CACHE VALLEY PRINCIPAL AQUIFER STORAGE AND RECOVERY
SITE ASSESSMENT: PHASE I

by Kevin Thomas, Robert Q. Oaks, Jr., Paul Inkenbrandt, Walid Sabbah, and Mike Lowe

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Cover photo: *View of Cache Valley from Green Canyon toward the southwest.*

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EXECUTIVE SUMMARY

Aquifer storage and recovery (ASR) is the artificial recharge of water into an aquifer, where it is stored for later withdrawal. Artificial recharge is generally achieved either by ponding water in surface basins, where it can seep into the soil and infiltrate into the aquifer (surface spreading), or by injecting the water directly into the aquifer through a well (injection) (Bouwer, 2002).

Aquifer storage and recovery allows for the storage of water in the subsurface, while preventing losses from evaporation that occur with surface reservoirs. Using ASR projects in Cache Valley may provide water planners and managers with increased flexibility in managing ground-water resources.

A clay confining layer above the principal aquifer, coupled with the distribution of the Salt Lake Formation, a less transmissive formation, limits potential surface-spreading sites to a narrow band along the eastern mountain front of Cache Valley between Green Canyon and Millville Canyon. We identified two potential surface-spreading sites within this target area, one near the mouth of Green Canyon in North Logan, and one east of Providence. Both sites are gravel pits on private property.

Since injection wells can penetrate clay layers to reach the aquifer, potential injection sites are limited only by the lateral extent of the principal aquifer, which is roughly a triangle between Smithfield, Wellsville, and Hyrum. We identified an unused well near River Park Drive in the Island area of Logan that penetrates the principal aquifer and would be suitable for use as an injection well. Logan City currently owns the well.

Injection of water using the River Park well is an advantageous recharge method over the surface-spreading sites. The principal advantages of this injection well are (1) the sediments underlying the surface-spreading sites are uncertain and would require drilling exploration wells to verify the absence of the clay confining layer or other strata that would prevent water from infiltrating into the principal aquifer, whereas the injection well is completed within the target aquifer zone; (2) the well has already been drilled and has been constructed in a manner that will allow injecting water; and (3) aquifer tests have been conducted on the well and consequently, the hydrogeologic properties surrounding the well are known.

BACKGROUND

Introduction

Cache Valley is a rural area in northern Utah (figure 1) experiencing an increase in urbanization and ground-water use. Ground water, mostly from the basin-fill aquifer, provides a significant proportion of the drinking-water supply in Cache Valley. The increased use of ground water, exacerbated by periods of drought, has resulted in an overall decline of water levels in wells (figure 2) and the reduction of flow rates from some springs. Maintaining adequate ground-water supplies and limiting the potential for well interference are critical issues in determining the extent and nature of future development in Cache Valley. Local government officials and citizens in Cache County have expressed concern about the potential impact that development may have on ground-water quantity and quality, particularly privately owned domestic wells completed in the basin-fill aquifer. Local government officials would like to investigate the possibility of using excess runoff in the spring to augment ground-water resources through artificial ground-water recharge as part of one or more aquifer storage and recovery projects. Aquifer storage and recovery within the basin-fill aquifer, via either land-surface infiltration or injection wells, potentially offers a partial solution to problems associated with water-level decline in Cache Valley. Such a project can help stabilize water-level declines, 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.

The objective of this study is to assess the feasibility of aquifer storage and recovery in the principal basin-fill aquifer (figure 3) in Cache Valley. This project is a phased-approach project with four phases: (1) an assessment of the potential for aquifer storage and recovery projects in Cache Valley, including the identification of potential sites, recommendation of most appropriate methods (surface spreading/ponding versus injection wells), permitting requirements, and determination of data-collection needs, (2) collection and analysis of pre-project-implementation baseline data, (3) design and implementation of a pilot project, and (4) collection of post-project data and evaluation of results to determine whether aquifer storage and recovery project goals were met and whether full-scale aquifer storage and recovery in Cache Valley is warranted.

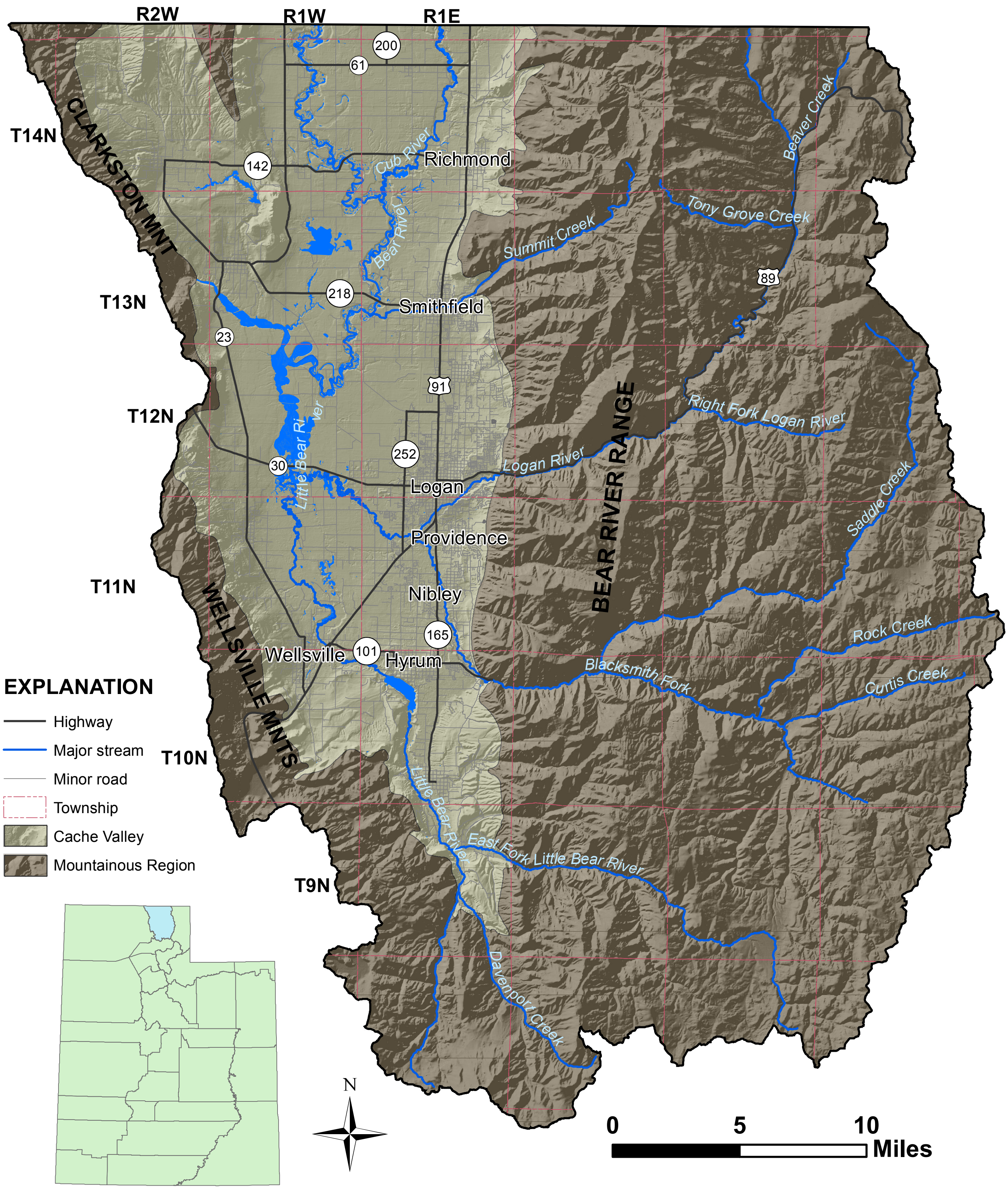

Figure 1. Cache Valley is in Cache County in northern Utah.

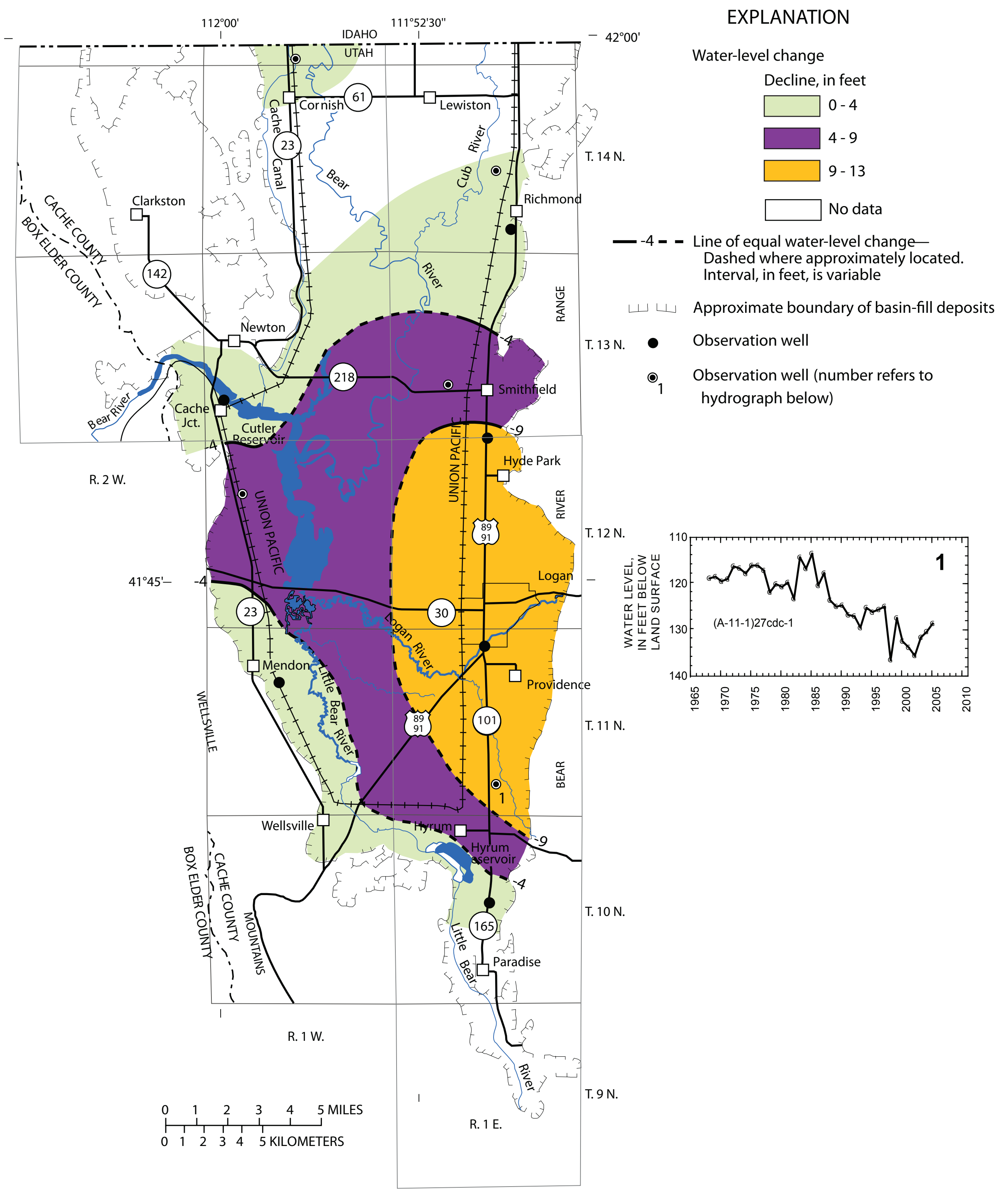

Figure 2. Map of Cache Valley showing changes of water levels from March 1975 to March 2005 (modified from Burden, 2005).

Location and Geography

Cache Valley (figure 1) is a north-south-trending valley with an area of about 660 square miles in northeastern Utah and southeastern Idaho. About 365 square miles of the valley is in Utah. In Utah, Cache Valley is bordered by the Bear River Range to the east, the Wellsville Mountains to the southwest, the Cache Butte Divide and Junction Hills to the West, and Clarkston Mountain to the northwest. The valley floor ranges in elevation from about 4400 to 5400 feet. Peaks in the Wellsville Mountains and Bear River Range reach elevations above 9000 feet.

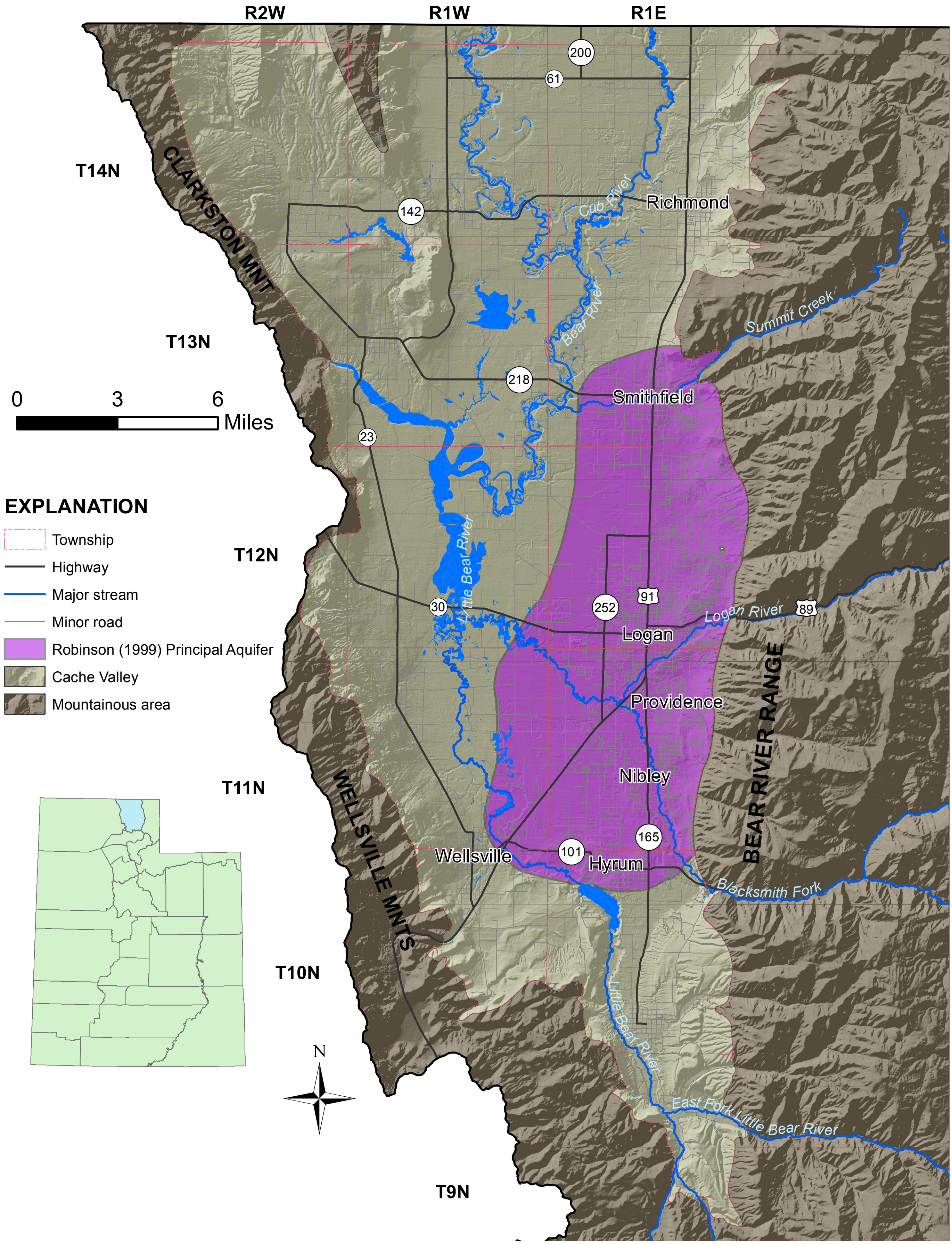

Figure 3. *Extent of the principal aquifer as delineated by Robinson (1999).*

The Bear River, the largest tributary to Great Salt Lake, flows through Cache Valley, entering Utah from the north and exiting Cache Valley between Clarkston Mountain and the Wellsville Mountains. Several large tributaries to the Bear River, including the Logan River, Blacksmith Fork, and Little Bear River, originate in the mountains surrounding Cache Valley in Utah.

Water Use and Distribution

In 2008, Cache Valley had a total of 24,586 connections, 22,763 of which are domestic connections (Utah Division of Water Rights, 2010). Towns in the principal aquifer area service a majority of those connections. Total withdrawal from wells in Cache Valley, Utah for 2008 was 34,500 acre-feet (Burden, 2009). Of the 34,500 acre-feet, irrigation wells pumped 13,700 acre-feet (40%), industrial wells pumped 5,900 (17%), public supply wells pumped 12,900 (37%), and domestic and stock wells pumped 2,000 acre-feet (6%). Of the 237,950 acres of Cache Valley, Utah, 96,534 acres (41%) are irrigated agricultural areas, 8612 acres (4%) are semi-irrigated, 30,415 acres (13%) are urban, 71,359 acres (30%) are non-irrigated, and the rest (12%) are other miscellaneous designations (Utah Division of Water Resources, 2010). There are approximately 365 miles of irrigation canals in the Utah portion of Cache Valley.

Available population and land-use statistics are for Cache County as a whole; most people in the county live in Cache Valley. From 2000–2007, population in Cache County increased by 2.3 percent (Demographic and Economic Analysis Section, 2008). The July 1, 2007, population of Cache County is estimated at 108,887; projected population is 266,711 by 2050, representing an increase of approximately 157,000 residents (Demographic and Economic Analysis Section, 2005).

Previous Investigations

Peterson (1946) conducted an early investigation of the quantity of ground-water supply available in Cache Valley. Gardner and Israelsen (1954) and Israelsen and others (1955) discussed aquifers in Cache Valley and methods of drainage of the shallow unconfined aquifer in lowland areas of Cache Valley. Beer (1967) evaluated southern Cache Valley's basin-fill aquifer to determine those areas having the best potential for water development based on available water supply, chemical quality, and potential ground-water withdrawal rates.

U.S. Geological Survey (USGS) workers Bjorklund and McGreevy (1971) conducted a detailed study of the water resources of Cache Valley, Utah and Idaho, with the help of previously collected published data (McGreevy and Bjorklund, 1970). They created a hydrologic budget for the valley, conducted four aquifer tests, created a conceptual diagram of the valley, and divided the valley into separate hydrogeologic regions.

Clyde and others (1984) constructed the first numerical model of Cache Valley, Utah, using an early finite-difference model. They based their model on Bjorklund and McGreevy's (1971) conceptual model, including one confined and one unconfined aquifer. They separated their model into the zones that Bjorklund and McGreevy delineated. They concluded that the areas of highest transmissivity in the valley are at the mouths of the Logan River and Smithfield Canyon, although Inkenbrandt (2010) determined that their transmissivity values near the mouth of Smithfield Canyon were approximately an order of magnitude too high.

Anderson and others (1994) mapped ground-water recharge and discharge areas for Cache Valley's basin-fill aquifer. They subdivided the basin-fill aquifer into (1) primary recharge—less than 20 feet of clay as recorded in well drillers' records and a downward hydrologic gradient, (2) secondary recharge—confining layers (greater than 20 feet) and a downward hydrologic gradient, and (3) discharge areas—upward hydrologic gradients using water-well records and water-level data. They stated that recharge from the extensively fractured adjacent consolidated rock 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.

USGS workers Kariya and others (1994) completed a detailed examination of Cache Valley's water resources using data collected by Roark and Hanson (1992). Their investigation consisted of the construction and calibration of a MODFLOW (McDonald and Harbaugh, 1988) computer model, a hydrologic budget, and an aquifer test.

Robinson (1999) conducted a thorough hydrostratigraphic and hydrologic examination on the valley. Robinson (1999) characterized the chemistry and hydrostratigraphy of ground-water 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: (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).

Lowe and Wallace (1999a, b, 2001; Wallace and Lowe, 1999) delineated ground-water quality of the basin-fill aquifer. Sanderson and Lowe (2002) assessed ground-water sensitivity and vulnerability to pesticides for the principal basin-fill aquifer in Cache Valley. Lowe and others (2003) classified ground water in the Utah portion of the Cache Valley basin-fill aquifer under the Utah Water Quality Board total-dissolved-solids concentration classification system, and made recommendations for septic-tank soil-absorption system density based on ground-water flow available for mixing.

Using the same grid as Kariya and others (1994) and revised parameters, Myers (2003) simulated Cache Valley ground-water conditions using MODFLOW (McDonald and Harbaugh, 1988). Myers also constructed a hydrologic budget for Cache Valley. Myers concluded that the aquifers in Cache Valley are recharged along the margins of the valley from the surface and through subsurface flow from the surrounding mountain ranges. Myers' model suggests that droughts may have a much greater influence on stream and spring discharges than increased pumping from wells.

Oaks (2004) assessed decreased flows from artesian wells in the College Ward area. Weber (2004) studied canal leakage in Cache Valley. 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.

Geologic Setting

Structurally, Cache Valley is bounded by north-striking, high-angle normal faults (the East Cache and West Cache fault zones). It forms the southern end of a series of half-grabens within an extensional corridor between the Wasatch and Teton normal fault systems (Evans and Oaks, 1996). Both the East Cache and West Cache fault zones have been subdivided into three segments. Both fault zones show evidence of recurrent Quaternary movement, including Holocene events (McCalpin, 1994; Black and others, 1999, 2000).

The mountains surrounding Cache Valley consist primarily of Precambrian to Permian sedimentary and metamorphic rocks, predominantly limestone, dolomite, shale, and quartzite (Williams, 1948, 1958; Bjorklund and McGreevy, 1971). The Tertiary Salt Lake Formation, primarily tuffaceous sandstone and conglomerate, forms an almost continuous belt in the foothills surrounding the valley and underlies Quaternary deposits within Cache Valley (Williams, 1962; Evans and Oaks, 1996). Gravity survey data (Oaks and others, in preparation) and drillers' logs suggest that the Salt Lake Formation is nearly at the surface along the mountain front north of Green Canyon and south of Blacksmith Fork Canyon (figure 4). The tuffaceous portions of the Salt Lake Formation contain swelling clays, which impede the flow of ground water (Smith 1997).

The valley floor in Cache Valley is underlain by unconsolidated basin fill of varying thickness. The greatest thickness is near the eastern margin of the valley just southwest of Logan (Evans and Oaks, 1996). The basin fill consists mostly 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 present Cache Valley floor 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 3) is within a triangle between Smithfield, Wellsville, and Hyrum, and may be up to 500–700 feet thick (after mud interbeds are subtracted). Mud interbeds increase to the west until they dominate in most places west of the valley center. These basin-fill deposits cover and lap onto the Salt Lake Formation where it is exposed or shallowly buried in the valley. The thickest portions of the main aquifer coincide with major gravity lows in the valley, between Nibley and College Ward, along U.S. Highway 91 through North Logan, and along the Logan River (Oaks and others, in preparation).

