (Twx) based on oncolites that are similar to those in the Wasatch Formation to the east in the Bear River Range (Oaks and Runnells, 1992) (see note below on age under unit Twl). In the Pole Creek valley, east of Cache Valley, Coogan and King (2016) mapped similar oncolitic limestones as undivided Tertiary rocks (Tu, see above).

K-Ar isotopic ages from samples taken near the base of the Norwood-Fowkes strata to the north in the Mount Pisgah quadrangle are about 44 and 49 Ma (on hornblende and biotite, respectively) (Smith, 1997). These ages imply reworking of the tuff prior to deposition (two separate air-fall events) or K-Ar disequilibrium (alteration of one of the minerals; biotite typically alters more easily than hornblende). These ages are older than the Norwood and younger Fowkes ages in Utah (38–40 Ma) (see also Tn under heading “Sub Willard Thrust - Ogden Canyon Area”) and are more like the older Fowkes Formation ages in Wyoming (48–49 Ma) (see unit Tf-Fowkes Formation in Coogan and King, 2016). Fowkes isotopic ages and fossil evidence indicate the older Fowkes strata are essentially the time equivalent of the Bridger Formation in Wyoming (Nelson, 1973, 1974; see also Lillegraven, 1993, figures 4O and 4P).

Tw, Tw?

Wasatch Formation (Eocene and upper Paleocene) – Typically red to brownish-red sandstone, siltstone, mudstone, and conglomerate with minor gray limestone and marlstone locally (see Twl); lighter shades of red, yellow, tan, and light gray present locally and more common in uppermost part, complicating mapping of contacts with overlying similarly colored Norwood and Fowkes Formations; clasts typically rounded Neoproterozoic and Paleozoic sedimentary rocks, mainly Neoproterozoic and Cambrian quartzite; basal conglomerate more gray and less likely to be red, and containing more locally derived angular clasts of limestone, dolomite and sandstone, typically from Paleozoic strata, for example in northern Causey Dam quadrangle; sinkholes indicate karstification of limestone beds; thicknesses on Willard thrust sheet likely up to about 200 to 400 feet (60–120 m) in the James Peak and Huntsville quadrangles, 400 to 600 feet (120–180 m) in Sharp Mountain, Dairy Ridge, and Horse Ridge quadrangles, about 1300 feet (400 m) in Monte Cristo Peak quadrangle, about 1100 feet (335 m) in northeast Browns Hole quadrangle, about 2200 feet (670 m) in southwest Causey Dam quadrangle, about 2600 feet (800 m) at Herd Mountain in Bybee Knoll quadrangle, and about 1300 feet (400 m) in northwest Lost Creek Dam quadrangle; thickness varies locally due to considerable relief on basal erosional surface, for example along Right Fork South Fork Ogden River, and along leading edge of Willard thrust; much thicker, about 5000 to 6000 feet (1500–1800 m), south of Willard thrust sheet near Morgan. Wasatch Formation is queried (Tw?) where poor exposures may actually be surficial deposits. The Wasatch Formation is prone to slope failures because it is at least locally clay rich and poorly consolidated. Permeability in the Wasatch Formation is complicated due to karst, clay content, limestone beds, and variable cementation that is so strong in some areas that quartzite clasts are broken through rather than around during fracturing. This variability is indicated by perched springs in the unit (King, this report). Other information on the Wasatch Formation is in Tw descriptions under the heading "Sub-Willard Thrust - Ogden Canyon Area" since Tw strata are extensive near Ogden Valley and cover the Willard thrust, Ogden Canyon, and Elk and Durst Mountains areas.

Along the South Fork Ogden River, Wasatch strata are mostly pebble, cobble, and boulder conglomerate with a matrix of smaller gravel, sand, and silt in the Browns Hole quadrangle, and coarse-grained sandstone to granule conglomerate as well as siltstone and mudstone to the east in the Causey Dam quadrangle. The Wasatch weathers to boulder-covered dip(?) slopes north of the South Fork Ogden River, for example in Evergreen Park. Along the South Fork, the Wasatch Formation is separated from the underlying Hams Fork Member of the Evanston Formation by an angular unconformity of a few degrees, with the Hams Fork containing less siltstone and mudstone than the Wasatch and having a lighter color.

Twa?

Wasatch Formation or units of another age – Reddish-brown weathering, weakly consolidated, quartzite-clast conglomerate and mudstone mapped near Devils Gate Valley; similar to Wasatch Formation but unqueried Wasatch strata are typically so well cemented that conglomerate clasts, as well as matrix, fracture; poorly bedded, with estimated 10 to 20 degree dips; boulders not obvious, despite Ezell (1953) mapping it as characteristically bouldery (Tb); clasts mainly tan, greenish, and purple cobbles and boulders derived from Geertsen Canyon (tan) and upper Neoproterozoic quartzite (green=?; purple=Mutual?) bedrock, as reported by Crittenden and Sorensen (1985a), but their unit (TKwe) includes younger rocks (Tslc, Thv?) and unconsolidated material (Quaternary colluvium and lags, and possibly QT); unconformably overlies Paleozoic rocks with considerably more paleotopography than to north in Mount Pisgah quadrangle; if gently dipping, about 500 feet (150 m) thick west of Sink Hole valley.

Another similar Twa? area, east of Devils Gate Valley, was mapped as TKwe by Crittenden and Sorensen (1985a). But, it is next to a sinkhole and the color may be reddish residuum (terra rossa) produced during karst development in the area, or be inherited from eroded Wasatch Formation rock, like the poorly resistant Tsl/Tnf exposures to the east. Other poorly resistant exposures adjacent to this Twa? look bouldery, with some brownish coloration like the Tslc exposures at Rendezvous Peak, and have been mapped as Qcg/Tsnf?.

The unit label is queried because the unit may be older and/or younger than Wasatch strata. Older Paleocene and Cretaceous K-Ar isotopic ages, similar to the age of the Evanston Formation, have been reported by Williams (1964) and Oaks and others (1999) for the basal "Tertiary" rocks that unconformably overlie the Oquirrh Formation in the southern Cache Valley. However, these ages are suspect due to large uncertainty margins, suggesting the ages are inaccurate or are averages of several air-fall events (that is, deposits are reworked). Also, lower Paleocene rocks (58–65 Ma) have not been documented in northern Utah (see figure 2 in Coogan and King, 2016). Younger, reddish, moderately to poorly cemented conglomerates and unconsolidated gravels are present on Elk and Durst Mountains, so part of the Twa? unit in the Mantua quadrangle may be derived from eroding Wasatch conglomerate. On Elk and Durst Mountains Eocene-Oligocene reddish conglomerates (Tcg) are interbedded with the tuffaceous Norwood Formation (Tn); and Miocene, Pliocene (Tcy, Thv) and Quaternary conglomerate and gravel (QT) unconformably overlie the Norwood Formation (Coogan and King, 2006). So, red coloration alone is not an age indicator.

Twl, Twl?

Limestone of Wasatch Formation (Eocene and upper Paleocene) – Gray, oncolitic limestone and light-gray to white marlstone; discontinuous, grades laterally into Tw; mapped in Monte Cristo Peak and Sharp Mountain quadrangles; 0 to 300 feet thick (0–90 m). The setting of limestone in a syncline and likely lacustrine origin are possible evidence for a piggy-back basin on Willard thrust sheet; see Coogan (1992b) for the piggy-back basin on Crawford thrust sheet. Limestone of Wasatch Formation queried where poor exposures may actually be surficial deposits.

Similar limestones were described by Oaks and Runnells (1992) in the Cowley Canyon Member of the Wasatch Formation to the north in the Bear River Range. These Cowley Canyon strata directly overlie Paleozoic rocks, as well as being within the Wasatch red beds, and are thicker in north-south-trending grabens (Oaks and Runnells, 1992).

The Monte Cristo Peak and Sharp Mountain limestone outcrops were described as tuffaceous and stromatolitic (oncolitic) limestone in the Salt Lake Group by Hafen (1961) and Smith (1965). Smith (1965) collected one *Planorbis* sp. (his designation) fresh-water gastropod fossil from a limestone. This gastropod genus and the Planorbidae family of gastropods are not restricted to the Pliocene and/or Miocene, so they are present in rocks that are older than the Salt Lake Group/Formation (see for example Yen, 1948; Pierce, 1993). Williams (1948, p. 1146–7) noted *Planorbis* sp. and *Physa bridgerensis* Meek (also a fresh-water gastropod) at his Cowley Canyon locality 10, not far north of the map area (see Williams, 1958, p. 71). But Williams (1948) quoted F. Stearns MacNeil of the U.S. Geological Survey, who stated the specimens are like those from near Ft. Bridger, Wyoming (Bridger Formation) and *Physa bridgerensis* is lower and middle Eocene. Bridgerian is the Fowkes Formation age, not Wasatch Cowley Canyon age (Wasatchian), so the limestone could be tuffaceous Fowkes Formation.

Twc, Twc?

Basal conglomerate of Wasatch Formation (Eocene and upper Paleocene) – Red-orange- and tan-weathering, cobble conglomerate, mainly containing Neoproterozoic and Cambrian quartzite clasts; contains basal more gray colored, angular-clast conglomerate with clasts from nearby Paleozoic limestone, dolomite and sandstone on Baldy Ridge (mapped as Twc?) and in northern Causey Dam quadrangle (not mapped separately from Tw); 0 to 400 feet (0–120 m) thick. Unit queried where conglomerate may be Cretaceous (Keh, Kwc).

CRETACEOUS

Keh, Keh?

Hams Fork Member of Evanston Formation (Upper Cretaceous) – Light-gray to tan conglomerate with lesser conglomeratic sandstone, and sandstone, with quartzite and chert clasts, as exposed along South Fork Ogden River; lower Hams Fork markedly coarsens to cobble conglomerate dominated by Cambrian and Neoproterozoic quartzite clasts (not mapped separately); about 300 to 1000 feet (140–300 m) thick along South Fork Ogden River, thinning to west; thins to absence to north and west along regional angular unconformities. DeCelles and Cavazza (1999, figure 7A) showed a basal conglomerate as 66 feet (20 m) thick in the Causey Dam quadrangle. Unconformably truncated beneath Wasatch Formation and overlies Cretaceous Weber Canyon Conglomerate and Paleozoic rocks, with angular unconformity, along Right Fork South Fork Ogden River, indicating northern Causey Dam quadrangle, northwestern Horse Ridge, and western Dairy Ridge quadrangles were areas of high paleotopography (after Coogan, 2006a-b). The Hams Fork on the Willard thrust sheet is less prone to slope failures than other exposures in the map area; note lack of mudstones in this unit description.

These South Fork Ogden River Keh exposures are not the same lithologically as those in the Lost Creek drainage, and outside the map area near Devils Slide and in Echo Canyon; but these outcrops form a nearly continuous band down the South Fork and along the east flank of Elk and Durst Mountains to Devils Slide and other exposures to the east. The lithology of Keh along the east flank of Elk and Durst Mountains also differs from that in the other areas mentioned.

Kwc, Kwc?

Weber Canyon Conglomerate (Upper Cretaceous) – Tan and gray conglomerate with cobbles of Mississippian Lodgepole Limestone (75–100%), and lesser amounts of Cambrian and Neoproterozoic quartzites and Paleozoic sandstone (Wells Formation?), as exposed along Right Fork South Fork Ogden River, entirely on the Willard thrust sheet; clasts derived from paleotopographic ridge developed on Lodgepole Limestone to northwest in Causey Dam quadrangle; note clast composition here is not like that outside the map area to southeast in Lost Creek drainage and near Devils Slide, where the unit was named and dated by fossils; overlies older rocks with major angular unconformity and unconformably underlies Hams Fork Member of Evanston Formation (Keh); only about 300 feet (90 m) exposed.

WILLARD THRUST SHEET

Outer marine shelf sequence or miogeoclinal basin sequence of Coogan (1992a).

TRIASSIC

Dinwoody Formation strata are inferred to be in the core of Beaver Creek syncline by Mullens (1969, cross section A–A′). However, no Triassic strata are exposed on the Willard thrust sheet (see Coogan and King, 2016).

PERMIAN

Pp

Park City and Phosphoria Formations, undivided (Permian) – Meade Peak and Grandeur Member descriptions from Coogan and King (2016). Includes (in descending order):

Ppf

Franson Member of Park City Formation, and several thin members of both Formations (Permian) – Interbedded chert, limestone, sandstone, and some phosphatic rock in upper 140 feet (40 m) (Shedhorn, Ervay, Retort, and Rex Members); mainly light- and medium-gray, cherty limestone and dolomite in lower 260 feet (80 m) (Franson Member); forms ledgy slopes in upper part over cliffy lower part; about 400 feet (120 m) total thickness (Schell and Gere, 1964; Mullens, 1969).

Ppm

Meade Peak Phosphatic Shale Member of Phosphoria Formation (Lower Permian) – Dark-gray phosphatic limestone, dolomite, siltstone and darker shale; slope and swale former; near Causey Dam, 262 feet (80 m) measured by Schell and Gere (1964).

Ppg

Grandeur/Lower Member of Park City Formation (Lower Permian) – Dark-gray limestone and dolomite that is phosphatic in upper part and locally cherty; near Causey Dam, 258 feet (77 m) measured by Schell and Gere (1964).

PERMIAN AND PENNSYLVANIAN

PIPwe

Wells Formation (Lower Permian and Pennsylvanian) – Light-gray to off-white to orangish-gray, thick-bedded, carbonate-cemented quartzose sandstone in upper part, interbedded with minor gray to light-gray, thick-bedded limestone and minor dolomite in lower part; only about 400 feet (120 m) thick in Causey Dam quadrangle (Mullens, 1969, upper Wells; Coogan and King, 2016). Later revised to entire Wells by Mullens (1972), based on Mississippian fossils in underlying units.

North of the map area on the Willard thrust sheet in the Bear River Range and northwest of Causey Dam, the top of the Wells is eroded; it is about 600 to 700 feet (180–210 m) thick in the adjacent Paradise and Porcupine Reservoir quadrangles and 1000 feet (300 m) to at least 1200 feet (360 m) thick farther north near Logan (for details see Coogan and King, 2016).

The Wells seems to be thicker to east of Causey Dam and the Willard thrust sheet (opposite the expected), with about 1050 feet (320 m) of overturned Wells in the Dairy Ridge quadrangle, even with the base truncated by the Willard thrust (see Coogan, 2004a).

The Wells Formation is at least partly equivalent to the thick Weber Sandstone to the south near Devils Slide and even thicker Oquirrh Formation to the west near Brigham City (~5000 feet [1525 m]) (Jensen and King, 1996). The Causey Dam section is very thin compared to the Weber near Devils Slide, where it is at least 2500 feet (>760 m) thick, even though the Devils Slide section is off the Willard thrust sheet (see Coogan and King, 2006), and paleogeographically east of Devils Slide and the Bear River Range. The thinner "Oquirrh Formation" in the Bear River Range on the Willard thrust sheet is probably Wells strata that was deposited on a marine shelf rather than in the Oquirrh basin (see basin extent in Jordan and Douglass, 1980). The lack of a discernable West Canyon Limestone in the Bear River Range also supports the Wells designation rather than the Oquirrh Formation.

MISSISSIPPIAN

A karst plain in present on Mississippian through Cambrian rocks in the northwest part of the map area in the Mantua and James Peak quadrangles mostly north of the study area; Devonian rocks are mostly missing in these quadrangles. Sinkholes may be present in Mississippian rocks in the Monte Cristo Peak quadrangle in the study area, but the Wasatch Formation (Tw) mostly obscures these rocks.

Mgb, Mgb?

Great Blue Limestone, lower member (Upper Mississippian) – Ledge-forming, medium to dark-gray, fossiliferous limestone mapped on the north boundary of the Mantua and James Peak quadrangles, where it occupies the Monroe Canyon Limestone stratigraphic interval; queried between Clay Valley and Sink Hole, where the Little Flat Formation would be too thick without a fault or the Great Blue being present; incomplete thickness of lower member exposed; about 800 feet (245 m) thick north of the map area.

Mmo, Mmo?

Monroe Canyon Limestone (Upper Mississippian) – Includes upper gray dolomite (or dolomitized limestone) and limestone, middle gray, cherty limestone and minor siltstone, and lower thick-bedded and cliff-forming gray dolomite and limestone with lesser sandstone; varies from about 700 to 1100 feet (210–335 m) thick and may thicken to the south and east. Monroe Canyon strata may or may not be present below the Wasatch Formation in the concealed syncline in the east-central part of the Monte Cristo Peak quadrangle.

The Monroe Canyon Limestone is roughly equivalent to the Great Blue Limestone and upper Humbug Formation strata to the west near Brigham City on the Willard thrust sheet. Monroe Canyon lithologies and fossils in the map area imply the upper and middle strata are the middle medium-bedded limestone of the type Monroe Canyon (see Dutro and Sando, 1963), although chert is atypical. The lower strata have the lithology and fossil characteristics of the massive limestone member of the Monroe Canyon in its type area (see Dutro and Sando, 1963), but here do not consistently weather to massive outcrops like the massive limestone member elsewhere.

Mlf, Mlf?

Little Flat Formation (Mississippian) – Gray, tan, and reddish-tan, calcareous to dolomitic sandstone, and gray sandy limestone and dolomite; grades upward into mostly dolomite; less resistant than overlying and underlying map units; phosphatic shale at base (Delle Phosphatic Member); about 800 feet (245 m) thick, including Delle in Causey Dam quadrangle and likely about 900 feet (270 m) thick to northwest. The Little Flat is roughly equivalent to the lower Humbug Formation and Deseret Limestone strata to the west.

The Little Flat Formation is likely present below the Wasatch Formation in the concealed axis of the syncline in the Monte Cristo Peak quadrangle, because it is exposed on both flanks of the syncline just to the south in the Causey Dam quadrangle.

Mlfd, Mlfd?

Delle Phosphatic Member of Little Flat Formation (Lower Mississippian) – Mostly poorly resistant, typically vegetated, brownish-orange weathering, phosphatic shale; also dark resistant cherty limestone and less resistant calcareous siltstone; non-resistant zone is about 40 to 80 feet (12–25 m) thick.

Mlf–Ml

Little Flat Formation or Lodgepole Limestone (Lower Mississippian) – Gray limestone in fault contact with Lodgepole Limestone and on strike but not in contact with Little Flat Formation in Mantua quadrangle; might be either unit.

Ml, Ml?

Lodgepole Limestone (Lower Mississippian) – Gray, ledge and cliff-forming, fossiliferous limestone (lime mudstone [micrite] to wackestone); locally cherty, containing black chert nodules, particularly at top; capped by 100-foot (30 m) -thick dolomite in Causey Dam quadrangle; estimate 750 to 900 feet (230–275 m) thick in the map area (see for example Ezell, 1953; Crittenden and Sorensen, 1985a); structurally thickened in the Horse Ridge quadrangle (Coogan, 2006b).

The type Lodgepole is overlain by the Mission Canyon Limestone (Sando and Dutro, 1974), with no Delle between them; so with the Delle marking the base of the Little Flat, this unit might better be called Gardison Limestone.

MISSISSIPPIAN AND DEVONIAN

MDcl, MDcl?

Cottonwood Canyon Member of Lodgepole Limestone and Leatham Formation (Lower Mississippian and Upper Devonian) – Poorly exposed recess or a slope of dark-colored shale, siltstone, and thin-bedded silty to shaly limestone; reported thicknesses of 10 to 100 feet (3–30 m) (see details in Coogan and King, 2016). Units previously placed in both the Beirdneau and Lodgepole Formations.

DEVONIAN

Descriptions modified from Coogan (2006a-b). Thickness estimates near Causey Dam are from Coogan and King (2016). Sinkholes are present on Devonian through Cambrian rocks in the Monte Cristo Peak area and in the Horse Ridge quadrangle.

Db

Beirdneau Sandstone (Upper Devonian) – Tan, reddish-tan, and yellowish-gray dolomitic to calcareous sandstone and siltstone, and silty to sandy dolomite and limestone; contact ledge “limestone” 10 to 20 feet (3–6 m) at top; locally contains distinctive beds of intraformational conglomerate consisting of small red fragments of siltstone and sandstone in silty limestone matrix, and scattered halite molds in fine-grained rock (Mullens, 1969); estimate 0 to 500 feet (0–150 m) thick and absent in west part of the map area (see details in Coogan and King, 2016). Unit referred to as the “upper” Jefferson member or Three Forks Formation by some previous workers.

The Beirdneau is missing at the unconformity between the Lodgepole and Hyrum Formations (Stansbury uplift of Rigby, 1959) and may not have been present over the uplift in the Sharp Mountain quadrangle, but the next oldest unit is on a ridge top and Beirdneau removal could post-date the Stansbury uplift.

North of the map area, Beirdneau strata are 500 to 1100 feet (150–335 m) thick, apparently thinning to the south (after Brooks, 1954; Mullens and Izett, 1964; Three Forks of Benson, 1965; Williams, 1971). So this unit thins rapidly to the south and west over the Stansbury uplift (compare to Rigby, 1959).

Dhw

Hyrum and Water Canyon Formations, undivided (Devonian) – See descriptions below.

Dh, Dh?

Hyrum Dolomite (Upper and Middle Devonian) – Dark- to medium-brownish-gray dolomite; weathers distinctive, chocolate-brown color and is typically more resistant and darker colored than silty and sandy overlying Beirdneau and underlying Water Canyon Formations; estimate 0 to 675 feet (0–205 m) thick and absent in northwest part of the map area (see details in Coogan and King, 2016), and seems to thin to the south and west over Stansbury uplift (compare to Rigby, 1959). This unit is “lower” Jefferson member of some previous workers.

Dwc, Dwc?

Water Canyon Formation (Lower Devonian) – Thin- to medium-bedded, reddish-tan and gray siltstone and very light-gray to light-tannish-gray weathering, thinly laminated, at least locally sandy, typically medium-gray dolomite with some limestone; forms light-colored to orangish-hued slopes; contains fragments of fossil fish plates (Mullens, 1969); estimate 100 to 460 feet (30–140 m) thick in the map area and thinning to south (see details in Coogan and King, 2016); thins to the east and apparently irregularly to the south, probably over the Tooele arch (see Hintze, 1959) or due to erosion during the Late Devonian Stansbury uplift (see Rigby, 1959). However, the uplift is complicated, possibly by paleotopography, because to the north near the Blacksmith Fork River the Water Canyon thins to 230 to 320 feet (70–100 m) (after Brooks, 1954; Taylor, 1963; Williams and Taylor, 1964; Mullens and Izett, 1964), yet it is about 1200 feet (365 m) thick in the Mount Pisgah quadrangle (King and others, 2017), and to the north in the Bear River Range is about 600 feet (180 m) thick near Logan (see Taylor, 1963; Williams and Taylor, 1964).

SILURIAN AND ORDOVICIAN

SOlf

Laketown and Fish Haven Dolomites, undivided (Silurian and Ordovician) – Dark- to light-gray, cherty dolomite; combined unit thins southward from 600 feet (180 m) in Dairy Ridge quadrangle to 360 feet (110 m) in Horse Ridge quadrangle (Coogan, 2006a-b); farther west thins southward from 1365 feet (415 m) in the Sharp Mountain quadrangle (Hafen, 1961) to about 530 to 650 feet (160–200 m) in the Causey Dam area (Mullens, 1969).

Sl, Sl?

Laketown Dolomite (Silurian and Ordovician) – Medium- to dark-gray, medium to very thick bedded, cliff-forming dolomite; locally cherty, with irregular blebs, stringers, and layers of chert at various horizons; conodonts and sparse, poorly preserved corals reported by Mullens (1969); Coogan and King's (2016) lower contact appears to be what Williams (1948, 1958) mapped in the Bear River Range; 400 to 1240 feet (120–380 m) thick in the map area (see details in Coogan and King, 2016), and the Laketown thins to the south and apparently to the east, probably over the Tooele arch (see Hintze, 1959) and is missing south of the Willard thrust sheet at Ogden Canyon, but this may be influenced by erosion over the Stansbury uplift (see Rigby, 1959).

ORDOVICIAN

Another karst plain is present on Ordovician through Cambrian rocks in the Sharp Mountain quadrangle north of the study area, in addition to the karst plain to the west in the James Peak and Mantua quadrangles.

Ofh, Ofh?

Fish Haven Dolomite (Upper Ordovician) – Dark-gray, thick- to very thick bedded dolomite with white chert as small nodules; commonly with dull-medium-gray to light-gray mottling on weathered surfaces; forms resistant ridge or cliff where distinguishable from more recessive dolomites at the base of the overlying Laketown Dolomite; contains fossil corals; in the map area 80 to 165 feet (25–50 m) thick, and thins to the south, but is about as thick off the Willard thrust sheet at Ogden Canyon as on the Willard thrust sheet (see details in Coogan and King, 2016). At least locally unconformably overlies shale of lower Swan Peak Formation and Garden City Formation where entire Swan Peak is missing.

Osp, Ospq,

Osps

Swan Peak Formation (Lower and Middle? Ordovician) – Tan to orangish-tan to pale-reddish-tan, cliff- and ridge-forming upper quartzite (Ospq) underlain by recessive weathering lower part (Osps) containing interbedded dark shale and siltstone, some similar quartzite, as well as limestone beds; 0 to about 250 feet (0–75 m) thick, thickest in northwest part of map area. Only lower part (Osps) is present below unconformity in eastern Mantua, James Peak, and Sharp Mountain quadrangles; entire Swan Peak missing to east in the Monte Cristo Peak area, near Causey Dam, on leading edge of Willard thrust sheet in the Curtis Ridge, Dairy Ridge, and Horse Ridge quadrangles (see Coogan and King, 2016 for details). So the Swan Peak Formation is missing over the Tooele arch on the southeast part of the Willard thrust sheet. The upper part of the Garden City Formation was likely eroded, as well as Swan Peak, over the Tooele arch (see Hintze, 1959).

Ogc, Ogc?

Garden City Formation (Lower Ordovician) – Gray to tan weathering, dark-gray to gray, thin- to medium-bedded, silty limestone; contains tan to yellowish-weathering, less resistant, wavy, silty to argillaceous laminae to inch-scale layers that are more abundant in lower part; intraformational, flat-pebble conglomerate present in lower half; ledge forming; chert near the top of unit (black nodules and stringers) and in lowermost part; at least locally fossiliferous (see Mullens, 1969); 500 to 1200 feet (150–365 m) thick in the map area (see details in Coogan and King, 2016), and thins to the south over the Tooele arch (see Hintze, 1959).

Outcrops exhibit faint, axial-planar cleavage where mesoscopically folded to the east nearer the Willard thrust fault (Coogan, 2006a-b), indicating potential for fracture porosity in subsurface.

ORDOVICIAN AND CAMBRIAN

Csn, Csn?

St. Charles and Nounan Formations, undivided (Lower Ordovician and Upper Cambrian) – See descriptions below.

Csc, Csc?

St. Charles Formation (Lower Ordovician and Upper Cambrian) – Mostly dark-gray, medium- to thick-bedded dolomite; contains subordinate medium-gray dolomite and limestone; all with tan-weathering mottling and recesses of crude laminae to inch-scale layers of sandstone and siltstone; overall gray to tan weathering and ledge forming; uppermost part contains light-colored, typically pink, chert; lower part is less resistant, light-gray, tannish-gray weathering, thin-bedded, silty and sandy limestone and dolomite, and silty shale, with tannish-gray, medium-bedded, cross-bedded Worm Creek Quartzite Member (Upper Cambrian) that is locally present; total thickness about 500 to 1000 feet (150–300 m) (see details in Coogan and King, 2016) and may thin to south and east over Tooele arch (see Hintze, 1959).

CAMBRIAN

Descriptions of units below Nounan Formation largely from Coogan (2006a-b).

Cn, Cn?

Nounan Formation (Upper Cambrian) – Medium-gray to dark-gray, very thick to thick-bedded, light to medium gray and tan-weathering, typically cliff forming, variably sandy and silty dolomite and lesser limestone, with crude laminae to partings and mottling of sandstone and siltstone that weather tan or reddish; little sandstone and siltstone in more resistant lower part; about 600 to 1150 feet (180–350 m) thick (see details in Coogan and King, 2016), thins to the south and east over the Tooele arch (see Hintze, 1959).

Cbo

Bloomington Formation (Middle Cambrian) – Olive to tan shale and gray, nodular limestone; 600 feet (180 m) thick near Sharp Mountain (Hafen, 1961), and 650 feet (200 m) thick to south near Causey Dam (Mullens, 1969); a report of a 918-foot (280 m) thickness in Baldy Ridge section (Rigo, 1968), Causey Dam quadrangle may be faulted strata, but east of Baldy Ridge about 935 feet (285 m) thick in Dairy Ridge quadrangle, thickening to south to 1550 feet (470 m) thick in Horse Ridge quadrangle (Coogan, 2006a-b). Divided into members where possible (descending):

Cbc, Cbc?

Calls Fort Shale Member (Middle Cambrian) – Brown-weathering, slope-forming, olive-gray to tan-gray, thin bedded, shale and micaceous argillite with minor, thin-bedded, dark-gray, silty limestone; 75 to 125 feet (23–40 m) thick on the leading edge of the Willard thrust sheet (Coogan, 2006a-b; see Rigo, 1968), 100 to 120 feet (30–35 m) thick in Causey Dam quadrangle and about 400 feet (120 m) thick in Huntsville quadrangle (see Coogan and King, 2016). The Calls Fort is at least locally prone to slope failures due to high clay content and is an aquitard.

Cbm, Cbm?

Middle limestone member (Middle Cambrian) – Dark to medium-gray, thick- to thin-bedded, argillaceous limestone with tan-, yellow-, and red-weathering, wavy, silty layers and partings; contains subordinate olive-gray and tan-gray, thin-bedded, shale and micaceous argillite; typically forms “rib” or cliff between less resistant shale members; on leading edge of Willard thrust sheet, thickens southward from 425 feet (130 m) in Dairy Ridge quadrangle to 850 feet (260 m) in Horse Ridge quadrangle (Coogan, 2006a-b), but may be faulted, since about 400 feet (120 m) thick just to west on flanks of Baldy and Knighton Ridges; 680 feet (200 m) thick in Huntsville quadrangle.

Cbh, Cbh?

Hodges Shale Member (Middle Cambrian) – Brown-weathering, slope-forming, olive-gray to tan-gray, thin-bedded, shale and micaceous argillite, and thin- to thick-bedded, dark- to medium-gray limestone with tan-, yellow-, and red-weathering, wavy, silty layers and partings; typically vegetated slope former; along leading edge of Willard thrust sheet thickens southward from 410 feet (125 m) in Dairy Ridge quadrangle, to 600 feet (180 m) in Horse Ridge quadrangle (Coogan, 2006a-b); to west about 300 feet (90 m) thick on flank of Baldy Ridge in Causey Dam quadrangle and in the Huntsville quadrangle (see Coogan and King, 2016). The Hodges is at least locally prone to slope failures due to high clay content and is an aquitard.

Cbk, Cbk?

Blacksmith Formation (Middle Cambrian) – Typically medium-gray, very thick to thick-bedded, dolomite and dolomitic limestone with tan-weathering, irregular silty partings to layers; weathers to lighter gray cliffs and ridges; 250 to 760 feet (75–230 m) thick in the map area, and is thin in the Huntsville quadrangle and thickens to north, west, and east, and thickens southward on leading edge of thrust sheet (see details in Coogan and King, 2016).

Cu–Cl

Ute and Langston Formations, undivided (Middle Cambrian) – Unit only used in Mantua quadrangle; see each formation for descriptions; about 800 feet (245 m) thick.

Cu, Cu?

Ute Formation (Middle Cambrian) – Interbedded gray thin- to thick-bedded limestone with tan-, yellowish-tan-, and reddish-tan-weathering, wavy, silty layers and partings, and olive-gray to tan-gray, thin-bedded shale and micaceous argillite; and minor, medium-bedded, gray to light-gray dolomite; sand content in limestone increases upward such that calcareous sandstone is present near top of formation; mostly slope and thin ledge former; base less resistant (more argillaceous) than underlying Langston Formation; estimate 450 to 1000 feet (140–300 m) thick and thinnest on leading edge of Willard thrust sheet (see details in Coogan and King, 2016). The Ute is at least locally prone to slope failures due to high clay content and contains aquitards.

Cl, Cl?

Langston Formation (Middle Cambrian) – Upper part is gray, sandy dolomite and limestone that weathers to ledges and cliffs; middle part is yellowish- to reddish-brown to gray weathering, greenish-gray, fossiliferous shale and lesser interbedded gray, laminated to very thin bedded, silty limestone (Spence Shale Member); basal part is light-brown-weathering, ledge forming gray limestone and dolomite with local poorly indurated tan, dolomitic sandstone at bottom; basal part that is less resistant (Naomi Peak Member) is present at least in northwest part of the map area; conformably overlies Geertsen Canyon Quartzite; 200 to 400 feet (60–120 m) thick (see details in Coogan and King, 2016).

CAMBRIAN AND NEOPROTEROZOIC

Cgc, Cgc?

Geertsen Canyon Quartzite (Middle and Lower Cambrian and possibly Neoproterozoic) – In the west mostly buff (off-white and tan) quartzite, with pebble conglomerate beds; pebbles are mostly rounded light-colored quartzite; contains cross-bedding, and pebble layers and lenses; colors vary from tan and light to medium gray, with pinkish, orangish, reddish, and purplish hues; outcrops darker than these fresh quartzite colors; cliff forming; some brown-weathering, interbedded micaceous argillite and quartzite common at top and mappable locally; pebble to cobble conglomerate lenses more abundant in middle part of quartzite, and basal, very coarse-grained arkose locally; near Huntsville, total thickness about 4200 feet (1280 m), including upper argillite about 375 feet (114 m) thick and basal coarse-grained arkosic to feldspathic quartzite about 300 to 400 feet (90–120 m) thick (Crittenden and others, 1971). Overall seems to be thinner near Browns Hole. Unit called Prospect Mountain Quartzite and Pioche Shale (argillite at top) by some previous workers.

Upper and lower parts of Crittenden and others (1971; Crittenden, 1972; Sorensen and Crittenden, 1979) are not mappable outside the Browns Hole and Huntsville quadrangles, likely because the marker cobble conglomerate and change in grain size and feldspar content reported by Crittenden and others (1971) is not at a consistent horizon; quartz-pebble conglomerate beds are present in most of the Geertsen Canyon Quartzite.

To the east on leading margin of Willard thrust sheet, the Geertsen Canyon is thinner, an estimated 3200 feet (975 m) total thickness (Coogan, 2006a-b), and may be divided into different members, though informal members to west and east are based on conglomerate lenses near member contact and feldspathic lower member (see Crittenden and others, 1971; Coogan, 2006a-b).

Cgcu

Upper part in west – Mostly buff quartzite with pebble conglomerate beds increasing downward; colors vary from tan and light to medium gray, with pinkish, orangish, reddish, and purplish hues; brown-weathering, interbedded micaceous argillite and quartzite common at top and mappable locally; reported thicknesses vary from 2250 to 3400 feet (685–1035 m). Near Huntsville, separation of upper and lower parts based on 10- to 200-foot (3–60 m) thick zone of 1- to 8-foot (0.3–2 m)-thick cobble conglomerate lenses at bottom of upper part (see Coogan and King, 2016).

Cgcl, Cgcl?

Lower part in west – Typically conglomeratic and feldspathic quartzite, with 300- to 400-foot (90–120 m), basal, very coarse-grained, more feldspathic or arkosic quartzite; 1175 to 1700 feet (360–520 m) thick and at least 200 to 400 feet (60–120 m) thinner near Browns Hole (see Coogan and King, 2016). Unit queried where poor exposures may actually be surficial deposits.

Cgu

Upper member in east – Tan, white, and light-gray, medium- to coarse-grained, cross-bedded, thick-bedded quartzite; base of upper part is marked by a resistant, light-colored quartzite with quartz-pebble conglomerate containing white and pink quartz and rare jasper clasts; incompletely exposed, so thickness uncertain (Coogan, 2006a-b). Contact between members in east is partly based on purplish color of upper part of lower member (Coogan, 2006a-b), so upper-lower contact may shift in quartzite and is uncertain in Sawmill and Hansen Canyons, southern Dairy Ridge quadrangle.

Cgl

Lower member in east –Typically conglomeratic and feldspathic; contains a purplish-gray upper part and a light-colored lower part; thickness about 600 to 1300 feet (180–400 m), thickening northward in Dairy Ridge quadrangle (Coogan, 2006a-b).

NEOPROTEROZOIC

Zrx

Neoproterozoic formations, undivided (Neoproterozoic) – Unit used in parentheses in block landslides or possible block landslide where the bedrock is an unknown Neoproterozoic formation or is several formations.

Zb

Browns Hole Formation (Neoproterozoic)

Zbq, Zbq?

Quartzite member (Neoproterozoic?) – Locally mappable north of the Middle Fork Ogden River due to lighter colored, more resistant beds than adjacent overlying Geertsen Canyon Quartzite, but has same resistance as quartzite higher in Geertsen Canyon unit, and is not distinctly red or terra-cotta colored despite previous descriptions (see Crittenden and others, 1971; Crittenden, 1972; Sorensen and Crittenden, 1979); this “white”, almost vitreous quartzite (Crittenden and Sorensen, 1985a) is absent on leading edge of Willard thrust sheet and in part of the James Peak quadrangle, and obscure near North Fork of Ogden River; 0 to 285 feet (0–85 m) thick. The local “white” quartzite unit is lithologically distinct from the typically feldspathic and conglomeratic lower Geertsen Canyon Quartzite, and thus may be unconformably overlain by the Geertsen Canyon Quartzite (King, this report). Much of the reddish-orange color seems to be along fault zones and be "bleeding" from the underlying hematitic Browns Hole.

Zbv, Zbv?

Volcanic member (Neoproterozoic) – Poorly resistant, gray to reddish-gray weathering, typically vegetated, metamorphosed (but with no fabric), brownish- to purplish-red (hematitic) volcanic-clast meta-sedimentary and fragmental(?) meta-volcanic rock; volcanic material and clast size decreases to south and east, so mostly volcanic meta-sandstone with some argillite near South Fork Ogden River and on leading margin of Willard thrust sheet (Coogan, 2006a); meta-andesite lava flows reported in James Peak quadrangle (Blau, 1975); 180 to 460 feet (55–140 m) thick near Ogden River forks (after Crittenden and others, 1971; Crittenden, 1972; Sorensen and Crittenden, 1979); only 20 to 200 feet (6–60 m) thick in exposures on leading edge of Willard thrust sheet in Dairy Ridge quadrangle (Coogan, 2006a).

Zm?c

Mutual Formation? and Caddy Canyon Quartzite (Neoproterozoic) – Unit mapped on leading margin of Willard thrust sheet where Inkom Formation is absent and exposures have characteristics of both formations (see Coogan, 2006a). Reddish-gray, pink, tan, and light-gray, thick-bedded, locally vitreous quartzite, and conglomeratic and feldspathic quartzite; upper part of unit darker colored, but because the Inkom is not present, dark part may or may not be the Mutual Formation; total exposed thickness about 725 to 1300 feet (220–400 m), apparently thickening northward (or underlying argillitic strata mapped as Zpc? pinches out northward); base truncated by Willard thrust where Zpc? not mapped.

Zm, Zm?

Mutual Formation (Neoproterozoic) – Grayish-red to purplish-gray, medium to thick-bedded quartzite with pebble conglomerate lenses; also reddish-gray, pink, tan, and light-gray in color and typically weathering to darker shades than, but at least locally indistinguishable from, Geertsen Canyon Quartzite; commonly cross-bedded and locally feldspathic; contains argillite beds and, in the James Peak quadrangle, a locally mappable medial argillite unit; 435 to 1200 feet (130–370 m) thick in Browns Hole quadrangle (Crittenden, 1972), thinnest near South Fork Ogden River, and thicker to northwest, up to about 2600 feet (800 m) thick in Huntsville and James Peak quadrangles; may be as little as 300 feet (90 m) thick south of the South Fork Ogden River; absent or thin on leading edge of Willard thrust sheet (see unit Zm?c); thins to south and east.

Zi, Zi?

Inkom Formation (Neoproterozoic) – Overall gray to reddish-gray weathering, poorly resistant, psammite and argillite, with gray-weathering meta-tuff lenses in lower part; upper half dominantly dark-green, very fine grained meta-sandstone (psammite) with lower half olive gray to lighter green-gray, greenish gray-weathering, laminated, micaceous meta-siltstone (argillite); lower greenish-weathering part missing near South Fork Ogden River and the Inkom is less than 200 feet (60 m) thick; in Mantua quadrangle, Inkom typically 300 feet (90 m) thick, and is only less than 200 feet (60 m) thick where faulted; 360 to 450 feet (110–140 m) thick northeast of Huntsville (Crittenden and others, 1971), and absent on leading edge of Willard thrust sheet (Coogan, 2006a); location of "pinch-out" not exposed.

Zcc, Zcc?

Caddy Canyon Quartzite (Neoproterozoic) – Mostly vitreous, almost white, cliff-forming quartzite; colors vary and are tan, light-gray, pinkish-gray, greenish-gray, and purplish-gray, that are typically lighter shades than the Geertsen Canyon Quartzite; 1000 to 2500 feet (305–760 m) thick in west part of the map area, thickest near Geertsen Canyon in Huntsville quadrangle (Crittenden and others, 1971; Crittenden, 1972) where it appears to include 600 feet (180 m) of Papoose Creek strata or mixed Papoose Creek and Caddy Canyon rocks (see Zpc–Zcc); 1500 feet (460 m) thick near South Fork Ogden River (Coogan and King, 2006); thinner, 725 to 1300 feet (220–400 m) thick, and less vitreous on leading edge of Willard thrust sheet (Coogan, 2006a-b).

Lower contact with Kelley Canyon Formation is gradational with brownish-gray quartzite and argillite beds over a few tens to more than 200 feet (3–60 m) (see Crittenden and others, 1971). Where thick, this gradational-transitional zone is what is mapped as the Papoose Creek Formation. Near Geertsen Canyon, this transition zone is 600 feet (180 m) thick and was mapped with and included in the Caddy Canyon Quartzite by Crittenden and others (1971, figure 7), and in the Caddy Canyon and Kelley Canyon Formations by Crittenden (1972, see lithologic column).

Zpc–Zcc

Papoose Creek and Caddy Canyon Formations, undivided (Neoproterozoic) – North of Perry Canyon in the Mantua quadrangle, these strata previously mapped as Zpc contains brown-weathering, medium- to coarse-grained quartzite (see Sorensen and Crittenden, 1976a; Crittenden and Sorensen, 1985a). This likely resulted in difficulty identifying the gradational contact with the overlying Caddy Canyon Quartzite and resulted in Coogan and King (2016) mapping a Zpc–Zcc gradational unit of variable thickness, rather than mapping complex structure like Crittenden and Sorensen (1985a).

Zpc, Zpc?

