CACHE VALLEY AQUIFER STORAGE AND RECOVERY—PHASE II

by Paul Inkenbrandt, Kevin Thomas, and Christian Hardwick

OPEN-FILE REPORT 615
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES
2013

CACHE VALLEY AQUIFER STORAGE AND RECOVERY—PHASE II

by Paul Inkenbrandt, Kevin Thomas, and Christian Hardwick

Cover photo: *View west of the Green Canyon gravel pit from the foothills of the Bear River Range, looking towards Clarkston Mountain.*

OPEN-FILE REPORT 615
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES
2013

STATE OF UTAH
Gary R. Herbert, Governor

DEPARTMENT OF NATURAL RESOURCES
Michael Styler, Executive Director

UTAH GEOLOGICAL SURVEY
Richard G. Allis, Director

PUBLICATIONS
contact
Natural Resources Map & Bookstore
1594 W. North Temple
Salt Lake City, UT 84114
telephone: 801-537-3320
toll-free: 1-888-UTAH MAP
website: mapstore.utah.gov
email: geostore@utah.gov

UTAH GEOLOGICAL SURVEY
contact
1594 W. North Temple, Suite 3110
Salt Lake City, UT 84114
telephone: 801-537-3300
website: geology.utah.gov

CONTENTS

FIGURES

TABLES

PLATE

CACHE VALLEY AQUIFER STORAGE AND RECOVERY—PHASE II

by Paul Inkenbrandt, Kevin Thomas, and Christian Hardwick

ABSTRACT

During the spring of 2011, a gravel excavation site (pit) at the mouth of Green Canyon in North Logan City, Utah, was modified by the city to retain excess flow from the Green Canyon catchment. From August 2011 to March 2012, the Utah Geological Survey (UGS) monitored the flow of water into the gravel pit, and recorded gravity data and groundwater levels at several sites within a mile of the gravel pit. The UGS conducted four two-day measuring campaigns during August 2011, September 2011, October 2011, and March 2012.

The UGS observed a significant increase in gravity from August to September to the southwest of the gravel pit, which indicates an increase in the amount of water in that region from August to September. Most of the water is likely traveling from the gravel pit towards the region of the principal aquifer. Lack of correlation between well-water level and gravity changes at two nearby wells implies that there are two separate aquifer systems in the vicinity of the gravel pit: an upper unconfined aquifer and a lower confined/semi-confined aquifer. While more gravity and hydrologic measurements and an observation well are strongly recommended for this site, the UGS suggests that Cache County continue efforts to develop the gravel pit into an aquifer storage and recovery site.

INTRODUCTION

Cache Valley is a rural area in northern Utah (figure 1) experiencing rapid population growth and increased groundwater use. Groundwater is a significant source of drinking water for Cache Valley residents. During some relatively wet years, such as water-year 2011, surface water discharge may exceed usable quantities and surface-impoundment storage capabilities for several months. Members of the Cache County government are seeking tools to help them better manage the Cache Valley groundwater system. Aquifer storage and recovery (ASR) allows for excess surface water to augment groundwater supplies in Cache Valley's basin-fill aquifer through direct infiltration or use of an injection well. ASR can help stabilize water levels, as well as provide water planners and managers with increased flexibility in managing the water supply of the basin, by providing a source of supplemental supply.

In the summer of 2011, North Logan City diverted excess surface-water discharge from the Green Canyon catchment out of Green Canyon via a main stream channel/canal into a series of three improvised infiltration pits located at an active gravel mining operation. The infiltration of the water provided an excellent opportunity to study how water flows into Cache Valley's basin-fill sediments, and our Phase I study (Thomas and others, 2011) of artificial recharge in Cache County recommended the gravel pits near Green Canyon as a candidate for an artificial recharge site. The objective of this study (Phase II) is to determine the flow direction and fate of infiltrated seasonal runoff through the gravel pit at the mouth of Green Canyon into basin-fill sediments.

Location and Geography

Cache Valley is a north-south-trending valley that straddles the border of Cache County, Utah, and Franklin County, Idaho. In Utah, Cache Valley is bordered by the Bear River Range to the east and the Wellsville Mountains and Clarkston Mountain to the west (figure 1).

The study focuses on the area at the mouth of Green Canyon, between the town of North Logan and the foothills of the Bear River Range. The gravel mining operation is located immediately west of the mouth of Green Canyon.

Previous Investigations

Lowe (1987) and Lowe and Galloway (1993) created a 1:24,000-scale geologic map of the North Logan area, including the area of the gravel pit. They also provided a geologic interpretation and geologic cross sections of the area. Dover (1995) created the 1:100,000-scale Logan 30' x 60' geologic map that includes the Utah portion of Cache Valley (figure 2).

Anderson and others (1994) mapped groundwater recharge and discharge areas for Cache Valley's basin-fill aquifer (figure 3). Based on water-level data from well drillers' logs, they subdivided the basin-fill aquifer into (1) primary recharge areas—less than 20 feet of clay and a downward hydrologic gradient, (2) secondary recharge areas—confining layers (greater than 20 feet of clay) and a downward hydrologic gradient, and (3) discharge areas—upward hydrologic gradients. They stated that recharge into the basin fill from the extensively fractured bedrock at the mountain front is highly probable. Anderson and others (1994) recognized extensive confining layers in Cache Valley, noting that the valley has a greater percentage of clay in the unconsolidated basin-fill deposits than the other Wasatch Front basin-fill valleys.

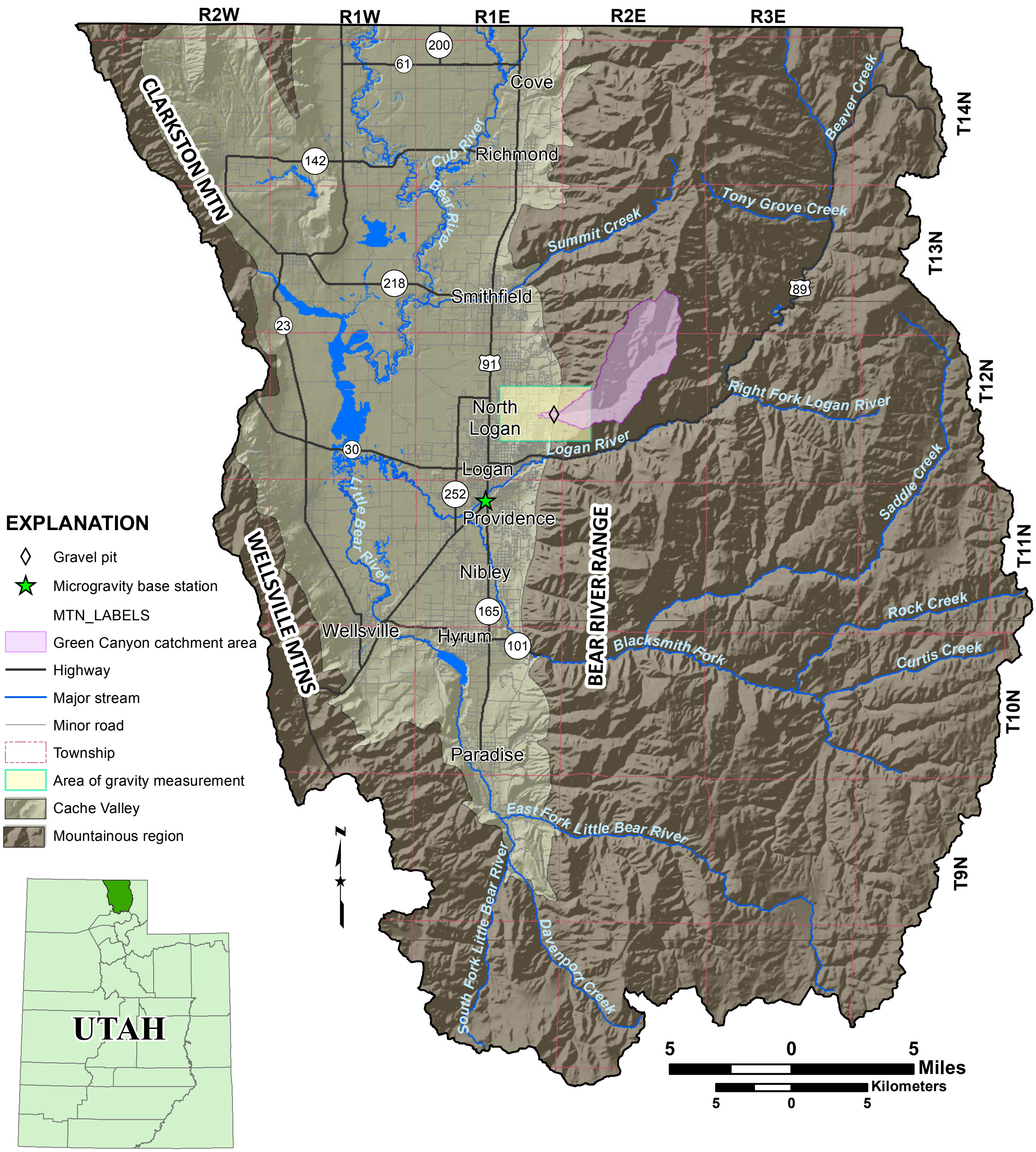


Figure 1. Location of the study area in Cache County, Utah.

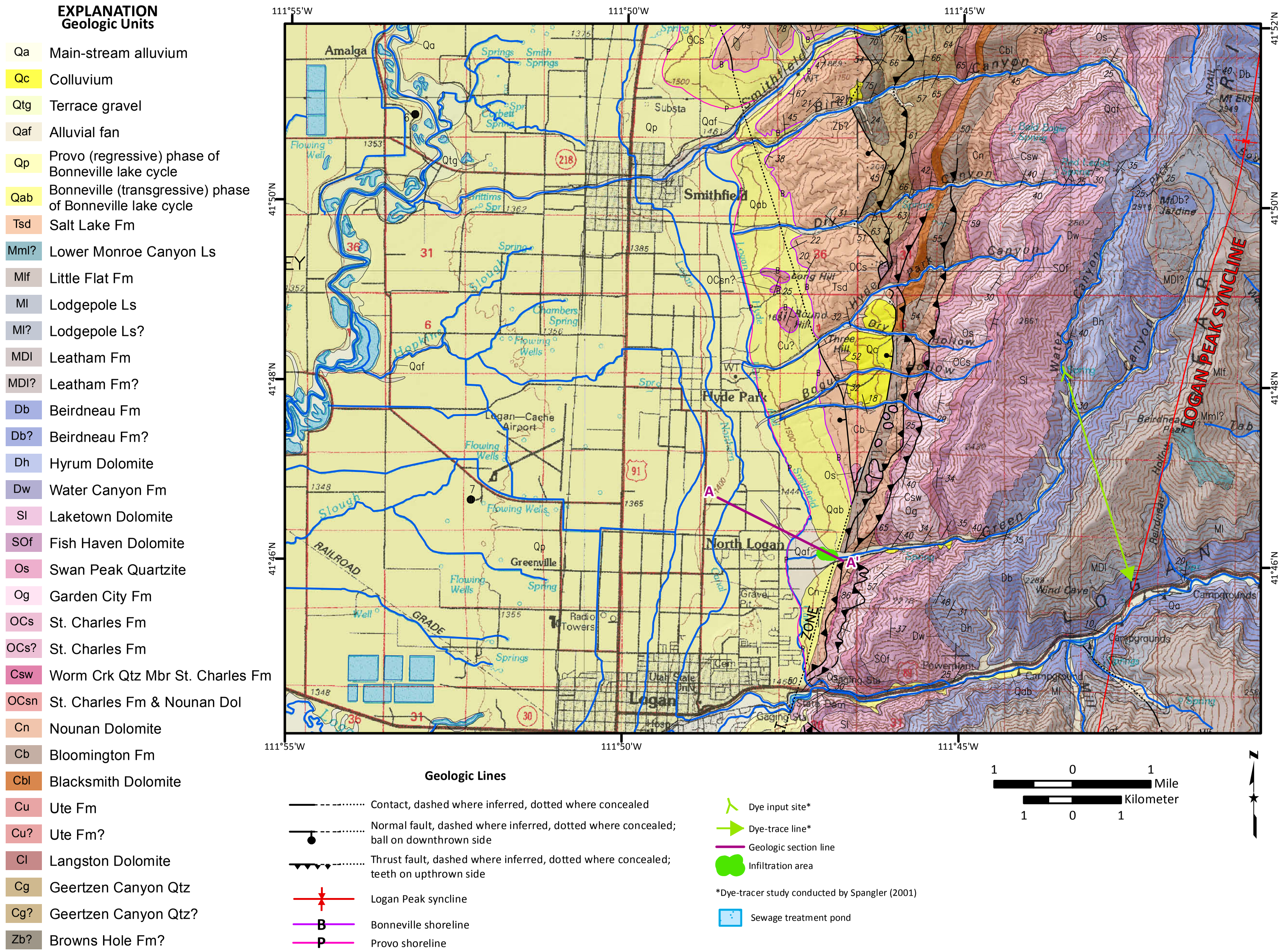


Figure 2. *Geologic map of eastern Cache Valley modified from Dover (1995). This map includes the karst flow line from Green Canyon to DeWitt spring (Spangler, 201). Figure 5 is a geologic cross section of the section line A to A'.*

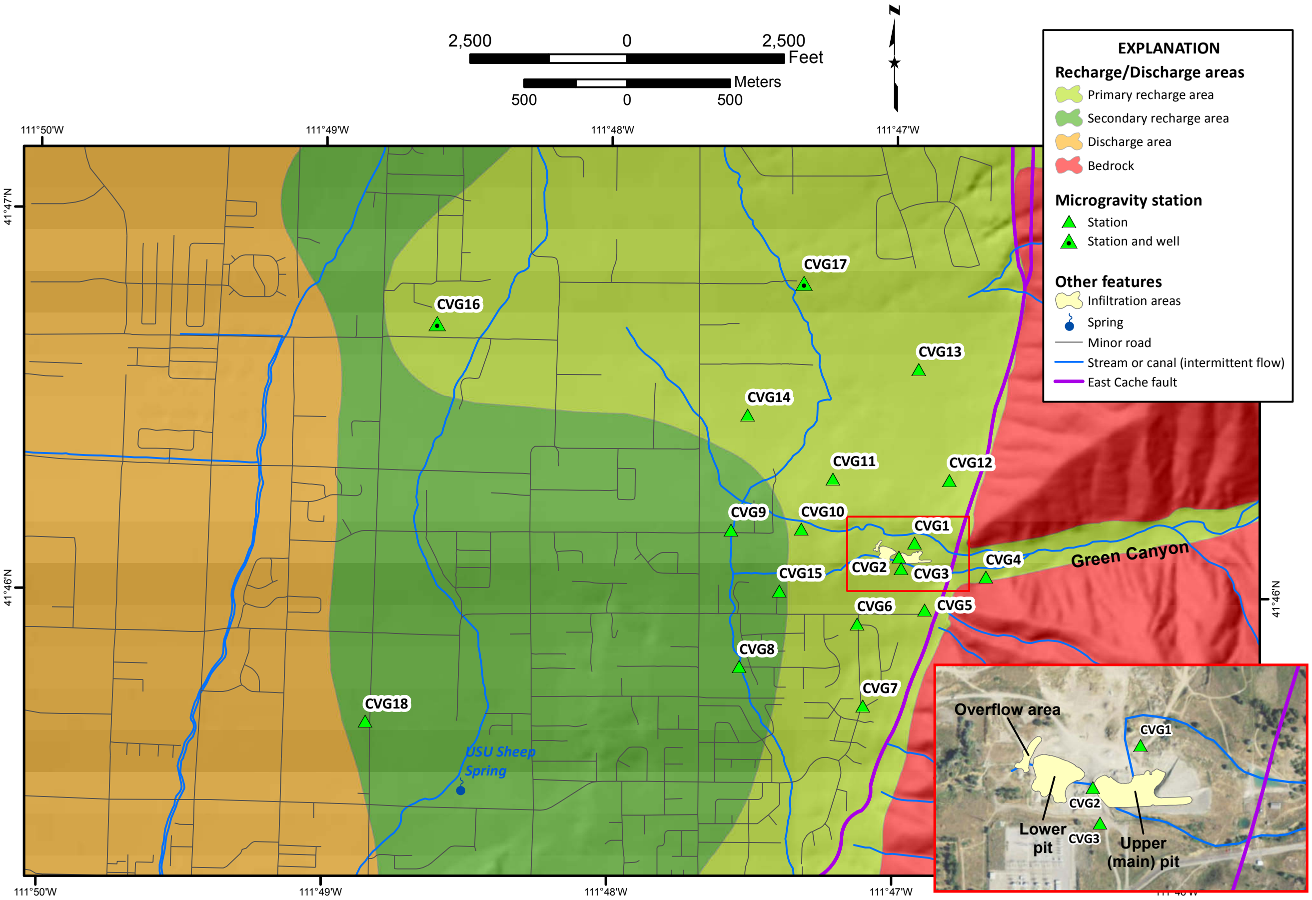


__Figure 3.__ Groundwater recharge and discharge areas as delineated by Anderson and others (1994) and location of microgravity stations. Primary recharge areas contain no confining layers thicker than 20 feet and have a downward vertical gradient. Secondary recharge areas contain confining layers thicker than 20 feet and a general downward vertical gradient. Discharge zones have an upward vertical gradient. Inset (red border) shows detail of infiltration pit area.

Robinson (1999) conducted a thorough hydrologic examination of the valley that characterized the chemistry and hydrostratigraphy of groundwater and surface-water interaction in the Cache Valley basin-fill aquifer. He created seven cross sections of the basin fill material in the Utah portion of Cache Valley using well drillers' logs. Robinson's (1999) cross sections presented two continuous confining layers terminating near Cache Valley's eastern margin. Robinson described five major hydrostratigraphic units in descending order: (1) an unconfined aquifer (Qau), (2) an upper confining layer (B1), (3) an upper confined aquifer (A1), (4) a lower confining layer (B2), and (5) a deep confined aquifer (A2) (table 1 and figure 4).

Inkenbrandt (2010) examined transmissivity of the basin-fill material. He compiled aquifer tests and specific-capacity data, and used Robinson's (1999) nomenclature to identify the hydrostratigraphic units from which wells in Cache Valley derive water.

To assess the potential for aquifer storage and recovery projects in Cache Valley, Thomas and others (2011) examined maps and aerial photographs, constructed several geologic sections of the area (figure 5), and interpolated aquifer transmissivity values (figure 6) from Inkenbrandt (2010). They looked for potential ASR sites in areas of high aquifer transmissivity, near water sources, and lacking significant and continuous confining layers. Their choices for optimal sites for surface spreading are close to the Bear River Range, beyond the eastern extent of the confining layers (figure 3), and in areas where the Salt Lake Formation is not near the surface (figure 2). For a more comprehensive bibliography on the Cache Valley area, see Inkenbrandt (2010) or Thomas and others (2011).

Geologic Setting

North-striking, steeply-dipping normal faults (the East Cache and West Cache fault zones) are the structural boundaries of Cache Valley. Both fault zones have been subdivided into three segments, and both fault zones show evidence of recurrent Quaternary movement (McCalpin, 1994; Black and others, 1999).

The mountain massifs surrounding Cache Valley consist of Precambrian to Permian sedimentary and metamorphic rocks, including limestone, dolomite, shale, and quartzite (Williams, 1948, 1958; Bjorklund and McGreevy, 1971). Tertiary Salt Lake Formation, primarily tuffaceous sandstone and conglomerate, forms a belt along the foothills surrounding the valley and underlies Quaternary deposits within Cache Valley (Williams, 1962; Evans and Oaks, 1996). Gravity survey data (Oaks and Langenheim, in preparation) and drillers' logs suggest that the Salt Lake Formation is close to the surface along the mountain front north of Green Canyon and south of Blacksmith Fork Canyon. Swelling clays within the tuffaceous portions of the Salt Lake Formation can impede the flow of groundwater (Smith, 1997).

Cache Valley contains unconsolidated basin fill of varying thickness. The basin fill consists of fluvial and lacustrine deposits that interfinger with alluvial-fan deposits and, to a lesser extent, deltaic and landslide deposits along the valley margins (Lowe, 1987; Lowe and Galloway, 1993; Evans and Oaks, 1996). Much of the floor of Cache Valley is covered with offshore lacustrine silt and clay deposited during the Bonneville lake cycle between about 12,000 and 29,000 years ago (Oviatt and others, 1992).

The principal basin-fill aquifer (figure 4) is present in the subsurface between Smithfield, Wellsville, and Hyrum, and may be up to 700 feet thick (after the thicknesses of mud interbeds are subtracted). The proportion of fine-grained particles increases to the west, and the valley center is dominantly fine grained. These basin-fill deposits cover and lap onto the Salt Lake Formation where it is exposed or shallowly buried in the valley (Thomas and others, 2011).

Two thick clay confining layers are present in the upper 120 to 170 feet of the basin fill in the area of the principal aquifer (table 1 and figure 4). Both layers rise and pinch out eastward at higher altitudes at the deltas (Bjorklund and McGreevey, 1971; Robinson 1999). Both layers extend nearly to the mountain front between the Logan River delta and the Blacksmith Fork delta. Laterally continuous gravel deposits 20 to 40 feet thick separate the two confining layers, and constitute the upper confined aquifer of Robinson (1999).

Transmissivity values in the Salt Lake Formation are typically an order of magnitude lower and have a higher standard deviation than those of the principal aquifer (Inkenbrandt, 2010). Generally, the lower transmissivities and tuffaceous portions of the Salt Lake Formation make it a poor aquifer.