Two thick clay confining layers are present in the upper 120–170 feet of the basin fill. 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 comprise the upper confined aquifer of Robinson (1999).

Transmissivity values in the Salt Lake Formation are typically an order of magnitude lower and less continuous than those of the principal aquifer in the valley (Inkenbrandt, 2010). The lower transmissivities and tuffaceous portions of the Salt Lake Formation make it a generally poor aquifer.

Ground-Water Conditions

Occurrence

Ground water in Cache Valley occurs under perched, confined, and unconfined conditions (Bjorklund and McGreevy, 1971). The basin fill is unconsolidated sediment consisting of multiple layers of silt, sand, and gravel, which were deposited in fluvial, alluvial-fan, landslide, and nearshore lacustrine environments, which are separated by layers of silt and clay that were primarily deposited in offshore lacustrine environments (Bjorklund and McGreevy, 1971; Lowe, 1987, plate 2; Lowe and Galloway, 1993, plate 2). The basin fill is more than several hundred feet thick at many locations in the valley center (Kariya and others,

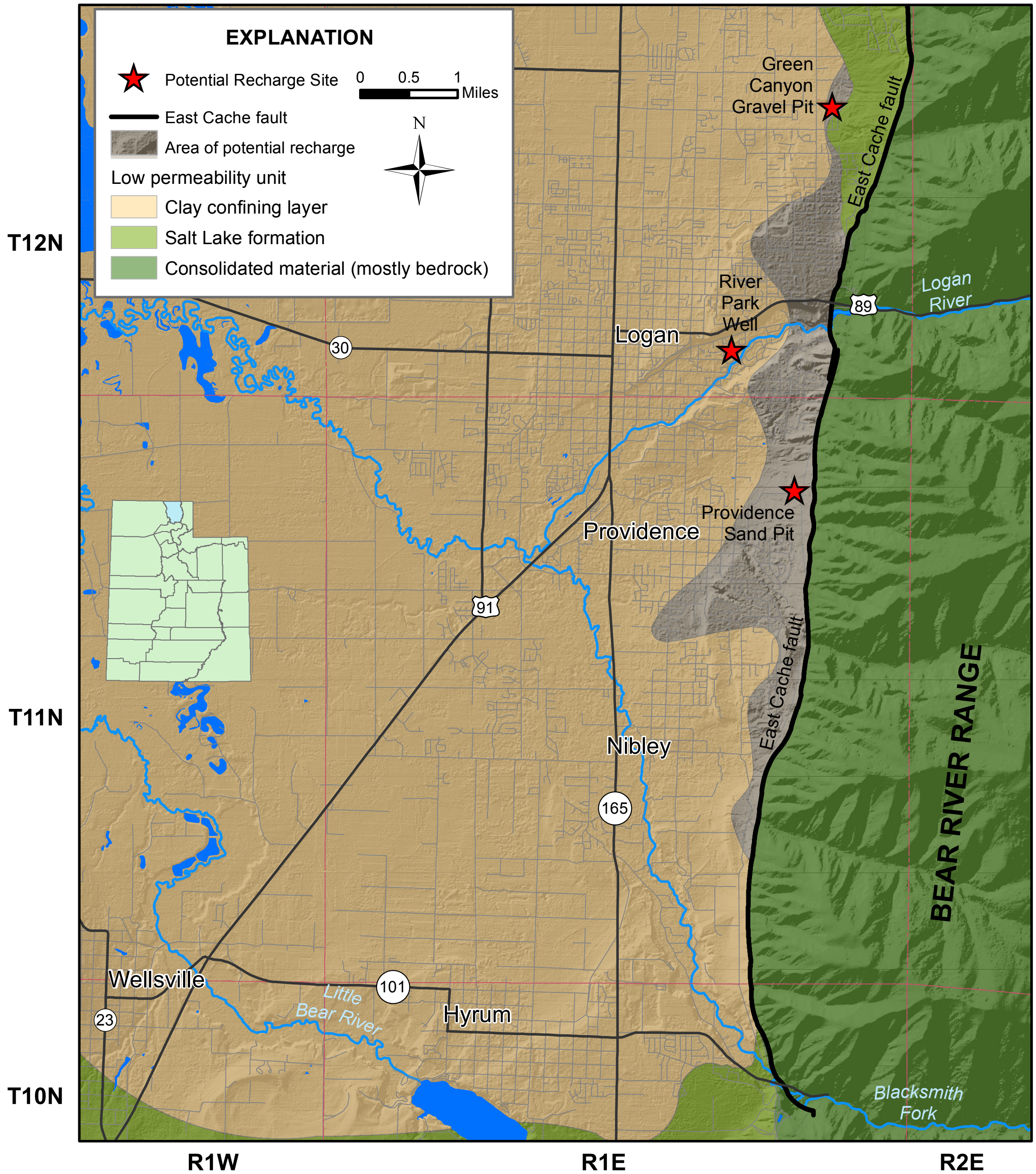

Figure 4. *Extent of clay confining layers, consolidated rock, and area of potential recharge based on geologic sections and well drillers' records.*

1994). In the area between Smithfield and Newton, unconsolidated sediments are up to about 1340 feet thick (Bjorklund and McGreevy, 1971). The principal aquifer (figure 3), the aquifer that is primarily used for 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 ground water 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. Kariya and others (1994) developed a conceptual model (figure 5) for the principal aquifer in the central portion of Cache Valley in which ground water is primarily under leaky confined conditions due to the discontinuous nature of the clay and silt confining layers. Based on evidence from over 200 drillers' logs and from isotopic signatures and carbon-14 age estimates, Robinson (1999) developed a conceptual model (later improved by Olsen [2007]; figure 6) of non-leaky confining layers separating the shal-

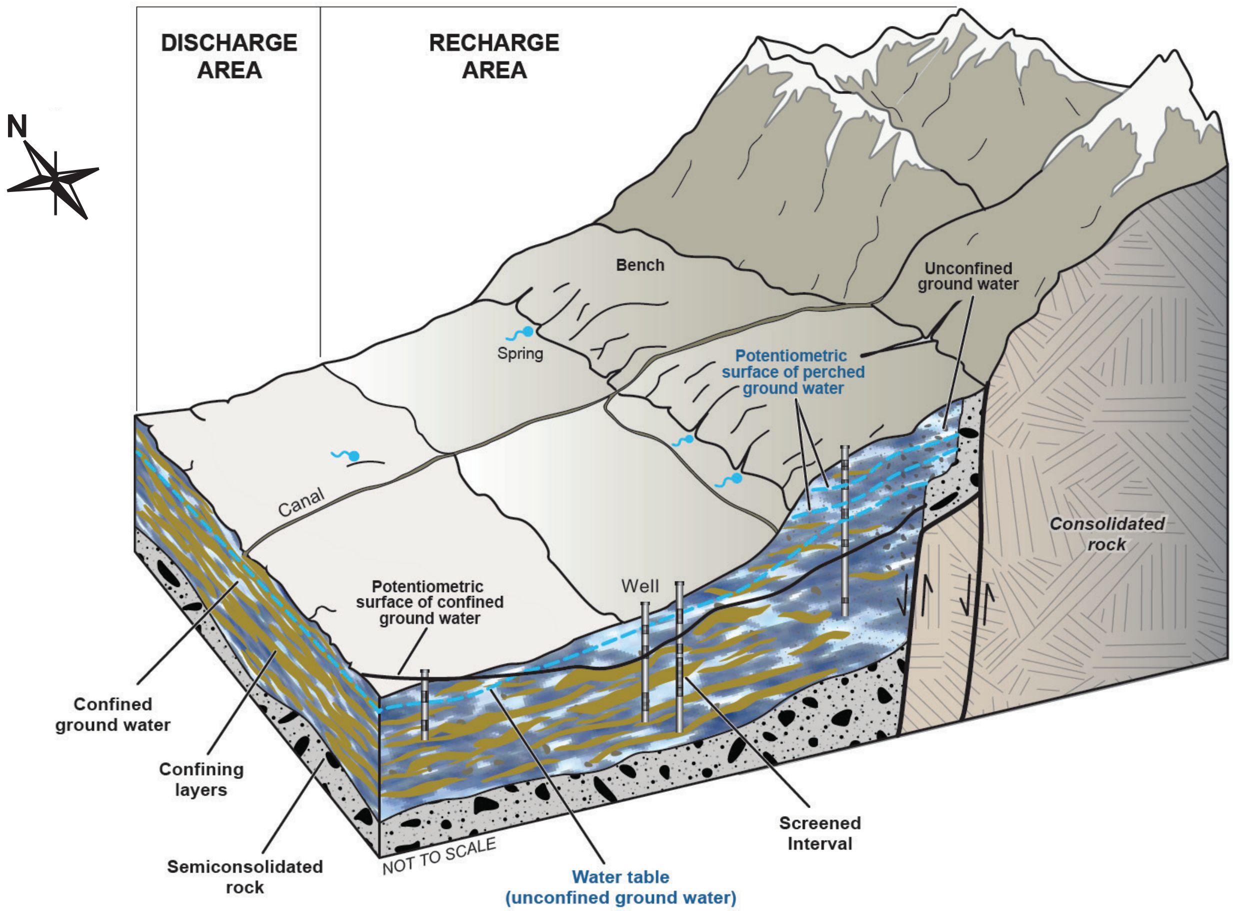

Figure 5. *Schematic block diagram showing conceptual model of Cache Valley's hydrostratigraphy (modified from Kariya and others, 1994).*

low unconfined aquifer, and other minor aquifers from the principal aquifer. The boundary between unconfined and confined conditions is gradational near the margins of the basin. The confined portion of the principal aquifer is typically overlain by a shallow unconfined aquifer (Bjorklund and McGreevy, 1971). Our study shows, with new geologic sections, that both confining layers (table 1) continue virtually to the mountain front in low areas between deltas (figure 4).

Depth to Ground Water

Depth to ground water 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). Long-term water levels in Cache Valley's principal aquifer were relatively constant between 1945 and 1982 (Kariya and others, 1994), but declined as much as 13 feet from March 1975 to March 2005 (figure 2) (Burden and others, 2005), though subsequent hydrographs published by Burden and others (2009) show several feet of rebound in most areas since 2005. Seasonal water-level changes ranged from a few feet to about 20 feet (Kariya and others, 1994, figure 12). Water levels are generally highest in the summer in northern Cache Valley, lowest in the summer in southeastern Cache Valley, and show no consistent seasonal pattern of water-level fluctuations in southwestern Cache Valley (Kariya and others, 1994).

Ground-Water Flow

Ground-water flow in Cache Valley's principal aquifer is north-northwest in southern Cache Valley. In most of the valley, ground-water 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) that extend across most of the valley limit a majority of the valley surface infiltration to the shallow, unconfined aquifer. Recharge

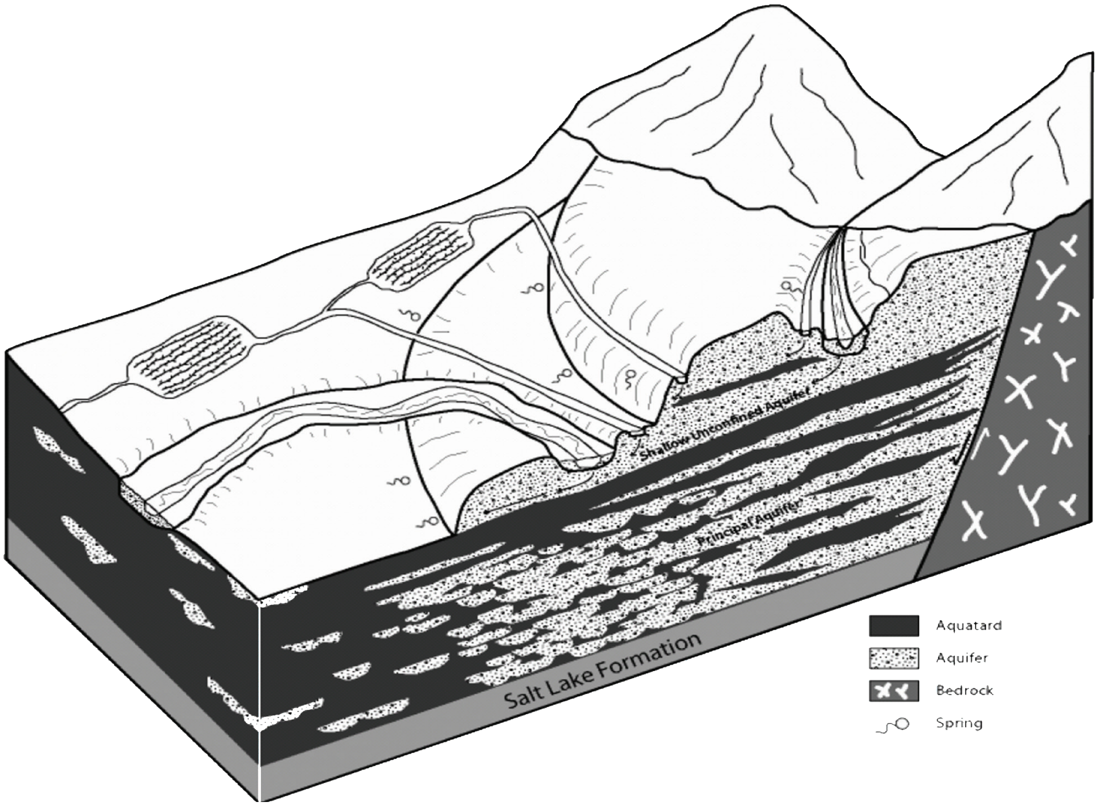

Figure 6. *Schematic block diagram showing Olsen's (2007) conceptual model of Cache Valley's hydrostratigraphy based on Robinson's (1999) results.*

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 4) 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 ground-water discharge from seepage (Kariya and others, 1994). Ground-water uses include 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 is obtained from wells completed in the confined, unconsolidated aquifers of the basin-fill aquifer. In 1994, the U.S. Geological Survey (USGS) estimated the average shortage (recharge minus discharge) in Cache Valley aquifer system to be 117,000 acre-feet (Kariya and others, 1994). Appendix A contains a detailed, revised water budget for the Utah portion of Cache Valley.

Ground-Water Quality

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

Lowe and others (2003) sampled 165 wells and one spring in 1997. The water was analyzed for general chemistry and nutrient content by the Utah Division of Epidemiology and Laboratory Services. Water from 46 of the wells was analyzed for organics and pesticides. TDS concentrations ranged from 178 to 1758 mg/L, and average background TDS was 381 mg/L (Lowe and others, 2003). Most of the ground water in the principal aquifer had TDS concentrations generally less than 500 mg/L. However, one sample

Table 1. *Major Cache Valley hydrostratigraphic units and their associated properties (modified from Robinson, 1999).*

Unit (Average thickness, ft)	Description	Water-Bearing Properties
Qau (50)	Quaternary alluvium undifferentiated 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)	Upper confining layer 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)	Deltaic deposits 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)	Upper confined aquifer 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)	Lower confining layer 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)	Lower confined aquifer unconsolidated to semiconsolidated thickly bedded gravels and sands; discontinuous lenses of silt, clay and marl; woody debris, peat, and shells sometimes present	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)	Tertiary Salt Lake, undifferentiated 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)	Tertiary Wasatch, undifferentiated 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)	Paleozoic, undifferentiated 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

from a well, completed to 24 feet deep in the shallow unconfined aquifer at a mink ranch west of Nibley, yielded ground water with a TDS concentration of 1236 mg/L. Average TDS was 453 mg/L for water from deep (>200 ft) wells, 331 mg/L for water from medium-depth (100–200 ft) wells, and 414 mg/L for water from shallow wells (<100 ft) completed in the principal aquifer. Average TDS for water from the wells for which we had no depth information, typically older wells drilled or dug before well logs were required, was 843 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. A total of seven wells, one northwest of Lewiston, two near Cornish, three southwest of Hyrum, and the mink ranch well with high TDS, yielded water samples that exceed the U.S. Environmental Protection Agency ground-water-quality (health) standard of 10 mg/L for nitrate. High-nitrate levels may be attributed to contamination from septic-tank systems, feed lots, and/or fertilizer. Average nitrate concentration was 1.21 mg/L for water from deep wells, 1.98 mg/L for water from medium-depth wells, and 4.47 mg/L for water from shallow wells completed in the principal aquifer. Average nitrate concentration for water from the wells for which we had no depth information was 6.06 mg/L. The spring yielded water with a nitrate concentration of 3.91 mg/L.

A water sample from a well near the confluence of the Little Bear River and the Bear River yielded an arsenic value of 100 µg/L, ten times the ground-water-quality standard of 10 µg/L. A number of wells throughout the valley contained water with elevated iron concentrations that exceed the secondary ground-water-quality standard of 300 µg/L, but are not considered harmful to human health. Of water wells tested for pesticides, only one well yielded water with a value above the detection limit for atrazine, but the value was below the ground-water-quality standard.

Review of Ground-Water Models

We reviewed two ground-water models created for the Cache Valley basin fill, one published by the USGS (Kariya and others, 1994) and the other a publication based on a master's thesis at Utah State University (Myers, 2003). These models are summarized in appendix B. Myers (2003) started with the Kariya and others (1994) model and adjusted it based on a different conceptual model and hydrologic budget. Kariya and others (1994) and Myers (2003) constructed their models to better understand water-supply interactions between the surface and the subsurface of the valley-fill material in Cache Valley.

The geologic complexity is already known, and the still-unknown geologic features of this basin make it unlikely that any model at this point in time can represent the actual hydrologic environment accurately. Either model may prove to be better at predicting the hydrologic changes that increased withdrawals will cause, or one may prove better in some parts of the basin and the other model may be better in other parts.

One of the most important differences between the two ground-water models is the continuity of confining layers overlying the principal aquifer. Kariya and others (1994) assumed that the principal aquifer is under leaky-confined conditions, whereas Myers (2003) assumed that the principal aquifer is confined across most of its extent. Such an absence of a continuous confining layer in the valley would imply that the confined aquifers in Cache Valley are hydraulically connected with each other and with the unconfined aquifers.

Several authors (Israelsen and McLaughlin, 1935; Williams, 1962; Bjorklund and McGreevy, 1971; Clyde and others, 1984; Anderson and others, 1994; Robinson, 1999) reported thick, continuous clay layers covering the principal aquifer and terminating within a mile of the western margin of the Bear River Range. Although the continuous nature of the confining layers has been substantiated, the vertical hydraulic conductivity of the confining layers has not yet been determined. The vertical hydraulic conductivity of these thick, continuous layers might be high enough in some areas to correspond to the model of Kariya and others (1994), though Inkenbrandt (2010) compiled most of the aquifer tests conducted in Cache Valley and found that leaky-aquifer-test analysis techniques were not applicable to any of those tests.

Although the model of Myers (2003) was intended as a revision of the model of Kariya and others (1994), there is no consensus as to which model better represents the actual hydrologic conditions. For example, Timani and Peralta (2010) successfully applied both models when researching optimization techniques for pumping in the valley.

Both Kariya and others (1994) and Myers (2003) explicitly stated the limitations of their models. In his limitations section, Myers (2003) explained that, due to a large cell size, his model is intended for basin-wide applications only, and recommended not using the model for small-scale applications. Kariya and others (1994) warned that modelers should be cautious when applying their model to simulate hydrologic effects near the mountains, because the amount of subsurface inflow from the consolidated rock of the Bear River Range into the unconsolidated basin fill was unknown. Kariya and others (1994) also warned of applying recharge values outside of the range of the calibrated model, because the model was only calibrated for a specific range of recharge rates. Since Myers' model (2003) is based on Kariya and others' (1994), it shares these same limitations.

AQUIFER-RECHARGE INVESTIGATION

Surface Spreading

Introduction

To assess the potential for aquifer storage and recovery projects in Cache Valley, we examined maps and aerial photographs, constructed nine cross sections of the area (figures 7–17), and interpolated aquifer transmissivity values (figure 18) from Inkenbrandt (2010). We looked for sites in areas of high aquifer transmissivity, near water

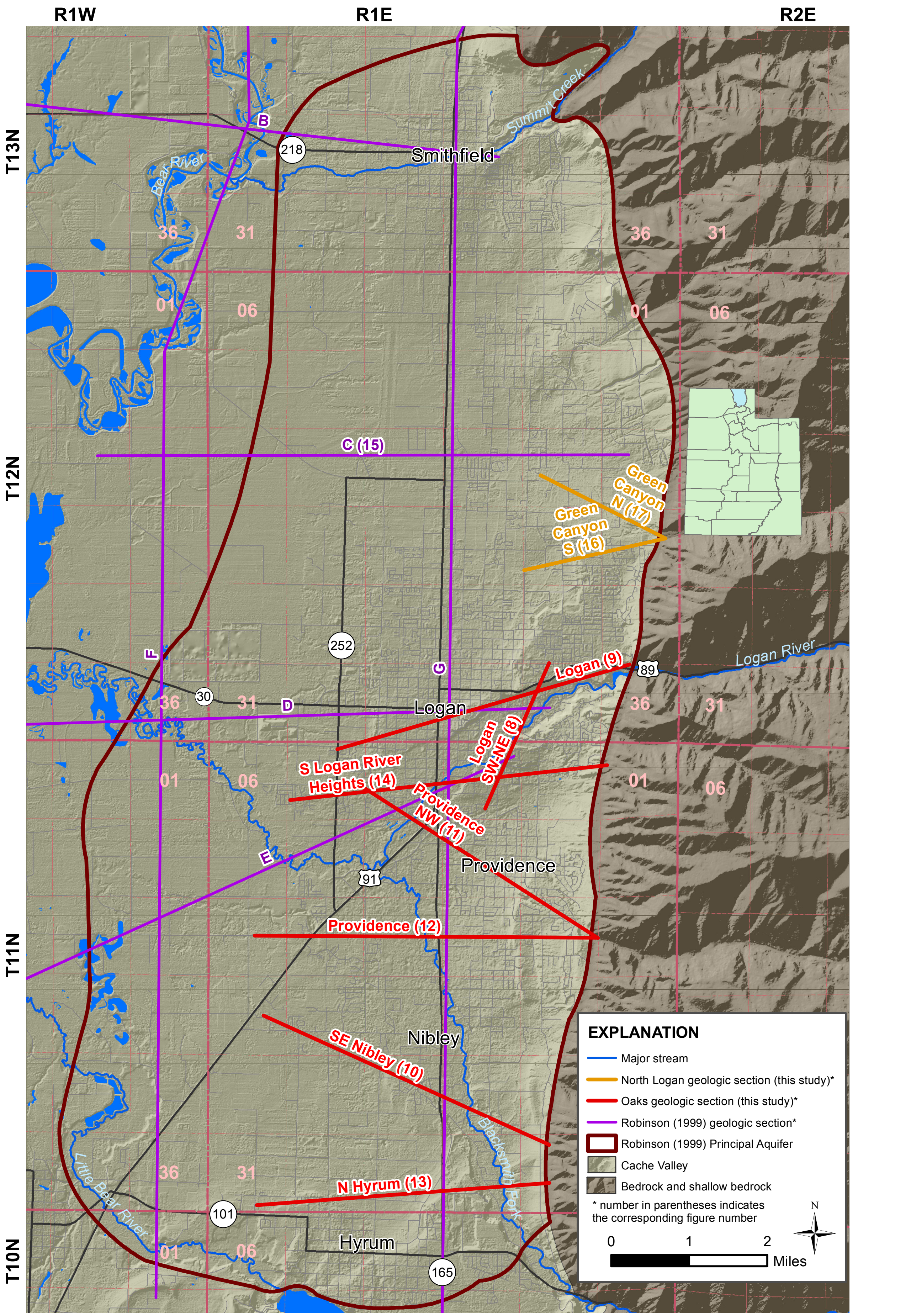

Figure 7. Location of geologic sections examined for this study. Robinson's (1999) geologic sections are purple and geologic sections made for this study are in red and orange.