Papoose Creek Formation (Neoproterozoic) – Gray to brownish-gray to olive-gray argillite to psammite; metasiltstone interbedded with quartzose metasandstone and quartzite; argillite darker colored with greenish-gray, micaceous bedding surfaces; 750 to 1000 feet (230–300 m) thick in Mantua quadrangle. The Papoose Creek is at least locally prone to slope failures because it has been deeply weathered to clay, likely during the Eocene and/or Paleocene (see for example Wilf, 2000). The argillites are aquitards.

The Papoose Creek unit seems to be the transition zone between the Caddy Canyon Quartzite and the Kelley Canyon Formation. Coogan and King (2016) mapped a queried Zpc, 100- to 200-foot (30–60 m) thick, south of the Middle Fork of the Ogden River because the unit was not field checked.

Coogan and King (2016) mapped interbedded gray quartzite (like Caddy Canyon) and reddish- and greenish-gray argillite (like Kelley Canyon) in the Dairy Ridge quadrangle; it is up to about 300 feet (90 m) thick, with its base truncated by the Willard thrust (see Zkc? of Coogan, 2006a). Other exposed Neoproterozoic units thin to east, so this may be the entire Papoose Creek thickness.

Zkc, Zkc?

Kelley Canyon Formation (Neoproterozoic) – Dark-gray to black, gray to olive-gray-weathering argillite to phyllite, with rare metacarbonate (for example basal meta-dolomite); silvery gray weathering reportedly characteristic (Sorensen and Crittenden, 1976b), but silvery looking due to micas in phyllite rather than being a weathering characteristic; grades into overlying Caddy Canyon quartzite with increasing quartzite; gradational interval mapped as Papoose Creek Formation (Zpc); 1000 feet (300 m) thick in Mantua quadrangle; reportedly 2000 feet (600 m) thick near Huntsville (Crittenden and others, 1971, figure 7), but only shown as about 1600 feet (500 m) thick to Papoose Creek transition zone by Crittenden (1972). The Kelley Canyon Formation is prone to slope failures because it has been deeply weathered to clay, likely during the Eocene and/or Paleocene (see for example Wilf, 2000). The argillites and phyllites are aquitards.

Zmc, Zmc?

Maple Canyon Formation, undivided (Neoproterozoic) – Upper part green to greenish-gray, feldspathic quartzite to metaconglomerate, separated by laminated argillite, with buff quartzite and thin beds of gray meta-limestone near Perry Canyon; lower part feldspathic meta-sandstone and argillite; about 1000 feet (300 m) total thickness reported, but member thicknesses add up to more than 1000 feet (300 m) (see Crittenden and others, 1971; Sorensen and Crittenden, 1976a-b; Crittenden and Sorensen, 1985a); argillites and phyllites in the Maple Canyon are at least locally prone to slope failures because they are deeply weathered to clay, likely during the Eocene and/or Paleocene (see for example Wilf, 2000), and the argillites are aquitards; basal argillite of previous workers is actually part of formation of Perry Canyon. Members are actually lithosomes, so more work is needed to justify formal Formation designation.

Zmcc, Zmcc?, Zmcc1, Zmcc1?, Zmcc3, Zmcc3?,

Zmcc2, Zmcc2?

Upper (conglomerate) member (Neoproterozoic) – At top (Zmcc3) and bottom (Zmcc1), light-gray coarse-grained, quartzite to pebble and small cobble meta-conglomerate with local tan-weathering, dark-gray, meta-graywacke matrix; thin olive-gray, laminated, weakly resistant argillite, with silvery phyllite locally in middle (Zmcc2); 60 to 500 feet (20–150 m) total thickness; thickness of sub-units varies considerably and these sub-units may be absent locally; conglomerate beds appear thickest in northeast part of Huntsville quadrangle, possibly more than 200 feet (60 m) thick, while middle argillite appears less than 50 feet (15 m) thick; only divided into subunits to show structure in Huntsville quadrangle.

Zmcg, Zmcg?

Lower (green arkose) member (Neoproterozoic) – Grayish-green, fine-grained feldspathic meta-graywacke and sandy argillite, with local quartzite lenses up to 200 feet (60 m) thick; weathers darker gray to brown to greenish-gray and greenish-brown; 500 to 1000 feet (150–305 m) thick and lower thickness would eliminate the need for faulting in southwest part of Huntsville quadrangle (see Coogan and King, 2016). This unit is prone to slope failures because it has been deeply weathered to clay, likely during the Eocene and/or Paleocene (see for example Wilf, 2000); even the sandy argillites are aquitards.

NEOPROTEROZOIC AND MESOPROTEROZOIC

Zarx

Argillite of lower member of Maple Canyon Formation or upper member of Formation of Perry Canyon (Proterozoic) – Greenish-gray argillite to meta-graywacke in poor exposures on east side of Ogden Valley (Zarx and Qdlb/Zarx) and on dip slope west of Ogden Valley; weathering, lack of bedding, and lack of exposures of overlying conglomerate member of Maple Canyon preclude separation of these stratigraphically adjacent units. This unit is prone to slope failures because it has been deeply weathered to clay, likely during the Eocene and/or Paleocene (see for example Wilf, 2000). The argillites are aquitards.

ZYp, ZYp?

Formation of Perry Canyon (Neoproterozoic and possibly Mesoproterozoic) – Argillite to meta-graywacke upper unit, middle meta-diamictite, and basal slate, argillite, and meta-sandstone; phyllitic at least south of Pineview Reservoir; due to overturned folding, only one diamictite unit (Adolph Yonkee, Weber State University, February 2, 2011, email communication) rather than two (see Crittenden and others, 1983); total thickness likely less than 2000 feet (600 m). Perry Canyon unit queried in knob west of North Fork Ogden River in North Ogden quadrangle because rock is quartzite that may be in this unit or the Papoose Creek Formation. The formation of Perry Canyon is prone to slope failures because it has been deeply weathered to clay, likely during the Eocene and/or Paleocene (see for example Wilf, 2000). The argillites and phyllites are aquitards.

Zpu, Zpu?

Upper member (Neoproterozoic) – Olive drab to gray, thin-bedded slate to argillite to phyllite to micaceous meta-siltstone to meta-graywacke to meta-sandstone in variable proportions such that unit looks like both the "greywacke-sandstone" and "mudstone" members of previous workers; unit identification based on underlying diamictite in Mantua quadrangle; rare meta-gritstone and meta-diamictite (actually conglomerate?; see Yonkee and others, 2014); locally schistose; meta-sandstone contains poorly sorted lithic, quartz, and feldspar grains in silty to micaceous matrix; meta-sandstone is quartzose in outcrops on west margin of Mantua quadrangle (Crittenden and Sorensen, 1985a) and medial zone of sandstone is feldspathic east of Ogden Valley, where mapped and described as argillite member of Maple Canyon Formation by Crittenden (1972) and Sorensen and Crittenden (1979); thickness uncertain, but appears to be about 600 feet (180 m) thick on west flank of Grizzly Peak in the Mantua quadrangle and about 1000 feet (300 m) thick between Ogden Canyon and North Ogden divide. In Ogden Valley typically non-resistant and tan weathering such that gray to green to dark-gray fresh color is seldom seen except in cut slopes and excavations. This unit is prone to slope failures because it has been deeply weathered to clay, likely during the Eocene and/or Paleocene (see for example Wilf, 2000). The argillites and phyllites are aquitards.

Zpi

Altered meta-intrusive diorite (Proterozoic) – North-northeast-trending, green-weathering dike(?), about 300 to 400 feet (90–120 m) wide, cutting the mudstone unit (ZYpm) north of Cobble Creek as mapped by Crittenden and Sorensen (1985b).

Described by Balgord (2011) as greenstone that cuts the meta-basalt and overlying meta-diamictite in klippe north of North Ogden Pass, but not described differently than meta-basalt rocks.

Other greenstone bodies are involved in the large Ogden Valley landslide block, such that stratigraphic relationships are obscured and their age relationships with Zpu, Zpd, and ZYpm are not known.

Zpd, Zpd?

Diamictite member (Neoproterozoic) – Tan to gray weathering, gray to dark-gray meta-diamictite containing pebble to boulder-size quartzite and granitoid (quartzo-feldspathic gneiss) clasts in dark-gray sandy (up to granule size) to micaceous argillite matrix; fuschsite-bearing quartzite clasts minor but distinctive; local meta-pillow lava (unit Zpb) and meta-limestone at and near base, and local altered intrusive diorite (unit Zpi) (Crittenden and Sorensen, 1985b); appears to be up to 200 to 400 feet (60–120 m) thick in the map area but is about 1000 feet (300 m) thick to the west in the Willard quadrangle.

From Balgord and others (2013, and Balgord, 2011) detrital zircon uranium-lead and lead-lead maximum depositional ages on the upper part of the diamictite are about 650 to 690 Ma with about a 120-million-year gap to about 800 Ma on the lower part of the diamictite. This major unconformity is within the meta-volcanic (Zpb) unit to the west of the map area on Fremont Island, such that the diamictite above the meta-volcanics and where the meta-volcanics are missing in the Ogden map area may be considerably younger than the lower diamictite.

Near Lewis Peak in the North Ogden quadrangle, the diamictite contains typical granitoid and quartzite clasts with minor sedimentary and volcanic rock clasts of cobble to boulder size in a dark gray quartzose pebbly to sandy to micaceous argillite matrix (after Balgord, 2011). Granitoid clasts look like they are from the Farmington Canyon Complex.

The diamictite reportedly has a large volcanic component in the klippe north of the North Ogden divide with most clasts being mafic volcanic rocks from the underlying meta-basalt (Zpb) and a few large "basement" clasts in a greenish-colored matrix with about 50% sand and silt (Balgord, 2011). This implies the klippe diamictite lacks the quartzite and granitoid clasts of the typical diamictite and may be a volcanic unit (Zpb) rather than part of the diamictite member.

Zpb

Basaltic meta-volcanic rocks (Proterozoic) – Green meta-basalt pillow lava and other basaltic fragmental material in the klippe north of North Ogden divide; appears to underlie meta-diamictite; thickness uncertain.

ZYpm, ZYpm?

"Mudstone" member (Neoproterozoic and possibly Mesoproterozoic) – Gray- and green-weathering, black, non-foliated argillite and sandy argillite, and slate; grades laterally into black chloritoid schist that contains scattered pyrite cubes; appears to be about 1000 feet (300 m) thick in Willard Basin and 1800 feet (550 m) thick on North Ogden-Mantua quadrangle boundary. This unit is prone to slope failures because it has been deeply weathered to clay, likely during the Eocene and/or Paleocene (see for example Wilf, 2000). The argillites and sandy argillites are aquitards.

The "mudstone" member unconformably overlies the Facer Formation near Willard Peak (Balgord, 2011). The relationship between the mudstone and diamictite is uncertain. No meta-diamictite is present near Willard Peak, so Coogan and King (2016) could not tell if the mudstone-diamictite contact is conformable. Crittenden and Sorensen (1985b) mapped a band of mudstone in diamictite on the north margin of the Ogden Valley landslide mass (QTms?) that may or may not be in-place bedrock.

MESOPROTEROZOIC AND PALEOPROTEROZOIC?

YXf, YXf?

Facer Formation (Proterozoic) – Contains (in order of abundance): quartzite (YXfq), pelitic phyllite and schist (YXfs), and quartz-muscovite (or sericite) schist (not mapped separately), with sparse mafic bodies (discordant meta-diorite, mapped as YXfdi, and unmapped concordant meta-gabbro [<90% amphibole]), leucocratic gneiss (YXfgn), meta-carbonate (too small to show separately on this map) and meta-conglomerate; also contains distinctive green micaceous quartzite, lustrous, reddish-black quartz hematite (specularite) schist (not mapped separately), and tourmaline-bearing pegmatite (not mapped separately); truncated by Willard thrust fault; estimate 2500 feet (760 m) total thickness (Crittenden and Sorensen, 1980), with about 1700 feet (500 m) of schist exposed east of Willard Canyon and about 800 feet (240 m) of unconformably underlying leucogneiss exposed on west margin of the map area. Facer Formation queried where poor exposures may actually be surficial deposits. The Facer Formation is at least locally prone to slope failures because it has been deeply weathered to clay, likely during the Eocene and/or Paleocene (see for example Wilf, 2000). The phyllites are aquitards.

Dr. Adolph Yonkee (Weber State University, February 2, 2011, email communication) stated (using the Xf unit symbols of Crittenden and Sorensen, 1985a) that the upper part of the Facer (south of Facer Creek and best exposed near Willard Canyon) is phyllitic and schistose (Xfs) with interbedded quartzite (Xfq) and lesser conglomerate beds (Xfcg), mafic bodies (unmapped), and carbonate bodies (Xfd, Xfls). He stated the lower part of the Facer (north and barely south of Facer Creek) is quartzitic gneiss (Xfgn) with pegmatite (Xfp), mafic bodies (Xfdi), and quartzite (Xfvq, Xfq [in landslide block]) bodies. So the lower Facer is only exposed near Facer Creek.

Members of previous workers are actually lithosomes, and are poorly exposed and mapped, with much undivided Xf (Coogan and King's 2016 YXf) on their maps. So, more work is needed to justify formal formation designation. From previous mapping divided into lithosomes, with descriptions, except for thicknesses, after Crittenden and Sorensen (1980).

YXfq, YXfq?

Quartzite (Proterozoic) – Off-white- to tan-weathering, white to very pale gray, vitreous to translucent, highly jointed or fractured, yet cliff-forming quartzite with minor white mica (sericite or muscovite) and rare chlorite; intercalated with fine- to coarse-grained quartz-muscovite (sericite) schist; locally "intruded" by thin (<1 m) tourmaline-bearing pegmatites (Crittenden and Sorensen, 1985a) and associated with coarser quartz-muscovite schist (Crittenden and Sorensen, 1980; in the Mantua quadrangle, quartzite bands are about 100 to 550 feet (30–160 m) thick (see Coogan and King, 2016).

YXfs, YXfs?

Pelitic phyllite and schist (Proterozoic) – Grayish-green and grayish-purple (chloritic to hematitic) pelitic rocks (siltstone and mudstone) metamorposed into slate and phyllite, and sericite, chlorite, and/or chloritoid schist; near Willard Peak includes meta-conglomerate beds, Xfcg of Crittenden and Sorensen (1985a), with clasts that are mainly (80%) white to pale-gray quartzite from Facer Formation in a sparse gray pelitic matrix; from previous mapping interlayered with quartzite (Xfq of Crittenden and Sorensen, 1985a) and local dolomite (Xfd of Crittenden and Sorensen, 1985a); in the Mantua quadrangle, schist and phyllite bands are about 30 to 350 feet (10–100 m) thick (see Coogan and King, 2016). This unit (YXfs) is prone to slope failures because it has been deeply weathered to clay, likely during the Eocene and/or Paleocene (see for example Wilf, 2000). The phyllites are aquitards.

YXfdi

Meta-diorite pod (Proterozoic) – Fine-grained hornblende diorite in undivided Facer (YXf) on north side of Facer Creek in Mantua quadrangle; discordant, with primary hornblende and feldspar, so atypical of amphibolites elsewhere in Facer Formation and isotopically dated meta-diorite pod; 33 to 130 feet (10–40 m) thick (Crittenden and Sorensen, 1985a), though shown as much thicker on their map.

YXfgn, YXfgn?

Leucocratic gneiss (Proterozoic) – Composed of quartz and microcline with minor sericite and mucsovite; mapped between Perry Canyon and Facer Creek northeast of White Rock; locally intercalated with quartzite and quartz-muscovite schist (both in Coogan and King's [2016] undivided unit YXf), grading into these rocks to the south (Crittenden and Sorensen, 1985a); meta-arkose of Crittenden and Sorensen (1980) is feldspathic meta-sandstone since they reported <50% feldspar; thickness indeterminate.

This quartzitic gneiss may be metamorphosed igneous rock (orthogneiss) or sedimentary rock (paragneiss). The gneiss appears to unconformably underlie YXfs and YXfq and be the lower Facer, but its base is not exposed. This gneiss does not appear to grade into Crittenden and Sorensen's (1985a) quartzite map unit (Xfq).

SUB-WILLARD THRUST - OGDEN CANYON AREA
and Tertiary strata that are younger than the Willard thrust sheet

These strata are a transitional marine shelf sequence between deeper-water strata now exposed on the Willard thrust sheet and shallower-water strata exposed to the east on Elk and Durst Mountain and the Crawford thrust sheet (see for example Coogan, 1992a). The Ordovician Tooele arch and Devonian Stansbury uplift have affected the area, so the units and lithologies exposed in the Ogden Canyon area (Yonkee and Lowe, 2004; King and others, 2008) are not the same as those to the east on Elk and Durst Mountains (Coogan and King, 2006; Coogan and others, 2015), or those exposed to the south in the Wasatch Range (see Bryant, 1984, 1988, 1990).

Silurian and some Ordovician strata are missing in the Ogden Canyon, Wasatch Range, and Elk and Durst Mountains areas (for example, Laketown Dolomite and Swan Peak Quartzite), and Devonian through upper Cambrian strata are thinner over the Stansbury uplift and Tooele arch (see Rigby, 1959; Hintze, 1959). Also, strata in the Ogden Canyon area have been tectonically thinned and duplicated to triplicated during movement on the Ogden and Willard thrust faults (see for example Yonkee and others, 1997; Yonkee and Lowe, 2004). This means the map-unit thicknesses are highly variable and, though Coogan and King (2016) attempted to present numbers that are undeformed thicknesses, the thicknesses reported may be inaccurate due to deformation.

TERTIARY

Ts

Tertiary strata, undivided – Only used in Ogden Canyon area where Norwood and Wasatch Formations are in landslide block [Qms?(Ts)], and below old fan (QTaf/Ts) near Maples recreation area (formerly campground), Snow Basin quadrangle; latter may be on or below the Willard thrust.

Tn, Tn?

Norwood Formation (lower Oligocene and upper Eocene) – Typically light-gray to light-brown altered tuff (claystone), altered tuffaceous siltstone and sandstone, and conglomerate; unaltered tuff, present in type section to south of map area, is rare; locally colored light shades of red and green; variable calcareous cement and zeolitization; involved in numerous landslides of various sizes due to high clay content and is an aquitard; exposed thickness up to 7000 feet (2135 m), thickest between Ogden Valley and Morgan Valley; thins to south to about 2800-foot (850 m) thickness exposed in type area south of map area; may thin to north since estimated 2000-foot (600 m) thickness exposed on west side of Ogden Valley (see Coogan and King, 2016).

The Norwood Formation is generally considered younger than the Fowkes Formation (isotopically dated at 39–40 Ma and 48–49 Ma) (see also unit Tnf in text on Willard thrust sheet cover rocks). However, the Norwood K-Ar isotopic ages of about 38 Ma (Evernden and others, 1964, p. 182–183) and 39 Ma (Mann, 1974) are not much different than the younger Fowkes ages (39–40 Ma). The basal part of a similar unit to the north in western Cache Valley was isotopically dated at 44 and 49 Ma (see unit Tnf under Willard thrust sheet cover rocks). Also, the strata near Morgan that were isotopically dated are at least 2500 feet (800 m) above the base of the Norwood and much older strata may be present in Ogden Valley.

Isotopic ages indicate a bimodal age distribution (~39–40 & 48–49 Ma) for Fowkes strata exposed along the Utah-Wyoming border. The older Fowkes ages and paleontological evidence indicate the older Fowkes strata are essentially the time equivalent of the Bridger Formation to the east in the Green River Basin, Wyoming. As yet, older Fowkes cannot be distinguished in the field from younger Fowkes (see Coogan and King, 2016), so abandoning the Fowkes name for just the older Bridger-age strata and using the Norwood name on the younger strata is premature.

Tw, Tw?

Wasatch Formation (Eocene and upper Paleocene) – Typically red to brownish-red sandstone, siltstone, mudstone, and conglomerate with minor gray limestone and marlstone locally; conglomerate clasts mainly rounded Neoproterozoic and Paleozoic sedimentary rocks, typically Neoproterozoic and Cambrian quartzite; basal conglomerate more gray and less likely to be red, and contains more locally derived angular clasts of limestone, dolomite and sandstone, typically from Paleozoic strata; lighter shades of red, yellow, tan, and light gray present locally and more common in uppermost part of Wasatch strata, complicating mapping of contacts with overlying similarly colored Norwood and Fowkes Formations; only 200 to 400 feet (60–120 m) thickness exposed in northern Snow Basin quadrangle and thicker to south and east of map area with 750 to 1300 feet (230–400 m) in southern Snow Basin quadrangle, about 2500 feet (760 m) exposed in Peterson quadrangle, and greatest thickness about 5000 to 6000 feet (1500–1800 m) southeast of Morgan; thinner east of leading edge of Willard thrust sheet, typically 600 feet (180 m) thick or less in Lost Creek drainage; thicknesses vary locally due to considerable relief on basal erosional surface, for example along leading edge of Willard thrust. The Wasatch Formation is at least locally prone to slope failures because it can be clay rich and poorly consolidated. Permeability in the

Wasatch Formation is complicated due to karst, clay content, limestone beds, and variable cementation that is so strong in some areas that quartzite clasts are broken through rather than around during fracturing. The variability is indicated by perched springs in the unit.

Td

Igneous dikes (Tertiary?) – Strongly chloritically altered, dark-colored, non-foliated mafic dikes intruding Farmington Canyon Complex in Ogden 7.5′ quadrangle; contain altered hornblende, biotite, and feldspar phenocrysts in a fine-grained matrix. May be Tertiary, but most chloritic alteration in the enclosing rocks is Cretaceous (Yonkee and Lowe, 2004), suggesting the dikes are Cretaceous or older.

CRETACEOUS

KXc

Chloritic gneiss, cataclasite, mylonite, and phyllonite (Cretaceous and Proterozoic) – Dark- to gray-green, variably fractured and altered rock with local micaceous cleavage; contains variable amounts of fine-grained, recrystallized chlorite, muscovite, and epidote; present in shear and fracture zones, and in diffuse altered zones associated with quartz pods that crosscut basement rocks (Yonkee, 1992; Yonkee and others, 1997); locally includes quartz veins (see Bryant, 1988, p. 5–6, 8); some linear zones of this unit mapped as faults by Bryant (1988). Unit produced by mostly Cretaceous deformation and greenschist-facies alteration that overprints various Farmington Canyon Complex protoliths (Yonkee and Lowe, 2004). However, Bryant (1988) indicated that some quartz veins and pods may be related to Neoproterozoic (late Precambrian) alteration.

MISSISSIPPIAN

Mh

Humbug Formation (Mississippian) – Gray- to tan- to reddish-gray and reddish-tan weathering, interbedded calcareous to dolomitic, quartzose sandstone, and sandy limestone and dolomite; lower part contains more sandstone and is less resistant than upper part; contact with Deseret Limestone may not be consistent; about 700 to 800 feet (215–245 m) thick and reportedly up to 1000 feet (300 m) thick (Sorensen and Crittenden, 1972) where upper contact not exposed. On this map, the Humbug-Deseret contact in the Snow Basin quadrangle is corrected from King and others (2008), so the Deseret is now thicker.

Mde

Deseret Limestone (Mississippian) – Pale-brown weathering, ledge- and cliff-forming dolomite and limestone, becoming sandy upward; about 500 feet (150 m) thick.

Mded

Delle Phosphatic Member of Deseret Limestone (Lower Mississippian) – Dark, poorly resistant, shaly, phosphatic strata at base of Deseret mapped separately where possible at map scale.

Mg, Mg?

Gardison Limestone (Lower Mississippian) – Gray, ledge- and cliff-forming, fossiliferous limestone and lesser dolomitic limestone; widespread crinoid and brachiopod fossil fragments; locally cherty; bedding becomes thicker upward; about 500 to 800 feet (150–245 m) thick (King and others, 2008). Lodgepole or Madison Limestone of some workers.

DEVONIAN

Named on western Willard thrust sheet so names may not be appropriate here.

Db

Beirdneau Sandstone – Reddish-tan to tan to yellowish-gray, dolomitic to calcareous sandstone and siltstone, some silty to sandy dolomite and limestone, and lesser intraformational (flat-pebble) conglomerate; less resistant than adjacent map units; likely 250 to 300 feet (75–90 m) thick.

The contact with the Hyrum Dolomite does not appear to be mapped at a consistent horizon. Argillaceous uppermost part of Beirdneau reported in the Huntsville quadrangle by Yonkee and Lowe (2004) is likely the Cottonwood Canyon Member of the Lodgepole Limestone and underlying Leatham Formation (Devonian).

Dhw, Dhw?

Hyrum and Water Canyon Formations, undivided – Estimate 300 to 440 feet (90–135 m) thick. Both formations missing to south near Salt Lake City.

Hyrum Dolomite - Brownish-gray and gray, ledge-forming dolomite and minor limestone; weathers distinctive dark-chocolate brown; about 200 to 350 feet (60–107 m) thick; thinner over the Stansbury uplift and thicker to east. Unconformably overlies Water Canyon Formation.

Water Canyon Formation - Interbedded, slope-forming, light-colored dolomitic to calcareous sandstone and siltstone and silty to sandy dolomite and limestone; 30 to 100 feet (9–30 m) thick; thinned by erosion over Stansbury uplift or limited deposition over the Tooele arch and thicker to the east.

SILURIAN

Because the Laketown Dolomite is missing over the Tooele arch (see Hintze, 1959), the unit is missing at Ogden Canyon, to the south near Salt Lake City, to the east on Elk and Durst Mountains, and on the Crawford thrust sheet.

ORDOVICIAN

Ordovician formations were named on the eastern Paris-Willard thrust sheet so usage below the Willard thrust in the Wasatch Range may not be appropriate.

Ofg, Ofg?

Fish Haven and Garden City Formations, undivided (Ordovician) – Swan Peak Formation, which is between these units, is missing over Tooele arch, so missing at Ogden Canyon and also to east on Elk and Durst Mountains.

Ofh, Ofh?

Fish Haven Dolomite (Ordovician) – Medium- to dark-gray, cliff-forming dolomite; locally cherty; in less deformed areas, likely 200 to 225 feet (60–70 m) thick (see Sorensen and Crittenden, 1972, 1974), so not thinned here over Tooele arch.

Ogc, Ogc?

Garden City Formation (Ordovician) – Pale-gray to buff-weathering, ledge-forming dolomite, silty dolomite and limestone, and minor siltstone, typically as bedding partings; lower part typically less resistant than upper part, so slope and ledge forming; 200 to 400 feet (60–120 m) thick; thins over Tooele arch.

ORDOVICIAN AND CAMBRIAN

Units were named on the eastern Paris-Willard thrust sheet so names may not be appropriate below the Willard thrust in the Wasatch Range.

Csn

St. Charles and Nounan Formations, undivided (Ordovician and Cambrian) – See descriptions below.

Csc, Csc?

St. Charles Formation (Ordovician and Cambrian) – Light- to medium-gray, cliff- and ledge-forming dolomite; lower part calcareous sandstone and sandy dolomite that forms slopes, locally contains Worm Creek Quartzite Member at base; 400 to 660 feet (120–200 m) thick (Rigo, 1968; Sorensen and Crittenden, 1972) and thickens to north; thins over Tooele arch.

CAMBRIAN

Nounan, Bloomington, Maxfield and Tintic Formations are thinner to the east on Elk and Durst Mountains, though the Ophir Formation is about the same thickness (compare Yonkee and Lowe, 2004, to Coogan and King, 2006). These marine strata should thin to the east on the paleo-continental shelf. Nounan and Bloomington Formations were named on the Paris-Willard thrust sheet, so usage below the Willard thrust in the Wasatch Range may not be appropriate and is compounded by the Bloomington and Maxfield being partly equivalent from fossil data.

Cn, Cn?

Nounan Dolomite (Cambrian) – Medium-gray, typically thick-bedded, cliff-forming dolomite and some limestone; 500 to 750 feet (150–230 m) thick and thinning over Tooele arch.

The Nounan was not mapped to the south near Salt Lake City by Bryant (1990), but his overly thick Maxfield Limestone unit may include the upper two members of the Ophir Formation and/or all of the Nounan Formation. Also, the Bloomington Formation, typically present between the Nounan and Maxfield strata, was not mapped to the south in the Wasatch Range (see Bryant, 1984, 1988, 1990).

Cbom, Cbom?

Bloomington Formation and Maxfield Limestone, undivided (Cambrian) – Used where these units are thinned by deformation directly below Willard thrust fault.

Cbo, Cbo?

Bloomington Formation (Cambrian) – Lithologically similar to Calls Fort (upper) and Hodges (lower) Shale Members of this formation; contains brown-weathering, slope-forming, 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; 40 to 200 feet (12–60 m) thick and thickens to north, but likely highly deformed; thins over Tooele arch. The Bloomington is at least locally prone to slope failures due to high clay content and contains aquitards. *Eldoradia* sp. trilobite fossil in Ogden Canyon (Rigo, 1968) supports correlation with the Calls Fort Member, but this would require the Maxfield Limestone to be partly equivalent to the Bloomington Formation.

Cmo, Cmo?

Maxfield Limestone and/or Ophir Formation (Middle Cambrian) – Used for carbonate and argillite rocks in thrust windows directly below Willard thrust fault in North Ogden quadrangle; rocks are similar to carbonate and argillite strata in both units.

Cm, 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 (see Yonkee and Lowe, 2004; King and others, 2008 for more member details); member thicknesses highly variable due to deformation; total thickness about 600 to 900 feet (180–270 m) (King and others, 2008). The Maxfield is at least locally prone to slope failures due to high clay content and contains aquitards.

According to Yonkee and Lowe (2004), the trilobite fossils reported by Rigo (1968) in the middle limestone of the Ophir Shale are actually in the basal limestone member of the Maxfield. These *Elrathia* trilobites can be used as a proxy for the Middle Cambrian *Bolaspidella* zone (see Robison, 1976, figure 4) and this zone is in the Bloomington Formation shales on the Willard thrust sheet (see Oviatt, 1986; Jensen and King, 1996, table 2). This supports the Maxfield Limestone as partly equivalent to the Bloomington Formation, but leaves the Blacksmith Dolomite without an equivalent carbonate unit below the Willard thrust sheet. However, Rigo (1968) did not provide a usable sample location and the sample location is not on the map of Crittenden and Sorensen (1985b) or Yonkee and Lowe (2004).

Co, Co?

Ophir Formation (Middle Cambrian) – Upper and lower brown-weathering, slope-forming, gray to olive-gray, variably calcareous and micaceous to silty argillite to slate with intercalated gray, silty limestone beds; middle ledge-forming, gray limestone; total thickness about 450 to 650 feet (140–200 m) (Sorensen and Crittenden, 1972) where likely less deformed, but highly deformed in most outcrops. The Ophir is at least locally prone to slope failures due to high clay content and contains aquitards.

Rigo (1968) reported *Ehmaniella* sp. trilobites from the lower member, fossils that indicate an early Middle Cambrian age (Robison, 1976). These trilobites may be in the upper and, possibly, lower Ute Formation on the Willard thrust sheet (see unit Cu), leaving the Langston Formation and possibly the lower Ute Formation without lithologically equivalent strata below the Willard thrust sheet.

Only subdivided north of Ogden Canyon to show structure.

Cou

Upper shale (Middle Cambrian) – About 130 to 260 feet (40–80 m) thick.

Com-Col

Middle limestone and lower shale (Middle Cambrian) – Middle limestone about 100 feet (30 m) thick, but deformed to 15 to 165 feet (5–50 m) thick. Lower shale about 100 to 145 feet (30–45 m) thick.

Ct, 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; quartzite is tan, white, reddish tan and pale-orange tan with abundant cross-bedding; argillite more abundant at top and quartz-pebble conglomerate increases downward; greenish-tan to purplish-tan to tan, arkosic sandstone, conglomerate, and micaceous argillite at base that is 50 to 200 feet (15–60 m) thick and derived from unconformably underlying gneissic and schistose Farmington Canyon Complex; about 1100 to 1500 feet (335–450 m) thick.

PALEOPROTEROZOIC

Xa

Mafic bodies (Paleoproterozoic?) – Dark greenish-gray to black pods and dikes of plagioclase and hornblende referred to as amphibolites despite greater abundance of plagioclase; typically non- to strongly foliated pods in granitic gneiss (Yonkee and Lowe, 2004); only larger bodies mapped; a few to 330 feet (100 m) long and up to 65 feet (20 m) wide (Crittenden and Sorensen, 1985b). Unit appears to post-date Farmington Canyon Complex, and may be related to lamprophyres elsewhere in Wasatch Range, but unit may include intrusions that are part of the complex.

Xfc

Farmington Canyon Complex (Paleoproterozoic) – Migmatitic gneiss, granitic gneiss, quartz-rich gneiss, and biotite-rich schist, with lesser layers to pods of white quartzite, pegmatite, amphibolite, mafic rocks, and meta-ultramafic rocks; migmatitic gneiss contact with granitic gneiss is gradational (after Yonkee and Lowe, 2004) and migmatitic gneiss seems to be interlayered with granitic gneiss west of Middle Peak; pods and layers are typically gradational into surrounding rock, with diffuse unmappable contacts and/or too small to show at map scale; gneisses contain widespread mafic bodies and are cut by variably deformed pegmatite dikes (mostly unmapped). Barnett and others (1993) reported the various isotopic ages of the complex and concluded it is Paleoproterozoic (~1700 Ma) in age.

All Farmington Canyon units display local retrograde alteration, largely chloritic, partly related to Cretaceous hydrothermal fluids. More detailed information on the complex is available in Bryant (1988) and Yonkee and Lowe (2004). The Farmington Canyon Complex rocks are at least locally prone to slope failures because it has been deeply weathered to clay, likely during the Eocene and/or Paleocene (see for example Wilf, 2000). Where possible divided into:

Xfcm, Xfcm?

Migmatitic gneiss (Paleoproterozoic) – Medium- to light-pink-gray, strongly foliated and layered (migmatitic) quartzo-feldspathic rock with widespread garnet and biotite; also contains unmapped granitic gneiss pods, and some thin layers of sillimanite-bearing, biotite-rich schist.

Xfcg

Granitic gneiss (Paleoproterozoic) – Present in both footwall and hanging wall of Ogden floor thrust. Light- to pink-gray, moderately to strongly foliated, fine- to medium-crystalline, hornblende-bearing, quartzo-feldspathic rock with minor orthopyroxene.

Xfch

Hornblende-plagioclase gneiss (Paleoproterozoic) – Only present in footwall of Ogden floor thrust. Dark-gray to black, moderately to strongly foliated, with minor garnet, quartz, and biotite in some layers.

Xfcb, Xfcb?

Biotite-rich schist (Paleoproterozoic) – Medium-gray to dark-brown, strongly foliated, biotite-rich schist with widespread garnet and sillimanite; displays alternating biotite-rich and quartz-feldspar-rich bands that are rotated into complex fold patterns; cut by garnet-bearing pegmatite dikes; also contains some thin layers of amphibolite, quartz-rich gneiss, and granitic gneiss; gradational contacts with migmatitic gneiss.

Xfcq

Quartz-rich gneiss (Paleoproterozoic) – Milky- to green-white with plagioclase and chrome-green mica; locally contains thin layers of biotite-rich schist and amphibolite.

Xfcu

Meta-ultramafic and mafic rocks (Paleoproterozoic) – Black to green-black, variably foliated, pyroxene-bearing meta-gabbro to amphibolite, with varying amounts of plagioclase, and dark-green to black pyroxene-amphibole-olivine-bearing ultramafic rock, hornblendite, and amphibolite; form pods in granitic gneiss but only larger bodies mapped.

Xfcs

Mica-rich schist and gneiss (Paleoproterozoic) – Only present in footwall of Ogden floor thrust. Gray-brown, strongly foliated, schist to gneiss containing variable amounts of muscovite, biotite, quartz, and feldspar, with minor garnet in some layers; contains some thin layers of hornblende-plagioclase gneiss.

CRAWFORD THRUST SHEET, HORSE RIDGE AND DAIRY RIDGE QUADRANGLES AND LOST CREEK DRAINAGE, AND ELK AND DURST MOUNTAINS AREA

Units exposed at Devils Slide are likely present in the subsurface east and south of the Willard thrust fault.

Tertiary strata and the Cretaceous Hams Fork Member of the Evanston Formation are younger than and overlie the Crawford thrust sheet. Exposed Paleozoic rocks are part of a transitional marine shelf sequence. Subsurface thicknesses outside the map area are included due to the lack of drill holes into the Crawford thrust sheet within the map area.

TERTIARY

Ts

Tertiary strata, undivided – Used where multiple Tertiary map units are in landslide blocks [Qms(Ts), Qms?(Ts), Qmso(Ts), and Qmso?(Ts)], and for a very poorly exposed outcrop with characteristics of units Thv, Tcy, Tcg, Tn, and Tw near Elk Mountain.

Thv, Thv?

Fanglomerate of Huntsville area (Pliocene and/or Miocene) – Typically dark-weathering, poorly to moderately consolidated, pebble to boulder gravel in brown to reddish-brown silt and sand; gravel and matrix reflect erosion of red Wasatch Formation, as well as Paleozoic and Precambrian rocks exposed on Elk and Durst Mountains; in contrast, where fanglomerate is next to Tintic Quartzite (Ct) exposures, clasts are mostly angular to subangular Tintic

Quartzite, with less red matrix; overlies conglomeratic rocks (Tcy, Tcg) with angular unconformity, yet is folded with unit Tcy into syncline just west of faults bounding Durst Mountain; estimate 0 to 500 to possibly 1000 feet (0–150–300 m) thick on west flank of Elk and Durst Mountains, with upper estimate assuming unit not faulted or folded. Unit Thv queried where may be underlying conglomerate (Tcy) and where poor exposures may actually be surficial deposits.

The Thv unit is more age restricted than the Huntsville fanglomerate named by Eardley (1955). His unit included Holocene, Pleistocene, Pliocene, Miocene, and Oligocene(?) fanglomerates (see Coogan and King, 2016, units Qcg, Qng, QTaf, Thv, and Tcy units). The age of unit Thv may overlap with the Salt Lake Formation.

Tcy, Tcy?

Younger unnamed Tertiary conglomeratic rocks (Pliocene and Miocene?) – Rounded, pebble- to boulder-size, quartzite-clast conglomerate with gray, tan, or reddish-gray to reddish-tan 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° vs >10° in Morgan quadrangle south of map area) and more regular bedding in Tcy; unconformity becomes less distinct to north and unit Tcy apparently pinches out in Durst Mountain quadrangle northwest of Elk Mountain; estimate up to 200 to 400 feet (60–120 m) thick.

Given bedding dips of less than 10 degrees, unit Tcy may be the same age (Pliocene and late Miocene) as the Salt Lake Formation conglomerate (Tslc) on the Willard thrust sheet. Unit Tcy was included in Huntsville fanglomerate (see Thv) of Eardley (1955). Unit Tcy likely as impermeable as units Tcg and Tn.

Tcg, Tcg?

Unnamed Tertiary conglomeratic rocks (Oligocene?) – Characterized by rounded, cobble- to boulder-size, quartzite-clast conglomerate with pebbles and less than 10 percent to more than 50 percent gray, tan, or reddish-gray to reddish-tan clay-rich matrix; conglomerate clasts locally angular to subangular Tintic Quartzite and angular to rounded lower Paleozoic carbonate rocks; interbedded with tan, gray, and reddish-brown pebble-bearing mudstone to sandstone and some claystone (altered tuff); most beds poorly indurated and poorly exposed; in Durst Mountain quadrangle, about 3000 feet (900 m) thick northwest of Elk Mountain, though faulting may make this estimate too large, thinning southward to 500 to 700 feet (150–210 m) thick in Morgan quadrangle south of map area.

Some non-conglomeratic beds in Tcg look like gray upper Norwood Formation (Tn) and are locally tuffaceous (altered to clay), indicating the units are interbedded. Further, some Tcg pebble beds have carbonate and chert clasts (like the Norwood) and lesser quartzite clasts, and Tcg conglomerate includes rare altered tuff clasts from the Norwood Formation. Despite altered (clay rich) tuffaceous matrix, unit Tcg seems to be less prone to slope failures (mass movements) than Norwood strata, but is still mostly impermeable.

Tn, Tn?

Norwood Formation (lower Oligocene and upper Eocene) – For information see descriptions under heading "Sub-Willard Thrust - Ogden Canyon Area."

Tw, Tw?

Wasatch Formation (Eocene and upper Paleocene) – For information see descriptions under heading "Sub-Willard Thrust - Ogden Canyon Area."

CRETACEOUS

Keh, Keh?

Hams Fork Member of Evanston Formation (Upper Cretaceous) – Light-gray, brownish-gray, and tan sandstone, conglomeratic sandstone, and quartzite- and chert-pebble conglomerate, and variegated gray, greenish-gray, and reddish-gray mudstone; coal beds are present up to 200 feet (60 m) above contact with basal conglomerate, or, if conglomerate is missing, the base of Hams Fork Member; carbonaceous shale and coal only present near Lost Creek Dam; member coarsens downward becoming basal conglomerate (unit Kehc); in Durst Mountain quadrangle northest of Elk Mountain, lower Hams Fork coarsens downward to gray and brownish-gray, cobble conglomerate containing distinctive Neoproterozoic quartzite clasts (not mapped separately) (Coogan and King, 2006); unit Keh about 300 to 1000 feet (140–300 m) thick along South Fork Ogden River (thickest on Willard thrust sheet), thinning to west, with about 1000-foot (300 m) thickness to south in Durst Mountain quadrangle (Coogan and King, 2006) northest of Elk Mountain; thins southward from 1200 feet (365 m) near Lost Creek Dam to about 600 feet (180 m) south of map area in Devils Slide quadrangle, and northward to less than 450 feet (140 m) thick in Horse Ridge and Dairy Ridge quadrangles (Coogan, 2006a-b); unconformably truncated and locally absent beneath Wasatch Formation. Hams Fork queried (Keh?) where outcrop may be Wasatch Formation (Tw). The Hams Fork is at least locally prone to slope failures due to high clay content and poor consolidation. Like unit Tw, permeability is variable.

Kehc, Kehc?

Basal conglomerate of Hams Fork Member (Upper Cretaceous) – Tan, brownish-gray, and gray, cobble to boulder conglomerate with minor interbedded gray, carbonaceous mudstone; conglomerate contains greater than 80% Neoproterozoic and Cambrian quartzite clasts, but locally contains roughly 5% clasts of Jurassic and Triassic sandstone and Precambrian crystalline basement (schist and gneiss) (DeCelles, 1994); 150 feet (45 m) thick in the hanging wall of the Crawford thrust in the Lost Creek drainage (Coogan, 2004a-b).

