THE WEBER RIVER BASIN AQUIFER STORAGE AND RECOVERY PILOT PROJECT

Hugh Hurlow, Mike Lowe, Marek Matyjasik, and Paul Gettings

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Cover photo: *View west of sedimentation basin (foreground) and infiltration basin #3.*

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THE WEBER RIVER BASIN AQUIFER STORAGE AND RECOVERY PILOT PROJECT

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ABSTRACT

This report describes the Weber River Basin Aquifer Storage and Recovery pilot project, a three-year, multi-agency cooperative effort to evaluate the feasibility of artificial recharge of ground water in the Weber Delta area, northern Utah. Declining ground-water levels, recent drought, the prospect of increasing future water-use demands, and the likelihood of success based on previous experiments were the main reasons for initiating the project.

The study area is about one mile (1.6 km) west of the mouth of Weber Canyon, where the Weber River flows from the Wasatch Range to the Weber Delta subdistrict of the east shore area of Great Salt Lake. The Weber Delta formed during Pleistocene time, where the Weber River flowed into Lake Bonneville, which covered much of northern Utah west of the Wasatch Range. Interbedded sand and gravel deposits of Lake Bonneville and previous deep-lake cycles form the Sunset (shallower) and Delta (deeper) aquifers, the principal aquifers in the east shore area. The Delta aquifer is the primary source of ground water in the area. A fine-grained confining interval separates the Sunset and Delta aquifers, except within about one mile (1.6 km) of the canyon mouth, where they cannot be distinguished.

The Delta aquifer is recharged primarily by infiltration from the Weber River, and secondarily by westward underflow from bedrock aquifers in the Wasatch Range. Discharge is primarily from water wells, and secondarily by evapotranspiration, springs, and seepage along the eastern margin of Great Salt Lake. Ground-water levels in the Delta aquifer have declined by 30 to 80 feet (10–24 m) during the past 50 years due to large withdrawal by wells. Water quality in the aquifers and the Weber River is generally good; total-dissolved-solids concentrations are typically less than about 500 mg/L, and the water is dominantly calcium-magnesium-bicarbonate type.

The pilot project included three infiltration experiments during which water was diverted from an irrigation canal into four infiltration basins: (1) March 18 to July 2, 2004 (about 800 acre-feet [1 hm^3]); (2) March 17 to May 23, 2005 (about 450 acre-feet [0.55 hm^3]) and August 17 to October 31, 2005 (about 250 acre-feet [0.31 hm^3]); and (3) June 23 to November 1, 2006 (1130 acre-feet [1.4 hm^3]).

The water level in a newly constructed observation well on the pilot project site rose about one foot (0.3 m) during the first infiltration experiment. During the second infiltration experiment, the water level in the observation well rose 5.65 feet (1.72 m) during the initial phase of diversion and infiltration, decreased until diversion resumed, and rose another 4.25 feet (1.3 m) during the second phase. These relatively small water-level increases in the observation well contrasted with records from nearby wells, in which water levels declined by as much as 40 feet (12 m).

During the first infiltration experiment, the concentration of total dissolved solids in Weber River water decreased from 268 to 144 mg/L during peak stream flow from late March to early July, then returned to normal values (~350 mg/L). Total-dissolved-solids concentrations in water wells in the area, including the pilot project site observation well, remained constant throughout the sampling period. A similar pattern was observed during the second infiltration experiment.

A high-precision gravity study conducted to track the infiltrated ground water revealed substantial increases in gravity below the infiltration site within a month after the beginning of the first two recharge experiments. After that time, the area of increased gravity migrated to the east and south of the infiltration site. During the second recharge experiment, measured gravity values were greater, reached their maximum more quickly, and occurred over a slightly wider area than during the first recharge experiment. We interpret these differences to reflect the presence of more pore water in the vadose zone below the pilot project site and adjacent areas, due to a combination of greater precipitation on the valley floor prior to initiation of the second recharge experiment, greater infiltration of Weber River water during March 2005, and incomplete drainage

of water infiltrated during the first recharge experiment.

The infiltrated water perches and spreads laterally on the top of a fine-grained layer, encountered at about 116 feet (35 m) depth by the observation well and observed in a gravel pit east of the pilot project site, and flows slowly downward through this layer into the Delta aquifer. Because the water introduced from the infiltration basins percolates into the main water table over a greater area than the infiltration basins, the water-level change at any point is small, as illustrated by hydrographs from the pilot project observation well during and after diversion of water into the infiltration basins.

A numerical ground-water flow model of the east shore aquifer system, including the pilot project site, was constructed to better understand the regional ground-water flow system and the effects of the infiltration experiments. The model is calibrated to transient ground-water conditions created by steadily declining water levels due to large withdrawal by water wells. The model accurately represents the infiltration experiments as indicated by matching the water-level changes in the observation well and the shape, size, and distribution of the mound of artificially recharged ground water as measured by the high-precision gravity surveys. The modeled recharge-mound crest declines and migrates outward from the infiltration site and, for example, is 0.2 feet (6 cm) high about 6 miles (10 km) from the infiltration basins 700 days after the end of diversion. Recharge from the infiltration basins, therefore, will reach several water-supply wells owned by the Weber Basin Water Conservancy District within two years of the end of infiltration. Water-level changes at these wells may be slight compared to annual changes due to natural recharge and pumping, but flow to the wells will increase.

The infiltration basins at the pilot project site can accommodate about 800 to 1100 acre-feet per year (1–1.4 hm^3/yr) of infiltration to the ground-water table in the Delta aquifer over the time period early March to early November. Proximity to the South Weber canal makes the pilot project site convenient, but accounts from previous artificial recharge experiments in the area suggest that substantially greater infiltration can be achieved in the gravel pits to the east.

INTRODUCTION

Scope and Purpose

This report presents the results of the Weber River Basin Aquifer Storage and Recovery (WRBASR) pilot project, a three-year effort to evaluate the feasibility of long-term enhanced ground-water recharge and aquifer storage and recovery (ASR) at the mouth of Weber Canyon in Davis and Weber Counties, northern Utah (figure 1; plate 1). Aquifer storage and recovery is the use and management of ground-water aquifers as water-storage and, in some cases, treatment facilities. The primary objectives of the pilot project were to (1) study the feasibility of artificial recharge and ASR near the mouth of Weber Canyon, (2) design and implement an initial experiment to evaluate the effectiveness of artificial ground-water recharge in the area, (3) conduct a high-precision gravity study to map the extent of recharged water, (4) formulate a numeric model of the local hydrogeology and the recharge experiment, and (5) make recommendations and devise a long-term plan for ASR in the study area.

The pilot project was a multi-agency cooperative effort, led by the Weber Basin Water Conservancy District (WBWCD) and funded by the U.S. Bureau of Reclamation, with matching funds from WBWCD and other participating agencies. Additional cooperating agencies included the Utah Division of Water Resources, Weber State University, the University of Utah Department of Geology and Geophysics, and the Utah Geological Survey (UGS).

The pilot project used surface spreading of water diverted from the Weber River during the spring runoff season, and this approach will likely be used in the area in the future. Much of the recharged water will likely be recovered by existing or new water-supply wells, although recovery of the artificially infiltrated water was not part of the pilot project. Injection of water through wells, or a combination of wells and infiltration basins, may become the preferred long-term alternative depending on the costs of leasing or purchasing property.

The pilot project consisted of (1) a literature search, primarily limited to the geology of the study area and previous artificial recharge experiments in Utah, and determination of data collection needs, (2) collection and analysis of baseline data prior to project implementation, (3) design and implementation of three recharge experiments at the mouth of Weber Canyon, from March 18 to July 2, 2004; from March 17 to May 23 and August 17 to September 26, 2005; and from June 23 to November 1, 2006, (4) collection of data during and after the first and second recharge experiments, and (5) evaluation of the recharge experiments, including formulation of a ground-water flow model, and preparation of this report. New data collected during the pilot project included water-level and water-chemistry analyses from wells in and near the recharge basins, water chemistry of the Weber River, and high-precision gravity measurements.

The main impetus for this project is a water-table decline of up to 80 feet (24 m) in the Delta aquifer, the principal aquifer of the Weber Delta area, during the past 50 years (figures 2a and 3; details provided below). The decline began in the 1950s, and is due to a combination of factors

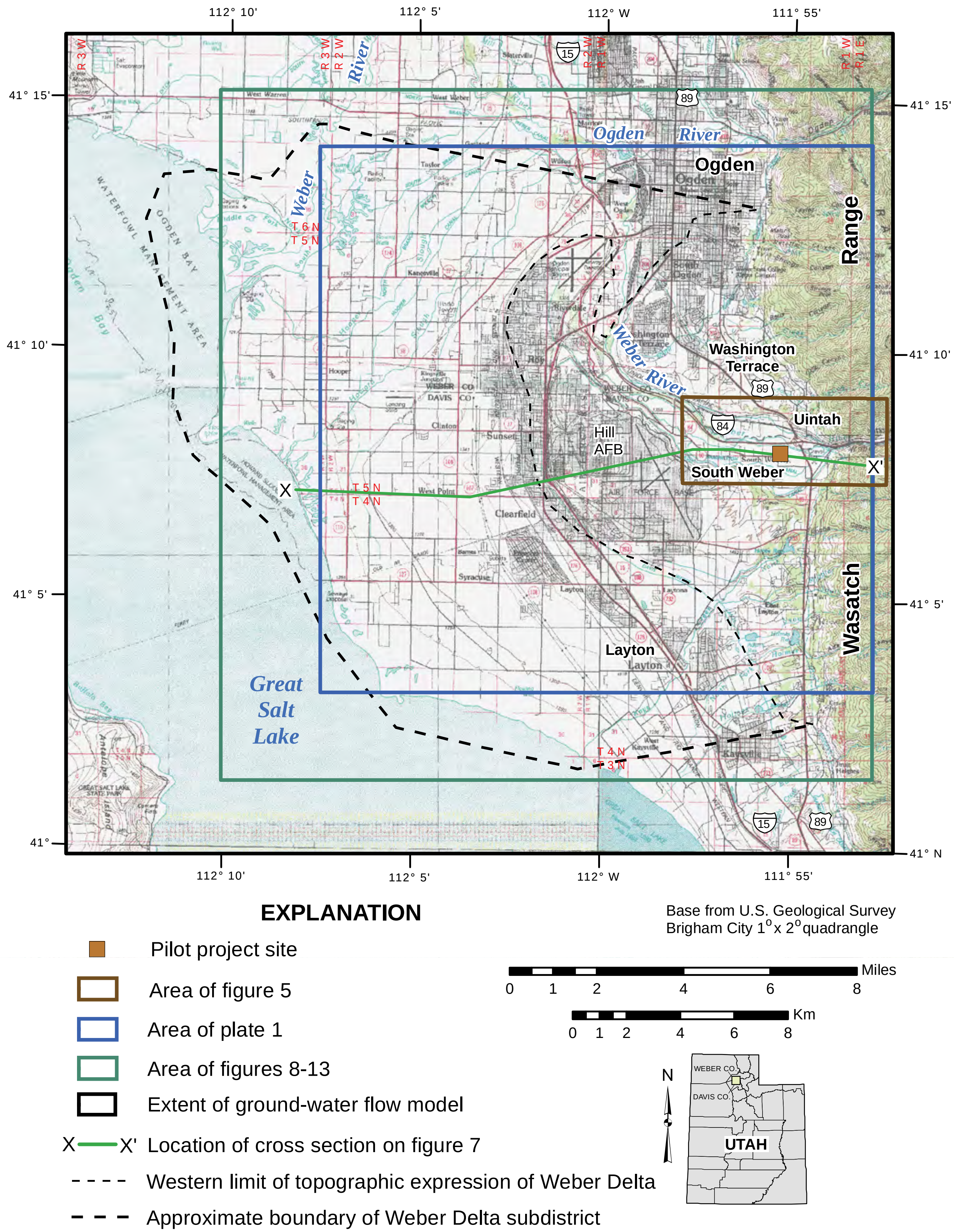


Figure 1. *The Weber River Basin Aquifer Storage and Recovery pilot project study area, Weber Delta, and the Weber Delta subdistrict.*