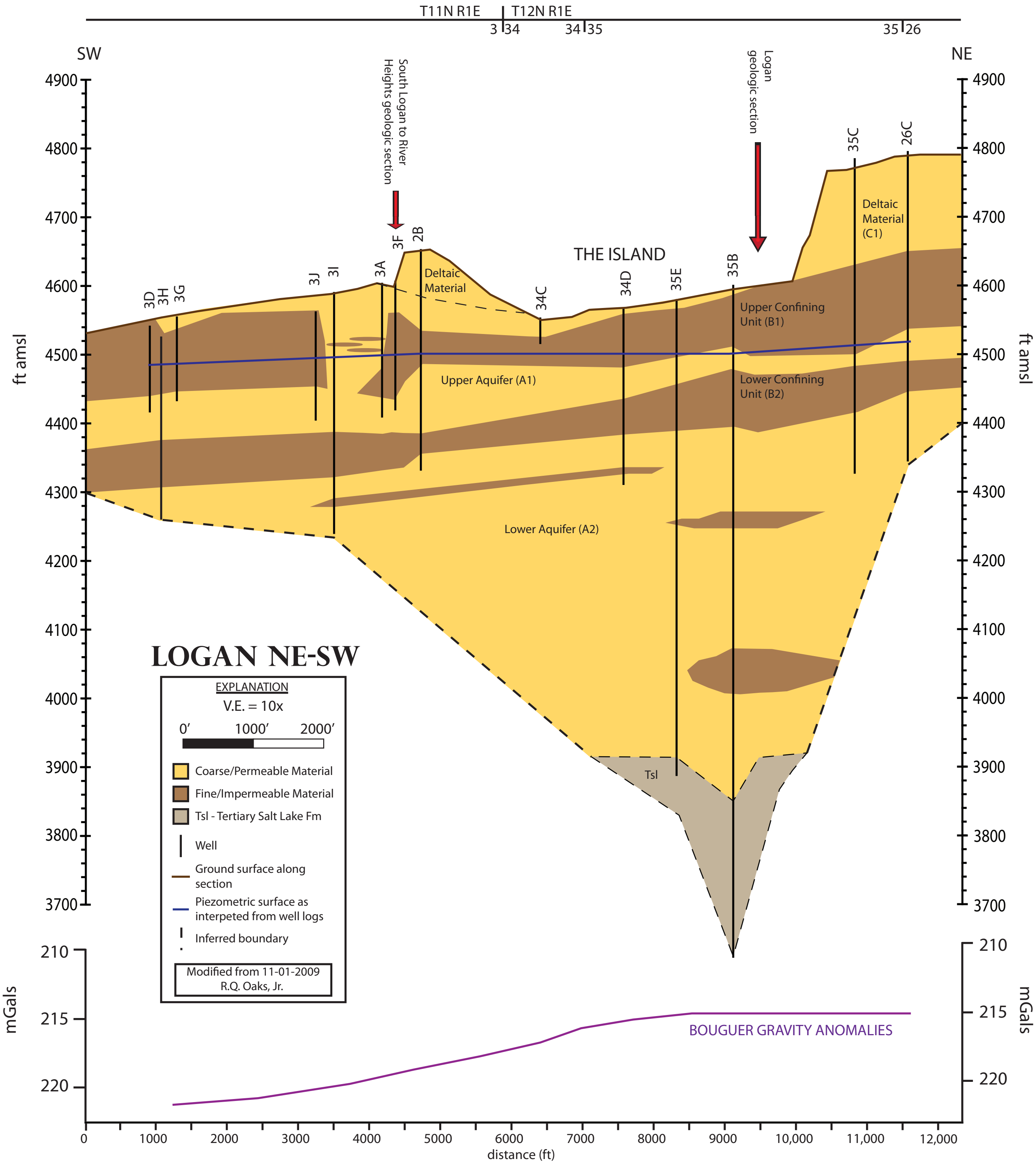

Figure 8. *Northeast to southwest geologic section of Logan area basin fill. See figure 7 for location of section.*

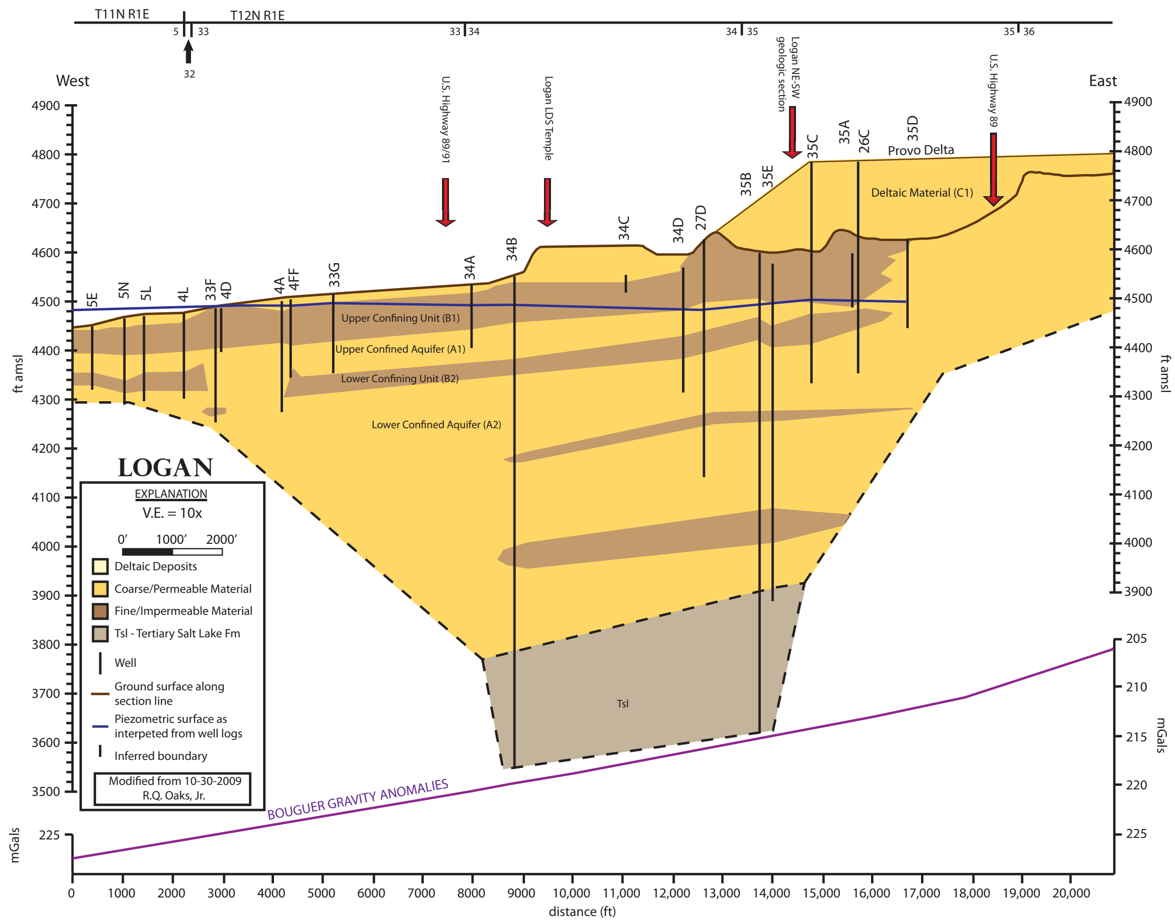

Figure 9. *West-southwest to east-northeast geologic section of Logan area basin fill. See figure 7 for location of section.*

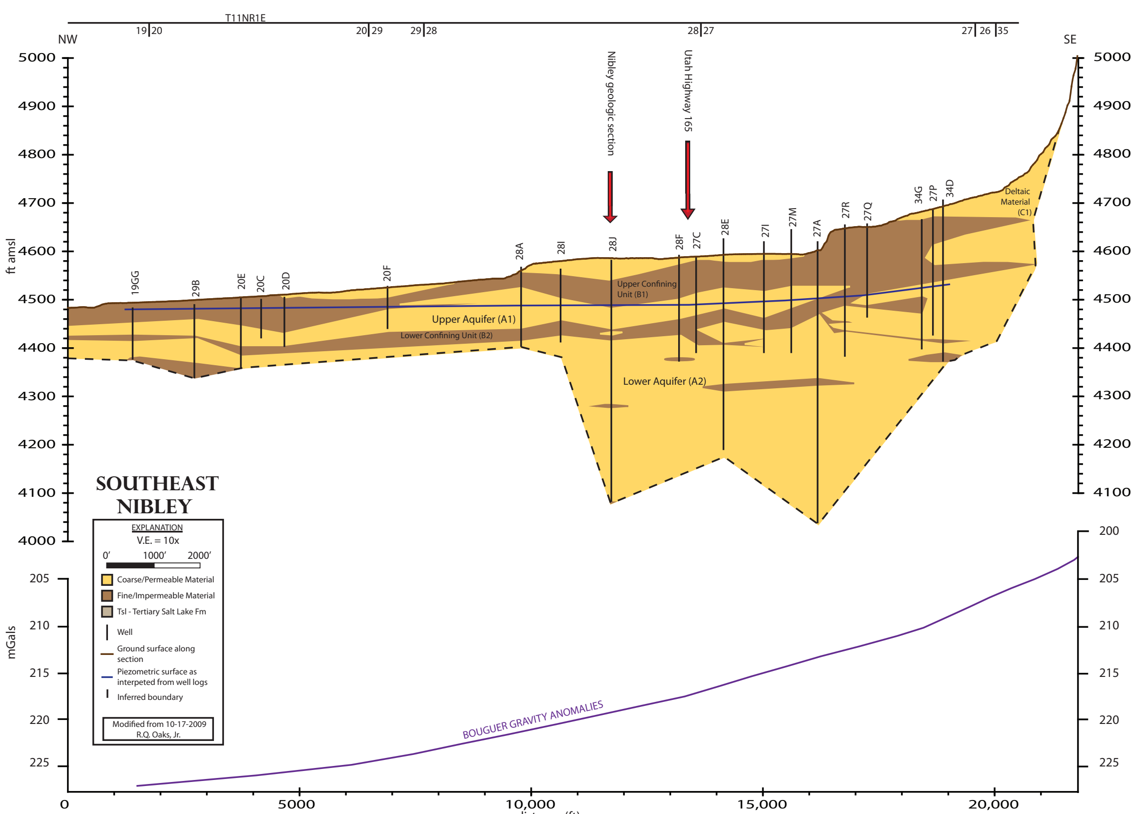

Figure 10. *Northwest to southeast geologic section of southeast Nibley area basin fill. See figure 7 for location of section.*

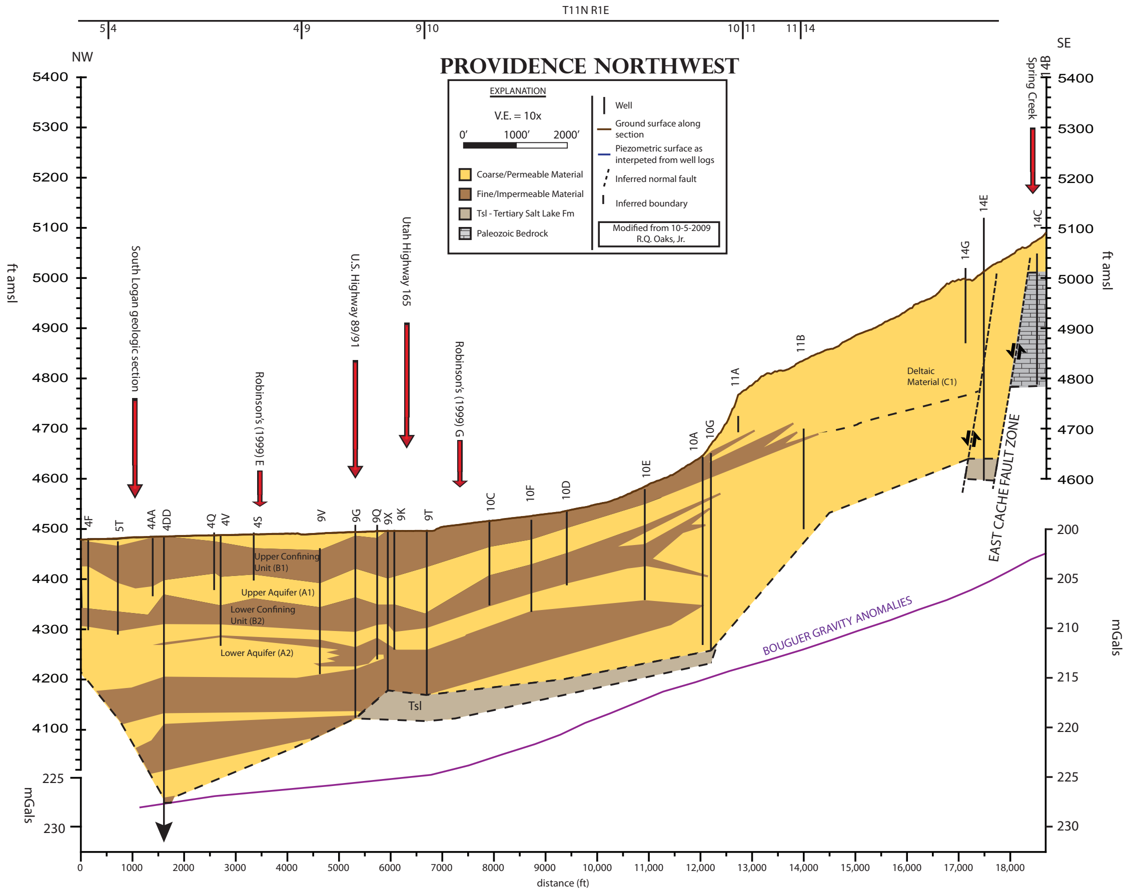

Figure 11. *Northwest to southeast geologic section of Providence area basin fill. See figure 7 for location of section.*

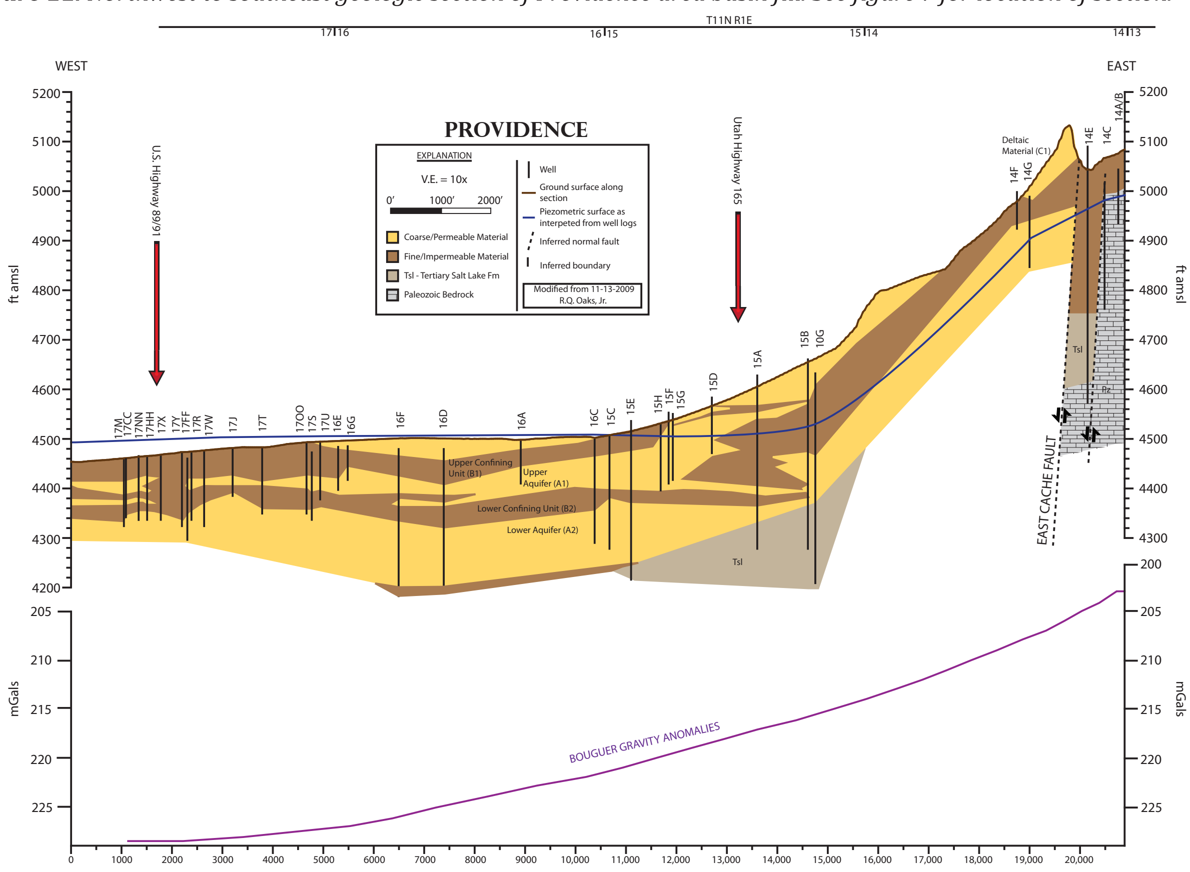

Figure 12. *East to west geologic section of Providence area basin fill. See figure 7 for location of section.*

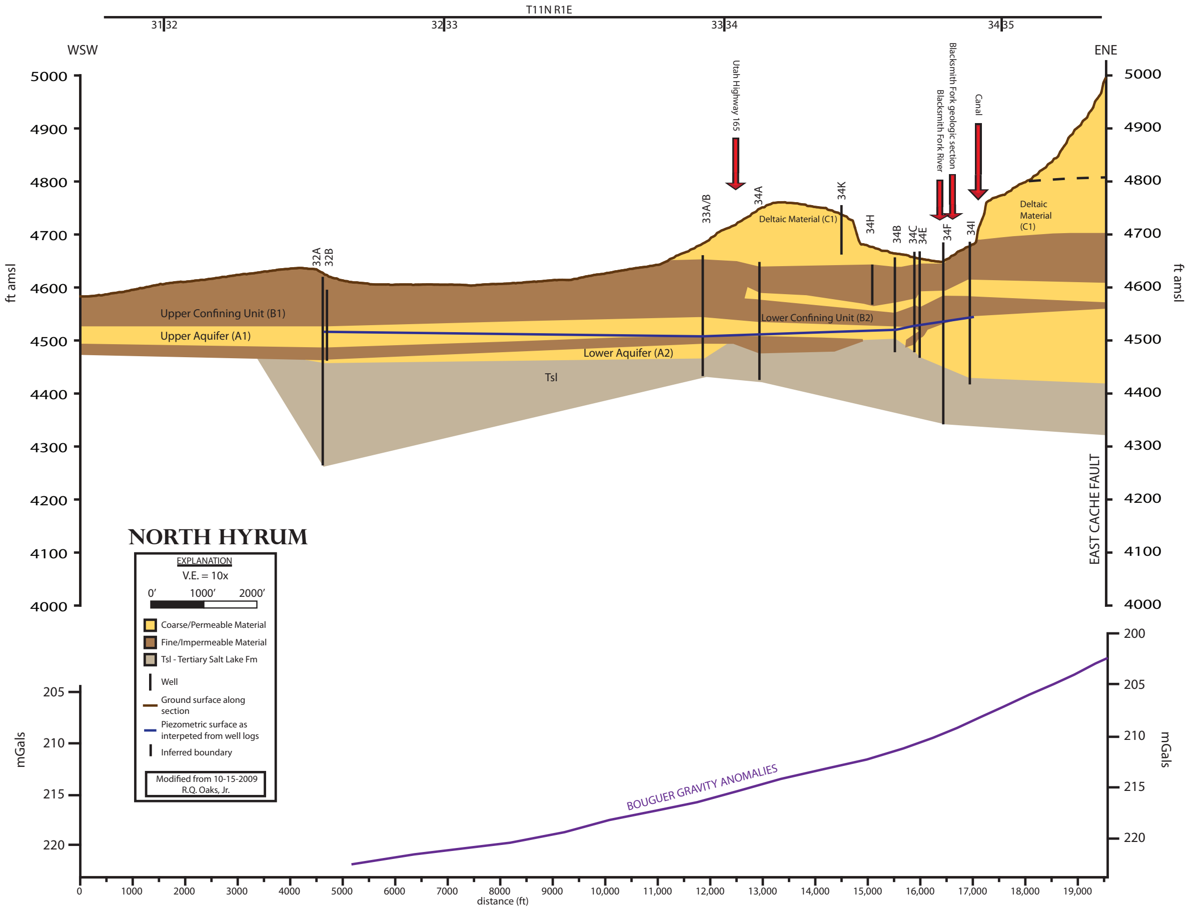

Figure 13. *West-southwest to east-northeast geologic section of North Hyrum area basin fill. See figure 7 for the location of the section.*