The deposits in the Green Canyon gravel (infiltration) pit are moderately to well sorted, cobble-sized, clast-supported gravels. Most of the clasts in the gravel pit are well rounded. These deposits are deltaic materials (Thomas and others, 2011), likely deposited at the Provo stage of ancient Lake Bonneville. Cross sections (figure 5; Robinson, 1999; Thomas and others, 2011) indicate that the gravels in the pit likely are underlain by the Salt Lake Formation at a depth of less than 100 feet. Many of the wells surrounding the gravel pit are screened to the Salt Lake Formation. The Salt Lake Formation is of moderate to high transmissivity (approximately 900–2000 ft^2/day) in the area of the gravel pit (Inkenbrandt, 2010), so infiltration from the gravel pit to the Salt Lake Formation may be possible. However, the principal aquifer, especially A2, is the ultimate target for artificial recharge, and not the Salt Lake Formation.

Table 1. *Hydrostratigraphic units in Cache Valley, as described by Robinson, 1999.*

Unit (Avg. thickness, ft)	Description	Water-Bearing Properties
Qau (50)	<u>Quaternary alluvium undifferentiated</u> cobbles, gravel, sand, and silt; well to poorly sorted; unconsolidated; eolian sand and spring tufa	generally highly to moderately conductive; unconfined; transmissivities generally adequate for stock wells; TDS less than 1,000 mg/L
B1 (60)	<u>Upper confining layer</u> clay grading to silt, sand, and gravel near the valley margins	considered to be a highly impermeable aquitard; vertical gradients as great as 0.5
C1 (>200)	<u>Deltaic deposits</u> cobbles, gravel, sand, and silt; well to poorly sorted; unconsolidated	transmissivities are generally the highest in the valley; unconfined to confined; high water quality
A1 (30)	<u>Upper confined aquifer</u> gravels to cobbles interbedded with sand and silt; clay beds present in discontinuous lenses	moderately conductive but relatively low thickness gives low transmissivities; water generally contains much iron; well-confined
B2 (30)	<u>Lower confining layer</u> thickly bedded clay containing thin gravel lenses near the valley margins	considered to be a highly impermeable aquitard; vertical gradients as great as 0.5
A2 (1,340)	<u>Lower confined aquifer</u> unconsolidated to semi-consolidated thickly bedded gravels and sands; discontinuous lenses of silt, clay, and marl; woody debris, peat, and shells present in places	conductivities very low to very high; these sediments compose the major aquifer of the valley; TDS is generally less than 300 mg/L, but may exceed 3,000 mg/L
Tsl (9,000)	<u>Tertiary Salt Lake Formation, undifferentiated</u> tuff, and mostly tuffaceous and calcareous siltstone, sandstone, and conglomerate, limestone and marl	conductivities generally low, but may be high locally in solution cavities or fanglomerate facies; water quality is highly variable
Tw (150)	<u>Tertiary Wasatch Formation, undifferentiated</u> poorly consolidated red-colored cobble- to boulder-bearing conglomerate	conductivities generally low to moderate; low well discharges possible; source of some springs
Pzu (>>10,000)	<u>Paleozoic, undifferentiated</u> well consolidated to slightly metamorphosed sandstones, shales, dolomites, and limestones; possibly containing solution cavities	permeability is predominately due to fractures and solution cavities, ranging from very low to locally quite high; TDS ranges from 150 to 310 mg/L

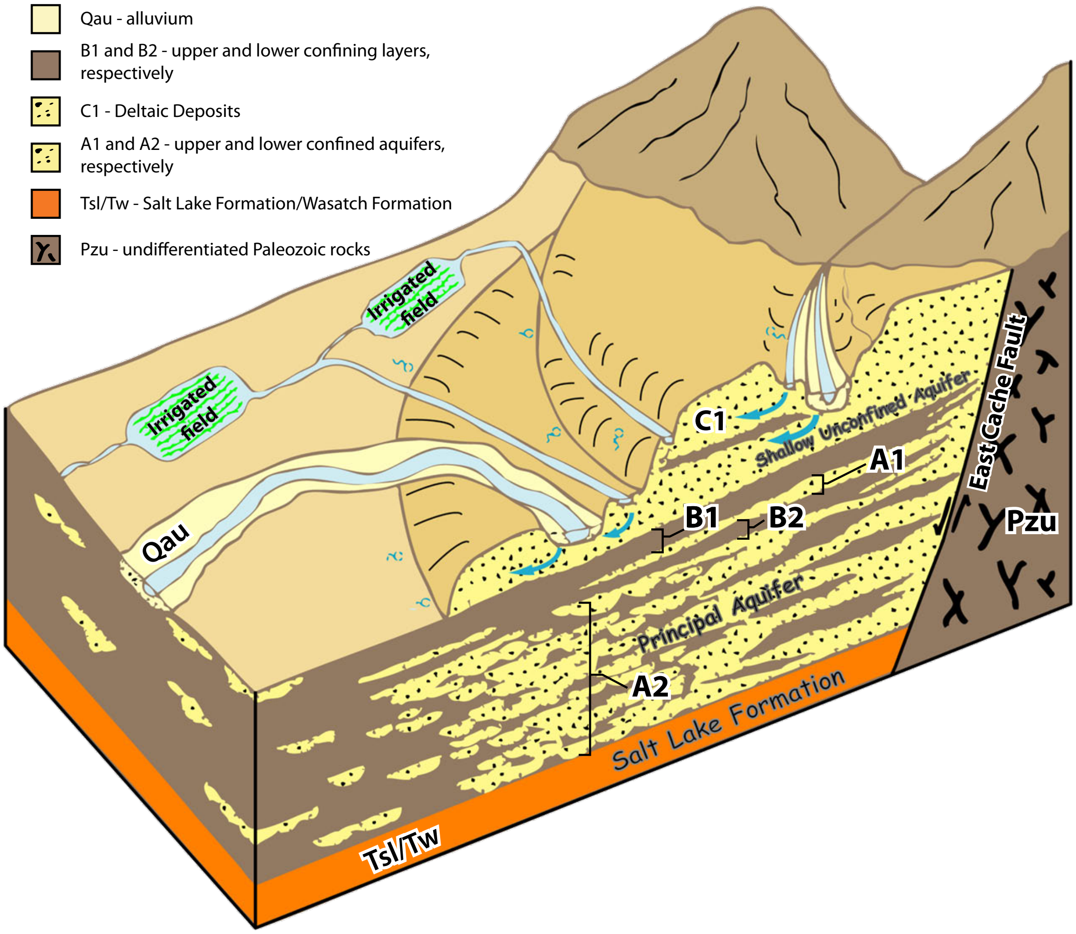


Figure 4. Conceptual block diagram of Cache Valley hydrostratigraphic units (modified from Olsen, 2007). See table 1 for a description of the units. This diagram best represents the area near Logan, Utah. Near North Logan, the Salt Lake Formation is closer to the land surface.

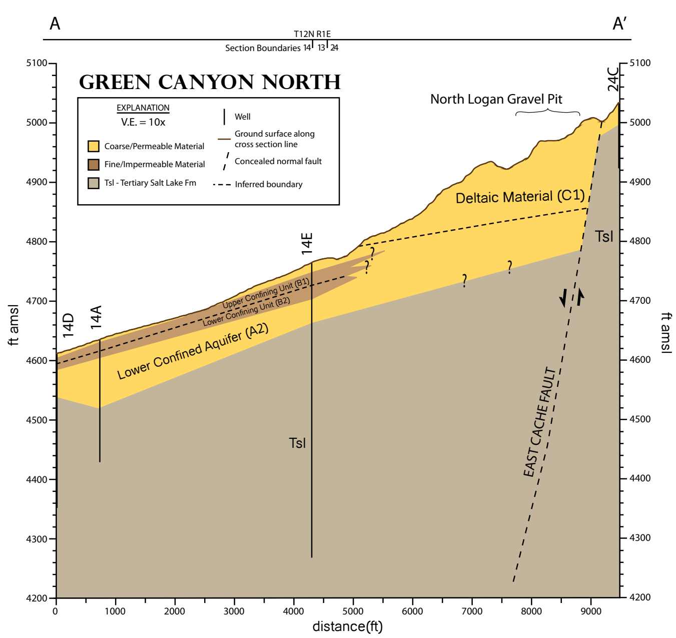


Figure 5. Geologic cross section of the area near the mouth of Green Canyon, modified from Thomas and others (2011). The location of this cross section is shown on figure 2. Well data are in Thomas and others (2011).

Groundwater Conditions

Occurrence

The principal aquifer (figure 3), the primary aquifer for water-well-derived drinking-water supplies, consists of a complex multiple-aquifer system under both unconfined and confined conditions (Bjorklund and McGreevy, 1971; Kariya and others, 1994). Bjorklund and McGreevy (1971) concluded that groundwater in the principal aquifer is mostly under unconfined conditions along the margins of Cache Valley, but is under confined conditions in many areas toward the center of the valley where many flowing wells exist.

The boundary between unconfined and confined conditions is gradational near the margins of the basin. The confined portion of the principal aquifer typically is overlain by a shallow unconfined aquifer (Bjorklund and McGreevy, 1971). Thomas and others (2011) concluded that both confining layers continue nearly to the mountain front in low areas between deltas (figure 5).

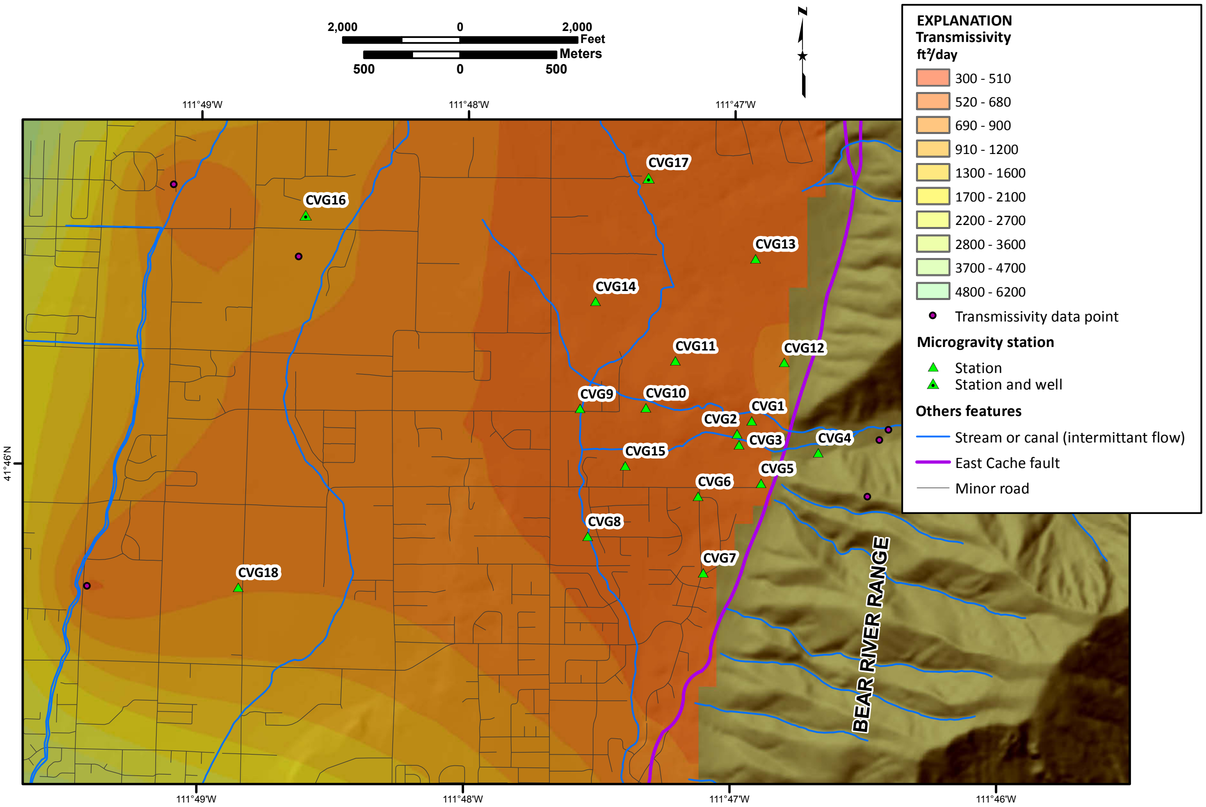


Figure 6. *Results of co-kriging all horizontal transmissivity values from specific capacity and aquifer test data. Modified from Inkenbrandt and Lachmar (2012). Note that uncertainty of transmissivity is high near the edges of the valley due to sparsity of transmissivity data.*

Depth to Groundwater

Depth to groundwater in unconsolidated deposits in Cache Valley ranges from at or near the ground surface in the central portion of the valley to more than 300 feet in deltaic areas along the valley margins (Bjorklund and McGreevy, 1971). Seasonal water-level changes range from a few feet to about 20 feet (figure 12 of Kariya and others, 1994).

Groundwater Flow

Groundwater flow in Cache Valley's principal aquifer is north-northwest in southern Cache Valley. In most of the valley, groundwater flow is typically from adjacent topographic highlands toward the valley center, generally toward the Bear River (Bjorklund and McGreevy, 1971, plate 4). Horizontal hydraulic gradients are higher near the valley margins, and decrease toward the center of the valley (Kariya and others, 1994).

Hydrologic Budget

Recharge to the basin-fill aquifer system is from infiltration of precipitation, streams, canals, ditches, and irrigated fields, and by subsurface inflow from consolidated rock along valley margins (Kariya and others, 1994). The two continuous confining layers (table 1), which extend across most of the valley, constrain a majority of the valley surface infiltration to the shallow, unconfined aquifer. Recharge to the confined gravel layers that make up the bulk of the principal aquifer is limited to surface infiltration at areas in the valley where the clay layers are discontinuous or not present and to infiltration from the adjacent mountains. Most recharge takes place in areas along the valley margins (figure 3) where unconsolidated materials have the greatest permeability and vulnerability to surface sources of pollution (Bjorklund and McGreevy, 1971).

Discharge from the basin-fill aquifer includes evapotranspiration, well-water withdrawal, and seepage to springs and Cutler Reservoir (Kariya and others, 1994). Of the major streams in Cache Valley, the Bear River, including Cutler Reservoir, receives the largest amount of groundwater discharge from seepage (Kariya and others, 1994).

Groundwater uses include the following: municipal water supply, domestic water supply, agricultural irrigation and stock watering, and municipal and industrial uses. Although some wells and springs in fractured rock are used for public water supply in Cache Valley, some of the public water supply and most domestic water supply are obtained from wells completed in the confined, unconsolidated aquifers of the basin-fill aquifer, most of which would be considered the principal aquifer (Robinson, 1999).

For the year 1990, discharge exceeded recharge in the Cache Valley aquifer system by an estimated 117,000 acre-feet (Kariya and others, 1994). The recharge for 1990 was 214,000 acre-feet, 101,000 acre-feet of which was from canal seepage, whereas discharge was 331,000 acre-feet, of which 130,000 acre-feet was released as seepage to streams and reservoirs. Bjorklund and McGreevy also considered seepage from canals as an important source of recharge. Water budgets from Myers (2001) and Kariya and others (1994) indicate a water-budget deficit (groundwater storage decrease) during years of lower than average precipitation. The budgets are based on groundwater-level and precipitation data (Rowland, 2009), especially during the relatively dryer periods of the early 1990s and 2000s.

The Green Canyon gravel (infiltration) pit is near a number of water supplies with discharges adequate to conduct an ASR project. The closest water supply is a diversion of the natural channel from the Green Canyon catchment (figure 3). The next closest water supplies are the Logan, Hyde Park, and Smithfield canals and three wells owned by North Logan, the Green Canyon Wells 1, 2, and 3. These wells have an outlet that feeds into the Logan, Hyde Park, and Smithfield canals, and thus could be used to supplement water-use requirements of an ASR project.

Groundwater Quality

Groundwater quality in Cache Valley's principal aquifer is generally very good, with calcium, magnesium, and bicarbonate composing the major dissolved constituents. Bjorklund and McGreevy (1971) reported total-dissolved-solids (TDS) concentrations to be mostly below 800 mg/L, though warm saline groundwater having TDS concentrations in excess of 1600 mg/L has been documented near Newton.

Lowe and others (2003) sampled 165 wells and one spring in 1997. TDS concentrations ranged from 178 to 1758 mg/L, having an average background TDS of 381 mg/L (Lowe and others, 2003). Most of the groundwater in the principal aquifer has TDS concentrations of less than 500 mg/L. The spring yielded water with a TDS concentration of 368 mg/L. Nitrate-plus-nitrite concentrations in Cache Valley's principal aquifer ranged from less than 0.02 to 35.77 mg/L, with an average (background) nitrate concentration of 1.9 mg/L.

METHODS

Introduction

The objectives of this study are to better understand the recharge (into the ground) of seasonal runoff at the infiltration pit and through the basin-fill sediments at the mouth of Green Canyon, and to determine, if possible, which aquifer unit(s) store the infiltrating water. To do this, we conducted a field survey of the area, then estimated local groundwater flow conditions, the amount of water infiltrating into the aquifer system at the pit, the behavior of the infiltrating water, the impacts on the North Logan community, the direction and volume flow of groundwater, and the groundwater flow from the infiltration area to the surrounding aquifers.

Field Survey

Bob Fotheringham of Cache County made the UGS aware of the infiltrating water in early August of 2011, meaning that we were unable to record measurements before this time. Interviews with North Logan City officials did not yield information on when the infiltration pits were constructed. Estimates of timing of the construction of the infiltration pits are discussed further in the Results and Discussion section of this report.

To better understand the surface water and groundwater systems surrounding the area of the upper and lower infiltration pits (figure 3 inset), we first surveyed the infiltration area. We also determined the dimensions of the infiltration pits and the amount of surface water flow into the ASR site to estimate the amount of water that infiltrated into the ground at the pits.

We visited the field area a total of five times. During the initial visit (August 4, 2011), we photographed the gravel pit area and established locations for the hydrologic and microgravity measurements. Owing to their complexity and importance to the study, the microgravity measurements will be discussed separately (see Gravity Method section). During the following four visits (table 2), we photographed the area, recorded gravity measurements, and measured hydrologic parameters. We also measured the dimensions and elevation of the infiltration pits and the elevation of the water surface in the main infiltration pit.

During each field visit, we captured several hundred photographs of the infiltration pits and surrounding area to record hydrologic and geomorphic changes over time. We took several panoramic pictures from different angles (figures 7, 8, and 9).

Hydrologic Measurements

Hydrologic measurements consisted of the elevation of the water standing in the upper (main) infiltration pit (figure 10), the flow of surface water to the main pit, depth to water in two wells, and discharge of USU Sheep Spring (figure 3). We measured the elevation of the water ponding in the main infiltration pit using a staff gage located near the middle of the pit, coupled with high-accuracy (<1 cm) Trimble Global Navigation Satellite (GNSS) equipment using the TURN Global Positioning System. We measured the flow of surface water into the gravel pit and the outflow of Sheep Spring with an open-channel field stream velocity meter. We used an electronic water-level measuring tape to measure the depth to water in the wells. In the well at CVG 16, we measured groundwater level hourly with a pressure transducer from September to October.

We determined the dimensions of the infiltration areas by walking several transects with a high-accuracy continuously

Table 2. *Timeline of events at the infiltration pits near the mouth of Green Canyon.*

Date	Qualitative hydrologic conditions	Field work completed	Other activities
Early May to early June, 2011	Snowpack begins to melt (figure 18) and flow down Green Canyon in the form of surface water flow.		In anticipation of large amounts of surface flow, North Logan City builds infiltration pits at the mouth of Green Canyon.
Middle to late June, 2011	Aerial photographs, snowmelt, and river hydrographs (figures 16 and 18) indicate peak flow of surface water out of Green Canyon and into the infiltration pits occurred. Flow from Green Canyon exceeded the capacity of the upper and lower infiltration pits and flowed into two ponds downstream of the infiltration pits.		Aerial photography flown in late June (Microsoft, 2012).
8/4/2011	Large amount of water ponded in upper pit and some water ponded in lower pit. Steady stream of surface water flowing into upper pit area.	Initial field visit by UGS.	
8/10/2011–8/11/2011	Less water ponded in pits and flowing into pit area than during prior UGS visit on 8/4/2011.	Gravity sites selected; 1st round of gravity and hydrologic measurements began.	Aerial photography flown on 8/11/2011 (Google, 2012).
9/21/2011–9/22/2011	Less water ponded in pits and flowing into pit area than during prior UGS visit on 8/11/2011.	2nd round of gravity and hydrologic measurements collected.	
10/26/2011–10/27/2011	More water ponded in pits and flowing into pit area than during prior UGS visit on 9/22/2011, but still much less water than observed on 8/11/2011.	3rd round of gravity and hydrologic measurements collected.	
3/21/2012–3/22/2012	No water flowing into pits from main canal. Small flow (<10gpm) of water flowing into upper pit from Park Pond overflow. Very small amount of water ponding in upper pit.	4th round of gravity and hydrologic measurements collected.	

recording Trimble GPS. We also measured and identified points of interest, such as the elevations of outflow pipes, highest elevation of deposited silt, the shape and elevation of the impoundment structures (dams), and the location and elevations of the two inflow streams (figure 10). We interpreted the maximum elevation of fine silt deposits as the highest water level that occurred in each of the two infiltration pits. The GPS measurements we recorded are rough measurements and should not be used for definitions of legal boundaries or other legal purposes. Elevation accuracy was limited by the measurement technique of carrying the device while it was measuring and is within one foot of the actual elevation for the pits' dimensions, and within an inch of the actual elevations of the water levels.