Weber Canyon Conglomerate (Upper Cretaceous) – On Crawford thrust sheet, only exposed southeast of map area in Lost Creek drainage and near Devils Slide. Red, gray, and tan, boulder to cobble conglomerate with minor sandstone and mudstone interbeds; near Devils Slide, clasts from Tintic Quartzite, Weber Sandstone, Nugget Sandstone, Lodgepole Limestone, Park City Formation, and Twin Creek Limestone (DeCelles, 1994) (list order not by age or abundance); Coogan (2003, unpublished) noted clasts of Neoproterozoic quartzite, Paleozoic carbonate, and Triassic siltstone at Toone Canyon (no note of Twin Creek clasts) that are not present to south by DeCelles (1994).

Unit also mapped entirely on Willard thrust sheet along Right Fork South Fork Ogden River in Causey Dam quadrangle. This conglomerate is very different, implying a different source area (see Kwc description under "Willard Thrust Sheet" heading).

CRETACEOUS

Kelvin Formation (Lower Cretaceous) – Only exposed south and east of map area. Upper half contains tan and gray, coarse-grained, cross-bedded sandstone and pebbly sandstone with abundant chert; interbedded with reddish-gray and minor gray-green mudstone; middle part contains thin, discontinuous beds of nodular, blue-gray and lavender, micritic limestone; lower half is chert-pebble conglomerate beds separated by recessive reddish-gray mudstone and sandstone zones; approximately 2500 feet (700 m) thick in Toone Canyon, Lost Creek Dam quadrangle, but top not exposed (Coogan, 2004b), about twice as thick to south near Henefer (see Coogan and King, 2016). The Kelvin Formation is mostly impermeable.

JURASSIC

Stump and Preuss Formations, undivided (Upper and Middle Jurassic) – Only mapped south and east of map area. Poorly exposed, mostly reddish, poorly bedded strata; about 1000 feet (300 m) thick at Toone Canyon, Lost Creek drainage (Coogan, 2004b).

Stump Formation (Upper and Middle Jurassic) – Only exposed south and east of map area. Pale red, yellow, and gray shale and calcareous sandstone; at least locally glauconitic green and greenish-gray; 220 to 250 feet (68–76 m) thick (Pipiringos and Imlay, 1979). Potential groundwater source since listed as reservoir rock in Pineview, Utah gas and oil field (see Ver Ploeg and De Bruin, 1982); see Blazzard (1979) and Cook and Dunleavy (1996) for permeability and porosity in the field.

Jp

Preuss Redbeds (Middle Jurassic) – Red and purplish-red sandstone, siltstone, and shale, with anhydrite; halite near base in subsurface; mapped separately at the head of Lost Creek in Horse Ridge quadrangle; about 900 feet (270 m) exposed. The Preuss is mostly impermeable and is a cap rock for Twin Creek gas and oil reservoirs.

Jtc

Twin Creek Limestone (Middle Jurassic) – Mostly white- to gray-weathering, shaly limestone with some shale; in Lost Creek drainage member thicknesses total about 2850 feet (870 m) (Coogan, 2004b); similar, though incomplete thicknesses of 2722 and 2600 feet (825 and 790 m) measured outside the map area at Devils Slide and to north at Watton (now Walton) Canyon/Birch Creek, Meachum Ridge quadrangle, respectively (Imlay, 1967, p. 11 and 13), with top thrust truncated at Devils Slide. Potential groundwater source since listed as reservoir rock in numerous gas and oil fields near Evanston, Wyoming (see Ver Ploeg and De Bruin, 1982). Porosity, permeability, and other reservoir information is summarized in Chidsey (2016, table 4.1). Variable permeability enhanced by cleavage noted in member descriptions; compare to Bruce (1988) for non-fractured permeabilities in gas and oil fields.

Member descriptions are from Coogan (2004b; 2006a-b) because Imlay's (1967) Watton (now Walton) Canyon/Birch Creek descriptions would make it an atypical section.

Jtgc

Giraffe Creek Member (Middle Jurassic) – Gray, greenish-gray and tannish-gray, calcareous sandstone and lime grainstone; contains intraformational conglomerate in Meachum Ridge quadrangle; structurally thickened in synclinal hinges between Lost Creek Dam and Meachum Ridge area; 225 feet (70 m) exposed total thickness.

Jtl

Leeds Creek Member (Middle Jurassic) – Light-gray, thin- to very thick bedded, clay-rich, micritic limestone with tan silt partings; locally exhibits bedding-normal, pencil cleavage; forms barren, scree-covered slopes; 1000 to 1300 feet (300–395 m) exposed thickness.

Jtw

Watton Canyon Member (Middle Jurassic) – Dark-gray, lime micrite (mudstone) and wackestone and minor oolite packstone; forms prominent ridges; locally exhibits bedding-normal, stylolitic, spaced cleavage; about 400 feet (120 m) exposed thickness.

Jtb

Boundary Ridge Member (Middle Jurassic) – 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; 100 to 250 feet (30–75 m) exposed thickness.

Jtr

Rich Member (Middle Jurassic) – Light-gray, thin- to very thick bedded, 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; about 425 to 540 feet (130–165 m) exposed thickness.

Jts

Sliderock Member (Middle Jurassic) – Dark-gray, very thick bedded, lime wackestone in upper part and dark-gray, pelecypod and crinoid grainstone in lower part; covered middle part at Devils Slide may be variegated siltstone and shaley sandstone exposed at Birch Creek (see Imlay, 1967); forms small ridges; 100 to 227 feet (30–70 m) exposed thickness.

Jtgs

Gypsum Spring Member (Middle Jurassic?) – Red siltstone and sandstone, and gray, vuggy dolomite, with anhydrite in subsurface; 208 feet (65 m) exposed thickness. Despite its sharp upper and lower contacts (Imlay, 1967, p. 18), the Gypsum Spring is separated from overlying and underlying units by unconformities (see Imlay, 1980, figures 26–28).

Jn

Nugget Formation (Lower Jurassic) – Pale-grayish-orange, pinkish-tan, and locally off-white, well-cemented, cross-bedded quartz sandstone with frosted sand grains; 1100 to 1360 feet (335–415 m) thick (see Coogan and

King, 2016). Potential groundwater source since listed as reservoir rock in numerous gas and oil fields near Evanston, Wyoming (see Ver Ploeg and De Bruin, 1982); permeabilities and porosities in gas and oil fields are summarized in Chidsey (2016, table 3.1).

In the Durst Mountain quadrangle, a major fault must be present between Quarry Hollow and the Cambrian rocks to the north near the South Fork Ogden River. The stratigraphic separation between the Nugget and Cambrian exposures is about 10,500 feet (3200 m) in less than a mile, but the location and type of fault is uncertain. The Cambrian strata, along with the Cambrian window in the Browns Hole quadrangle north of the South Fork Ogden River, may be a sliver (horse) within the Willard thrust fault (see Coogan and King, 2016), an origin that was implied by Schirmer (1985, p. 151). If so, the Willard thrust sheet ramps upward from Permian in the north to Jurassic in the south in the footwall.

TRIASSIC

ꞦaA

Ankareh Formation, Higham Grit, and Timothy Sandstone and Porteneauf Limestone Members of Thaynes Formation, undivided (Triassic) – Mixture of reddish shale, siltstone, sandstone, and limestone; about 1250 to 1400 feet (380–425 m) thick south of map area near Devils Slide; to north, structurally thinned where exposed near leading edge of Willard thrust (Coogan, 2006a-b); thinner where exposed in Lost Creek drainage (~1150 feet [350 m]), but about 1400 feet (425 m) thick in subsurface east of map area (see Coogan and King, 2016). Unit mostly impermeable.

Contains subunits:

Wood Shale Tongue of the Ankareh Formation (Triassic) – Brownish orange-red to brownish-red shale, siltstone and sandstone; locally mica-bearing; called Stanaker or upper member by some workers; 600 to 680 feet (180–210 m) thick near Devils Slide and about 500 feet (150 m) thick in Lost Creek drainage (Coogan, 2004a).

Higham Grit, and Timothy Sandstone and Portneuf Limestone Members of the Thaynes Formation, undivided (Triassic) – Gray and greenish-gray, mica-bearing, quartz-granule sandstone at top (Higham); greenish-gray, lithic-pebble conglomerate with green siltstone clasts and rare fossil wood fragments in middle (Timothy); and thin (2 feet [0.6 m]), gray and lavender, mottled micritic limestone (with gray chert) locally at base (Portneuf); up to 200 feet (9–60 m) thick in Lost Creek drainage. In subsurface northeast of the map area, estimate 55 to 90 feet (15–27 m) of this unit was cut in the Birch Creek fold belt (Coogan, 2004a).

Lanes Tongue of the Ankareh Formation (Triassic) – Brownish-red shale, siltstone, and sandstone, with some buff to gray siltstone and sandstone; called Mahogany Member by some workers; 600 to 725 feet (180–220 m) thick near Devils Slide, but only about 450 feet (140 m) thick in Lost Creek drainage. In subsurface northeast of the map area, the about 840 feet (256 m) of Lanes cut in the Birch Creek fold belt but may be structurally thickened (see Coogan and King, 2016).

Ꞧt

Thaynes Formation, undivided (Lower Triassic) – Brownish-gray, thin-bedded, calcareous siltstone; gray, thin-bedded, silty shale; and thin- to medium-bedded, gray, fossiliferous limestone in upper and lower part; separated by a resistant ridge of gray, very thick to medium-bedded, fossiliferous limestone in middle part (Coogan, 2004a, 2006a-b; Coogan and King, 2016); estimated thickness of 1850 feet (565 m) (upper tongue of Dinwoody not included) in Devils Slide quadrangle south of map area, about the same total thickness as in Lost Creek drainage, 1835 feet (560 m) (Coogan, 2006a-b; note revision to Coogan, 2004a) that may or may not include upper tongue of Dinwoody; structurally thinned to about 1300 feet (400 m) in Dairy Ridge quadrangle (Coogan, 2006a). Potential groundwater source since listed as reservoir rock in two gas and oil fields near Evanston, Wyoming (see Ver Ploeg and De Bruin, 1982); see Sieverding and Royse (1990) for porosity and permeability; potential fracture permeability if tightly folded as in Chicken Creek field south of Evanston.

Member names are after Kummel (1954). Note that Kummel's (1954) members, from about 70 miles (110 km) to the north of the map area near Bear Lake in Idaho, are recognizable near Devils Slide south of the map area and that most of these members are recognizable another 25 miles (40 km) to the southwest near Salt Lake City, Utah (see Mathews, 1931; Solien and others, 1979). Member descriptions are from Coogan (2004a, 2006a-b) and Coogan and King (2016).

Upper calcareous siltstone member (Lower Triassic) – Brownish-gray, thin-bedded, calcareous siltstone and thin-bedded, gray, fossiliferous limestone; about 1040 feet (315 m) thick.

Middle shale member (Lower Triassic) – Poorly resistant, gray, thin-bedded, calcareous, silty shale; about 100 feet (30 m) thick.

Middle limestone member (Lower Triassic) – Gray, thick- to medium-bedded, fossiliferous, ridge-forming limestone; about 110 to 230 feet (33–70 m) thick.

Lower shale member (Lower Triassic) – Gray to brownish-gray, thin-bedded, calcareous siltstone to silty shale; at Devils Slide lower half is likely reddish-colored sandy siltstone of Decker tongue of Ankareh Formation; structurally thinned beneath and near the Willard thrust (Coogan 2006a-b); about 185 to 375 feet (55–115 m) thick.

Lower limestone member (Lower Triassic) – Gray to grayish-brown, thick- to thin-bedded, fossiliferous limestone; *Meekoceras* ammonite zone at base; about 250 feet (75 m) thick.

Upper tongue of Dinwoody Formation (Lower Triassic) – Greenish-gray and tan, calcareous siltstone and silty limestone; about 250 feet (75 m) thick.

₮wd

Woodside and Dinwoody Formations, undivided (Lower Triassic) – Red sandy shale and siltstone over greenish-gray calcareous siltstone and silty limestone; about 900 feet (300 m) total thickness near Devils Slide south of map area; structurally thinned where exposed near leading edge of Willard thrust sheet in Dairy Ridge quadrangle (Coogan, 2006a).

To the north in Idaho, these formations intertongue (Kummel, 1954). Upper tongue of Dinwoody recognized at Devils Slide and Dairy Ridge. Subsurface thickness of combined unit in map area is about 1040 feet (320 m) (see Coogan and King, 2016).

₮w

Woodside Formation (Lower Triassic) – Dark-red, sandy shale and siltstone, with some sandstone; 500 to 600 feet (150–180 m) thick at Devils Slide (see Coogan and King, 2016). Northeast of the map area in subsurface, about 700 to 750 feet (215–230 m) of Woodside was cut in the Birch Creek fold belt, with the upper tongue of Dinwoody likely included in the Thaynes (see Coogan and King, 2016). Mostly impermeable.

₮d

Dinwoody Formation (Lower Triassic) – Greenish-gray and tan, calcareous siltstone and silty limestone; about 300 feet (90 m) thick at Devils Slide. Northeast of the map area, about 325 feet (100 m) of Dinwoody was cut in subsurface in the Birch Creek fold belt (see Coogan and King, 2016). Permeability uncertain; but potential groundwater source since listed as reservoir rock in one small gas and oil field near Evanston, Wyoming (see Ver Ploeg and De Bruin, 1982).

PERMIAN

Pp, Pp?

Park City and Phosphoria Formations, undivided (Permian) – Interbedded carbonate rock and highly organic to phosphatic shale; total thickness 675 feet (205 m) at Elk Mountain. See Williams (1943), Cheney and others (1953), Cheney (1957), Schell and Moore, (1970), Coogan (2006a), and Coogan and King (2006) for more details. Permeability variable; but, potential groundwater source since Phosphoria Formation listed as reservoir rock in several gas and oil field near Evanston, Wyoming (see Ver Ploeg and De Bruin, 1982); in Wyoming terminology this probably means both formations.

In the Durst Mountain quadrangle, the stratigraphic offset between this unit and the lower Humbug Formation (Mhl) across the Bennett Creek fault (thrust?) is in excess of 4000 feet (1200 m).

Member descriptions and thicknesses are from exposures (Coogan, 2006a; Coogan and King, 2016); subsurface subunit thicknesses northeast of the map area are from the the Birch Creek fold belt (see Coogan and King, 2016). Members queried where member identification is uncertain.

Ppf, Ppf?

Franson Member of Park City and Rex Chert Member of the Phosphoria Formation (Permian) – Interbedded gray to pinkish-gray to dark-gray, vuggy, cherty limestone, with lesser gray shale and calcareous sandstone, and dark-gray and black, bedded chert; about 240 to 300 feet (75–90 m) thick. In subsurface 300 feet (90 m) thick.

Ppm, Ppm?

Meade Peak Phosphatic Shale Member of the Phosphoria Formation (Permian) – Gray limestone, dark-gray to black, phosphatic siltstone and shale, and gray, calcareous sandstone; 170 to 300 feet (50–90 m) thick. In subsurface about 180 feet (55 m) thick.

Ppg, Ppg?

Grandeur Member of Park City Formation (Permian) – Light-gray, calcareous to dolomitic sandstone, with some gray chert; about 220 to 310 feet (65–95 m) thick. In subsurface about 240 feet (75 m) thick.

PERMIAN AND PENNSYLVANIAN

PIPwe

Wells Formation (Lower Permian and Pennsylvanian) – Light-gray to tannish-gray, very thick-bedded, cross-bedded, fine-grained sandstone; greater than 1050 feet (320 m) thick, because base of overturned Wells is truncated by Willard thrust (Coogan, 2006a). In subsurface east of map area, 1033 feet (315 m) of Wells was cut in the Louisiana Land & Exploration 1-34 well in the Neponset Reservoir NW quadrangle, thicker than nearby wells, but reasonable since Wells thickens to south and west (see Coogan and King, 2016).

PIPwu

Weber Sandstone (Lower Permian and Pennsylvanian) – Gray, well-cemented, quartzose sandstone, with dolomite and siltstone in lower part (lower part not exposed in map area); estimate 2600 feet (790 m) thick south of map area near Devils Slide. Previously reported thicknesses (Eardley, 1944; Bissell and Childs, 1958; Mullens and Laraway, 1973) are likely from complexly folded strata and are likely across a back thrust. Weber is equivalent to at least part of the Wells Formation. Potential groundwater source since listed as reservoir rock in gas and oil fields near Evanston, Wyoming (see Ver Ploeg and De Bruin, 1982); Weber porosities and permeabilities are reported in Hoffman and Kelley (1981), Ver Ploeg and De Bruin (1982), and Sieverding and Royse (1990).

On Coogan and King (2016), the Weber is divided into a lower part (IPwl), about 1000 feet (300 m) thick (Coogan and others, 2017), with distinct regular bedding and an upper part (PIPwu) with less distinct bedding, and a marker limestone (PIPwls); only the upper part is exposed in the map area.

Weber strata south of Sheep Herd Creek in the Durst Mountain quadrangle are about 800 feet (240 m) thick (Coogan and King, 2006), and are separated from Mississippian strata to the north by Sheep Herd Creek such that a fault with 1000 to 3000 feet (300–900 m) of stratigraphic offset must be between these outcrops. The orientation of the fault is not known, but the Weber strata are displaced down relative to the Mississippian rocks.

PENNSYLVANIAN

Not exposed in map area, present to south near Morgan but may not be present in map area in subsurface.

Morgan Formation (Pennsylvanian) – Thrust faulted “into” Weber Sandstone rather than intertongued, and may not be present in map area. Reddish brown-weathering sandstone, siltstone and limestone that grade northward into light-gray lower part of Weber Sandstone; south of map area 0 to 1000 feet (0–300 m) thick in Morgan quadrangle.

Blackwelder (1910) described the Morgan Formation and underlying Round Valley Limestone (his Morgan-Mississippian limestone) contact as an unconformity with red strata that bear clasts of the underlying limestone and chert over a cavernous weathered surface of limestone. This description is significant enough that Eardley (1944, p. 832–833) quoted Blackwelder (1910), and Coogan and King (2016) included it because it implies karst development. This contact relationship explains the rapid thinning of the Morgan Formation to the north (it was not deposited everywhere above the unconformity) and is similar to the Amsden-Madison contact in Wyoming (although the Amsden and Madison are older); see for example Mallory (1967) and Sando (1974).

Round Valley Limestone (Pennsylvanian, and possibly Mississippian) – May not be present in map area; as exposed south of map area, mostly light-gray, fine-grained limestone with regular bedding visible on aerial photographs; about 375 to 400 feet (115–120 m) thick near Morgan (Sadlick, 1955; Crittenden, 1959, p. 70; Mullens and Laraway, 1973). Round Valley Limestone is possibly time equivalent to Amsden Formation in Wyoming, although Amsden is lithologically more like the Morgan Formation.

MISSISSIPPIAN

King thinks the Mississippian and Devonian (Mmo, Mlf, Ml, Db, and Dh) exposures just east of the study area in Howard Hollow in the Horse Ridge quadrangle are part of the Willard thrust sheet because the concealed gap between upright steeply dipping Monroe Canyon Limestone (Mmo) and Thaynes (TRt) Formation exposures is only about one-third that needed for the about 3000 feet (900 m) of Triassic (TRw and TRd) and Permian (Pp and PIPwe) strata needed between the outcrops. Coogan (1992a, 2006b) placed the Howard Hollow strata on the Crawford thrust sheet, while Peyton and others (2011) showed them in a Willard thrust fault sliver west of a Willard thrust fault imbricate. At the minimum, a fault is required between these exposures; this fault may be a footwall imbricate of the Willard thrust. To the west only about one-half of the ~3000 feet (900 m) of stratigraphic separation that is needed is present between outcrops of the Devonian Hyrum Formation (Dh) in Howard Hollow and the middle member of the Bloomington Formation (Cbm) to the west on the Willard thrust sheet.

Mississippian strata (Madison, Mission Canyon, and Lodgepole) are potential groundwater sources since listed as reservoir rocks in gas and oil fields near Evanston, Wyoming (see Ver Ploeg and De Bruin, 1982); porosities and pemeabilities are reported in Hoffman and Kelly (1981), Sieverding and Royse (1990), and McGarry and Hunt (1992a-b).

Doughnut Formation (Upper Mississippian) – Possibly equivalent to upper Monroe Canyon Formation to north, while interval to east is in an unconformity. Not exposed in map area, present to south near Morgan but may not be present in map area in subsurface.

Upper member (Upper Mississippian) – Limestone and siltstone; about 300 feet (90 m) thick near Morgan (Mullens and Laraway, 1973; Crittenden, 1959, p. 70, his units 3–6; Coogan and King, 2016).

Lower shale member (Upper Mississippian) – Poorly exposed siltstone, black shale, and limestone; about 200 feet (60 m) thick near Morgan (Coogan and others, 2015) (see also Mullens and Laraway, 1973; Crittenden, 1959, p. 70, his unit 2).

Mmo

Monroe Canyon Limestone (Mississippian) – Tannish-gray, fossiliferous, vuggy, sandy dolomite; incomplete section about 1200 feet (365 m) thick in Howard Hollow, top not exposed (Coogan, 2006b). This is four times thicker than near Laketown, Utah on Willard thrust sheet (see Sandberg and Gutshick, 1979), but the top of the Monroe Canyon is truncated by an unconformity at Laketown and the Howard Hollow thickness is comparable to that in Idaho (see Sando and others, 1981). In subsurface about 950 feet (290 m) of Monroe Canyon was cut in American Quasar Hoffman well on the Crawford thrust sheet to northeast near Randolph, Utah.

Mh

Humbug Formation (Mississippian) – Interbedded carbonate and calcareous to dolomitic quartzose sandstone (see also Crittenden, 1959, p. 70, his unit 1). Roughly equivalent to lower Monroe Canyon Limestone and upper Little Flat Formation to north; interval to east is in an unconformity.

Mhu

Upper part (Mississippian) – Limestone with sandstone beds near base, about 400 feet (120 m) thick at Durst Mountain (Coogan and King, 2006) just south of map area.

Mhl

Lower part (Mississippian) – Sandstone with limestone and dolomite interbeds, about 300 feet (90 m) thick at Durst Mountain just south of map area. Contact placed so lower member is less resistant than upper member (Coogan and King, 2006).

Mlf

Little Flat Formation (Mississippian) – White to light-tan, light-orange to tan weathering, fine-grained, calcareous sandstone; 970 feet (295 m) thick in Howard Hollow (Coogan, 2006b), slightly (~15%) thicker than near Laketown on Willard thrust sheet (see Sandberg and Gutschick, 1979). Outcrops of Little Flat Formation on the Willard thrust sheet in the map area are darker colored and contain about half carbonate rocks and the basal Delle Phosphatic Member. The Delle is present in subsurface on the Crawford thrust sheet north and east of the map area.

Mde

Deseret Limestone (Mississippian) – Limestone, dolomite and sandstone, with dark, non-resistant phosphatic shale at base (Delle Phosphatic Member, Mded); about 500 feet (150 m) thick at Durst Mountain (Coogan and King, 2006) just south of map area. Deseret probably equivalent to most of Little Flat Formation (Mlf) mapped in Horse Ridge quadrangle.

Ml

Lodgepole Limestone (Mississippian, Osagean-Kinderhookian) – Dark-gray, thin-bedded, lime micrite (mudstone) to wackestone; locally cherty; at least locally fossiliferous; about 650 feet (200 m) thick on Durst Mountain (Coogan and King, 2006) just south of map area. Structurally thickened to 1300 feet (395 m) in Howard Hollow, even thicker than the 900-foot (270 m) thickness on Willard thrust sheet (Coogan, 2006b).

The type Lodgepole is overlain by the Mission Canyon Limestone with no Delle present (Sando and Dutro, 1974), so, with the Delle marking the lower contact of the Little Flat and Deseret, this unit might better be called Gardison Limestone.

In subsurface east of the Willard thrust, well data from the Birch Creek fold belt northeast of the map area indicate about 680 to 930 feet (210–280 m) of Lodgepole was cut, and the shaly Cottonwood Canyon Member of Madison/Lodgepole and Leatham Formation are likely present (see Coogan and King, 2016).

On Durst Mountain south of map area, a basal recessive interval that is likely the Cottonwood Canyon Member of Lodgepole Limestone and the underlying Leatham Formation (Devonian) is not consistently mapped in the Lodgepole or underlying Beirdneau Formations (Coogan and others, 2015).

DEVONIAN

The Beirdneau, Hyrum, and Water Canyon names are from the Willard thrust sheet and may not be appropriate for strata deposited in shallower water on the paleo-continental shelf, in what is now the Crawford thrust sheet. Typically on the Crawford thrust sheet to the north and east, Beirdneau=Three Forks and Hyrum=Jefferson with no Water Canyon equivalent (see Benson, 1966, p. 2570; Johnson and others, 1991). Coogan and King (2016) chose to retain the Willard thrust sheet names because they have traditionally been used. These strata are also called the Darby (Three Forks plus Jefferson) in subsurface (Wyoming terminology). Unit thickness estimates are by King from south of Cottonwood Canyon (just south of map area) in the Durst Mountain quadrangle (see Coogan and King, 2006).

Darby Formation (Devonian) – Subsurface unit of some workers in map area that contains calcareous to dolomitic shale, sandstone, and dolomite; similar to Beirdneau and Hyrum Formations on Elk and Durst Mountains (see Db and Dh below). Pontential groundwater source since listed as reservoir rock in one gas and oil field near Evanston, Wyoming (see Ver Ploeg and De Bruin, 1982).

Db

Beirdneau Sandstone (Devonian) – Tan, reddish-tan, and yellowish-gray, calcareous to dolomitic sandstone, siltstone, some sandy dolomite and limestone, and lesser intraformational conglomerate; less resistant than adjacent units; brownish-gray dolomite resembling Hyrum Dolomite in middle part; about 200 to 300 feet (60–90 m) thick in Howard Hollow and on Durst Mountain (Coogan, 2006b; Coogan and King, 2006). Beirdneau-Hyrum contact may not be consistently mapped on Durst Mountain south of map area (Coogan and others, 2015).

The Beirdneau is typically called Three Forks Formation (Wyoming terminology) in subsurface. In the Birch Creek fold belt northeast of the map area, Coogan (1992a, figure 33) showed an upper Darby about 400 feet (120 m) thick, with a log signature like the Beirdneau/Three Forks, while several wells apparently penetrated about 400 to 500 feet (120–150 m) of Three Forks (see Coogan and King, 2016).

Dhw

Hyrum and Water Canyon Formations, undivided (Devonian) – See descriptions below.

Dh

Hyrum Dolomite (Devonian) – Dark- to medium-brownish-gray and gray, medium-bedded dolomite; weathers distinctive, dark-chocolate brown; more resistant at top and bottom with center of less resistant beds that grade laterally into reddish, dirty carbonate and limy sandstone and siltstone like the Beirdneau Sandstone; about 250 to 450 feet (75–140 m) thick at Durst Mountain just south of map area (Coogan and King, 2006).

In Howard Hollow, 725 feet (220 m) of Hyrum are present but the base is not exposed, and this is thicker than the Hyrum is on the Willard thrust sheet (675 feet [205 m]) (Coogan, 2006b). So this large thickness and proximity to concealed Willard thrust fault implies structural thickening of the Hyrum and/or the Howard Hollow Dh unit includes Water Canyon Formation strata.

The Hyrum is typically called Jefferson Formation (Wyoming terminology) in subsurface. In the Birch Creek fold belt northeast of the map area, Coogan (1992a, figure 33) showed a lower Darby about 600 feet (180 m) thick, with a log signature like the Hyrum/Jefferson, and several wells apparently penetrated about 540 feet (165 m) of Jefferson (see Coogan and King, 2016).

Dwc, Dwc?

Water Canyon Formation (Devonian) – Light-yellow-gray to medium-gray, interbedded calcareous to dolomitic sandstone and silty to sandy dolomite and limestone, with sandstone below carbonate; less resistant than underlying and overlying units; estimated thickness 200 feet (60 m) at Durst Mountain just south of map area (Coogan and King, 2006). Queried because altered along fault and may be Hyrum Dolomite (Dh).

East of the map area in the Amoco Deseret WIU well in the Peck Canyon quadrangle, about 400 feet (120 m) of what appears to be Devonian Water Canyon strata was cut, but the Water Canyon does not appear to be present northeast of the map area in the Birch Creek fold, likely due to an unconformity (Coogan, 2004c; see Coogan and King, 2016).

SILURIAN AND ORDOVICIAN

Silurian and Ordovician strata are missing, along with the Cambrian part of St. Charles Formation, on Elk and Durst Mountains due to thinning over the Stansbury uplift and/or Tooele arch (see Rigby, 1959; Hintze, 1959). Use of the Laketown Dolomite name by some workers might be a leftover from the incorrect identification of these rocks in the Crawford Mountains as Silurian rather than Ordovician (see Berdan and Duncan, 1955, for correction). This unit is shown correctly as the Ordovician Bighorn Dolomite at the state line by Dover (1985, 1995) and M'Gonigle and Dover (1992), while the Silurian mistake is present on the Wyoming state geologic map (see Love and Christiansen, 1985) though later corrected by a note in Love and others (1993).

Note that about 15 miles (25 km) northwest of Durst Mountain 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, present between the Nounan and Maxfield Formations. The Nounan, Maxfield, and Tintic Formations are also thicker in Ogden Canyon than on Elk and Durst Mountains, though the Ophir Formation is about the same thickness (see Yonkee and Lowe, 2004).

ORDOVICIAN

Bighorn Dolomite (Upper Ordovician) – Gray, finely crystalline, thick-bedded dolomite with diverse fossils as exposed in the Crawford Mountains northeast of the map area; identified as Fish Haven Dolomite in some reports (for example Ott, 1980), though Ordovician is missing on Elk and Durst Mountains (see Coogan and King, 2006). Strata identified as Ordovician Bighorn Dolomite are present in subsurface and are bounded by unconformities. Coogan (1992a, figure 33) showed about 900 feet (270 m) of Bighorn in the Birch Creek fold belt, but other interpretations of this and other deep wells in the fold belt northeast of the map area are possible. To the east of the map area, about 900 feet (270 m) of Bighorn was cut in the Amoco Deseret WIU well in the Peck Canyon quadrangle (Coogan, 2004c; see Coogan and King, 2016). Potential groundwater source since listed as reservoir rock in gas and oil fields near Evanston, Wyoming (see Ver Ploeg and De Bruin, 1982); porosities and permeabilities are reported in Sieverding and Royse (1990).

CAMBRIAN

Nounan, Maxfield, Ophir and Tintic Formation descriptions are from exposures on Durst Mountain, with thickness estimates from south of Cottonwood Canyon (just south of map area) in the Durst Mountain quadrangle (Coogan and King, 2006).

Cn

Nounan Formation (Cambrian) – Medium-dark-gray, thick-bedded dolomite and some limestone; estimated thickness 350 to 400 feet (105–120 m). The Nounan Formation does not appear to be present to the northeast of the map area in the Birch Creek fold belt, likely due to the unconformity that excised Silurian and Ordovician strata, and the Cambrian part of the St. Charles Formation elsewhere in the map area (see Coogan and King, 2016).

Gallatin Limestone and Gros Ventre Formation, undivided (Middle Cambrian) – Subsurface unit of some workers in map area; contains thin-bedded, silty limestone, oolitic limestone, and shale. The Gallatin is mostly limestone like the Maxfield Limestone on Elk and Durst Mountains, while the Gros Ventre is shale over limestone over shale like the Ophir Shale on Elk and Durst Mountains.

Coogan (1992a, figure 33) showed about 250 feet (75 m) of Gallatin and about 750 feet (230 m) of Gros Ventre in the Birch Creek fold belt northeast of the map area, but other interpretations of this and other deep wells in the fold belt are possible. In particular, the Hawk Springs well showed a Cambrian top at a change from dolomite (Bighorn) to limestone with about 400 feet (120 m) of carbonate at the top (likely Gallatin) above about 400 feet (120 m) of mixed carbonate and shale (Gros Ventre?) (see Coogan and King, 2016).

Cm, Cm?

Maxfield Limestone (Middle Cambrian) – Limestone and calcareous siltstone; estimated thickness 300 feet (60 m). Queried where may be Nounan Formation (Cn). The Maxfield is at least locally prone to slope failures due to high clay content and contains aquitards. Bloomington Formation is not present on Elk and Durst Mountains. Strata in subsurface that are lithologically similar to Maxfield are called Gallatin Limestone (Wyoming terminology).

Co

Ophir Formation (Middle Cambrian) – Upper slope-forming, brown-weathering, olive-gray argillite with intercalated gray limestone beds; middle, ledge-forming, thin to medium bedded, gray micritic limestone with silty partings and layers; and lower brown-weathering, olive-gray argillite and siltstone with lesser gray limestone beds, and mainly siltstone and sandstone in lower 60 feet (20 m); argillites typically have micaceous sheen; estimated total thickness 440 to 725 feet (135–220 m). The Ophir is at least locally prone to slope failures due to high clay content and contains aquitards. In subsurface, lithologically similar strata (shale over limestone over shale) are called Gros Ventre Formation (Wyoming terminology) and are thrust truncated.

Ct

Tintic Quartzite (Middle and Lower? Cambrian) – Tan quartzite, conglomeratic in lower half with Neoproterozoic quartzite pebbles and cobbles; basal 50 to 100 feet (15–30 m) arkosic conglomerate of Farmington Canyon Complex material; about 1000 feet (300 m) thick.

Basal Cambrian strata have not been penetrated in boreholes east of map area, since they are below a regional thrust fault (decollement). Flathead Sandstone (Wyoming terminology) used on cross section by Coogan (1992a) below decollement east of Durst Mountain. The Flathead is feldspathic to arkosic in Wyoming and, though younger and thinner, occupies the stratigraphic interval of the Tintic Quartzite (Ct).A change to the thicker, less feldspathic Tintic Quartzite (Ct) may be near the western edge of the Archean Wyoming Province, because these crystalline rocks would be a source for feldspar. The western edge of the Wyoming Province has not been documented, but the aeromagnetic map of the United States (USGS, 2002) shows a roughly north-south trending change from near Devils Slide north through the Monte Cristo Range.

PALEOPROTEROZOIC

Xfc

Farmington Canyon Complex (Paleoproterozoic) – Micaceous schistose and gneissic crystalline rocks with small bodies of amphibolite and pegmatite, variously called dikes and pods. More detailed information on the complex to the west in the Wasatch Range is available in Bryant (1988), Barnett and others (1993), and Yonkee and Lowe (2004).

Table A-1. *Comparison of Marine Oxygen Isotope Stages (OIS) to middle Rocky Mountain glaciation, Great Basin lake cycles, and North American continental glaciation, with ages in kilo-years (ka) (from Coogan and King, 2016, table 3). Ages are approximate because they are determined by different methods. Marine OIS ages from Bassinot and others (1994) and when marked with asterisks indicates ages from en.wikipedia.org/wiki/Marine_isotope_stage accessed April 20, 2016. Middle Rocky Mountain glacial ages mostly from data in Phillips and others (1997). Great Basin lake cycle ages from numerous sources, in particular McCalpin (1986)=a, Kaufman and others (2001)=b, and Balch and others (2005)=c.*

Marine OIS **(bold)**, in ka	middle Rocky Mtn glaciation in ka	Great Basin lake cycle in ka	North American continental glaciation in ka	Notes, in ka
				Mazama ash, 6.74 Hallett and others, 1997
2, 11-24, 14-29*	“Pinedale” 12-23	Bonneville 12-30; Lake Lahontan	**major**, late Wisconsin end 10	major continental=middle Rocky Mtn glaciers
4, 57-71 both	likely obliterated by “Pinedale”	Cutler Dam 59b; 82a	early Wisconsin start 75	
6, 127-186, 130-191*	“Bull Lake” 101?, 111-131, 163?	Little Valley >112-126; 138a; 153-187c; Lake Manly in Death Valley	**major**, late Illinoian end 125	major continental=middle Rocky Mtn glaciers
8, 242-301, 243-300*	“Sacagawea Ridge”? >245	Pokes Point?, >271c	early Illinoian start 265	moraine age from Phillips and others, 1997
10, 334-364, 337-374*			pre-Illinoian A, formerly Kansan 300?-435	type Kansan is Nebraskan in age, so now use pre-Illinoian
12, 427-474, 424-478*	“Sacagawea Ridge” >245 on moraine; best guess for “Sacagawea Ridge” since major continental glaciers	Pokes Point by Oviatt and others, 1999	**major**, pre-Illinoian B, formerly Kansan 300?-435	moraine age from Phillips and others, 1997; major continental=middle Rocky Mtn glaciers
14, 528-568, 533-563*		pre Pokes Point 600? (>500<610)	“Nebraskan” end 500, pre-Illinoian C	
16, 621-659, 621-676*	“Sacagawea Ridge”?, Lava Creek B ash (640) in fluvial deposits correlated across Dinwoody Lake by Chadwick and others, 1997	“Lava Creek” lake, pre Pokes Point 600?	**major**, pre-Illinoian D, Nebraskan	ash age Lanphere and others, 2002; major continental=middle Rocky Mtn glaciers; could be “Cedar Ridge”
18, 712-760, 712-761*	older “Cedar Ridge”? Washakie Point?	“Lake Dominguez” top, Bishop ash (760)	pre-Illinoian E?	ash age Izett and Obradovich, 1991
20, 787-<820, 790-814*	type “Washakie Point”, not reverse polarized, so not Marine OIS 20			775±10 bottom of Brunhes paleomagnetism from Bassinot and others, 1994
22, 865->879, 866-900*. **24**, 917-936*			pre-Illinoian F	
38, 1244-1264*. **40**, 1286-1304*			pre-Illinoian G	Mesa Falls ash, 1285 Lanphere and others, 2002
64, 1782-1802.5*			pre-Illinoian I?, “Nebraskan” start 1800	1770 top of Olduvai paleomagnetism
78?, 2043-2088*		“Lake Dominguez” bottom, Huckleberry Ridge ash (2060)		ash age Lanphere and others, 2002

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APPENDIX B

GEOPHYSICAL AND LITHOLOGIC LOG DATA

Table B-1. *Gravity Data*

ID	StationID	Longitude (°)	Latitude (°)	Elevation (m) NGVD29	Height above ellipsoid (m)	Obs (mGal)	sigma	Bouguer anomaly (mGal)
0	HPOB	-111.761696	41.255032	1504.681	1489.758	979767.617	0.001	-219.576
1	OV01	-111.751757	41.262306	1507.291	1492.413	979773.181	0.001	-213.092
2	OV02	-111.763313	41.260832	1499.242	1484.329	979768.248	0.001	-219.114
3	OV03	-111.776954	41.261745	1499.299	1484.362	979769.343	0.001	-218.150
4	OV04	-111.807048	41.262171	1497.075	1482.089	979779.547	0.001	-207.481
5	OV05	-111.801903	41.264694	1497.844	1482.869	979775.900	0.001	-212.513
6	OV06	-111.795671	41.263599	1497.347	1482.380	979774.179	0.001	-214.453
7	OV07	-111.787861	41.262077	1498.823	1483.867	979771.968	0.001	-216.605
8	OV08	-111.783496	41.267747	1496.704	1481.769	979768.901	0.001	-219.576
9	OV09	-111.755126	41.295386	1543.001	1528.278	979778.120	0.001	-201.089
10	OV10	-111.758508	41.283217	1516.074	1501.263	979778.293	0.001	-208.682
11	OV11	-111.761940	41.273344	1504.405	1489.539	979772.178	0.001	-215.188
12	OV12	-111.772545	41.276638	1501.992	1487.101	979771.026	0.001	-218.222
13	OV13	-111.806225	41.274908	1497.743	1482.782	979775.073	0.001	-214.964
14	OV14	-111.806177	41.284612	1500.919	1485.973	979773.353	0.001	-216.681
15	OV15	-111.813545	41.307828	1520.253	1505.378	979775.868	0.001	-210.517
16	OV16	-111.781710	41.368244	2286.582	2272.371	979633.483	0.001	-206.305
17	OV17	-111.804010	41.352300	1922.063	1907.596	979704.989	0.001	-204.31
18	OV18	-111.829943	41.336598	1633.495	1618.722	979766.441	0.001	-199.517
19	OV19	-111.922206	41.311722	1643.030	1628.079	979769.474	0.001	-183.016
20	OV20	-111.899292	41.320489	1882.170	1867.334	979723.043	0.001	-190.756
21	OV21	-111.881096	41.334454	1585.957	1571.092	979778.174	0.002	-196.109
22	OV22	-111.883900	41.365878	1628.857	1614.096	979772.582	0.001	-198.914
23	OV23	-111.907209	41.359213	1738.604	1723.814	979756.833	0.001	-192.363
24	OV24	-111.873651	41.360682	1601.464	1586.686	979780.740	0.001	-195.482
25	OV25	-111.870942	41.345946	1575.864	1561.020	979777.175	0.001	-201.991
26	OV26	-111.758698	41.247009	1500.144	1485.216	979769.207	0.001	-217.965
27	OV27	-111.739204	41.249717	1515.895	1501.022	979774.436	0.001	-209.763
28	OV28	-111.726782	41.235080	1528.432	1513.588	979772.918	0.001	-207.735
29	OV29	-111.711325	41.240527	1532.678	1517.898	979772.221	0.001	-207.842
30	OV30	-111.720705	41.251898	1529.874	1515.073	979776.087	0.001	-204.614
31	OV31	-111.784383	41.280115	1498.513	1483.602	979769.753	0.001	-219.935
32	OV32	-111.779391	41.293108	1503.209	1488.371	979774.032	0.001	-216.881
33	OV33	-111.798825	41.296877	1501.567	1486.684	979772.639	0.001	-218.867
34	OV34	-111.863379	41.333434	1558.603	1543.717	979776.199	0.001	-206.225
35	OV35	-111.847425	41.329882	1541.994	1527.121	979779.074	0.001	-206.007
36	OV36	-111.839013	41.313593	1523.293	1508.383	979778.611	0.001	-208.433
37	OV37	-111.852916	41.318453	1536.429	1521.520	979776.238	0.001	-208.191
38	OV38	-111.877492	41.319547	1628.688	1613.837	979767.377	0.001	-197.599
39	OV39	-111.830212	41.300735	1502.185	1487.250	979781.169	0.001	-207.621
40	OV40	-111.825235	41.306625	1514.335	1499.425	979779.034	0.001	-209.869