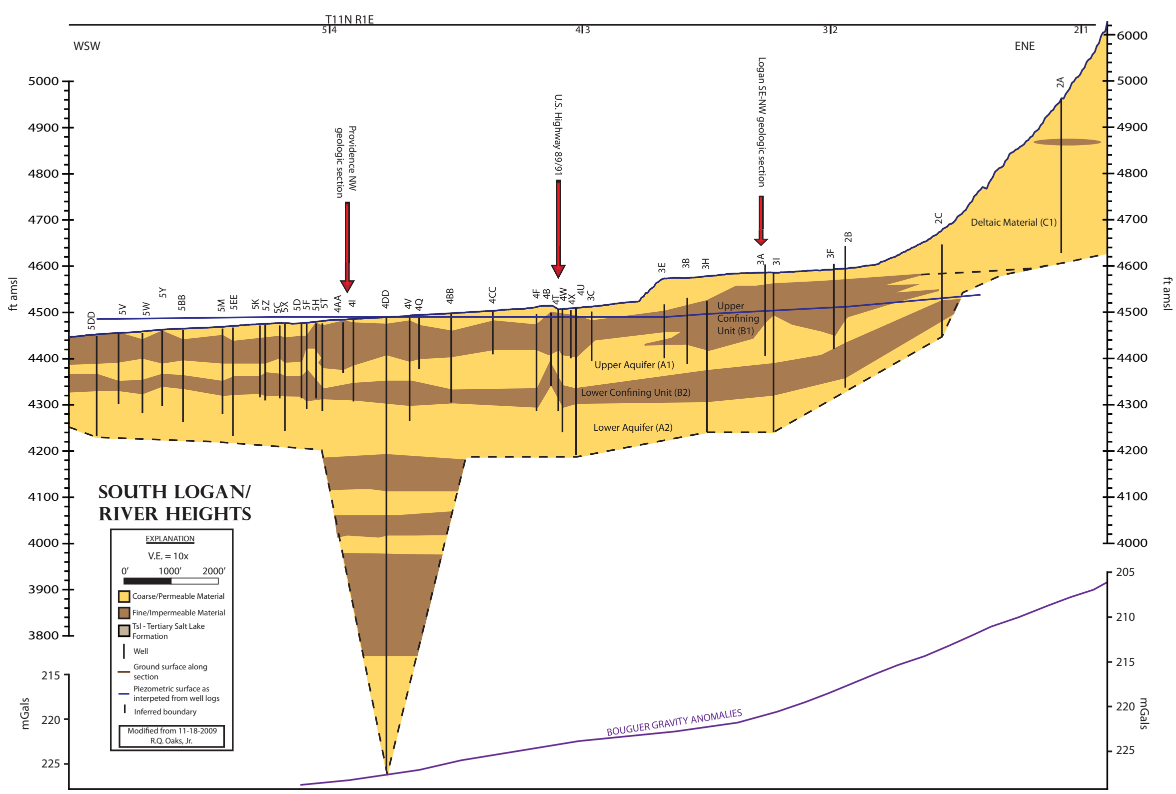

Figure 14. *East-northeast to west-southwest geologic section of south Logan-River Heights area basin fill. See figure 7 for the location of the section.*

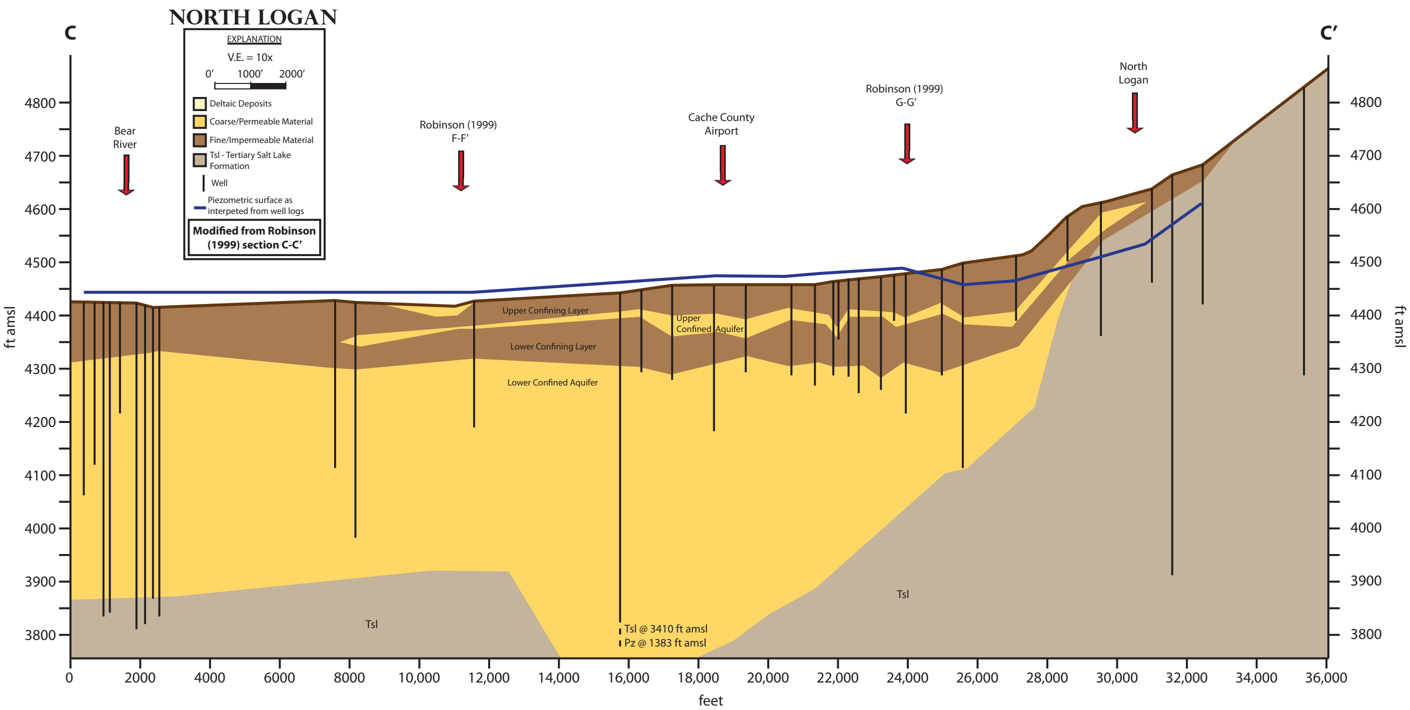

Figure 15. *East to west geologic section C–C’ constructed by Robinson (1999) of North Logan area basin fill. See figure 7 for the location of the section.*

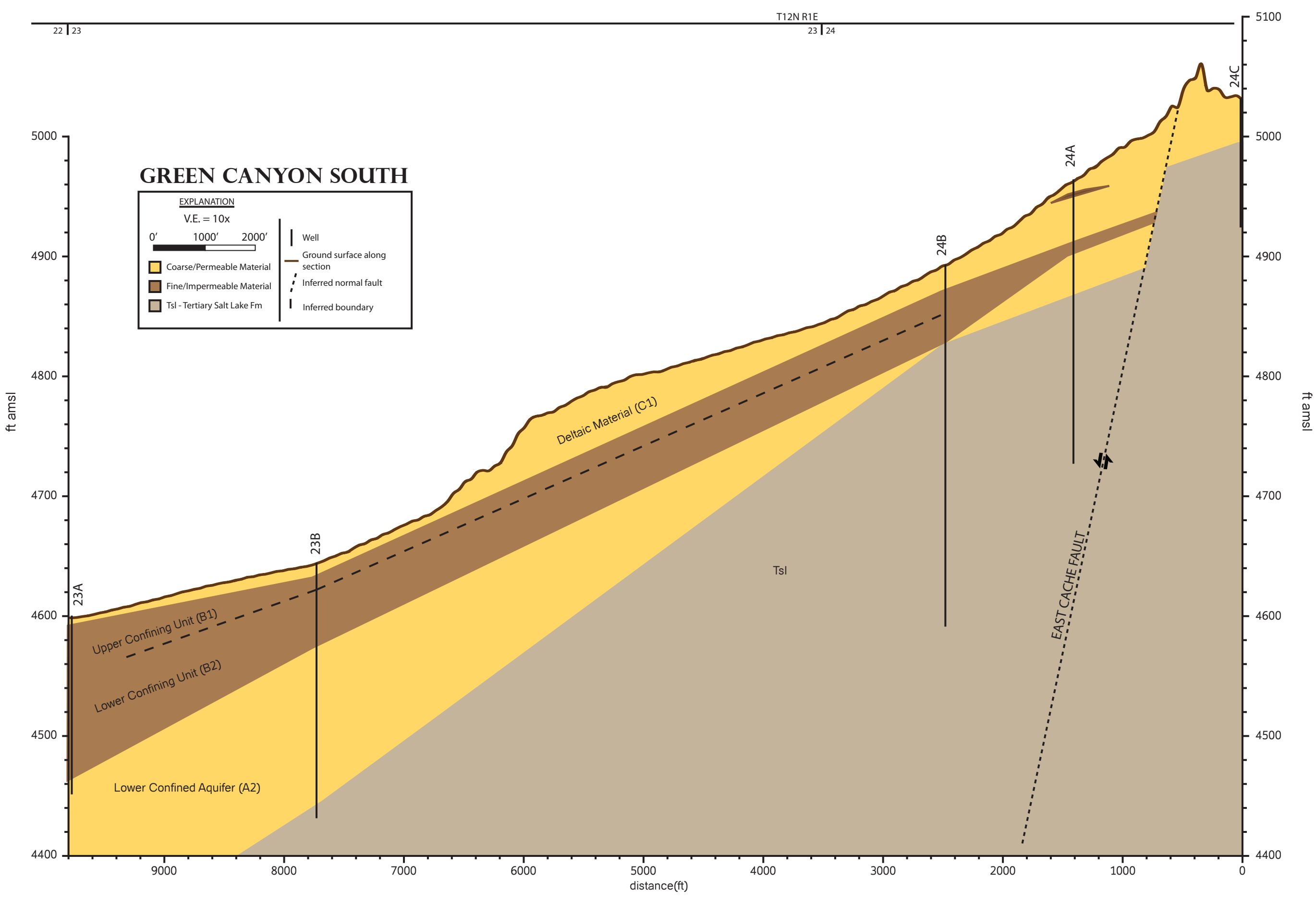

Figure 16. *Northeast to southwest geologic section of Green Canyon area basin fill. See figure 7 for the location of the section.*

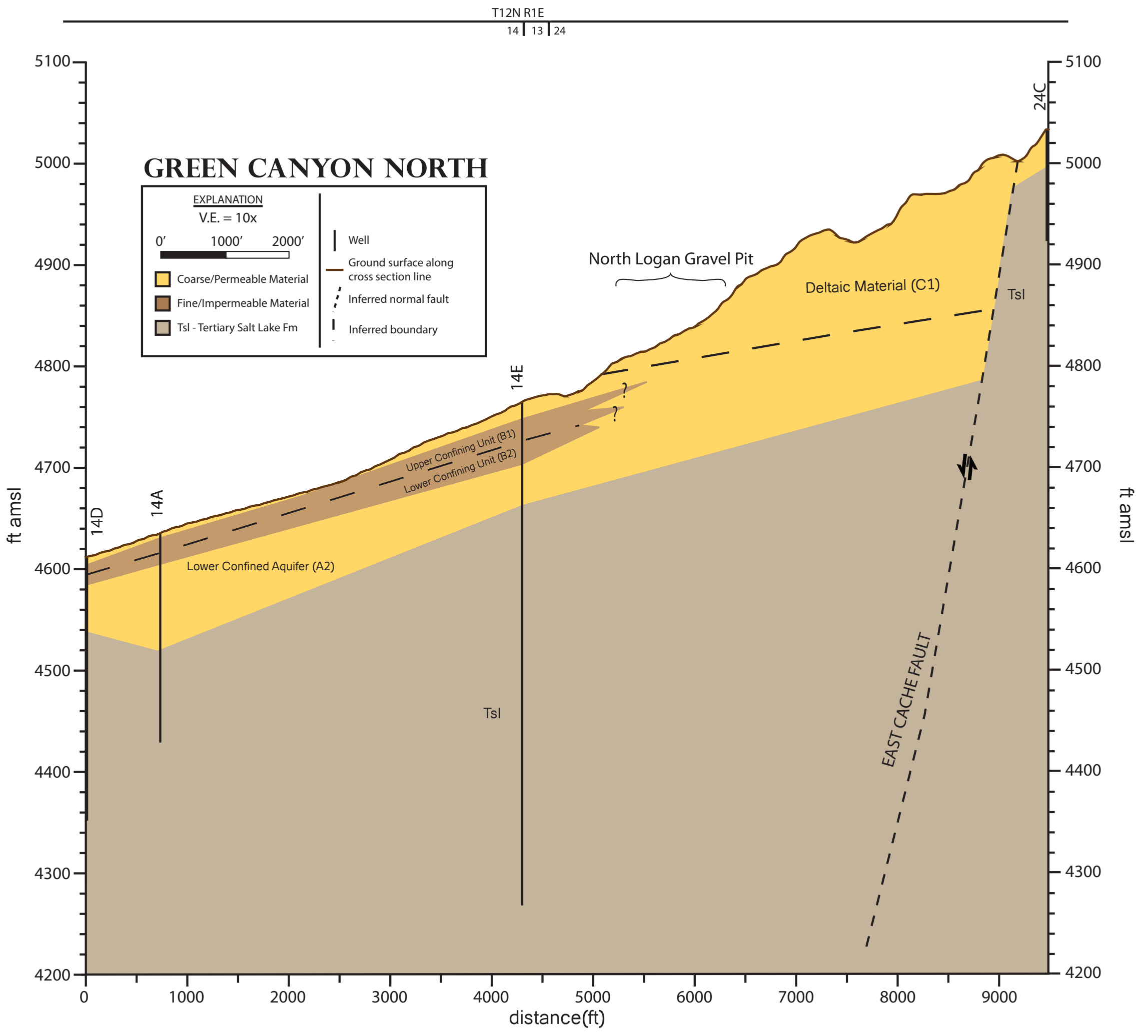

Figure 17. *Southeast to northwest geologic section of Green Canyon area basin fill. See figure 7 for the location of the section.*

sources, that lacked significant and continuous confining layers. Optimal sites for surface spreading will be close to the Bear River Range, beyond the eastern extent of the confining layers, and in areas where the Salt Lake Formation is not near the surface. The optimal area for surface-spreading sites is highlighted in figure 4.

Aquifer Transmissivity

Transmissivity is a rate at which water flows through the thickness of an aquifer under a specified hydraulic gradient. High transmissivity areas are more conducive to recharge. Researchers (Bjorklund and McGreevy, 1971; Clyde and others 1984; Kariya and others 1994; Myers 2003) have confirmed that the highest transmissivity values in Cache Valley are within the principal basin-fill aquifer. Transmissivity data from Inkenbrandt (2010) were interpolated to determine the distribution of hydraulic parameters in the principal aquifer (figure 18). Values of transmissivity for the principal aquifer are highest near deltaic deposits from Lake Bonneville and decrease away from the deltaic deposits (to the west). We chose potential recharge areas with generally high transmissivity (>1,000 ft^2/day).

Map Examination

We examined the main potential surface-spreading area (figure 4) through aerial photographs and geographic information layers from the Utah Automated Geographic Reference Center (AGRC) to find potential surface-spreading sites. The AGRC layers include mines (SGID93.GEOSCIENCE.MinesGNIS), land-ownership parcels (SGID93.CADASTRE.Parcels_Cache), and rivers and canals (SGID93.WATER.StreamsNHDHighRes).

We picked several existing excavated areas within the potential surface-spreading area delineated (figure 4) in the area of the principal aquifer. We used high-resolution aerial photographs (Utah Automated Geographic Reference Center, 2010) from 2009 to verify the existence and activity of excavations. We used the AGRC rivers and canals layers to see if water sources existed near the excavations.

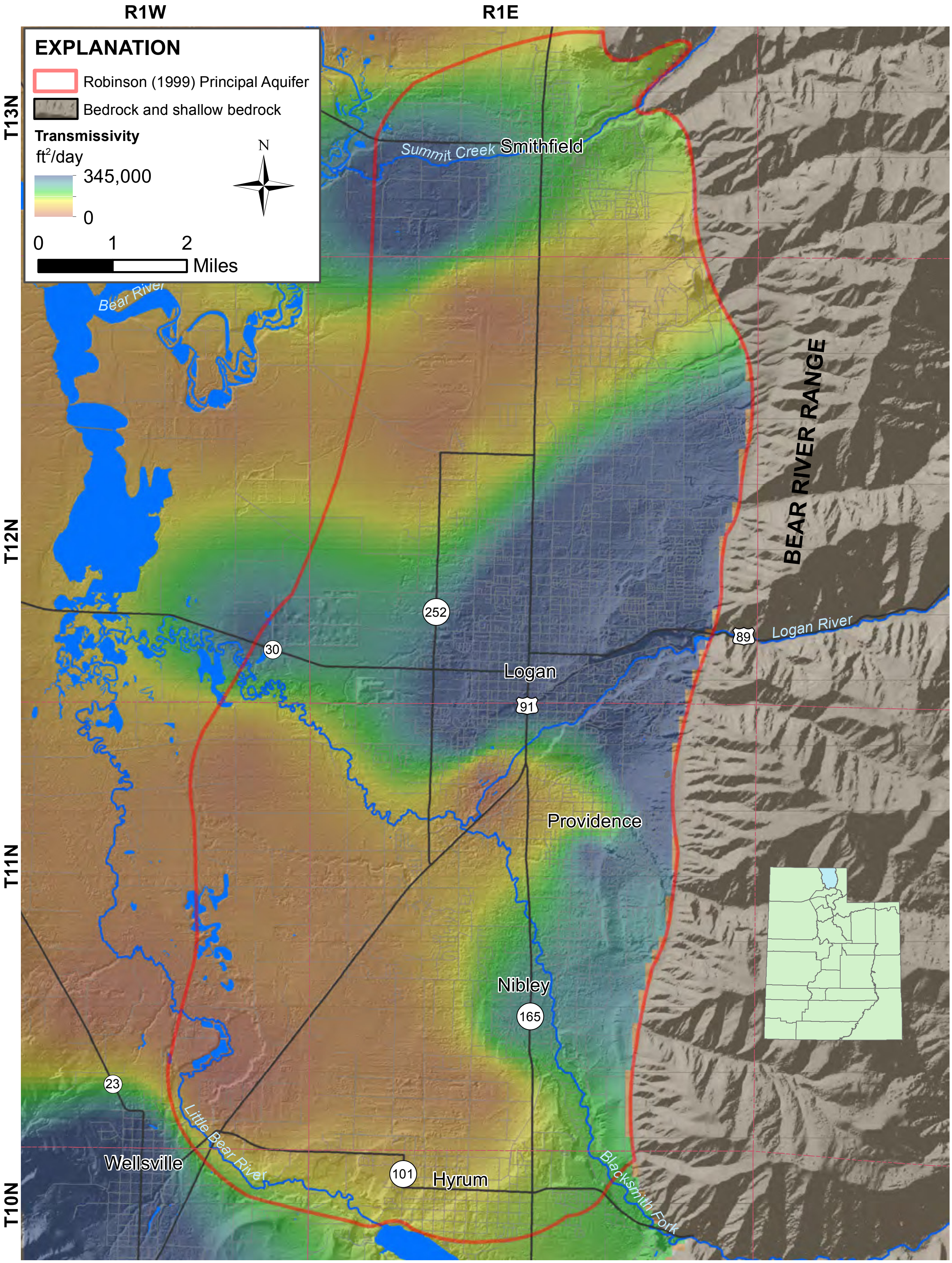

Figure 18. *Transmissivity distribution in the principal aquifer (outlined in red). We interpolated data from Inkenbrandt (2010) for this study.*

Although geology remains an important consideration for potential surface-spreading sites, logistics such as land ownership are also important. For each site that we examined, we looked at land ownership. We also looked for appropriated areas, which may or may not have existing excavations, owned by the municipalities along the eastern margin of the valley between Green Canyon and Millville Canyon.

Figure 4 shows the areas where the clay confining layers are not recorded in drillers logs. A layer of silt or clay one to two feet thick can impede the downward percolation of water from the surface-water infiltration ponds. Thus it is very important to determine the existence and continuity of fine-grained material in the basin fill at potential recharge sites, even those within the potential surface-spreading area. Geologic sections drawn through the basin fill can help in the determination of the feasibility of a site.

Geologic Sections

To determine if low-permeability layers are present beneath the potential sites we examined, we created and reviewed several geologic sections of the study area (figures 7–17). Robinson (1999) used well drillers' records to construct seven cross sections of the basin-fill material in Cache Valley, one of which is presented herein (figure 15). Six of Robinson's geologic sections intersect the principal aquifer. However, due to lack of available well-log information, all of the geologic sections terminate more than 0.5 mile away from the valley margin—the area where surface spreading would be feasible.

Robert Oaks, Jr., made ten geologic sections within the principal aquifer based on water well drillers' logs, seven of which we present in this report (figures 8–14). The geologic sections reinforce Robinson's (1999) interpretation of the basin-fill stratigraphy, with continuous confining layers and two distinct confined gravel units. Oaks extended his geologic sections to the east valley margin. However, few well records are available near the margin of the valley, which limits knowledge of sediment distribution in the area of the potential recharge sites.

Site Selection

Using the methods described in the above sections, we picked several sites to investigate in the field. We sought sites with an appropriate geologic setting, a water source to supply recharge, and with adequate access. We settled on two potential surface spreading sites, one in Providence and one in North Logan.

Providence sand pit: The first surface-spreading site (figures 19 and 20) is along the eastern Cache Valley margin between Logan and Providence. This site is an abandoned sand pit on property owned by Stan Checketts. There are three excavated areas on the property and an additional excavated pit on adjacent property to the south (figures 19 and 20). The elevation of the lowest, primary excavated area is 4910 feet (National Geodetic Vertical Datum [NGVD] of 1929). The walls of the excavated area are approximately 35 feet high along the eastern side and gradually decline to the west. A small hill of excavated material surrounds the sand pit to the east. The main excavated area is approximately 0.7 acre, and the combined area of all three pits is approximately 1.3 acres.

Sediment in outcrops of the Providence site is sandy with intermittent clay lenses/laminae from 0.5 to 12 inches thick, and a few gravel-rich debris flow deposits. The sand in the pit is fine to medium grained, well sorted, and subrounded. The gravel in channels is well sorted and clast-supported, and fines upwards from cobbles to coarse sand. The deposits in the area are likely near-shore/shallow-water sand deposited by the Bonneville stage of ancient Lake Bonneville (Gilbert, 1890). These deposits likely represent a distal deltaic system. Lack of spring systems down-gradient of the sand pit provides support that the subsurface does not contain perched systems or lateral aquitards that would be conducive to development of springs. Figure 4 shows that the clay confining layers pinch out west of this site.