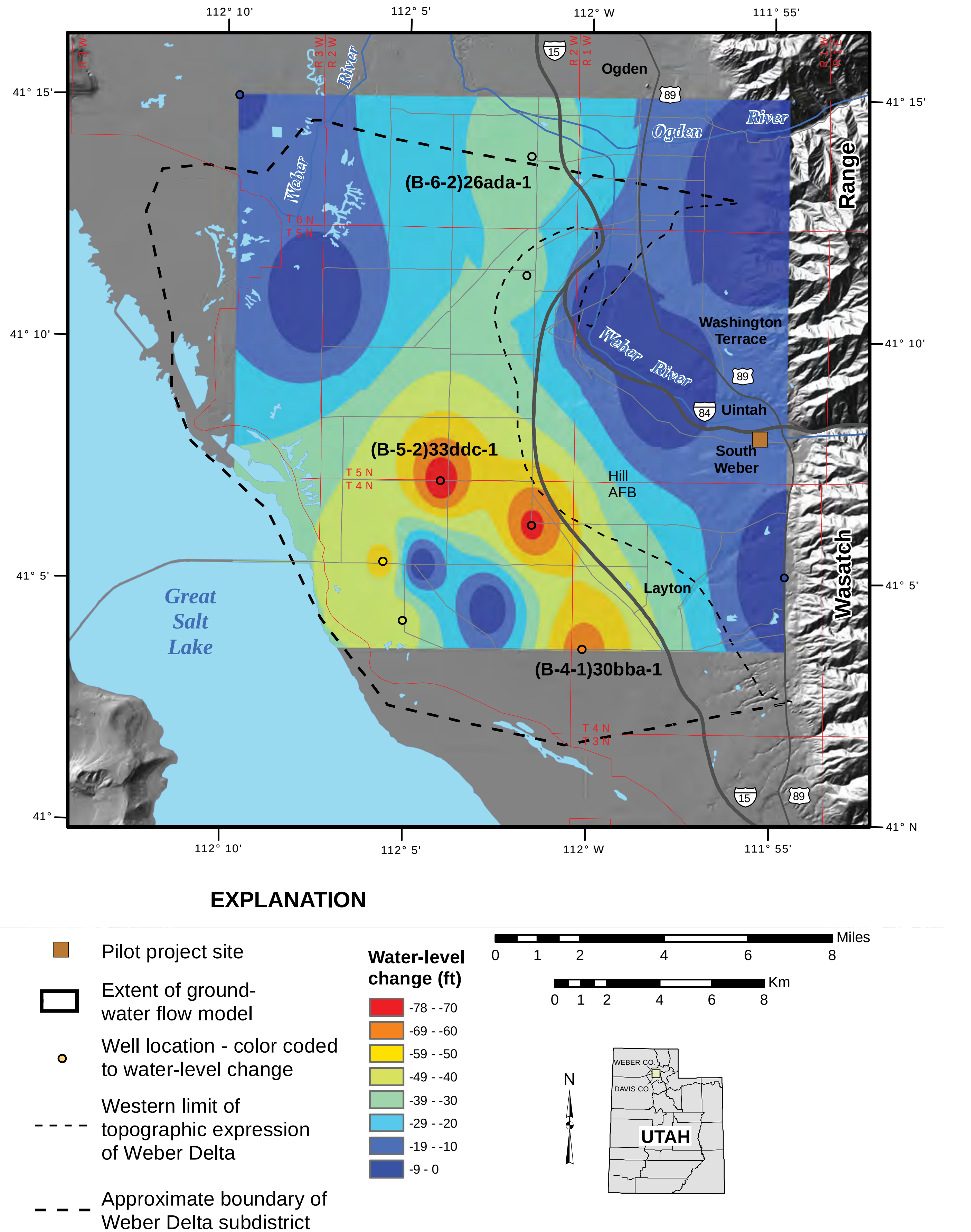


Figure 2a. *Changes in water levels in the Delta aquifer during the past 50 years. Data are from the U.S. Geological Survey (2005). Well numbers correspond to water-level plots on figure 3.*

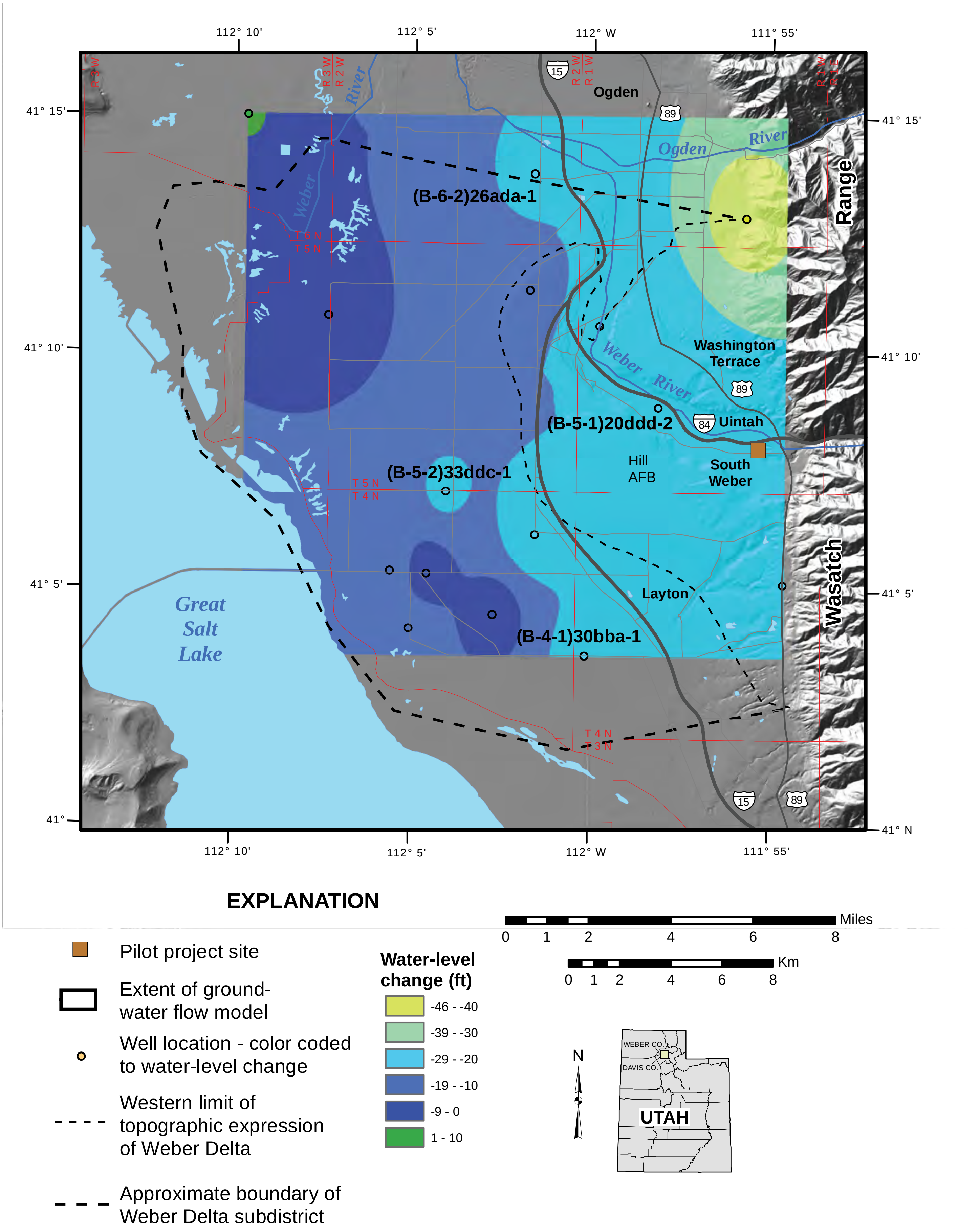


Figure 2b. *Changes in water levels in the Delta aquifer during the past 20 years. Data are from the U.S. Geological Survey (2005). Well numbers correspond to water-level plots on figure 3.*