Table B-1. Continued

ID	StationID	Longitude (°)	Latitude (°)	Elevation (m) NGVD29	Height above ellipsoid (m)	Obs (mGal)	sigma	Bouguer anomaly (mGal)
41	OV41	-111.830537	41.284746	1572.325	1557.359	979770.074	0.001	-201.666
42	OV42	-111.824805	41.284789	1516.739	1501.770	979776.604	0.001	-208.813
43	s0	-111.891279	41.372251	1651.100	1636.359	0.000	0	-195.585
44	s1	-111.874082	41.370681	1678.200	1663.478	0.000	0	-192.285
45	s2	-111.870542	41.370015	1650.800	1636.083	0.000	0	-192.085
46	s3	-111.873184	41.363382	1603.200	1588.437	0.000	0	-193.585
47	s4	-111.877847	41.365711	1616.400	1601.648	0.000	0	-193.885
48	s5	-111.884173	41.365117	1626.100	1611.335	0.000	0	-198.085
49	s6	-111.872638	41.358342	1600.800	1586.011	0.000	0	-194.885
50	s7	-111.873069	41.352132	1587.100	1572.281	0.000	0	-200.285
51	s8	-111.870500	41.345945	1576.700	1561.856	0.000	0	-201.585
52	s9	-111.868316	41.341007	1570.900	1556.037	0.000	0	-202.485
53	s10	-111.892005	41.333400	1676.400	1661.549	0.000	0	-191.985
54	s11	-111.877694	41.333138	1579.800	1564.931	0.000	0	-197.985
55	s12	-111.867971	41.333146	1557.500	1542.610	0.000	0	-203.585
56	s13	-111.863197	41.333230	1560.300	1545.414	0.000	0	-204.985
57	s14	-111.847368	41.331508	1545.000	1530.135	0.000	0	-203.585
58	s15	-111.825808	41.338904	1663.300	1648.564	0.000	0	-198.185
59	s16	-111.844176	41.336965	1585.600	1570.770	0.000	0	-199.585
60	s17	-111.837018	41.336948	1594.400	1579.597	0.000	0	-199.485
61	s18	-111.850662	41.336958	1551.400	1536.551	0.000	0	-200.685
62	s19	-111.850410	41.333135	1547.200	1532.334	0.000	0	-203.785
63	s20	-111.933118	41.316781	1524.000	1508.960	0.000	0	-188.185
64	s21	-111.907765	41.317613	1796.200	1781.342	0.000	0	-189.185
65	s22	-111.872461	41.312998	1683.100	1668.199	0.000	0	-196.185
66	s23	-111.898500	41.319726	1886.700	1871.864	0.000	0	-191.685
67	s24	-111.876451	41.326072	1567.300	1552.422	0.000	0	-199.185
68	s25	-111.863165	41.323946	1544.400	1529.503	0.000	0	-206.485
69	s26	-111.863092	41.318370	1573.400	1558.492	0.000	0	-204.385
70	s27	-111.871252	41.318853	1612.400	1597.502	0.000	0	-199.785
71	s28	-111.852502	41.318158	1536.500	1521.591	0.000	0	-208.185
72	s29	-111.843989	41.320491	1529.200	1514.305	0.000	0	-207.585
73	s30	-111.839501	41.313188	1520.000	1505.088	0.000	0	-207.985
74	s31	-111.824559	41.316697	1535.000	1520.138	0.000	0	-206.785
75	s32	-111.832927	41.336964	1632.800	1618.015	0.000	0	-199.785
76	s33	-111.863139	41.310971	1625.800	1610.883	0.000	0	-199.785
77	s34	-111.831399	41.308997	1519.100	1504.186	0.000	0	-208.485
78	s35	-111.824406	41.310883	1522.200	1507.310	0.000	0	-208.585
79	s36	-111.824530	41.304399	1514.600	1499.685	0.000	0	-209.285
80	s37	-111.806476	41.304640	1508.500	1493.632	0.000	0	-212.685
81	s38	-111.811762	41.304202	1510.300	1495.413	0.000	0	-211.985
82	s39	-111.815172	41.300875	1509.100	1494.189	0.000	0	-211.985
83	s40	-111.799688	41.300663	1503.300	1488.433	0.000	0	-215.785
84	s41	-111.783165	41.299339	1507.500	1492.684	0.000	0	-214.385
85	s42	-111.814745	41.293415	1506.300	1491.363	0.000	0	-212.985
86	s43	-111.805480	41.293385	1503.900	1488.984	0.000	0	-215.485

Table B-1. *Continued*

ID	StationID	Longitude (°)	Latitude (°)	Elevation (m) NGVD29	Height above ellipsoid (m)	Obs (mGal)	sigma	Bouguer anomaly (mGal)
87	s44	-111.796475	41.293288	1496.000	1481.108	0.000	0	-217.685
88	s45	-111.789412	41.293251	1492.300	1477.429	0.000	0	-218.485
89	s46	-111.777927	41.292978	1503.600	1488.767	0.000	0	-214.785
90	s47	-111.767188	41.293353	1519.100	1504.314	0.000	0	-207.785
91	s48	-111.757607	41.293887	1535.300	1520.555	0.000	0	-202.285
92	s49	-111.753765	41.295724	1545.300	1530.585	0.000	0	-201.185
93	s50	-111.749075	41.296646	1569.700	1555.013	0.000	0	-200.785
94	s51	-111.745011	41.296303	1575.500	1560.830	0.000	0	-200.385
95	s52	-111.739174	41.298183	1590.100	1575.470	0.000	0	-200.385
96	s53	-111.735749	41.299382	1597.200	1582.596	0.000	0	-200.385
97	s54	-111.732261	41.300691	1604.500	1589.923	0.000	0	-200.785
98	s55	-111.776691	41.287814	1501.100	1486.245	0.000	0	-214.185
99	s56	-111.776380	41.285023	1506.000	1491.133	0.000	0	-214.985
100	s57	-111.776650	41.280064	1495.000	1480.110	0.000	0	-217.285
101	s58	-111.760202	41.282824	1513.600	1498.780	0.000	0	-208.685
102	s59	-111.761571	41.278811	1510.300	1495.454	0.000	0	-212.185
103	s60	-111.761353	41.273660	1504.800	1489.937	0.000	0	-215.385
104	s61	-111.784713	41.275478	1488.900	1473.972	0.000	0	-220.185
105	s62	-111.761290	41.270135	1503.900	1489.023	0.000	0	-216.485
106	s63	-111.776693	41.267958	1488.600	1473.680	0.000	0	-220.585
107	s64	-111.805699	41.287934	1502.700	1487.766	0.000	0	-215.785
108	s65	-111.805671	41.281785	1501.100	1486.147	0.000	0	-215.185
109	s66	-111.805745	41.272464	1487.400	1472.434	0.000	0	-212.885
110	s67	-111.819093	41.278502	1507.500	1492.519	0.000	0	-209.285
111	s68	-111.819677	41.273679	1506.300	1491.317	0.000	0	-205.685
112	s69	-111.822038	41.268486	1507.500	1492.507	0.000	0	-199.585
113	s70	-111.796187	41.264352	1495.000	1480.034	0.000	0	-213.985
114	s71	-111.776506	41.260816	1500.800	1485.862	0.000	0	-217.985
115	s72	-111.766767	41.256076	1503.900	1488.969	0.000	0	-217.785
116	s73	-111.758319	41.256375	1505.400	1490.487	0.000	0	-218.485
117	s74	-111.768319	41.251090	1494.100	1479.157	0.000	0	-215.685
118	s75	-111.760983	41.262807	1499.600	1484.699	0.000	0	-218.785
119	s76	-111.741762	41.263237	1514.900	1500.057	0.000	0	-208.785
120	s77	-111.728528	41.262963	1525.500	1510.707	0.000	0	-204.985
121	s78	-111.720656	41.261388	1533.100	1518.336	0.000	0	-204.785
122	s79	-111.710968	41.262180	1545.600	1530.882	0.000	0	-204.085
123	s80	-111.700846	41.262607	1550.200	1535.530	0.000	0	-206.285
124	s81	-111.723576	41.244021	1522.200	1507.370	0.000	0	-206.285
125	s82	-111.720946	41.246058	1524.900	1510.084	0.000	0	-205.285
126	s83	-111.720654	41.255908	1531.300	1516.513	0.000	0	-204.585
127	s84	-111.728255	41.256060	1525.500	1510.682	0.000	0	-205.485
128	s85	-111.747061	41.256214	1512.100	1497.217	0.000	0	-211.485
129	s86	-111.741849	41.256169	1820.000	1805.133	0.000	0	-209.185
130	s87	-111.741170	41.252007	1514.900	1500.026	0.000	0	-209.385
131	s88	-111.736024	41.243787	1515.800	1500.929	0.000	0	-209.685
132	s89	-111.755677	41.247828	1503.300	1488.379	0.000	0	-217.085

Table B-1. Continued

ID	StationID	Longitude (°)	Latitude (°)	Elevation (m) NGVD29	Height above ellipsoid (m)	Obs (mGal)	sigma	Bouguer anomaly (mGal)
133	s90	-111.778136	41.249985	1488.900	1473.941	0.000	0	-213.985
134	s91	-111.768600	41.244654	1516.100	1501.150	0.000	0	-213.985
135	s92	-111.796120	41.245371	1536.800	1521.814	0.000	0	-203.785
136	s93	-111.821206	41.237769	1726.700	1711.692	0.000	0	-197.985
137	s94	-111.835425	41.257993	1501.100	1486.097	0.000	0	-192.585
138	s95	-111.845562	41.225030	1813.600	1798.584	0.000	0	-188.585
139	s96	-111.880300	41.250621	1435.900	1420.828	0.000	0	-189.185
140	s97	-111.907818	41.238165	1386.800	1371.618	0.000	0	-189.185
141	s98	-111.926492	41.235782	1348.700	1333.362	0.000	0	-185.185
142	s99	-111.784867	41.262240	1500.200	1485.250	0.000	0	-216.485

TEM Models and Data

TEM data were collected at useful sites where the UGS was able to obtain permission from the land owner. The processing and revised inversions of TEM data result in 1D resistivity models of each TEM station. These models can be cross-correlated with downhole lithologic and resistivity logs of proximal water wells. The models can also be used as a reference for future resistivity surveys in Ogden Valley. This appendix presents the raw TEM data and model results for each TEM site shown on figure 11 in the report.

TEM data files are in Universal Sounding Format (USF), an ASCII format file with a main header, sounding headers, and data blocks. The USF files for each of the Ogden Valley TEM stations can be used to reprocess the sounding data and create/revise resistivity models.

Link to TEM Data Files: https://ugspub.nr.utah.gov/publications/special_studies/ss-165/ss-165.zip

Files include:

AppB_Geophys_Lithology\TEM_StationOV01_20160627_102247_265.usf

AppB_Geophys_Lithology \TEM_StationOV02_20160627_115905_031.usf

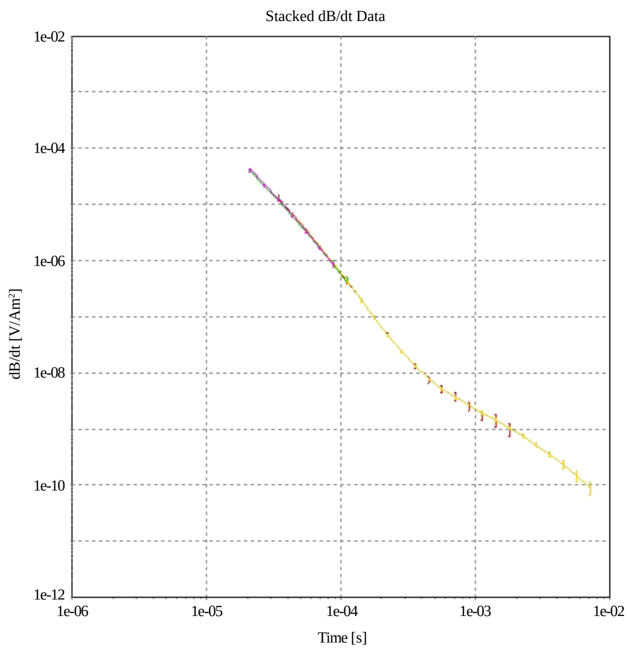
AppB_Geophys_Lithology \TEM_StationOV03_20160627_161020_625.usf

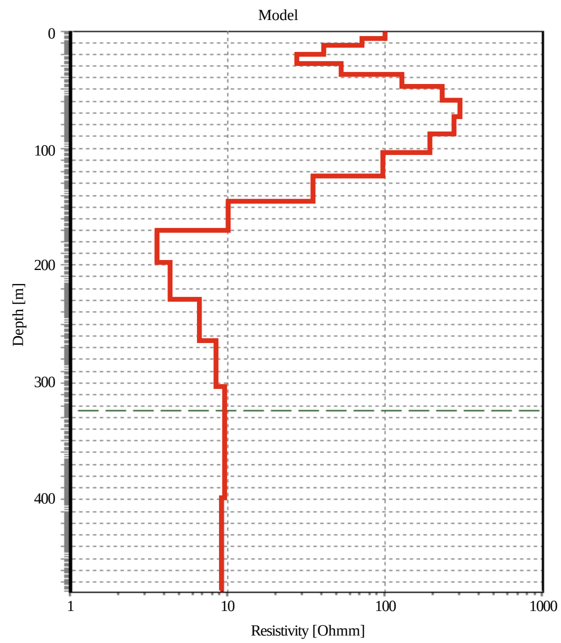
AppB_Geophys_Lithology \TEM_StationOV04_20160627_171218_140.usf

OV01 Smooth

Database Name: Project100.gdb
UTMX: 432317
UTMY: 4569669
EPSG: NAD83 UTM zone 12N
Data Points: 54
Importer: WalkTEMImporter
Version: 2.3.1.0
Data Residual: 0.7
No. of Layers: 20
DOI: 324m
Program: ViewTEM.exe, version 2.0.2.0

#	Res	ResSTD	Thk	ThkSTD	Dep	DepSTD
1	99.3	1.71	5.7	1.001	5.7	1.001
2	71.5	1.42	6.44	1.001	12.1	1.001
3	41.1	1.41	7.27	1.001	19.4	1.001
4	27.7	1.30	8.21	1.001	27.6	1.000
5	52.3	1.42	9.27	1.001	36.9	1.000
6	129	1.61	10.5	1.001	47.4	1.000
7	233	1.71	11.8	1.001	59.2	1.000
8	297	1.75	13.3	1.001	72.5	1.000
9	277	1.74	15.1	1.001	87.6	1.000
10	191	1.67	17	1.001	105	1.000
11	96.1	1.57	19.2	1.001	124	1.000
12	34.8	1.47	21.7	1.001	145	1.000
13	9.94	1.37	24.5	1.001	170	1.000
14	3.55	1.26	27.6	1.001	198	1.000
15	4.28	1.28	31.2	1.001	229	1.000
16	6.58	1.59	35.2	1.001	264	1.000
17	8.52	2.14	39.8	1.001	304	1.000
18	9.38	2.93	44.9	1.001	349	1.000
19	9.44	3.81	50.7	1.001	399	1.000
20	9.22	4.68				

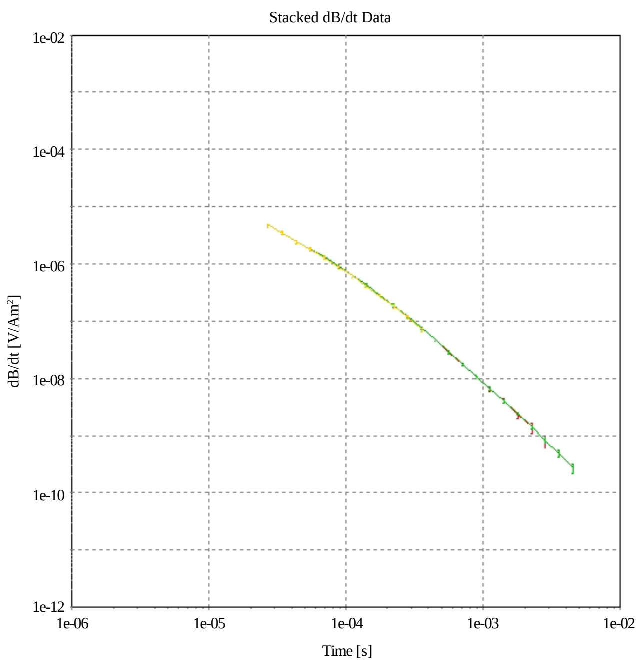


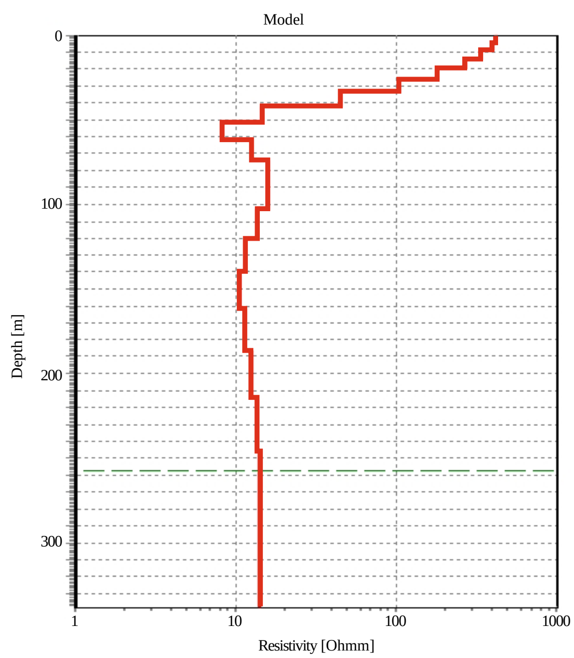


OV02 Smooth

Database Name: Project100.gdb
UTMX: 430524
UTMY: 4572437
EPSG: NAD83 UTM zone 12N
Data Points: 59
Importer: WalkTEMImporter
Version: 2.3.1.0
Data Residual: 0.3
No. of Layers: 20
DOI: 257m
Program: ViewTEM.exe, version 2.0.2.0

#	Res	ResSTD	Thk	ThkSTD	Dep	DepSTD
1	422	2.04	4.03	1.001	4.03	1.001
2	393	1.83	4.55	1.001	8.58	1.001
3	338	1.65	5.14	1.001	13.7	1.001
4	264	1.50	5.8	1.001	19.5	1.000
5	180	1.39	6.55	1.001	26.1	1.000
6	102	1.31	7.39	1.001	33.5	1.000
7	44.2	1.26	8.35	1.001	41.8	1.000
8	14.4	1.17	9.42	1.001	51.2	1.000
9	8.13	1.12	10.6	1.001	61.9	1.000
10	12.6	1.18	12	1.001	73.9	1.000
11	15.8	1.22	13.6	1.001	87.4	1.000
12	15.6	1.24	15.3	1.001	103	1.000
13	13.6	1.24	17.3	1.001	120	1.000
14	11.5	1.25	19.5	1.001	140	1.000
15	10.6	1.26	22	1.001	162	1.000
16	11.2	1.33	24.9	1.001	186	1.000
17	12.4	1.48	28.1	1.001	214	1.000
18	13.6	1.70	31.7	1.001	246	1.000
19	14.1	1.98	35.8	1.001	282	1.000
20	14.2	2.27				

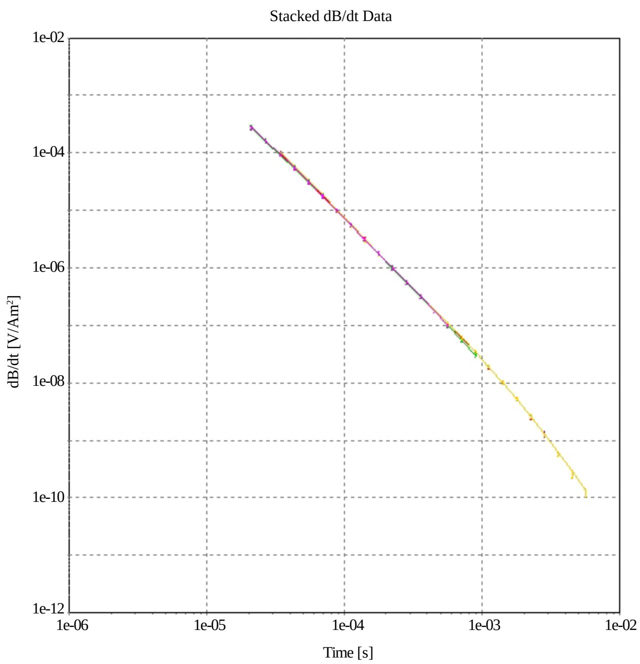


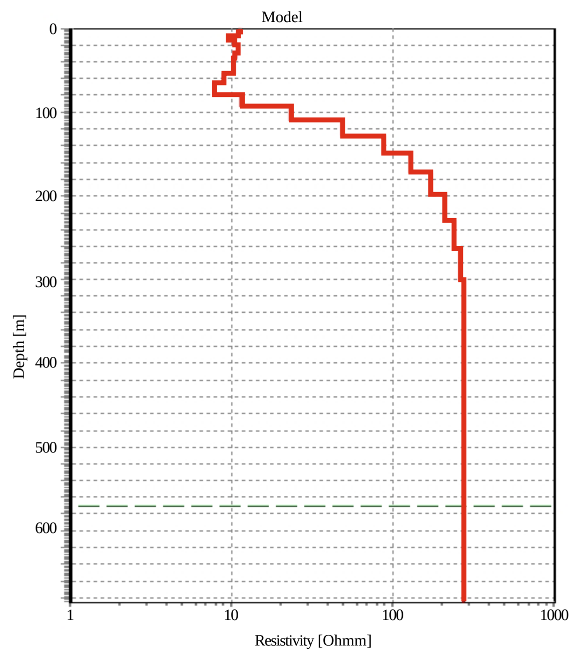


OV03 smooth

Database Name: Project100.gdb
UTMX: 430430
UTMY: 4570690
EPSG: NAD83 UTM zone 12N
Data Points: 77
Importer: WalkTEMImporter
Version: 2.3.1.0
Data Residual: 0.7
No. of Layers: 20
DOI: 571m
Program: ViewTEM.exe, version 2.0.2.0

#	Res	ResSTD	Thk	ThkSTD	Dep	DepSTD
1	11.2	1.27	4.31	1.001	4.31	1.001
2	10.9	1.37	4.86	1.001	9.17	1.001
3	9.4	1.27	5.49	1.001	14.7	1.001
4	10.2	1.34	6.2	1.001	20.9	1.000
5	10.9	1.27	7	1.001	27.9	1.000
6	10.5	1.29	7.9	1.001	35.8	1.000
7	10.2	1.37	8.92	1.001	44.7	1.000
8	10.3	1.40	10.1	1.001	54.7	1.000
9	9.04	1.35	11.4	1.001	66.1	1.000
10	7.76	1.35	12.8	1.001	78.9	1.000
11	11.4	1.28	14.5	1.001	93.4	1.000
12	23.3	1.54	16.4	1.001	110	1.000
13	48.5	1.67	18.5	1.001	128	1.000
14	86.3	1.91	20.9	1.001	149	1.000
15	130	2.25	23.5	1.001	173	1.000
16	173	2.66	26.6	1.001	199	1.000
17	210	3.13	30	1.001	229	1.000
18	239	3.66	33.9	1.001	263	1.000
19	261	4.25	38.3	1.001	301	1.000
20	276	4.91				

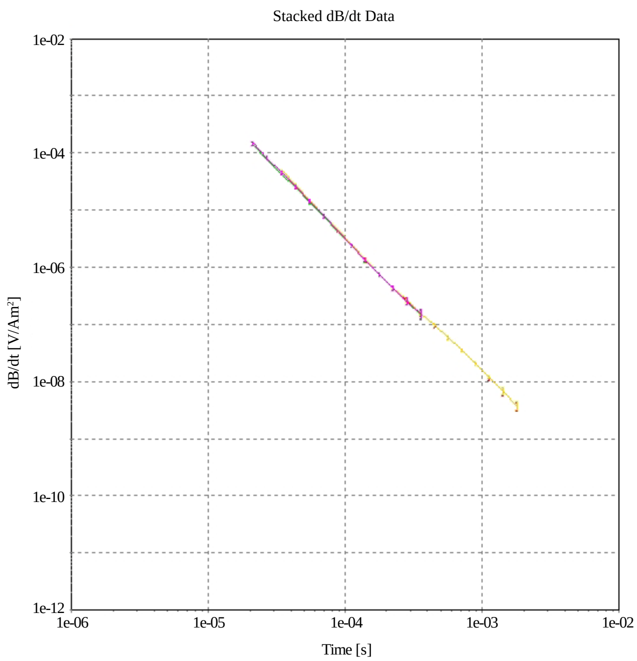




OV04 Smooth

Database Name: Project100.gdb
UTMX: 430947
UTMY: 4570672
EPSG: NAD83 UTM zone 12N
Data Points: 70
Importer: WalkTEMImporter
Version: 2.3.1.0
Data Residual: 0.5
No. of Layers: 20
DOI: 144m
Program: ViewTEM.exe, version 2.0.2.0

#	Res	ResSTD	Thk	ThkSTD	Dep	DepSTD
1	23.4	1.77	2.51	1.001	2.51	1.001
2	22.1	1.48	2.84	1.001	5.35	1.001
3	19.9	1.51	3.2	1.001	8.55	1.001
4	17.6	1.57	3.61	1.001	12.2	1.000
5	16.3	1.48	4.08	1.001	16.2	1.000
6	16.3	1.42	4.61	1.001	20.8	1.000
7	17.5	1.47	5.2	1.001	26	1.000
8	19	1.46	5.87	1.001	31.9	1.000
9	19.7	1.45	6.63	1.001	38.5	1.000
10	18.6	1.46	7.48	1.001	46	1.000
11	15.6	1.44	8.45	1.001	54.5	1.000
12	11.5	1.41	9.54	1.001	64	1.000
13	8.37	1.37	10.8	1.001	74.8	1.000
14	7.5	1.37	12.2	1.001	86.9	1.000
15	9.31	1.42	13.7	1.001	101	1.000
16	13.5	1.52	15.5	1.001	116	1.000
17	18.8	1.70	17.5	1.001	134	1.000
18	23.5	2.02	19.8	1.001	153	1.000
19	26.9	2.50	22.3	1.001	176	1.000
20	29.5	3.13				



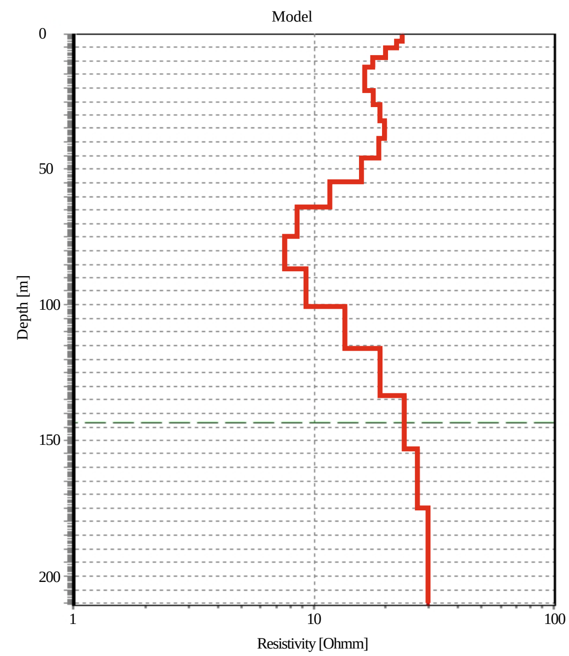


Table B-2. *Depth to bedrock at well locations interpreted from drillers' logs.*

Hydro ID[1]	Well Depth (ft)	WIN[2]	Easting (NAD83 m)	Northing (NAD83 m)	Land Elev. (ft)	Unit Top Depth (ft)	Material[3]	Bedrock Elev (ft)
				Logs that indicate bedrock				
12	153	6146	433153	4572761	4941	141	Tn	4800
15	101	6608	425382	4580535	5414	69	Tn	5345
32	600	9408	426895	4574070	5469	241	Pal	5228
41	257	9880	441781	4568097	5112	190	Pro	4922
42	230	9886	429213	4573805	5016	195	Tn	4821
60	992	10456	438726	4569629	5292	17	Pro	5275
76	143	11053	426014	4579468	5309	143	Pro	5166
78	224	11056	426274	4578456	5274	58	Pro	5216
86	363	11170	426910	4574633	5291	351	Pal	4940
88	302	11174	426718	4574016	5553	105	Pal	5448
89	210	11182	430286	4571747	5133	80	Tn	5053
94	235	11195	426765	4577791	5212	170	Tn	5042
95	150	11198	426514	4577282	5241	137	Qm	5104
97	285	11203	426321	4576528	5212	150	Qm	5062
103	189	11241	430995	4570681	4977	146	Tn	4831
117	200	12181	424299	4581931	5765	120	Pro	5645
118	270	12199	426298	4576343	5212	244	Qm	4968
133	700	16177	425655	4576029	5375	226	Pal	5149
136	502	16507	430278	4570149	5272	2	Pro	5270
152	182	18242	445011	4570089	5259	37	Pal	5222
157	192	19779	427830	4572660	5538	27	Pro	5511
158	240	19953	427812	4572557	5586	46	Pro	5540
160	169	20317	428325	4572058	5671	42	Pro	5629
163	320	20760	428037	4572454	5560	40	Pro	5520
189	400	25750	426360	4580170	5385	61	Tn	5324
201	580	28057	426995	4573703	5622	213	Pal	5409
210	95	29743	443189	4568528	5177	48	Pro	5129
211	160	29765	431162	4566183	5960	120	Qm	5840
214	465	30660	431254	4566183	5897	112	Qm	5785
218	240	31249	427986	4574358	5118	177	Pro	4941
222	200	31847	429127	4574978	5035	117	Tn	4918
229	366	33821	440620	4567023	5151	52	Pal	5099
232	286	34546	428532	4577163	5117	215	Pro	4902
237	355	35002	428516	4577117	5114	300	Pro	4814
240	391	35658	439194	4564363	5079	0	TcgA	5079
241	512	35784	433497	4565620	5243	34	Tn	5209
247	253	427530	424898	4580474	5573	22	Tn	5551
248	221	427631	425114	4579314	5424	95		5329
264	200	432252	440441	4568164	5066	152	Pal	4914
265	175	432628	440270	4567991	5056	148	Pal	4908
278	210	435422	441525	4568288	5121	16	PZcaA?	5105
282	300	436178	438460	4568636	4977	53	Pro	4924
283	804	436293	440171	4569475	5692	58	Pro	5634
294	200	438188	427717	4574565	5139	149	Pal	4990
373	250	10557	439476	4564933	5020	65	TcgA	4954
375	220	10559	439577	4564999	5018	68	TcgA	4950
386	160	11059	427023	4578508	5207	160	Pro	5047
401	165	11162	427384	4574435	5242	161	Pro	5081

Table B-2. *Continued.*

Hydro ID[1]	Well Depth (ft)	WIN[2]	Easting (NAD83 m)	Northing (NAD83 m)	Land Elev. (ft)	Unit Top Depth (ft)	Material[3]	Bedrock Elev (ft)
Logs that indicate bedrock								
405	518	11168	428086	4573906	5202	265	shale	4937
407	247	11173	426156	4574684	5497	75	Pal	5422
408	170	11175	426834	4574592	5324	160	Pal	5164
426	77	11251	431271	4569529	4943	53	Tn	4890
430	52	11269	433747	4566797	4947	48	Tn	4899
432	162	11271	428815	4576204	5081	83	tn	4998
433	290	11296	426289	4576470	5224	240	Pal	4984
435	160	11298	430100	4571799	5233	25	Tn	5208
440	253	11368	425385	4579923	5425	105	Tn	5320
441	120	11379	429107	4575741	5067	108	Pal	4959
449	110	15687	428956	4575694	5062	104	Pal	4958
450	170	16042	426721	4579544	5286	75	Pro	5211
456	141	19544	426166	4574815	5446	12	Pal	5434
462	525	21886	430057	4574927	5109	80	Tn	5029
474	165	33368	431107	4576930	5562	30	Tn	5532
475	268	25075	430741	4576305	5367	30	Pro	5337
488	140	430867	439299	4570783	5988	0	Pro	5988
520	147	10560	439078	4565043	5020	80	TcgA	4940
545	739	28707	431167	4570432	4968	170	Pro	4798
562	0	31943	424333	4581933	5769	100	Pro	5669
660	370	5242	430914	4574609	5117	78	Tn	5039
3596	700	33595	431721	4575949	5644	115	Pal	5529
3600	0	28847	441861	4568195	5106	45	Pro	5061
3601	152	438583	434436	4566711	4924	60	Tn?	4864
3603	710	1205	429894	4572992	4951	84	Tn	4867
3734	600	none	432008	4568354	4826	565	Tn	4261
3742	747	30297	433530	4567034	4943	0	Tn?	4943
3745	565	none	429719	4572811	5045	88	Tn	4957
3751	0	none	429436	4567330	4916	241		4675
Logs of basin fill to total depth used as minimum bedrock depth								
85	280	11158	429295	4574659	5018	280		<4738
131	206	16019	427118	4577552	5177	206		<4971
149	335	17964	431238	4569124	4937	326		<4611
165	160	21507	438201	4568349	4984	160		<4824
223	212	32225	439825	4567185	5026	212		<4814
226	285	33196	440538	4567800	5059	285		<4774
279	245	435839	438781	4567817	5007	245		<4765
311	152	8854	427410	4578918	5221	0		<5069
317	56	9613	436621	4571211	5025	56		<4969
371	130	10554	439328	4566190	5000	0		<4970
469	91	31885	439652	4568073	5033	91		<4942
470	147	29866	427961	4578089	5159	0		<5012
627	169	none	431505	4568549	4907	169		<4738
636	400	none	432159	4568883	4874	400		<4474
649	300	none	427006	4577078	5160	300		<4860
3564	511	11257	432162	4569201	4915	511		<4404
3743	507	none	431953	4568644	4828	507		<4321

[1] HydroID is the unique site identifier used in this report
[2] WIN is the unique well identification number used by Utah Division of Water Rights
[3] Material codes: Pal = Paleozoic bedrock; Pro = Proterozoic bedrock; PZcaA = Paleozoic carbonate aquifer; Qm = Quaternary landslide block; TcgA = Tertiary conglomeratic aquifer; Tn = Tertiary Norwood Formation

Table B-3. *Wells used to create valley-fill cross sections.*

HydroID[1]	WIN[2]	NWIS ID[3]	Well Depth (ft)	Land Elevation (ft)	Easting (NAD83 m)	Northing (NAD83 m)
Cross Section A-A' South Fork (listed west to east)						
3744	See note		216	4828	431705	4568480
3734	See note		600	4826	431999	4568353
429	11268		144	4928	434319	4568430
308	7156		185	4931	435626	4568229
256	430532		245	4948	436700	4568476
220	31736	411540111445301	100	4957	437116	4568125
459	21002		149	4977	437983	4568275
50	10043		102	4990	438377	4568134
46	10011	411538111433001	101	5000	438737	4568044
264	432252		200	5066	440441	4568164
278	435422		210	5121	441525	4568288
3600	28847		220	5106	441861	4568195
Cross Section B-B' Middle Fork (listed west to east)						
149	17964		335	4937	431238	4569124
428	11256		380	4920	432016	4569203
108	11260		400	4913	432289	4569397
271	433881		346	4933	432273	4571515
425	11239		105	4920	433613	4571555
424	11235	411734111471501	126	4918	434056	4571575
422	11231		101	4928	434421	4571403
102	11234	411704111464101	100	4938	434913	4570500
101	11232		102	4921	434814	4571398
36	9614		126	4934	435186	4570766
316	9612	411715111452301	50	5016	436551	4570917
317	9613		56	5025	436621	4571211
Cross Section C-C' North Fork (listed north to south)						
117	12181		200	5765	424299	4581931
15	6608		101	5414	425382	4580535
385	11049		33	5373	425494	4580024
76	11053		143	5309	426014	4579468
368	10270		118	5262	426542	4579089
387	11060		71	5213	426982	4578431
392	11142	412102111521700	106	5211	427042	4578035
82	11150		204	5172	427315	4577174
161	20588		150	5123	428254	4576518
116	11661		111	5079	428310	4575959
196	26963		130	5062	428709	4575660
222	31847		200	5035	429127	4574978
85	11158		280	5018	429295	4574659
80	11064		140	5012	429380	4574532
396	11155	411833111500401	75	5003	429853	4573827
409	11180	411820111494601	75	4983	430510	4573218
411	11184		127	4945	431586	4571651
105	11255		400	4913	432120	4569175
3742	30297		747	4943	433530	4567034
430	11269		52	4947	433747	4566797

Notes: Logs for wells 3744 and 3734 are wells 29 and 46, respectively, from Leggette and Taylor (1937).
[1] HydroID is the unique site identifier used in this report
[2] WIN is the unique well identification number used by Utah Division of Water Rights
[3] NWIS ID is USGS National Water Information System identifier

APPENDIX C

AQUIFER CHARACTERISTICS

Reference List of Utah Division of Drinking Water Drinking-Water Source Protection Documents and Aquifer Test Methods Cited on Table C-1.

Aquifer Science, 2001, Drinking water source protection plan for Town of Huntsville water system: Salt Lake City, Utah, unpublished consultant's report for Huntsville Town, variously paginated.

Avery, C., 1994, Ground-water hydrology of Ogden Valley and surrounding area, eastern Weber County, Utah, and computer simulation of ground-water flow in the valley fill aquifer system: Utah Department of Natural Resources Technical Publication No. 99, 84 p.

Barrett, D., and Osborn, M., 2010, Spring Mountain source protection plan, Spring Mountain spring: Liberty, Utah, unpublished Spring Mountain Mutual Water Company report, 5 p.

Bishop, C.E., and Lowe, M., 1999, Delineation of drinking water source protection zones for Green Hills Country Estates well 02, Weber County, Utah: Utah Geological Survey Report of Investigation 240, 25 p.

Carter and Burgess, 1999a, The Wadman replacement well #2 preliminary evaluation report: Salt Lake City, Utah, unpublished consultant's report for Wadman Investments, 31 p.

Carter and Burgess, 1999b, The Wadman well #3 preliminary evaluation report: Salt Lake City, Utah, unpublished consultant's report for Wadman Investments, 31 p.

Cooper, H.H., and Jacob, C.E., 1946, A generalized graphical method for evaluating formation constants and summarizing well field history: American Geophysical Union Transactions, v. 27, p. 526–534.

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***Table C-1.** Aquifer characteristics compiled from Utah Division of Drinking Water source protection documents.*

Hydro ID[1]	Easting (NAD83 m)	Northing (NAD83 m)	WIN[2]	Source Name	System Name	Well Depth (ft)	Geologic Description	Hydrogeologic Unit[3]	Test Method[4]	T (ft²/day)	Transmissivity Notes	K (ft/day)	Hydraulic Conductivity Notes	Reference[4]
516	435170	4569669	9806	Well No. 1	Casey Acres Water Co.	132	valley fill	PrinConf		2050	avg of 100-4000	103	avg from Avery, 1994	Terracon, 1998a
3598	424752	4581347	NA	Subdivision well	Durfee Creek Subdiv.	332	Mutual Fm.	CZqH		300		3	median from Avery, 1994	Terracon, 2001f
256	436700	4568476	430532	Bison Creek Well no. 1	Eden Water Works Co.	245	valley fill	PrinConf		1800	based on aquifer tests of Ogden City wells, Avery, 1994	150	median from Avery, 1994	Millennium Science and Engineering, 2007
660	430914	4574609	5242	Reservoir well	Eden Water Works Co.	370	Norwood Tuff	TvC		110	specific capacity data			LarWest Internat'l Engineering and CH2M Hill, 1997b
3603	429894	4572992	1205	Clarke east well	Eden Water Works Co.	710	valley fill	PrinConf		60,000	specific capacity data			LarWest Internat'l Engineering and CH2M Hill, 1997b
3745	429719	4572810	NA	Clarke west well	Eden Water Works Co.	565	Norwood Tuff	TvC		50	specific capacity data			LarWest Internat'l Engineering and CH2M Hill, 1997b
3600	441861	4568195	28847	Eagle Family Meadows Trailer Park	Fraternal Order Eagles	220	Maple Canyon Fm.	ZsiC	Cooper-Jacob, 1946	39	recovery data	1		SHC Consulting, 2004
60	438726	4569629	104560	Well 02	Green Hills Co. Estates	1010	Formation of Perry Canyon	ZsiC	Moench, 1984	697	avg of 564-830	1	average of 0.78-1.16	Bishop and Lowe, 1999
241	433497	4565620	35784	Hawkins Creek Estates well	Hawkins Creek Estates	450	Norwood Tuff	TvC		115		5	from Avery, 1994	Great Basin Engineering - North, 2005
623	434475	4566715	5252	Mitchel well	Lakeview Water Co.	197	valley fill (possibly Norwood Tuff)	TvC	Cooper-Jacob, 1946	117		6		Paul Hansen Associates, 2008
3741	432834	4566390	5251	Peterson well	Lakeview Water Co.	500	sandstone and conglomerate (possibly Norwood Tuff)	TvC		490	from K and 98 ft screen length	5	from Avery, 1994	Terracon, 1998b
3742	433530	4567034	30297	Proposed "new" well	Lakeview Water Co.	450	valley fill	PrinConf		5000	from K and 100 ft screen length	50	from Avery, 1994	Terracon, 1998c
152	445011	4570089	18242	Camp well	LDS Church	182	Ute and Blacksmith Limestones, undivided	PZcaA	Fabbri (1997) from specific capacity	127		13		Terracon, 2001e
201	426995	4573703	28057	Valley View Stake Camp well	LDS Church	580	Formation of Perry Canyon?	ZsiC	Cooper-Jacob, 1946	6		0.06		Stantec Consulting, 2004
133	425655	4576029	16177	Smith well	Liberty Pipeline Co.	707	Maxfield Limestone (possibly some Ophir Fm.)	PZcaA	Cooper-Jacob, 1946 in Driscoll, 1986	1243		12		Gardner Engineering, 2002
163	428037	4572454	5261	Well No. 2	Nordic Mtn Water Co.	320	Maple Canyon Fm.? (Weston Engineering, 1996)	ZsiC	Cooper-Jacob, 1946	113				Ward Engineering Group, 1998b
506	428034	4571680	6925	Well No. 1	Nordic Mtn Water Co.	260	Formation of Perry Canyon	ZsiC	Cooper-Jacob, 1946	25				Ward Engineering Group, 1998a
537	427639	4575398	23106	Rhodes Well	Nordic Mtn Water Co.	390	valley fill	Prin	Cooper-Jacob, 1946	2406	from drawdown test; 499 from recovery	15	from drawdown; 3.05 from recovery	Sunrise Engineering, Inc., 2001
3581	427810	4573089	5272	Well No. 3	Nordic Mtn Water Co.	291	Quaternary alluvial fan	Prin	Cooper-Jacob, 1946	60				Ward Engineering Group, 1999a
428	432016	4569203	11256	Pineview Reservoir well field well 1	Ogden City	380	valley fill	PrinConf	Theis, 1935 (recovery data)	69,030		314		Eckhoff, Watson, and Preator Engineering, 1996
125	431894	4565350	24160	Olympeak Estates well	Olympeak Estates	450	Norwood Tuff	TvC	Theis, 1935 (bailer tests nearby)	94		1		Michael L. Aldrich and Associates, 1996
438	431803	4566122	11303	Wadman Replacement well no. 2	Pineview Heights	122	Norwood Tuff	TvC	Theis, 1935 (bailer tests nearby)	94		1		Carter and Burgess, 1999a
3602	431365	4566090	11301	Wadman well no. 3	Pineview Heights	620	Norwood Tuff	ZsiC	Theis, 1935 (bailer tests nearby)	94		2		Carter and Burgess, 1999b
136	430278	4570149	16507	Well No. 3	Pineview West	502	Maple Canyon Fm.	ZsiC	Cooper-Jacob, 1946	11				Ward Engineering Group, 1999b
633	430954	4568991	11249	Well No. 2	Pineview West	142	valley fill	ZsiC	Cooper-Jacob, 1946	12				Ward Engineering Group, 2000
618	436186	4579960	436850	Hidden Lake well	Powder Mountain	1600	Nounan Formation	PZcaA	Cooper-Jacob, 1946	675	from pumping data; 490 from recovery data			Loughlin Water Associates, LLC., 2014
-	427151	4561351	NA	Blue Grouse well	Snow Basin Resort	1670	Tintic Quartzite	CqA	Cooper-Jacob, 1946; Theis, 1935	43	from constant rate test; 62 from recovery			Stantec Consulting, 2000
-	427852	4561273	NA	Bluebell Flats well	Snow Basin Resort	1755	Maxfield Limestone	PZcaA	Cooper-Jacob, 1946; Theis, 1935	70	from constant rate test; 36 from recovery			Stantec Consulting, 2000
-	427238	4560780	NA	High Span well	Snow Basin Resort	2447	Tintic Quartzite	CqA	Cooper-Jacob, 1946; Theis, 1935	470	from constant rate test; 1730 from recovery			Stantec Consulting, 2000
3407	440585	4563415	NA	Upper Bennett/Monastery Spring	Town of Huntsville	NA	Humbug Fm.	PZcaA		1375	avg from Avery, 1994	3	avg from Avery, 1994	Aquifer Science, 2001
3408	440539	4563447	NA	Middle/Lower Bennett Spring	Town of Huntsville	NA	Humbug Fm.	PZcaA		1375	avg from Avery, 1994	3	avg from Avery, 1994	Aquifer Science, 2001
3409	440358	4563726	NA	Lower/Virgil Peterson Spring	Town of Huntsville	NA	Park City Fm.	PZcaA		1375	avg from Avery, 1994	3	avg from Avery, 1994	Aquifer Science, 2001
3599	427061	4578632	123519	Subdivision well	Willow Creek Subdiv.	160	valley fill	Prin		2250	avg from Avery, 1994	38	avg from Avery, 1994	Terracon, 2002
3597	429815	4575004	5580	Pump Station well	Wolf Creek Water	400	Quaternary alluvium	Prin		900	from K and 180 ft screen length	5	from Avery, 1994	Terracon, 2001d

[1] HydroID is the unique site identifier used in this report

[2] WIN is the unique well identification number used by Utah Division of Water Rights

[3] Aquifer codes: PrinConf = principal confined valley-fill aquifer, Prin = principal unconfined valley-fill aquifer, TvC = Tertiary volcanic confining unit (Norwood Fm), PZcaA = Paleozoic carbonate aquifer, CqA = Cambrian quartzite aquifer, CZqH = Cambrian and Proterozoic quartzite heterogeneous unit, ZsiC = Proterozoic siliciclastic confining unit.