There is little water available near the site for recharge diversion. Although several small mountain canyons are east of the Providence sand pit, their streams are intermittent and are not practical as water sources. Spring Creek, the nearest perennial stream, is 0.7 mile west and 325 vertical feet lower than the site. Thus, we would have to pump water up from Spring Creek. There is also a small irrigation canal 0.25 miles northwest and 200 vertical feet down from the site, but it may not carry sufficient discharge for the diversion needed for the recharge project. The nearest municipal water-supply hook-up is a fire hydrant located near the easternmost extent of 1400 East, 0.5 mile north of and 100 feet lower than the site. River Heights owns the water-supply rights associated with the hydrants. There are houses at higher elevations than the potential recharge site, so pressure of the city system should be sufficient to reach the sand pit.

The Providence site has many features that are appropriate for surface spreading, but also has some uncertainties and drawbacks. We picked this location because (1) it is within the potential surface spreading area (figure 4); (2) it has already partially been excavated; and (3) no major confining layers appear in a local geologic section (figures 7 and 11) between the site and the principal aquifer. The drawbacks of this site are: (1) water would have to be transported or pumped to the site, as there is not a water supply in the immediate vicinity of the location; (2) although the clay confining layers are not mapped beneath the site, the nearest well is over 0.5 mile away, so their presence or ab-

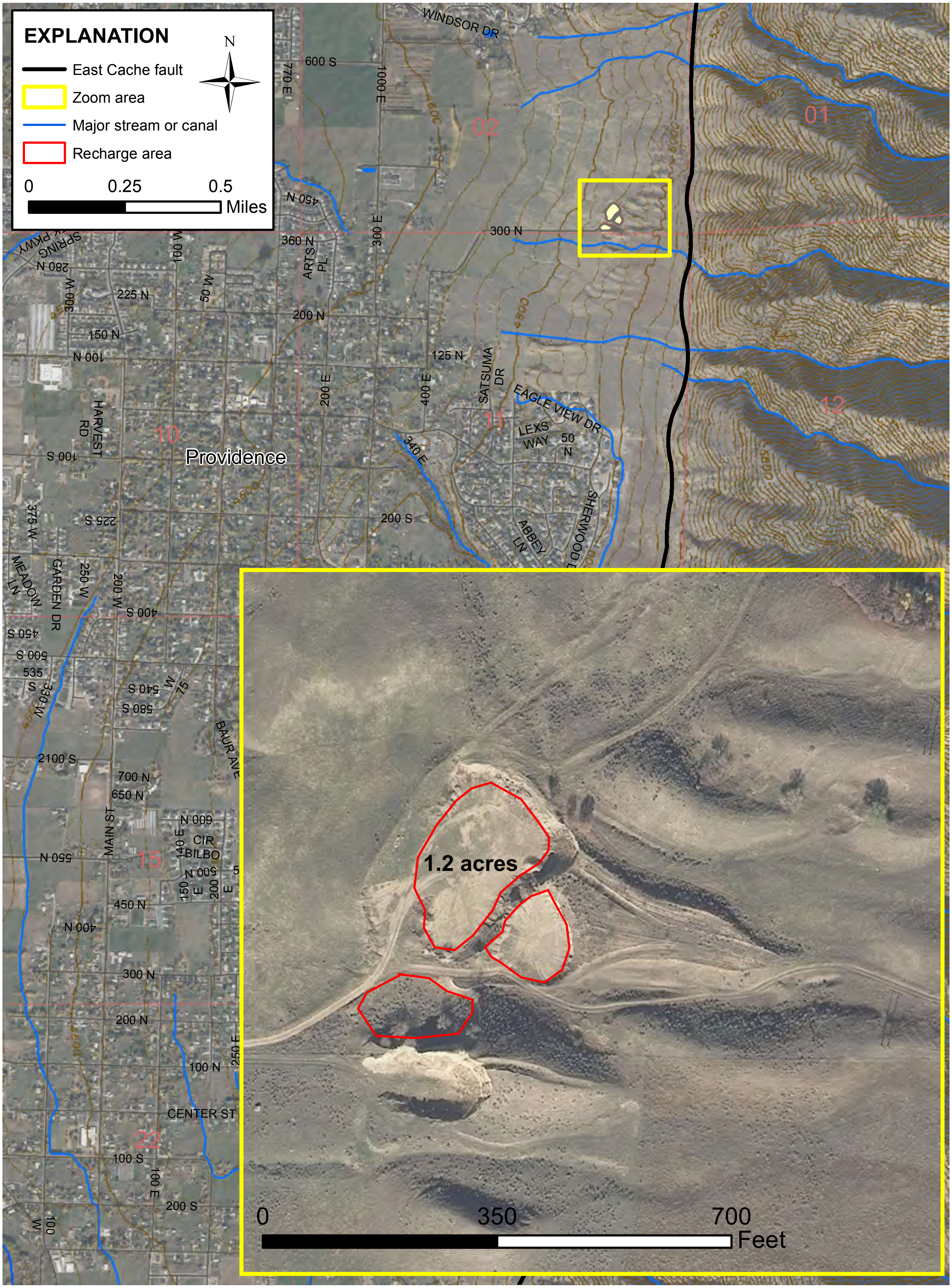

Figure 19. *Location and aerial photograph of the Providence sand pit site.*

Figure 20. Photographs of Providence sand pits. A. Pit area looking east. B. Close-up view of gravel lens. C. Close-up view of fine sandy material.

sence would have to be ascertained through drilling test boreholes; (3) the excavated area of the site may be too small (1.3 acres) for adequate recharge; and (4) the fine sand in the pit may be easily clogged with silt when exposed to large amounts of sediment-laden recharge water.

North Logan gravel pit: The second surface-spreading site (figures 21 and 22) is an inactive gravel pit in North Logan east of Green Canyon. The inactive gravel pit is west of and adjacent to an active gravel pit. The active gravel pit is east of the Logan, Hyde Park, and Smithfield Canal, at the mouth of Green Canyon. Crystal Springs Cattle Company owns the property of the lower gravel pit. The approximate pit elevation is 4795 feet above mean sea level. It is at 2100 North 1700 East, North Logan. The surface area of the pit floor is 6.4 acres. The gravel pit is approximately 20 feet deep at its deepest and its depth tapers down to the north.

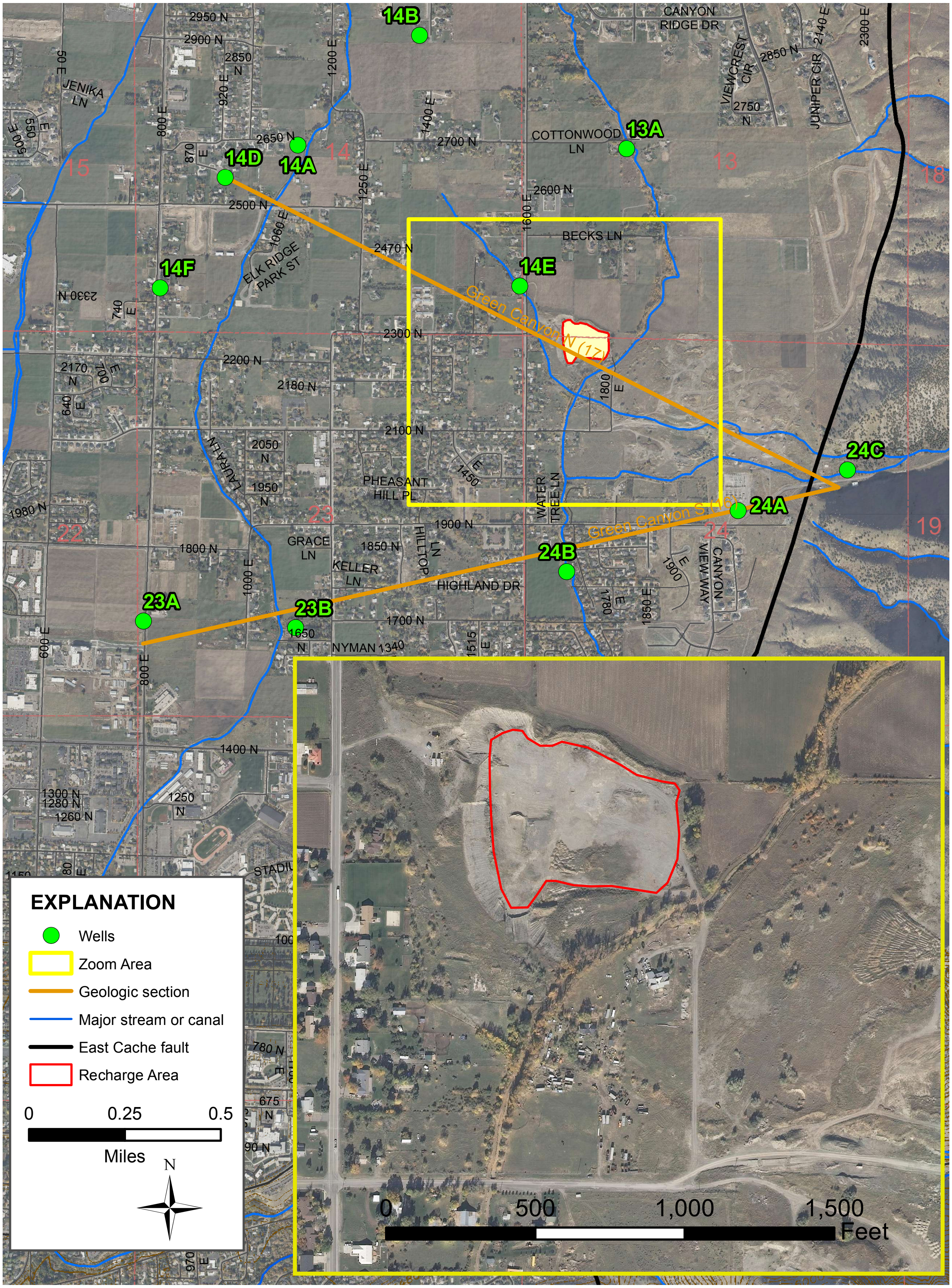

Figure 21. *Location and aerial photograph of the North Logan gravel pit site.*

Figure 22. *Photographs of North Logan gravel pits. A. Pit area, southeast view toward Green Canyon. B. West view of pit wall. C. South view of pit wall.*

The deposits in this gravel pit are medium to well sorted, cobble-sized, clast-supported gravels. Most of the clasts in the gravel pit are well rounded. These deposits are representative of deltaic materials. They were likely deposited at the Provo stage of ancient Lake Bonneville. Cross sections indicate that the gravels in the pit are likely 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 Salt Lake Formation is not the ultimate target for artificial recharge.

The North Logan gravel pit is near a number of water supplies with discharges adequate to conduct an ASR project. The closest water supply is the Logan, Hyde Park, and Smithfield canal, which borders the southern and eastern edge of the gravel pit. The next closest water supply is two wells owned by North Logan, the Green Canyon Wells one and two. These wells have an output that feeds into the Logan, Hyde Park, and Smithfield canal, and thus could be used to alleviate water-use requirements for caused by the water needed for an ASR study. Both water sources are uphill from the gravel pit, so no pumping would be required.

Like the Providence sand pit site, the North Logan gravel pit has advantages and disadvantages. This is a good site for an aquifer recharge project because: (1) the sediment in the area of the site is highly permeable gravel, (2) there are good water sources in the immediate vicinity of the site, and (3) the gravel pit covers an area that would be adequate for an aquifer recharge project. The disadvantages to this site are (1) the pit likely overlies the Salt Lake Formation, which is not the target for artificial recharge and probably would not to allow water to flow easily from the site to the principal aquifer; and (2) it is situated upslope and to the south of a new housing subdivision, so any lateral spreading of water to the north and west could impact basements in the subdivision.

Injection Wells

Introduction

Artificial recharge into the principal aquifer can also be accomplished by an injection well. The main consideration in siting an injection well is high transmissivity of the aquifer. Since injection wells can penetrate through clay confining layers, potential sites are not limited by their presence.

Injection wells present some drawbacks relative to surface-spreading sites. Water managers generally favor surface spreading because an injection well requires extra permitting to ensure that the quality of the water injected into the aquifer is as good as or better than the water in the aquifer (appendix C). Because the water in Cache Valley's principal aquifer is generally very high quality, surface water would likely require treatment before it could be injected into the aquifer. Treatment and injection of water into an aquifer could impose a much greater cost than a surface-spreading system. Also, the cost of drilling a well adequate for injection would be thousands of dollars.

An injection well could potentially be located anywhere in the principal basin-fill aquifer (figure 3). We identified a pre-existing, large-diameter well within a very transmissive portion of principal aquifer, which is a good injection site.

River Park Well

We considered one potential injection site, the River Park well, owned by Logan City. The River Park well (35E) is located just off River Park Drive (south 517 ft, east 914 ft from the west ¼ corner of Section 35, T. 12 N., R. 1 E., SLB&M) (figures 7, 8, and 23) and is at an elevation of 4593 ft (NGVD 1929). The River Park well's current water right number is 9925003P00, with Utah Division of Water Rights well-identification number 22493. The River Park well has a diameter of 20 in. and a total depth of 681 ft (figure 24). The static depth to water in the River Park well was 102.86 ft, measured at 2200 hours on July 9, 2008. There is currently no pump set in the River Park well.

Logan City may have treated water available during non-peak times during the day, especially during the winter. If water is available, it can be injected into the aquifer. The River Park well is attractive for ASR because (1) it is on land already owned by Logan City; (2) it is within an existing distribution system where clean water is available and there is need for the withdrawn water; (3) it is already drilled and finished to standards suitable for ASR; (4) it is currently unused and has no pump due to turbidity issues; and (5) it is in an area of declining ground-water levels.

The River Park well is a large-diameter well that is screened to most of the principal aquifer. The well is screened from 200 feet to 658 feet in highly permeable material (figure 24). A recent aquifer test performed by Inkenbrandt (2010) at the River Park well indicates that the transmissivity of the principal aquifer in this location is 300,000 ft^2/day and the storativity is 0.00024. This very high transmissivity is ideal for the injection of water.

The River Park well is in an area of high pumping and moderate drawdown (figure 2). It is 837 feet distant, at an azimuth of 142 degrees from the Crockett well (35B on figure 9), a large municipal well owned by Logan City that pumps an approximate maximum of 5000 gallons per minute (gpm). The Center Street well (34B on figure 9), a Logan City well near the intersection of Canyon Road and Center Street (north 820 ft, east 1220 ft from the southwest corner of Section 34, T. 12 N., R. 1 E. SLB&M) at an elevation of 4542 ft above mean sea level, pumps an approximate maximum of 2500 gpm. It is 5000 ft distant, at an azimuth of 250 degrees from the River Park well.

To examine if the River Park well could accommodate considerable amounts of injected water over time, we modeled the ground-water mounding that would be created by injection. For our primary scenario we used a Cooper-Jacob (1946) forward solution in AQTESOLV (Duffield, 2006) to model the injection. We used boundary settings in AQTESOLV (Duffield, 2006) to account for a nearby low-permeability boundary, likely created by the East Cache fault (Inkenbrandt, 2010).

We assumed a well efficiency of 30%, based on the configuration of casing perforations. Well efficiency would likely decrease with increases in injection rate.

Our primary scenario involved injecting 7000 gpm into the River Park well continuously for one year, which would introduce a total of 11,300 acre-feet of water into the principal aquifer. The projected maximum rise in potentiometric surface is 9 feet adjacent to the well, and decreases away from the well (figure 25). The projected increase in the potentiometric surface between the well and the East Cache fault is greater than to the west of the well, owing to the low-permeability boundary we presume is created by the East Cache fault (Inkenbrandt, 2010). The projected maximum water-level buildup inside the well casing is 30 feet, which would bring the water level to approximately 73 feet below ground surface.

Additionally, we used the Theis (1935) approximation to predict the potential water-level buildup over time based on various injection rates. We used a 1-foot radius to model the buildup of water levels in the well. We modeled the expected buildup from 1 to 10,000 days of continuous pumping, at rates of 1000, 5000, and 10,000 gpm. We used this wide range of pumping rates and extended time frame to help bracket the potential range of water-level buildup in the well and rise of the potentiometric surface.

The projected increase in the potentiometric surface after 10,000 days ranges from 1 to 16 feet (figure 26). The maximum projected rise in potentiometric surface (16 feet) is based on injecting 10,000 gpm of water continuously for 10,000 days. At our assumed well efficiency, the maximum projected water-level buildup in the well would be 50 feet after 10,000 days (figure 27). Since the depth to water in

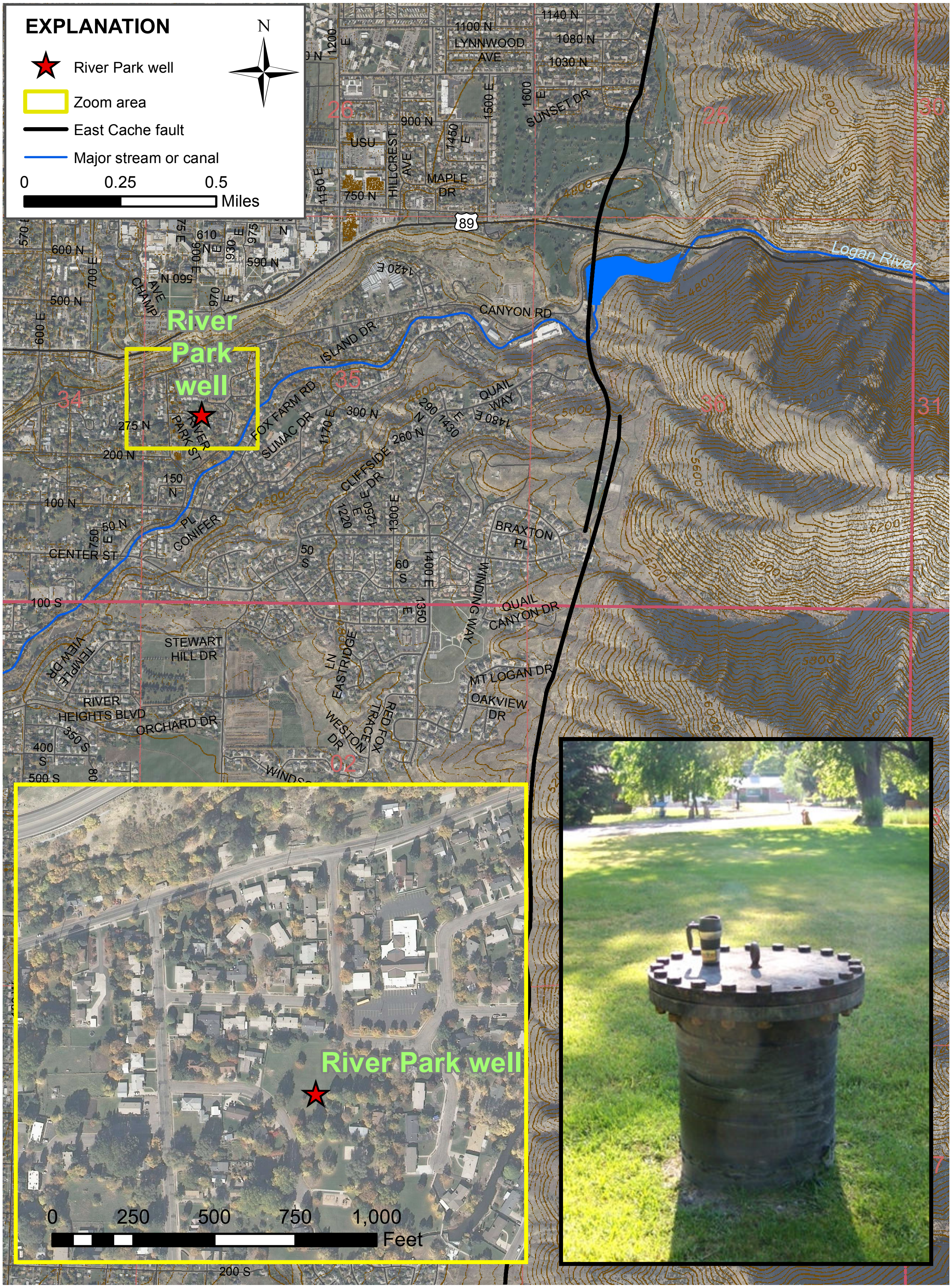

Figure 23. *Location and photographs of River Park well.*

WELL DRILLER'S REPORT

State of Utah
Division of Water Rights
For additional space, use "Additional Well Data Form" and attach

RECEIVED JUN 25 2001 WATER RIGHTS SALT LAKE

Well Identification PROVISIONAL WELL: 99-25-003-P-01

RECEIVED AUG - 9 2001 WATER RIGHTS SALT LAKE

Owner *Note any changes*
Logan City
255 North Main
Logan, UT 84321
Contact Person/Engineer: Derrick Kimb[...]

Well Location *Note any changes*

SOUTH 517 feet EAST 914 feet from the W4 Corner of
SECTION 35, TOWNSHIP 12N, RANGE 1E, SLB&M.

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

Drillers Activity Start Date: 7/25/00 Completion Date: 4/20/01

Check all that apply: [X] New [ ] Repair [ ] Deepen [ ] Clean [ ] Replace [ ] Public Nature of Use:
If a replacement well, provide the location of the new well. ____ feet north/south and ____ feet east/west of the existing well.

DEPTH (feet) FROM	TO	BOREHOLE DIAMETER (in)	DRILLING METHOD	DRILLING FLUID
0	45	44	Auger	None
45	180	28	Cable tool	Bent/Water
180	681	24"	Cable tool	Bent/Water

Well Log

DEPTH (feet) FROM	TO	WATER	PERMEABLE high	PERMEABLE low	CLAY	SILT	SAND	GRAVEL	COBBLES	BOULDER	OTHER	ROCK TYPE	COLOR	DESCRIPTIONS AND REMARKS (e.g., relative %, grain size, sorting, angularity, bedding, grain composition, density, plasticity, shape, cementation, consistency, water bearing, odor, fracturing, minerology, texture, degree of weathering, hardness, water quality, etc.)
0	12						X	X						
12	35	X	X		X									Boulders, Sand, Gravel
35	50	X	X		X			X	X					↓
50	80	X	X		X			X						↓
80	120	X	X					X						↓
120	170	X	X		X									↓
170	180	X	X		X			X						↓
180	230	X	X					X	X					↓
230	250	X	X		X			X						↓
250	260	X	X					X						↓

(UNCONSOLIDATED: Clay, Silt, Sand, Gravel, Cobbles, Boulder, Other; CONSOLIDATED: Rock Type)

Static Water Level

Date 6-12-01 Water Level 100.52 feet Flowing? [ ] Yes [X] No
Method of Water Level Measurement Electric tape If Flowing, Capped Pressure n/a PSI
Point to Which Water Level Measurement was Referenced 2+ Ground Elevation (If known) ____
Height of Water Level reference point above ground surface 98.52 feet Temperature n/a [ ] °C [ ] °F

Well Log

Figure 24. Well driller's report for the River Park well.