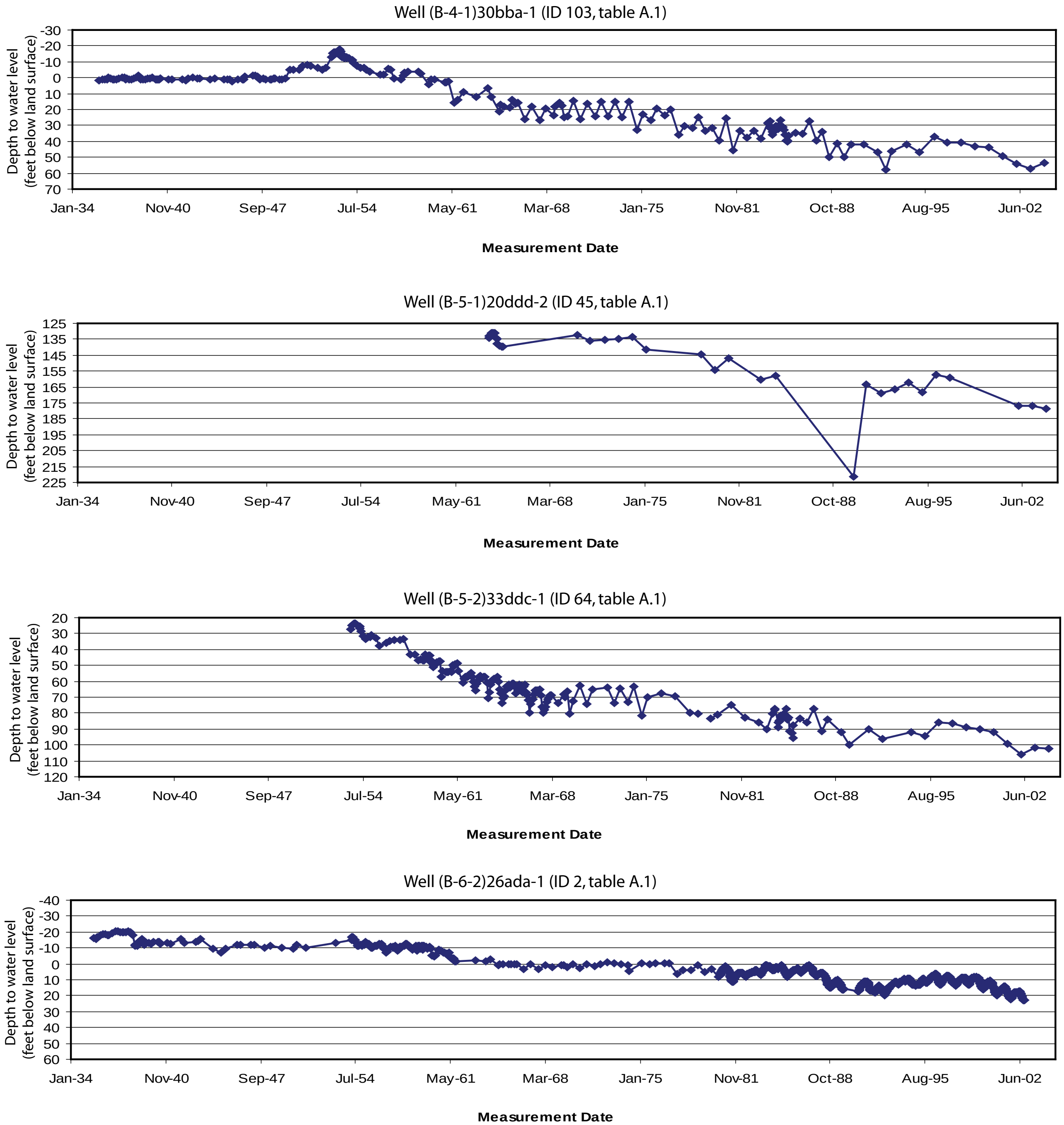


Figure 3. *Water-level records of wells in the Weber Delta area of the east shore aquifer system (data from the U.S. Geological Survey, 2005). See figure 2 for locations and table A1 for well records.*

that cause average annual discharge to be greater than the average annual recharge in the Delta aquifer, principally increased withdrawal of ground water and, at times, lower-than-average precipitation in the area.

Previous Hydrogeologic Investigations

Feth and others (1966) studied the basin-fill deposits and hydrogeologic conditions in the Weber Delta district, and reported on artificial recharge experiments conducted by the U.S. Bureau of Reclamation at the mouth of Weber Canyon during the 1950s. Bolke and Waddell (1972) mapped ground-water quality and evaluated changes in water levels and ground-water quality in the East Shore area. Clyde and others (1984) constructed a ground-water flow model to evaluate the potential for diverting water from the Weber River at the mouth of Weber Canyon for use as a source of artificial recharge for the Weber Delta area. Clark and others (1990) re-evaluated ground-water conditions in the East Shore area and constructed a numerical model of the East Shore aquifer in the Weber Delta area to evaluate the effects of ground-water withdrawals. Anderson and others (1994) mapped ground-water recharge and discharge areas for the principal aquifers along the Wasatch Front, including aquifers in the Weber Delta district.

Study Area

Location, Geography, and Ground Water

The project study area is in the Weber Delta district of the east shore aquifer system (Feth and others, 1966), which contains the principal aquifer in Davis County and western Weber County. This area is referred to as the Weber Delta subdistrict of the Weber Delta district (figure 1) (Feth and others, 1966; Gates, 1995). The Weber Delta district covers an area of about 400 square miles (1000 km^2), and extends westward from the Wasatch Range to Great Salt Lake and southward from North Ogden to Farmington (figure 1) (Feth and others, 1966; Clark and others, 1990; Gates, 1995). The Weber River, which flows from east to west through the study area, is a primary source of recharge to aquifers in the Weber Delta district (Clark and others, 1990). Two principal aquifers, the Sunset and Delta, are present in the central part of the Weber Delta district (Feth and others, 1966), where ground water is generally under confined conditions. Along the western margin of the Wasatch Range, where ground water is unconfined, the Sunset and Delta aquifers cannot be delineated from hydrogeologic data (Feth and others, 1966).

The Delta aquifer is the primary source of ground water in the Weber Delta subdistrict (Clark and others, 1990). From 1953 to 1985, water levels declined an average of 27 feet (8 m) in wells located in the confined part of the Delta aquifer, with a maximum drop of 50 feet (15 m) near the principal pumping center for the district (Clark and others, 1990). During the same period, water levels in the unconfined part of the Weber Delta subdistrict declined as much as 40 feet (12 m) in wells at the mouth of Weber Canyon (Clark and others, 1990), indicating that ground-water mining is a concern. The trend of declining water levels has continued; during the past 20 years, water levels in most of the Weber Delta declined 10 to 30 feet (3–10 m) (figure 2b). This long-term overdraft of the aquifer has not only increased pumping lifts and hence operational costs, but could also initiate land subsidence and/or salt-water intrusion from Great Salt Lake.

The east shore area is a topographic basin extending northward from the Salt Lake salient to southeastern Box Elder County, and from the western margin of the Wasatch Range to the eastern shore of Great Salt Lake (Clark and others, 1990). The study area for this report includes the central-eastern portion of the east shore area, and is in the lower Weber River drainage basin in northern Utah's heavily populated Wasatch Front (figure 1). The eastern part of the study area is in the Wasatch Range section of the Rocky Mountain physiographic province, and the central and western parts of the project area are in the Wasatch Front Valleys section of the Basin and Range physiographic province (Stokes, 1977). Elevation ranges from about 5800 feet (1770 m) in the Wasatch Range in the southeast corner of the study area to about 4420 feet (1350 m) at the Weber River near the northwest corner. The north-south-trending Wasatch fault zone near the base of the Wasatch Range is the approximate boundary between the two physiographic provinces.

The Weber Delta, the largest of the deltas associated with Pleistocene Lake Bonneville (Gilbert, 1890), was deposited mainly by the Weber and Ogden Rivers. Weber Delta deposits include interlayered, unconsolidated gravel, sand, and fine-grained sediments that are up to about 1500 feet (457 m) thick near the canyon mouths, and gradually thin to the west, north, and south (Feth and others, 1966; Clyde and others, 1984). Erosion by the Weber River through the Weber Delta has formed a terraced, flat-bottom, U-shaped valley, with the arms of the U forming approximately 300-foot- (90 m) high bluffs extending to the top of the delta surface at an elevation of roughly 4800 feet (1460 m).

Population and Land Use

The study area (figure 1; plate 1) is a few miles south of Ogden, and includes parts of the communities of Uintah and Washington Terrace in Weber County and South Weber in Davis County. The combined 2000 census population of Uintah, Washington Terrace, and South Weber is about 14,000, and is projected to increase by over 70 percent by 2030 (Demographic and Economic Analysis Section, 2005).

In addition to residential development, the principal land uses are U.S. Defense Department activities at Hill Air Force Base, gravel pits just west of the Wasatch Range, commercial sales and rental businesses, and job training at the Weber Basin Job Corps Center. The Weber River is used for recreational activities such as fishing and kayaking.

Climate

The study area has a temperate and semiarid climate (Feth and others, 1966). Based on data from the Ogden Pioneer Powerhouse weather station about 7 miles (11 km) northwest of the pilot project site, temperatures in the study area reach a normal maximum of 90.5ºF (32.5ºC) in July and a normal minimum of 21.0ºF (-6.1ºC) in January; the normal mean annual temperature is 52.9ºF (11.6ºC) (Moller and Gillies, 2008). Normal mean annual precipitation is 23.84 inches (60.6 cm), and mean annual evapotranspiration is 45.29 inches (115.0 cm) (Moller and Gillies, 2008). The average number of frost-free days is 151 (Moller and Gillies, 2008).

Ground-Water Issues In Utah

Declining ground-water levels and water quality due to increasing use pose problems, to varying degrees, in much of Utah, especially along the Wasatch Front and in the southwestern part of the state (Utah Division of Water Resources, 2005). Utah had the fourth-greatest population growth rate in the United States between 1990 and 2000, and its population is projected to increase from 2.3 million in 2000 to about 5.4 million in 2050 (Utah Governor's Office of Planning and Budget, 2005). Also, Utah has the second-highest per capita water use in the United States (Utah Division of Water Resources, 2001). These combined factors greatly stress Utah's ground-water supply now and will do so increasingly in the future, even if recently implemented conservation efforts (Utah Division of Water Resources, 2001) are effective. Freshwater withdrawals in Utah during 2000 totaled about 5.3 million acre-feet (6535 hm^3); about 55% of this was from ground water (Utah Division of Water Resources, 2005). The primary uses of ground water in Utah are irrigation (81%) and public supply (13%) (Utah Division of Water Resources, 2005). Annual combined municipal and industrial use is projected to increase from about 904,000 acre-feet (1100 hm^3) in 2000 to 1.95 million acre-feet (2400 hm^3) by 2050, assuming current per capita use (Utah Division of Water Resources, 2001).

Increased ground-water use, especially during the past 30 years, has caused ground-water levels to decline in much of Utah. Ground-water levels in 12 of the state's 36 main ground-water development areas, including those in the most populated areas, declined by 20 to 100 feet (6–30 m) from 1950 to 2004 (Utah Division of Water Resources, 2005). Lower ground-water levels create many water-supply problems, including greater pumping costs, decreased water quality, greater incidence of water-rights conflicts, and decreased spring flow (Utah Division of Water Resources, 2005). Other negative impacts include land subsidence, aquifer compaction resulting in permanently decreased storage and transmissive capacity, and ground cracking; these problems are relatively rare in Utah, but their frequency will likely increase if ground water levels continue to decline in the future (Lund and others, 2005; Utah Division of Water Resources, 2005).

The low annual statewide precipitation in Utah (13 inches per year [33 cm/yr], the second-lowest state average in the U.S.) and uneven distribution of precipitation in both time and space also contribute to Utah's water-supply problems. The vast majority of precipitation falls in the Wasatch and Uinta Mountains, and this water moves mainly toward Great Salt Lake as both surface water and ground water, or into the Colorado River drainage system (Utah Division of Water Resources, 2001; Moller and Gillies, 2008). Most of the remainder of the state has low precipitation and recharge rates, resulting in very limited ground-water supply.

Utah experienced six to eight consecutive years of drought from 1994 to 2004, depending on location (figure 4) (Utah Division of Water Resources, 2005). Drought periods have occurred in Utah since precipitation records have been kept, and can be expected in the future. Decreased stream discharge during drought leads to increased ground-water withdrawal, but ground-water recharge is also severely reduced during drought, causing ground-water levels to decline more rapidly (Utah Division of Water Resources, 2005). Ground-water levels in areas of heavy withdrawal do not necessarily recover during periods of greater-than-average precipitation (Clark and others, 1990; Utah Division of Water Resources, 2005).