Groundwater Infiltration Estimates

We did not directly measure the infiltration of water into the ground at the infiltration pit site. Instead, we assumed that all surface water flowing into the pit was being infiltrated into the ground at the main pit, with the exception of a minor part of the water being lost to evaporation. We assumed that most of the surface water that flowed into the pits infiltrated into the ground and that surface flow to the pit was steady between measured events. We then linearly interpolated the infiltration rate between the measurement events to determine the total water infiltrated.

We made a digital elevation model (DEM) of the area of the infiltration pits by interpolating the elevation and location points recorded in the field and draped the DEM with aerial photography. We then manually adjusted the DEM to match and align the draped photography to field-collected photographs (figure 10).

Using the DEM of the infiltration area and water elevation data collected in the field, we estimated the volume of water ponded in the main infiltration pit during each event (field water level measurements, aerial photographs, and elevation of silt deposits). We calculated the volume of water in the main pit during each event by subtracting the elevation of the bottom of the main pit from a level plane representing the surface of the water at the time of each event. We estimated the maximum volume of standing water ponded in the infiltration areas using the elevation of the bottom of the discharge pipes and the maximum elevations of silt deposits.

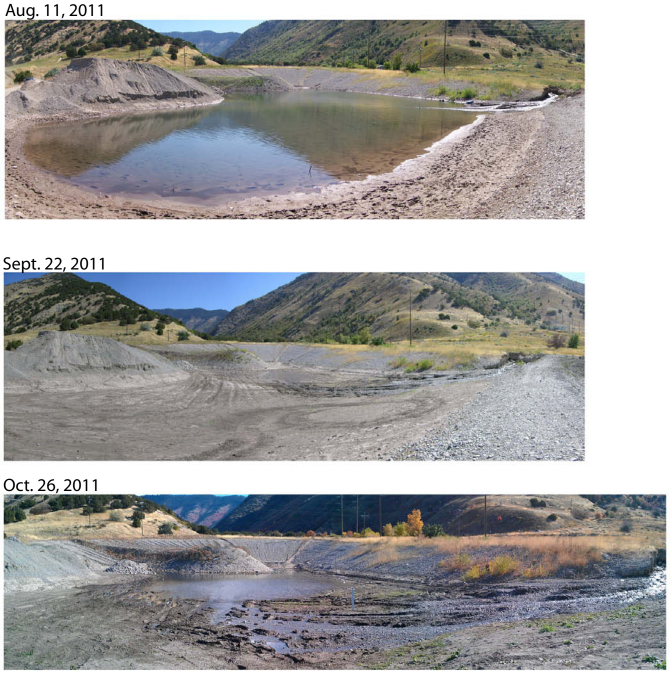


Figure 7. *Panoramas of the upper (main) pit looking southeast towards Green Canyon, taken on three occasions.*

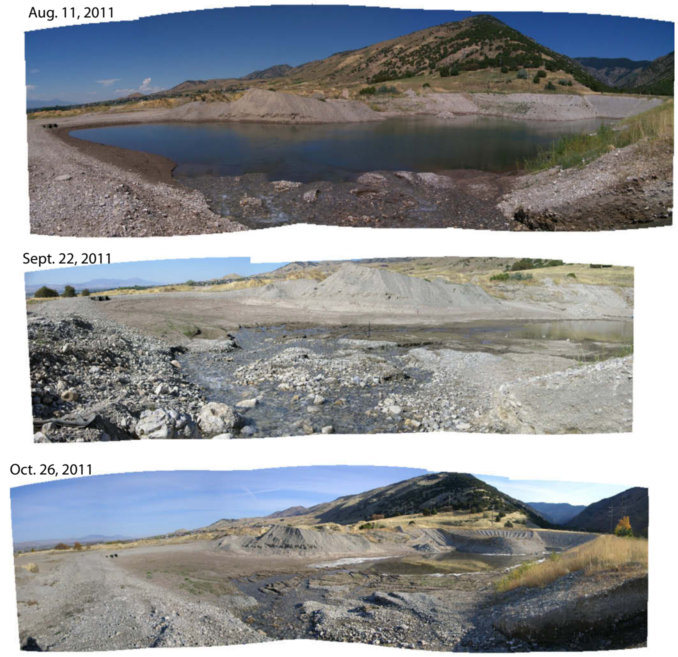


Figure 8. *Panoramas of the upper (main) pit looking northeast near the delta, taken on three occasions.*

Figure 9. *Panoramas of infiltration pits from September and October, 2011, taken from a benchmark at 5086 ft in the SE1/4NE1/4 section 24, T. 12 N., R. 1 E., Salt Lake Base Line and Meridian, looking northwest.*

At the time of each of our field-based main pit water level and flow measurements, water was not flowing through the overflow pipes from the upper (main) infiltration pit (figure 10). For each measurement, we have assumed that the amount of water infiltrating at the main pit is equivalent to the amount of surface water flowing into the pit area from the channel(s) (minus some loss to evaporation) (figure 11). This assumes that the water level in the pit is at a steady state at the time of measurement, and only rises or falls in response to changes in input surface water flow.

The relationship between inflow into the pit and water levels was approximated by linear correlation of measured surface water inflow to the area in the main pit available for infiltration at the time of measurement. To determine the exact surface area of each measurement event, we used the DEM and the measured pond water-level elevations. Using three sets of main pit water level and surface water flow measurements in combination with high precision pit dimension measurements, we correlated surface area of infiltration in the upper pit to surface water flow into the pit from the contributing streams (table 3). The linear equation describing the correlation is:

$$q = 0.00027 \times A - 2.0312 \qquad (1)$$

where:

q = surface water flow into upper pit (in ft^3/sec)

A = surface area for infiltration (in ft^2)

The relationship is only based on three field-measured points, but has an r^2 value of 0.998.

Based on this relationship between main pit water levels, which dictate pit surface area available for infiltration, and flow into the pit established from the correlation, we estimated surface water flow into the pit during the highest water levels (based on highest silt elevations) and during dates of aerial photography. Using dated aerial photographs and the DEM we created, we were able to estimate the elevation of water in the pit in the photographs based on the lateral extent of the water, which enabled us to estimate the volume of water in the pits at the time of the aerial photograph and the surface area in the pits covered by water (area available for infiltration).

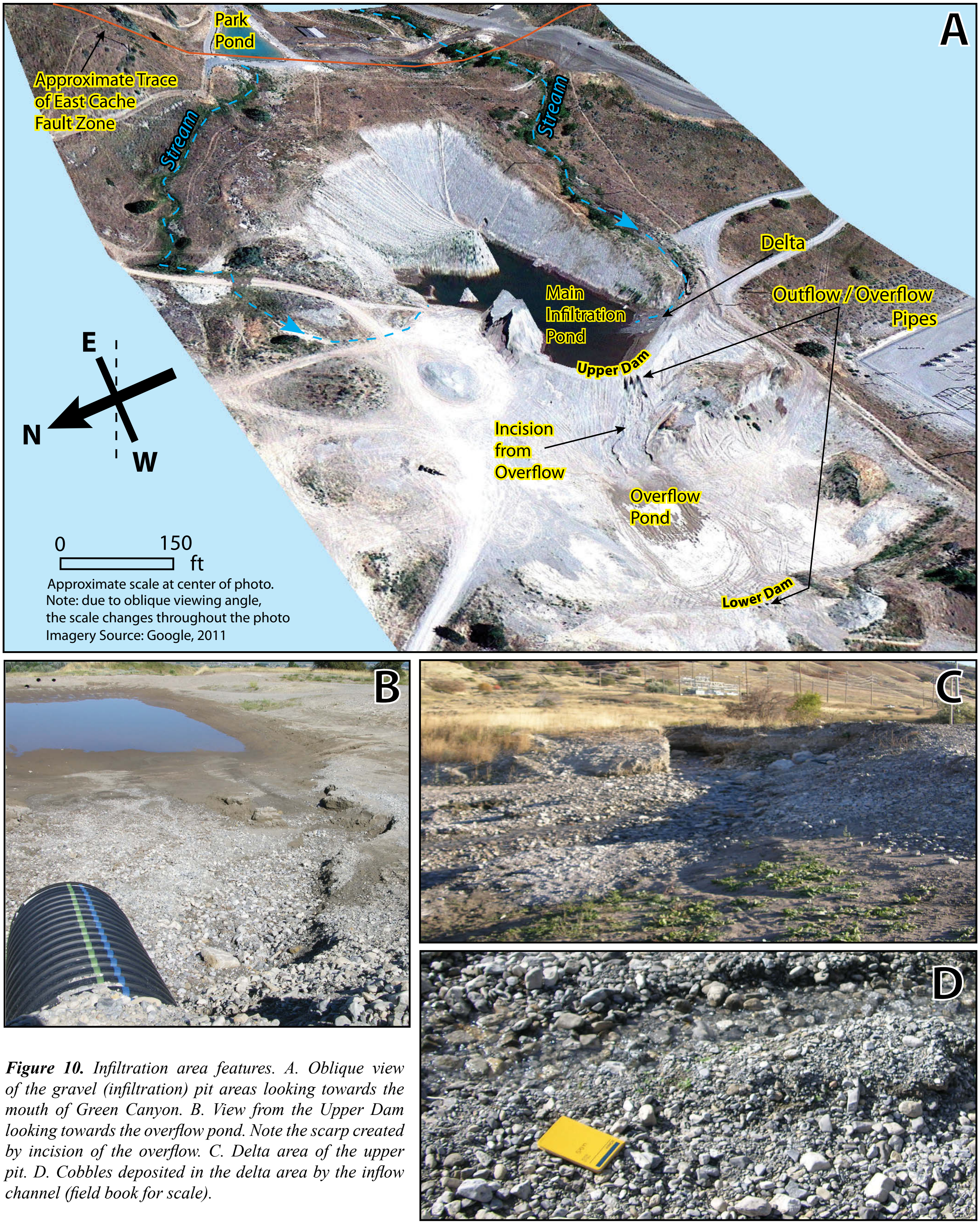


Figure 10. *Infiltration area features. A. Oblique view of the gravel (infiltration) pit areas looking towards the mouth of Green Canyon. B. View from the Upper Dam looking towards the overflow pond. Note the scarp created by incision of the overflow. C. Delta area of the upper pit. D. Cobbles deposited in the delta area by the inflow channel (field book for scale).*

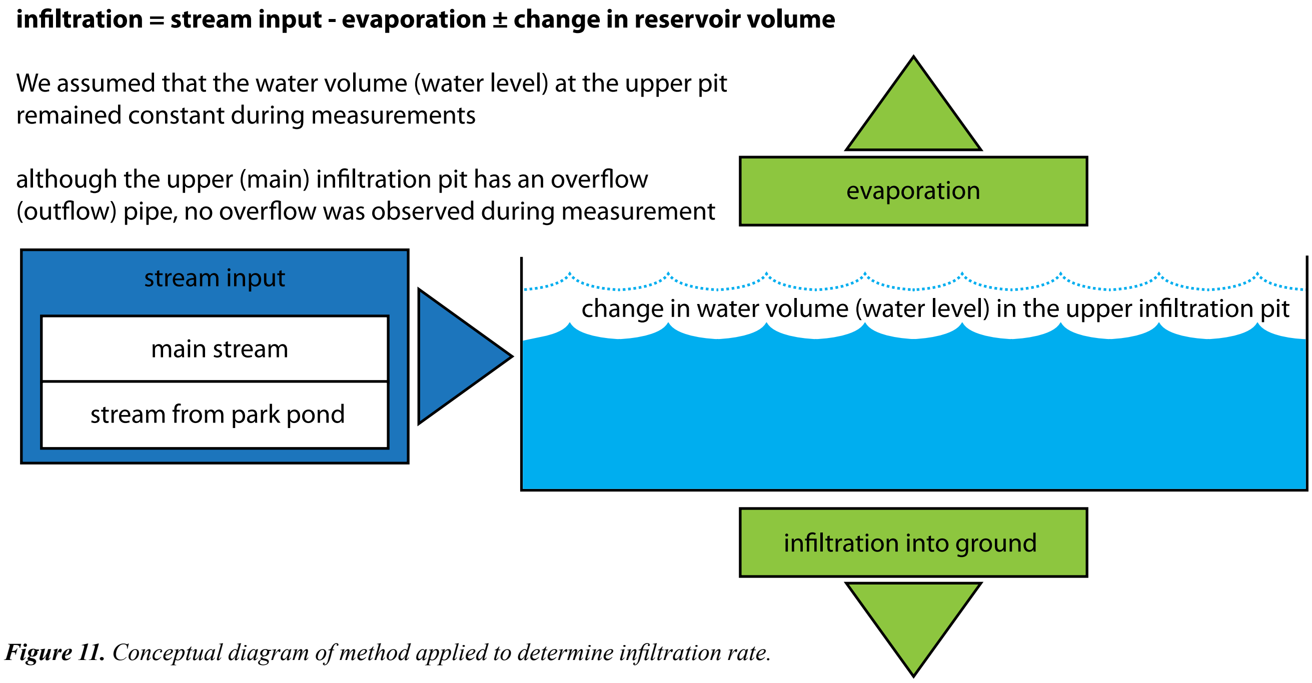


Figure 11. Conceptual diagram of method applied to determine infiltration rate.

We assumed that the start date of infiltration was May 11, 2012, when soils at the SNOTEL station reached maximum soil moisture, and when SNODAS shows a large spike in snowmelt rates (National Operational Hydrologic Remote Sensing Center, 2004). We also assumed zero infiltration at the start date, then linearly interpolated between values of infiltrated water volumes. We discretized the infiltration rates to get daily values of infiltration rate, and then summed the daily values to get the estimated cumulative volume of water infiltrated into the upper infiltration pit.

Infiltration Model

To predict the possible behavior of the infiltrating water, we created a simplified infiltration (groundwater change) model using AQTESOLV (Duffield, 2006) (figure 12). The model treated the infiltration pits as horizontal wells having negative discharges (table 4) and incorporated discharges of the Logan City wells southwest of the site. We added a constant head boundary 500 feet east of the gravel pit area (east of the North Logan City wells in Green Canyon) to account for the east to west gradient and inflow of water coming in from the mountainous area. For the model, we used a bulk transmissivity of 750 feet/day, a storativity of 0.02, and an aquifer thickness of 520 feet, based on nearby measured values (Robinson, 1999; Inkenbrandt, 2010). The bulk values group the aquifer properties of the Salt Lake Formation, the fractured carbonates of the Bear River Range, and the alluvium, and do not consider heterogeneities like the East Cache fault, or lenses of materials of differing aquifer properties. The estimated infiltration rates of the infiltration ponds and the North Logan wells are listed in table 3. The dimensions applied to the horizontal wells that represent the pit in the model were 100 ft (30 m) length and 32 ft (10 m) diameter, which is an approximation of the area avail-

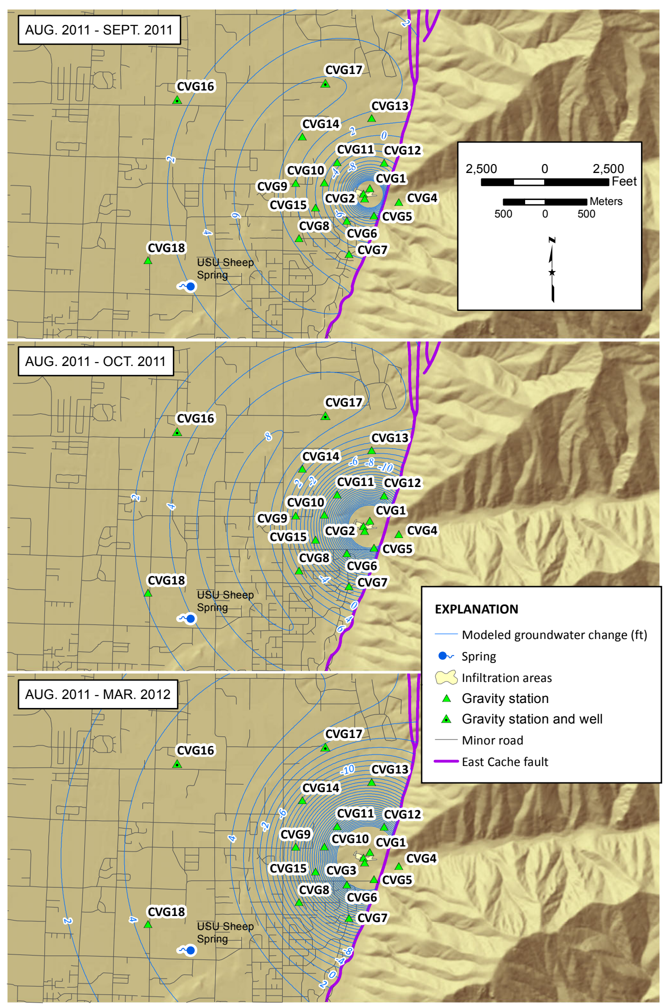


Figure 12. Modeled groundwater change based on the estimates of infiltrated water into Green Canyon gravel pits. A positive number indicates an increase in groundwater level over time.

Table 3. *Estimated infiltration rates at the infiltration pit. Values for 6/25/2012 were estimated from the elevations of the maximum extent of the area covered in silt.*

Date	Volume of water in pit	Area of infiltration	Stream input	Evaporation	Infiltration rate[3]	Infiltrated water[4]	Infiltrated water[4]
	ft^3	ft^2	ft^3/sec	ft/day	ft/day	ft^3/day	ac-ft/day
6/25/2011[1]	224,130[2]	58,650[2]	13.4	0.49	19	1,132,540	26
8/11/2011	104,190	44,500	10.0	0.49	19	843,670	19
9/22/2011	2300	9290	0.1	0.49	7	66,390	2
10/27/2011	5850	14,700	2.2	0.49	12	181,870	4

[1] *The estimated date of 6/25/2012 is based on the date of peak flow for the Logan River and an aerial photograph dated in late June of 2011 (Microsoft, 2012).*

[2] *Values estimated from the elevations of the maximum extent of the silt, minimum elevations of outflow pipes, and aerial photography (Microsoft, 2012).*

[3] *Infiltration rate is equal to stream input divided by area of infiltration minus evaporation.*

[4] *Infiltrated water equal to stream input minus evaporation.*

Table 4. *Locations and discharge rates used to model the mounding of groundwater created by infiltrating water.*

	UTM Easting (m)	UTM Northing (m)	Date	Days	Discharge[1][3] (m^3/d)	Discharge[1] (ft^3/d)
Upper Pit	434984	4624348	6/25/2011	0	-32,070	-1,132,540
			8/11/2011	47	-23,890	-843,670
			9/22/2011	89	-1880	-66,390
			10/27/2011	124	-5150	-181,870
			11/22/2011[2]	150	0	0.00
Lower Pit	434856	4624372	6/25/2011	0	-15000	-6.1
			8/11/2011	47	0	0.00
North Logan Well 1	435524	4624286	6/25/2011	0	850	0.4
			7/25/2011	30	2880	1.2
			8/24/2011	60	3080	1.3
			9/23/2011	90	2110	0.9
			10/23/2011	120	160	0.1
			11/22/2011[2]	140	0	0
North Logan Well 2	435623	4624414	6/25/2011	0	450	15,890
			7/25/2011	30	1820	64,270
			8/24/2011	60	1905	67,270
			9/23/2011	90	1175	41,490
			10/23/2011	120	81	2860
			11/22/2011[2]	140	0	0.00

[1] *The term "discharge" refers to infiltration of water into the ground when the sign is negative and pumping from a well when the sign is positive.*

[2] *The last value on 11/22/2011 is a date when infiltration was assumed to be negligible. The model required a date of discontinued infiltration and we did not record measurement on 11/22/2011.*

[3] *Well pumping data was based on monthly use data reported by North Logan (Utah Division of Water Rights, 2012).*

able for infiltration in both pits. Dimensions for the North Logan wells were taken from the well drillers' logs (appendix A).

Local Groundwater Conditions

We examined existing groundwater-level data to determine: 1) the dominant direction of groundwater flow, 2) the horizontal groundwater gradient, and 3) changes in groundwater levels in the area over time.

Potentiometric Surface Map

To understand where groundwater moves in the area near Green Canyon, we created a potentiometric surface (groundwater level) map for the area from existing groundwater-level data (figure 13). The potentiometric surface map indicates groundwater flow direction and horizontal groundwater gradients, which are useful in understanding where infiltrating water is moving.

We compiled data from existing springs from NHDplus database (USEPA and USGS, 2005), groundwater levels from the U.S. Geological Survey (USGS) National Water Information System (NWIS) database (USGS, 2001), and groundwater levels from the Water Rights Points of Diversion (WRPOD) database maintained by the Utah Division of Water Rights (UDWR). We collected all available data for Cache County, over all available times, from 1905 to 2012.

Using a 30-feet horizontal resolution DEM from the USGS National Elevation Dataset (NED) (Gesch, 2002; Gesch and others, 2007), we attributed elevation values to each dataset. To determine groundwater-level elevation (total head) for the NWIS and WRPOD data, we subtracted measured depth to groundwater from the DEM elevation at each point's location. For the spring data, we assumed that the surface elevation of the NHDplus springs represented the general potentiometric surface, although not all springs are continuously flowing and some springs may have total heads greater than that of the land surface elevation.

We interpolated the groundwater-level elevation values, using a natural neighbor technique (Sibson, 1981) that produces a smooth (not angular) result, is local (uses only a subset of points surrounding a query point), and has interpolated heights that are guaranteed to be within the range of the samples used. Multiple groundwater-level elevations at the same point recorded at different times were averaged to eliminate multiple records at one location.