ADDITIONAL WELL DATA FORM

Water Right #____________

OWNER NAME

Page____of_____

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 (e.g. relative %, grain size, sorting, angularity, bedding, grain composistion, density, plasticity, shape, cementation, consistancy, water bearing, odor, fracturing, minerology, texture, degree of weathering, hardness, water quality, etc.)
260	290				X				X					
290	310				X									
310	320				X				X					
320	400							X	X					
400	410						X							
410	420						X	X						
420	660						X			X				Boulders with Very little Sand.
1060	681											Limestone		Hard unfractured.

RECEIVED
AUG - 9 2001
WATER RIGHTS
SALT LAKE

Well Log

Figure 24. continued

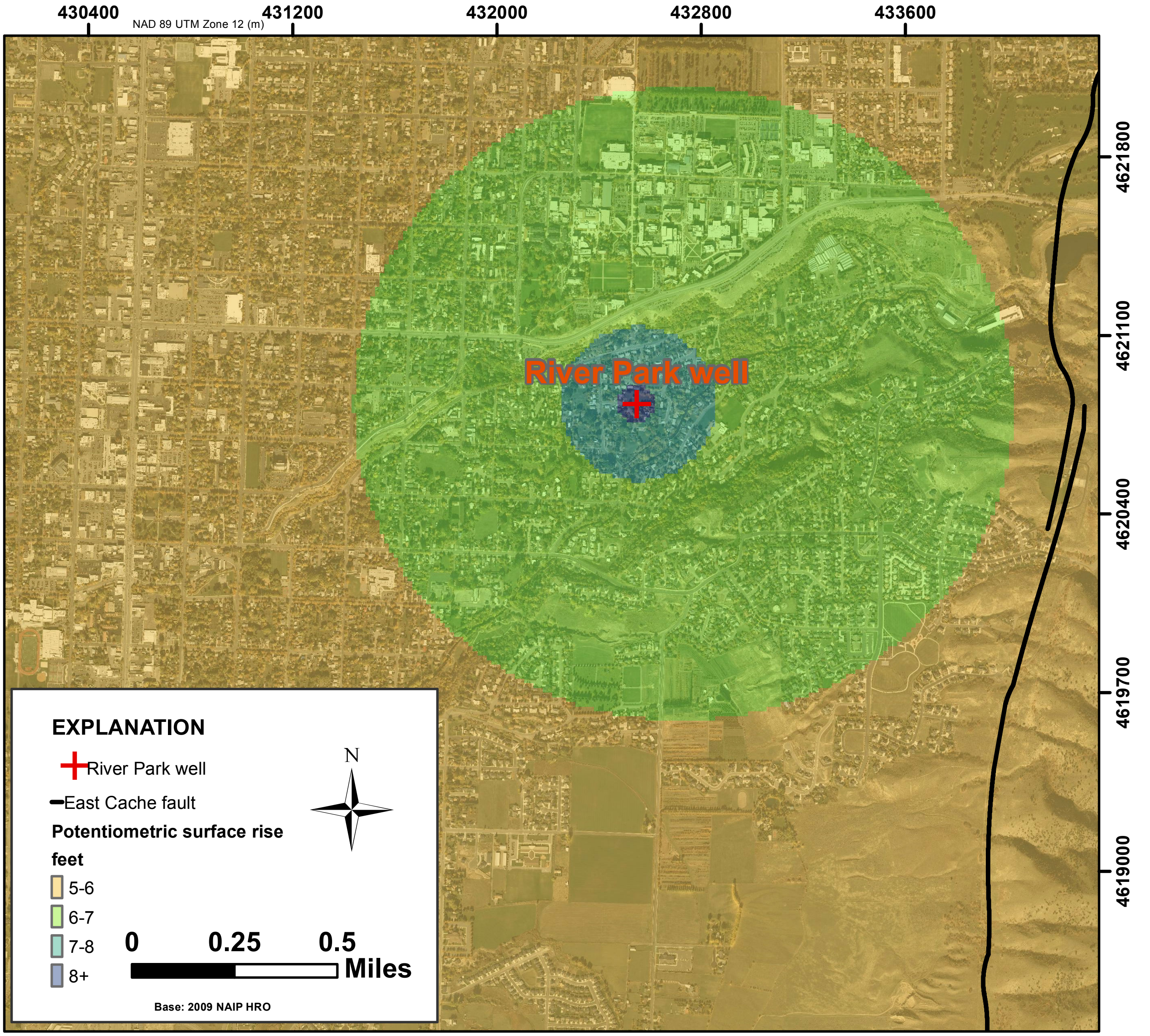

Figure 25. *Projected rise in potentiometric surface from injecting 7000 gallons per minute into the River Park well for one year.*

the River Park well is roughly 103 feet from ground surface, it is unlikely that injecting water into the River Park well would cause either the potentiometric surface or water level in the well to rise above ground level. We estimate that the injection of 10,000 gpm into the aquifer for 10,000 days would result in the addition of approximately 440,000 acre-feet of water into the aquifer. None of these scenarios considered extraction of water from the nearby Crockett and Center Street wells, owned by Logan City. Pumping from these wells would cause potentiometric surface increases to be smaller than those projected by our modeling.

Use of the River Park well has several advantages and disadvantages. The River Park well is a good site for aquifer recovery because (1) it is screened across the majority of a highly transmissive portion of the principal aquifer; (2) a new injection well would not have to be drilled, provided that the River Park well meets the necessary criteria of an injection well; (3) injection would be into a known recharge area of the principal aquifer (Anderson and others, 1994); (4) previous researchers (Bjorklund and McGreevy, 1971; Kariya, 1994; Inkenbrandt, 2010) have compiled a significant amount of information on the area surrounding the well, which eases future modeling efforts; and (5) water injected into the River Park well could be withdrawn back through that well and/or through one or both of the Crockett and Center Street wells.

The major drawbacks to using the River Park well are: (1) the cost of treating and injecting water into the principal aquifer, as compared to the lower cost of surface infiltra-

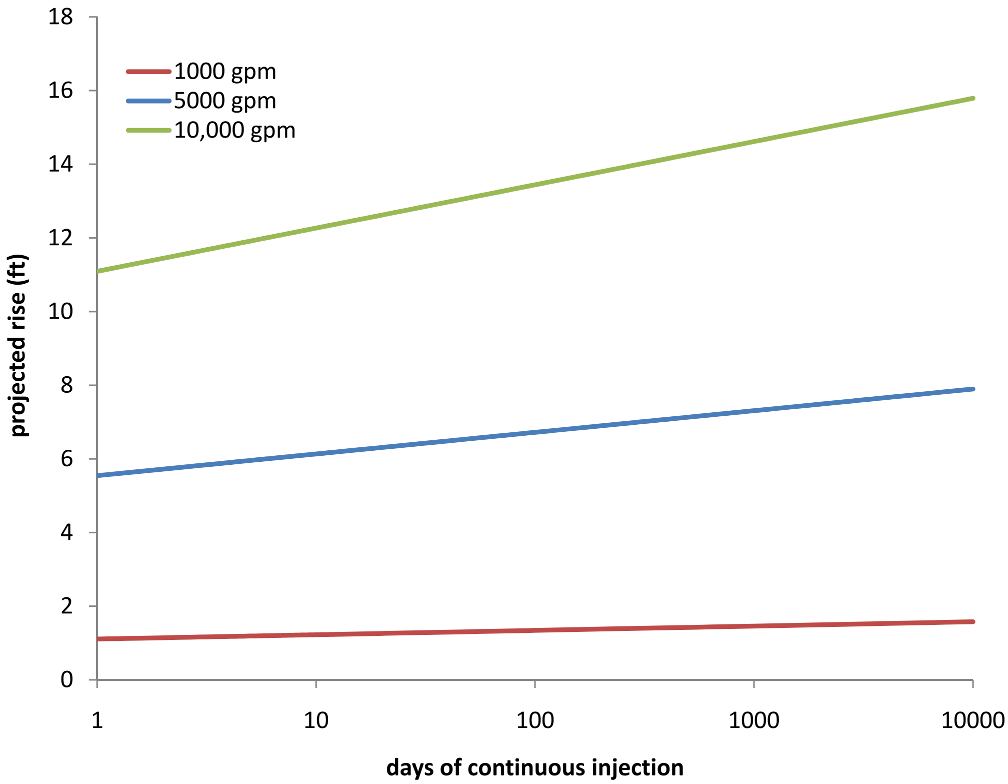

Figure 26. *Projected rise in potentiometric surface at the River Park well from continuous injection at various rates for 10,000 days.*

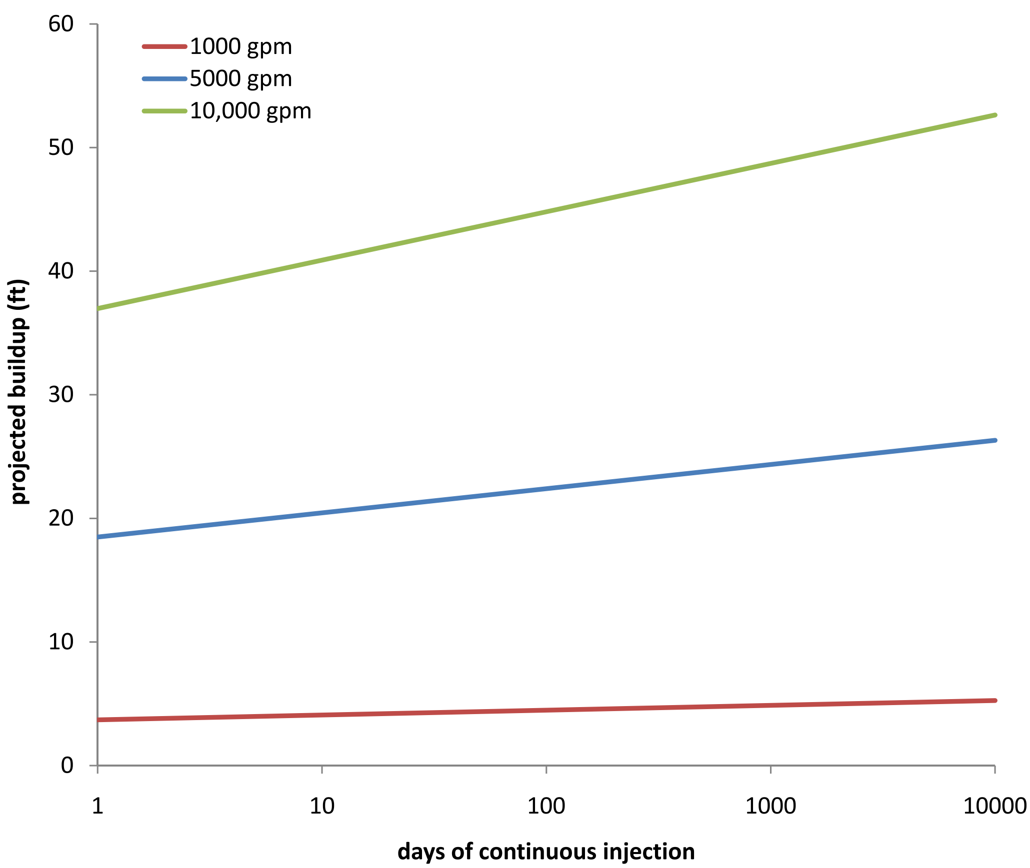

Figure 27. *Projected water-level buildup in the River Park well from continuous injection at various rates for 10,000 days.*

tion; (2) injection wells are prone to clogging; and (3) city officials reported that they had problems with silty water when withdrawing water from the River Park well, although repeated cycles of injecting and withdrawing water could potentially clear the silt out of the formation.

Water Quality at Proposed ASR Sites

Total-dissolved-solids concentrations in ground water at all three proposed ASR sites are less than 250 mg/L (Lowe and others, 2003, plate 1). This likely reflects the high quality of water naturally recharging the ground-water system in these areas, and indicates that local sources of water that would be used to artificially recharge the proposed surface-spreading sites should be of sufficient quality. These low total-dissolved-solids concentrations will be taken into account by regulatory agencies (appendix A) determining treatment standards for water used for recharge at the proposed injection-well site.

RECOMMENDATIONS

Direct injection into the aquifer is the most effective way to recharge the principal aquifer in Cache Valley. It offers several advantages over the two proposed surface-spreading sites: 1) the well has already been drilled and completed in a manner and across a depth appropriate for injecting water into the principal aquifer; 2) the aquifer properties near the well have been studied and determined to be appropriate for injection (Inkenbrandt, 2010); and 3) numerous researchers (Anderson and others, 1994; Kariya and others, 1994; Robinson, 1999; this report) and well-drillers' records have already described the basin-fill stratigraphy of this area, in contrast to the surface spreading sites, which would require drilling test boreholes to determine if water would be able to infiltrate directly into the principal aquifer. We feel these advantages outweigh the drawbacks presented by direct injection.

Regardless of the ASR method chosen, Myers' (2003) ground-water model must be modified to make it more appropriate for the chosen ASR site. Since Myers' (2003) model is a basin-wide model with a fairly coarse grid, the cell sizes in the immediate vicinity of the ASR site would need to be refined to provide a better estimation of the potential impact an ASR project would have on the aquifer. Additional adjustments would need to be made to compensate for the model's limitations near the mountain front.

Injection Well

If direct injection into the aquifer is selected, we recommend using a downhole camera to verify the integrity of the well completion and ensure that the well is in fact suitable for injection. Injection and withdrawal of water require permits from the Utah Division of Water Rights and the Utah Division of Water Quality. Applications and an example of monitoring requirements (with an example from Leamington, Utah) are provided in appendix C. A pilot project should be designed to test injection into the well. A water-delivery and injection system should be specifically designed to minimize the clogging problems common to injection wells.

Pre-existing ground-water levels and quality should be determined in order to track changes as the pilot project progresses. We recommend sampling at least 5 of the closest surrounding wells to determine the basic water quality and the static water levels in each well at least twice in the same year (successive late spring and late fall) to determine if the water chemistry is seasonally variable. All wells should be sampled within two days for each sampling interval. We recommend sampling the water source, which is used to recharge the aquifer, also sampling multiple times to detect seasonal variation. We recommend analyzing the samples for the following: NO_3^+, NO_2, TDS, Ca, Na, bicarbonate, CO_2, CO_3, Cl, Fe, K, SO_4, Mg, As, temperature, pH, Cu, and Pb.

Surface Spreading

If surface spreading is selected, it is necessary to investigate the subsurface deposits at the chosen site. The continuity of the confining layers in the two areas of interest for surface spreading has yet to be determined, because there are insufficient water-well drillers' records to provide details of the basin stratigraphy at those locations. The nearest well logs to the surface-spreading sites are over 0.5 mile away and provide evidence of the clay confining layers in both areas. Based on our investigation, the Providence sand pit site is preferred over the North Logan gravel pit.

Drilling at least one borehole with a minimum diameter of 3 inches at the selected surface-spreading site would clarify the subsurface sediment distribution. Drill cuttings/sediment core should be thoroughly described, because low-permeability layers as thin as an inch may influence the effects of attempted aquifer recharge.

The well-driller's log of the nearest well (0.6 mile north) comparable in altitude to the Providence site shows a hard-packed gravel with clay from 83 to 100 feet below surface. To ensure that this potentially low-permeability layer is not laterally continuous, the minimal depth of the borehole in the Providence surface-spreading site must be 100 feet. Ideal depth of the borehole would be 350 feet, which is the estimated depth to the upper confining layer observed to the east (figure 4). If some level of lateral spreading is acceptable, but if most of the water infiltrating into the sand eventually reaches the principal aquifer, the minimum borehole depth should be 100 feet below land surface.

At the North Logan gravel pit, surrounding well drillers' logs and a geologic section from Robinson indicate that the Salt Lake Formation is within 100 feet of the surface. To ensure that the hydrologic characteristics of the underlying sediments are adequate for infiltration, the borehole must extend into the top of the Salt Lake Formation at a depth of approximately 100 feet.

Borehole geophysical logging of the wells is also recommended. A minimal borehole diameter of 3 inches is required to fit the geophysical tools down the borehole. The UGS owns borehole geophysical-logging tools that are suitable for this part of the project. The tools available for our use include normal and lateral resistivity, caliper, natural gamma ray, fluid resistivity, and fluid temperature. The borehole should remain uncased until logging is complete, unless sediment caving requires casing, as down-hole geophysical equipment is most effective in uncased holes. A natural gamma-ray tool could detect clay layers in the principal aquifer if used in the River Park well, to provide a check for the description given in the well-drillers' logs.

A high-precision gravity survey can be used to track the movement of ground water away from a surface-spreading or injection site (Hurlow and others, in review). The high-precision Trimble global positioning system and the Scintrex CG-5 gravimeter, both of which are owned by the UGS, are excellent tools for determining the changes in levels and in the approximate ground-water mass through time. The survey would require installation of roughly 25–30 measuring stations in a rough grid pattern surrounding the site. The stations would be spaced approximately 0.25 mile apart near the site, with the spacing expanding to approximately 0.5 mile at the edge of the grid. Specific details of the gravity measurement grids would be based on the site(s) selected. The baseline gravity at the selected site(s) would be measured so that subsequent changes can be determined.

The Utah Division of Water Rights requires a permit for any excavation exceeding 30 feet in depth. The Utah Division of Water Quality requires an ASR permit, and the Utah Division of Water Rights will require ground-water recovery and ground-water recharge permits. The Utah Division of Water Quality's permit requirements and an example of monitoring requirements (with an example from Leamington, Utah), and the Utah Division of Water Rights permit-application forms are provided in appendix C.

Pre-existing ground-water levels and quality should be determined in order to track changes as the pilot project progresses. We recommend sampling at least 5 of the closest surrounding wells to determine the basic water quality and the static water levels in each well at least twice in the same year (successive late spring and late fall) to determine if the water chemistry is seasonally variable. All wells should be sampled within two days for each sampling interval. We recommend sampling the water source, which is used to recharge the aquifer, also sampling multiple times to detect seasonal variation. We recommend analyzing the samples for the following: NO_3^+, NO_2, TDS, Ca, Na, bicarbonate, CO_2, CO_3, Cl, Fe, K, SO_4, Mg, As, temperature, pH, Cu, and Pb.

CONCLUSIONS

ASR is feasible in Cache Valley through injection into an existing well on River Park Drive, in the Island area of Logan (figure 23). The River Park well is completed within the principal aquifer and our investigation shows that the aquifer would be able to accommodate large quantities of injected water (up to 10,000 gallons per day) at the site (figures 25–27). Since an existing suitable injection well has been identified, one of the drawbacks to a direction injection ASR project, namely the high cost of drilling such a well, has been eliminated.

Two continuous clay confining layers and the Tertiary Salt Lake Formation within Cache Valley limit potential surface-spreading sites to a narrow band along the mountain front on the eastern margin of the valley, between Green Canyon and Millville Canyon (figure 4). We identified two potential surface-spreading sites within this band, but it is uncertain whether the clay confining layers extend below these sites. Test boreholes would be required to determine whether the clay confining layers, or other strata that could potentially impede the infiltration of water into the principal aquifer, are present.

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APPENDICES

APPENDIX A
HYDROLOGIC BUDGET

INTRODUCTION

Cache Valley is bordered by the Bear River Range in the east, the Wellsville Mountains in the southwest, and Clarkston Mountain in the northwest. The Bear River is the largest stream in Cache Valley, entering from Idaho in the north and exiting on the west side of the valley between the Wellsville Mountains and Clarkston Mountain. The Logan River, Blacksmith Fork, and Little Bear River originate in the mountains surrounding Cache Valley and drain into the Bear River.

The Cache Valley drainage basin, which extends into the mountains surrounding the valley, includes the entire Cache County area. Most of the stream flow that crosses the Utah part of Cache valley originates in this local drainage basin. The mountainous portion of the Cache Valley drainage basin, referred to herein as bedrock consists of consolidated to poorly consolidated bedrock deposits of Precambrian to Tertiary age. Quaternary-age unconsolidated basin-fill units comprise the principal aquifer in the Utah portion of Cache Valley. Figure A1 shows the location of the Cache Valley study area along with its drainage basin boundary, main streams, and their streamflow gage stations.

The objective of this section is to integrate a detailed water budget for the Utah portion of Cache Valley.

WATER FLOW BUDGET ESTIMATION

To create an updated water budget, we investigated all inflow and outflow components. Inflow components include (1) stream flow, (2) precipitation, (3) ground-water seepage and spring flow into streams, and (4) unconsumed water returned from irrigation, power, municipal, and industrial uses. Outflow components include (1) stream flow, (2) consumptive use by plants through evapotranspiration, (3) evaporation from open water of irrigation canals, streams, and reservoirs, (4) seepage into ground water, and (5) water diversion for irrigation, power generation, municipal, and industrial uses.

Although many researchers studied the hydrology of Cache Valley, we focused on two studies when updating the water budget for the Utah portion of the study area, Bjorklund and McGreevy (1971) and Kariya and others (1994). Bjorklund and McGreevy (1971) conducted the most detailed hydrogeological study for Cache Valley (both the Utah and Idaho portions). They reported a total recharge of 1,700,000 acre-ft/yr and an equivalent total discharge with negligible change in storage in both surface water and ground-water budgets. It was not possible to isolate the Utah portion of the Bjorklund and McGreevy flow budget from the rest of the valley. Bjorklund and McGreevy (1971) concluded that about 4000 acre-feet (5 million m^3) of ground-water moves annually through the Cache Valley basin fill from Idaho into Utah. Kariya and others (1994) estimated both surface-water and ground-water flow budgets for Cache Valley. They estimated a ground-water flow budget for the principal unconsolidated basin-fill aquifer both conceptually and by using a ground-water flow model. They calibrated their ground-water model for 1969 steady-state conditions and 1982–1990 transient conditions. Their calibrated ground-water flow budget for the unconsolidated basin fill of Cache Valley (combined Utah and Idaho portions) showed a total recharge of 459 cubic feet per second (332,301 acre-ft/yr) and a total discharge of 416 cubic feet per second (301,170 acre-ft/yr).

Surface-Water Flow Budget

We estimated the water budget (first step precipitation-derived budget) for Cache Valley during the past 10 water years (2000–2009) by collecting and/or estimating precipitation, infiltration, evapotranspiration, streamflow, and basin areas. Table A1 shows the estimated natural water budget for Cache Valley subdivided by bedrock and basin-fill aquifers.

Basin Area

The Utah portion of the Cache Valley drainage basin, which includes the entire Cache County area, has an area of 1172 square miles (3035 km^2). In Utah, the unconsolidated basin fill has an area of approximately 360 square miles (932 km^2), and the bedrock uplands have an area of 812 square miles (2103 km^2). We multiplied the area of various portions of Cache County by precipitation rates to estimate the volume of water entering the valley via precipitation.