Aquifer Storage and Recovery

Conjunctive management refers to the coordinated and combined use of surface water and ground water (Utah Division of Water Resources, 2005). Conjunctive management has many manifestations, but the unifying concepts include (1) storing excess surface water, including spring runoff, for use during times of shortage, (2) recognizing the close connection between surface water and ground water and managing them accordingly, and (3) adapting facilities and water-management strategies to the characteristics of the water supply and hydrogeology of the individual basins in which the method is applied (Utah Division of Water Resources, 2005). Conjunctive management of ground water, including ASR, could help mitigate the negative impacts of future drought periods in Utah if it is widely practiced in the state.

Aquifer storage and recovery, a form of conjunctive management, is a method of enhancing recharge to an underground aquifer by introducing excess surface water into the aquifer for later use. Benefits of ASR include increased ground-water reserves, stabilization of declining ground-water levels, mitigation of water-supply problems during drought or times of high demand, and, in some cases, improvement of the chemical quality of water (Pyne, 1995; Utah Division of Water Resources, 2005). The method is a low-cost alternative to constructing surface-storage facilities.

Artificial ground-water recharge has long been recognized as a means of introducing water into the ground-water system to enhance ground-water quality, reduce pumping lifts, store water, or salvage storm-water runoff (Clyde and others, 1984; Pyne, 1995). Aquifer storage and recovery projects involve the storage of water in an aquifer via artificial ground-water recharge when water is available, and recovery of the stored water from the aquifer during times when water is needed (Pyne, 1995). Artificial ground-water recharge can be accomplished by spreading or ponding of surface water in areas where surficial deposits are highly permeable, or by injection of surface water into an aquifer using wells (Clyde and others, 1984). Although losses of water stored via artificial ground-water recharge

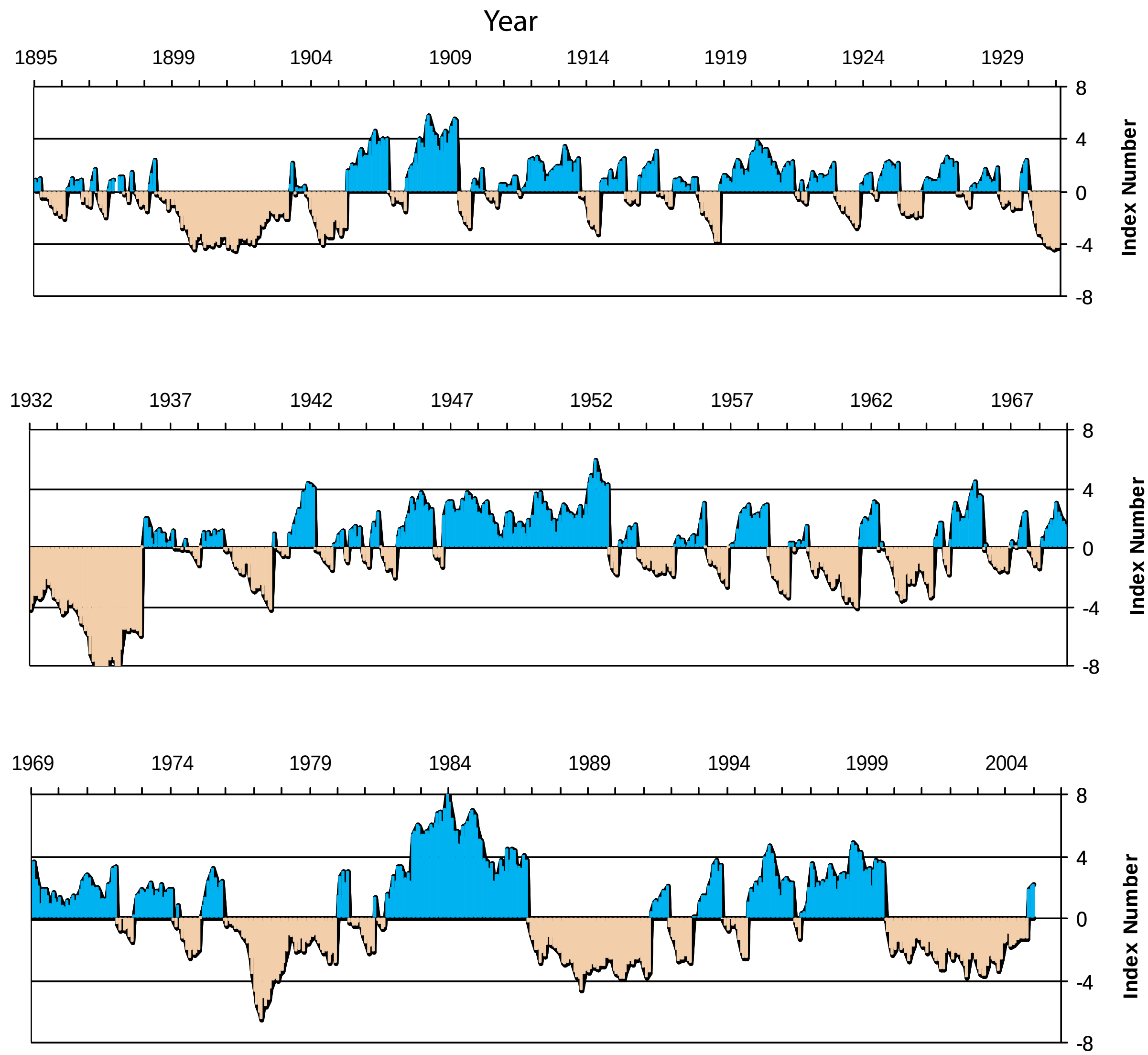


Figure 4. *Palmer hydrological drought index (PHDI) for the northern mountains of Utah (Utah Division of Water Resources, 2005). The PHDI is a measure of hydrologic conditions for a particular area, based on precipitation, outflow, and storage, that indicates the relative departure of hydrologic conditions from "normal." PHDI values greater than 4.0 indicate "extremely wet," -0.5 to 0.5 "normal," and less than -4.0 "extreme drought" conditions, respectively (Utah Division of Water Resources, 2005).*

occur, principally due to water moving vertically or laterally out of the target aquifer before recovery, the significant losses of water through evaporation in surface-water storage facilities are avoided (Clyde and others, 1984).

Aquifer storage and recovery within the Delta aquifer, either via land-surface infiltration or injection wells, potentially offers a partial solution to the problems associated with the water-level decline in the Weber Delta subdistrict, if it can be practiced at a sufficiently large scale. Aquifer storage and recovery could also provide water planners and managers with increased flexibility in managing the water supply of the subdistrict and a source of supplemental supply. During the 1950s, the U.S. Bureau of Reclamation conducted a series of on-site aquifer recharge experiments in the Delta aquifer using gravel pits at the mouth of Weber Canyon (Clyde and others, 1984). The experiments were conducted adjacent to the mountain front, about 1 mile (1.6 km) east-southeast of the recharge site for this study (Feth and others, 1966). At the time of the U.S. Bureau of Reclamation experiments, the gravel pit had an area of 3.25 acres (1.32 hm^2). Infiltration proceeded continuously at 7 cubic feet per second per acre (0.5 $m^3/s/hm^2$), and produced a temporary water-level increase of 34 feet (10.4 m) in a nearby observation well (Clyde and others, 1984).

GEOLOGIC AND HYDROLOGIC SETTING

Geologic units exposed in the study area include a variety of Quaternary surficial deposits and the Precambrian Farmington Canyon Complex (figure 5; appendix B). Qua-

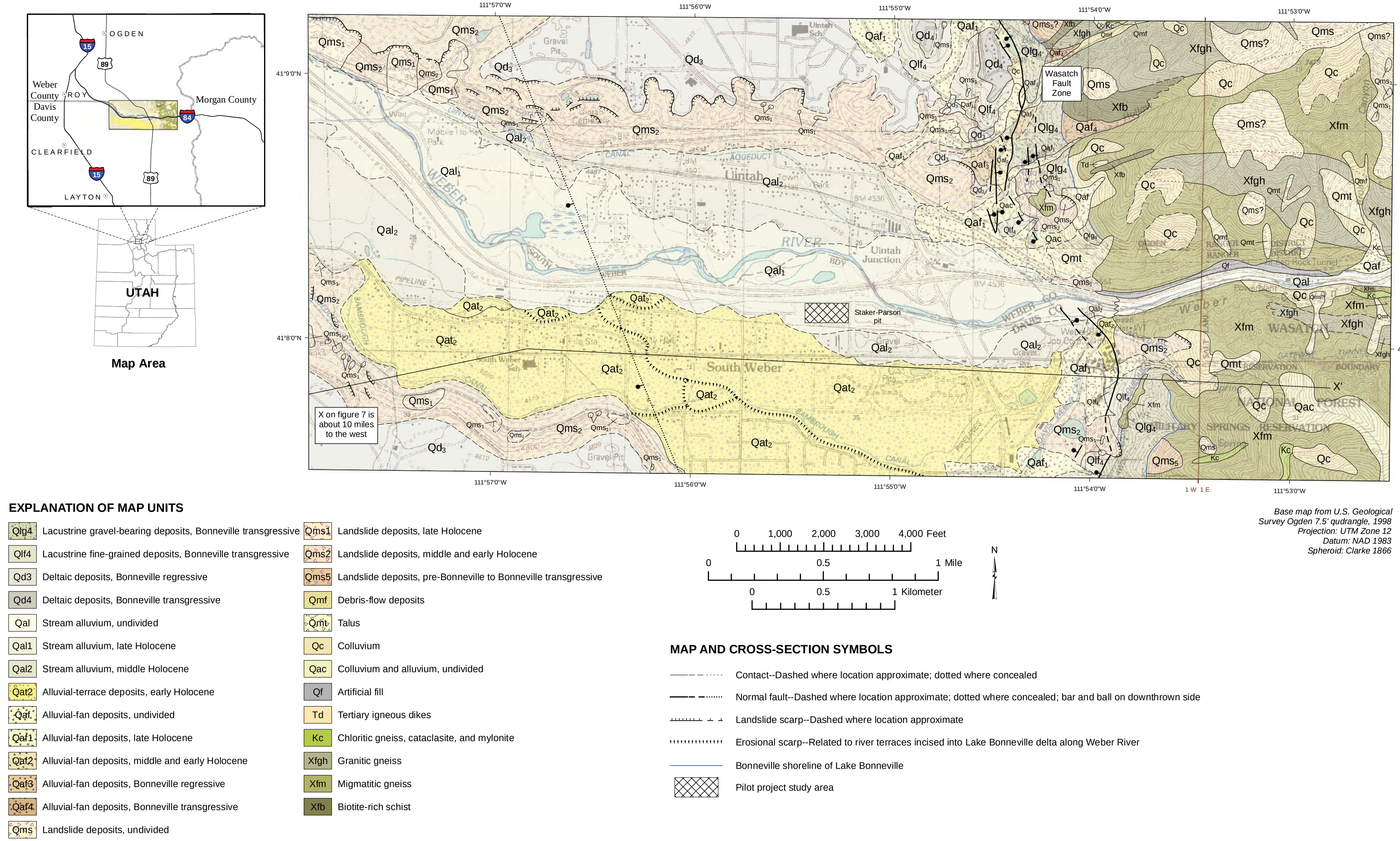


Figure 5. *Geology of the Weber River Aquifer Storage and Recovery Project area, Davis and Weber Counties, Utah (modified from Yonkee and Lowe, 2004).*

ternary deltaic, fluvial, alluvial-fan, and landslide deposits overlie a thick sequence of Quaternary-Tertiary basin-fill deposits in the western part of the study area. The Farmington Canyon Complex, which forms the Wasatch Range in the study area, consists of Neoproterozoic high-grade metamorphic and igneous rocks (Bryant, 1984). The principal structural feature in the study area is the Wasatch normal-fault zone, which formed during late Cenozoic extensional deformation (Hintze, 1988). Many of the fractures in bedrock of the Farmington Canyon Complex formed during Cretaceous deformation (Yonkee and Lowe, 2004).