[4] See appendix C reference list

Table C-2. *Aquifer properties determined from specific capacity data.*

Aquifer[1]	PLSS[2]	HydroID[3]	WIN[4]	Latitude	Longitude	Transmissivity (ft^2/day)	Hydraulic Conductivity (ft/day)	Test Date	Method	Screen Length (ft)	Yield (cfs)	Draw-down (ft)	Pump Duration (hr)	Well Diam. (in)	Well Depth (ft)
Prin	(A- 6- 1) 1aac	499	4773	41.291	-111.780	130	63	01/20/1995	BAILING	2	0.022	20	20	6	112
Prin	(A- 6- 1)24aba	NA	10564	41.249	-111.783	500	50	06/12/1965	BAILER	10	0.134	32	25	10	125
Prin	(A- 6- 2) 5bbc	317	9613	41.290	-111.757	180	13	05/03/1961	BAILER	14	0.011	6	1	6	56
Prin	(A- 6- 2) 5ccb	120	12721	41.282	-111.758	31	5	08/05/1996	BAILER	6	0.022	60	1	6	101
Prin	(A- 6- 2) 5ccc	315	9611	41.279	-111.758	52	17	06/15/1991	BAILER	3	0.033	60	4	8	150
Prin	(A- 6- 2) 6bca	324	9763	41.288	-111.774	510	100	01/25/1990	PUMP	5	0.1	22	5	8	100
Prin	(A- 6- 2) 6daa	322	9758	41.286	-111.759	260	22	09/01/1968	BAILER	12	0.033	12	1	8	36
Prin	(A- 6- 2) 6dad	319	9632	41.283	-111.759	320	64	01/17/1967	BAILER	5	0.033	10	1	8	100
Prin	(A- 6- 2) 6dad	320	9634	41.282	-111.759	5500	550	02/03/1964	BAILER	10	0.089	2	2.5	8	46
Prin	(A- 6- 2) 6dcd	NA	16422	41.280	-111.764	14	2	10/01/1997	BAILER	8	0.018	105	1	6	110
Prin	(A- 6- 2) 6ddc	177	23940	41.279	-111.763	16	2	07/12/2001	BAILER	10	0.022	110	1	6	157
Prin	(A- 6- 2) 7aab	332	9777	41.278	-111.763	130	NA	07/30/1968	BAILER	-	0.018	14	2	6	92
Prin	(A- 6- 2) 7aab	514	9770	41.279	-111.762	230	230	08/07/1964	BAILER	1	0.022	10	2	6	84
Prin	(A- 6- 2) 7aba	312	8921	41.277	-111.765	70	10	05/07/1995	BAILER	7	0.027	35	1	6	110
Prin	(A- 6- 2) 7abb	40	9803	41.278	-111.768	220	25	05/24/1990	BAILER	9	0.045	20	1	6	142
Prin	(A- 6- 2) 8dda	176	23850	41.266	-111.740	17	2	07/02/2001	BAILER	10	0.022	100	1	8	161
Prin	(A- 6- 2) 8dda	192	26282	41.266	-111.742	20	2	11/29/2002	BAILER	10	0.022	85	1	8	160
Prin	(A- 6- 2) 8ddb	3560	9783	41.267	-111.742	440	9	05/21/1970	BAILER	50	0.067	15	1	8	160
Prin	(A- 6- 2) 9caa	457	20244	41.270	-111.732	30	0.3	08/19/1999	BAILER	95	0.045	120	1	8	150
Prin	(A- 6- 2) 9ccb	NA	23994	41.266	-111.738	9	1	08/03/2001	BAILER	10	0.022	170	1	8	238
Prin	(A- 6- 2) 9ccc	NA	26137	41.265	-111.738	17	1	10/21/2002	BAILER	12	0.033	150	1	8	160
Prin	(A- 6- 2)11ccc	NA	14265	41.264	-111.700	30	10	12/12/1996	BAILER	3	0.022	60	1	8	195
Prin	(A- 6- 2)14bad	343	9931	41.262	-111.693	5700	1100	10/10/1988	PUMP	5	0.134	3	5	8	37
Prin	(A- 6- 2)14bad	340	9881	41.262	-111.694	580	580	04/17/1964	BAILER	1	0.022	4	1	6	22
Prin	(A- 6- 2)14bad	341	9882	41.262	-111.694	390	390	03/27/1963	BAILER	1	0.011	3	2	6	23
Prin	(A- 6- 2)14bbc	128	15688	41.261	-111.700	94	23	05/27/1997	BAILER	4	0.053	50	1	8	104
Prin	(A- 6- 2)14bbd	81	11146	41.262	-111.697	57	14	04/19/1996	AIR	4	0.045	80	10	8	104
Prin	(A- 6- 2)15bbd	168	22135	41.260	-111.718	220	22	06/13/2000	BAILER	10	0.022	10	1	6	127
Prin	(A- 6- 2)15bca	510	8520	41.259	-111.717	89	13	03/15/1995	BAILER	7	0.029	30	1	6	155
Prin	(A- 6- 2)15bca	11	6125	41.259	-111.717	51	13	05/15/1994	BAILER	4	0.029	50	1	6	163

Table C-2. *Continued.*

Aquifer[1]	PLSS[2]	HydroID[3]	WIN[4]	Latitude	Longitude	Transmissivity (ft^2/day)	Hydraulic Conductivity (ft/day)	Test Date	Method	Screen Length (ft)	Yield (cfs)	Draw-down (ft)	Pump Duration (hr)	Well Diam. (in)	Well Depth (ft)
Prin	(A- 6- 2)15bcb	442	11461	41.259	-111.719	43	4	03/25/1996	BAILER	10	0.027	55	1	6	116
Prin	(A- 6- 2)15bcb	112	11402	41.259	-111.720	47	5	02/19/1996	BAILER	10	0.027	50	1	6	120
Prin	(A- 6- 2)15cbc	303	4743	41.255	-111.720	27	7	11/06/1993	BAIL TEST	4	0.029	90	1	6	160
Prin	(A- 6- 2)16aac	NA	23726	41.261	-111.725	380	130	06/07/2001	BAILER	3	0.045	12	1	6	101
Prin	(A- 6- 2)16acc	NA	10050	41.257	-111.729	100	9	12/05/1988	BAILER	12	0.022	20	1	6	110
Prin	(A- 6- 2)16ada	353	10035	41.260	-111.721	230	230	08/01/1973	BAILER	1	0.022	10	2	6	106
Prin	(A- 6- 2)16add	355	10052	41.257	-111.721	88	5	06/11/1986	BAILER	17	0.033	35	2	8	112
Prin	(A- 6- 2)16bac	354	10051	41.261	-111.734	92	5	09/29/1986	BAILER	20	0.033	35	2	6	120
Prin	(A- 6- 2)16bad	46	10011	41.261	-111.731	480	23	04/25/1979	BAILER	21	0.022	5	2	6	101
Prin	(A- 6- 2)16bbb	156	19524	41.264	-111.738	84	84	06/07/1999	BAILER	1	0.045	47	1	8	151
Prin	(A- 6- 2)16bbd	50	10043	41.262	-111.736	230	7	06/30/1977	BAILER	32	0.022	10	2	6	102
Prin	(A- 6- 2)16bbd	NA	10042	41.262	-111.736	170	8	08/12/1985	BAILER	20	0.033	20	2	6	120
Prin	(A- 6- 2)16bca	30	9374	41.260	-111.736	350	35	09/26/1984	BAILER TEST	10	0.033	10	2	6	115
Prin	(A- 6- 2)16bcc	NA	17413	41.258	-111.739	150	19	05/21/1998	BAIL TEST	8	0.04	25	1	6	140
Prin	(A- 6- 2)16bdb	27	8864	41.260	-111.734	2600	430	04/29/1995	BAILER	6	0.045	2	1	6	110
Prin	(A- 6- 2)16cad	NA	18715	41.254	-111.730	34	34	02/21/1999	BAILER	1	0.022	53	1	8	133
Prin	(A- 6- 2)16cba	49	10041	41.255	-111.735	490	44	06/30/1986	BAILER	11	0.045	10	2	6	131
Prin	(A- 6- 2)16cbb	114	11504	41.255	-111.738	2200	1100	03/27/1996	BAIL	2	0.111	6	2	6	100
Prin	(A- 6- 2)16cbc	45	10007	41.255	-111.740	480	32	09/10/1976	BAILER	15	0.022	5	2	6	105
Prin	(A- 6- 2)16cbd	513	9500	41.255	-111.737	660	16	11/30/2000	BAILER	40	0.045	7	1	8	143
Prin	(A- 6- 2)16cbd	172	22997	41.255	-111.736	740	53	07/26/1984	BAILER TEST	14	0.033	5	2	6	122
Prin	(A- 6- 2)16cdd	NA	18430	41.251	-111.733	98	98	11/28/1998	BAILER	1	0.022	20	1	8	133
Prin	(A- 6- 2)16daa	350	10012	41.256	-111.723	230	10	07/30/1979	BAILER	22	0.022	10	2	6	102
Prin	(A- 6- 2)16dab	381	11014	41.255	-111.723	130	64	01/08/1996	BAIL	2	0.027	20	1	6	116
Prin	(A- 6- 2)16dac	351	10025	41.254	-111.724	540	39	11/10/1971	BAILER	14	0.078	15	1	6	115
Prin	(A- 6- 2)16dad	349	10009	41.254	-111.721	1300	60	09/15/1978	BAILER	21	0.022	2	2	6	101
Prin	(A- 6- 2)16dbd	178	24030	41.254	-111.727	140	140	07/30/2001	BAILER	1	0.045	30	1	6	123
Prin	(A- 6- 2)16dcd	453	18151	41.251	-111.726	200	29	09/27/1998	AIR LIFT	7	0.111	60	10	8	107
Prin	(A- 6- 2)16ddd	35	9536	41.250	-111.721	1300	1300	07/31/1984	BAILER TEST	1	0.056	5	4	6	100

Table C-2. Continued.

Aquifer[1]	PLSS[2]	HydroID[3]	WIN[4]	Latitude	Longitude	Transmissivity (ft^2/day)	Hydraulic Conductivity (ft/day)	Test Date	Method	Screen Length (ft)	Yield (cfs)	Draw-down (ft)	Pump Duration (hr)	Well Diam. (in)	Well Depth (ft)
Prin	(A- 6- 2)17aad	369	10537	41.261	-111.740	1400	140	10/18/1995	AIR LIFT	10	0.111	10	10	6	101
Prin	(A- 6- 2)17ddd	358	10157	41.250	-111.741	510	100	06/25/1987	BAILER	5	0.047	10	2	6	97
Prin	(A- 6- 2)19acb	347	10006	41.245	-111.768	140	140	07/06/1964	BAILER	1	0.011	10	2	1	75
Prin	(A- 6- 2)19bbd	512	9301	41.247	-111.774	280	9	08/09/1983	PUMP TEST	30	0.033	12	2	8	163
Prin	(A- 6- 2)19bda	154	18579	41.245	-111.770	9	2	01/12/1999	PUMP	5	0.013	121	3	6	238
Prin	(A- 6- 2)20ada	53	10168	41.244	-111.740	260	9	09/15/1967	BAILER	30	0.1	43	6	6	110
Prin	(A- 6- 2)21aaa	372	10555	41.249	-111.721	990	99	08/18/1980	BAILER	10	0.045	5	2	8	100
Prin	(A- 6- 2)21abd	NA	13550	41.247	-111.727	170	21	09/10/1996	BAILER	8	0.027	15	1	8	109
Prin	(A- 6- 2)21aca	460	21092	41.244	-111.728	460	23	12/02/1999	BAILER	20	0.022	5	1	6	130
Prin	(A- 6- 2)21adb	371	10554	41.245	-111.724	170	17	06/24/1982	BAILER	10	0.033	20	2	6	130
Prin	(A- 6- 2)21cba	301	4314	41.242	-111.735	3300	1600	09/15/1993	BAIL/ SURGE/ PUMP	2	0.134	5	2	6	62
Prin	(A- 6- 2)21cbd	367	10217	41.239	-111.735	70	1	05/28/1970	BAILER	67	0.022	30	2	6	105
Prin	(A- 6- 2)28aab	376	10561	41.234	-111.725	210	11	07/27/1970	BAILER	19	0.033	15	1	8	117
Prin	(A- 7- 1) 6ccb	385	11049	41.368	-111.891	390	390	10/06/1962	BAILER	1	0.011	3	2	6	33
Prin	(A- 7- 1) 6ddd	NA	11048	41.368	-111.874	36	0.4	08/05/1972	BAILER	100	0.016	40	2	6	142
Prin	(A- 7- 1) 7aba	26	8700	41.365	-111.879	610	100	04/12/1995	BAILER	6	0.029	5	1	6	101
Prin	(A- 7- 1) 7abb	77	11054	41.365	-111.883	320	18	08/ /1972	BAILER	18	0.047	15	1	6	120
Prin	(A- 7- 1) 7acd	368	10270	41.360	-111.878	3100	280	09/21/1995	BAILER	11	0.053	2	1	6	118
Prin	(A- 7- 1) 7dad	NA	10124	41.356	-111.875	340	49	10/24/1995	PUMP	7	0.056	19	24	10	121
Prin	(A- 7- 1) 8caa	304	5833	41.359	-111.865	46	12	04/13/1994	BAILER	4	0.029	55	1	6	130
Prin	(A- 7- 1) 8cba	311	8854	41.359	-111.869	37	4	03/15/1981	BAILER	10	0.04	90	1	8	152
Prin	(A- 7- 1)17bbb	392	11142	41.351	-111.872	840	35	01/ /1972	NA	24	0.078	10	1	6	106
Prin	(A- 7- 1)17bbc	390	11139	41.350	-111.871	110	110	08/06/1969	BAILER	1	0.022	20	2	6	82
Prin	(A- 7- 1)17bcc	393	11148	41.346	-111.873	150	3	09/24/1975	BAILER	45	0.022	15	2	6	115
Prin	(A- 7- 1)17bcc	395	11151	41.345	-111.871	290	290	08/27/1964	BAILER	1	0.022	8	2	6	75
Prin	(A- 7- 1)17ccc	391	11140	41.338	-111.872	110	5	03/22/1972	BAILER	20	0.022	20	2	6	102
Prin	(A- 7- 1)17dda	446	13225	41.340	-111.856	320	65	09/09/1996	BAIL TEST	5	0.04	12	1	8	127
Prin	(A- 7- 1)17ddb	70	10653	41.339	-111.858	140	17	10/23/1995	TEST PUMP	8	0.078	60	8	8	141
Prin	(A- 7- 1)17ddb	56	10341	41.340	-111.858	860	290	09/30/1995	BAIL TEST	3	0.04	5	1	6	121

Table C-2. Continued.

Aquifer[1]	PLSS[2]	HydroID[3]	WIN[4]	Latitude	Longitude	Transmissivity (ft²/day)	Hydraulic Conductivity (ft/day)	Test Date	Method	Screen Length (ft)	Yield (cfs)	Draw-down (ft)	Pump Duration (hr)	Well Diam. (in)	Well Depth (ft)
Prin	(A- 7- 1)17ddd	59	10413	41.338	-111.855	26	3	10/02/1995	BAILER	10	0.022	70	1	6	115
Prin	(A- 7- 1)18ada	414	11190	41.347	-111.876	230	78	11/01/1969	BAILER	3	0.033	15	3	6	83
Prin	(A- 7- 1)18adb	93	11194	41.347	-111.878	33	2	11/08/1976	BAILER	21	0.022	60	2	6	116
Prin	(A- 7- 1)19aad	96	11201	41.334	-111.874	39	3	03/ /1972	BAILER	16	0.045	100	2	8	200
Prin	(A- 7- 1)19aad	NA	11202	41.334	-111.875	210	7	01/08/1972	BAILER	30	0.067	30	2	10	140
Prin	(A- 7- 1)19abc	NA	6650	41.335	-111.882	4	0.4	06/21/1995	PUMP TEST	10	0.009	225	24	6	234
Prin	(A- 7- 1)20aaa	NA	11208	41.337	-111.856	29	29	07/09/1969	BAILER	1	0.018	55	2	6	75
Prin	(A- 7- 1)20aab	NA	9322	41.337	-111.857	170	22	06/03/1995	BAILER	8	0.045	25	1	6	110
Prin	(A- 7- 1)20aad	3490	9411	41.334	-111.854	74	9	06/10/1995	BAILER	8	0.045	55	1	6	110
Prin	(A- 7- 1)20aad	417	11213	41.334	-111.855	110	NA	06/26/1972	BAILER	NA	0.022	20	2	6	93
Prin	(A- 7- 1)20adb	116	11661	41.332	-111.857	2600	320	04/09/1996	BAILER	8	0.045	2	1	6	111
Prin	(A- 7- 1)20bab	421	11218	41.336	-111.868	380	29	01/ /1972	BAILER	13	0.056	15	1	6	127
Prin	(A- 7- 1)20bbc	99	11219	41.334	-111.872	660	23	08/10/1965	BAILER	29	0.056	10	5	6	106
Prin	(A- 7- 1)20cad	NA	22575	41.327	-111.865	3700	16	11/ /2000	NA	240	1.671	55	24	20	400
Prin	(A- 7- 1)20ddb	489	36	41.325	-111.858	990	990	03/21/1992	BAILER TEST	1	0.1	12	4	6	103
Prin	(A- 7- 1)20ddd	NA	16309	41.324	-111.855	980	240	09/03/1997	BAILER	4	0.045	5	1	6	105
Prin	(A- 7- 1)21bab	NA	11046	41.337	-111.849	24	1	10/12/1976	BAILER	30	0.022	80	2	6	125
Prin	(A- 7- 1)21bac	NA	25527	41.334	-111.849	14	1	07/05/2002	BAILER	12	0.022	125	1	6	140
Prin	(A- 7- 1)21bba	161	20588	41.337	-111.850	52	NA	10/01/1999	BAILER	NA	0.022	36	1	8	150
Prin	(A- 7- 1)21bbb	197	27211	41.335	-111.854	20	2	05/13/2003	BAILER	10	0.022	90	1	6	120
Prin	(A- 7- 1)21bbb	NA	11043	41.335	-111.854	24	4	06/26/1970	BAILER	7	0.022	80	2	6	92
Prin	(A- 7- 1)21bbc	NA	11045	41.334	-111.854	32	32	07/18/1969	BAILER	1	0.018	50	2	6	81
Prin	(A- 7- 1)21bbd	480	24721	41.335	-111.850	23	2	10/07/2002	BAILER	10	0.022	76	1	8	130
Prin	(A- 7- 1)21bbd	NA	11042	41.335	-111.851	170	8	10/31/1985	BAILER	20	0.033	20	2	6	140
Prin	(A- 7- 1)21bbd	190	25980	41.334	-111.850	100	10	09/21/2002	BAILER	10	0.022	20	1	6	130
Prin	(A- 7- 1)21bcb	NA	11047	41.333	-111.853	480	30	11/25/1974	BAILER	16	0.022	5	2	6	NA
Prin	(A- 7- 1)21cab	384	11039	41.328	-111.847	250	31	10/20/1968	BAILER	8	0.042	16	1	8	42
Prin	(A- 7- 1)21cad	383	11033	41.328	-111.846	63	4	05/17/1971	BAILER	17	0.022	33	2	6	77
Prin	(A- 7- 1)21cbb	196	26963	41.329	-111.852	65	7	04/06/2003	BAILER	10	0.045	60	1	8	130
Prin	(A- 7- 1)21cdb	188	24834	41.325	-111.847	470	93	03/01/2002	BAILER	5	0.045	10	1	6	105

Table C-2. Continued.

Aquifer[1]	PLSS[2]	HydroID[3]	WIN[4]	Latitude	Longitude	Transmissivity (ft²/day)	Hydraulic Conductivity (ft/day)	Test Date	Method	Screen Length (ft)	Yield (cfs)	Draw-down (ft)	Pump Duration (hr)	Well Diam. (in)	Well Depth (ft)
Prin	(A- 7- 1)21ddb	NA	11040	41.326	-111.838	4200	420	07/28/1968	PUMP	10	0.067	2	1	4	37
Prin	(A- 7- 1)27bab	388	11061	41.322	-111.829	40	1	06/25/1963	PUMP	30	0.004	10	3	4	144
Prin	(A- 7- 1)28abb	400	11161	41.321	-111.843	100	100	11/26/1991	PUMP	1	0.04	40	6	8	240
Prin	(A- 7- 1)28bad	85	11158	41.320	-111.845	100	5	09/15/1970	BAILER	20	0.033	30	1	6	280
Prin	(A- 7- 1)28bad	80	11064	41.320	-111.846	230	45	04/20/1989	PUMP	5	0.078	36	2.5	6	140
Prin	(A- 7- 1)28bbd	111	11317	41.319	-111.850	2800	710	01/08/1996	SURGE PLATE/BAIL	4	0.089	4	10	8	120
Prin	(A- 7- 1)28bca	448	13779	41.318	-111.851	67	2	11/ /1996	BAILER	28	0.027	35	1	8	180
Prin	(A- 7- 1)28bdd	477	25714	41.316	-111.845	630	130	08/15/2002	BAIL	5	0.089	15	1	6	80
Prin	(A- 7- 1)28cab	33	9428	41.313	-111.848	45	5	06/24/1995	BAILER	10	0.027	52	1	6	352
Prin	(A- 7- 1)28ccb	397	11156	41.310	-111.852	390	33	10/06/1978	BAILER	12	0.022	6	2	6	92
Prin	(A- 7- 1)28dac	396	11155	41.313	-111.838	200	200	09/10/1962	BAILER	1	0.011	6	2	4	75
Prin	(A- 7- 1)28dbb	399	11160	41.315	-111.844	330	42	12/ /1988	PUMP	8	0.033	10	1	6	88
Prin	(A- 7- 1)28dbb	478	24962	41.314	-111.843	470	93	03/16/2002	BAILER	5	0.045	10	1	6	86
Prin	(A- 7- 1)28dbb	398	11159	41.314	-111.844	110	110	09/25/1970	BAILER	1	0.022	20	2	6	89
Prin	(A- 7- 1)29aad	526	11167	41.320	-111.855	28	28	10/18/1971	BAILE	1	0.022	70	2	6	136
Prin	(A- 7- 1)29aba	404	11165	41.321	-111.860	33	1	10/22/1975	BAILER	40	0.022	60	2	6	145
Prin	(A- 7- 1)29aca	458	20938	41.318	-111.859	66	3	11/08/1999	BAILER	20	0.022	30	1	6	128
Prin	(A- 7- 1)29acb	402	11163	41.317	-111.863	210	2	02/ /1977	PUMP	120	0.201	120	36	6	300
Prin	(A- 7- 1)29acc	406	11169	41.317	-111.863	60	0.3	07/18/1983	BAILER	190	0.033	50	2	8	300
Prin	(A- 7- 1)29ada	436	11300	41.318	-111.855	51	3	11/15/1974	BAILER	15	0.022	40	2	6	285
Prin	(A- 7- 1)29ada	403	11164	41.317	-111.855	51	51	08/07/1974	BAILER	1	0.022	40	2	6	146
Prin	(A- 7- 1)29adc	309	8431	41.316	-111.858	27	7	03/01/1995	BAIL TEST	4	0.022	65	0.5	6	300
Prin	(A- 7- 1)29baa	87	11172	41.321	-111.864	210	5	10/03/1962	PUMP	40	0.033	20	30	4	105
Prin	(A- 7- 1)29dbb	28	9021	41.315	-111.863	60	0.3	07/18/1983	BAILER TEST	190	0.033	50	2	8	300
Prin	(A- 7- 1)33adb	3603	1205	41.303	-111.839	100,000	3500	10/19/1992	PUMP TEST	30	0.446	0.667	24	10	93
Prin	(A- 7- 1)34ddd	411	11184	41.293	-111.817	210	100	06/ /1987	PUMP	2	0.078	40	4	6	127
Prin	(A- 7- 1)35bdc	91	11188	41.302	-111.810	1100	230	06/21/1981	BAILER	5	0.094	10	6	6	101
Prin	(B- 7- 1) 1adb	NA	19907	41.376	-111.895	120	8	07/27/1999	BAILER	15	0.045	35	1	8	125
Prin	(B- 7- 1) 1adc	529	11369	41.374	-111.894	7	1	10/15/1966	BAILER	5	0.009	100	2	6	130
PrinConf	(A- 6- 1) 1aaa	423	11233	41.293	-111.778	220	32	07/05/1970	BAILER	7	0.045	20	1	6	93
PrinConf	(A- 6- 1) 1aaa	101	11232	41.291	-111.779	140	69	11/15/1989	BAILER	2	0.036	25	1	6	102

Table C-2. *Continued.*

Aquifer[1]	PLSS[2]	HydroID[3]	WIN[4]	Latitude	Longitude	Transmissivity (ft^2/day)	Hydraulic Conductivity (ft/day)	Test Date	Method	Screen Length (ft)	Yield (cfs)	Draw-down (ft)	Pump Duration (hr)	Well Diam. (in)	Well Depth (ft)
PrinConf	(A- 6- 1) 1aba	422	11231	41.291	-111.783	510	510	10/04/1991	PUMP	1	0.123	27	3	6	101
PrinConf	(A- 6- 1) 1baa	424	11235	41.293	-111.787	17	1	10/03/1977	BAILER	26	0.016	80	2	6	126
PrinConf	(A- 6- 1)10dba	149	17964	41.271	-111.821	3	0.2	09/17/1998	BAILING	20	0.011	300	10	6	335
PrinConf	(A- 6- 1)11bdc	107	11259	41.272	-111.809	15,000	150	12/15/1971	PUMP	100	5.566	50	24	20	400
PrinConf	(A- 6- 1)11cab	105	11255	41.271	-111.810	14,000	1400	03/31/1984	PUMP	10	5.816	57	29	20	400
PrinConf	(A- 6- 1)12aac	NA	6059	41.276	-111.781	130	26	04/20/1995	5 HP PUMP	5	0.056	50	50	10	170
PrinConf	(A- 6- 1)12dcd	429	11268	41.265	-111.784	730	120	10/21/1960	BAILER	6	0.018	3	4	4	144
PrinConf	(A- 6- 2) 6cab	327	9766	41.286	-111.771	250	2	10/15/1978	BAILER	105	0.045	18	1	6	105
PrinConf	(A- 6- 2) 6cab	326	9765	41.286	-111.773	250	50	11/01/1978	BAILER	5	0.045	18	1	6	105
PrinConf	(A- 6- 2) 6cba	121	13133	41.285	-111.774	36	5	08/19/1996	BAILER	7	0.027	64	1	6	120
PrinConf	(A- 6- 2) 6cba	36	9614	41.286	-111.774	290	41	07/10/1989	BAILER	7	0.045	15	1	8	126
PrinConf	(A- 6- 2) 6cba	325	9764	41.285	-111.775	330	110	07/11/1979	BAILER	3	0.045	14	1	6	103
PrinConf	(A- 6- 2) 6cbb	370	10539	41.285	-111.776	8	0.1	11/09/1995	BAILER	100	0.022	205	1	6	220
PrinConf	(A- 6- 2) 6cbc	199	27333	41.282	-111.776	24	2	05/23/2003	BAILER	12	0.022	75	1	6	115
PrinConf	(A- 6- 2) 7bba	516	9806	41.277	-111.775	7600	380	10/09/1980	BAILER	20	0.134	2	1	12	130
PrinConf	(A- 6- 2) 7bbb	39	9800	41.278	-111.776	51	2	05/12/1971	BAILER	35	0.022	40	2	6	155
PrinConf	(A- 6- 2) 7bbb	331	9774	41.278	-111.777	28	4	07/27/1960	BAILER	7	0.009	30	2	4	88
PrinConf	(A- 6- 2) 7cac	500	4836	41.268	-111.771	20	5	12/02/1993	BAIL TEST	4	0.029	120	1	6	130
PrinConf	(A- 6- 2) 7cac	431	11270	41.268	-111.773	1200	120	08/20/1982	BAILER	10	0.056	5	1	8	148
PrinConf	(A- 6- 2) 7daa	9	6036	41.271	-111.759	340	170	05/20/1994	BAILER	2	0.04	12	1	6	221
PrinConf	(A- 6- 2) 7dac	334	9801	41.268	-111.762	23	2	08/31/1971	BAILER	10	0.022	83	2	6	123
PrinConf	(A- 6- 2) 7dbd	333	9780	41.269	-111.765	51	5	06/28/1968	BAILER	10	0.011	20	2	6	84
PrinConf	(A- 6- 2) 7dda	124	14292	41.267	-111.761	980	200	12/ /1996	BAILER	5	0.045	5	1	6	107
PrinConf	(A- 6- 2) 9ccc	165	21507	41.264	-111.738	130	45	02/21/2000	BAILER	3	0.022	15	1	8	160
PrinConf	(A- 6- 2)16bbb	NA	22841	41.264	-111.739	210	21	10/13/2000	BAILER	10	0.022	10	1	8	130
PrinConf	(A- 6- 2)17aaa	459	21002	41.264	-111.740	33	2	11/22/1999	BAILER	20	0.022	54	1	8	149
PrinConf	(A- 6- 2)17aac	439	11333	41.261	-111.742	510	260	02/23/1996	AIR PUMP	2	0.089	20	5	6	100
PrinConf	(A- 6- 2)17aac	299	1668	41.261	-111.744	620	620	NA	BAILER TEST	1	0.111	20	4	8	110
PrinConf	(A- 6- 2)17aad	447	13474	41.261	-111.741	120	12	09/02/1996	BAILER	10	0.053	40	1	8	120
PrinConf	(A- 6- 2)17acb	378	10938	41.259	-111.749	560	79	11/20/1995	BAILER	7	0.053	10	1	6	110
PrinConf	(A- 6- 2)17adb	NA	10534	41.260	-111.743	860	290	10/11/1995	BAIL & PUMP	3	0.089	12	3	6	100

Table C-2. *Continued.*

Aquifer[1]	PLSS[2]	HydroID[3]	WIN[4]	Latitude	Longitude	Transmissivity (ft^2/day)	Hydraulic Conductivity (ft/day)	Test Date	Method	Screen Length (ft)	Yield (cfs)	Draw-down (ft)	Pump Duration (hr)	Well Diam. (in)	Well Depth (ft)
PrinConf	(A- 6- 2)17cab	359	10162	41.255	-111.752	740	37	10/08/1985	BAILER	20	0.033	5	2	6	122
PrinConf	(A- 6- 2)17cdb	52	10158	41.252	-111.754	1600	74	07/31/1978	NA	22	0.056	4	2	6	107
PrinConf	(A- 6- 2)17daa	297	144	41.257	-111.742	180	30	04/09/1992	PUMP TEST	6	0.078	45	2.5	6	95
PrinConf	(A- 6- 2)17ddb	173	23268	41.253	-111.743	81	12	02/02/2001	BAILER	7	0.022	25	1	6	114
PrinConf	(A- 6- 2)18aba	NA	6286	41.264	-111.764	76	76	11/01/1983	BAILER TEST	1	0.033	40	2	8	100
PrinConf	(A- 6- 2)20baa	146	17630	41.248	-111.749	220	22	06/19/1998	BAILER	10	0.045	20	1	6	119
PrinConf	(A- 6- 2)20bab	502	6086	41.248	-111.754	610	150	04/24/1994	BAILER	4	0.058	10	1	6	NA
PrinConf	(A- 6- 2)20bad	310	8629	41.248	-111.752	430	61	03/18/1995	BAILER	7	0.058	14	1	6	101
PrinConf	(A- 6- 2)20bca	10	6088	41.246	-111.756	190	47	04/18/1994	BAILER	4	0.058	30	1	6	133
PrinConf	(A- 7- 1)34aca	129	15696	41.303	-111.823	980	110	05/09/1997	BAILER	9	0.045	5	1	6	141
PrinConf	(A- 7- 1)34adb	410	11181	41.304	-111.820	590	65	07/10/1982	BAILER	9	0.056	10	1	6	144
PrinConf	(A- 7- 1)35cbc	72	10948	41.299	-111.814	300	61	02/10/1996	TEST PUMP	5	0.178	74	72	8	177
KTcgA	(A- 6- 3) 5aba	130	15966	41.292	-111.629	25	1	07/02/1997	BAILER	45	0.022	70	1	8	150
KTcgA	(A- 6- 3) 5abb	148	17774	41.292	-111.630	2600	130	07/27/1998	BAILER	20	0.045	2	1	6	170
KTcgA	(A- 7- 3)16dcd	542	27390	41.335	-111.610	40	8	07/02/2003	BAILER	5	0.022	46	1	8	102
KTcgA	(A- 7- 3)29cdc	198	27238	41.307	-111.635	13	0.1	07/02/2003	BAILER	145	0.022	115	1	12	280
KTcgA	(A- 7- 3)29cdc	132	16086	41.308	-111.636	460	46	07/21/1997	BAILER	10	0.022	5	1	6	200
KTcgA	(A- 7- 3)29dda	180	24142	41.309	-111.623	7	0.1	08/25/2001	BAILER	95	0.018	190	1	6	200
KTcgA	(A- 7- 3)30abd	67	10583	41.318	-111.647	410	82	07/16/1985	BAILER	5	0.076	20	2	6	76
KTcgA	(A- 7- 3)30aca	NA	18095	41.317	-111.648	39	2	09/17/1998	BAILER	20	0.022	47	1	8	150
KTcgA	(A- 7- 3)30dba	4	1679	41.313	-111.648	32	0.5	NA	PUMP TEST	65	0.022	68	24	12	170
KTcgA	(A- 7- 3)30dbd	153	18282	41.312	-111.646	13	1	11/06/1998	BAILER	15	0.022	130	1	8	160
KTcgA	(A- 7- 3)30dca	122	13352	41.309	-111.648	8	1	08/18/1997	BAILER	10	0.011	100	1	6	120
KTcgA	(A- 7- 3)30dcc	195	26864	41.308	-111.649	20	1	04/28/2003	BAILER	25	0.022	86	1	8	170
KTcgA	(A- 7- 3)30dcc	66	10577	41.308	-111.649	59	6	05/04/1990	PUMP	10	0.022	40	24	8	100
KTcgA	(A- 7- 3)30dcd	NA	26509	41.307	-111.647	18	18	02/28/2003	BAILER	1	0.022	100	1	6	120
KTcgA	(A- 7- 3)30ddc	137	16627	41.307	-111.646	57	1	11/14/1997	BAILER	46	0.022	33	1	8	150
KTcgA	(A- 7- 3)31aaa	NA	24273	41.306	-111.643	30	1	10/01/2001	BAILER	50	0.022	60	1	8	180
KTcgA	(A- 7- 3)31aab	NA	16423	41.307	-111.645	31	1	09/23/1997	BAILER	45	0.022	60	1	6	150
KTcgA	(A- 7- 3)31aab	2	97	41.305	-111.645	93	16	03/13/1992	PUMP TEST	6	0.018	20	5	6	180
KTcgA	(A- 7- 3)32aaa	145	17593	41.306	-111.624	5	0.3	06/15/1998	BAILER	20	0.018	240	1	8	240

Table C-2. Continued.