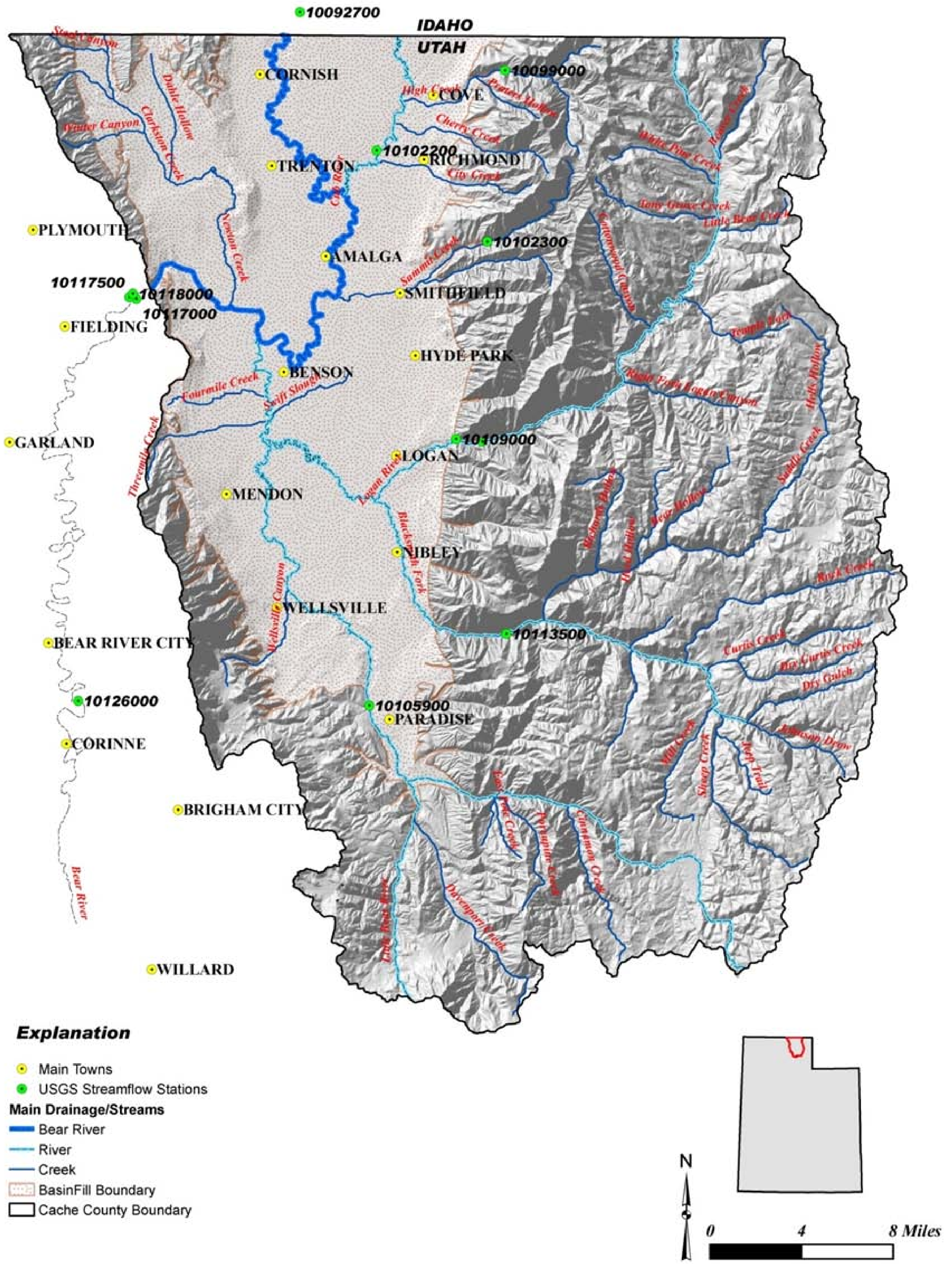

Figure A1. *Location map of Cache Valley, Cache County, Utah.*

Precipitation

Precipitation is the primary input of water into the Cache Valley drainage basin. To create the surface water budget, we assumed that precipitation ultimately either evaporates, infiltrates into the ground, or becomes part of streamflow (table A1). We estimated precipitation in the study area using PRISM data (PRISM Group, Oregon State University, 2009) available online in the form of grid raster files with a 4-km cell size. We downscaled to a 1-km grid cell size for a finer grid resolution. Figure A2 shows the spatial distribution of the 10-yr average (2000–2009) annual precipitation. The 10-yr average annual precipitation in the Cache Valley drainage basin is 25.3 inches, resulting in an average annual volume of 1,578,000 acre-ft.

The basin-fill area receives about 18.3 inches per year of precipitation, equivalent to an annual volume of 351,000 acre-ft. The bedrock area receives about 28.3 inches per year of precipitation which is equivalent to 1,227,000 acre-ft/yr (table A1).

Infiltration

We applied the Maxey-Eakin method (Maxey and Eakin, 1949) to estimate infiltration of precipitation. Figure A3 shows the spatial distribution of the 10-yr average (2000–2009) annual recharge from this infiltration. The 10-yr average annual recharge in Cache County is 6.2 inches per year (equivalent to 386,000 acre-ft/yr), the basin-fill aquifer aver-

Table A1. *Summary of the components of the surface-water budget.*

		Maxey and Eakin (1949) Estimate of Infiltration of Precipitation		Measured Contribution of Precipitation to Streamflow		Water Budget Equation Estimate of Evapotranspiration of Precipitation		Measured Precipitation	
	Year	inch	acre-ft	inch	acre-ft	inch	acre-ft	inch	acre-ft
Basin-fill *Area = 230,094 acres*	2000	2.8	52,834	1.7	33,141	12.9	246,549	17.3	332,525
	2001	1.3	24,612	1.5	28,396	11.5	220,002	14.2	273,010
	2002	1.2	23,283	1.5	28,191	11.3	217,516	14	268,990
	2003	1.7	33,037	1.4	27,696	12.2	234,544	15.4	295,276
	2004	4.2	81,429	1.4	26,491	15	288,503	20.7	396,423
	2005	6.5	124,864	2.2	42,315	17.4	332,846	26.1	500,025
	2006	5.9	112,560	2.4	46,792	13.8	263,699	22.1	423,050
	2007	2.2	42,973	1.6	31,151	10.9	208,208	14.7	282,331
	2008	3.3	63,594	1.8	33,792	12.1	232,587	17.2	329,972
	2009	5.6	107,968	2.1	39,822	13.5	259,238	21.2	407,028
	10-yr	3.5	66,715	1.8	33,779	13.1	250,369	18.3	350,863
Bedrock *Area = 519,785 acres*	2000	6.7	290,342	6.3	273,023	15	648,147	28	1,211,513
	2001	5.5	237,519	5	216,524	13.6	590,167	24.1	1,044,210
	2002	5.2	223,349	5	215,451	13	563,849	23.1	1,002,649
	2003	6.1	263,761	5	215,932	15	648,892	26.1	1,128,586
	2004	7.6	327,198	4.3	187,574	18.5	800,177	30.4	1,314,949
	2005	8.7	378,338	10	432,750	16.3	703,960	35	1,515,048
	2006	10.1	435,391	11.3	489,554	11.5	498,418	32.9	1,423,364
	2007	5.8	250,556	5.9	253,942	11.1	480,274	22.7	984,772
	2008	8.5	369,795	7	304,282	13.9	601,634	29.5	1,275,711
	2009	9.7	420,544	8.9	386,191	13.1	566,351	31.7	1,373,086
	10-yr	7.4	319,679	6.9	297,522	14.1	610,187	28.3	1,227,389
Overall Cache County *Area = 749,879 acres*	2000	5.5	343,177	4.9	306,164	14.3	894,696	24.7	1,544,037
	2001	4.2	262,131	3.9	244,920	13	810,169	21.1	1,317,220
	2002	3.9	246,631	3.9	243,642	12.5	781,365	20.3	1,271,639
	2003	4.7	296,797	3.9	243,628	14.1	883,436	22.8	1,423,862
	2004	6.5	408,627	3.4	214,064	17.4	1,088,680	27.4	1,711,372
	2005	8.1	503,202	7.6	475,064	16.6	1,036,806	32.2	2,015,072
	2006	8.8	547,951	8.6	536,346	12.2	762,117	29.5	1,846,414
	2007	4.7	293,529	4.6	285,093	11	688,481	20.3	1,267,103
	2008	6.9	433,389	5.4	338,074	13.3	834,220	25.7	1,605,683
	2009	8.5	528,513	6.8	426,013	13.2	825,589	28.5	1,780,114
	10-yr	6.2	386,395	5.3	331,301	13.8	860,556	25.3	1,578,252

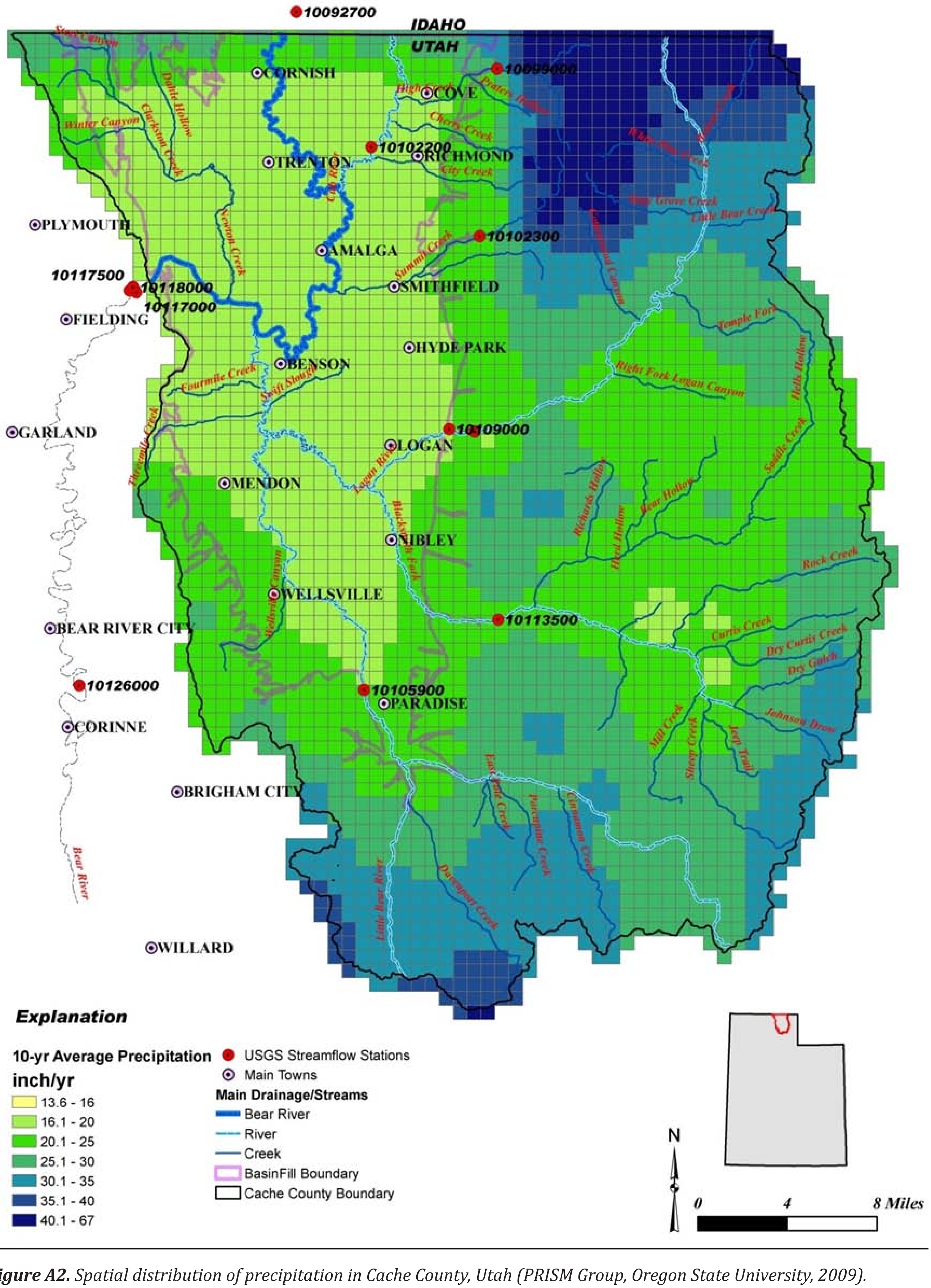

Figure A2. Spatial distribution of precipitation in Cache County, Utah (PRISM Group, Oregon State University, 2009).

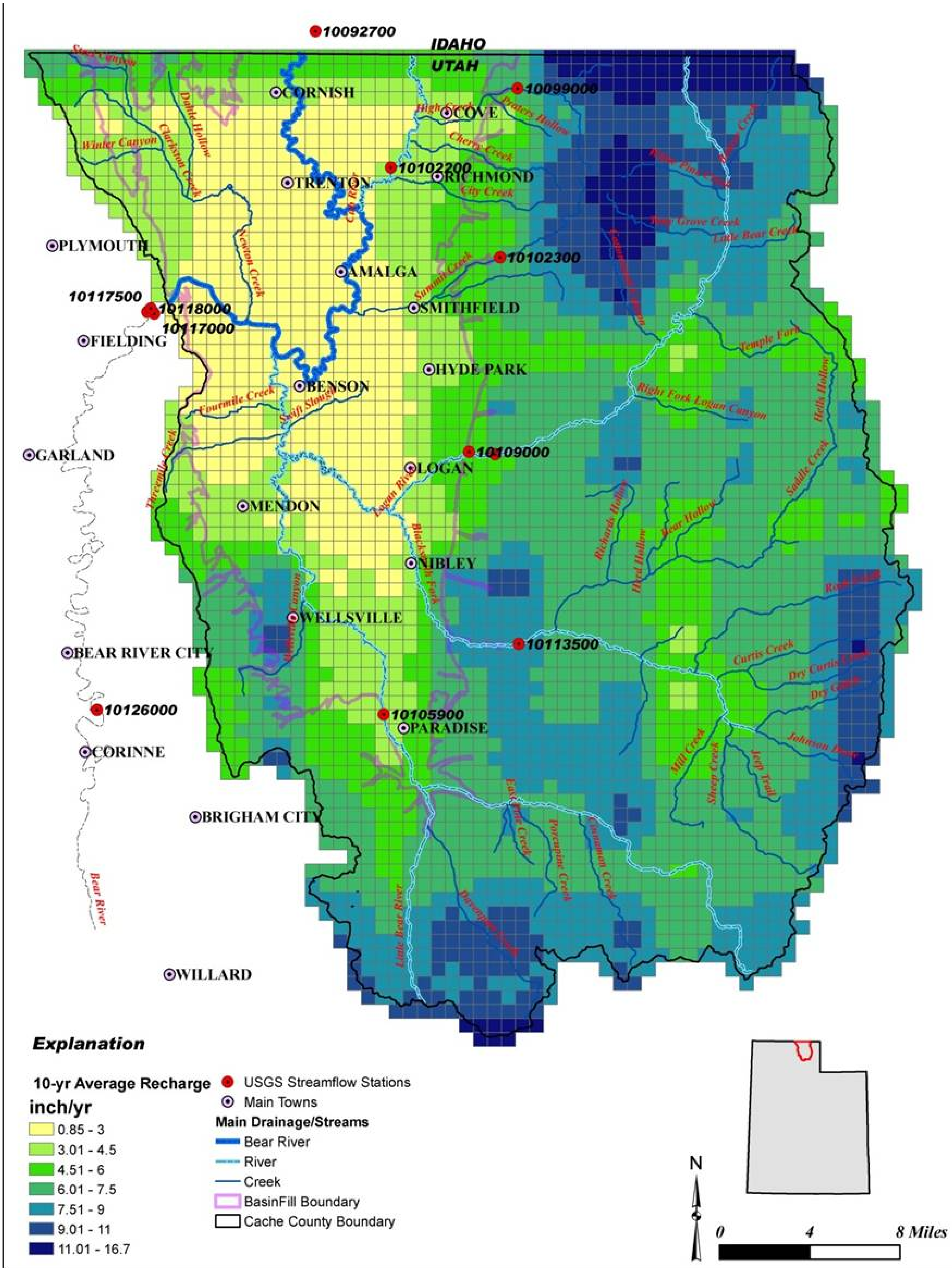

Figure A3. *Spatial distribution of recharge from precipitation in Cache County, Utah.*

age recharge rate is 3.5 inches per year (equivalent to 67,000 acre-ft/yr), and the bedrock outcrops receive an average recharge of 7.4 inches per year (equivalent to 320,000 acre-ft/yr) (table A1).

Streamflow

This section describes the methodology we used estimate the volume of precipitation contributing to streamflow and the amount of streamflow entering and leaving the Cache Valley basin system. The annual streamflow runoff entering or leaving Cache Valley (table A2) was estimated for the last 10 water years (2000–2009) based on streamflow measurements and/or estimates at 10 U.S. Geological Survey (USGS) streamflow gage stations available online at the USGS website (U.S. Geological Survey, 2010). Missing data for inactive stations were interpolated using linear regression equations based on available data from the closest active stations.

The 10-year average (2000–2009) estimated streamflow entering Cache Valley from Idaho at the Idaho/Utah border is 530,000 acre-ft/yr of which 418,000 acre-ft/yr enters Utah via the Bear River (USGS streamflow station #10092700) and 112,000 acre-ft/yr enters the valley via the Cub River (USGS streamflow station #10102200) (table A2). In addition to sources from Idaho, Cache Valley receives 298,000 acre-ft/yr from six mountain streams that drain to the Bear River

Table A2. *Ten-year (2000–2009) average streamflow volumes from 10 USGS stream gage stations in Cache Valley.*

USGS-ID	Gage Station Name	10-yr Average
		acre-ft/yr
Stream flow entering Cache Valley		
10105900	Little Bear River At Paradise, Utah	**49,411**
10113500	Blacksmith Fork Above Utah Power & Light Company State Dam Near Hyrum, Utah	**65,564**
10109000	Logan River Above State Dam Near Logan, Utah	**135,404**
10108400	Logan Hyde Park And Stream Canal At Head Near Logan, Utah	**13,611**
10102300	Summit Creek Above Diversions Near Smithfield, Utah	**11,499**
10102200*	Cub River Near Richmond, Utah (Originated in Idaho)	**112,036**
10102200	Cub River Near Richmond, Utah (Originated in Utah mountains)	**22,034**
10092700	Bear River At Idaho-Utah State Line, Idaho	**418,080**
	Sub-total	**827,638**
Stream flow leaving Cache Valley		
10117000	Hammond (East Side) Canal Near Collinston, Utah	**38,041**
10117500	West Side Canal Near Collinston, Utah	**201,044**
10118000	Bear River Near Collinston, Utah	**628,727**
	Sub-total	**867,812**
Stream flow within Cache Valley		
10102200	Cub River Near Richmond, Utah (Originated in Utah basin fill)	**15,312**
	Ungaged flow within Cache Valley basin fill (modified from Kariya and others, 1994)	**18,467**
	Sub-total	**33,779**

** Cub River Near Richmond stream flow was subdivided by origination of flow, based on the area percentage, into three flow areas; the flow originated in Idaho portion (75%), the flow originated in the east mountains of Utah portion (15%), and the flow originated in the basin fill of Utah portion (10%).*

from bedrock areas to the east and south (table A2). These streams, ordered from northeast to southeast, include:

- Cub River (USGS streamflow station #10102200) which drains 22,000 acre-ft/yr from High Creek and other minor mountain streams.
- Summit Creek (USGS streamflow station #10102300) which drains 12,000 acre-ft/yr.
- Logan-Hyde Park (USGS streamflow station #10108400) which drains 14,000 acre-ft/yr.
- Logan River (USGS streamflow station #10109000) which drains 135,000 acre-ft/yr.
- Blacksmith Fork (USGS streamflow station #10113500) which drains 66,000 acre-ft/yr.
- Little Bear River (USGS streamflow station #10105900) which drains 49,000 acre-ft/yr.

Thus, the total combined surface water inflow from streams entering Cache Valley from Idaho and from Utah mountains east and southeast of its valley floor is about 828,000 acre-ft/yr (table A2).

Stream flows leave the valley floor of Cache Valley through three streams/canals at the Bear River outlet near Collinston with a combined total annual outflow of 868,000 acre-ft/yr (table A2). These three streams/canals include:

- Bear River near Collinston (USGS streamflow station #10118000) which drains about 629,000 acre-ft/yr out of the study area toward Great Salt Lake.
- Hammond Canal near Collinston (USGS streamflow station #10117000) which discharged a 30-year average (1969–1990) flow of about 38,000 acre-ft/yr out of the study area for power generation by Utah Power and Light Company. We estimated the streamflow using values from Kariya and others (1994) because no current flow records are available.
- West Side Canal near Collinston (USGS streamflow station #10117500) which discharged a 30-year average (1969–1990) flow of about 201,000 acre-ft/yr out of the study area for power generation by Utah Power and Light Company. We estimated the streamflow using values from Kariya and others (1994) because no current flow records are available.

Evapotranspiration

Evapotranspiration was estimated by subtracting the estimated recharge and stream flows from the total precipitation using the general water budget equation *[Evapotranspiration = Precipitation – Infiltration – Streamflow Runoff]* (table A1). The underlying assumption for this estimate is that there are no minor losses and no change in storage.

The 10-yr average (2000–2009) annual evapotranspiration from the Cache Valley drainage basin is 13.8 inches per year which is equivalent to 860,600 acre-ft/yr. Evapotranspiration from the basin-fill aquifer was estimated at an average of 13.1 inches per year, which is equivalent to 250,400 acre-ft/yr. Evapotranspiration from the bedrock outcrops was estimated at an average rate of 14.1 inches per year which is equivalent to a volume of 610,200 acre-ft/yr (table A1).

Evaporation from open water bodies including streams, reservoirs and lakes was estimated in this study by multiplying their surface area by the evaporation rate. We measured digitized streams, reservoirs, and lakes to estimate the surface area of open water bodies as 2592 acres. The Utah State University Climate Center website (2009) reports real-time evaporation rates. We combined the evaporation estimates of four stations in the study area to get an average evaporation rate of 50.7 inches year (table A3). Multiplying evaporation rate by the area of open water bodies resulted in a total evaporation from surface water bodies of 10,950 acre-ft per year. The evaporation from surface water bodies makes up part of the estimated 250,400 acre-ft/yr total evapotranspiration.

Summary

In summary, the 10-yr average annual recharge estimated using the Maxey and Eakin (1949) method in the Cache Valley drainage basin is 6.2 inches per year, equivalent to a volume of 386,000 acre-ft/yr. The basin-fill aquifer area receives an average contribution of precipitation to stream flow at a rate of 1.8 inches per year from direct precipitation which is equivalent to a volume of 33,800 acre-ft/yr. The bedrock area receives average contribution of precipitation to stream flow at a rate of 6.9 inch/yr which is equivalent to 297,500 acre-ft/yr (table A1).