Stratigraphy

Quaternary Surficial Deposits

Quaternary surficial deposits in the study area were formed by lacustrine, deltaic, alluvial, and mass-movement processes (figure 5; appendix B). These deposits generally form a thin veneer over Quaternary and Tertiary basin-fill deposits. Lacustrine deposits are mixed gravel and sand near the mountain front, and grade westward to sand, silt, and clay. Deltaic and alluvial deposits (figure 5) are predominantly sand and gravel. Mass-movement deposits contain chaotic mixtures of large bedrock blocks and detritus ranging from clay to boulder size.

Basin-Fill Deposits

Overview: The valleys along the Wasatch Front are linked, north-south-trending structural grabens that have been the site of accumulation of sediment since their inception in early Tertiary time (Eardly, 1955). The active Wasatch normal fault forms the eastern margin of these depositional basins. Gravity, seismic, and drill-hole data indicate that the sediments filling the grabens are locally up to 10,000 feet (3000 m) thick (Feth and others, 1966; Cook and others, 1967; Glenn and others, 1980; Zoback, 1983; McNeil and Smith, 1992). The basin fill likely includes an older sequence of Eocene to Oligocene strata consisting of a mixture of conglomerate, sandstone, reworked tuff, and minor lacustrine limestone similar to those preserved beneath parts of eastern Great Salt Lake (Constenius, 1996) and locally exposed on Antelope Island (Willis and Jensen, 2000). These older basin-fill deposits are overlain by Miocene to Pliocene rocks of the Salt Lake Formation that consist of heterogeneous mixtures of poorly consolidated sedimentary rocks and reworked tuff (Miller, 1991). The Miocene to Pliocene basin fill is, in turn, overlain by less-consolidated Quaternary basin-fill and surficial deposits, which are predominantly fluvial, lacustrine, and deltaic in origin (Feth and others, 1966). The Quaternary basin-fill sediments are the primary focus of this report because they comprise the principal ground-water aquifers.

The study area is within the hydrologically closed Lake Bonneville basin, and water flowing into this basin leaves by evapotranspiration. The Lake Bonneville basin has been an area of internal drainage for much of the past 15 million years, and lakes of various sizes have existed in the area during most of that time (Currey and others, 1984). Figure 6 shows the approximate time periods of, and the approximate elevations reached during, the past three lake cycles in the Lake Bonneville basin. Due to this history of deep-lake cycles interspersed with periods when lakes stood at low levels or were not present, the Quaternary basin-fill deposits in the study area consist of complexly interfingering, overall westward-fining bodies of gravel, sand, silt, and clay deposited in lacustrine and fluvial environments (Feth and others, 1966; Sprinkel, 1993).

Feth and others (1966) divided the Quaternary lacustrine and fluvial basin-fill deposits into, from bottom to top, (1) a lower interval, (2) the Delta aquifer, (3) a middle confining interval, (4) the Sunset aquifer, and (5) an upper confining interval (figure 7). The lower interval was partly deposited in a marginal lacustrine environment and consists mostly of thin-bedded silt and fine sand (Sprinkel, 1993). The Delta aquifer consists of interbedded cobble to pebble gravel and gravelly sand. The middle confining interval consists mostly of thin-bedded silt and fine sand and interbedded pebbly sand, deposited in marginal lacustrine and fluvial environments (Sprinkel, 1993). The Sunset aquifer consists of pebble gravel, pebbly sand, and well-sorted medium to coarse fluvial sand. The upper confining interval consists mostly of thin-bedded silt and sand likely deposited in a brackish lacustrine environment. The deposits forming the Sunset and Delta aquifers gradually thin and become increasingly finer grained away from the canyon mouths (figure 7; plate 2). Within about 1 mile (1.6 km) of the Wasatch Range front, the Sunset and Delta aquifers cannot be distinguished because the fine-grained layer that separates them becomes thin to locally absent, and the east shore aquifer system consists of thick-bedded sand and gravel that contain thin, discontinuous beds of silt and/or clay.

Basin-fill deposits in the vicinity of the WRBASR project site: We investigated the geology of basin-fill deposits near the project site to assist in analyzing the results of the recharge experiments and to delineate the geometry of model layers for the ground-water flow model. Previous investigations in the east shore area (Feth and others, 1966; Clyde and others, 1984; Clark and others, 1990) were broader in scope than this study and several water wells, including the observation well for this project, have been drilled since the time of those reports, justifying our additional work. We obtained drillers' logs for water wells within an approximately 10-mile (16 km) radius of the recharge site (plate 1; appendix A) and a detailed log of the observation well constructed for this project (appendix C), and used them to construct 13 new

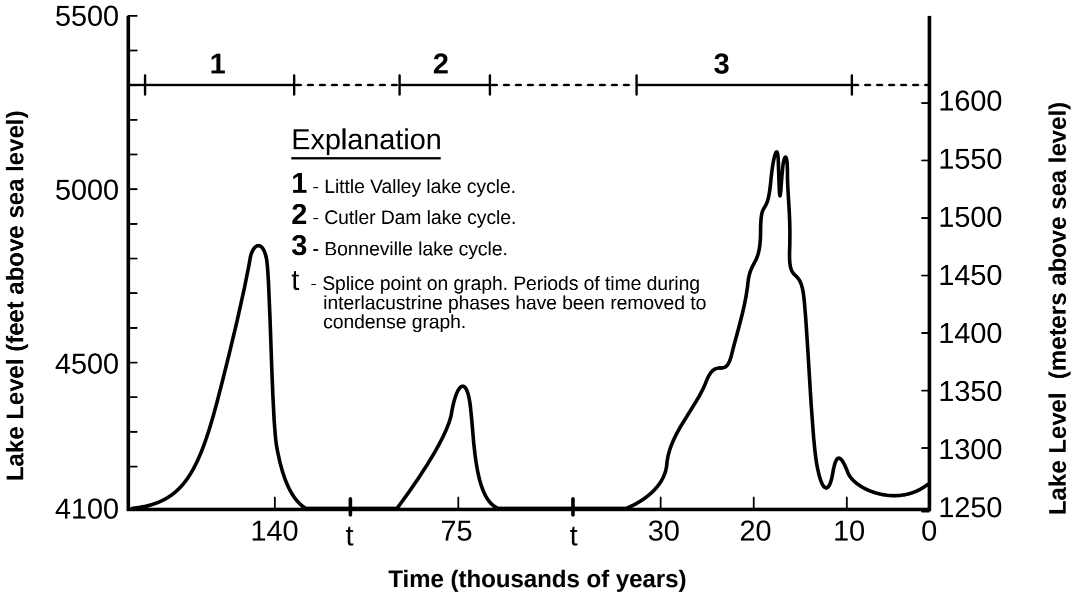


Figure 6. *Schematic hydrograph of probable lake levels in the Lake Bonneville basin for the past 150,000 years. Numbered solid lines above lake level curves represent time periods of lake cycles. Dashed lines at top of plot represent interlacustrine periods when lakes in the Lake Bonneville basin stood at relatively low levels or were nonexistent. After Machette and others (1992).*

geologic cross sections through the basin fill (plates 1 and 2; plate 2 shows six representative sections).

The cross sections (plate 2) show the approximate distribution of grain size with depth in the study area. The sections are based on drillers' logs of water wells (Utah Division of Water Rights, 2004), which vary in detail and quality. Lateral correlations between wells and assignment of aquifers are subjective and are based in part on previous work (Feth and others, 1966; Clyde and others, 1984), although our placement of contacts differs from theirs for some wells, as shown on the sections. Despite these minor differences, our interpretation of the subsurface geometry of the Sunset and Delta aquifers in the study area is generally consistent with that of Feth and others (1966). In addition, we delineated a fine-grained layer approximately in the middle of the Delta aquifer that is persistent over the study area, as noted by Clyde and others (1984). The hydrologic significance of this fine-grained layer is not known.

Figures 8 to 13 show structure-contour and isopach maps of the Sunset and Delta aquifers, the confining layer separating them, and the fine-grained layer within the Delta aquifer, derived from the cross sections constructed for this study. The cross sections form an irregular grid across the study area, and were cross-correlated at tie points, so they form an internally consistent data set. The tops of the aquifers are near or at the land surface in the eastern part of the study area, and slope gently westward so that they are progressively deeper below the land surface to the west. As noted by other workers, the average grain size decreases westward in both aquifers and they are more difficult to differentiate. Aquifer thickness generally varies gradually, although both have local areas of prominent thickening. Anomalously thick or thin parts of the aquifers based on a single well should be regarded with caution, as they may be based on an inaccurate or generalized well log.

We examined sediments exposed in the northern pit of the Staker-Parson South Weber pit, just east of the pilot project recharge site (figure 5), and performed grain-size analyses on several samples. Most of the exposed material is fine- to medium-grained, well-sorted, cross-bedded sand to pebbly sand. Lenticular, fine-grained layers less than 1 foot (0.3 m) thick and composed principally of silt are interbedded in the sand. The thickest fine-grained layer, about 130 feet (40 m) below the top of the pit, is about 1 foot (0.3 m) thick and is composed chiefly of silt and about 20% or less clay. The pit foreman used an excavator to dig a 5-foot-wide (1.5 m), 10-foot-deep (3 m) trench in the base of the pit. The trench walls exposed about 6 feet (2 m) of medium-grained, well-sorted, cross-bedded sand, above well-sorted cobble gravel.