Aquifer[1]	PLSS[2]	HydroID[3]	WIN[4]	Latitude	Longitude	Transmissivity (ft^2/day)	Hydraulic Conductivity (ft/day)	Test Date	Method	Screen Length (ft)	Yield (cfs)	Draw-down (ft)	Pump Duration (hr)	Well Diam. (in)	Well Depth (ft)
KTcgA	(A- 7- 3)32aaa	143	17544	41.306	-111.623	440	22	06/03/1998	BAILER	20	0.022	5	1	8	150
KTcgA	(A- 7- 3)32ada	522	10574	41.301	-111.623	14	1	05/01/1987	PUMP	10	0.013	70	1	8	100
KTcgA	(A- 7- 3)32baa	183	24254	41.306	-111.632	11	0.1	10/04/2001	PUMP	82	0.022	170	1	4.5	412
KTcgA	(A- 7- 3)32bab	182	24197	41.305	-111.636	14	0.4	09/12/2001	BAILER	35	0.022	116	1	8	140
KTcgA	(A- 7- 3)32bac	134	16377	41.304	-111.636	23	2	09/11/1997	BAILER	10	0.022	80	1	6	120
KTcgA	(A- 7- 3)32bad	63	10568	41.304	-111.632	8	0.4	08/03/1987	PUMP	20	0.011	100	1	8	260
KTcgA	(A- 7- 3)32bbb	NA	16717	41.306	-111.639	120	15	11/28/1997	BAILER	8	0.022	17	1	6	110
KTcgA	(A- 7- 3)32bbd	193	26420	41.304	-111.637	39	2	01/13/2003	BAILER	20	0.022	47	1	8	140
KTcgA	(A- 7- 3)32ddc	155	19231	41.294	-111.625	11	1	05/10/1999	BAILER	20	0.022	145	1	8	200
KTcgA	(A- 7- 3)32ddd	194	26579	41.294	-111.623	26	1	02/12/2003	BAILER	50	0.022	70	1	6	150
KTcgA	(A- 7- 3)33bab	5	1874	41.306	-111.616	53	3	01/27/1993	PUMP TEST	20	0.011	20	2	5	280
KTcgA	(A- 7- 3)33bba	NA	8186	41.306	-111.618	36	0.2	02/21/1995	BAILER	150	0.045	108	1	6	230
KTcgA	(A- 7- 3)33cbd	65	10576	41.297	-111.619	18	1	07/03/1982	PUMP	20	0.04	200	12	10	292
KTcgA	(A- 7- 3)33ccd	NA	26803	41.293	-111.619	18	2	03/01/2003	BAILER	10	0.022	100	1	6	150
KTcgA	(A- 7- 3)33ccd	64	10575	41.293	-111.618	54	3	07/13/1982	BAILER	20	0.045	80	3	6	140
TvC	(A- 6- 1)23bbb	29	9166	41.249	-111.815	28	0.5	05/24/1995	BAILER	60	0.027	80	1	6	NA
TvC	(A- 6- 1)23caa	115	11608	41.242	-111.807	3100	69	04/01/1996	BAILER	45	0.053	2	1	6	160
TvC	(A- 6- 1)23cbc	127	15581	41.240	-111.814	12	0.045	05/01/1997	BAILER	270	0.027	175	1	6	375
TvC	(A- 6- 1)23ccd	125	14947	41.237	-111.813	1	0.004	03/25/1997	BAILER	408	0.004	165	2	12	42
TvC	(A- 6- 1)23daa	141	17474	41.242	-111.799	460	30	06/01/1998	BAILER	15	0.022	5	1	6	280
TvC	(A- 6- 1)23dbc	139	17142	41.240	-111.805	230	2	03/18/1998	BAILER	100	0.022	10	1	4	245
TvC	(A- 6- 1)23dbc	166	22055	41.239	-111.805	620	21	05/25/2000	BAILING	30	0.078	15	8	6	178
TvC	(A- 7- 1) 6dbb	189	25750	41.370	-111.881	110	6	04/02/2003	AIR LIFT	20	0.167	150	8	8.63	400
TvC	(A- 7- 1)18aad	94	11195	41.348	-111.876	470	7	08/29/1978	BAILER	70	0.045	10	1	6	235
TvC	(A- 7- 1)21bbd	432	11271	41.334	-111.851	220	2	11/20/1980	BAILER	103	0.067	30	1	6	162
TvC	(A- 7- 1)28cad	42	9886	41.313	-111.846	19	2	08/07/1995	BAILER	10	0.027	115	1	6	230
TvC	(A- 7- 1)28cdb	13	6153	41.311	-111.848	230	23	06/13/1994	BAIL TEST	10	0.022	10	2	6	505
TvC	(A- 7- 1)29dbd	405	11168	41.313	-111.859	72	1	12/05/1974	PUMP	63	0.111	157	14	10	518
TvC	(A- 7- 1)35ada	12	6146	41.304	-111.799	76	8	06/01/1994	SURGED/ PUMPED	10	0.045	60	12	10	153
TvC	(B- 7- 1) 1add	15	6608	41.373	-111.892	620	620	06/27/1994	BAIL TEST	1	0.033	8	1	0.25	101
TvC	(B- 7- 1) 1dda	440	11368	41.367	-111.892	16	1	08/13/1970	BAILER	23	0.022	120	2	6	253

Table C-2. *Continued.*

Aquifer[1]	PLSS[2]	HydroID[3]	WIN[4]	Latitude	Longitude	Transmissivity (ft^2/day)	Hydraulic Conductivity (ft/day)	Test Date	Method	Screen Length (ft)	Yield (cfs)	Draw-down (ft)	Pump Duration (hr)	Well Diam. (in)	Well Depth (ft)
ZsiC	(A- 6- 1) 3dbc	528	11238	41.283	-111.824	70	2	06/20/1967	BAILER	30	0.022	30	2	6	187
ZsiC	(A- 6- 1) 3dbc	103	11241	41.284	-111.824	330	7	09/24/1982	BAILER	49	0.056	17	1	6	NA
ZsiC	(A- 6- 2) 9bad	60	10456	41.276	-111.732	2200	3	05/01/1997	PUMP W/AIR	692	0.446	30	240	8	992
ZsiC	(A- 6- 2)14bac	41	9880	41.262	-111.695	5	0.04	10/ /1973	PUMP	152	0.011	150	3	10	NA
ZsiC	(A- 7- 1) 7aab	450	16042	41.365	-111.876	3100	51	05/20/1998	AIR LIFT	60	0.223	10	22	6	170
ZsiC	(A- 7- 1)22bab	475	25075	41.335	-111.828	220	11	10/09/2002	TEST PUMP	20	0.668	286	2.5	12	NA
ZsiC	(A- 7- 1)29bdb	401	11162	41.318	-111.868	310	15	06/07/1989	PUMP	20	0.078	28	4	6	165
ZsiC	(A- 7- 1)30adb	171	22926	41.318	-111.878	5	1	11/25/2000	BAILER	10	0.022	300	1	8	391
ZsiC	(A- 7- 1)32acc	158	19953	41.301	-111.862	14	0.1	08/19/1999	BAILER	115	0.022	120	1	8	240
ZsiC	(A- 7- 1)32acc	157	19779	41.302	-111.862	23	2	07/20/1999	BAILER	15	0.022	77	1	8	192
ZsiC	(A- 7- 1)32dba	163	20760	41.300	-111.860	330	8	10/27/1999	TEST PUMP	40	0.116	38	8	10	320
ZsiC	(A- 7- 1)32ddb	160	20317	41.297	-111.857	98	2	09/14/1999	BAILER	60	0.022	20	1	8	169
Qal	(A- 6- 2)12cca	336	9859	41.266	-111.679	2900	2900	08/17/1990	PUMP	1	0.089	4	8	6	37
Qal	(A- 6- 2)12cca	338	9862	41.266	-111.678	1600	1600	03/28/1990	PUMP	1	0.078	6	8	6	30
Qm	(A- 7- 1)18dba	95	11198	41.344	-111.878	56	3	06/10/1963	BAILER	20	0.022	40	6	6	NA
Qm	(A- 7- 1)19abc	118	12199	41.335	-111.881	79	20	08/20/1996	AIR	4	0.022	30	10	6	270
Qm	(A- 7- 1)19cbd	NA	24464	41.327	-111.889	3	0.2	11/10/2001	BAILER	12	0.011	261	0.75	6	261
Qm	(A- 7- 1)30aca	300	2104	41.317	-111.880	680	43	03/22/1993	AIR FROM DRILL	16	0.056	10	10	6	140
CZqH	(A- 6- 3) 6ccd	152	18242	41.280	-111.657	170	17	08/01/1999	PUMP	10	0.067	40	4	8	182
PPundiff	(A- 7- 1)21bdc	441	11379	41.330	-111.847	36	4	02/07/1996	BAILER	10	0.027	65	1	6	120
PPundiff	(A- 7- 1)21cba	449	15687	41.329	-111.851	22	4	05/01/1997	BAILER	6	0.022	83	1	6	110
PPundiff	(A- 7- 1)29bbc	86	11170	41.320	-111.873	15	0.3	11/08/1991	BAILER	45	0.022	115	1	6	363
PPundiff	(A- 7- 1)30aad	408	11175	41.319	-111.874	270	27	10/07/1980	BAILER	10	0.04	15	1	6	170
PPundiff	(A- 7- 1)30dab	32	9408	41.315	-111.877	31	3	09/11/1995	BAIL TESTS	10	0.045	213	12	0.25	600

[1] Aquifer codes: Qal = Quaternary alluvium, Qm = Quaternary landslide blocks, PPundiff = undifferentialed Paleozoic or Proterozoic bedrock, all other codes as given in the main text of this paper
[2] PLSS is public land survey system identifier based on section, township, range, and quadrant divisions of Utah
[3] HydroID is the unique site identifier used in this report
[4] WIN is the unique well identification number used by Utah Division of Water Rights

APPENDIX D

WELL AND SITE INFORMATION, WATER LEVELS, DISCHARGE MEASUREMENTS, CHEMISTRY, ENVIRONMENTAL TRACER, AND STREAM GAUGING DATA

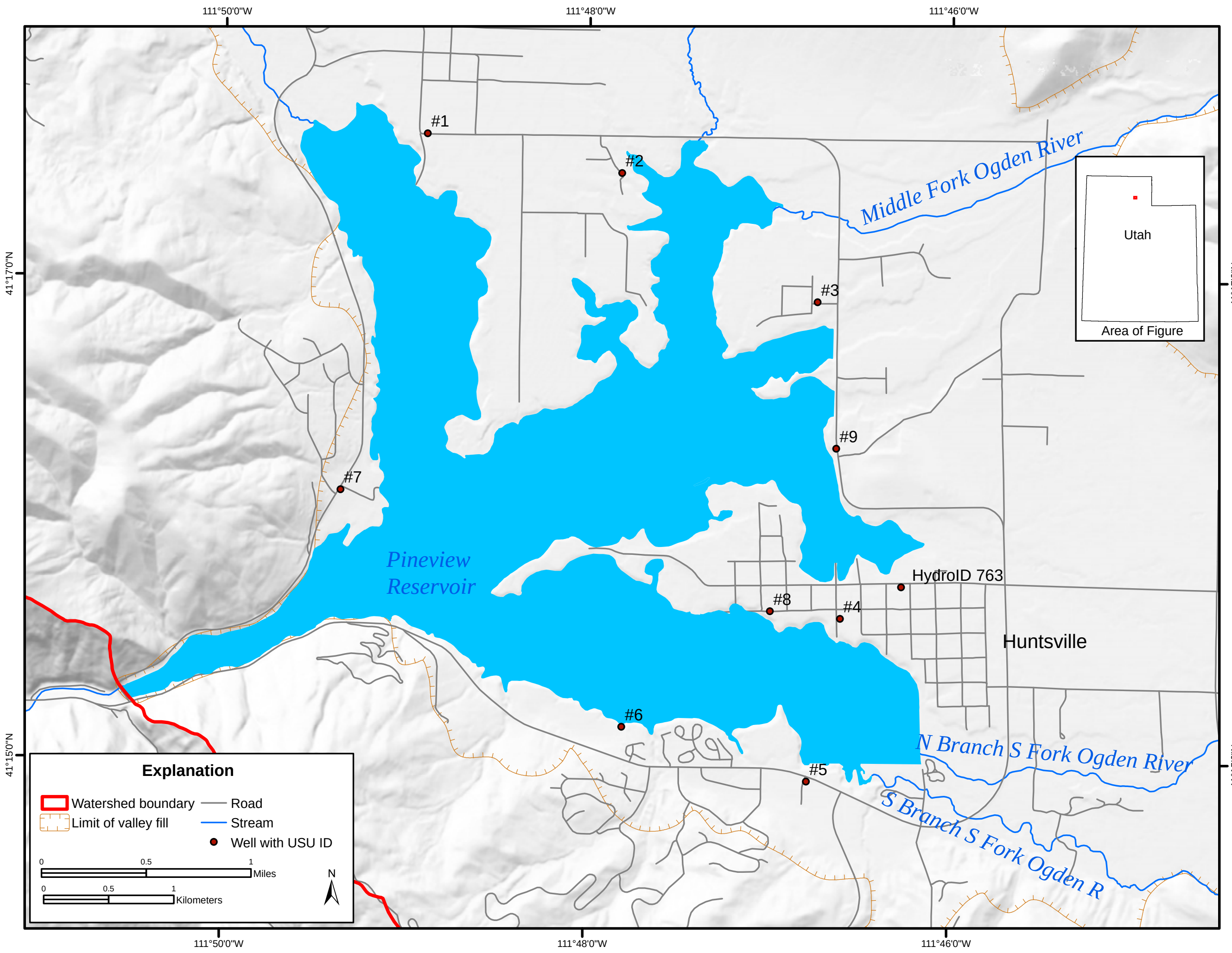

Figure D-1. *Location of Utah State University shallow unconfined wells (Reuben, 2013).*

Table D-1a. *Site information and summary of available data for wells.*

HydroID[1]	WIN[2]	Name/Owner	Easting (NAD83 m)	Northing (NAD83 m)	Land elevation (ft)	Top screen (ft)	Bottom screen (ft)	No. of screen intervals	Screen length[3] (ft)	Aquifer[4]	Gen. chemistry	Nutrients	Trace metals	^{3}H and ^{14}C	Noble gases	^{2}H and ^{18}O	Water level
15	6608	-	425382	4580535	5432	5363	5352	1	1	TvC							1
22	7635	-	445851	4574461	6329	6211	6204	1	7	KTcgA							
26	8700	-	426522	4579597	5293	5202	5196	1	6	Prin	1	1				1	1
58	10362	-	447849	4571897	5548	5368	5308	2	60	KTcgA	1	1				2	
63	10568	-	447087	4572737	5751	5711	5491	1	220	KTcgA						1	
65	10576	-	448152	4571957	5463	5230	5171	2	59	KTcgA						1	
83	11154	-	430773	4574730	5106	5046	4711	4	335	TvC	1	1	1			1	1
103	11241	-	430995	4570681	4977	4837	4788	1	49	PrinConf						1	2
105	11255	Ogden City #2	432120	4569175	4882	4706	4507	4	199	PrinConf						1	2
107	11259	Ogden City #5	432265	4569254	4882	4597	4497	1	100	PrinConf						1	2
108	11260	Ogden City #6	432289	4569397	4908	4652	4528	1	124	PrinConf	1			1	1	1	2
113	11403	-	424311	4578873	5734	5589	5577	1	12	ZsiC						1	1
120	12721	-	436494	4570325	4977	4883	4877	1	6	Prin		1					
123	13396	-	445814	4574025	6161	6047	6041	1	6	KTcgA	1	1				1	
129	15696	-	431145	4572759	4958	4857	4817	2	40	PrinConf	1	1				1	2
133	16177	Liberty Pipeline	425655	4576029	5375	4925	4675	2	250	PZcaA						1	
136	16507	-	430278	4570149	5272	5032	4770	2	262	ZsiC						1	1
141	17474	-	433017	4565900	5282	5022	5007	1	15	TvC	1		1			1	2
144	17564	-	437224	4566406	4951	4850	4840	1	10	PrinConf						1	
152	18242	-	445011	4570089	5259	5087	5077	1	10	CZqH						1	
153	18282	-	445868	4573639	6083	5943	5928	1	15	KTcgA						1	
156	19524	-	438205	4568286	4975	4860	4828	2	32	Prin	1	1				2	1
158	19953	-	427812	4572557	5586	5466	5351	1	115	ZsiC	1			1	1	1	2
159	20041	-	439157	4565963	4991	4886	4871	1	15	Prin	1	1	1			2	2
169	22156	-	436749	4570037	4963	4889	4877	2	12	Prin						1	1
170	22266	-	436890	4570031	4961	4891	4881	1	10	Prin	1			1	1	1	1
171	28054	-	426501	4574272	5530	5360	5105	3	255	ZsiC							1
172	22997	-	438315	4567263	4985	4885	4877	1	8	Prin	1	1				1	1
182	24197	-	446778	4572860	5774	5674	5639	1	35	KTcgA						1	

Table D-1a. *Continued.*

HydroID[1]	WIN[2]	Name/Owner	Easting (NAD83 m)	Northing (NAD83 m)	Land elevation (ft)	Top screen (ft)	Bottom screen (ft)	No. of screen intervals	Screen length[3] (ft)	Aquifer[4]	Gen. chemistry	Nutrients	Trace metals	^{3}H and ^{14}C	Noble gases	^{2}H and ^{18}O	Water level
184	24443	-	436862	4567255	4929	4829	4822	1	7	PrinConf	1	1	1	1	1	2	2
187	24722	-	428822	4576514	5087	4990	4941	4	49	Prin	1	1	1			1	1
189	25750	-	426370	4580176	5385	5135	4985	2	150	TvC, ZsiC	1			1	1	2	2
200	28054	-	426538	4574274	5514	5366	5059	5	307	PZcaA						1	
203	28210	-	438189	4565695	4970	4927	4866	4	61	Prin						2	2
212	30008	-	448395	4572931	5538	5538	5328	2	210	Q						1	
220	31736	-	437116	1568125	4958	4934	4919	1	15	PrinConf						1	
226	33196	-	440538	4567800	5059	4901	4799	3	102	Prin	1	1					
233	34557	-	441693	4567777	5095	4986	4981	1	5	Prin	1	1	1			1	1
255	430416	-	427906	4573668	5277	5157	5112	1	45	ZsiC						1	
271	433881	Valley View Elementary	432273	4571515	4933	4843	4587	3	256	PrinConf						1	2
280	435901	-	447675	4572327	5587	5412	5372	2	40	KTcgA						1	
281	436167	-	438539	4566589	4998	4903	4883	1	20	Prin							1
282	436178	-	438460	4568636	4977	4877	4687	5	190	PZcaA	1					1	1
285	437007	-	435005	4569311	4930	4800	4790	1	10	PrinConf	1			1	1		
288	437332	-	436038	4570335	4958	4840	4838	open	2	Prin	1	1				1	1
289	437373	-	438941	4567825	5013	4913	4911	open	2	Prin						1	
294	438188	-	427717	4574565	5139	5000	4944	3	56	Prin						1	1
311	8854	-	427410	4578918	5221	5081	5071	1	10	Prin	1	1	1			1	1
315	9611	-	436500	4570023	4967	4845	4842	1	3	Prin	1	1	1				
317	9613	-	436621	4571211	5025	4985	4971	1	14	Prin	1	1				1	1
325	9764	-	435121	4570625	4940	4840	4837	1	3	PrinConf	1	1	1			2	2
334	9801	-	436185	4568840	4930	4807	4806	open	1	PrinConf						2	2
348	10008	-	439080	4568021	5011	4905	4904	open	1	Prin	1	1				2	2
349	10009	-	439590	4567236	5021	4915	4894	1	21	Prin	1	1				1	1
354	10051	-	438593	4568031	4990	4890	4870	1	20	Prin						1	1
363	10170	-	436942	4566541	4950	4856	4846	1	10	PrinConf	1					2	1
375	10559	-	439577	4564999	5018	4898	4798	1	100	TcgA	1	1	1			1	1
378	10938	-	437356	4567790	4963	4863	4856	1	7	PrinConf						1	
386	11059	-	427023	4578508	5207	5047	5000	open	47	ZsiC	1	1				2	2
394	11149	-	427050	4577592	5174	5070	5054	1	16	Prin						1	1
406	11169	-	427764	4574302	5176	5066	4876	1	190	Prin	1	1					
413	11187	-	433985	4572433	4944	4879	4849	2	30	PrinConf	1	1				1	2
418	11215	-	427391	4576399	5114	4974	4964	1	10	Prin	1	1				1	1

Table D-1a. *Continued.*

HydroID[1]	WIN[2]	Name/Owner	Easting (NAD83 m)	Northing (NAD83 m)	Land elevation (ft)	Top screen (ft)	Bottom screen (ft)	No. of screen intervals	Screen length[3] (ft)	Aquifer[4]	Gen. chemistry	Nutrients	Trace metals	^{3}H and ^{14}C	Noble gases	^{2}H and ^{18}O	Water level
422	11231	-	434421	4571403	4928	4827	4826	open	1	PrinConf	1	1					
423	-		434913	4571563	4939	4939	4924	open	15	PrinConf							1
424	11235	-	434056	4571575	4918	4818	4792	1	26	PrinConf						1	1
428	11256	Ogden City #1	432016	4569203	4923	4823	4722	1	101	PrinConf							2
431	11270	-	435315	4568830	4940	4802	4792	1	10	PrinConf						1	1
433	11296	-	426289	4576470	5224	4994	4934	1	60	ZsiC	1	1	1			1	1
435	11298	-	430100	4571799	5233	5093	5073	1	20	ZsiC						1	1
439	11333	-	437809	4567975	4962	4864	4862	1	2	PrinConf						1	1
440	11368	-	425395	4579932	5425	5195	5172	1	23	TvC	1	1				1	1
443	11720	-	428095	4575080	5060	4960	4950	1	10	Prin						2	2
452	17712	-	440564	4567459	5061	4957	4954	open	3	Prin	1	1	1			1	1
454	18198	-	434762	4572585	5066	5026	5016	1	10	Prin						2	2
468	33972	-	439084	4565973	4990	4911	4910	open	1	Prin	1	1					
474	33368	Cottonwoods Well/Wolf Ck WSID	431107	4576930	5562	5442	5275	2	167	TvC, ZsiC	1			1	1		2
477	25714	-	429296	4574080	4996	4921	4916	1	5	Prin	1	1	1			2	2
492	1683	-	447474	4574282	5955	5850	5830	2	20	KTcgA						1	
508	7728	-	447069	4574319	6260	6160	6075	1	85	KTcgA						1	
516	9806	-	435170	4569669	4923	4818	4798	1	20	PrinConf						1	1
520	10560	-	439078	4565043	5020	4880	4873	open	7	TcgA	1			1	1	1	
530	12975	-	447814	4572333	5554	5354	5254	1	100	KTcgA						1	
532	18482	-	447017	4572651	5702	5617	5597	1	20	KTcgA						1	
545	28707	Pineview West Water Company	431167	4570432	4968	4910	4230	4	680	Shallow+ZsiC							1
609	434407	Utah State University	431105	4568901	4940	4910	4900	1	10	Prin							1
615	436134	-	427784	4574149	5204	5094	4904	1	190	Prin						1	1
618	436850	Hidden Lake well	436186	4579960	8882	7902	7302	1	600	PZcaA						2	
633	-	-	430902	4568774	4980	4839	4838	unknown	1	ZsiC						1	
762	31821	-	440126	4567027	5039	4957	4941	1	16	Prin							1
763	-	-	435411	4568147	4918	4904	4870	1	34	PrinConf							2
764	-	-	430842	4572260	-	-	-	-	-	Prin							1

Table D-1a. Continued.

HydroID[1]	WIN[2]	Name/Owner	Easting (NAD83 m)	Northing (NAD83 m)	Land elevation (ft)	Top screen (ft)	Bottom screen (ft)	No. of screen intervals	Screen length[3] (ft)	Aquifer[4]	Gen. chemistry	Nutrients	Trace metals	^3H and ^{14}C	Noble gases	^2H and ^{18}O	Water level
3564	11257	Ogden City #3	432155	4569204	4920	4714	4540	1	174	PrinConf							2
3587	-	Warm Springs well	430793	4575361	5230	4970	4830	2	140	TvC	1			1	1	2	
3596	33595	Highlands Well/Wolf Creek WSID	431721	4575949	5644	-	-	-	-	CZqH							1
3597	-	Eden Hills well	429815	4575004	5106	-	-	-	-	Prin						1	2
3598	-	Liberty Pipeline Co	424752	4581347	5608	-	-	-	-	CZqH							1
3599	-	Willow Creek Subdivision Well	427061	4578632	5211	-	-	-	-	Prin							1
3600	28847	Fraternal Order of Eagles	441861	4568195	5106	4926	4889	1	37	ZsiC						1	1
3601			434436	4566711	4924	4812	4772	1	40	PrinConf						1	1
3602	11301	-	431365	4566090	5797	-	-	-	-	ZsiC							1
3603	1205	Clark Well/ Eden Water Works	429894	4572992	4951	4901	4871	1	30	PrinConf	1			1	1	1	1
3638	11258	Ogden City #4	432209	4569178	4910	-	-	-	-	PrinConf							2
3669	20782	Snowbasin combined wells	428439	4562625	8000	-	-	-	-	ZsiC						1	
3673	composite	Ogden City wells composite sampled at treatment plant	432136	4569296	4921	NA	NA	NA	NA	PrinConf						2	
										Total number of samples:	42	31	13	10	10	97	97

[1] HydroID is the unique site identifier used in this report
[2] WIN is the unique well identification number used by Utah Division of Water Rights
[3] Total length including blanks if well has multiple screen intervals
[4] Aquifer codes: PrinConf = principal confined valley-fill aquifer, Prin = principal unconfined valley-fill aquifer, Shallow = shallow unconfined aquifer, Q = Quaternary alluvium, TcgA = Tertiary conglomerate aquifer, TvC = Tertiary volcanic confining unit (Norwood Fm), KTcgA = Cretaceous and Tertiary conglomerate aquifer (including Wasatch Fm), PZcaA = Paleozoic carbonate aquifer, CZqH = Cambrian and Proterozoic quartzite heterogeneous unit, ZsiC = Proterozoic siliciclastic confining unit

Table D-1b. *Site information and summary of available data for precipitation, stream, and surface-water sites.*

HydroID[1]	Description	Easting (NAD83 m)	Northing (NAD83 m)	Land elevation (ft)	Aquifer[2]	Gen. chemistry	Nutrients	Trace metals	^{3}H and ^{14}C	Noble gases	^{2}H and ^{18}O	Discharge
				Precipitation								
3632	Hunstville Library: PRCP-1 & SNW-1	435406	4568085	4931	-						17	
3633	Pizzel Spring: PRCP-2 & SNW-2	434352	4579287	7279	-						15	
3634	Hidden Lake lift: PRCP-3 & SNW-3	436097	4580114	8899	-						17	
3635	Monte Cristo: PRCP-4 & SNW-4	451276	4584583	7241	-						17	
				Springs								
3407	Monestary Spring	440585	4563415	5337	PZcaA						1	
3408	Bennett Spring #3	440539	4563447	5298	PZcaA						1	
3416	East of Meadows CG	447184	4571013	5431	KTcgA	1	1				1	
3419	Pizzel Spring	434302	4579290	7335	CZqH						2	
3424	Seepage northwest of Huntsville	436528	4568199	4933	Shallow						1	
3434	Burnett Spring	431454	4575431	5355	CZqH						1	
3435	Liberty Springs	426247	4575543	5168	PZcaA						1	
3438	Upper North Fork CG	422998	4580419	5954	ZsiC	1	1				1	
3441	Pizzel Spring #2	434349	4581096	8157	CZqH						1	
3595	Huntsville town culinary springs composite sample	440560	4563492	5258	PZcaA	1	1				1	
3647	Patio Springs	430802	4575361	5241	Prin						1	
3648	west spring below Causey Dam	449950	4571814	5515	KTcgA						1	
3649	Spring near head of Spring Creek	437324	4567875	4959	Shallow						1	
3650	Limestone Spring	450279	4581719	6649	KTcgA	1	1				2	
3651	east spring below Causey Dam	450180	4571877	5518	KTcgA						1	
3652	Keisel Spring	451739	4573862	5706	PZcaA	1			1	1	2	
3653	Spring off of Hwy 39 near pass	450396	4584450	7054	KTcgA	1	1				2	
3654	2900 E 3350 N	426517	4574635	5344	PZcaA						1	
3656	Snowflake/Crooked Spring	430519	4577097	5573	ZsiC	1					2	
3657	Lefty Spring	435921	4579288	8076	PZcaA						1	
3658	Wheeler Spring	427545	4562900	6528	PZcaA	1	1				2	
3659	Spring near Lower Meadows CG	446357	4570792	5347	KTcgA						1	
3660	Upper Meadows CG hydrant	446784	4571267	5333	Q						1	

Table D-1b. *Continued.*

HydroID[1]	Description	Easting (NAD83 m)	Northing (NAD83 m)	Land elevation (ft)	Aquifer[2]	Gen. chemistry	Nutrients	Trace metals	^{3}H and ^{14}C	Noble gases	^{2}H and ^{18}O	Discharge
				Springs								
3661	Causey Spring	453719	4575712	6204	PZcaA						1	
3662	Lefty's Canyon unnamed spring 1	436811	4579191	8119	PZcaA						1	
3663	Lefty's Canyon unnamed spring 2	436768	4579223	8092	PZcaA						1	
3666	Spring near Maple CG near Snowbasin	427528	4564253	6290	Q						1	
3667	Spring on edge of Green Pond	429608	4561562	6525	Q						1	
3668	Wildcat Spring	428186	4562393	6735	Q						1	
3671	Spring at head of creek through Cardon ranch	436779	4568215	4936	Shallow	1	1				1	
3672	Spring at head of Cache Valley Creek	428497	4582585	6503	CZqH	1	1				1	
				Stream								
734	South Fork Ogden River USGS Gage nr Huntsville	443543	4568782	5191	-	1	1				3	2
755	Beaver Ck nr mouth at rd to Causey Dam	448307	4571930	5449	-						1	
3337	North Branch South Fork at Hwy 39	436184	4566669	4937	-						3	9
3338	South Branch South Fork at Hwy 39	435916	4566377	4922	-						3	9
3339	Huntsville South Bench Canal at 8900 E	438410	4565787	4976	-						2	2
3340	Bennett Creek at Huntsville water plant	439529	4565110	5005	-						2	2
3341	Monastary Canal abv Huntsville Ditch	440699	4565633	5040	-						1	2
3342	South Branch South Fork at 8800 E bridge	438314	4566188	4979	-						1	2
3343	South Branch South Fork at 9500 E	439608	4566913	5017	-						2	2
3344	North Branch South Fork at 9500 E	439607	4567027	5018	-						2	2
3345	Bally Watts Creek above confluence with South Branch SF	437772	4565848	4962	-						1	2
3346	Eden Cemetery Stream at 1900 N	433271	4571599	4915	-						1	1
3349	Middle Fork Irrigation flume	436651	4571828	5064	-						1	2
3350	Little Bench Ditch to Jensen Ranch from MF at OVC	436946	4571401	5070	-						1	2
3351	Bally Watts Creek at Falcon Way	438798	4563947	5153	-						1	1
3352	Cache Valley Creek at shooting range	427121	4580223	5419	-						2	3
3353	Upper Middle Fork at USGS Flume	438236	4572222	5217	-	1	1				3	4
3354	Middle Fork at Ogden Valley Canal	436858	4571518	5065	-						2	2
3355	Garden of Eden Channel at 7100 E	434932	4571190	4926	-						2	2
3356	Middle Fork at 7100 E	434928	4570985	4923	-						2	8
3357	Dry Hollow Creek	434910	4570111	4909	-						2	4
3358	North Fork at Hwy 158	430644	4571899	4920	-						1	9

Table D-1b. *Continued.*

HydroID[1]	Description	Easting (NAD83 m)	Northing (NAD83 m)	Land elevation (ft)	Aquifer[2]	Gen. chemistry	Nutrients	Trace metals	^{3}H and ^{14}C	Noble gases	^{2}H and ^{18}O	Discharge
				Stream								
3359	North Branch South Fork at 8600 E	437854	4566983	4976	-						1	2
3360	South Fork at Ogden Valley Canal Diversion	441572	4567757	5094	-						1	2
3361	Kelly and Maple Creek before Spring Creek	436218	4568381	4927	-						1	2
3362	Maple Canyon Creek	438718	4569671	5291	-						2	2
3363	Kelly Canyon at Maple Drive	438735	4568984	5102	-						1	2
3364	North Fork at Farron's Bridge	429196	4574514	5015	-						2	2
3365	North Fork at Preserve Gate	428643	4576550	5098	-						1	2
3366	North Fork blw diversion dam	425682	4579798	5355	-						1	2
3367	North Fork at Lomondi Camp Entrance	424708	4580875	5481	-	1	1				3	3
3368	Durfee Creek at North Fork Park Road	424828	4580847	5478	-						2	2
3369	Cold Canyon Creek abv N. Fork	424805	4580811	5472	-						2	2
3371	Broadmouth Canyon Creek at Jones' Ranch	428169	4579343	5366	-						2	3
3372	Sheep Creek abv Jones' Ranch road	426950	4579494	5267	-						2	2
3373	Sheep Creek blw Jones' Ranch road	426962	4579324	5260	-						2	2
3374	Spring Creek at USGS flume	435818	4568433	4917	-						3	10
3375	Wolf Creek in old Hwy 162 culvert	429970	4573786	5002	-						1	2
3376	Thimbleberry Creek	426219	4578857	5271	-						2	2
3377	Pine Creek at south culvert under old Hwy 162	428559	4574484	5058	-						1	2
3378	Pine Creek diversion at north culvert under old Hwy 162	428536	4574500	5058	-						1	2
3379	Liberty Spring Creek at 3600 N old Hwy 162	427891	4574969	5071	-						2	2
3380	Sheep Creek at The Preserve entrance	428682	4576517	5094	-						1	3
3381	North Fork at Camp Utaba Bridge	424157	4581836	5625	-						1	2
3390	Geertsen Creek abv 1900 N	433953	4571631	3390	-						1	3
3391	channel W of Geertsen Ck abv 1900 N	433777	4571577	4900	-						1	1
3403	7800 E Canal	436204	4568984	4941	-						1	1
3594	Liberty Spring Ck blw conf w Pole Canyon Ck	429138	4574255	5015	-						2	2
3604	N. Fork at old Hwy 162 north of Eden	426974	4578235	5199	-						2	3

Table D-1b. *Continued.*

HydroID[1]	Description	Easting (NAD83 m)	Northing (NAD83 m)	Land elevation (ft)	Aquifer[2]	Gen. chemistry	Nutrients	Trace metals	^{3}H and ^{14}C	Noble gases	^{2}H and ^{18}O	Discharge
				Stream								
3639	Wolf Creek Irrigation Flume	431214	4577325	5614	-						2	2
3641	Wheatgrass Canyon above Causey Reservoir	451682	4573780	5730	-						1	
3642	Liberty Springs at 100 S 8000 E	436607	4568148	4937	-						1	
3643	Pole Canyon Ck at old Hwy 162	429066	4574199	5028	-						1	
3644	Liberty Spring Ck above Pole Canyon Ck conf	429123	4574266	5018	-						1	
3645	Kelly Canyon at 7800 E	436278	4568576	4936	-						1	
3646	Creek from Cardon Ranch at driveway	436623	4568272	4936	-						1	1
3670	Liberty Spring Creek at 2900 E	426559	4575452	5150	-	1	1				1	
3674	Ogden Valley Canal 14	431282	4573384	4986	-						1	1
3675	Coal Hollow Creek abv conf with North Fork	429981	4573019	4959							1	1
				Surface water								
3636	Reservoir outflow at Pineview Water Treatment Plant	428975	4567344	4822	-	1	1				10	
3655	Pineview Reservoir at Middle Inlet Beach	434141	4569694	4900	-						2	
3664	Pineview Reservoir at Old Hwy fishing access	431585	4571150	4890	-						1	
3665	Pineview Reservoir at beach along Hwy 39	431460	4567952	4904	-						1	
					Total number of samples:	15	13	0	1	1	209	142

[1] HydroID is the unique site identifier used in this report

[2] Aquifer codes: Prin = principal unconfined aquifer, Shallow = shallow unconfined aquifer, Q = Quaternary alluvium, KTcgA = Cretaceous and Tertiary conglomerate aquifer (including Wasatch Fm), PZcaA = Paleozoic carbonate aquifer, CZqH = Cambrian and Proterozoic quartzite heterogeneous unit, ZsiC = Proterozoic siliciclastic confining unit

Table D-2. Water level in wells in Ogden Valley measured in 2016.

HydroID[1]	Easting (NAD83 m)	Northing (NAD83 m)	Aquifer[2]	Land elev. (ft)	Land elev. source[3]	Spring 2016 Date-time	Spring 2016 WL below LSD (ft)	Spring 2016 Water-level elev. (ft)	Fall 2016 Date-time	Fall 2016 WL below LSD (ft)	Fall 2016 Water-level elev. (ft)
15	425382	4580535	TvC	5413.83	TURN	4/11/16 11:33	16.13	5397.70	-	-	-
26	426503	4579679	Prin	5293.06	TURN	4/11/16 14:30	53.46	5239.60	-	-	-
83	430773	4574730	TvC	5106.42	TURN	5/2/16 15:45	29.30	5077.12	-	-	-
103	430995	4570681	PrinConf	4976.80	TURN	4/12/16 12:25	32.11	4944.69	9/27/16 17:50	52.65	4924.15
113	424311	4578873	ZsiC	5733.88	DEM	4/18/16 14:00	84.90	5648.98	-	-	-
129	431145	4572759	PrinConf	4958.07	TURN	4/20/16 10:20	33.25	4924.82	9/27/16 17:00	44.40	4913.67
136	430278	4570149	ZsiC	5271.63	Trimble	4/19/16 12:22	120.95	5150.68	-	-	-
141	433017	4565900	TvC	5281.92	TURN	5/4/16 14:00	232.25	5049.67	9/27/16 10:40	244.10	5037.82
156	438205	4568286	Prin	4974.75	TURN	5/4/16 16:20	14.65	4960.10	-	-	-
158	427812	4572557	ZsiC	5585.68	TURN	4/21/16 10:00	29.72	5555.96	9/28/16 15:00	17.40	5568.28
159	439157	4565963	Prin	4990.86	TURN	4/28/16 10:47	11.03	4979.83	9/26/16 10:35	15.13	4975.73
169	436749	4570037	Prin	4962.95	TURN	5/3/16 10:25	9.45	4953.50	-	-	-
170	436890	4570031	Prin	4961.27	TURN	5/3/16 9:46	10.50	4950.77	-	-	-
171	426501	4574272	ZsiC	5518.62	TURN	4/19/16 15:44	153.99	5364.63	-	-	-
172	438315	4567263	Prin	4985.27	DEM	5/2/16 14:30	18.10	4967.17	-	-	-
184	436862	4567255	PrinConf	4929.44	Trimble	5/3/16 17:36	3.00	4926.44	10/3/16 12:00	6.65	4922.79
187	428822	4576514	Prin	5087.02	TURN	4/20/16 17:45	7.31	5079.71	-	-	-
189	426360	4580170	TvC, ZsiC	5384.61	TURN	4/11/16 13:45	31.06	5353.55	9/27/16 15:30	56.99	5327.62
203	438189	4565695	Prin	4969.72	TURN	4/28/16 10:15	2.95	4966.77	9/26/16 11:35	5.43	4964.29
233	441693	4567777	Prin	5095.12	Trimble	4/28/16 13:23	20.00	5075.12	-	-	-
271	432273	4571515	PrinConf	4933.07	TURN	4/12/16 14:02	39.40	4893.67	10/14/16 12:15	42.70	4890.37
281	438539	4566589	Prin	4984.51	TURN	5/4/16 15:49	16.90	4967.61	-	-	-
282	438460	4568636	PZcaA	4976.52	Trimble	5/3/16 15:00	19.45	4957.07	-	-	-
288	436038	4570335	Prin	4958.15	TURN	5/3/16 11:30	25.90	4932.25	-	-	-
294	427717	4574565	Prin	5139.18	TURN	4/20/16 13:45	39.46	5099.72	-	-	-
311	427410	4578918	Prin	5220.72	TURN	4/11/16 15:50	32.40	5188.32	-	-	-
317	436621	4571211	Prin	5025.44	TURN	4/12/16 15:42	7.59	5017.85	-	-	-
325	435121	4570625	PrinConf	4940.38	TURN	4/27/16 13:40	26.20	4914.18	9/28/16 17:50	34.91	4905.47
334	436185	4568840	PrinConf	4930.31	TURN	4/27/16 17:15	6.50	4923.81	9/28/16 16:10	7.46	4922.85
348	439080	4568021	Prin	5011.10	Trimble	4/28/16 14:08	37.80	4973.30	9/28/16 15:40	35.04	4976.06
349	439590	4567236	Prin	5020.69	TURN	4/28/16 11:48	28.78	4991.91	-	-	-

Table D-2. *Continued.*

HydroID[1]	Easting (NAD83 m)	Northing (NAD83 m)	Aquifer[2]	Land elev. (ft)	Land elev. source[3]	Spring 2016 Date-time	Spring 2016 WL below LSD (ft)	Spring 2016 Water-level elev. (ft)	Fall 2016 Date-time	Fall 2016 WL below LSD (ft)	Fall 2016 Water-level elev. (ft)
354	438593	4568031	Prin	4990.27	TURN	5/2/16 13:06	23.72	4966.55	-	-	-
363	436942	4566541	PrinConf	4949.56	TURN	5/4/16 10:45	8.65	4940.91	-	-	-
375	439577	4564999	TcgA	5017.66	TURN	4/28/16 9:45	4.37	5013.29	-	-	-
386	427023	4578508	ZsiC	5207.46	TURN	4/11/16 16:32	16.78	5190.68	9/27/16 16:00	28.77	5178.69
394	427050	4577592	Prin	5174.06	TURN	4/18/16 11:11	44.27	5129.79	-	-	-
413	433985	4572433	PrinConf	4944.21	TURN	5/5/16 17:15	9.40	4934.81	9/26/16 10:43	12.71	4931.50
418	427391	4576399	Prin	5114.38	TURN	4/20/16 17:11	39.84	5074.54	-	-	-
423	434913	4571563	PrinConf	4936.60	TURN	4/12/16 14:54	3.93	4932.67	-	-	-
424	434056	4571575	PrinConf	4918.46	TURN	4/27/16 12:27	17.66	4900.80	-	-	-
431	435315	4568830	PrinConf	4940.19	TURN	5/2/16 11:30	34.12	4906.07	-	-	-
433	426289	4576470	ZsiC	5224.45	TURN	4/21/16 10:50	0.77	5223.68	-	-	-
435	430100	4571799	ZsiC	5232.85	TURN	4/19/16 17:22	34.60	5198.25	-	-	-
439	437809	4567975	PrinConf	4962.15	Trimble	5/3/16 13:25	11.04	4951.11	-	-	-
440	425385	4579923	TvC	5424.60	TURN	4/11/16 13:07	79.59	5345.01	-	-	-
443	428095	4575080	Prin	5060.30	TURN	4/20/16 15:25	6.38	5053.92	9/27/16 14:00	15.45	5044.85
452	440564	4567459	Prin	5060.97	Trimble	4/28/16 12:26	27.20	5033.77	-	-	-
454	434762	4572585	Prin	5066.45	TURN	5/5/16 18:00	6.50	5059.95	10/14/16 14:05	12.83	5053.62
474	431107	4576930	TvC, ZsiC	5561.69	TURN	4/26/16 16:14	106.19	5455.50	9/26/16 17:00	158.00	5403.69
477	429296	4574080	Prin	4996.21	TURN	4/27/16 10:30	14.74	4981.47	9/26/16 18:00	27.09	4969.12
516	435170	4569669	PrinConf	4922.90	TURN	4/27/16 15:45	16.65	4906.25	-	-	-
545	431167	4570432	Shallow	4967.76	TURN	4/12/16 9:10	42.51	4925.25	-	-	-
609	431105	4568901	Prin	4940.04	TURN	4/12/16 11:20	15.22	4924.82	-	-	-
615	427784	4574149	Prin	5204.48	TURN	4/26/16 0:00	84.95	5119.53	-	-	-
3596	431721	4575949	CZqH	5643.58	TURN	4/26/16 14:50	285.54	5358.04	-	-	-
3597	429815	4575004	Prin	5106.39	TURN	4/26/16 15:25	33.39	5073.00	9/27/16 12:00	33.03	5073.36
3598	424752	4581347	CZqH	5607.99	TURN	4/19/16 9:23	1.96	5606.03	-	-	-
3599	427061	4578632	Prin	5210.56	TURN	4/19/16 10:09	28.20	5182.36	-	-	-
3600	441861	4568195	ZsiC	5105.89	TURN	4/28/16 15:00	49.10	5056.79	-	-	-
3601	434436	4566711	PrinConf	4924.18	TURN	4/18/16 13:42	26.00	4898.18	-	-	-
3602	431365	4566090	ZsiC	5797.24	DEM	5/4/16 12:43	112.50	5684.74	-	-	-
3603	429894	4572992	PrinConf	4951.13	TURN	4/21/16 13:27	8.53	4942.60	-	-	-

Table D-2. *Continued.*

HydroID[1]	Easting (NAD83 m)	Northing (NAD83 m)	Aquifer[2]	Land elev. (ft)	Land elev. source[3]	Spring 2016 Date-time	Spring 2016 WL below LSD (ft)	Spring 2016 Water-level elev. (ft)	Fall 2016 Date-time	Fall 2016 WL below LSD (ft)	Fall 2016 Water-level elev. (ft)
USGS											
762	440126	4567027	Prin	5039.37	DEM	3/15/16 12:33	28.97	5010.40	-	-	-
763	435411	4568147	PrinConf	4918.30	DEM	3/15/16 11:47	21.40	4896.90	10/18/16 14:08	24.19	4894.11
764	430842	4572260	Prin	4947.51	DEM	3/15/16 9:25	39.13	4908.38	-	-	-
Ogden City (water levels measured while wells pumping)											
105	432120	4569175	PrinConf	4913.44	DEM	4/23/16	94.38	4819.06	9/15/16	98	4815.44
107	432265	4569254	PrinConf	4913.44	DEM	4/23/16	101.29	4812.15	9/15/16	114	4799.44
108	432289	4569397	PrinConf	4913.44	DEM	4/23/16	116.50	4796.94	9/15/16	123	4790.44
428	432016	4569203	PrinConf	4920.00	DEM	4/23/16	110.33	4809.67	9/15/16	114	4806.00
3564	432155	4569204	PrinConf	4920.00	DEM	4/23/16	79.00	4841.00	9/15/16	86	4834.00
3638	432209	4569178	PrinConf	4910.16	DEM	4/23/16	112.67	4797.49	9/15/16	135	4775.16

Abbreviations: Elev. = elevation, WL = water level, LSD = land surface datum

[1] HydroID is the unique site identifier used in this report

[2] Aquifer codes: PrinConf = principal confined valley-fill aquifer, Prin = principal unconfined valley-fill aquifer, Shallow = shallow unconfined aquifer, TcgA = Tertiary conglomerate aquifer, TvC, Tertiary volcanic confining unit (Norwood Fm), PZcaA = Paleozoic carbonate aquifer, CZqH = Cambrian and Proterozoic quartzite heterogeneous unit, ZsiC = Proterozoic siliciclastic confining unit