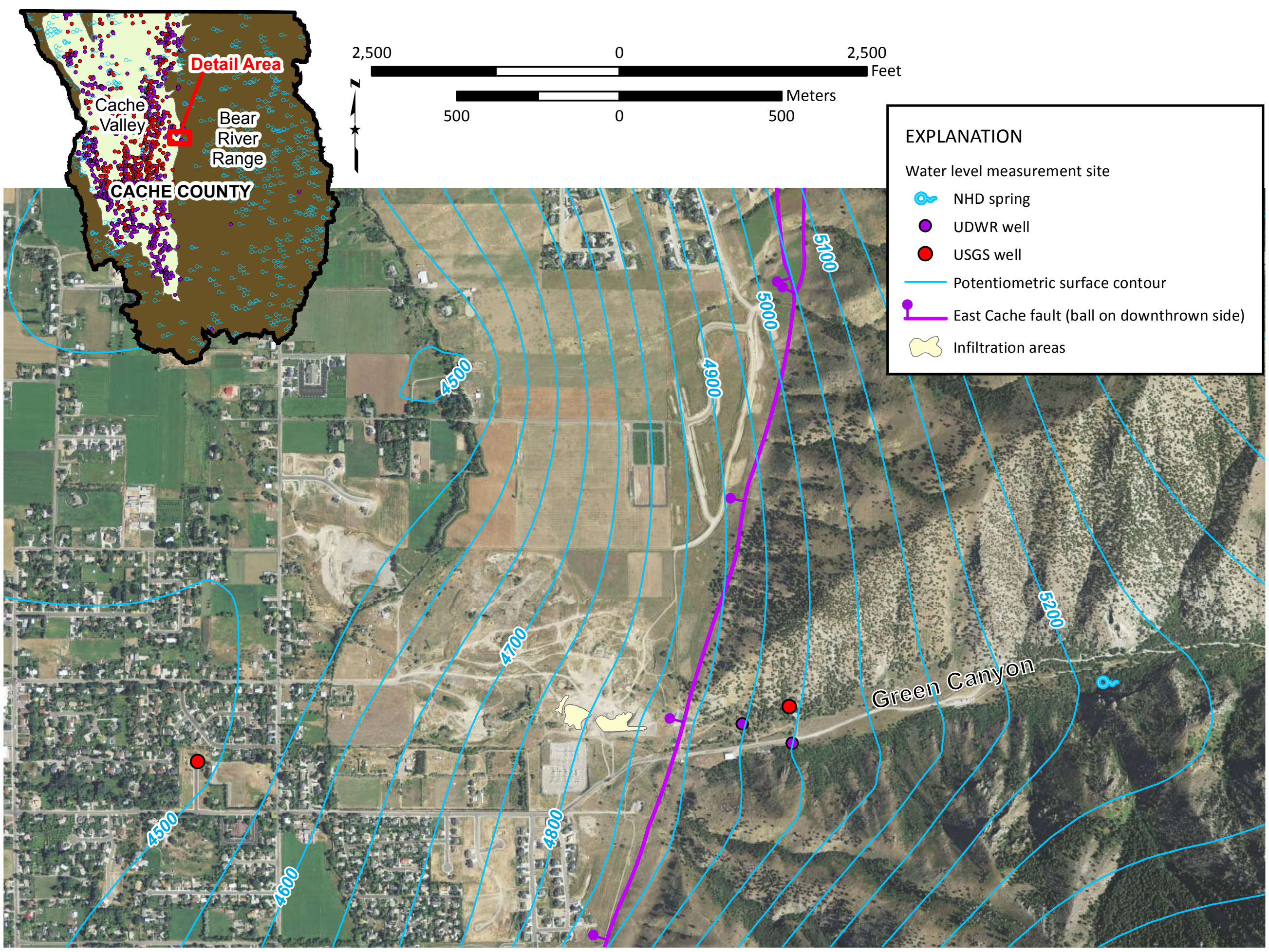


Figure 13. Potentiometric surface map of area near gravel pits and mouth of Green Canyon. All wells and springs in Cache Count were used to make the map. Base aerial photograph from Google (2011).

We calculated the slope and aspect of the potentiometric surface map. The slope of the potentiometric surface is equivalent to the horizontal hydraulic groundwater gradient of the area, and the slope direction indicates the horizontal groundwater flow direction (figure 14).

Groundwater-Level Time Series

We examined water levels over time in selected wells in the NWIS database nearest to the gravel pit that had multiple measurements from 2011 to 2012 (plate 1). We plotted each well's water-level series by feet of total head above mean sea level from January 2011 to June 2012 (figure 15). We also examined stream discharge to investigate relationships between surface water and groundwater (figure 16).

Hydrologic Budget

To understand the movement and flow of infiltrated water at the mouth of Green Canyon, we have to understand the quantity and timing of water moving through the upgradient Green Canyon catchment. Several factors determine how much and when water ultimately reaches the area of infiltration (figure 17): precipitation, recharge into the mountain bedrock and Green Canyon alluvium, the timing of snowmelt, water lost to the subsurface and adjacent basins, water lost to evapotranspiration, and water captured and released by North Logan City. We estimated the water budget for the time from September 1, 2010, to September 30, 2011, to account for times when the snowpack is present and to adjust for limited availability of North Logan City data.

Precipitation and Snowmelt

We obtained Green Canyon catchment precipitation data from PRISM Climate Group (2012). We then used SNOTEL (NRCS, 2012) and SNOw Data Assimilation System (SNODAS) (National Operational Hydrologic Remote Sensing Center, 2004) data to estimate the timing and volume of snowmelt flow down Green Canyon.

The PRISM Climate Group (2012) weather station data are interpolated and adjusted for topography. To estimate the precipitation input, we downscaled PRISM precipitation data from a 2.5 mile (4 km) grid to a 0.3 mile (0.5 km) grid, and clipped it to the Green Canyon catchment; then we averaged the precipitation for each subcatchment within the greater Green Canyon catchment.

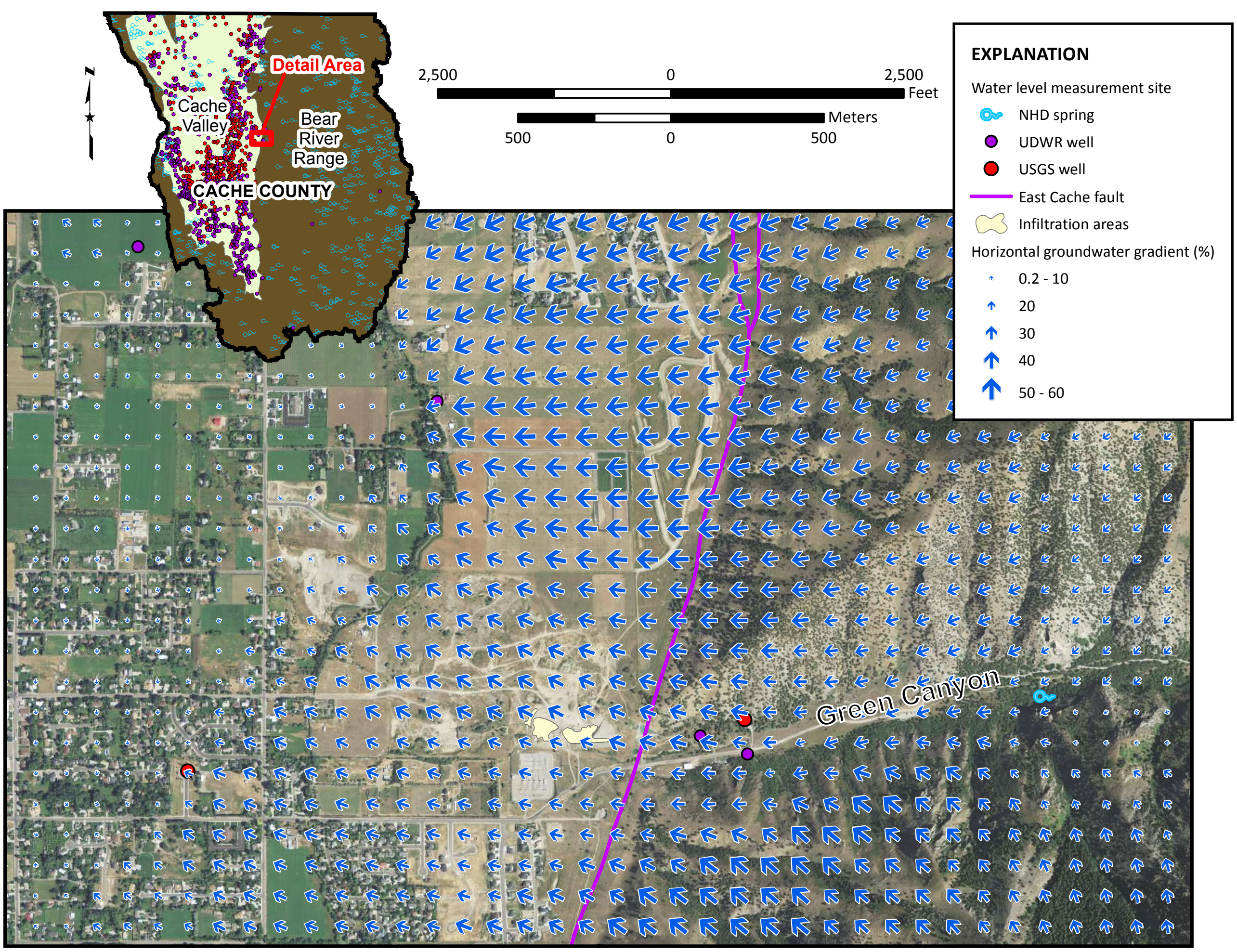


Figure 14. *Groundwater gradient and flow direction. The size and direction of the arrows indicate approximate slope of the potentiometric surface. The slope is steepest (gradient is highest) north of Green Canyon in the primary recharge areas. Base aerial photograph from Google (2011).*

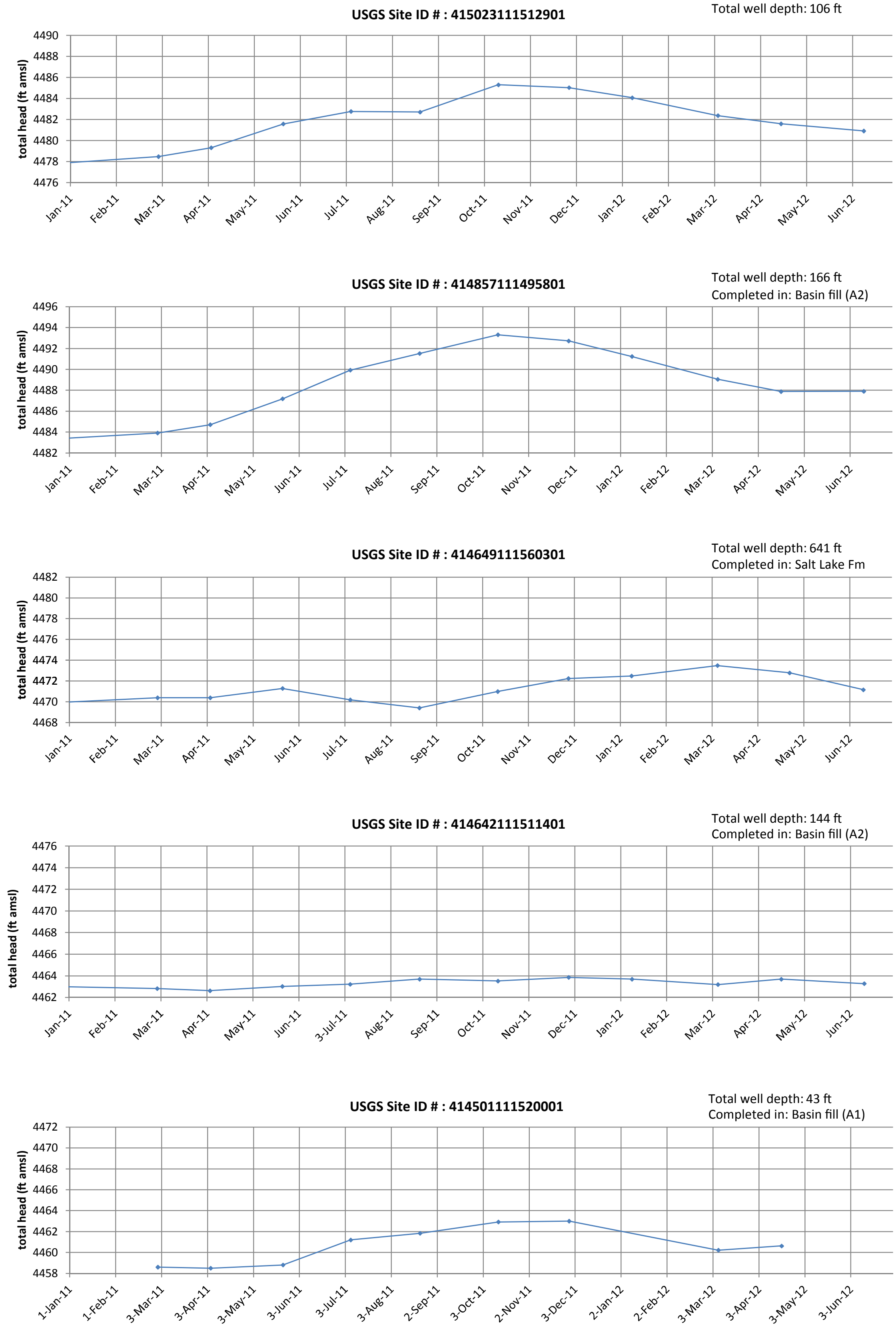
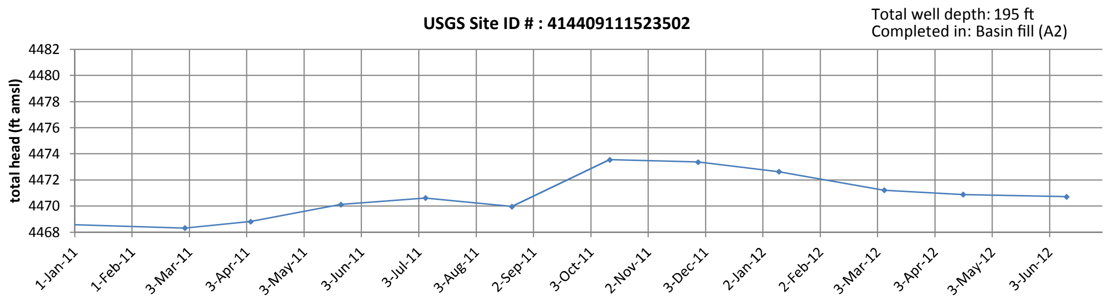
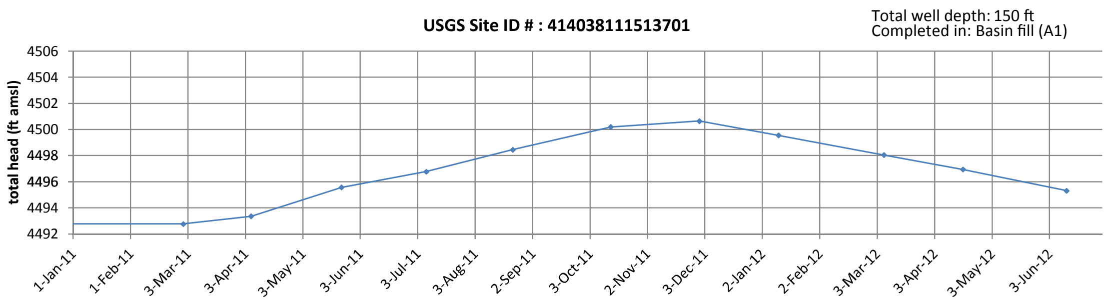
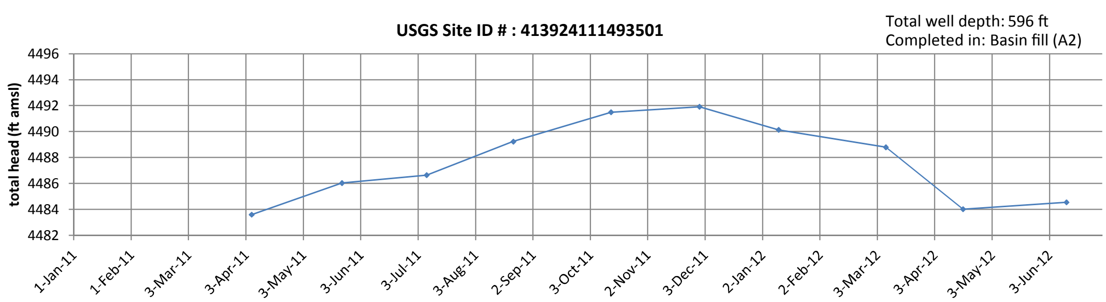
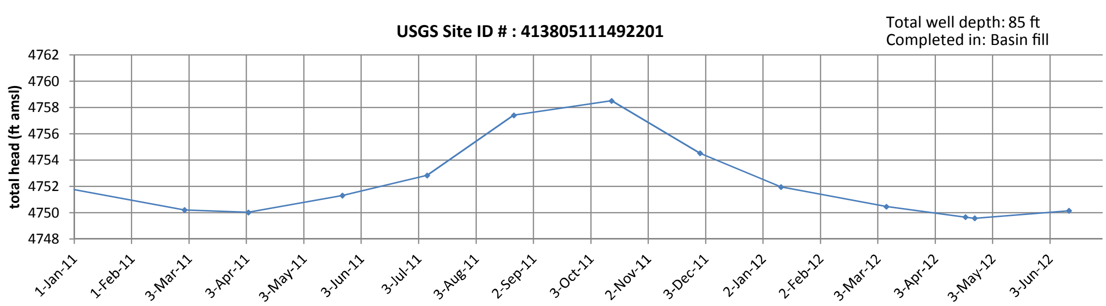


Figure 15. *Groundwater levels over time in wells monitored by the USGS. See plate 1 for well locations.*









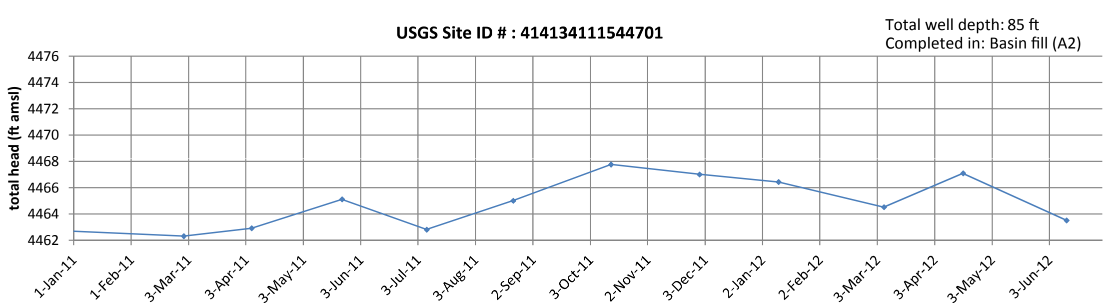


Figure 15. *Continued.*

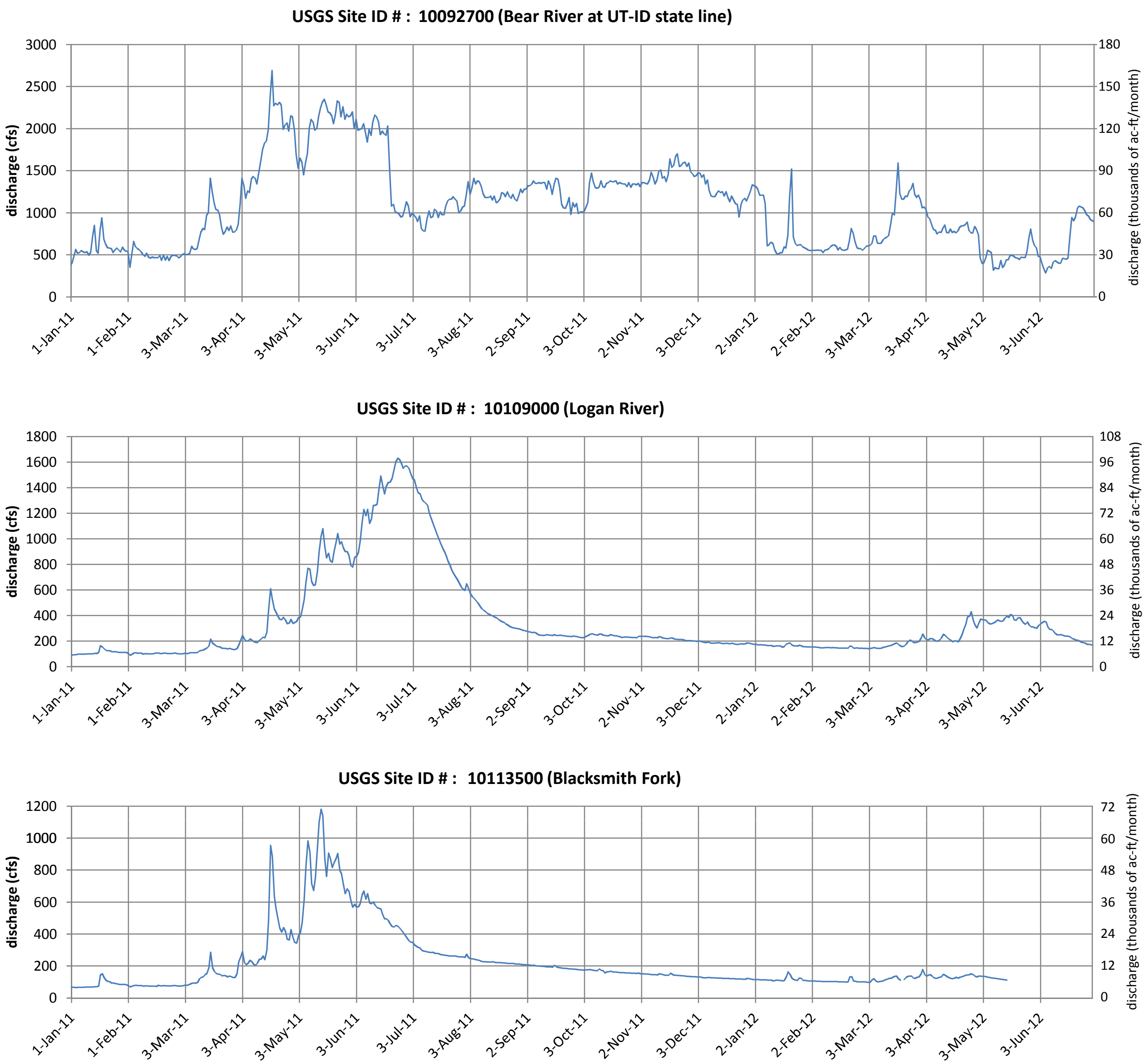


Figure 16. *Discharge over time in streams monitored by the USGS. See plate 1 for gage locations.*