The WRWCD employed the U.S. Bureau of Reclamation to install an observation well at the west end of the pilot project site, to a depth of 301 feet (92 m) (appendix C; well 118, table A1 and plate 1). The purpose of the well is to measure variations in water levels and water chemistry before, during, and after infiltration episodes. The driller collected and analyzed cuttings every 5 feet (1.5 m), resulting in a detailed log of the basin-fill sediments adja-

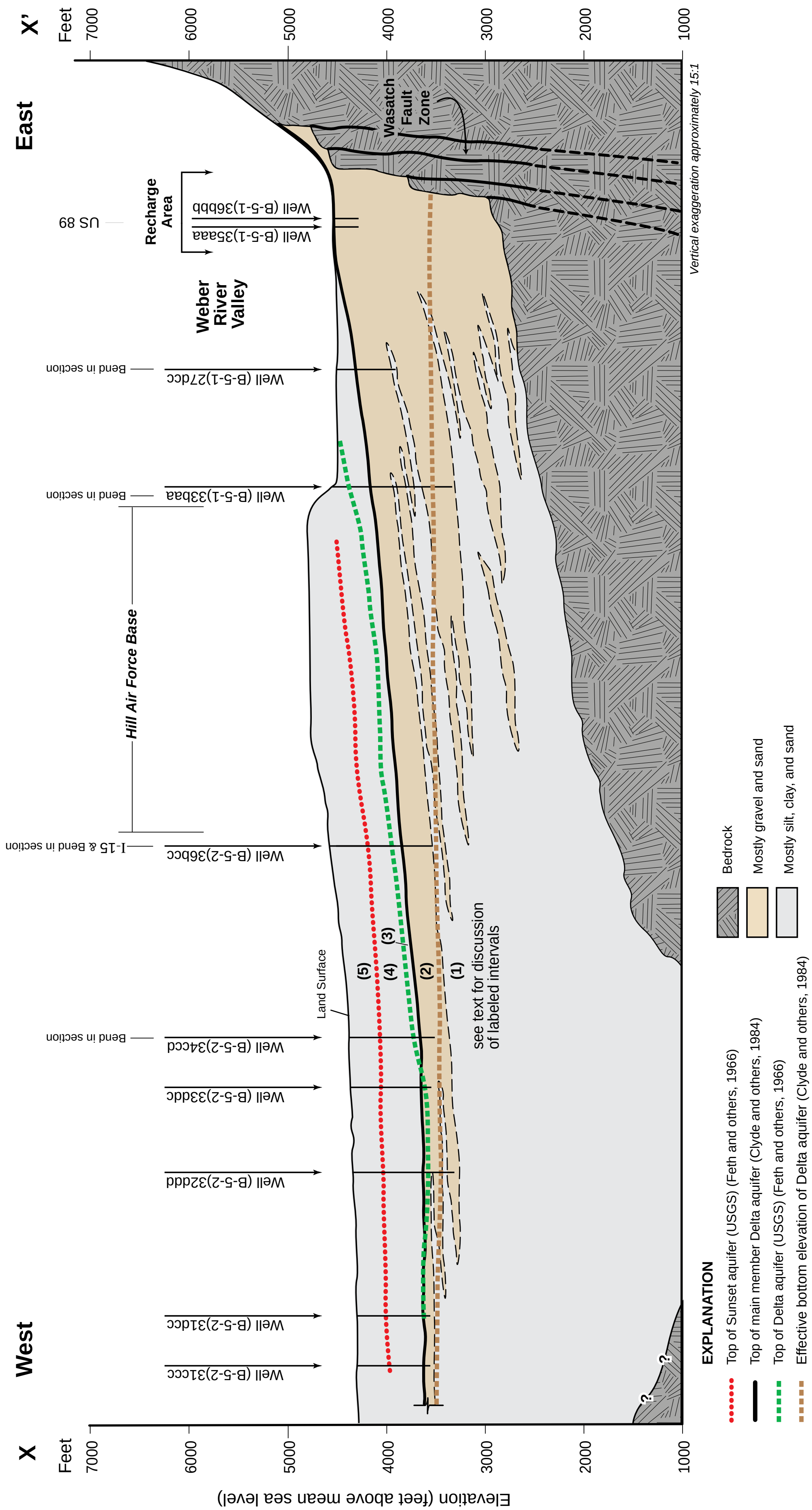


Figure 7. *Geologic profile through the central Weber Delta subdistrict, east shore area of Great Salt Lake, Utah, modified from Clyde and others (1984). See figure 1 for location and appendix A for explanation of well-numbering system. Numbers in parentheses are keyed to discussion in text.*

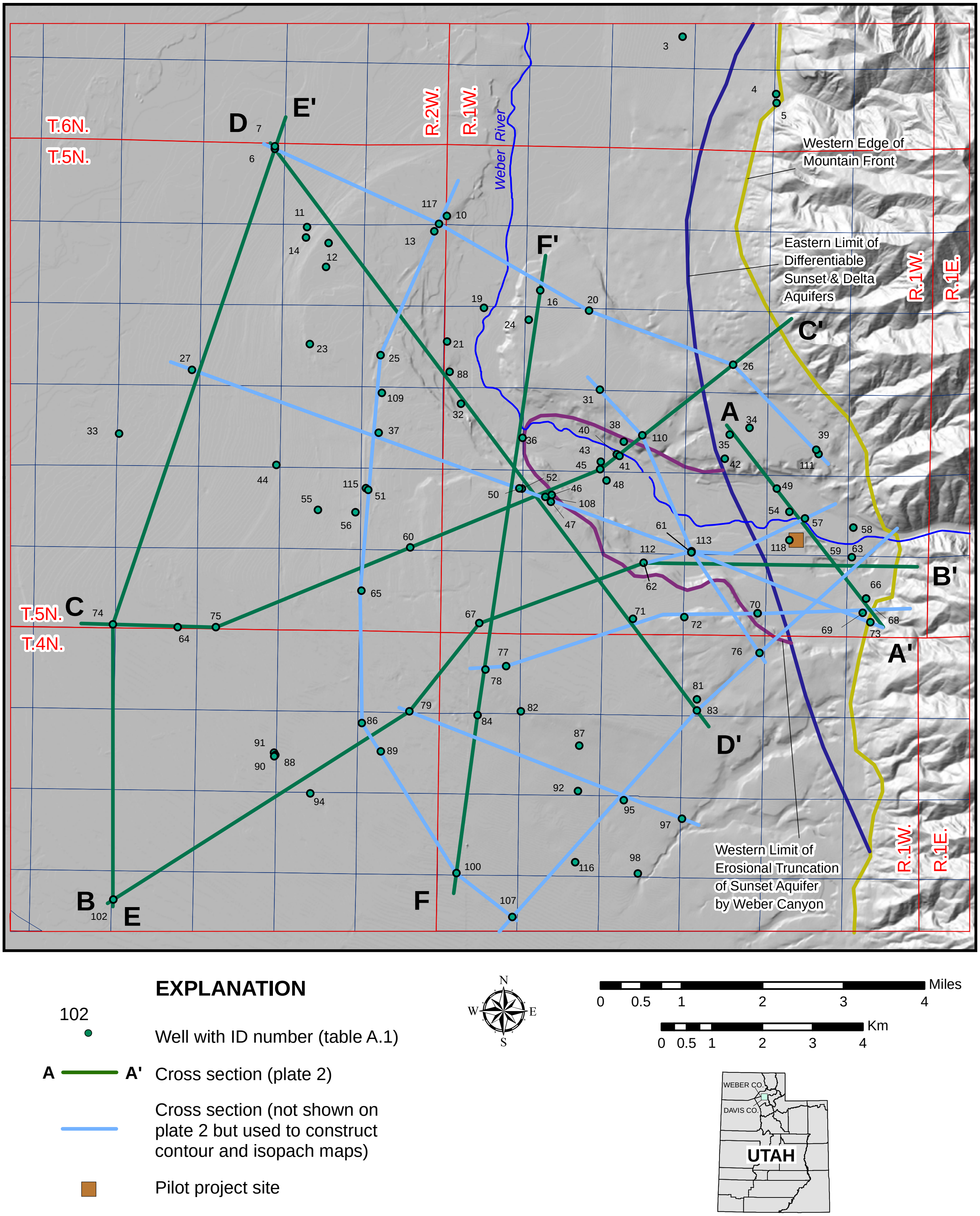


Figure 8. Location of contour and isopach maps of aquifers in study area.