[3] Land elev. source: TURN = Turn GPS, Trimble = read from Trimble GPS display in field, DEM = 10 m Digital Elevation Model

Table D-3. *Stream and canal discharge measurements, grouped by river drainage and sorted from upstream to downstream.*

Hydro ID[1]	Site Name	Easting (NAD 83 m)	Northing (NAD 83 m)	Seepage run[2]	Date	Time	Discharge (cfs)	Rating (%)	Discharge error (cfs)	Conductivity (µS/cm)	Temperature (°C)	Remarks[3]
					North Fork Ogden River							
3386	North Fork abv Utaba Reservoir	423596	4582326	Misc.	8/18/15	12:20	3.0	10	0.3	-	-	
3386	North Fork abv Utaba Reservoir	423596	4582326	Misc.	9/28/15	10:20	3.0	10	0.3	137	12.2	
3387	Cutler Creek abv Utaba Reservoir	423552	4582052	Misc.	8/18/15	13:40	1.9	8	0.1	-	-	
3387	Cutler Creek abv Utaba Reservoir	423552	4582052	Misc.	9/28/15	11:26	1.6	10	0.2	167	11.7	
3381	North Fork at Camp Utaba Bridge	424157	4581836	Mar2016	3/9/16	15:45	22.9	8	1.8	83	7.0	
3381	North Fork at Camp Utaba Bridge	424157	4581836	Nov2016	11/8/16	12:00	5.5	8	0.4	146	3.3	
3385	North Fork blw Utaba Reservoir at North Fork Park Rd	424258	4581642	Misc.	9/29/15	10:02	4.7	10	0.5	152	11.1	
3367	North Fork at Lomondi Camp Entrance	424708	4580875	Mar2016	3/9/16	15:25	27.3	5	1.4	111	6.7	
3367	North Fork at Lomondi Camp Entrance	424708	4580875	Misc.	9/20/16	17:10	0.7	5	0.0	144	14.6	
3367	North Fork at Lomondi Camp Entrance	424708	4580875	Nov2016	11/8/16	9:55	6.6	5	0.3	146	5.1	
3369	Cold Canyon Creek abv N. Fork	424805	4580811	Mar2016	3/9/16	14:30	1.3	8	0.1	206	5.0	
3369	Cold Canyon Creek abv N. Fork	424805	4580811	Nov2016	11/8/16	12:15	0.11	8	0.0	256	6.3	
3368	Durfee Creek at North Fork Park Road	424828	4580847	Mar2016	3/9/16	16:00	5.5	5	0.3	86	6.1	
3368	Durfee Creek at North Fork Park Road	424828	4580847	Nov2016	11/8/16	11:15	0.05	10	0.0	110	6.5	
3394	Canal from diversion gate at N Fork Middle Gate Park	425408	4580493	Misc.	9/29/15	14:30	0.5	8	0.0	1254	16.2	
3388	North Fork at Cook's Cabin	425237	4580341	Misc.	8/18/15	16:40	5.5	8	0.4	-	-	
3388	North Fork at Cook's Cabin	425237	4580341	Misc.	9/29/15	13:15	4.8	8	0.4	-	-	
3366	North Fork blw diversion dam	425682	4579798	Mar2016	3/9/16	14:40	36.2	8	2.9	118	6.2	
3366	North Fork blw diversion dam	425682	4579798	Nov2016	11/8/16	8:20	9.3	2	0.2	153	3.6	
3376	Thimbleberry Creek	426219	4578857	Mar2016	3/8/16	16:30	7.2	5	0.4	165	5.9	
3376	Thimbleberry Creek	426219	4578857	Nov2016	11/8/16	9:07	0.14	5	0.0	208	6.0	
3604	N. Fork at old Hwy 162 north of Eden	426974	4578235	Mar2016	3/9/16	13:30	37.6	10	3.8	135	6.5	
3604	N. Fork at old Hwy 162 north of Eden	426974	4578235	Misc.	9/20/16	16:30	0	NA	0.0	-	-	
3604	N. Fork at old Hwy 162 north of Eden	426974	4578235	Nov2016	11/8/16	9:55	3.3	8	0.3	154	5.5	
3365	North Fork at Preserve Gate	428643	4576550	Mar2016	3/9/16	12:25	32.2	8	2.6	134	7.0	
3365	North Fork at Preserve Gate	428643	4576550	Nov2016	11/8/16	12:00	0	0	0.0	-	-	
3380	Sheep Creek at The Preserve entrance	428682	4576517	Mar2016	3/9/16	13:00	26.2	8	2.1	135	8.5	
3380	Sheep Creek at The Preserve entrance	428682	4576517	Misc.	3/10/16	12:15	22.1	8	1.8	137	8.7	
3380	Sheep Creek at The Preserve entrance	428682	4576517	Nov2016	11/8/16	12:00	0	0	0.0	-	-	
3364	North Fork at Farron's Bridge	429196	4574514	Mar2016	3/9/16	11:00	67.7	8	5.4	157	6.1	
3364	North Fork at Farron's Bridge	429196	4574514	Nov2016	11/8/16	11:15	1.2	8	0.1	183	9.5	
3379	Liberty Spring Creek at 3600 N old Hwy 162	427891	4574969	Mar2016	3/9/16	17:05	4.9	5	0.2	378	8.5	

Table D-3. *Continued.*

Hydro ID[1]	Site Name	Easting (NAD 83 m)	Northing (NAD 83 m)	Seepage run[2]	Date	Time	Discharge (cfs)	Rating (%)	Discharge error (cfs)	Conductivity (µS/cm)	Temperature (°C)	Remarks[3]
3379	Liberty Spring Creek at 3600 N old Hwy 162	427891	4574969	Nov2016	11/8/16	12:57	2.2	5	0.1	362	10.7	
3377	Pine Creek at south culvert under old Hwy 162	428559	4574484	Mar2016	3/9/16	18:00	1.3	5	0.1	335	4.3	
3377	Pine Creek at south culvert under old Hwy 162	428559	4574484	Nov2016	11/8/16	13:00	0	NA	0.0	-	-	
3378	Pine Creek diversion at north culvert under old Hwy 162	428536	4574500	Mar2016	3/9/16	18:30	0.85	8	0.1	465	4.8	
3378	Pine Creek diversion at north culvert under old Hwy 162	428536	4574500	Nov2016	11/8/16	13:56	0.18	8	0.0	360	10.6	
3594	Liberty Spring Ck blw conf w Pole Canyon Ck	429138	4574255	Mar2016	3/9/16	11:35	15.8	8	1.3	402	6.9	
3594	Liberty Spring Ck blw conf w Pole Canyon Ck	429138	4574255	Nov2016	11/8/16	16:30	2.7	5	0.1	393	8.6	
3639	Wolf Creek nr Wolf Creek Irrigation diversion	431214	4577325	Mar2016	3/9/16	6:00	6.0	10	0.6	-	-	By Wolf Creek Irrigation
3639	Wolf Creek nr Wolf Creek Irrigation diversion	431214	4577325	Nov2016	11/8/16	16:30	3.7	8	0.3	279	7.4	
3375	Wolf Creek in old Hwy 162 culvert	429970	4573786	Mar2016	3/9/16	10:10	7.7	20	1.5	415	4.9	
3375	Wolf Creek in old Hwy 162 culvert	429970	4573786	Nov2016	11/8/16	15:45	1.2	8	0.1	322	10.5	
3370	North Fork at Roper Ranch	430032	4573077	Mar2016	3/9/16	17:50	82.5	10	8.2	236	7.3	
3370	North Fork at Roper Ranch	430032	4573077	Nov2016	11/8/16	17:00	0	NA	0.0	-	-	
3675	Coal Hollow Creek abv conf with North Fork	429981	4573019	Misc.	11/8/16	17:40	0.02	50	0.0	286	5	
3358	North Fork at Hwy 158	430644	4571899	Mar2016	3/9/16	8:30	96.2	8	7.7	222	3.7	
3358	North Fork at Hwy 158	430644	4571899	Misc.	3/21/16	18:00	70.7	8	5.7	-	-	
3358	North Fork at Hwy 158	430644	4571899	Misc.	6/21/16	9:40	8.7	5	0.4	313	12.9	
3358	North Fork at Hwy 158	430644	4571899	Misc.	9/8/16	19:10	0.20	50	0.1	-	-	Visual estimate
3358	North Fork at Hwy 158	430644	4571899	Misc.	9/19/16	16:15	0	NA	0.0	-	-	
3358	North Fork at Hwy 158	430644	4571899	Misc.	10/7/16	15:30	0	NA	0.0	-	-	
3358	North Fork at Hwy 158	430644	4571899	Nov2016	11/8/16	17:10	0	NA	0.0	-	-	
3358	North Fork at Hwy 158	430644	4571899	Misc.	3/8/17	14:00	136.5	2	2.7	-	-	
3358	North Fork at Hwy 158	430644	4571899	Misc.	7/11/17	16:30	5.9	2	0.1	-	-	
					Sheep Creek							
3352	Cache Valley Creek at shooting range	427121	4580223	Misc.	8/31/15	14:15	0.13	10	0.0	-	-	
3352	Cache Valley Creek at shooting range	427121	4580223	Mar2016	3/10/16	13:50	0.18	8	0.0	95	8.2	
3352	Cache Valley Creek at shooting range	427121	4580223	Nov2016	11/8/16	13:30	0.03	10	0.0	166	9.0	
3372	Sheep Creek abv Jones' Ranch road	426950	4579494	Mar2016	3/10/16	14:37	4.7	10	0.5	135	9.6	
3372	Sheep Creek abv Jones' Ranch road	426950	4579494	Nov2016	11/8/16	13:05	0.01	50	0.003	171	9.1	
3373	Sheep Creek blw Jones' Ranch road	426962	4579324	Mar2016	3/10/16	15:30	5.4	8	0.4	117	8.9	
3373	Sheep Creek blw Jones' Ranch road	426962	4579324	Nov2016	11/8/16	14:10	0.10	10	0.0	195	12.7	
3371	Broadmouth Canyon Creek at Jones' Ranch	428169	4579343	Misc.	8/31/15	15:10	9.9	5	0.5	-	-	
3371	Broadmouth Canyon Creek at Jones' Ranch	428169	4579343	Mar2016	3/10/16	13:45	3.0	10	0.3	96	7.1	
3371	Broadmouth Canyon Creek at Jones' Ranch	428169	4579343	Nov2016	11/8/16	14:45	0.20	5	0.0	125	10.1	

Table D-3. Continued.

Hydro ID[1]	Site Name	Easting (NAD 83 m)	Northing (NAD 83 m)	Seepage run[2]	Date	Time	Discharge (cfs)	Rating (%)	Discharge error (cfs)	Conductivity (µS/cm)	Temperature (°C)	Remarks[3]
					Geertsen Creek							
3605	Geertsen Creek Bar B upper flume	434201	4572851	Mar2016	3/7/16	18:00	3.9	10	0.4	-	-	By Cascade Water Resources
3605	Geertsen Creek Bar B upper flume	434201	4572851	Nov2016	10/30/16	9:00	0.71	10	0.1	-	-	By Cascade Water Resources
3391	channel W of Geertsen Ck abv 1900 N	433777	4571577	Misc.	8/24/15	13:10	1.81	8	0.1	-	-	
3390	Geertsen Creek abv 1900 N	433953	4571631	Misc.	8/24/15	15:00	3.52	8	0.3	-	-	
3390	Geertsen Creek abv 1900 N	433953	4571631	Nov2016	11/7/16	14:51	0.39	8	0.0	191	10.2	
3390	Geertsen Creek abv 1900 N	433953	4571631	Misc.	7/11/17	16:00	NA	NA	NA	-	-	Under water. Pineview Reservoir full.
3348	Geertsen Creek abv conf, blw 1900 N	433833	4571528	Mar2016	3/7/16	18:00	10.9	5	0.5	122	6.8	Essentially the same as location 3390
3347	Geertzen Ck blw conf, 100' abv Pineview Reservoir	433788	4571482	Misc.	3/7/16	17:00	14.0	5	0.7	170	7.4	
3346	Eden Cemetery Stream at 1900 N	433271	4571599	Misc.	3/7/16	16:00	2.2	5	0.1	450	10.0	
					Middle Fork Ogden River							
3353	Upper Middle Fork at USGS Flume	438236	4572222	Misc.	8/25/15	11:00	0.27	10	0.0	-	-	
3353	Upper Middle Fork at USGS Flume	438236	4572222	Mar2016	3/7/16	11:20	40.5	5	2.0	111	3.6	
3353	Upper Middle Fork at USGS Flume	438236	4572222	Misc.	9/20/16	15:03	0.85	8	0.1	257	18.1	
3353	Upper Middle Fork at USGS Flume	438236	4572222	Nov2016	11/7/16	11:10	4.0	10	0.4	288	4.9	
3350	Little Bench Ditch to Jensen Ranch from MF at OVC	436946	4571401	Mar2016	3/10/16	13:50	3.7	5	0.2	109	6.4	
3350	Little Bench Ditch to Jensen Ranch from MF at OVC	436946	4571401	Nov2016	11/7/16	13:15	0.21	2	0.0	239	9.6	
3349	Middle Fork Irrigation flume	436651	4571828	Mar2016	3/7/16	13:10	0.68	5	0.0	158	8.3	
3349	Middle Fork Irrigation flume	436651	4571828	Nov2016	11/7/16	14:20	2.5	2	0.0	279	7.5	
3354	Middle Fork at Ogden Valley Canal	436858	4571518	Mar2016	3/7/16	17:15	42.6	8	3.4	110	6.0	
3354	Middle Fork at Ogden Valley Canal	436858	4571518	Nov2016	11/7/16	12:57	0.11	50	0.1	261	9.9	
3357	Dry Hollow Creek	434910	4570111	Misc.	8/24/15	15:02	2.5	10	0.3	-	-	
3357	Dry Hollow Creek	434910	4570111	Mar2016	3/7/16	18:20	3.2	5	0.2	212	6.4	
3357	Dry Hollow Creek	434910	4570111	Nov2016	11/7/16	16:10	0.29	5	0.0	309	10.2	
3357	Dry Hollow Creek	434910	4570111	Misc.	7/11/17	14:30	NA	NA	NA	-	-	Under water. Pineview Reservoir full.
3355	Garden of Eden Channel at 7100 E	434932	4571190	Mar2016	3/7/16	15:40	0.56	8	0.0	228	10.8	
3355	Garden of Eden Channel at 7100 E	434932	4571190	Nov2016	11/7/16	15:44	0.23	5	0.0	285	12.3	

Table D-3. Continued.

Hydro ID[1]	Site Name	Easting (NAD 83 m)	Northing (NAD 83 m)	Seepage run[2]	Date	Time	Discharge (cfs)	Rating (%)	Discharge error (cfs)	Conductivity (µS/cm)	Temperature (°C)	Remarks[3]
3356	Middle Fork at 7100 E	434928	4570985	Misc.	9/19/15	14:45	0.14	10	0.0	-	-	
3356	Middle Fork at 7100 E	434928	4570985	Mar2016	3/7/16	16:15	40.1	5	2.0	114	6.8	
3356	Middle Fork at 7100 E	434928	4570985	Misc.	3/21/16	17:00	26.5	0.08	0.0	-	-	
3356	Middle Fork at 7100 E	434928	4570985	Misc.	6/21/16	10:45	1.7	10	0.2	184	13.4	
3356	Middle Fork at 7100 E	434928	4570985	Misc.	9/8/16	17:00	0.40	50	0.2	-	-	Visual estimate
3356	Middle Fork at 7100 E	434928	4570985	Nov2016	11/7/16	15:05	0.45	8	0.0	253	9.9	
3356	Middle Fork at 7100 E	434928	4570985	Misc.	3/8/17	13:05	47.9	5	2.4	-	-	
3356	Middle Fork at 7100 E	434928	4570985	Misc.	7/11/17	15:00	1.5	50	0.8	-	-	Visual estimate
					Spring Creek							
3363	Kelly Canyon at Maple Drive	438735	4568984	Mar2016	3/8/16	18:00	0.82	8	0.1	314	4.2	
3363	Kelly Canyon at Maple Drive	438735	4568984	Nov2016	11/7/16	16:30	0	NA	0.0	-	-	
3362	Maple Canyon Creek	438718	4569671	Mar2016	3/8/16	17:30	2.2	10	0.2	152	9.7	
3362	Maple Canyon Creek	438718	4569671	Nov2016	11/7/16	16:55	0.01	5	0.0003	518	8.9	
3404	Northern 7800 E Canal	436195	4569387	Oct2015	10/1/15	16:20	1.3	8	0.1	468	20.5	
3403	7800 E Canal	436204	4568984	Oct2015	10/1/15	16:00	2.4	8	0.2	500	18.4	
3361	Kelly and Maple Creek before Spring Creek	436218	4568381	Mar2016	3/8/16	15:05	8.0	8	0.6	542	10.9	
3361	Kelly and Maple Creek before Spring Creek	436218	4568381	Nov2016	11/7/16	18:30	0.53	5	0.0	673	8.6	
3398	Pond overflow at house	436840	4567252	Oct2015	9/30/15	12:30	0.04	8	0.003	508	16	
3397	Spring Creek pond overflow	436617	4567438	Oct2015	9/30/15	11:35	0.11	10	0.0	472	14.1	
3399	Piped spring in NE corner of field	436957	4567933	Oct2015	9/30/15	13:04	0.13	8	0.0	538	13.7	
3395	Spring Creek at sheep pasture flume	436816	4568006	Oct2015	9/30/15	9:30	0.75	8	0.1	540	12.3	
3396	Spring Creek spring at driveway	436724	4567946	Oct2015	9/30/15	10:10	0.19	8	0.0	557	13.8	
3646	Creek from Cardon Ranch at driveway	436623	4568272	Misc.	9/21/16	12:45	0.84	5	0.0	-	-	
3405	Cardon Pond overflow	436562	4568297	Oct2015	10/1/15	17:00	0.31	10	0.0	552	15.3	
3400	Creek from Cardon Ranch at 7800 E	436197	4568319	Oct2015	9/30/15	14:45	2.7	8	0.2	515	16.4	
3374	Spring Creek at USGS flume	435818	4568433	Oct2015	10/1/15	14:00	4.7	5	0.2	527	16.6	
3374	Spring Creek at USGS flume	435818	4568433	Mar2016	3/8/16	16:20	12.1	5	0.6	515	10.4	
3374	Spring Creek at USGS flume	435818	4568433	Misc.	3/10/16	18:00	8.7	5	0.4	600	11	
3374	Spring Creek at USGS flume	435818	4568433	Misc.	3/21/16	16:00	5.6	5	0.3	-	-	
3374	Spring Creek at USGS flume	435818	4568433	Misc.	4/22/16	14:00	5.7	5	0.3	-	-	
3374	Spring Creek at USGS flume	435818	4568433	Misc.	6/21/16	12:25	3.6	5	0.2	520	17.5	
3374	Spring Creek at USGS flume	435818	4568433	Misc.	9/8/16	15:30	6.6	5	0.3	-	-	
3374	Spring Creek at USGS flume	435818	4568433	Nov2016	11/7/16	17:45	3.9	5	0.2	582	10.7	
3374	Spring Creek at USGS flume	435818	4568433	Misc.	3/8/17	12:00	10.0	2	0.2	-	-	
3374	Spring Creek at USGS flume	435818	4568433	Misc.	7/11/17	13:20	5.1	8	0.4	-	-	

Table D-3. Continued.

Hydro ID[1]	Site Name	Easting (NAD 83 m)	Northing (NAD 83 m)	Seepage run[2]	Date	Time	Discharge (cfs)	Rating (%)	Discharge error (cfs)	Conductivity (µS/cm)	Temperature (°C)	Remarks[3]
3402	Spring Creek upgradient of north flowing spring tributary	435533	4568486	Oct2015	10/1/15	11:00	4.7	8	0.4	535	13.8	
3401	Spring Creek before Pineview Reservoir	435092	4568460	Oct2015	10/1/15	10:00	4.9	5	0.2	547	12.9	
					South Fork Ogden River							
734	South Fork Ogden River USGS Gage nr Huntsville	443543	4568782	Mar2016	3/8/16	11:00	87.0	-	-	-	-	By USGS
734	South Fork Ogden River USGS Gage nr Huntsville	443543	4568782	Nov2016	11/9/16	7:36	25.0	-	-	391	4.6	By USGS
3360	South Fork at Ogden Valley Canal Diversion	441572	4567757	Mar2016	3/8/16	13:45	83.0	8	6.6	290	6.7	
3360	South Fork at Odgen Valley Canal Diversion	441572	4567757	Nov2016	11/9/16	9:00	24.3	5	1.2	414	4.7	
3344	North Branch South Fork at 9500 E	439607	4567027	Mar2016	3/8/16	11:45	43.1	8	3.4	296	4.8	
3344	North Branch South Fork at 9500 E	439607	4567027	Nov2016	11/9/16	10:11	10.7	8	0.9	405	6.1	
3343	South Branch South Fork at 9500 E	439608	4566913	Mar2016	3/8/16	12:20	34.9	10	3.5	273	4.9	
3343	South Branch South Fork at 9500 E	439608	4566913	Nov2016	11/9/16	11:20	6.4	8	0.5	401	6.9	
3359	North Branch South Fork at 8600 E	437854	4566983	Mar2016	3/8/16	10:15	36.6	8	2.9	301	3.2	
3359	North Branch South Fork at 8600 E	437854	4566983	Nov2016	11/9/16	12:10	0.00	NA	0.0	-	-	
3342	South Branch South Fork at 8800 E bridge	438314	4566188	Mar2016	3/8/16	10:50	32.4	8	2.6	277	3.7	
3342	South Branch South Fork at 8800 E bridge	438314	4566188	Nov2016	11/9/16	12:23	0.0	NA	0.0	-	-	
3337	North Branch South Fork at Hwy 39	436184	4566669	Misc.	8/20/15	15:25	5.5	10	0.5	-	-	
3337	North Branch South Fork at Hwy 39	436184	4566669	Misc.	9/8/15	14:20	6.5	10	0.6	-	-	
3337	North Branch South Fork at Hwy 39	436184	4566669	Mar2016	3/8/16	8:15	53.6	8	4.3	337	2.0	
3337	North Branch South Fork at Hwy 39	436184	4566669	Misc.	3/21/16	13:55	41.9	8	3.4	-	-	
3337	North Branch South Fork at Hwy 39	436184	4566669	Misc.	6/21/16	13:15	22.0	8	1.8	329	16.7	
3337	North Branch South Fork at Hwy 39	436184	4566669	Misc.	9/8/16	12:15	3.6	5	0.2	-	-	
3337	North Branch South Fork at Hwy 39	436184	4566669	Nov2016	11/9/16	10:15	3.5	5	0.2	425	8.5	
3337	North Branch South Fork at Hwy 39	436184	4566669	Misc.	3/8/17	11:15	99.2	2	2.0	-	-	
3337	North Branch South Fork at Hwy 39	436184	4566669	Misc.	7/11/17	17:40	19.7	5	1.0	-	-	
3351	Bally Watts Creek at Falcon Way	438798	4563947	Mar2016	3/10/16	10:45	3.3	8	0.3	298	2.7	
3733	Bally Watts Creek at 1800 S	438625	4565109	Nov2016	11/9/16	15:45	0	NA	0.0	-	-	
3341	Monastary Canal abv Huntsville Ditch	440699	4565633	Mar2016	3/10/16	11:40	0.79	5	0.0	262	9.8	
3341	Monastary Canal abv Huntsville Ditch	440699	4565633	Nov2016	11/9/16	12:35	0	NA	0.0	-	-	
3340	Bennett Creek at Huntsville water plant	439529	4565110	Mar2016	3/10/16	9:55	18.2	8	1.5	159	5.3	
3340	Bennett Creek at Huntsville water plant	439529	4565110	Nov2016	11/9/16	13:02	0.15	5	0.0	420	5.7	
3339	Huntsville South Bench Canal at 8900 E	438410	4565787	Mar2016	3/10/16	9:00	21.6	5	1.1	249	4.9	
3339	Huntsville South Bench Canal at 8900 E	438410	4565787	Nov2016	11/9/16	13:40	0.33	8	0.0	496	9.6	

Table D-3. *Continued.*

Hydro ID[1]	Site Name	Easting (NAD 83 m)	Northing (NAD 83 m)	Seepage run[2]	Date	Time	Discharge (cfs)	Rating (%)	Discharge error (cfs)	Conductivity (µS/cm)	Temperature (°C)	Remarks[3]
3345	Bally Watts Creek abv conf with South Branch SF	437772	4565848	Mar2016	3/8/16	14:20	28.6	10	2.9	229	8.9	
3345	Bally Watts Creek abv conf with South Branch SF	437772	4565848	Nov2016	11/9/16	14:00	1.5	8	0.1	456	9.7	
3338	South Branch South Fork at Hwy 39	435916	4566377	Misc.	8/20/15	11:36	6.8	10	0.7	-	-	
3338	South Branch South Fork at Hwy 39	435916	4566377	Misc.	9/8/15	11:10	6.2	10	0.6	-	-	
3338	South Branch South Fork at Hwy 39	435916	4566377	Mar2016	3/8/16	8:45	66.4	5	3.3	297	2.6	
3338	South Branch South Fork at Hwy 39	435916	4566377	Misc.	3/21/16	13:30	56.9	10	5.7	-	-	
3338	South Branch South Fork at Hwy 39	435916	4566377	Misc.	6/21/16	14:30	26.0	8	2.1	381	16.5	
3338	South Branch South Fork at Hwy 39	435916	4566377	Misc.	9/8/16	11:10	5.7	5	0.3	-	-	
3338	South Branch South Fork at Hwy 39	435916	4566377	Nov2016	11/9/16	11:50	6.8	2	0.1	479	8.8	
3338	South Branch South Fork at Hwy 39	435916	4566377	Misc.	3/8/17	10:15	131.9	2	2.6	-	-	
3338	South Branch South Fork at Hwy 39	435916	4566377	Misc.	7/11/17	10:30	21.4	2	0.4	-	-	
					Ogden Valley Canal							
3676	Feeder Canal, Parshall flume blw SF Diversion Dam	441512	4567732	Jul2016	7/19/16	-	65.0	-	-	-	-	Transducer. By WBWCD sta. 3+40
3677	Triple diversion, Head of Ogden Valley Canal	441281	4567739	Jul2016	7/19/16	-	38.0	-	-	-	-	By WBWCD sta. 10+42
3719	OVC01	441088	4567980	Jul2016	7/19/16	9:30	33.7	8	2.7	-	-	
3679	Turn out 1	440626	4568178	Jul2016	7/19/16	10:00	0	NA	0.0	-	-	
3680	Turn out 2	440431	4568200	Jul2016	7/19/16	10:10	0	NA	0.0	-	-	
3681	Turn out 3	440216	4568133	Jul2016	7/19/16	10:20	0	NA	0.0	-	-	
3720	OVC02	440210	4568133	Jul2016	7/19/16	11:10	32.7	10	3.3	-	-	
3682	Turn out 4	439930	4568241	Jul2016	7/19/16	11:30	0	NA	0.0	-	-	
3683	Turn out 5	439393	4568232	Jul2016	7/19/16	11:40	0	NA	0.0	-	-	
3721	OVC03	439383	4568253	Jul2016	7/19/16	11:50	33.5	10	3.3	-	-	
3684	Turn out 6	439220	4568436	Jul2016	7/19/16	12:15	0	NA	0.0	-	-	
3685	Turn out 7	438941	4568609	Jul2016	7/19/16	12:25	0	NA	0.0	-	-	
3686	Turn out 8	438722	4568789	Jul2016	7/19/16	12:35	0	NA	0.0	-	-	
3687	Turn out 9	438445	4569011	Jul2016	7/19/16	12:45	0	NA	0.0	-	-	
3723	OVC05	438456	4569018	Jul2016	7/19/16	13:30	31.5	10	3.1	-	-	
3688	Turn out 10	438115	4569208	Jul2016	7/19/16	14:00	0	NA	0.0	-	-	
3689	Turn out 11	437816	4569623	Jul2016	7/19/16	14:10	0	NA	0.0	-	-	
3724	OVC06	437828	4569624	Jul2016	7/19/16	14:33	31.0	10	3.1	-	-	
3690	Turn out 12	437730	4569751	Jul2016	7/19/16	14:50	0	NA	0.0	-	-	
3691	Turn out 13	437605	4569884	Jul2016	7/19/16	15:00	0	NA	0.0	-	-	
3692	Turn out 14	437424	4570056	Jul2016	7/19/16	15:10	0	NA	0.0	-	-	
3693	Turn out 15	437280	4570250	Jul2016	7/19/16	15:15	0.00	NA	0.0	-	-	

Table D-3. *Continued.*

Hydro ID[1]	Site Name	Easting (NAD 83 m)	Northing (NAD 83 m)	Seepage run[2]	Date	Time	Discharge (cfs)	Rating (%)	Discharge error (cfs)	Conductivity (µS/cm)	Temperature (°C)	Remarks[3]
3725	OVC07	437278	4570250	Jul2016	7/19/16	15:17	24.4	10	2.4	-	-	
3694	Turn out 16	437155	4570416	Jul2016	7/19/16	16:00	0	NA	0.0	-	-	
3695	Turn out 17	437121	4570769	Jul2016	7/19/16	16:30	0	NA	0.0	-	-	
3726	OVC08	436880	4571098	Jul2016	7/19/16	17:12	21.1	10	2.1	-	-	
3696	Turn out 18	436848	4571133	Jul2016	7/19/16	16:29	2.3	5	0.1	-	-	
3697	Turn out 19 (big turn out)	436845	4571156	Jul2016	7/19/16	17:00	0	NA	0.0	-	-	
3698	4' Parshall flume nr Jensen's Pond, transducer	436851	4571190	Jul2016	7/19/16	17:00	18.6	20	3.7	-	-	By WBWCD. May be falsely high due to submergence, sta. 224+00
3699	Turn out	436912	4571444	Jul2016	7/19/16	17:00	0	NA	0.0	-	-	
3700	Turn out and siphon	436855	4571497	Jul2016	7/19/16	17:00	0	NA	0.0	-	-	
3349	Middle Fork Irrigation flume	436651	4571828	Jul2016	7/19/16	15:39	0.65	10	0.1	-	-	By Cascade Water Resources
3678	OVC09B Turn out	436541	4571803	Jul2016	7/19/16	15:10	1.1	8	0.1	-	-	
3701	OVC09C Turn out for Middle Fork Irrigation Co	436538	4571778	Jul2016	7/19/16	15:10	4.0	8	0.3	-	-	WBWCD reports 4 cfs, sta. 253+40
3727	OVC09 4' Rectangular weir blw Middle Fork crossing	436538	4571778	Jul2016	7/19/16	15:10	12.7	8	1.0	284	18.4	WBWCD reports 13.02 cfs, sta. 253+69
3702	Turn out	435223	4572268	Jul2016	7/19/16	-	0	NA	0.0	-	-	
3728	OVC10	435180	4572280	Jul2016	7/19/16	14:12	12.4	8	1.0	295	18.3	
3731	Turn out to Browning Ranch OVC10.25B	434642	4572476	Jul2016	7/19/16	13:43	4.0	10	0.4	-	-	By WBWCD, sta. 327+00
3703	OVC10.25 weir	434646	4572486	Jul2016	7/19/16	13:43	12.2	8	1.0	300	18.5	
3704	OVC10.5 culvert	434046	4572811	Jul2016	7/19/16	12:30	12.8	8	1.0	-	-	
3705	OVC11	433592	4573075	Jul2016	7/19/16	12:17	11.5	8	0.9	309	17.8	
3707	Turn out and weir	432717	4573345	Jul2016	7/19/16	12:00	0.0	NA	0.0	-	-	
3729	OVC12	432693	4573344	Jul2016	7/19/16	11:33	10.3	5	0.5	308	18.1	
3708	Turn out	432282	4573365	Jul2016	7/19/16	11:15	0	NA	0.0	-	-	
3709	Turn out and weir to Cobabe Ranch	432169	4573178	Jul2016	7/19/16	-	3.0	10	0.3	-	-	By WBWCD, sta. 406+60
3730	OVC13	432171	4573181	Jul2016	7/19/16	11:01	7.9	5	0.4	311	17.6	
3711	OVC13.5 daylights, culvert (2 turn outs, weir)	431713	4573483	Jul2016	7/19/16	10:31	7.7	8	0.6	-	-	

Table D-3. Continued.

Hydro ID[1]	Site Name	Easting (NAD 83 m)	Northing (NAD 83 m)	Seepage run[2]	Date	Time	Discharge (cfs)	Rating (%)	Discharge error (cfs)	Conductivity (µS/cm)	Temperature (°C)	Remarks[3]
3732	Turn out to Fuller leased property	431676	4573484	Jul2016	7/19/16	10:31	0.50	15	0.1	-	-	WBWCD reports 0.5 cfs, sta. 450+98
3712	OVC13.75 Eden Irrigation Co, transducer	431612	4573497	Jul2016	7/19/16	9:58	7.7	10	0.8	309	16.6	WBWCD reports 8 cfs, sta. 452+00
3713	Turn out	431353	4573501	Jul2016	7/19/16	9:45	0	NA	0.0	-	-	
3674	OCV14	431282	4573384	Jul2016	7/19/16	9:21	6.2	8	0.5	306	16.0	

Abbreviations: abv = above, blw = below, conf = confluence, MF = Middle Fork of the Ogden River, SF = South Fork of the Ogden River, OVC = Ogden Valley Canal

Notes:
[1] HydroID is the unique site identifier used in this report
[2] Seepage run: Denotes whether the measurement was used to calculate seepage in the March 2016 seepage run (Mar2016), the July seepage run of the Ogden Valley Canal (Jul2016), the November 2016 seepage run (Nov2016), or is a miscellaneous measurement (Misc.)
[3] Sources of measurements other than UGS: Cascade Water Resources (consultant for Wolf Creek Irrigation Co.), USGS (real-time data from gauging station), Weber Basin Water Conservancy District (WBWCD) at their station (sta.) locations, Wolf Creek Irrigation Co.

Table D-4a. *Stream gain and loss by reach, grouped by river drainage and sorted from upstream to downstream.*

Reach ID	Name	March 2016 Seepage Run: Gain/ loss (cfs)[1]	Cumulative measurement error (cfs)	% of flow gained/lost[2]	Reach status	November 2016 Seepage Run: Gain/ loss (cfs)	Cumulative measurement error (cfs)	% of flow gained/ lost[2]	Reach status
North Fork Ogden River									
3624	Sheep Ck. and Broadmouth Canyon to Sheep Ck. at Preserve	9.1	3.0	70	gaining	-0.3	0.0	-100	losing
3617	North Fork Camp Utaba to Lomondi Camp	4.4	3.2	19	gaining	1.1	0.8	20	gaining
3618	North Fork Lomondi Camp to below diversion dam	2.2	4.6	6	within error (gaining)	2.5	0.5	36	gaining
3619	North Fork below diversion dam to old Hwy 162 north of Eden	-5.8	6.7	-13	within error (losing)	-6.1	0.5	-65	losing
3620	North Fork at old Hwy 162 north of Eden to Preserve gate	-5.4	6.3	-14	within error (losing)	-3.3	0.3	-100	losing
3621	North Fork Preserve Gate to Farron's bridge	9.3	10.1	16	within error (gaining)	1.2	0.1	100	gaining
3625	Liberty Spring Creek 3600 N to below conf. with Pole Canyon	8.7	1.6	122	gaining	0.3	0.3	11	within error (gaining)
3640	Wolf Creek from Wolf Creek Irrigation diversion to old Hwy 162	1.7	2.1	28	within error (gaining)	-2.5	0.4	-67	losing
3622	North Fork Farron's bridge to Roper Ranch	-8.6	16.5	-5	within error (losing)	-5.1	0.3	-132	losing
3623	North Fork Roper Ranch to Hwy 158	13.7	15.9	17	within error (gaining)	0.0	0.0	NA	dry
	Net gain or loss for drainage area [2]	**29.1**		**30**		**-12.2**		**-100**	
Middle Fork Ogden River, Geertzen Creek, Spring Creek									
3630	Geertsen Creek Bar B flume to 1900 N	7.0	0.9	178	gaining	-0.3	0.1	-45	losing
3626	Upper Middle Fork at USGS flume to Ogden Valley Canal	6.5	5.6	16	gaining	-1.2	0.5	-30	losing
3627	Dry Hollow Ck., lower MF, & "Garden of Eden" to Pineview Res.	1.2	5.6	3	within error (gaining)	0.9	0.1	769	gaining
3628	Kelly and Maple canyons mouths to conf. with Spring Creek	5.0	0.9	166	gaining	0.5	0.0	100	gaining
3629	Spring Creek to old USGS station	4.1	1.2	51	gaining	3.4	0.2	643	gaining
	Net gain or loss for drainage area [2]	**23.7**				**3.2**			
South Fork Ogden River									
3606	South Fork USGS station to OVC diversion	-4.0	6.6	-5	within error (losing)	-0.7	1.2	-3	within error (losing)
3607	OVC diversion to 9500 E	-5.0	13.6	-6	within error (losing)	-7.2	2.6	-30	losing
3608	NBSF 9500 E to 8600 E	-6.5	6.4	-15	losing	-10.7	0.9	-100	losing
3610	SBSF 9500 E to 8800 E	-2.4	6.1	-7	within error (losing)	-6.4	0.5	-100	losing
3612	Bennett Creek & Monastery Canal to HSBC at 8900 E	2.6	2.6	14	gaining	0.2	0.0	120	gaining
3616	Bally Watts & HSBC to SBSF	3.7	4.2	15	within error (gaining)	1.1	0.1	345	gaining
3615	SBSF 8800 E & Bally Watts to SBSF at Hwy 39	5.4	8.8	9	within error (gaining)	5.3	0.3	359	gaining
3609	NBSF 8600 E to Hwy 39	17.0	7.2	46	gaining	3.5	0.2	100	gaining
	Net gain or loss for drainage area[3]	**10.7**		**9**		**-14.9**		**-146**	
	Net gain or loss for all measured streams	**63.5**		**22**		**-23.9**		**-154**	

Abbreviations:

OVC	Ogden Valley Canal
MF	Middle Fork Ogden River
MFI	Middle Fork Irrigation Co.
NBSF	North Branch South Fork Ogden River
SBSF	South Branch South Fork Ogden River
Hwy	Highway
HSBC	Huntsville South Bench Canal
conf.	confluence

Notes:
[1] Values are not adjusted for loss to evaporation. Volume lost to evaporation between segment measurements is negligible
[2] % of flow gained/lost is the gain or loss of a reach divided by the discharge at the upstream end of that reach
[3] % net gain or loss is the sum of gains and losses of a drainage divided by the discharge of that drainage at our measurement location most proximal to Pineview Reservoir

Table D-4b. *Ogden Valley Canal July 19, 2016 seepage run gain and loss by reach, sorted from upstream to downstream.*

Reach ID	Name	Gain/loss (cfs)[1]	Cumulative measurement error (cfs)	% of flow gained/ lost[2]	Reach status
4000	triple diversion to OVC1	-4.3	2.7	-11	losing
4001	OVC1 to OVC2	-1.0	6.0	-3	within error (losing)
4002	OVC2 to OVC3	0.7	6.6	2	within error (gaining)
4003	OVC3 to OVC5	-2.0	6.5	-6	within error (losing)
4004	OVC5 to OVC6	-0.5	6.2	-2	within error (losing)
4005	OVC6 to OVC7	-6.6	5.5	-21	losing
4007	OVC7 to OVC8	-3.3	4.6	-14	within error (losing)
4009	OVC 8 to OVC nr. Jensens Pond minus take	-0.2	5.9	-1	within error (losing)
4011	Jensens Pond to MFI flume minus MFI take	-2.0	5.1	-10	within error (losing)
4012	MFI flume to OVC10	-0.3	2.0	-2	within error (losing)
4013	OVC10 to OVC 10.25 minus Browning take	3.8	2.4	30	gaining
4014	OVC10.25 to OVC 10.5	0.6	2.0	5	within error (gaining)
4015	OVC 10.5 to OVC11	-1.3	1.9	-10	within error (losing)
4016	OVC11 to OVC 12	-1.2	1.4	-10	within error (losing)
4017	OVC12 to OVC 13 minus Cobabe take	0.6	1.2	5	within error (gaining)
4018	OVC13 to OVC 13.5	-0.2	1.0	-2	within error (losing)
4019	OVC13.5 to OVC 13.75 minus Fuller take	0.5	1.5	6	within error (gaining)
4020	OVC13.75 to OVC 14	-1.5	1.3	-19	losing
	Net loss from canal on July 19, 2016[3]	**-18.0**		**-47**	**overall losing**

Abbreviations:
OVC Ogden Valley Canal
MFI Middle Fork Irrigation Co.