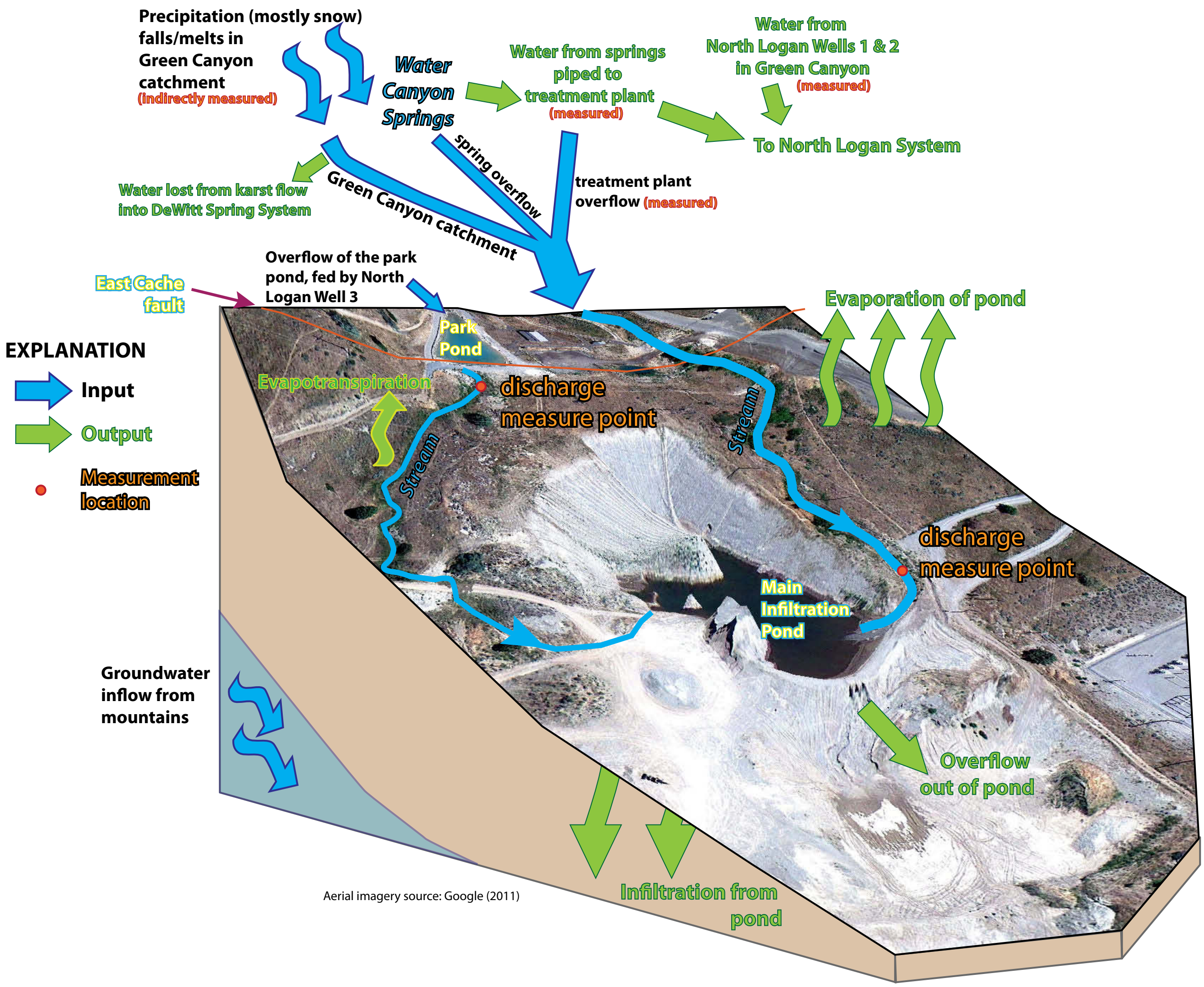


Figure 17. *Conceptual diagram of the Green Canyon catchment and the infiltration pond hydrologic budget.*

We processed SNODAS snowmelt and snow water equivalent (snowpack thickness) using a similar technique. SNODAS is a modeling and data assimilation system to provide estimates of snow cover and associated parameters (National Operational Hydrologic Remote Sensing Center, 2004). SNODAS integrates snow data from satellites, airborne platforms, and ground stations with model estimates of snow cover.

We compared snowmelt data for the Green Canyon catchment to data from the Tony Grove SNOTEL station, about one half mile northeast of the Green Canyon catchment. We also looked at soil moisture percentage at the Tony Grove station (figure 18).

North Logan City Water Treatment Plant

North Logan City owns and operates a water treatment plant (figure 19 A), and collects water from springs (figure 19 B) and three groundwater wells (the city measures water levels and discharge in only two of the wells; figure 19 C) in the mouth of Green Canyon. The water treatment plant does not treat well water, but treats water collected from Water Canyon Spring on the north fork of the canyon about four miles upstream of the plant. Water collected at the spring site and processed through the treatment plant is metered by North Logan City (figure 19B), and flow data are maintained by the Utah Division of Water Rights. To help manage excess flows into the treatment plant, North Logan City has an overflow pipe that diverts water (figure 19) into a ditch, which also serves as the output channel for the Green Canyon catchment. North Logan City also pumps water from Green Canyon well 3 into a pond that is upgradient of the infiltration pit. The overflow of the pond ultimately contributes to the surface water flowing to the pit.

Groundwater Recharge in the Mountains

To estimate the amount of water recharging into the mountains in the Green Canyon catchment, we applied a simplified Maxey-Eakin (1949) method. Using this method we assumed recharge in the mountain bedrock and alluvium in Green Canyon to be 25% of precipitation.

Water Lost to Other Basins

Spangler (2001) documented that water infiltrates into karst sinks along Water Canyon and Green Canyon and crosses the Green Canyon catchment boundaries, ending its course at DeWitt spring in Logan Canyon. The exact quantity of water lost has not been measured, but it is likely less than the approximately 10,000 ac-ft per year released by DeWitt spring (Utah Division of Water Rights, 2012). Assuming that the Green Canyon catchment contributes less than half of the annual flow to DeWitt spring (Spangler, 2001), we set the maximum potential loss to karst (interbasin flow) to 5000 ac-ft. While it is possible that more water may be lost to other basins via interbasin flow, it was not substantiated by Spangler (2001).

Evapotranspiration

Evapotranspiration was estimated using North American Land Data Assimilation System data (NLDAS, 2012). We used the 0.125-degree grid size monthly NLDAS data, modeled using NASA's NOAH land surface model. At 0.125-degree (roughly 8 miles) grid size, NLDAS data are fairly coarse and generally intended for use with larger basins, making it less reliable than other, finer data. To determine the evapotranspiration from NLDAS, we first downscaled the data to 3-mile (5 km) grid spacing, and clipped it to the Green Canyon catchment; we then averaged the evapotranspiration for each subcatchment within the greater Green Canyon catchment.

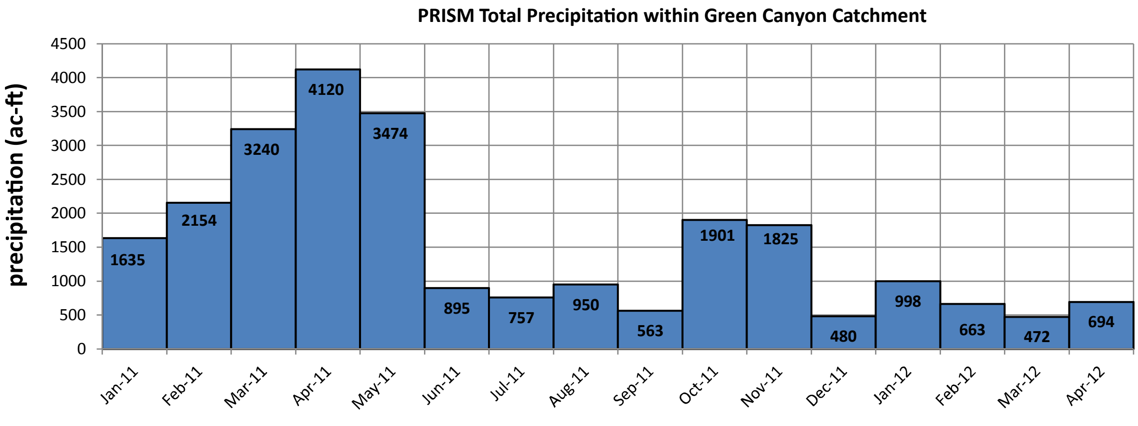
Gravity Method

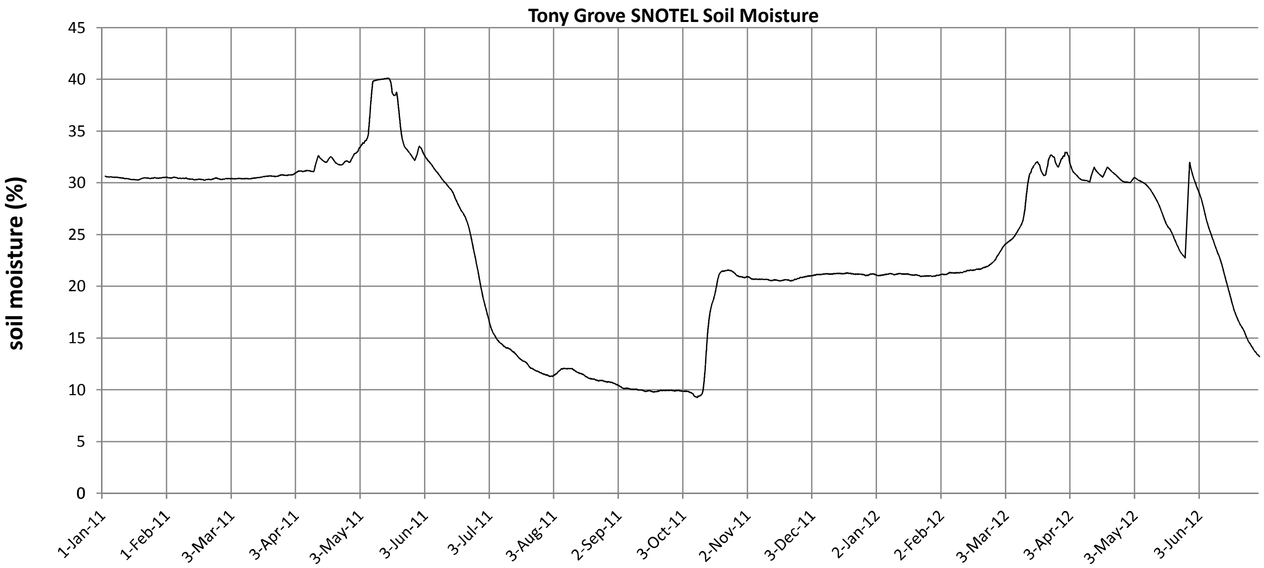
Water infiltrating from the gravel pit adds mass to the subsurface, which can be detected through careful, high-precision measurements of changes in gravity. Observed gravity changes can provide significant insight into groundwater storage changes of an aquifer (Pool and Eychaner, 1995; Chapman and others, 2008; Gettings and others, 2008). The repeating of station measurements along a series of nested loops helps to minimize uncertainty in the gravity data and enables more precise tracking of groundwater changes (Gettings and others, 2008).

The mean value of gravity at the Earth's surface is 9.8 m/s^2. In gravity surveys, the working unit Gal, for Galileo, is defined as 1 cm/s^2. Thus, the acceleration due to gravity at the Earth's surface is 980 Gal. For high-precision gravity surveys, signal amplitudes are on the order of µGal (10^{-6} Gal). A Scintrex CG-5 Autograv with a precision of 1 µGal was used to make gravity measurements for this study. Processing and analysis in accordance with Gettings and others (2008) results in measurement accuracy of 5 µGal.

Accurate determination of mass changes in a subsurface reservoir requires that station elevations be measured with high accuracy at the time of the gravity measurements to account for fluctuations in gravity due to changes in elevation. To minimize this error, we measured the ground elevation at each gravity site with a Trimble high-precision GNSS receiver using TURN. Reported errors in our elevation measurements were typically about 2 to 3 cm (table 5). Station locations are likely to have natural, relatively minor variations (up to 10 cm) in elevation. Given the vertical gravity gradient of -308.6 µGal/m, elevation changes affect the measured gravity at any location by up to 15 µGals (table 5). Most surveyed elevations had an absolute accuracy of better than 3 cm, resulting in gravity uncertainties due to elevation of less than 9 µGal, an acceptable value (table 5).

We established a network of 19 gravity stations (figure 20) around the Green Canyon gravel pit to provide temporal and spatial coverage of groundwater changes during and after in-





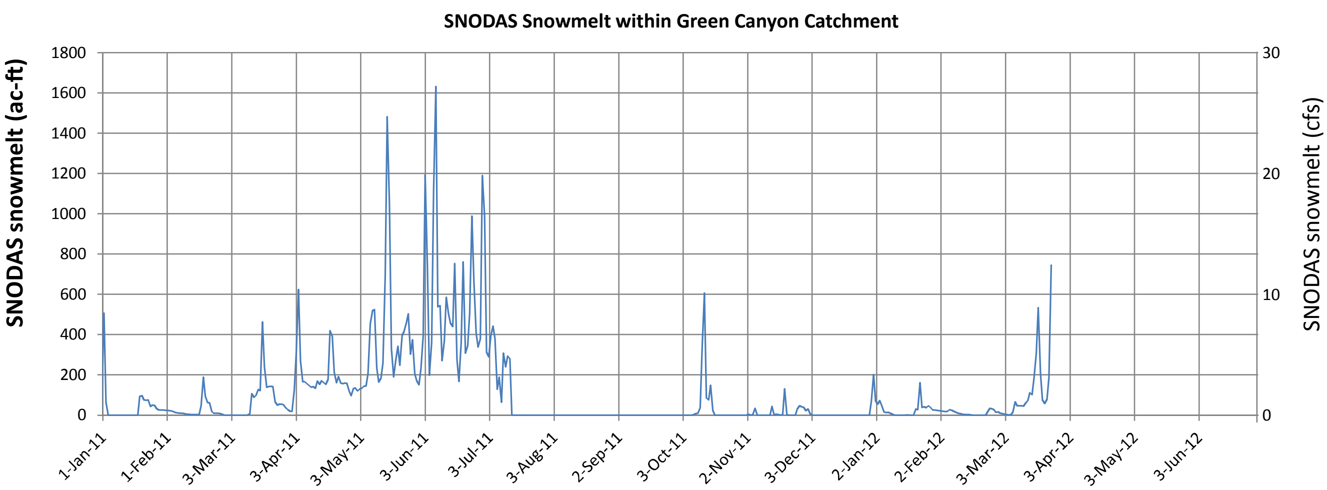


Figure 18. *Climate data from various sources. SNOTEL soil moisture is an approximation of snowmelt timing.*

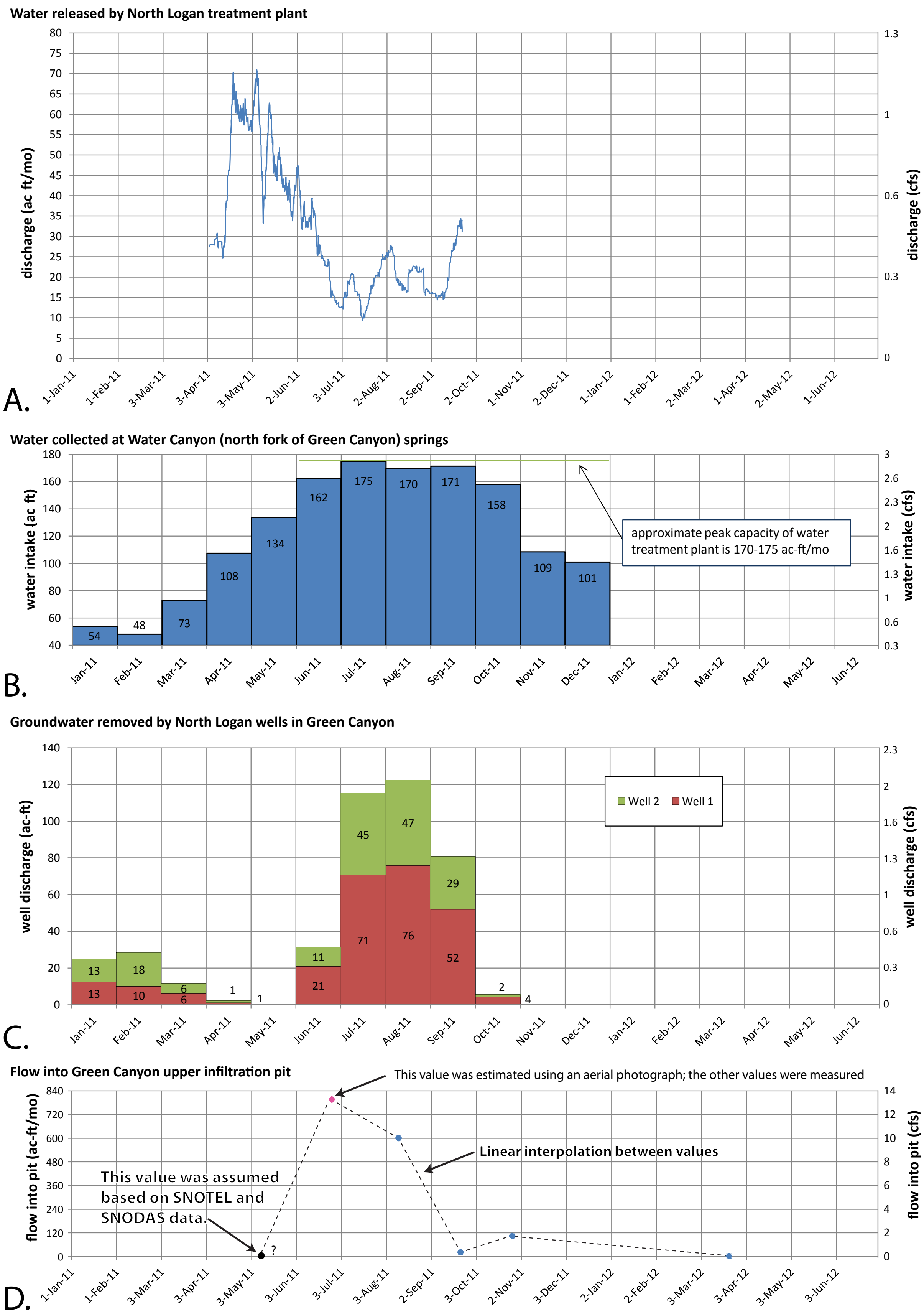


Figure 19. *Hydrologic data near the gravel pit. A.–C. Data from North Logan City. D. Estimated flow into infiltration pit. The estimate of total water infiltrated comes from the daily discretized culmination of interpolated flows between the plotted values, starting at 5/11/2012 and ending 9/22/2012.*

Table 5. *Elevation measurements recorded by the high precision Trimble GPS unit.*

	Elevation (meters)			GPS precision (meters)			Elevation change (meters)		Error from elevation change (µGal)	
STATION	8/10/2011	10/26/2011	3/21/2012	Aug	Oct	Mar	Aug-Oct	Aug-Mar	Aug-Oct	Aug-Mar
CVG0	1372.738	1372.717	1372.696	0.034	0.03	NA	0.021	0.042	6	13
CVG1	1517.243	1517.242	1517.212	0.016	0.03	0.043	0.001	0.031	0	10
CVG2	1514.105	1514.119	1514.129	0.028	0.021	0.05	-0.014	-0.024	-4	-7
CVG3	1515.535	1515.533	1515.543	0.029	0.017	0.031	0.002	-0.008	1	-2
CVG4	1534.194	1534.069	1534.104	0.037	0.05	0.032	0.125	0.090	39	28
CVG5	1540.439	1540.420	1540.425	0.028	0.036	0.04	0.019	0.014	6	4
CVG6	1504.001	1504.003	1504.009	0.03	0.022	0.02	-0.002	-0.008	-1	-2
CVG7	1503.964	1503.951	1503.95	0.025	0.023	0.025	0.013	0.014	4	4
CVG8	1475.092	1475.104	1475.099	0.018	0.019	0.022	-0.012	-0.007	-4	-2
CVG9	1474.087	1474.041	1474.043	0.017	0.018	0.027	0.046	0.044	14	14
CVG10	1488.170	1488.182	1488.186	0.016	0.031	0.017	-0.012	-0.016	-4	-5
CVG11	1488.759	1488.742	1488.735	0.033	0.02	0.048	0.017	0.024	5	7
CVG12	1522.082	1522.074	1522.06	0.024	0.024	0.035	0.008	0.022	2	7
CVG13	1508.477	1508.493	1508.476	0.026	0.036	0.026	-0.016	0.001	-5	0
CVG14	1457.371	1457.321	1457.355	0.023	0.029	0.022	0.050	0.016	15	5
CVG15	1486.009	1485.970	1485.96	0.025	0.036	0.02	0.039	0.049	12	15
CVG16	1404.201	1404.192	1404.219	0.024	0.02	0.024	0.009	-0.018	3	-6
CVG17	1479.718	1479.716	1479.72	0.021	0.015	0.027	0.002	-0.002	1	-1
CVG18	1400.858	1400.866	1400.859	0.017	0.018	0.014	-0.008	-0.001	-2	0

filtration. Because a stable substrate is needed for precise measurements, we established gravity stations on existing cement pads (such as sidewalks) to reduce the cost and impact of the surveys where possible. For three locations, we installed temporary gravity stations using concrete pads or paving stones secured by rebar. We repeated our gravity survey four times to monitor temporal changes in the local gravity over time on 10–11 August 2011, 21–22 September 2011, 26–27 October 2011, and 21–22 March 2012.