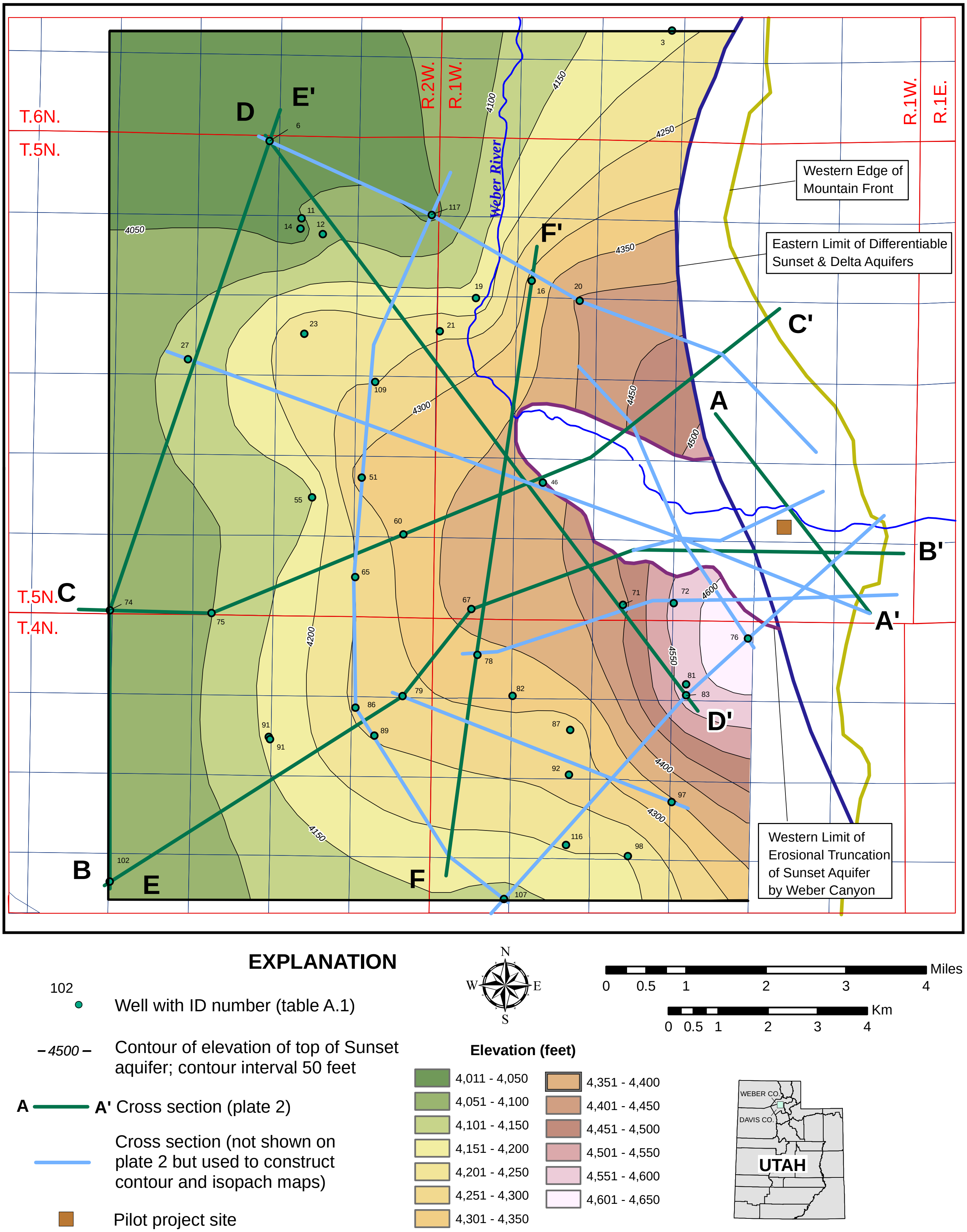


Figure 9. *Contour map of top of Sunset aquifer.*

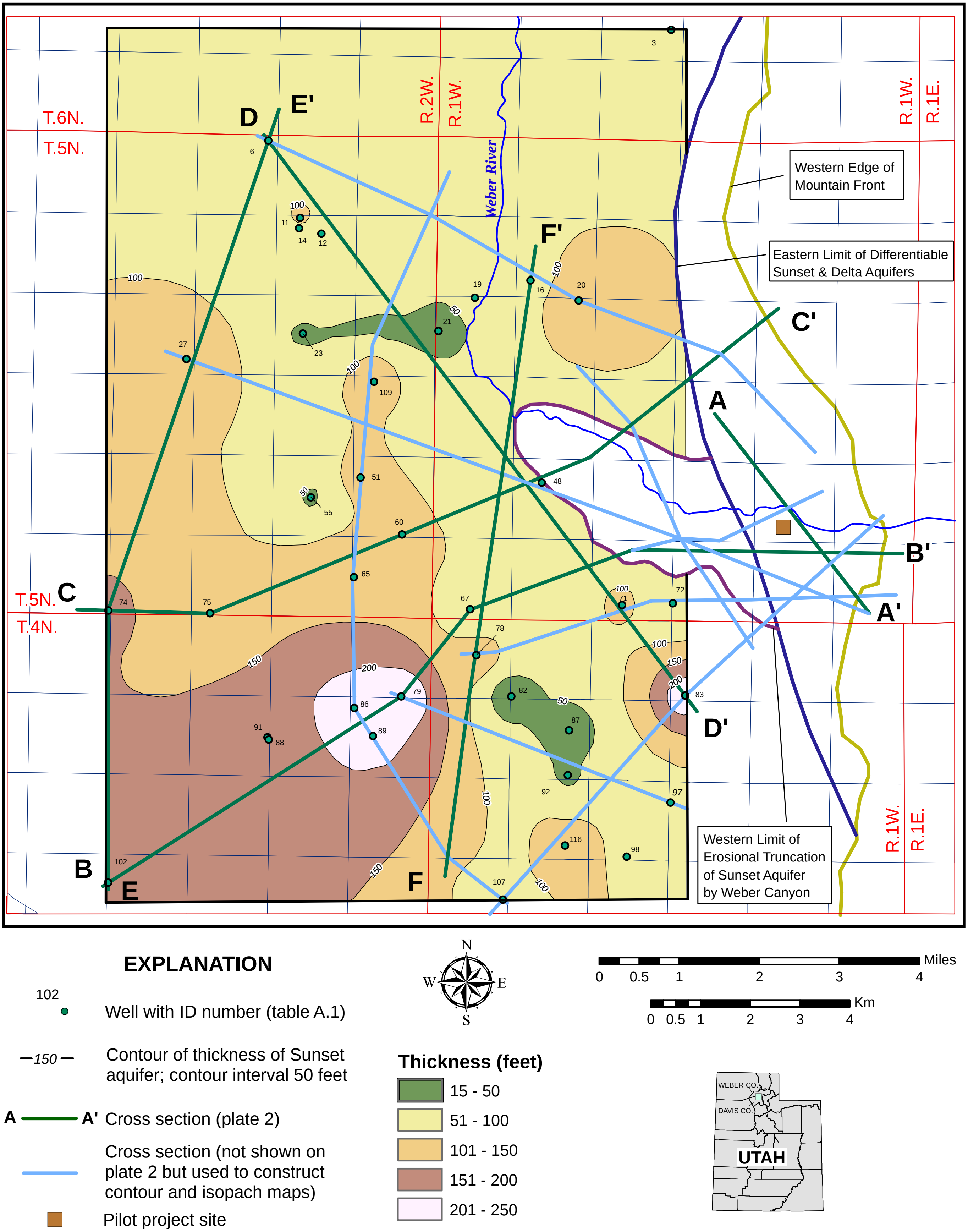


Figure 10. *Isopach map of Sunset aquifer.*

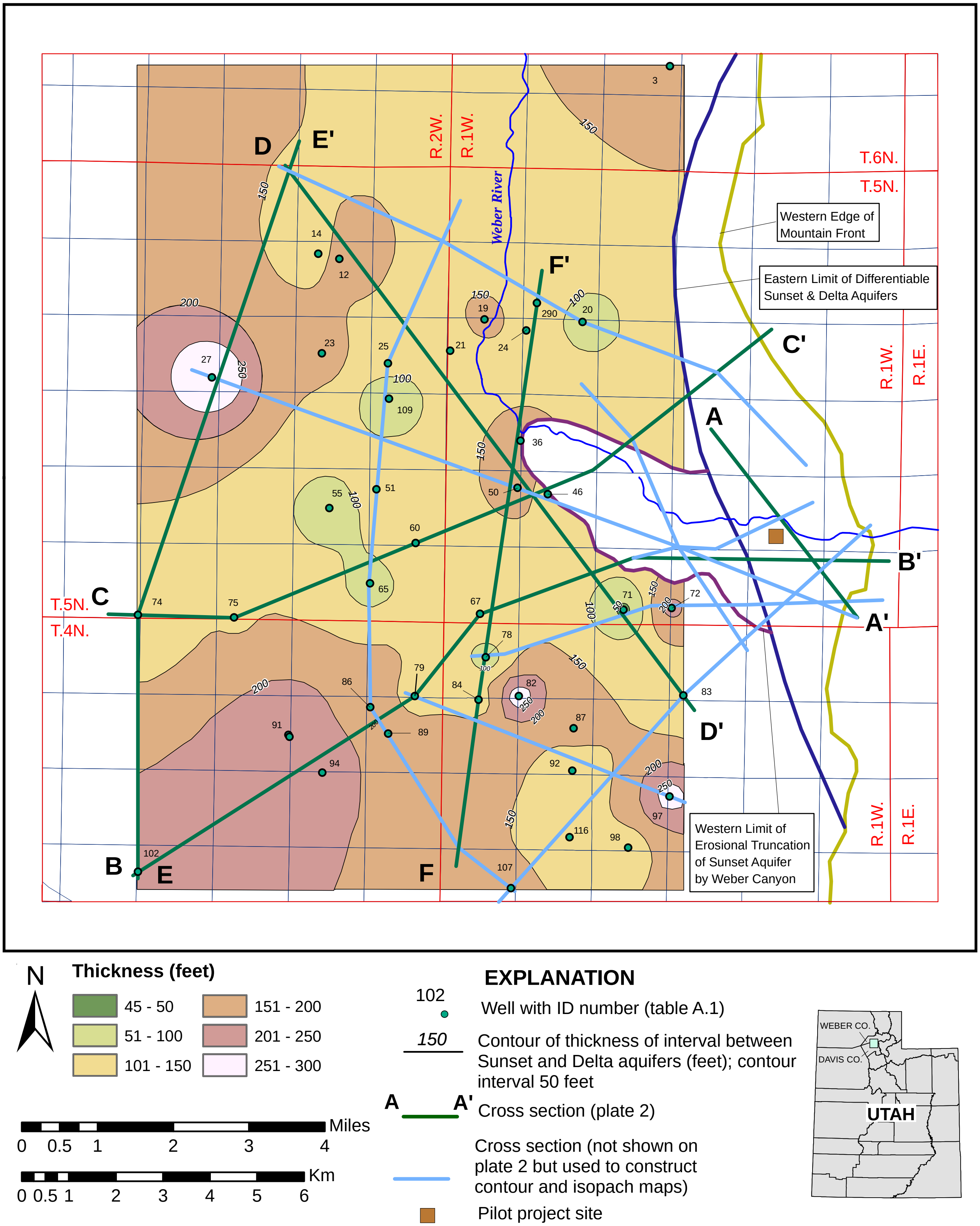


Figure 11. *Isopach map of fine-grained layer between Sunset and Delta aquifers.*