Notes:
[1] Values are not adjusted for loss to evaporation. Volume lost to evaporation between segment measurements is negligible
[2] % of flow gained/lost is the gain or loss of a reach divided by the discharge at the upstream end of that reach
[3] % net loss is the sum of gains, losses, and diversions divided by the discharge at the start of the canal

Table D-5. *Inorganic chemistry of samples from wells, springs, and surface-water in the Ogden Valley study area.*

Hydro ID[1]	Sample date	Aquifer[2]	pH[3]	Temp (°C)[3]	Cond. (µS/cm)[3]	TDS	Water type	Na^+ (mg/L)	K^+ (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Cl^- (mg/L)	HCO_3^- (mg/L)	SO_4^{2-} (mg/L)	NO_3 + NO_2 as N (mg/L)	NH_4^+ as N (mg/L)	PO_4^{3-} (mg/L)	Charge balance (%)
WL-58	09/22/2016	KTcgA	7.77	12.0	315	189	Ca-HCO_3	4.1	1.3	47.6	16.7	<3.5	210	<20	0.19	-	<0.003	0.0
WL-83	05/18/2016	TvC	7.24	10.9	1760	1366	Ca-Cl	100.0	<1.0	230.0	22.9	402.0	312	<20	1.15	<0.02	0.022	2.5
WL-108	05/23/2016	PrinConf	7.07	10.1	297	194	Ca-HCO_3	18.3	1.2	38.1	9.8	33.7	136	12[a]	1.43	-	-	1.5
WL-120	05/24/2016	Prin	-	10.2	372	-	-	-	-	-	-	-	-	-	3.36	-	-	-
WL-123	09/22/2016	KTcgA	7.50	9.6	304	186	Ca-HCO_3	5.9	<1.0	57.1	7.6	9.3	200	<20	0.50	-	0.008	-2.6
WL-129	07/13/2016	PrinConf	6.90	11.7	407	230	Ca-Na-HCO_3	22.7	1.9	38.3	11.1	48.7	132	<20	3.28	<0.05	0.012	-1.2
WL-141	05/25/2016	TvC	8.78	12.0	800	616	Na-HCO_3	199.0	8.7	34.7	14.7	126.0	421	42	0.64	0.03[a]	0.031	2.1
WL-156	05/17/2016	Prin	7.64	12.0	559	248	Ca-HCO_3	17.5	1.9	72.3	18.4	34.8	270	10[a]	2.17	<0.02	0.047	2.7
WL-158	05/25/2016	ZsiC	8.21	8.9	220	128	Ca-HCO_3	10.2	1.0	26.9	10.4	7.4	127	11[a]	0.06	-	-	2.9
WL-159	05/17/2016	Prin	7.77	10.5	890	436	Na-Cl	98.9	2.1	56.1	18.4	170.0	192	39	0.66	<0.02	0.072	-0.5
WL-170	05/23/2016	Prin	7.12	10.4	1185	798	Na-Cl	224.0	5.3	63.1	17.6	334.0	320	13[a]	1.13	-	-	-1.6
WL-172	05/24/2016	Prin	7.72	8.5	413	198	Ca-HCO_3	7.6	<1.0	53.1	14.3	13.3	214	9[a]	0.32	<0.02	0.007	1.4
WL-184	05/17/2016	PrinConf	7.77	9.8	400	190	Ca-HCO_3	9.0	1.0	56.9	14.8	13.2	222	9[a]	0.32	<0.02	0.009	3.2
WL-187	05/23/2016	Prin	7.20	10.4	362	194	Ca-HCO_3	11.3	1.0	55.8	6.3	24.1	161	<4	0.38	<0.02	0.052	5.7
WL-189	05/24/2016	TvC, ZsiC	8.28	16.2	297	182	Na-HCO_3	46.0	3.6	14.2	10.6	2.1	176	31	0.01	-	-	1.1
WL-226	05/17/2016	Prin	7.69	12.7	728	366	Ca-HCO_3	35.8	1.3	78.8	22.1	95.6	250	14[a]	1.96	<0.02	0.029	1.8
WL-233	05/17/2016	Prin	7.15	9.2	266	130	Ca-HCO_3	9.8	<1.0	35.0	9.1	11.1	134	8[a]	0.20	<0.02	0.091	4.8
WL-282	06/01/2016	PZcaA	7.97	12.4	516	282	Ca-Na-HCO_3	48.3	<1.0	39.8	12.0	60.2	176	12[a]	0.35	-	-	2.7
WL-285	05/24/2016	PrinConf	7.20	12.2	354	226	Ca-Na-HCO_3	27.1	1.4	38.4	9.9	36.3	144	16[a]	2.70	-	-	3.0
WL-288	05/25/2016	Prin	10.10	7.4	195	094	Ca-HCO_3	5.4	1.4	23.4	5.8	8.2	89	8[a]	0.75	0.02[a]	0.307	1.6
WL-311	05/18/2016	Prin	7.35	10.6	184	088	Ca-Na-HCO_3	11.9	<1.0	18.0	6.3	10.4	81	11[a]	0.70	<0.02	0.023	3.0
WL-315	05/25/2016	Prin	7.22	10.0	422	218	Ca-Na-HCO_3	44.6	1.2	31.4	8.7	62.0	128	8[a]	0.75	<0.02	0.027	2.9
WL-317	05/24/2016	Prin	7.26	8.9	190	094	Ca-HCO_3	5.2	2.3	24.5	4.4	5.3	95	15[a]	0.21	<0.02	0.052	-3.9
WL-325	05/23/2016	PrinConf	7.39	11.4	254	116	Ca-HCO_3	5.6	<1.0	37.8	7.6	10.9	123	9[a]	0.07	<0.02	0.012	4.9
WL-348	05/17/2016	Prin	7.65	12.3	524	274	Ca-HCO_3	11.5	<1.0	75.7	17.2	13.0	288	16[a]	2.85	<0.02	0.036	2.7
WL-349	05/17/2016	Prin	7.86	10.0	401	192	Ca-HCO_3	9.4	<1.0	54.5	15.0	16.3	216	8[a]	0.53	<0.02	0.010	2.6
WL-363	05/17/2016	PrinConf	7.94	8.6	376	164	Ca-HCO_3	7.7	<1.0	49.4	13.9	11.7	208	4[a]	0.27	-	-	1.9
WL-375	05/25/2016	TcgA	8.21	10.0	860	486	Na-HCO_3	162.0	1.6	22.7	8.2	54.0	268	112	0.06[a]	<0.02	0.015	3.8
WL-386	05/23/2016	ZsiC	6.81	10.4	225	102	Ca-HCO_3	5.6	<1.0	24.1	6.8	22.5	63	16[a]	1.64	<0.02	0.016	0.8
WL-406	05/23/2016	Prin	6.99	10.7	170	088	Ca-Na-HCO_3	12.2	<1.0	12.6	5.0	9.3	65	13[a]	2.57	<0.02	0.012	-0.1
WL-413	05/24/2016	PrinConf	7.42	11.0	178	110	Ca-HCO_3	8.3	1.1	15.6	4.8	23.1	48	4[a]	0.19	<0.02	0.040	1.3
WL-418	05/18/2016	Prin	7.55	9.4	384	210	Ca-HCO_3	8.5	<1.0	59.1	7.7	22.2	155	10[a]	7.56	<0.02	0.007	8.2
WL-422	05/24/2016	PrinConf	6.84	11.3	330	152	Ca-HCO_3	14.0	2.0	31.2	8.1	24.4	121	15[a]	0.05	0.12	0.857	-1.7

Table D-5. *Continued.*

Hydro ID[1]	Sample date	Aquifer[2]	pH[3]	Temp (°C)[3]	Cond. (µS/cm)[3]	TDS	Water type	Na^+ (mg/L)	K^+ (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Cl^- (mg/L)	HCO_3^- (mg/L)	SO_4^{2-} (mg/L)	NO_3 + NO_2 as N (mg/L)	NH_4^+ as N (mg/L)	PO_4^{3-} (mg/L)	Charge balance (%)
WL-433	05/18/2016	ZsiC	7.89	10.7	280	146	Ca-HCO_3	13.7	<1.0	31.2	10.5	9.3	151	12[a]	0.01	<0.02	0.025	0.9
WL-440	05/23/2016	TvC	7.03	11.4	77	028	Ca-HCO_3-SO_4	2.2	<1.0	8.0	2.1	2.5	20	17[a]	0.47	<0.02	0.003	-4.1
WL-452	05/17/2016	Prin	7.95	9.8	445	218	Ca-HCO_3	13.6	1.0	58.7	15.6	21.5	228	10[a]	0.58	<0.02	0.021	3.0
WL-468	05/17/2016	Prin	7.73	10.7	663	340	Ca-Na-HCO_3	45.5	1.9	59.5	20.4	71.3	238	25	2.09	<0.02	0.023	1.8
WL-474	05/26/2016	TvC	8.15	13.4	484	362	Ca-HCO_3-SO_4	20.4	<1.0	69.4	25.6	21.9	177	122	0.01	-	-	3.4
WL-477	05/23/2016	Prin	7.41	9.7	392	198	Ca-HCO_3	13.9	<1.0	54.2	11.5	20.2	183	15[a]	1.10	<0.02	0.007	5.0
WL-520	05/25/2016	TcgA	6.87	11.7	439	258	Ca-HCO_3	15.4	2.8	56.9	17.7	39.6	210	18[a]	1.69	-	-	1.0
ST-734	09/20/2016	-	8.58	13.4	359	170	Ca-HCO_3	3.9	<1.0	47.2	16.8	6.3	210	<20	<0.10	-	0.009	-1.3
ST-3353	09/20/2016	-	8.63	18.1	257	122	Ca-HCO_3	6.9	<1.0	36.3	6.1	11.7	134	<20	<0.10	-	0.007	-5.5
ST-3367	09/21/2016	-	7.72	14.6	144	076	Ca-HCO_3	2.7	<1.0	15.2	6.3	4.5	60	<20	<0.10	-	0.013	-3.8
SP-3416	09/22/2016	KTcgA	8.17	7.0	310	194	Ca-HCO_3	18.8	2.9	44.2	5.6	30.6	150	<20	0.37	-	0.008	-2.5
SP-3438	09/21/2016	ZsiC	7.88	11.1	288	160	Ca-HCO_3	2.6	<1.0	49.3	5.2	3.6	159	<20	<0.10	-	0.061	-1.5
WL-3587	05/24/2016	TvC	7.22	23.9	152	084	Ca-Na-HCO_3	11.1	2.1	13.3	5.4	9.4	69	12[a]	0.21	-	-	-0.2
SP-3595	09/21/2016	PZcaA	7.70	12.4	446	218	Ca-HCO_3	7.5	<1.0	57.9	17.6	10.1	255	<20	0.58	-	0.023	-2.0
WL-3603	05/26/2016	PrinConf	8.02	10.2	328	200	Ca-HCO_3	13.2	<1.0	56.2	10.7	25.5	172	12[a]	1.85	-	-	6.1
RES-3636	09/22/2016	-	8.15	18.2	320	170	Ca-HCO_3	8.8	1.2	43.1	9.4	15.9	156	<20	<0.10	-	0.016	-1.3
SP-3650	09/22/2016	KTcgA	7.74	7.4	390	234	Ca-HCO_3	3.5	<1.0	58.2	22.9	5.2	277	<20	0.47	-	0.005	-1.4
SP-3652	06/29/2016	PZcaA	7.90	9.0	461	240	Ca-HCO_3	5.0	<1.0	67.1	22.6	4.8	282	16[a]	-	-	-	3.4
SP-3653	09/22/2016	KTcgA	7.44	10.5	366	228	Ca-HCO_3	3.4	<1.0	76.4	7.4	4.8	257	<20	<0.10	-	0.009	-1.8
SP-3656	09/27/2016	ZsiC	-	13.1	236	124	Ca-HCO_3	7.2	<1.0	28.6	7.1	9.9	113	<20	0.33	-	0.008	-4.1
SP-3658	09/22/2016	PZcaA	7.70	5.9	364	186	Ca-HCO_3	2.4	<1.0	47.6	15.8	<3.5	209	<20	0.37	-	0.007	-1.8
ST-3670	09/22/2016	-	8.07	12.3	436	238	Ca-HCO_3	7.0	2.6	55.8	16.4	17.7	218	<20	0.60	-	0.016	0.2
SP-3671	09/21/2016	Shallow	7.16	11.5	620	332	Ca-HCO_3	22.6	1.6	72.7	19.1	45.1	275	<20	1.76	-	0.019	0.2
SP-3672	09/21/2016	CZqH	8.74	8.0	73	060	Ca-HCO_3-SO_4	2.8	<1.0	7.1	1.7	5.2	17	<20	2.00	-	0.011	-13.3

[1] HydroID is the unique site identifier used in this report

[2] Aquifer codes: PrinConf = principal confined valley-fill aquifer, Prin = principal unconfined valley-fill aquifer, Shallow = shallow unconfined aquifer, TcgA = Tertiary conglomerate aquifer, TvC = Tertiary volcanic confining unit (Norwood Fm), KTcgA = Cretaceous and Tertiary conglomerate aquifer (including Wasatch Fm), PZcaA = Paleozoic carbonate aquifer, CZqH = Cambrian and Proterozoic quartzite heterogeneous unit, ZsiC = Proterozoic siliciclastic confining unit

[3] Parameter measured in field

[a] Analyte detected and reported below minimum reporting limit

Table D-6. *Dissolved trace metal chemistry of samples from wells in the Ogden Valley study area.*

HydroID[1]	**Sample date**	**As (µg/L)**	**Ba (µg/L)**	**Cu (µg/L)**	**Hg (µg/L)**	**Pb (µg/L)**	**Se (µg/L)**	**Ag (µg/L)**	**Al (µg/L)**	**Fe (µg/L)**	**Mn (µg/L)**	**Zn (µg/L)**	**B (µg/L)**	**Ni (µg/L)**
		Primary standard						**Secondary standard**					**No standard**	
WL-83	05/18/2016	2.6	716.9	2.9	<0.2	0.23	<1.0	<0.5	<10.0	24	<5.0	11.1	<30.0	<5.0
WL-141	05/25/2016	9.7	<100.0	1.5	<0.2	<0.1	<1.0	<0.5	<10.0	<20	16.3	<10.0	121	<5.0
WL-159	05/17/2016	1.3	<100.0	2.1	<0.2	<0.1	<1.0	<0.5	<10.0	25	<5.0	24.0	44.7	<5.0
WL-184	05/17/2016	<1.0	<100.0	4.7	<0.2	0.15	<1.0	<0.5	<10.0	<20	<5.0	<10.0	<30.0	<5.0
WL-187	05/23/2016	1.8	101.7	1.6	<0.2	0.12	<1.0	<0.5	<10.0	49	<5.0	57.1	<30.0	<5.0
WL-233	05/17/2016	<1.0	<100.0	10.9	<0.2	0.33	<1.0	<0.5	24.2	61	5.9	48.2	32	<5.0
WL-311	05/18/2016	<1.0	<100.0	1.9	<0.2	<0.1	<1.0	<0.5	<10.0	183	7.0	<10.0	<30.0	<5.0
WL-315	05/25/2016	<1.0	<100.0	2.2	<0.2	0.27	<1.0	<0.5	<10.0	<20	<5.0	42.5	38.6	<5.0
WL-325	05/23/2016	<1.0	<100.0	140	<0.2	0.21	<1.0	<0.5	<10.0	<20	<5.0	13.0	<30.0	<5.0
WL-375	05/25/2016	<1.0	<100.0	2.1	<0.2	<0.1	<1.0	<0.5	<10.0	74	7.0	35.1	1440	<5.0
WL-433	05/18/2016	<1.0	<100.0	<1.0	<0.2	<0.1	<1.0	<0.5	<10.0	1120	21.2	11.7	<30.0	<5.0
WL-452	05/17/2016	<1.0	<100.0	16.4	<0.2	0.21	<1.0	<0.5	<10.0	<20	<5.0	103.7	<30.0	<5.0
WL-477	05/23/2016	<1.0	<100.0	2.8	<0.2	0.12	<1.0	<0.5	<10.0	<20	<5.0	20.6	<30.0	<5.0
EPA drinking water standards		10	2000	1300	2	15	50	100	50–200	300	50	5000	–	–

[1]HydroID is the unique site identifier used in this report

Table D-7. *Nitrate + nitrite (NO_3 + NO_2 as N in mg/L) concentrations in samples collected by Utah State University from shallow unconfined aquifer wells. Data from Reuben (2013, appendix G).*

Sample date	Well number								
	1	2	3	4	5	6	7	8	9
04/05/2010	2.5	2.8	2.7	4.8	3.5	N.A.	N.A.	N.A.	N.A.
04/19/2010	8.4	2.9	2.7	5.0	3.9	N.A.	N.A.	N.A.	N.A.
05/04/2010	4.5	2.6	2.4	4.2	3.5	N.A.	N.A.	N.A.	N.A.
06/08/2010	4.0	2.9	0.1	5.6	1.3	N.A.	N.A.	N.A.	N.A.
06/22/2010	8.9	3.0	0.2	5.6	4.2	N.A.	N.A.	N.A.	N.A.
07/20/2010	6.7	3.7	1.9	5.3	4.4	N.A.	N.A.	N.A.	N.A.
08/03/2010	2.8	3.5	2.9	5.2	4.8	N.A.	N.A.	N.A.	N.A.
10/05/2010	3.7	N.D.	3.0	4.4	3.6	N.A.	N.A.	N.A.	N.A.
10/12/2010	5.4	4.2	2.8	4.0	3.0	N.A.	N.A.	N.A.	N.A.
11/09/2010	5.8	4.3	2.8	0.0	4.0	N.A.	N.A.	N.A.	N.A.
12/07/2010	5.4	1.4	1.0	1.4	1.2	N.D.	0.2	N.A.	N.A.
01/13/2011	10	4.1	2.5	4.9	3.0	N.D.	0.1	N.A.	N.A.
02/08/2011	15	4.7	3.6	6.6	4.1	N.D.	0.1	N.A.	N.A.
03/22/2011	47	3.6	2.6	4.9	4.3	N.D.	1.2	N.A.	N.A.
04/19/2011	16	3.4	2.6	5.2	3.9	0.2	1.6	3.8	12
05/03/2011	28	3.9	3.0	6.0	4.6	0.7	1.4	4.9	13
06/07/2011	8.6	3.9	3.3	5.3	1.7	0.6	0.8	0.1	5.9
08/22/2011	5.5	5.3	2.9	6.3	8.8	0.4	0.4	4.2	3.6
09/19/2011	3.6	5.1	3.2	7.0	4.8	0.4	0.8	4.2	2.3
10/17/2011	4.5	5.0	2.5	7.2	4.6	0.5	0.4	4.8	2.0
11/14/2011	12	5.1	2.5	6.9	1.2	0.3	0.4	4.2	2.1

N.D. = not determined; N.A. = not applicable because the well was not constructed yet.

Geometric mean all samples n=136: 2.7

Statistics for samples collected 12/7/2010 through 11/14/2011

n	11	11	11	11	11	7	11	7	7
mean	14.1	4.1	2.7	5.6	3.8	0.4	0.7	3.7	5.8
std. dev.	13.0	1.1	0.7	1.6	2.1	0.2	0.5	1.7	4.8

Geometric mean of the arithmetic means of each well: 3.0

Reuben, T.N., 2013, Nutrient contribution of the shallow unconfined aquifer to Pineview Reservoir: Logan, Utah State University, Ph.D. dissertation, 159 p.

Table D-8. *Stable isotope composition of water samples in the Ogden Valley study area.*

HydroID[1]	Sample date	δ^2H (‰)	$\delta^{18}O$ (‰)	HydroID[1]	Sample date	δ^2H (‰)	$\delta^{18}O$ (‰)
			Precipitation (sorted by date)				
PRCP-3632	2/26/16	-127.9	-17.1	PRCP-3634	7/13/16	-37.3	-4.9
PRCP-3632	2/26/16	-131.1	-17.1	PRCP-3632	8/11/16	-38.2	-5.1
PRCP-3633	2/26/16	-141.0	-18.9	PRCP-3633	8/11/16	-42.2	-6.4
PRCP-3634	2/26/16	-174.5	-23.0	PRCP-3634	8/11/16	-53.4	-8.2
PRCP-3635	2/26/16	-145.5	-19.1	PRCP-3635	8/11/16	-46.5	-6.1
PRCP-3632	3/24/16	-89.6	-11.9	PRCP-3633	9/8/16	-33.8	-5.4
PRCP-3633	3/24/16	-107.0	-14.7	PRCP-3634	9/8/16	-31.2	-5.5
PRCP-3634	3/24/16	-91.6	-12.8	PRCP-3635	9/8/16	-6.4	0.1
PRCP-3635	3/24/16	-95.8	-12.8	PRCP-3635	9/26/16	-133.9	-18.6
PRCP-3633	4/21/16	-110.3	-15.1	PRCP-3632	10/7/16	-98.7	-13.8
PRCP-3634	4/21/16	-97.7	-13.8	PRCP-3633	10/7/16	-98.8	-14.2
PRCP-3632	4/22/16	-123.4	-17.0	PRCP-3634	10/7/16	-107.7	-15.5
PRCP-3635	4/22/16	-121.1	-16.3	PRCP-3635	10/7/16	-73.5	-10.4
PRCP-3632	5/23/16	-85.6	-11.3	PRCP-3632	11/7/16	-78.0	-11.2
PRCP-3633	5/23/16	-120.0	-16.0	PRCP-3633	11/7/16	-89.2	-13.0
PRCP-3634	5/23/16	-97.2	-13.5	PRCP-3634	11/7/16	-81.1	-12.1
PRCP-3635	5/23/16	-103.7	-14.1	PRCP-3635	11/7/16	-82.0	-11.6
PRCP-3632	6/17/16	-46.0	-5.4	PRCP-3632	12/2/16	-119.3	-16.8
PRCP-3633	6/17/16	-44.2	-6.7	PRCP-3635	12/2/16	-102.9	-15.2
PRCP-3634	6/17/16	-48.3	-7.4	PRCP-3632	12/29/16	-148.8	-19.6
PRCP-3635	6/17/16	-52.9	-7.7	PRCP-3635	12/29/16	-140.8	-18.5
PRCP-3632	7/13/16	-32.9	-3.4	PRCP-3632	1/30/17	-129.4	-17.4
PRCP-3633	7/13/16	-45.6	-6.4	PRCP-3634	1/30/17	-111.3	-15.2
			Snowpack (sorted by date)				
SNW-3635	2/16/16	-130.8	-17.1	SNW-3634	12/2/16	-130.7	-18.3
SNW-3632	2/26/16	-152.6	-19.8	SNW-3635	12/2/16	-146.3	-20.3
SNW-3633	2/26/16	-132.0	-17.4	SNW-3632	12/29/16	-160.4	-20.6
SNW-3634	2/26/16	-130.4	-17.4	SNW-3633	12/29/16	-161.6	-20.9
SNW-3633	3/24/16	-110.7	-15.0	SNW-3634	12/29/16	-157.4	-21.1
SNW-3634	3/24/16	-105.3	-14.3	SNW-3635	12/29/16	-182.5	-23.9
SNW-3635	3/24/16	-114.2	-15.2	SNW-3632	1/30/17	-141.2	-19.0
SNW-3634	4/21/16	-116.9	-16.0	SNW-3633	1/30/17	-145.1	-19.7
SNW-3632	12/2/16	-139.0	-19.4	SNW-3634	1/30/17	-140.9	-19.3
SNW-3633	12/2/16	-128.3	-18.3	SNW-3635	1/30/17	-148.5	-20.1
			Pineview Reservoir (sorted by date)				
RES-3655	4/21/16	-115.4	-15.0	RES-3636	9/8/16	-111.4	-14.3
RES-3636	4/27/16	-115.1	-14.9	RES-3636	9/22/16	-110.0	-13.9
RES-3636	6/17/16	-116.3	-15.2	RES-3636	10/7/16	-111.2	-14.3
RES-3636	7/14/16	-116.8	-15.5	RES-3636	11/8/16	-111.4	-14.3
RES-3665	9/8/16	-110.8	-14.2	RES-3636	12/2/16	-111.1	-14.3
RES-3655	9/8/16	-110.7	-14.2	RES-3636	12/29/16	-115.0	-14.7
RES-3664	9/8/16	-111.3	-14.3	RES-3636	1/30/17	-115.1	-15.0

Table D-8. *Continued.*

HydroID[1]	Sample date	δ^{2}H (‰)	δ^{18}O (‰)	HydroID[1]	Sample date	δ^{2}H (‰)	δ^{18}O (‰)
Streams (sorted by HydroID)							
ST-734	4/22/16	-122.9	-16.5	ST-3364	11/8/16	-118.7	-16.0
ST-734	9/20/16	-126.4	-17.1	ST-3365	4/21/16	-117.3	-15.9
ST-734	11/9/16	-127.1	-17.1	ST-3366	11/8/16	-120.1	-16.5
ST-755	5/5/16	-124.1	-16.5	ST-3367	4/21/16	-117.3	-16.0
ST-3337	4/22/16	-122.8	-16.5	ST-3367	9/20/16	-120.7	-16.6
ST-3337	9/8/16	-122.8	-16.6	ST-3367	11/8/16	-118.8	-16.3
ST-3337	11/9/16	-124.8	-16.8	ST-3368	4/21/16	-116.7	-15.7
ST-3338	4/22/16	-116.6	-15.5	ST-3368	11/8/16	-119.6	-16.4
ST-3338	9/8/16	-123.4	-16.6	ST-3369	4/21/16	-118.1	-16.1
ST-3338	11/9/16	-124.1	-16.7	ST-3369	11/8/16	-117.1	-15.9
ST-3339	4/22/16	-120.4	-16.0	ST-3371	5/5/16	-121.8	-16.2
ST-3339	11/9/16	-121.1	-16.1	ST-3371	11/8/16	-120.1	-16.2
ST-3340	4/22/16	-120.4	-16.1	ST-3372	4/21/16	-116.8	-15.6
ST-3340	11/9/16	-123.2	-16.4	ST-3372	11/8/16	-120.2	-16.2
ST-3341	4/22/16	-119.3	-15.7	ST-3373	4/21/16	-114.9	-15.3
ST-3342	4/22/16	-122.8	-16.5	ST-3373	11/8/16	-116.3	-15.5
ST-3343	4/22/16	-122.8	-16.5	ST-3374	4/22/16	-122.9	-16.3
ST-3343	11/9/16	-126.9	-17.1	ST-3374	9/8/16	-123.7	-16.5
ST-3344	4/22/16	-122.9	-16.5	ST-3374	11/7/16	-118.7	-15.9
ST-3344	11/9/16	-126.4	-17.0	ST-3375	11/8/16	-107.4	-14.0
ST-3345	11/9/16	-121.5	-16.2	ST-3376	4/21/16	-116.7	-15.7
ST-3346	4/21/16	-116.3	-15.2	ST-3376	11/8/16	-122.3	-16.6
ST-3349	11/7/16	-118.4	-15.9	ST-3377	4/21/16	-116.8	-15.8
ST-3350	11/7/16	-116.8	-15.5	ST-3378	11/8/16	-119.4	-15.9
ST-3351	4/22/16	-121.0	-16.2	ST-3379	4/21/16	-118.4	-16.1
ST-3352	4/21/16	-118.2	-15.7	ST-3379	11/8/16	-118.7	-16.3
ST-3352	11/8/16	-114.1	-15.4	ST-3380	4/21/16	-116.9	-15.5
ST-3353	4/21/16	-121.3	-16.3	ST-3381	11/8/16	-118.8	-16.4
ST-3353	9/20/16	-119.4	-15.6	ST-3390	11/7/16	-115.6	-15.7
ST-3353	11/7/16	-119.3	-16.0	ST-3391	4/21/16	-116.6	-15.3
ST-3354	4/21/16	-120.8	-16.2	ST-3403	4/22/16	-117.3	-15.4
ST-3354	11/7/16	-117.1	-15.5	ST-3594	4/21/16	-121.6	-16.4
ST-3355	4/21/16	-119.4	-15.7	ST-3594	11/8/16	-115.7	-15.8
ST-3355	11/7/16	-120.1	-15.9	ST-3604	4/21/16	-116.9	-15.8
ST-3356	4/21/16	-121.2	-16.3	ST-3604	11/8/16	-118.1	-16.2
ST-3356	11/7/16	-120.3	-16.1	ST-3639	4/21/16	-121.3	-16.4
ST-3357	4/21/16	-120.3	-16.1	ST-3639	11/8/16	-128.5	-16.7
ST-3357	11/7/16	-122.1	-16.4	ST-3641	5/5/16	-127.5	-17.2
ST-3358	4/21/16	-118.2	-15.9	ST-3642	4/22/16	-123.8	-16.5
ST-3359	4/22/16	-122.8	-16.5	ST-3643	4/21/16	-115.7	-15.6
ST-3360	4/22/16	-122.7	-16.5	ST-3644	4/21/16	-117.5	-15.9
ST-3360	11/9/16	-127.0	-17.1	ST-3645	4/22/16	-118.4	-15.4
ST-3361	11/7/16	-121.3	-16.1	ST-3646	4/22/16	-125.4	-16.7
ST-3362	4/22/16	-120.8	-16.0	ST-3670	9/22/16	-120.6	-16.6
ST-3362	11/7/16	-122.7	-16.4	ST-3674	7/19/16	-124.0	-16.8
ST-3363	4/22/16	-118.8	-15.6	ST-3675	11/8/16	-117.4	-16.1
ST-3364	4/21/16	-116.7	-15.7	-	-	-	-

Table D-8. *Continued.*

HydroID[1]	Sample date	δ^2H (‰)	$\delta^{18}O$ (‰)	HydroID[1]	Sample date	δ^2H (‰)	$\delta^{18}O$ (‰)
Springs (sorted by HydroID)							
SP-3407	4/26/16	-121.7	-16.3	SP-3653	5/5/16	-120.2	-15.7
SP-3408	4/26/16	-123.3	-16.4	SP-3653	9/22/16	-121.2	-16.1
SP-3416	9/22/16	-129.9	-17.5	SP-3654	5/5/16	-122.1	-16.6
SP-3419	4/21/16	-121.3	-16.5	SP-3656	4/26/16	-129.1	-17.2
SP-3419	9/26/16	-124.0	-17.0	SP-3656	9/27/16	-130.5	-17.6
SP-3424	4/22/16	-125.0	-16.6	SP-3657	5/26/16	-124.8	-16.9
SP-3434	4/21/16	-127.6	-17.0	SP-3658	5/26/16	-116.4	-15.9
SP-3435	5/3/16	-121.9	-16.5	SP-3658	9/22/16	-121.5	-16.9
SP-3438	9/21/16	-117.5	-16.3	SP-3659	6/1/16	-115.4	-15.0
SP-3441	5/5/16	-121.6	-16.3	SP-3660	6/1/16	-129.0	-17.2
SP-3595	9/21/16	-126.8	-17.1	SP-3661	6/29/16	-125.8	-16.7
SP-3647	4/26/16	-130.1	-17.4	SP-3662	6/2/16	-118.6	-16.1
SP-3648	5/5/16	-128.4	-17.2	SP-3663	6/2/16	-119.9	-16.2
SP-3649	5/3/16	-127.6	-16.9	SP-3666	7/13/16	-112.6	-14.0
SP-3650	5/5/16	-135.1	-18.0	SP-3667	7/13/16	-114.0	-15.2
SP-3650	9/22/16	-133.4	-18.0	SP-3668	7/13/16	-107.1	-13.4
SP-3651	5/5/16	-131.0	-17.4	SP-3671	9/21/16	-125.1	-16.9
SP-3652	5/5/16	-132.0	-17.6	SP-3672	9/21/16	-45.7	-7.1
SP-3652	6/29/16	-130.0	-17.3	-	-	-	-
Wells (sorted by HydroID)							
WL-26	4/11/16	-114.7	-14.9	WL-325	9/28/16	-120.0	-16.1
WL-58	5/31/16	-134.1	-17.7	WL-334	4/27/16	-130.2	-17.2
WL-58	9/22/16	-130.6	-17.3	WL-334	9/28/16	-129.8	-17.2
WL-63	5/31/16	-132.2	-17.5	WL-348	4/28/16	-125.7	-16.7
WL-65	6/1/16	-134.4	-17.8	WL-348	9/28/16	-124.7	-16.7
WL-83	5/2/16	-124.3	-16.2	WL-349	4/28/16	-126.3	-16.9
WL-103	4/12/16	-126.4	-16.5	WL-354	5/2/16	-128.0	-16.9
WL-105	4/18/16	-126.0	-16.8	WL-363	5/4/16	-126.9	-16.9
WL-107	4/18/16	-125.5	-16.6	WL-363	9/28/16	-125.7	-17.0
WL-108	5/23/16	-123.0	-16.4	WL-375	5/2/16	-138.9	-18.2
WL-113	4/18/16	-124.4	-16.9	WL-378	5/3/16	-128.1	-17.0
WL-123	6/1/16	-132.0	-17.6	WL-386	4/11/16	-122.3	-16.5
WL-129	9/27/16	-119.9	-15.9	WL-386	9/27/16	-120.7	-16.5
WL-133	4/19/16	-119.8	-16.4	WL-394	4/18/16	-116.0	-15.4
WL-136	4/12/16	-124.8	-16.7	WL-413	5/5/16	-123.9	-16.5
WL-141	9/27/16	-136.3	-18.1	WL-418	4/20/16	-117.1	-15.8
WL-144	5/4/16	-130.1	-17.0	WL-424	4/26/16	-126.4	-16.8
WL-152	6/1/16	-116.0	-15.4	WL-431	5/2/16	-130.2	-17.1
WL-153	6/1/16	-131.1	-17.4	WL-433	4/21/16	-126.6	-17.1
WL-156	5/4/16	-128.8	-17.1	WL-435	4/19/16	-124.1	-16.5
WL-156	9/28/16	-127.1	-17.0	WL-439	5/3/16	-128.7	-17.1
WL-158	4/21/16	-123.0	-16.7	WL-440	4/11/16	-129.4	-17.2
WL-159	4/28/16	-130.6	-17.2	WL-443	4/20/16	-121.1	-16.3
WL-159	9/26/16	-130.2	-17.4	WL-443	9/27/16	-120.0	-16.1
WL-169	5/3/16	-122.5	-16.0	WL-452	4/28/16	-125.5	-16.8
WL-170	5/3/16	-123.7	-16.3	WL-454	5/5/16	-122.9	-16.3

Table D-8. *Continued.*

HydroID[1]	Sample date	δ^2H (‰)	$\delta^{18}O$ (‰)	HydroID[1]	Sample date	δ^2H (‰)	$\delta^{18}O$ (‰)
WL-172	5/2/16	-128.6	-17.1	WL-454	10/14/16	-119.9	-16.3
WL-182	6/1/16	-132.8	-17.6	WL-477	4/27/16	-119.0	-16.1
WL-184	5/3/16	-128.3	-17.1	WL-477	9/26/16	-119.2	-16.2
WL-184	9/28/16	-125.6	-16.9	WL-492	5/31/16	-124.6	-16.3
WL-187	4/20/16	-125.5	-16.6	WL-508	5/31/16	-130.7	-17.3
WL-189	4/11/16	-132.2	-17.9	WL-516	4/27/16	-128.3	-17.0
WL-189	9/27/16	-123.7	-16.4	WL-520	5/25/16	-118.5	-15.5
WL-200	4/19/16	-121.3	-16.5	WL-530	5/31/16	-133.7	-17.7
WL-203	4/28/16	-123.0	-16.2	WL-532	6/1/16	-133.2	-17.7
WL-203	9/26/16	-120.0	-15.9	WL-615	4/26/16	-124.3	-16.7
WL-212	5/31/16	-132.8	-17.3	WL-618	5/26/16	-122.3	-16.5
WL-220	6/1/16	-132.4	-17.6	WL-618	9/26/16	-126.0	-17.3
WL-233	4/28/16	-125.1	-17.4	WL-633	4/12/16	-121.2	-16.1
WL-255	4/19/16	-125.0	-16.7	WL-3587	4/26/16	-129.9	-17.4
WL-271	4/13/16	-128.1	-16.9	WL-3587	9/27/16	-129.5	-17.4
WL-280	6/1/16	-134.0	-17.9	WL-3597	4/26/16	-127.6	-16.7
WL-282	5/3/16	-131.8	-17.3	WL-3600	4/28/16	-133.6	-17.7
WL-288	5/3/16	-125.0	-16.6	WL-3601	4/18/16	-132.2	-17.4
WL-289	5/4/16	-128.7	-17.1	WL-3603	4/21/16	-118.8	-16.1
WL-294	4/20/16	-124.1	-16.8	WL-3669	5/25/16	-118.9	-16.3
WL-311	4/11/16	-128.3	-17.0	WL-3673	4/18/16	-127.3	-17.0
WL-317	4/12/16	-124.5	-16.5	WL-3673	9/22/16	-123.2	-16.6
WL-325	4/27/16	-118.7	-15.8	-	-	-	-

[1] HydroID is the unique site identifier used in this report

Table D-9. *Stream gauging transducer levels and computed flow.*

Link to Excel file: https://ugspub.nr.utah.gov/publications/special_studies/ss-165/ss-165.xlsx

APPENDIX E

WATER BUDGET DATA

Table E-1. *Pineview Reservoir monthly release, 2003–2016, in acre-feet.*

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Water year
2003	250	158	66	495	6178	16,627	16,351	21,826	14,022	881	216	252	77,322	
2004	310	248	84	648	8561	11,400	15,664	19,077	13,743	4632	6	3320	77,693	71,084
2005	11,005	11,555	12,917	33,678	67,710	29,492	21,470	22,428	15,985	6242	9231	12,866	254,579	234,198
2006	8522	11,396	13,624	70,406	41,527	21,993	26,612	24,290	13,664	3214	3038	7139	245,425	260,373
2007	10,833	168	160	674	16,475	21,460	21,625	19,280	11,430	2958	240	248	105,551	115,496
2008	248	5467	7911	4966	14,575	22,399	26,034	28,965	15,525	3484	180	186	129,940	129,536
2009	9358	11,808	12,552	10,511	36,543	27,079	19,593	20,290	18,956	5151	248	368	172,457	170,540
2010	10,446	2337	294	444	7051	20,659	20,362	19,944	20,661	6753	6	5515	114,472	107,965
2011	12,923	11,732	31,248	71,671	80,428	78,743	23,302	17,619	17,307	6048	300	9916	361,237	357,247
2012	7617	4669	8920	5551	25,211	22,136	20,616	18,634	12,591	4597	887	520	131,949	142,209
2013	460	558	420	2134	10,317	13,304	15,161	16,095	9928	997	526	582	70,482	74,381
2014	634	616	310	1707	10,009	21,625	19,751	15,534	15,990	979	736	704	88,595	88,281
2015	684	666	466	2355	7912	13,635	17,935	18,621	15,048	1569	632	506	80,029	79,741
2016	496	468	248	15,038	32,113	17,983	22,404	19,696	13,583	1863	582	680	125,154	124,736

Volumes include release to Pineview Water Systems pipeline, Ogden City water treatment plant, and Ogden River.

Table E-2. *Estimated water use from wells and springs in Ogden Valley, calendar years 2003 to 2016, in acre-feet per year.*

Hydro ID[1]	Easting (NAD83 m)	Northing (NAD83 m)	Source[2]	System	Type	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
3673	432136	4569296	Well field (6 wells)	Ogden City	Well	10,201	10,201	10,619	11,192	11,591	11,094	11,145	12,034	11,904	11,896	11,336	12,371	10,886	11,664
NA	NA	NA	Domestic and unreported	NA	Well	*1620*	*1654*	*1687*	*1722*	*1757*	*1793*	*1829*	*1867*	*1905*	*1944*	*1983*	*2024*	2065	*2106*
NA	NA	NA	Domestic and unreported	NA	Spring	*49*	*50*	*51*	*53*	*54*	*55*	*56*	*57*	*58*	*59*	*61*	*62*	63	*64*
3407	440553	4563480	Bennett Spring	Huntsville	Spring	340	214	496	441	375	373	373	373	*238*	*170*	*136*	*119*	103	81
3409	440358	4563726	Lower Bennett Spring	Huntsville	Spring	28	27	29	33	26	29	*29*	29						
3408	440505	4563546	Virgil Peterson Spring	Huntsville	Spring	117	134	153	154	139	139	130	139						
3603	429732	4572801	Clarke east well	Eden Water Works	Well	17	13	39	104	89	13	6	9	9	111	84	63	74	67
3434	431454	4575431	Burnett Springs	Eden Water Works	Spring	157	249	253	259	198	222	243	198	249	200	173	215	830	2242
628	438633	4568798	Well 1	Green Hills Estates	Well	20	16	22	22	19	12	10	15	19	18	14	14	13	13
60	438716	4569629	Well 2	Green Hills Estates	Well	22	21	27	14	26	16	21	18	15	19	18	18	16	14
3741	432834	4566389	Peterson Well	Lakeview Water Co	Well			58	38	66	44	74	55		61	54	39	50	
3742	433530	4567034	Bowden Well	Lakeview Water Co	Well														17
623	434475	4566715	Mitchell Well	Lakeview Water Co	Well														31
133	425752	4576005	Smith Well1	Liberty Pipeline Co	Well	**287**	*189*	**92**	*23*	*23*	*23*	*23*	**126**	*154*	*154*	*154*	**182**	142	148
3637	421970	4582032	5 Cutler Canyon springs3	Liberty Pipeline Co	Spring	**96**	*63*	**31**	*36*	*36*	*36*	*36*	**42**	*51*	*51*	*51*	**61**	31	74
537	427631	4575398	Rhodes Well and 2 others	Nordic Mountain	Well						0	40					39	0	77
642	427883	4571672	Well No. 1	Nordic Mountain	Well		**26**	2	43	46	43	2	42	39	50	45	0	0	
3580	428027	4572454	Well No. 2	Nordic Mountain	Well		0	2	3	2	1	0	1	1	1	3	3	5	1
5381	427783	4573099	Well No. 3	Nordic Mountain	Well			40	1	1	1	2	1	1	1	2	2	0	0
3750	430538	4569675	Well No. 2	Pineview West	Well													4	4
545	431178	4570407	Well No. 3	Pineview West	Well													9	5
136	430247	4570217	Well No. 4	Pineview West	Well														21
618	436186	4579960	Hidden Lake Well	Powder Mt WSID	Well											0	0	0	11
3440	434432	4580862	Pizzel Spring No. 1	Powder Mt WSID	Spring							29	8	10	16	0			
3437	434611	4580058	Pizzel Spring No. 3	Powder Mt WSID	Spring										0	18	14	13	8
3748	444579	4582003	Cat Trail Upper Spring	Sunridge	Spring											2	1	7	3
3445	445358	4581881	System 3 Spring	Sunridge	Spring	0	0	0	0	0	0	0			39	39	38	35	29
3749	442138	4581530	System 4 Spring	Sunridge	Spring	0	0	0	1	1	0	3			6	9	9	9	7
3587	430793	4575361	Warm Springs Well4	Wolf Creek WSID	Well	59	*142*	224	*280*	*280*	*280*	*280*	335	*319*	*319*	*319*	*319*	303	*303*
3587	430793	4575361	Patio Springs 4	Wolf Creek WSID	Spring	119	*284*	449	*559*	*559*	*559*	*559*	670	*631*	*631*	*631*	*631*	592	*592*
Total wells						12,226	12,261	12,812	13,441	13,899	13,320	13,432	14,503	14,365	14,573	14,011	15,073	13,565	14,480
Wells excluding Ogden City well field and domestic wells						404	407	506	527	551	433	458	603	557	733	692	678	615	710
Wells excluding Ogden City well field						2025	2060	2193	2249	2308	2226	2287	2469	2461	2677	2675	2702	2680	2816
Total springs						905	1022	1463	1535	1388	1414	1458	1516	1237	1172	1119	1149	1682	3100
Total excluding Ogden City well field						2930	3082	3656	3784	3696	3640	3745	3985	3698	3849	3794	3851	4361	5916
Total						**13,131**	**13,283**	**14,275**	**14,976**	**15,287**	**14,734**	**14,890**	**16,019**	**15,602**	**15,745**	**15,130**	**16,222**	**15,247**	**17,580**

Notes:
Italicized values are estimated or interpolated from years having reported values
Bold data are based on potable water use reported in Division of Water Resources periodic water use surveys
WSID = Water and Sewer Improvement District

[1] HydroID is the unique site identifier used in this report
[2] Springs not included because their discharge is counted in irrigation distribution include: Leftys, Liberty/Lime Kiln, Fisher, and Wester springs
[3] Liberty Pipeline Co used Smith Well to meet 82% and 66% of need in 2015 and 2016, respectively, with the rest coming from the 5 Cutler Canyon Springs. We estimated that Smith well met 75% of LPC's need for other years with total potable usage data (2003, 2005, 2010)
[4] Proportion of Warm Springs Well to Patio Springs in 2015 was applied to Water Resources total use values in previous years

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