Station networks are always a compromise between the number of stations and the time available to occupy the network. We ensured that station spacing was no less than the estimated depth of investigation, and that far-field sites (those distal to the immediate area of investigation) were close enough for practical purposes, but sufficiently far that the infiltration should not influence the stations during the project lifetime.

Gravity measurements have nonlinear drifts due to transport and Earth tide effects, instrument tares (sudden jolts), other uncorrected noise, and innate linear drift of the gravimeter sensor. We repeated occupations of stations twice in a single survey to quantify and correct for the nonlinear noise. To compare measurements between surveys, one or more stations are assumed "stable," meaning there is no gravity change at these sites relative to the gravity changes of interest over time, and are used as reference stations. The apparent gravity changes at the reference station(s) provide a correction value for the gravity changes observed at the rest of the gravity stations and allow us to compute actual change. We apply this correction to all other gravity stations.

A high number of gravity readings over a short time improves statistical certainty and allows for quality control in processing (Gettings and others, 2008). We recorded 30-second averages of the gravity 20 times during each occupation, making each occupation last about 10 minutes. We then analyzed the readings to produce an estimate of the relative gravity at each station.

RESULTS AND DISCUSSION

Potentiometric Surface

The hydraulic gradients and flow directions inferred from the potentiometric surface map (figure 13) made for this study reflect the trends observed by others (Bjorklund and McGreevy, 1971; Kariya and others, 1991). The Green Canyon Wells 1 and 2 drinking water source protection plan (Bush and Gudgell, 2004) aligned the hydraulic groundwater gradient to the trend of Green Canyon Creek (south 79 degrees west). Hydraulic gradient is highest near and within the mountainous area and decreases towards the center of Cache Valley (figure 14). The groundwater flow direction is generally from east to west in the area of the Green Canyon gravel pit.

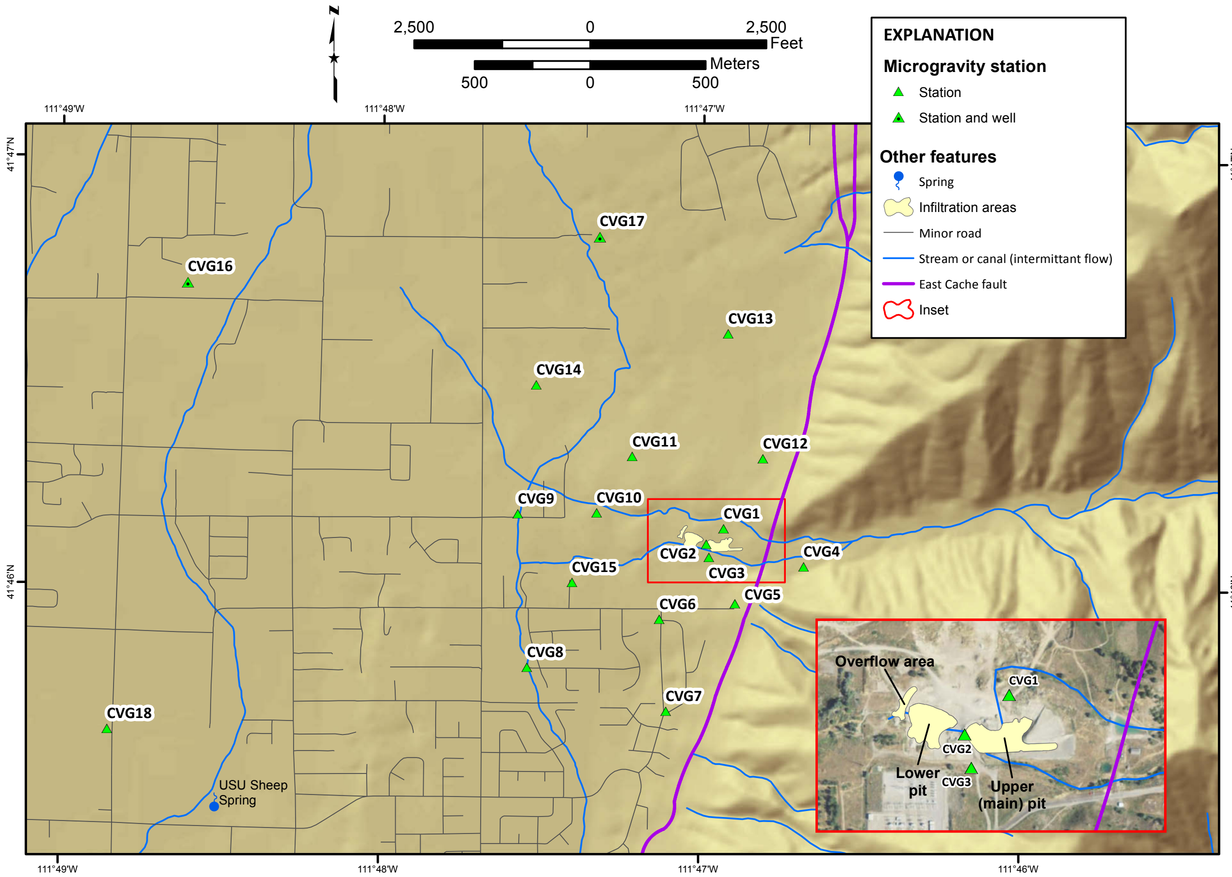


Figure 20. *Locations of microgravity stations. Station CVG0 is located at the front entrance of a hotel (not shown) southwest of the map area, at 853 S. Main, Logan, Utah.*

In creating figures 13 and 14, we assumed that all of the groundwater-level data points are hydraulically connected to some degree (i.e., we did not distinguish between aquifers) and that groundwater levels have not changed significantly over time. As a result, the figures represent very general estimates of the groundwater flow conditions in the area. The water-level data extend from 1905 to 2012, but most of the groundwater levels are post-1970.

The groundwater-level map (figure 13) and the accompanying flow map (figure 14) have several limitations. Most of the groundwater level elevations for the mountainous area near Green Canyon are from spring elevations, which may represent localized perched aquifers, or have discharges that represent groundwater levels higher than the spring's ground surface elevation. We have interpolated over large areas that lack data, so localized variations in the potentiometric surface, such as expected near the East Cache fault, are attenuated or smoothed out. Most of the water-level data in the valley area are from the principal aquifer, whereas most of the water-level data in the mountains are from spring elevations. Differences in head between confined aquifer units are within a few feet, whereas differences in head between unconfined and confined aquifer units can exceed 20 feet. Almost all of the water-level data from within the valley area are from confined aquifers, as wells are rarely completed in the unconfined aquifers (Inkenbrandt, 2010).

Based on results of a dye tracer study, Spangler (2001) documented karst groundwater flow from Green Canyon south-southeast to DeWitt spring in Logan Canyon (figure 2), which opposes the flow direction estimated from the potentiometric surface map. In this case, flow not in line with gradient indicates structurally controlled flow following the Logan Peak syncline and fracture sets associated with the syncline. However, flow from the Bear River Range to the subsurface basin fill at the mouth of Green Canyon is still likely because water-level elevations in the Bear River Range are significantly higher than those in Cache Valley basin fill.

Regional Groundwater-Level Fluctuations

Temporal changes in groundwater levels in wells in the Cache Valley region show similar trends in both basin-fill material and the Salt Lake Formation (figure 15, plate 1). Water levels started out low early in 2011, began to increase near May, and peaked during October to November, then subsequently declined in December. In most cases, water levels in March 2012 were higher than March 2011. Some of the wells show small dips in this trend, which may be related to local pumping near those wells. Water levels in wells screened to A1 or A2 wells shared similar trends.

The October to November peak in water levels (figure 15) may represent a delayed response in groundwater levels to the large influx of snowmelt and precipitation earlier in the year (figure 16). Alternatively, based on the large contribution of seepage from irrigation water in the Cache Valley water budget (Bjorklund and McGreevy, 1974; Kariya and others, 1994; Olsen, 2007), the observed groundwater level peak could be caused by delayed irrigation or canal seepage. No groundwater level changes in the wells could be attributed to the infiltration of water at the gravel pits, as any measurable water level increases created by pit infiltration would be masked by a much larger regional seasonal recharge signal. To detect the effects of the infiltration pit, measurement of a well more proximal to the pit is required.

Pit Infiltration

Based on the volume estimates from our point infiltration values, we estimate the total infiltration into the ground at the upper pit to be at least 2000 ac-ft from early May to September of 2011 (figure 19 D; table 3). Based on the measured surface water inflow and main pit overflow elevation and the total area covered by silt, estimated infiltration rates started at about 20 feet per day and decreased over time to about 13 feet per day (table 3).

We were only able to estimate infiltration at the upper pit. However, geomorphic and anecdotal evidence suggests that large amounts of water flowed through the upper pit overflow and into the lower pits. The geomorphic evidence included incision gullies near the upper pit overflow pipes (figure 10), cobbles deposited in the delta area of the upper pit, and a large areal extent of silt in both the lower and upper pits. Based on high precision GPS measurements of a dissected trench (incision gully) extending from the overflow pipe of the upper pit to the lower pit, a total of 4800 cubic feet of limestone cobbles were moved by water flowing out of the overflow pipes of the upper infiltration pond. The water created an incision gully 28 feet wide and 2.5 feet deep (figure 10B). Based on the surface area covered by water during the highest stages of pit water level elevations of the upper and lower infiltration pits, total surface water inflow to the pit was at least 20 cubic feet per second.

We see no correlation between the measured surface water flow into the infiltration pond and the water released from the North Logan City water treatment plant (figure 19), although we would expect one because the overflow contributes to the surface inflow stream. The lack of correlation could be due to measurement errors in either the field stream velocity meter or the overflow meter. A more likely explanation, however, is that the discharge of surface water from the Green Canyon catchment was also contributing to the surface flow entering the infiltration pits, which is substantiated by the hydrologic budget. Significant contributions from Green Canyon are likely because the flow into the gravel pit was about an order of magnitude higher than the flow leaving the plant.

Visual inspection of the infiltration area yielded no evidence of infiltrated water resurfacing in the immediate vicinity of the infiltration ponds. During periods when water was ponding in the upper infiltration pond without reaching the level of the overflow pipes, no water was observed to be issuing through or under the upper pond impoundment to the lower pond.

Recharge Mound Model

The modeled behavior of large amounts of water infiltrating at the pit shows increased water levels near the pit, decreasing radially with distance (figure 12). The increased groundwater levels induce a groundwater gradient higher than the natural gradient and would cause groundwater to flow in directions other than west (the natural groundwater flow direction).

Hydrologic Budget

The current source of surface water for infiltration at the gravel pits is the Green Canyon catchment. This catchment also likely provides groundwater underflow from the consolidated Paleozoic rocks and shallow alluvium of the mountains to the aquifers below the gravel pit in Cache Valley. The hydrologic budget was created to estimate (1) the amount of surface water that flowed out of the catchment to the gravel pits and (2) the amount of groundwater moving from the mountain to the area below the gravel pit. However, the hydrologic budget for the Green Canyon catchment was difficult to ascertain due to the lack of high resolution, field measured data. The results of the estimate of hydrologic budget are summarized in table 6.

Based on the PRISM data, total precipitation (including snow) for the Green Canyon catchment during water year 2011 (from the beginning of October 2010 to the end of September 2011) was 28,000 ac-ft, most of which fell and accumulated from November 2010 to March 2011. The total precipitation from January 2011 to December 2011 was 22,000 ac-ft. Historical averages of precipitation for Green Canyon Catchment from 1971 to 2000 show that average annual precipitation (Jan. to Dec.) is 23,000 ac-ft, and that precipitation is lowest from

Table 6. *Hydrologic budget of Green Canyon catchment. Values are very approximate and should be used for conceptual purposes only.*

IN - Water coming into Green Canyon catchment	
	(ac-ft/yr)
Precipitation	28,000
Groundwater Inflow from adjacent basins	NA①
OUT - Water leaving Green Canyon catchment	
	(ac-ft/yr)
Evapotranspiration	9800
Recharge (into ground) in the mountains (25% of precipitation)	6750
Interbasin flow (karst flow to DeWitt Spring)	5000
Runoff captured by North Logan near Water Canyon spring	1200
Runoff out of Green Canyon②	4250

① *We assumed no inflow from other basins.*
② *Determined by subtracting the other "OUT" components from precipitation.*

June to August and highest from November to March (PRISM Climate Group, 2012). PRISM grids indicate that most of the precipitation occurs at the highest elevations of the Green Canyon catchment, which is the eastern portion of the catchment (PRISM Climate Group, 2012).

The timing and geographic distribution of the majority of Green Canyon precipitation indicate that most of the water contributed to the basin is in the form of snow, which is substantiated by SNOTEL and SNODAS (figure 18). Although some of the snow melts over the winter months (figure 18), much of it accumulates. Based on river hydrographs and snow data (figures 16 and 18), snowmelt began in mid-May, climaxed in mid- to late June, and tapered off into late September.

Data from 1971 to 2000 (PRISM Climate Group, 2012) indicate that the average amount of precipitation that the Green Canyon catchment received was 23,100 ac-ft per year. However, personal communication with North Logan City water manager Terrel Huppi indicated that surface water rarely flows out of the mouth of Green Canyon. Based on this observation, and dye trace data from Spangler (2001), we can assume that most of the Green Canyon catchment water is (1) lost to karst flow to DeWitt Spring, (2) recharged into the fractured bedrock and alluvium in the mountains, (3) collected by North Logan City near Water Canyon Springs, and (4) lost to evapotranspiration. However, in the summer and fall of 2011, at least 2000 ac-ft of water made it into the upper infiltration pit, only 130 ac-ft of which was released by North Logan City's water treatment plant overflow. Based on the very approximate hydrologic budget in table 6, up to 4250 ac-ft emerged from the mouth of Green Canyon as surface water runoff.

Gravity Interpretation

As mentioned earlier, changes in gravity at a single location can indicate a change in the mass of groundwater below that point (e.g., increased amounts of water would increase the measured gravity). We observed gravity value differences between each field survey measurement, which we interpret to represent changes in groundwater storage. The stick maps of gravity values (figures 21–23) give us insight as to the lateral movement of groundwater, while comparing individual station measurements (figure 24) to nearby hydrologic measurements gives us insight into the vertical profile of the local aquifer systems.

Hydrogeologic conditions that can influence the correlation of microgravity measurements to hydrologic measurements include thick unsaturated zones occurring near recharge

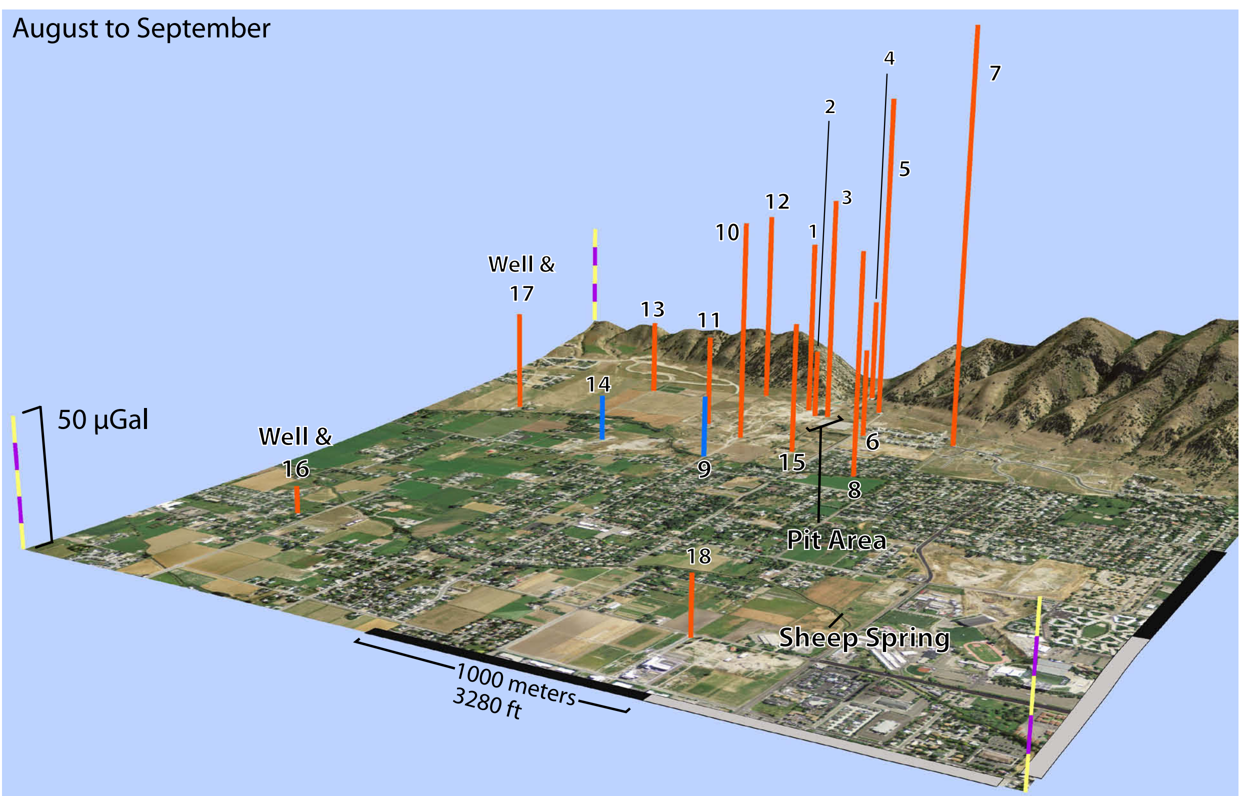


Figure 21. Microgravity changes from August to September 2011. Red bars are positive and indicate an increase in gravity (mass) over time. Blue bars are negative and indicate a decrease in gravity over time. Station numbers at bar tops (see figure 20). Base aerial photograph from Google (2011).

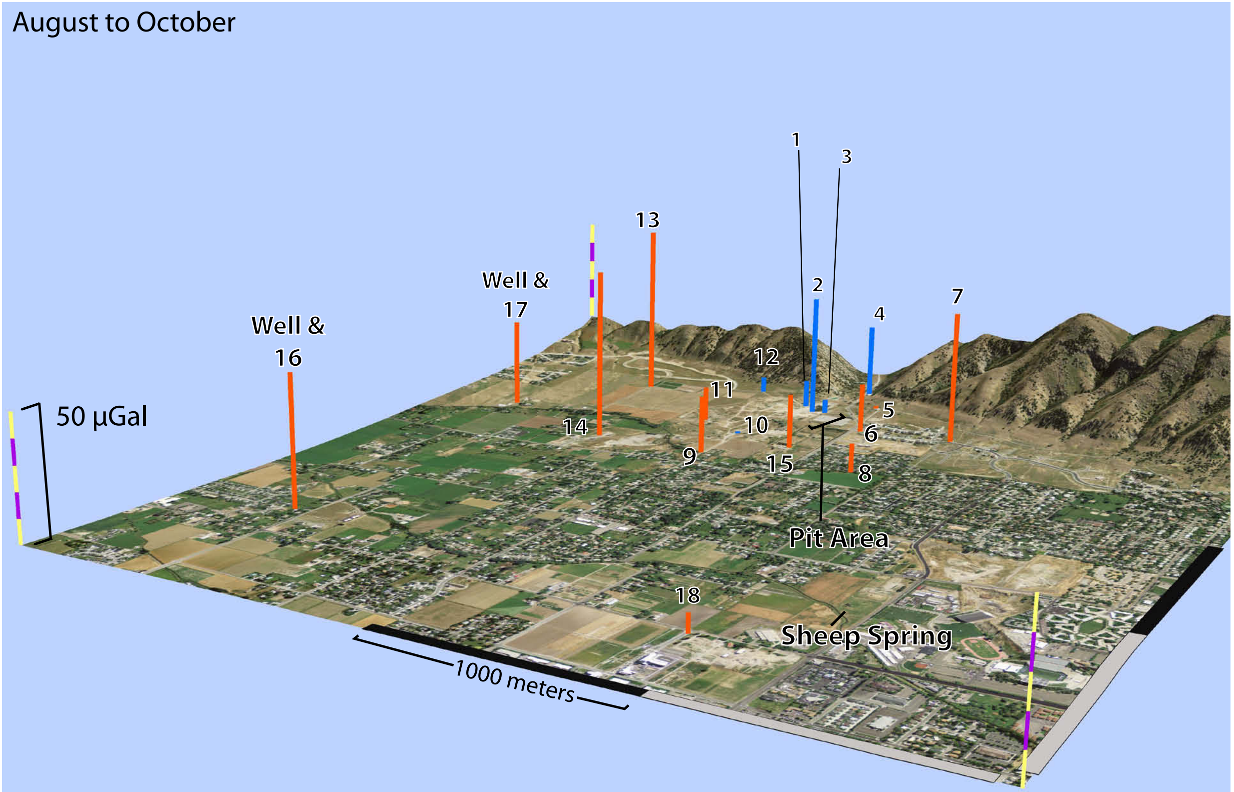


Figure 22. Microgravity changes from August to October 2011. Red bars are positive and indicate an increase in gravity (mass) over time. Blue bars are negative and indicate a decrease in gravity over time. Station numbers at bar tops (see figure 20). Base aerial photograph from Google (2011).