Table A4 shows the total water use in Cache County for the year 2000 which is assumed as being representative of current water use. The following flow items can be deduced from table A4:

Table A3. *Evaporation from open water bodies in the Utah portion of Cache Valley.*

USU Evaporation Station	Evaporation Rate (in/yr)
Logan	61.65
Logan Island	44.91
Drainage Farm	49.38
Lewiston	46.86
Average	**50.7**
Open water area (acres)	2,592
Annual Evaporation = Area*Evaporation rate	**10,951** (acre-ft/yr)

Table A4. *Year 2000 water use in the Utah portion of Cache Valley.*

Criteria	Ground-water	Surface-water	Total
	(acre-ft/yr)	(acre-ft/yr)	(acre-ft/yr)
Irrigation	10,899	279,522	**290,421**
Public Supply	36,571	1,299	**37,871**
Industrial	1,355	-	**1,355**
Aquaculture	8,098	-	**8,098**
Livestock	638	1,490	**2,128**
Total	**57,562**	**282,311**	**339,873**

Source: U. S. Geological Survey, 2010, Water use in Utah in year 2000.

online: http://ut.water.usgs.gov/infodata/wateruse.html

- Total ground-water use is about 57,600 acre-ft/yr, of which 30,000 acre-ft/yr is pumped from wells and 27,600 acre-ft/yr is discharged naturally from springs.
- Total surface-water use is about 282,300 acre-ft/yr.
- Total irrigation water use is about 290,400 acre-ft/yr, of which 279,500 acre-ft/yr is from surface water and 10,900 acre-ft/yr is from ground water.
- Total public water use is about 37,900 acre-ft/yr, of which 36,600 acre-ft/yr is from ground water and 1300 acre-ft/yr is from surface water.
- Total industrial water use is about 1350 acre-ft/yr totally derived from ground-water sources.
- Total aquaculture water use is about 8100 acre-ft/yr totally derived from ground-water sources.
- Total livestock water use is about 2130 acre-ft/yr, of which 640 acre-ft/yr is from ground-water and 1500 acre-ft/yr is from surface water.

We compiled all of the above values into one surface-water budget, shown in table A5. The net change in storage, which is the difference between total inflow and outflow, is -136,000 acre-ft/yr, which is about 10% of the total flow. The discrepancy could be related to estimation error, missing sources of inflow, or over-estimation of outflow. A thorough review and updating is required to make a more accurate water budget estimate.

Table A5. *Integrated surface-water budget for Utah portion of Cache Valley.*

Inflow Item	acre-ft/yr
Streamflow from Little Bear River (USGS streamflow station #10105900)	**49,411**
Streamflow from Blacksmith Fork (USGS streamflow station #10113500)	**65,564**
Streamflow from Logan River (USGS streamflow station #10109000)	**135,404**
Streamflow from Logan Hyde Park (USGS streamflow station #10108400)	**13,611**
Streamflow from Summit Creek (USGS streamflow station #10102300)	**11,499**
Streamflow from Cub River (USGS streamflow station #10102200)	**134,070**
Streamflow from Bear River near Collinston (USGS streamflow station #10092700)	**418,080**
Precipitation (combined rainfall and snow fall)	**350,863**
Ground-water seepage into streams	**70,000**
Ground-water spring discharge into streams	**58,000**
Unconsumed irrigation water	**97,000**
Unconsumed municipal and industrial water	**13,000**
Total Inflow	**1,416,502**
Outflow Item	**acre-ft/yr**
Streamflow into Bear River near Collinston (USGS station #10118000)	**628,727**
Streamflow into Hammond Canal near Collinston (USGS station #10117000)	**38,041**
Streamflow into West Side Canal near Collinston (USGS station #10117500)	**201,044**
Diversion from streams for irrigation water use	**279,500**
Diversion from streams for public water supply	**1300**
Seepage from streams, irrigation canals, and reservoirs into ground-water	**87,000**
Evapotranspiration (land, vegetation, water)	**250,369**
Infiltration from precipitation into ground-water	**66,715**
Total Outflow	**1,552,696**

Ground-Water Flow Budget

Unconsolidated basin-fill deposits constitute the primary water-bearing geologic unit with sediments ranging from clay and silt to sand, gravel, cobbles, and boulders of the alluvial-fan deposits. Coarse-grained permeable deposits predominate at the margins of the valley in the alluvial-fan sediments adjacent to the Bear River Range. Fine-grained less permeable deposits occur towards the center of the valley with sands interbedded with more silts and clays (Kariya and others, 1994). Most of the unconsolidated deposits in Cache Valley have confined ground-water conditions, and there are flowing artesian wells at the center of the valley floor (Bjorklund and McGreevy, 1971).

Although Kariya and others (1994) didn't classify their water budget estimate by state (Utah or Idaho), they posted the original MODFLOW simulation at the Utah Division of Water Rights website. We used the MODFLOW simulation to estimate the ground-water flow budget for the Utah portion of Cache Valley, which resulted in a total estimated recharge of 223,000 acre-ft/yr with an equivalent value for discharge (negligible change in storage), then updated flow items in that estimate and assumed that the other flow items shown in table A6 were acceptable.

Table A6. *Ground-water flow budget for Utah portion of Cache Valley (modified from Kariya and others, 1994).*

Recharge	**Acre-ft/yr**
Recharge from precipitation	**67,000** [a]
Seepage from unconsumed irrigation	23,000
Seepage from streams	1000
Seepage from canals	86,000
Subsurface inflow from bedrock	46,000
Subsurface inflow from Idaho basin fill and bedrock	**4000** [b]
Total	**227,000**
Discharge	**Acre-ft/yr**
Seepage to streams	70,000
Spring discharge	58,000
Evapotranspiration	36,000
Seepage to reservoirs	31,000
Withdrawals from wells	**30,000** [c]
Total	**225,000**

[a] *The 10-yr average (2000-2009) recharge from precipitation was estimated using Maxey and Eakin (1949)method*
[b] *This value is adapted from the estimated ground-water budget done by Bjorklund and McGreevy (1971).*
[c] *This value is the 10-yr average (2000-2009) well withdrawal.*

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APPENDIX B
REVIEW OF EXISTING MODEL

CURRENT GROUND-WATER FLOW MODELS

There are two MODFLOW (McDonald and Harbaugh, 1988) ground-water-flow models available for Cache Valley, Utah. The first is a U.S. Geological Survey model developed by Kariya and others (1994). The second is a Utah State University model developed by Myers (2003).

Kariya and Others (1994) Model

Kariya and others (1994) used the U.S. Geological Survey modular three-dimensional, finite-difference, ground-water flow simulator (MODFLOW) (McDonald and Harbaugh, 1988) to test and refine their conceptual proposal for the flow system in Cache Valley. The area covered by the saturated unconsolidated basin-fill deposits was discretized into a non-uniform, horizontal, quasi-three-dimensional, rectangular grid consisting of 82 rows and 39 columns, with up to six vertical layers of cells. The grid represents an area smaller than the actual area of unconsolidated basin fill because some deposits are not saturated. Kariya and others (1994) used a conceptual model of aquifers being under leaky confined conditions because of the hypothetical discontinuous nature of the confining beds of silt and clay in the central portion of Cache Valley. The model uses a vertical leakage term between the six vertical model layers, and assumes two-dimensional horizontal flow in the aquifer and one-dimensional vertical flow.

The model's rectilinear grid has a grid-cell spacing ranging from 0.5 mile by 0.375 mile to 1 mile on each side, which results in cell areas of 0.188 to 1 square mile. The y-axis of the model is oriented north-south, roughly parallel to the axis of the valley and to the primary surface-water drainages. Active cells in layers 1 and 2 represent an area of approximately 660 square miles, with 282 square miles in Utah. Layer 1 was simulated as an unconfined layer with an initial saturated thickness of 100 feet, wherein changes in the water levels cause the saturated thickness to vary from the initial 100 feet. Confined conditions may occur in some areas within the basin-fill deposits represented by layer 1. Layer 1 simulates evapotranspiration, discharge from wells and springs, and seepage to streams, rivers, and a reservoir. Layer 2 simulates saturated valley-fill material from 100 to 200 feet using a confined- or unconfined-layer option that allows the storage term to be converted from confined to unconfined in cells when calculated water levels drop below the top of the cell. Layers 3 through 6 were simulated using the confined-layer option. The depth of saturated basin-fill deposits simulated by layer 3 is from 200 to 300 feet, layer 4 from 300 to 500 feet, layer 5 from 500 to 1,000 feet, and layer 6 from 1,000 to 1,500 feet. Layer 6 allows simulation of pumping from deep municipal wells in the eastern part of the valley.

Kariya and others (1994) initially estimated hydraulic parameters based on single-well specific-capacity tests for layer 1. Initial transmissivity values of layers 2 through 6 were computed by multiplying the estimated hydraulic-conductivity values for layer 1 by the thickness of each layer. During the steady-state calibration of the model, input parameters were systematically varied and refined to a non-uniform distribution. The final distribution of transmissivity values for layers 2 through 4 can be obtained by multiplying the final hydraulic conductivity of layer 1 by the thickness of the layer in question. During calibration, transmissivity values in layers 5 and 6 were reduced to the value for layer 4 in order to be more consistent with aquifer-test data. For layer 1, to achieve a best fit between simulated and observed data, the final values of hydraulic conductivity for the calibrated model ranged from 1 to 100 feet per day. Transmissivity values used in the calibrated model for layers 2 to 4 range from 100 to 18,000 square feet per day. The steady-state simulation assumes the water flowing into the ground-water system equals the amount flowing out, with no change in ground-water storage. The vertical leakage used to represent confining units in the model were calculated based on the vertical hydraulic conductivity determined by comparing simulated vertical-head differences between layers. Cells in layer 1 with spring discharge are assigned an increased vertical conductance.

Boundary conditions for the Cache Valley model were based on a simplified hydrologic model. Kariya and others (1994) specified the lateral boundaries surrounding the active cells of the model as "no-flow" boundaries by assuming they coincided with low-permeability bedrock, except where inflow from adjacent consolidated rock or unconsolidated basin-fill deposits was identified during the calibration of the model. To simulate subsurface inflow into the main ground-water system of Cache Valley, general-head cells were used at the boundary of layer 1. The upper boundary of the model is a specified-flux boundary formed by using recharge, well, evapotranspiration, river, and drain packages of MODFLOW to simulate the infiltration and discharge of ground water. The lower boundary of the model is a no-flow boundary.

In the model, recharge of the Cache Valley basin-fill aquifer occurs (1) where infiltration of unconsumed irrigation water and precipitation occurs; (2) where perennial streams emerge from canyons, or canals flow across coarse-grained deposits along the margins of the valley, where water may infiltrate readily to the underlying ground-water system; and (3) from subsurface inflow. Alluvial fans and deltas adjacent to the Bear River Range are important recharge areas. Thirteen perennial streams enter the valley and flow toward the Bear River; ten of these are from the Bear River Range and three are from mountains on the west side of the valley. These tributaries contribute to the surface and subsurface water supplies. Before the time of large-scale irrigation, infiltration from streams flowing across the alluvial fans and deltas was probably the main source of ground water. By 1994, the infiltration of unconsumed irrigation water was almost as important (Kariya and others, 1994). The Kariya and others (1994) model estimated recharge across the modeled area of Cache Valley as 326,000 acre-feet per year. Ground-water discharge in Cache Valley is primarily from (1) seepage to the Bear, Cub, Logan, Blacksmith Fork, and Little Bear Rivers; (2) evapotranspiration in the marshes and wetlands; and (3) withdrawals from wells and springs. The largest component of ground-water discharge in Cache Valley is seepage to rivers; the net gain to flow in the Bear River (including Cutler Reservoir) from seepage between Smithfield and the Box Elder county line was 79 cubic feet per second (Herbert and Thomas, 1992). Estimated discharge across the modeled area of Cache Valley is 325,000 acre-feet per year (Kariya and others, 1994).

The model of Kariya and others (1994) did not simulate the approximately 45.5-square-mile Clarkston Bench area, because that area has its own individual basin-fill ground-water system, and is at a higher altitude than the ground-water system in Cache Valley. Consolidated rocks are at shallower depths in the Clarkston Bench area, and the unconsolidated basin fill is thin (about 20 feet thick, on average). Little is known of the thickness or extent of water-bearing material in the Clarkston Bench area.

The Myers (2003) Model

Myers (2003) used Robinson's (1999) conceptual model of multiple aquifers and at least two continuous non-leaky confining layers to develop a new numerical ground-water-flow model for Cache Valley. Like Kariya and others (1994), Myers (2003) used MODFLOW (McDonald and Harbaugh, 1988) and a similar grid. However, in addition to using a different conceptual model for the principal aquifer, Myers' (2003) boundary conditions, water budget, and hydraulic properties were different from those used by Kariya and others (1994).

Myers (2003) used the U.S. Geological Survey modular three-dimensional flow simulator (MODFLOW) (McDonald and Harbaugh, 1988) to test and refine Robinson's (1999) conceptual model of the flow system in Cache Valley. This conceptual model of Cache Valley considers the Cache Valley aquifer system to consist of an upper unconfined aquifer, an upper confined aquifer between two continuous confining layers, and a lower confined aquifer, as described in the Geologic Setting section of this report. The area covered by saturated unconsolidated basin-fill deposits was discretized into a non-uniform, three-dimensional rectangular grid consisting of 82 rows and 30 columns, with 11 vertical layers. The 11 layers in Myers's (2003) model represent the saturated, unconsolidated basin-fill deposits described by Robinson (1999).

The model's rectilinear grid has a grid-cell spacing ranging from 0.5 mile by 0.375 mile to 1 mile on each side, resulting in cell areas of 0.2 to 1 square mile. The y-axis of the model is oriented north-south, parallel to the axis of the valley and the primary surface-water drainages, like the model of Kariya and others (1994). Active cells in layer 1 simulate the unconfined aquifer and are assigned a thickness of 100 feet. Layers 2 and 4 simulate the upper and lower confining layers, with thicknesses of 60 feet and 30 feet, respectively. Layer 3 represents an upper confined aquifer with a thickness of 30 feet, and simulates saturated valley fill using a confined or unconfined layer option that allows the storage term to be converted from confined to unconfined in cells when calculated water levels drop below the top of the cell. Layers 5 through 11 represent a lower confined aquifer, with layer 5 having a thickness of 100 feet, layer 6 through 10 having a thickness of 200 feet each, and layer 11 having a thickness of 150 feet.

Myers (2003) initially estimated hydraulic parameters based on material descriptions, and reported values in textbooks. Initial horizontal and vertical hydraulic conductivity for the upper and lower confining layers was based on the layers consisting of clay in the center of the valley and of silt and sand toward the valley margins. The upper confined aquifer was assigned horizontal and vertical hydraulic conductivity based on proportions of sand and gravel to cobbles interbedded with discontinuous clay lenses. Initial horizontal and vertical hydraulic conductivity for the layers in lower confined aquifers were based on proportions of gravels and sands with discontinuous lenses of silt and clay.

Boundary conditions for the Cache Valley model were based on the hydrologic model of Robinson (1999). Myers (2003) specified the lateral boundaries surrounding the active cells of the model as "no-flow" boundaries by assuming they coincided with the low-permeability Salt Lake Formation, except where inflow from adjacent consolidated rock or unconsolidated basin-fill deposits was identified during the calibration of the model. To simulate subsurface inflow into the main ground-water system of Cache Valley, head-dependent cells were used at the boundary of layer 1. The upper boundary of model layer 1 is a specified-flux boundary to simulate infiltration of precipitation and unconsumed irrigation water, seepage from canals and streams, and withdrawals from wells and simulates evapotranspiration, discharge from wells and springs, and seepage to streams, rivers, and a reservoir. Layers 5 through 11 were simulated using the confined-layer option. The lower boundary of the model is a no-flow boundary.

During the steady-state calibration of the model, input parameters were systematically varied and refined to a nonuniform distribution. The final distribution of transmissivity values of layers 3, and 5 through 11 were computed by multiplying the estimated hydraulic conductivity values for layer 1 by the thickness of each layer. A general head boundary was introduced at the margins of the model during calibration to help match heads within the model. The steady-state simulation assumes that the water flowing into the ground-water system equals the amount flowing out, with no change in ground-water storage. Cells in layer 1 with spring, river, and evapotranspiration were changed in an attempt to discharge the correct amount of water.

Limitations of the Models

A ground-water-flow model is no more than a simulation of the real-world behavior of an aquifer system. Improvements in the quality of simulation are always possible, and a model should be considered a dynamic representation of nature, subject to further refinement and improvement. As new and more information becomes available, previous models should be modified or replaced. The subsequent models will become more reliable and more objective, and thus tools that can be used with increased confidence to predict aquifer responses to changes in climatic and human-induced conditions. The accuracy of a ground-water-flow model depends, in part, upon how accurately the conceptual model used to develop the flow model reflects the processes that actually control the aquifer system.

The accuracy of the ground-water-flow models of Cache Valley depends on three critical assumptions: (1) the aquifer system is conceptualized correctly; (2) the aquifer system is numerically approximated with only minor, recognized uncertainties; and (3) the values used to calibrate and verify the model are realistic and representative of the aquifer. The development of a model begins with a conceptual understanding of the physical system, and, the more refined the conceptual understanding, the better the model.

The following are some of the problems with the existing ground-water flow models of Cache Valley:

- The conceptualization of the aquifer system differs between the two ground-water flow models of Cache Valley, with neither model having all aspects of the aquifer system well understood.
- Both models were constructed using estimated, interpolated, or extrapolated values for large areas of the aquifer being modeled. This was because available data are not as comprehensive as preferred. In areas where data are limited, the simulation results are more questionable.
- Myers' (2003) sensitivity analysis indicated that the model was very sensitive to the hydraulic conductivity of the confining layers. However, no in-situ values of hydraulic conductivity have been measured for the confining layers.
- Kariya and others' (1994) sensitivity analysis indicated their model was sensitive to assigned values of hydraulic conductivity and transmissivity near the edges of the model. However, these assigned values were estimated from limited field data and substantially modified during calibration of their model.
- Kariya and others' (1994) final model parameter distribution correlates poorly with the geology of the area.
- The models of Kariya and others (1994) and Myers (2003) are calibrated, which means that, when assigned a certain combination of parameters and boundary conditions, the model will produce values near measured values of head at certain cells in the grid (for instance, measured water levels in wells from 1969). However, there is no guarantee that the combination of parameters assigned by trial-and-error are unique.

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APPENDIX C
REGULATORY REQUIREMENTS

CLASS V UIC PERMITS FOR AQUIFER STORAGE AND RECOVERY OPERATIONS

The following is a summary of Utah Division of Water Quality permitting requirements for Class I, III, IV and V injection wells provided by Rob Herbert, Environmental Program Manager, Ground Water Protection Section, Utah Division of Water Quality (Utah Division of Water Quality does not issue permits for Class II injection wells). The attached spreadsheet (attachment 1) dealing with water-quality monitoring of the injection well for the Leamington ASR project was produced by Candace Cady, Environmental Scientist, Ground Water Protection Section, Utah Division of Water Quality. The attachments are appended to help familiarize the reader with the paperwork and monitoring required for an aquifer storage and recovery program.

The Utah Bureau of Water Pollution Control (BWPC), now the Utah Division of Water Quality (DWQ), received primacy from EPA on February 10, 1983 to administer the Utah Underground Injection Control (UIC) program under section 1422 of the Safe Drinking Water Act for Class I, III, IV and V injection wells. The DWQ Ground Water Protection Section issues Class V UIC permits for aquifer storage and recovery (ASR) projects. Currently, there are three permitted ASR projects in Utah: 1) Brigham City Corporation; 2) Jordan Valley Water Conservancy District; and 3) Leamington Town. The current benefits of these ASR projects are for underground storage of treated high-quality mountain stream runoff or spring water for later use. A potential future use of ASR may be for disposal of treated domestic wastewater effluent for ground-water recharge in areas where surface discharge is not feasible or allowed due to UPDES regulatory constraints (e.g., within U.S. Forest Service areas). In addition to a Class V UIC Permit from DWQ, ASR operators are required to obtain a Recharge Permit and a Recovery Permit from the Division of Water Rights. DWQ also works closely with the Division of Drinking Water, which is the DEQ agency with regulatory oversight of the water production wells.

Under a UIC Class V ASR permit, operators are required to conduct comprehensive water quality monitoring of new sources for one or two years to ensure that the injected water will meet all Federal and State Drinking Water Maximum Contaminant Levels (MCLs), and State Ground Water Quality Standards. The maximum total dissolved solids of injected water shall not exceed 500 mg/L. After this initial comprehensive monitoring period has been completed, the monitoring parameter list is scaled back to an abbreviated list consisting of previously detected chemicals and parameters of concern. New ASR projects are required to assess the potential geochemical impact of injection on the quality of the receiving aquifer. A more detailed geochemical modeling effort would be required for an ASR project in which foreign waters (water that does not already naturally recharge an aquifer) are proposed to be injected for storage. The USGS has conducted several studies of ASR systems with the use of PHREEQC, a geochemical model designed to perform low-temperature aqueous geochemical calculations. Therefore, the tools are already available for assessing the potential geochemical impact from ASR projects.

UIC Class V ASR permits also require monitoring and continuous recording of injection volume, pressure, and flow rate, and hydrostatic head measurements in each well before and after each injection event. A UIC Class V ASR permit includes primarily three parts. Part I (Authorization to Operate) and Part II (General Permit Conditions) are fairly standardized with the exception of facility and permit identification information. Part III (Specific Conditions) includes the following elements:

A. Compliance Schedule items needed before injection commences.
   1. Memorandum of Understanding from the Division of Water Rights stating that the State Engineer has approved the Ground Water Recharge Permit Application and issued a Ground Water Recharge Permit.
   2. Comprehensive water quality analysis of the ground water from the aquifer into which injection will occur.

B. Construction Requirements for new wells.

C. Operation Requirements
   1. Injection Zone
   2. Injection Pressure Limitation
   3. Injection Rate Limitations
   4. Injection Volume Limitation
   5. Injection Fluid Limitations
   6. Security

D. Monitoring, Testing, and Reporting
  1. Injectate Characterization
  2. Monitoring of Operating Parameters
  3. Reporting

E. Plugging and Abandonment of Recharge Wells
  1. Plugging and Abandonment Plan
  2. Notice of Plugging and Abandonment
  3. Inactive Well

F. Financial Responsibility

G. Continuation of Expiring Permit

See http://www.waterquality.utah.gov/UIC/index.htm for more information.