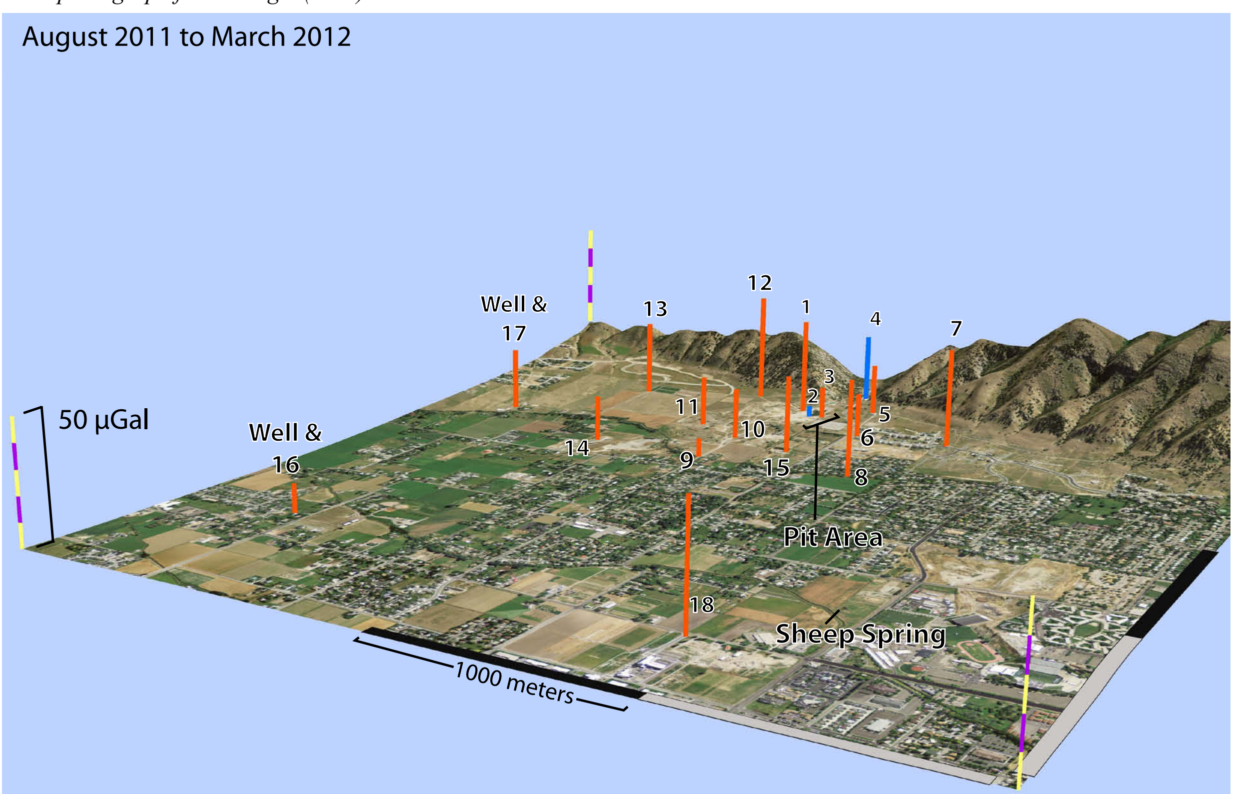


Figure 23. Microgravity changes from August 2011 to March 2012. Red bars are positive and indicate an increase in gravity (mass) over time. Blue bars are negative and indicate a decrease in gravity over time. Station numbers at bar tops (see figure 20). Base aerial photograph from Google (2011).

sources and perched, confined, multiple, and compressible aquifers (Pool, 2008). Also, well water levels may not be representative of a single aquifer.

In Basin and Range alluvial aquifers like the one in Cache Valley, groundwater-storage change occurs through changes in the water content of pore spaces in the unsaturated zone, draining and filling of pore space as water levels rise and fall in the unconfined regional and perched aquifers, and the expansion and contraction of saturated pore volume in compressible parts of the aquifer (Pool, 2008).

Comparison to Hydrologic Systems

Hydrologic measurements were taken simultaneously with gravity measurements at four locations: two "far-field" wells

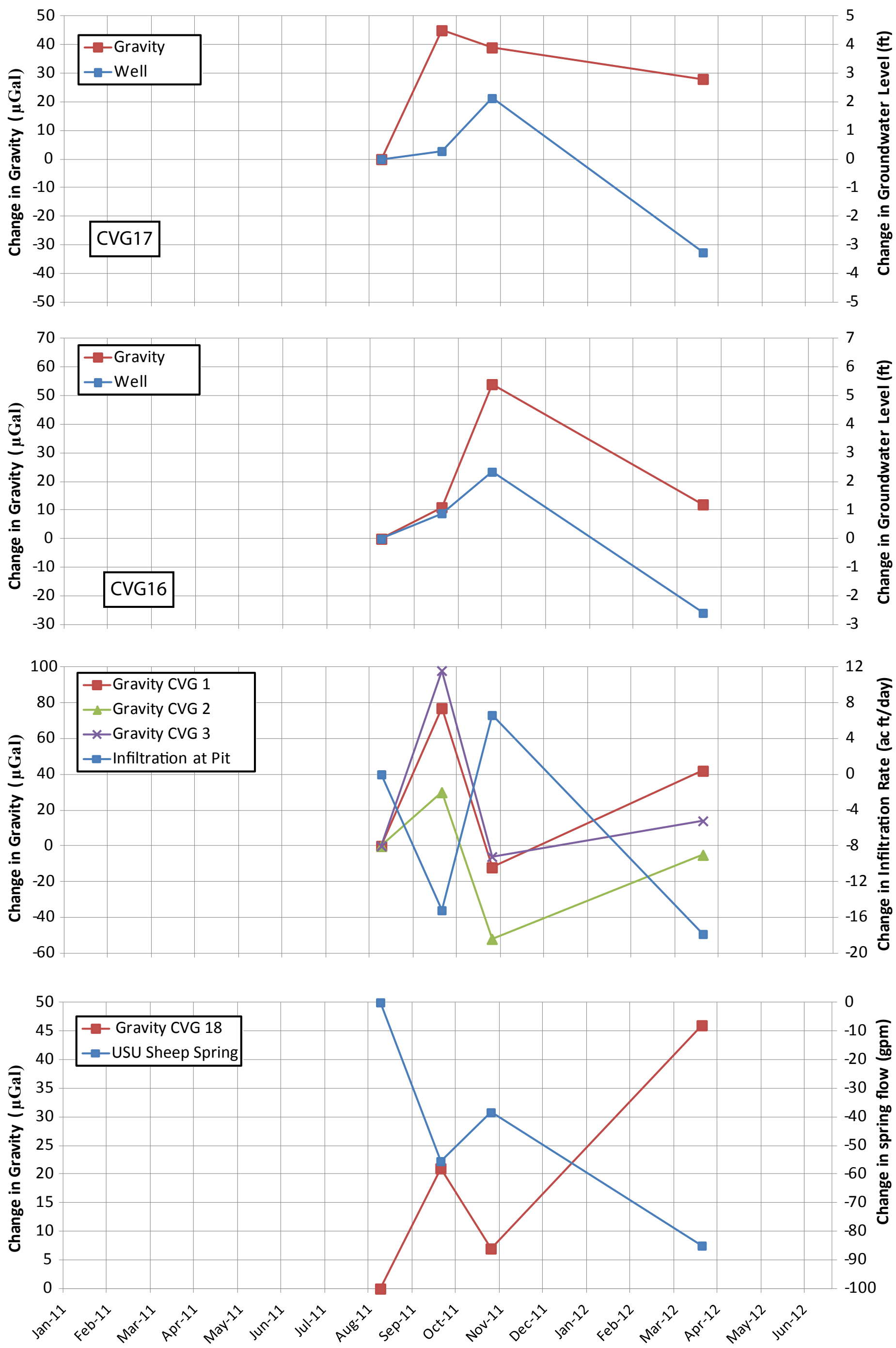


Figure 24. *Relative gravity changes and hydrologic measurements at selected gravity stations over time. The time scale of the graphs is the same as the graphs of USGS data in figures 15 to 16.*

(CV16 and CV17), USU Sheep Spring and nearby gravity station CVG18, and directly adjacent to the area of infiltration (ASR site). More mass will produce a relatively stronger gravity signal. Hydrologic trends in the well at CVG17 and at Sheep Spring did not match microgravity trends (figure 24). In both cases, this was likely caused by multiple aquifer systems, where separate water packages could be vertically stacked under the point of measurement.

CVG17 water level is representative of only a small thickness of the Salt Lake Formation. In the area of the well, localized perched aquifers may be present above and within the Salt Lake Formation. Poor correlation between the well and the microgravity indicates that we measured mass changes that were reflected by groundwater changes not in the well but possibly in the perched aquifers.

USU Sheep Spring's dominant water source is likely from the shallow unconfined aquifer (Olsen, 2007). Underlying the unconfined aquifer are the principal aquifer and the Salt Lake Formation. Discharge from the spring decreased from August to September by about 55 gallons per minute (gpm) then increased from September to October by about 20 gpm and finally decreased from October to March by about 46 gpm (figure 24). Gravity values measured at the CVG18 station are correlated with measured spring flow. However, the well at CVG18, screened to the Salt Lake Formation, is separated from the spring by about 0.25 mile, and significant aquifer heterogeneity may exist between the spring and the well at the gravity station.

The groundwater-level changes in the well at site CVG16 have a positive correlation to the gravity changes observed at the site (figure 24). The measured groundwater-level changes also matched the general trends observed in wells monitored by the USGS, meaning that the water storage changes inferred by gravity at CVG16 may be more related to regional changes in the groundwater system than changes caused by infiltration at the gravel pit.

Changes in gravity measurements at CVG1, CVG2, and CVG3 do not match the estimated flow into the gravel pit (figures 19D and 24), which should be directly correlated with the amount of water infiltrating at the pit. A possible explanation for the discrepancy is that the gravity signal from water coming into the system through the East Cache fault from Green Canyon and flowing under the gravel pit overwhelmed the gravity signal from water that infiltrated in the gravel pit. Although the East Cache fault was modeled as a low permeability boundary, some groundwater probably moves from the mountains to the valley fill across the fault, including through the Green Canyon alluvium. Another possible explanation is that the water moved vertically below the pit before spreading laterally, creating a delay between infiltrating volume measured and the lateral movement measured via gravity.

Gravity Changes

Gravity changes from August to September were greatest south of the gravel pit (figures 21 and 24–26). There were only small changes in the far field to the west, and relatively moderate increases to the immediate north and west at stations CVG12 and CVG10. The larger increase of gravity to the south could indicate a large amount of water moving south along the East Cache Fault Zone, due to enhanced fracture permeability created by the fault system.

The measured gravity differs from the modeled behavior in that there is not a smooth, semi-circular mound observed below the gravel pit. We likely did not observe a mound because we did not start measuring gravity until after the bulk of the water had infiltrated at the gravel pit between late June and early August. Heterogeneity in the basin-fill material could also contribute to a non-radial peak in gravity (i.e., more water moving to the south).

Gravity changes from August to October (figure 22) show an almost spatially symmetrical decrease in the immediate vicinity of the pit area, and general increases in all other surrounding areas. This is interpreted as water leaving the pit area from the time of late August to late October.

Gravity changes from August to March (figure 23) show a general increase in the gravity signal in most of the valley, while there was a decrease in gravity at CVG4.

CONCLUSIONS

Based on the high (as high as 100 μGal) change in gravity observed from August to September in the southern part of the study area, a large volume of water infiltrated from the pit is reaching the subsurface in the Logan area, south of North Logan. This area is highly connected to the principal aquifer, and some water is likely reaching the deeper portions of the principal aquifer in the Logan area.

Water infiltrating beneath the gravel pit likely disperses and moves laterally and vertically through the alluvial-fill material. Determining the exact amount of water entering each aquifer unit using gravity alone is unachievable for this complex aquifer system. The natural groundwater system at the mouth of Green Canyon is complex, and is further complicated by the operations of a municipal water supply system. Based on our estimated infiltration rates, the volume of infiltrated water from early May to September 2011 was at least 2000 acre-feet. An anomalously high volume of water was moving through the Cache Valley aquifer system during this study, which further complicated the investigation.

Because our measured microgravity signals indicate a large mass of water moving to the southwest, towards a high-use

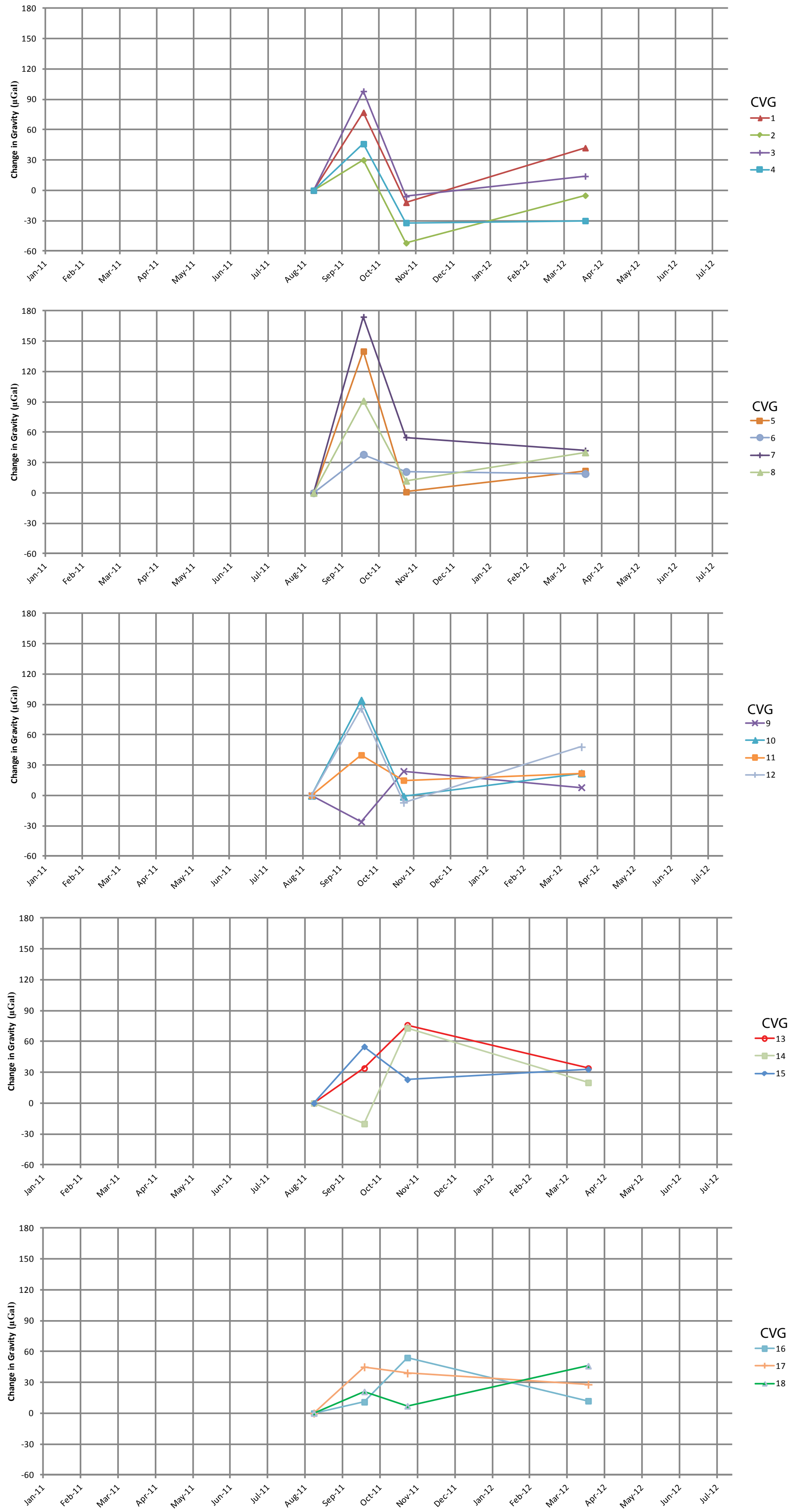


Figure 25. *Relative gravity changes at each gravity station (see figure 22 for gravity station locations) over time. The time scale of the graphs is the same as the graphs of USGS data in figures 15 to 16.*

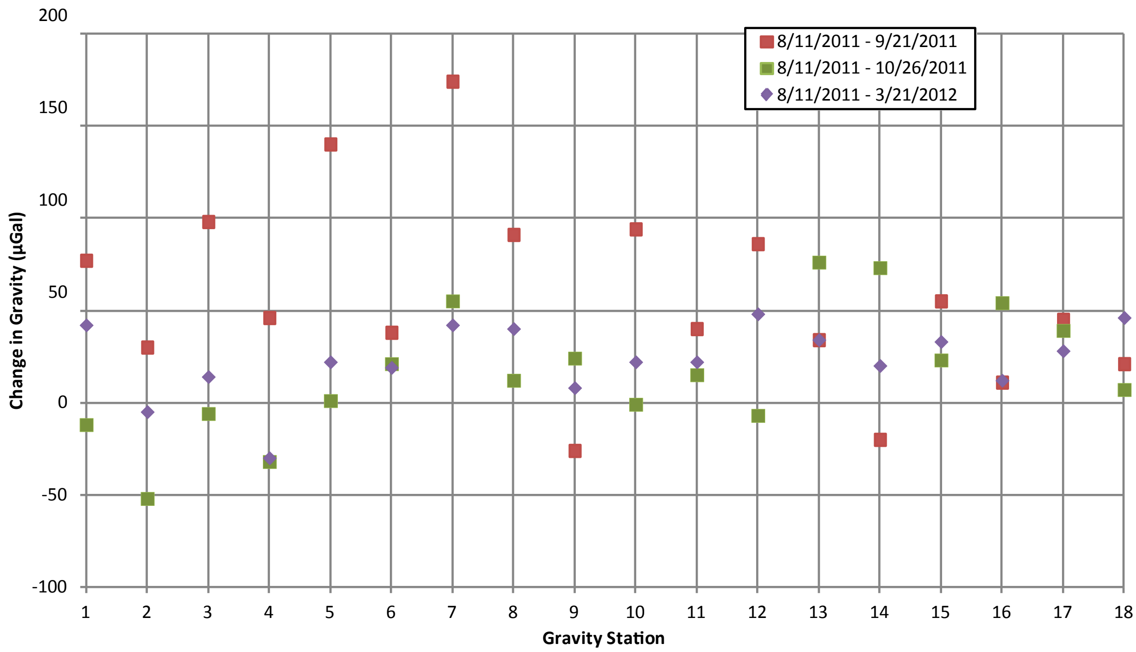


Figure 26. *Relative gravity changes at select gravity stations (see figure 20 for gravity station locations).*

area of the principal aquifer, the North Logan Green Canyon gravel pits could be an appropriate, though not ideal, location for aquifer storage and recovery. Though there is strong evidence that some water reaches the principal aquifer, due to the complexity of the system and the lack of high resolution data, we are unable to ascertain if most of the water infiltrated reaches the principal aquifer. Some water is likely lost to the shallow unconfined aquifer, and may cause increases in shallow groundwater occurrence farther downgradient from the ASR site, such as increased spring flow. If this site is chosen as an ASR site, or used for further study, we recommend installing a monitoring well in the immediate vicinity of the infiltration pond to better monitor the subsurface groundwater conditions in relation to microgravity measurements.

ACKNOWLEDGMENTS

The authors thank Paul Gettings for assisting with selecting gravity measurement locations and for reviewing our document. We also appreciate Bob Fotheringham's (Cache County) thoughtful reviews and commentary and his progressive approach to water management in Cache County. We appreciate continued support from Mr. Fotheringham and the Cache County Council in exploring the hydrogeology of Cache County. We are also grateful to Lucy Jordan, Mike Lowe, Hugh Hurlow, Robert Ressetar, Kimm Harty, and Rick Allis for their careful review of our manuscript.

REFERENCES

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

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

Black, B.D., Solomon, B.J., and Giraud, R.E., 1999, Surficial geology and paleoseismicity of the West Cache fault zone, Cache County, Utah, *in* Spangler, L.E., and Allen, C.J., editors, Geology of northern Utah and vicinity: Utah Geological Association Publication 27, p. 181–201.

Bush and Gudgell, 2004, Updated groundwater source protection plan—Green Canyon wells 1 & 2—water system no. 03015: Salt Lake City, unpublished consultant's report for the State of Utah Division of Drinking Water, 127 p.

Chapman, D.S., Sahm, E., and Gettings, P., 2008, Monitoring aquifer recharge using repeated high-precision gravity measurements—a pilot project in South Weber, Utah: Geophysics, v. 73, p. WA83–WA93.

Dover, J. H., 1995, Geologic map of the Logan 30' x 60' quadrangle, Cache and Rich Counties, Utah, and Lincoln and Uinta Counties, Wyoming: U.S. Geological Survey

Miscellaneous Investigations Series Map I-2210, scale 1:100,000.

Duffield, G.M., 2006, AQTESOLV for Windows, Version 4.01: HydroSOLVE, Inc., Reston, Virginia.

Evans, J.P., and Oaks, R.Q., Jr., 1996, Three-dimensional variations in extensional fault shape and basin form—the Cache Valley basin, eastern Basin and Range province, United States: Geological Society of America Bulletin, v. 108, p. 1580–1593.

Gesch, D.B., 2007, The national elevation dataset, *in* Maune, D., editor, Digital elevation model technologies and applications—the DEM users manual, 2nd Edition: Bethesda, Maryland, American Society for Photogrammetry and Remote Sensing, p. 99–118.

Gesch, D., Oimoen, M., Greenlee, S., Nelson, C., Steuck, M., and Tyler, D., 2002, The national elevation dataset: Photogrammetric Engineering and Remote Sensing, v. 68, no. 1, p. 5–11.

Gettings, P., 2010, High precision gravity measurements—techniques, software, and algorithms: unpublished consultant's report, 87 p.

Gettings, P., Chapman, D.S., and Allis, R., 2008, Techniques, analysis, and noise in a Salt Lake Valley 4-D gravity experiment: Geophysics, v. 73, p. WA71–WA82.

Google, 2012, Aerial photograph, flown on 8/11/2011: Online, https://maps.googlecom/maps?q=Green+Canyon+Drive,+North+Logan,+UT&hl=en&ll=41.767961,-111.782594&spn=0.006578,0.013937&sll=41.768395,-111.781945&sspn=0.003289,0.006968&oq=Green+Canyon+Drive&t=w&hnear=Green+Canyon+Dr,+North+Logan,+Cache,+Utah+84341&z=17, accessed December 2012.

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

Inkenbrandt, P.C., and Lachmar, T., 2012, *in* Hylland, M.D., and Harty, K.M., editors, Selected topics in engineering and environmental geology in Utah: Utah Geological Association Publication 41.

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

King, V.F., 2004, Water budget estimates for the Powder Mountain region, Cache and Weber Counties, Utah: methods and proper use of ground-water recharge estimations, *in* Spangler, L.E., editor, Ground water in Utah—resource, protection, and remediation: Utah Geological Association Publication 31, p. 219–234.

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

Lowe, M., and Galloway, C.L., 1993, Provisional geologic map of the Smithfield quadrangle, Cache County, Utah: Utah Geological Survey Map 143, 18 p., scale 1:24,000.

Lowe, M., Wallace, J., and Bishop, C.E., 2003, Ground-water quality classification and recommended septic tank soil-absorption system density maps, Cache Valley, Cache County, Utah: Utah Geological Survey Special Study 101, 31 p., scale 1:100,000, CD-ROM.

McCalpin, J.P., 1994, Neotectonic deformation along the east Cache fault zone, Cache County, Utah: Utah Geological Survey Special Study 83, 37 p.

Microsoft, 2012, Aerial photograph, flown late June 2012: Online, http://www.bing.commaps/?v=2&cp=41.768428~-111.781342&lvl=17&dir=0&sty=h&form=LMLTCC, accessed December 2012.

Myers, B., 2003, Simulation of groundwater flow in Cache Valley, Utah and Idaho: Logan, Utah State University, M.S. thesis, 80 p.

National Operational Hydrologic Remote Sensing Center, 2004, Snow Data Assimilation System (SNODAS): Online, http://nsidc.org/data/g02158.html, accessed 2012.

National Resources Conservation Service (NRCS), 2012, SNOwpack TELemetry (SNOTEL): Online, http://www.wcc.nrcs.usda.gov/nwcc/site?sitenum=823&state=ut, accessed 2012.

Oaks, R.Q., Jr., and Langenheim, V., in preparation, Gravity map of Cache Valley, unpublished gravity data.

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

Oviatt, C.G., Currey, D.R., and Sack, D., 1992, Radiocarbon chronology of Lake Bonneville, eastern Great Basin, USA: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 99, p. 225–241.

Pool, D.R., 2008, The utility of gravity and water-level monitoring at alluvial aquifer wells in southern Arizona: Geophysics, v. 73, n. 6, p. WA49–WA59.

Pool, D.R., and Eychaner, J., 1995, Measurements of aquifer-storage change and specific yield using gravity surveys: Ground Water, v. 33, p. 425–432.

PRISM Climate Group, 2012, Monthly gridded precipitation 2.5-arcmin (4 km): Online, Oregon State University, http://prism.oregonstate.edu, accessed May, 2012.

Robinson, J.M., 1999, Chemical and hydrostratigraphic characterization of ground water and surface water interaction in Cache Valley, Utah: Logan, Utah State University, M.S. thesis, 172 p.

Sibson, R., 1981, A brief description of natural neighbor interpolation (chapter 2), *in* Barnett, V., Interpreting multivariate data: Chichester, United Kingdom, John Wiley, p. 21–36.

Smith, K.A., 1997, Stratigraphy, geochronology, and tectonics of the Salt Lake Formation (Tertiary) of southern Cache Valley, Utah: Logan, Utah State University, M.S. thesis, 245 p.

Spangler, L.E., 2001, Delineation of recharge areas for karst springs in Logan Canyon, Bear River Range, northern Utah *in* Kuniansky, E.L., editor, 2001, U.S. Geological Survey Karst Interest Group Proceedings: Water-Resources Investigations Report 01-4011, p. 186–193.

Thomas, K., Oaks, R.Q., Jr., Inkenbrandt, P.C., Sabbah, W., and Lowe, M.V., 2011, Cache Valley principal aquifer storage and recovery: Utah Geological Survey Open File Report 579, 57 p.

U.S. Geological Survey (USGS), 2001, National Water Information System data available on the World Wide Web (Water Data for the Nation): Online, http://waterdata.usgs.gov/nwis, accessed April 2012.

U.S. Environmental Protection Agency (USEPA) and U.S. Geological Survey (USGS), 2005, National Hydrography Dataset Plus - NHDPlus, v 1.0: Online, http://www.horizon-systems.com/nhdplus, accessed April, 2012.

Utah Division of Water Rights, 2012, Public water supply records: Online, http://www.waterrights.utah.gov/cgi-bin/wuseview.exe>, accessed March, 2010.

Williams, J.S., 1948, Geology of the Paleozoic rocks, Logan quadrangle, Utah: Geological Society of America Bulletin, v. 59, p. 1121–1164.

Williams, J.S., 1958, Geologic atlas of Utah, Cache County: Utah Geological and Mineral Survey Bulletin 64, p. 1–103.

Williams, J.S., 1962, Lake Bonneville—geology of southern Cache Valley, Utah: U.S. Geological Survey Professional Paper 257-C, p. 131–152.

APPENDIX A

WLd

WELL DRILLER'S REPORT
State of Utah
Division of Water Rights

For additional space, use "Additional Well Data Form" and attach

Well Identification PROVISIONAL WELL: 93-25-001-P-01

Owner *Note any changes*
North Logan City
2076 North 1200 East
North Logan, UT 84321

Contact Person/Engineer:

Well Location *Note any changes*

SOUTH 1600 feet EAST 300 feet from the NW Corner of
SECTION 19, TOWNSHIP 12N, RANGE 2E, SLB&M.

Location Description: (address, proximity to buildings, landmarks, ground elevation, local well #)

Drillers Activity Start Date: 4-15-93 Completion Date: 9-8-93

Check all that apply:
☐ New ☐ Repair ☐ Deepen ☐ Abandon ☐ Replace ☐ Public Nature of Use:

DEPTH (feet) FROM	TO	BOREHOLE DIAMETER (in)	DRILLING METHOD	DRILLING FLUID
0	110	22"	Cable Tool	
110	506	16"	cable Tool	

Well Log

DEPTH (feet) FROM	TO	WATER	PERMEABLE high	PERMEABLE low	CLAY	SILT	SAND	GRAVEL	COBBLES	BOULDER	OTHER	ROCK TYPE	COLOR	DESCRIPTIONS AND REMARKS (include comments on *water quality* if known.)
0	4				X	X	X	X					Brown	slide rock w/surface soils.
4	40				X			X	X	X			Brown	No "clay"
40	61				X			X	X	X			Gray	
61	67				X			X	X	X			Brown	
67	89	X	X								X	Dolomite	Dark Gray	fractured First water at 71'
89	116										X	Dolomite	light Gray	very little fracturing no water
116	168	X		X							X	Dolomite	medium Gray	fratured a little water
168	183	X		X							X	Dolomite	light Gray & Gray	Dolomite marbled light & med. Gray
183	192	X		X							X	"	medium Gray	
192	223	X		X							X	"	light and medium Gray	marbled light & Dark Gray

Static Water Level

Date 9-8-93 Water Level 62' feet Flowing? ☐ Yes ☒ No

Method of Water Level Measurement Tape If Flowing, Capped Pressure ___ PSI

Point to Which Water Level Measurement was Referenced Ground Surface

Height of Water Level reference point above ground surface ___ feet Temperature 53 ☐ °C ☒ °F

Well Log.

Logan Canyon well #1

-3M-11-60

mined
B. C. T. B.
Sheet

REPORT OF WELL DRILLER
STATE OF UTAH

Application No. 90-25-01 TW
Claim No.
Coordinate No.

NERAL STATEMENT: Report of well driller is hereby made and filed with the State Engineer, in accordance with the laws of Utah. This report shall be filed with the State Engineer within 30 days after the completion or abandonment of the well. Failure to file such report constitutes a misdemeanor.)

(1) WELL OWNER:
North Logan City

(2) LOCATION OF WELL:
County Cache Ground Water Basin (leave blank)

630 feet, ~~East~~ West 50 feet from E 1/4 Corner

Section 24 T. 12 N R 1 E SLBM (strike words not needed)

(3) NATURE OF WORK (check):
New Well [X] Replacement Well [ ] Deepening [ ] Repair [ ] Abandon [ ]

If abandonment, describe material and procedure:

(4) NATURE OF USE (check):
Domestic [ ] Industrial [ ] Municipal [ ] Stockwater [ ] Irrigation [ ] Mining [ ] Other [ ] Test Well [X]

(5) TYPE OF CONSTRUCTION (check):
Rotary [ ] Dug [ ] Jetted [ ] Cable [X] Driven [ ] Bored [ ]

(6) CASING SCHEDULE:
Threaded [ ] Welded [X]

16" Diam. from +1 feet to 100 feet Gage .375

12" Diam. from +2 feet to 498 feet Gage .375

" Diam. from feet to feet Gage

New [X] Reject [ ] Used [ ]

(7) PERFORMATIONS:
Perforated? Yes [X] No [ ]

Type of perforator used Mill Slots

Size of perforations 1/8 inches by 1 3/4 inches

684 perforations from 152 feet to 209 feet

1,140 perforations from 248 feet to 343 feet

1644 perforations from 363 feet to 498 feet

perforations from feet to feet

perforations from feet to feet

(8) SCREENS:
Well screen installed? Yes [ ] No [X]

Manufacturer's Name

Type Model No.

Diam. Slot size Set from ft. to

Diam. Slot size Set from ft. to

(9) CONSTRUCTION:
Was well gravel packed? Yes [ ] No [X] Size of gravel:

Gravel placed from feet to feet

Was a surface seal provided? Yes [X] No [ ]

To what depth? 100 feet

Material used in seal: 50-50 Cement & Sand

Did any strata contain unusable water? Yes [ ] No [X]

Type of water: Depth of strata

Method of sealing strata off:

Was surface casing used? Yes [X] No [ ]

Was it cemented in place? Yes [X] No [ ]

(10) WATER LEVELS:
Static level 69 feet below land surface Date 11-30-90

Artesian pressure feet above land surface Date

LOG RECEIVED:

(11) FLOWING WELL:
Controlled by (check) Valve [ ] Cap [ ] Plug [ ] No Control [ ]

Does well leak around casing? Yes [ ] No [ ]

(12) WELL TESTS:
Drawdown is the distance in feet the water level is lowered below static level.

Was a pump test made? Yes [X] No [ ] If so, by whom? Rhodes Bros.

Yield: 600 gal./min. with 214 feet drawdown after 57 hours

Bailer test gal./min. with feet drawdown after hours

Artesian flow g.p.m. Date

Temperature of water 47° F Was a chemical analysis made? No [ ] Yes [X]

(13) WELL LOG:
Diameter of well 12" inches

Depth drilled 498 feet. Depth of completed well 498 feet.

NOTE: Place an "X" in the space or combination of spaces needed to designate the material or combination of materials encountered in each depth interval. Under REMARKS make any desirable notes as to occurrence of water and the color, size, nature, etc., of material encountered in each depth interval. Use additional sheet if needed.

From	To	Clay	Silt	Sand	Gravel	Cobbles	Boulders	Hardpan	Conglomerate	Bedrock	Other	REMARKS
0	3	X			X	X	X					Top Soil & Slide Rock
3	6	X										Brown
6	35	X			X	X	X					Clay & slide Rock
35	94	X								X		Fractured Dolomite
94	196									X		light Grey Dolomite
196	197									X		Black Dolomite
197	252									X		Light Grey Dolomite
252	338									X		Black Dolomite
338	347	X								X		Grey w/clay in Seams Dolomite
347	359									X		Grey Dolomite
359	370									X		Hard Black Limestone
370	383									X		Dark Grey Dolomite
383	?									X		Hard Black Limestone
	498											
												All Bedrock fractured with areas of fault Breccia ranging from Fine clay like to 3" diameter.

No 20 ages only 3" clay

Work started 9-25-90 19 Completed 11-29-90 19

(14) PUMP:
Manufacturer's Name

Type: H. P.

Depth to pump or bowles feet

Well Driller's Statement:

This well was drilled under my supervision, and this report is true to the best of my knowledge and belief.

Name Wright Drilling Inc. (Person, firm, or corporation) (Type or print)

Address 2800 So Main Nibley, UT 84332

(Signed) Ken Wright (Well Driller)

License No. 333 Date 12-4-90 19

USE OTHER SIDE FOR ADDITIONAL REMARKS

ADDITIONAL WELL DATA FORM

Water Right # 93-25-001-P-01

OWNER NAME North Logan City

Page 2 of 2

Well Log

DEPTH (feet) FROM	TO	WATER	PERMEABLE high	PERMEABLE low	UNCONSOLIDATED CLAY	SILT	SAND	GRAVEL	COBBLES	BOULDER	OTHER	CONSOLIDATED ROCK TYPE	COLOR	DESCRIPTIONS AND REMARKS (include comments on *water quality* if known.)
223	319	X		X							X	Dolomite	Dark Gray	
319	368	X		X							X	"	Medium Dark Gray	
368	377	X		X							X	"	White & Dk Gray	Marbled White & Dark Gray
377	436	X		X							X	"	Dark Gray	
436	? 506	X		X							X	"	Grayish Black	Hard fractured.

Construction Information

DEPTH (feet)		CASING			DEPTH (feet)		SCREEN ☐ PERFORATIONS ☐		
FROM	TO	CASING TYPE AND MATERIAL/GRADE	WALL THICK (in)	NOMINAL DIAM. (in)	FROM	TO	SLOT SIZE OR PERF SIZE (in)	SCREEN DIAM. OR PERF LENGTH (in)	SCREEN TYPE OR NUMBER PERF (per round/interval)
+1'	110'	steel A53-B	.375	16	122	506	1/8" x 3"	384'	94 per foot
+2'	506'	steel A53-B	.375	12"					

Well Head Configuration: cap tack welded Access Port Provided? ☐ Yes ☒ No

Casing Joint Type: welded Perforator Used: mill slots

DEPTH (feet)		FILTER PACK / GROUT / PACKER / ABANDONMENT MATERIAL		
FROM	TO	ANNULAR MATERIAL, ABANDONMENT MATERIAL and/or PACKER DESCRIPTION	Quantity of Material Used (if applicable)	GROUT DENSITY (lbs./gal.,# bag mix, gal./sack etc.)
0'	110'	sand & cement Grout 13 bag mix	17.5 cu. yds.	13 bag mix sand & cement

Well Development / Pump or Bail Tests

Date	Method	Yield	Units Check One GPM	CFS	DRAWDOWN (ft)	TIME PUMPED (hrs & min)
9-8-93	Deep well Turbine Pump	300	X		79	
9-8-93		350	X		143	
9-8-93		375	X		290	81.5 hours.

Pump (Permanent)

Pump Description:________ Horsepower:________ Pump Intake Depth:________feet

Approximate maximum pumping rate:________ Well disinfected upon completion? ☐ Yes ☐ No

Comments Description of construction activity, additional materials used, problems encountered, extraordinary circumstances, abandonment / procedures. *Use additional well data form for more space.*

Well seems to improve with pumping, however no detectable material in pumped water during final 31 hours of pumping.

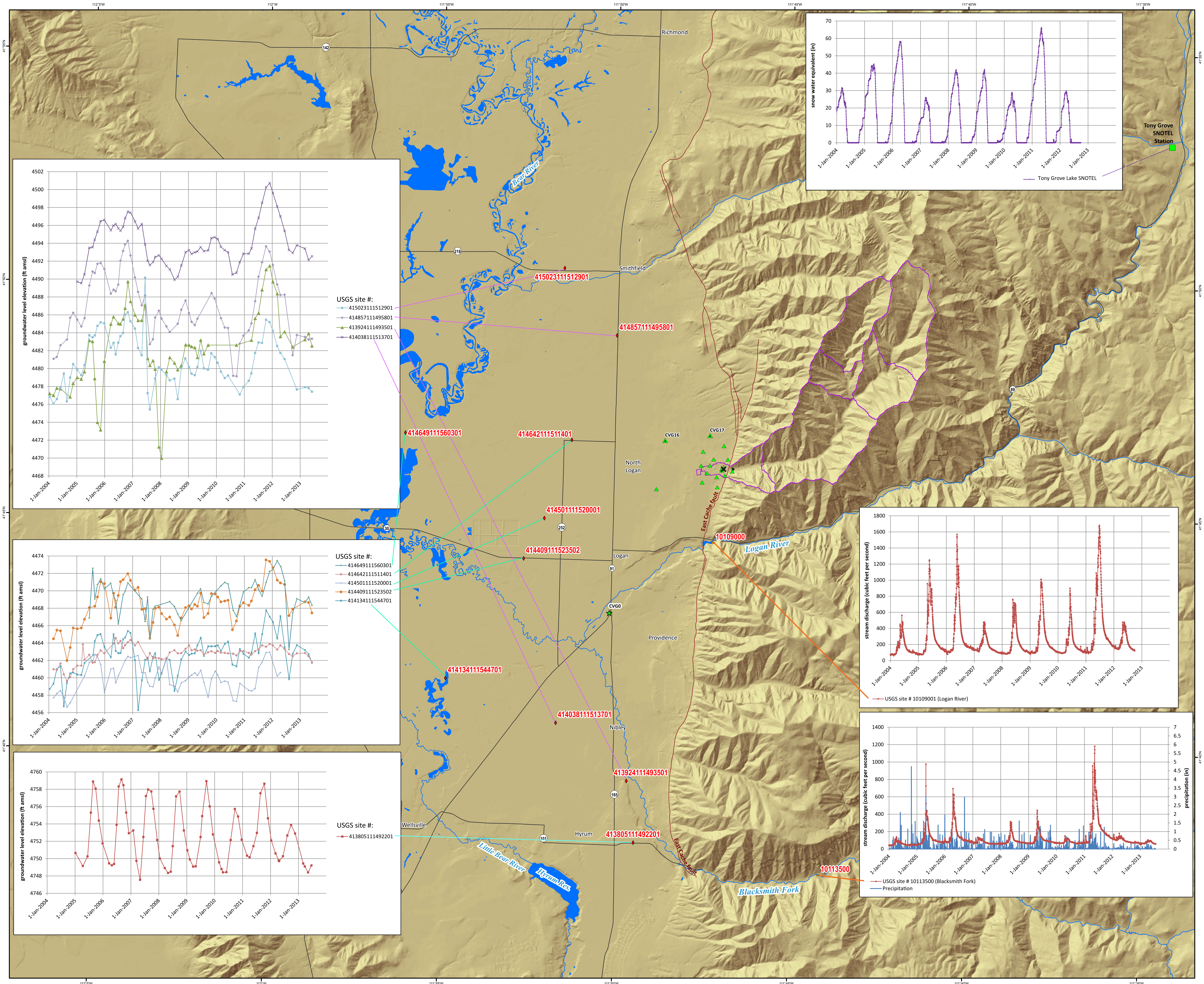
Well Driller Statement This well was drilled or abandoned under my supervision, according to applicable rules and regulations, and this report is complete and correct to the best of my knowledge and belief.

Name Wright Drilling Inc. License No. 333
(Person, Firm, or Corporation – Print or Type)

Signature Ken Wright Date 9-19-93
(Licensed Well Driller)

UTAH GEOLOGICAL SURVEY
a division of
Utah Department of Natural Resources

Hydrographs from Well and River Stations Monitored by the USGS



111°35'W

Cartography by Paul Inkenbrandt
Map base data from the Utah Automatic Geographic Resource Center
Hydrologic data from the U.S. Geological Survey
Projection: Transverse Mercator
Datum: NAD 1983

EXPLANATION

USGS Station
- Well
- Stream gage

Gravity station
- Station
- Station with well
- Base station

- Tony Grove SNOTEL Station
- Green Canyon gravel pit
- North Logan wells
- East Cache fault
- Green Canyon catchment
- Road

MN 12°15'
magnetic declination at center of map
2012

3 1.5 0 3 Miles
3.5 1.75 0 3.5 Kilometers