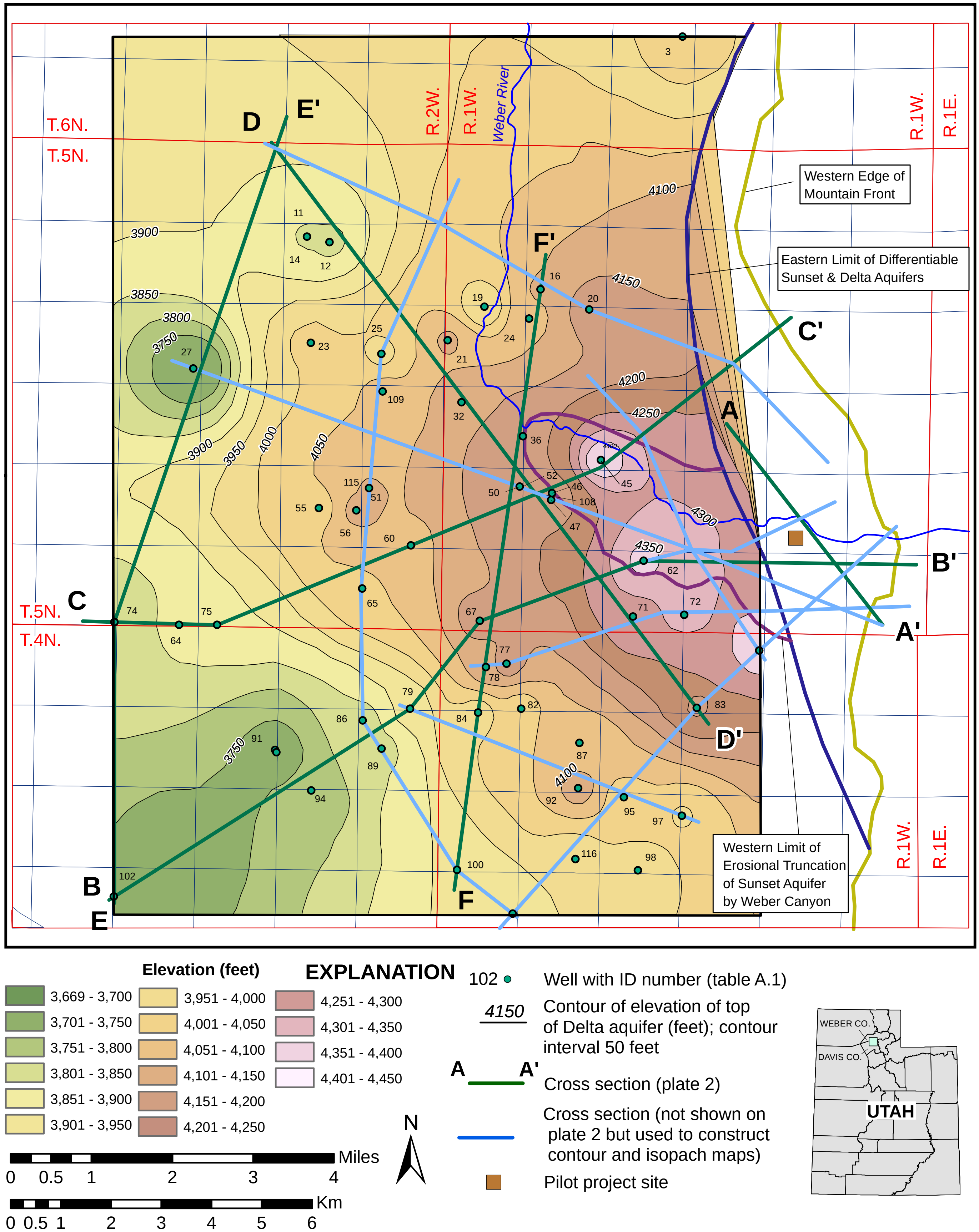


Figure 12. *Contour map of elevation of top of Delta aquifer.*

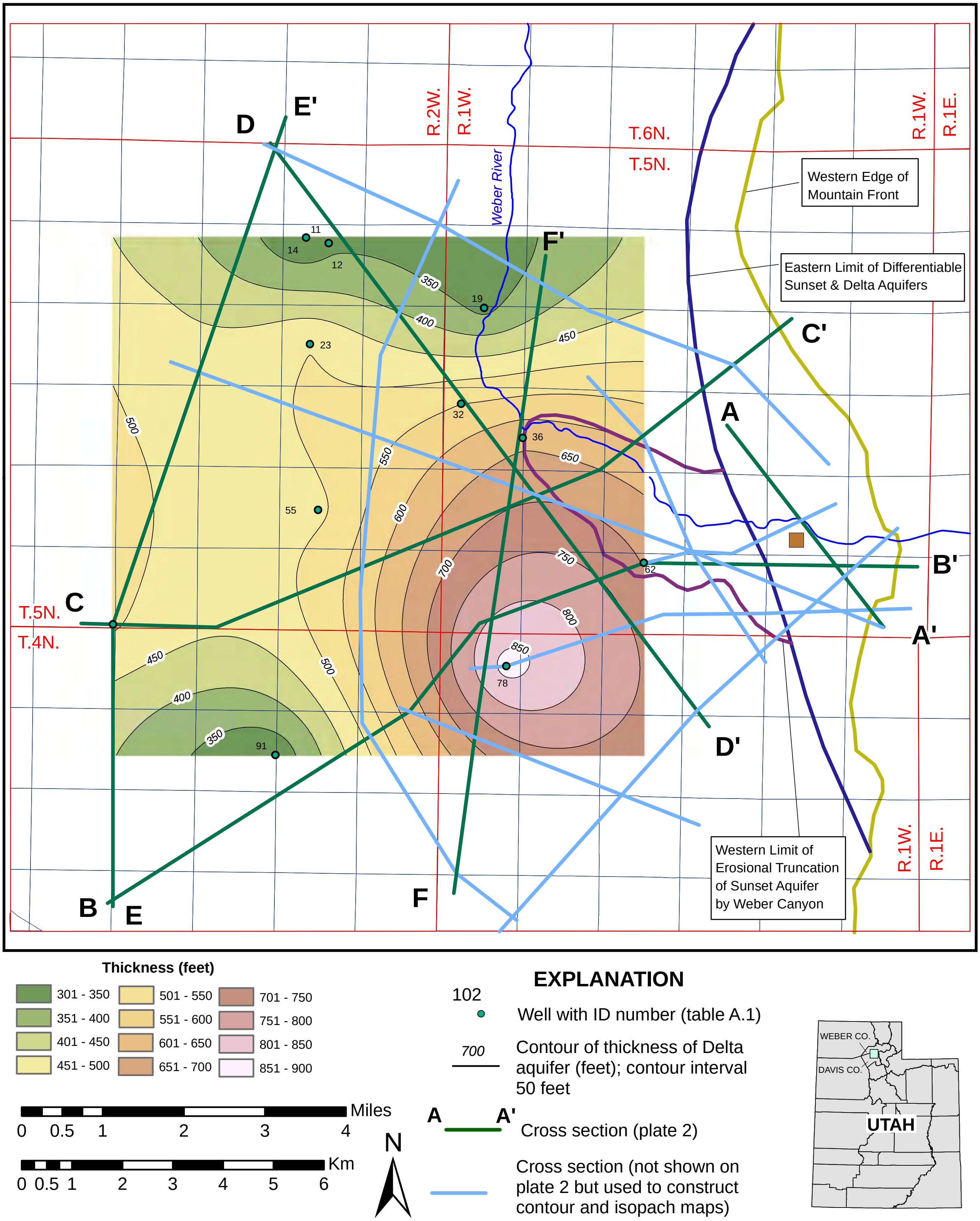


Figure 13. *Isopach map of Delta aquifer.*

cent to the infiltration basins. Most of the sediment varies from sand to gravel or coarser size (appendix C). The well encountered deposits composed of about 60% fines—mostly silt but also minor amounts of clay—and 40% fine sand, from 116 to 130 feet (35–39 m) depth (appendix C). The top 1 to 2 feet (0.3–0.6 m) of this layer is especially clay-rich (verbal communication from well driller). We believe that this is the same fine-grained layer exposed in the gravel pit east of the recharge area, described in the preceding paragraph. Sediment below the fine-grained layer is composed of 20 to 95% sand, 0 to 75% gravel, and 0 to 5% fines (appendix C). The well was screened below 270 feet (82 m), and the static water level after completion was about 231 feet (70 m).

Neoproterozoic Farmington Canyon Complex

The Farmington Canyon Complex comprises a complex mixture of high-grade metamorphic and igneous rocks, exposed in the Wasatch Range in the eastern part of the study area (figure 5) (Eardley, 1944, 1955; Bryant, 1984; Yonkee and Lowe, 2004). The Farmington Canyon Complex includes meta-ultramafic and mafic rocks, quartz-rich gneiss, biotite-rich schist, migmatitic gneiss, and granitic gneiss (appendix B; Yonkee and Lowe, 2004). Multiple joint sets are common in these rocks. The joints likely accommodate infiltration of snowmelt and rainfall. Some of this water migrates to the west and enters the basin-fill aquifers (Feth and others, 1966).

Surface Water

The Weber River contributes the vast majority of surface water flowing into and through the study area. The ultimate source of water in the Weber River is precipitation that falls on the slopes of the Wasatch Range and western Uinta Mountains. Runoff in the mountains forms tributary streams that flow into the Weber River. Annual flow in the Weber River at a gauging station near Ogden averaged 260,000 acre-feet per year (320 hm^3/yr) from 1890 to 1993 (Utah Division of Water Resources, 1997, table 5–1). Flow in the Weber River increases in Weber Canyon due to inflow from bedrock, and decreases west of the canyon mouth where the river loses water into basin fill (Feth and others, 1966). The Weber River enters the east shore area of Great Salt Lake through Weber Canyon 1 mile (1.6 km) east of the pilot project site, and flows within 1000 feet (305 m) of the site. The Ground-Water Flow Model section of this report presents more details about surface-water flow in the Weber Delta district.

The chemical quality of water in the Weber River is acceptable for most uses. Chemical analyses of Weber River water from a site about 4 miles (6 km) east of the mouth of Weber Canyon (table 1) indicate the water did not exceed U.S. EPA ground-water quality standards for any of the analyzed constituents for the 2000 to 2002 sampling period. The water is a calcium-sodium-magnesium-bicarbonate type and contains less than 400 mg/L dissolved solids. Spring Creek Canyon to the north of the Weber River has intermittent stretches and permanently flowing stretches. Ephemeral streams, which are completely dry during much of the year, drain the smaller canyons along the mountain front and the sides of Weber Canyon. Other streams in the area are typical of arid and semiarid areas, where channels are dry most of the time. The flow in these streams is the direct result of runoff from precipitation and is generally confined to the channels.

Ground Water

Introduction

Ground water in the study area occurs in two types of aquifers: fractured bedrock and unconsolidated basin-fill deposits. Ground water in the east shore area of Great Salt Lake is obtained principally from the basin-fill deposits, but the bedrock aquifers are an important source of recharge to the basin-fill aquifers. Basin-margin faults likely influence flow from the bedrock aquifers to the basin-fill aquifers in a spatially heterogeneous manner, by forming barriers and highly permeable pathways, depending on the details of fault-zone fabrics and stratigraphic juxtaposition along and across the fault.

Bedrock Aquifers

Fractured parts of the Farmington Canyon Complex likely have highly variable permeability and low storage, based on comparison to the Park City, Utah, area (Ashland and others, 2001; Yonkee and Lowe, 2004). The Gateway tunnel, which penetrates the Farmington Canyon Complex in the Wasatch Range just south of Weber Canyon, encountered considerable ground-water flow at various fractured intervals, with total discharge ranging from 180 to 450 gallons per minute (12–30 L/s) during completion of the tunnel in 1955 (Feth and others, 1966). Discharge increased markedly during April and May, reached a peak in June, and then decreased during late summer to fall, consistent with recharge during snowmelt and limited storage (Yonkee and Lowe, 2004). Flow in the Weber River increases by about 2000 gallons per minute (130 L/s) over a stretch of about 0.5 mile (0.8 km) along lower Weber Canyon, probably related to inflow from the Farmington Canyon Complex (Feth and others, 1966). The overall direction of ground-water flow in the Farmington Canyon Complex is likely westward, from higher elevations near the mountain crest toward lower elevations along the mountain front on the west side of the Wasatch Range, with local flow toward canyon bottoms, especially along Weber Canyon. Some discharge from the Farmington Canyon Complex is to springs and gaining parts of streams along the mountain front, and additional discharge to basin-fill aquifers may cross the Wasatch fault zone at depth (Yonkee and Lowe, 2004).

Table 1. *Water-quality data, Weber River - Gateway to Powerhouse (from U.S. EPA STORET database, accessed 2004).*

Date Sampled	Time Sampled	Alkalinity, Carbonate as $CaCO_3$ mg/L	Aluminum µg/L	Arsenic µg/L	Barium µg/L	Bicarbonate mg/L	BOD, Biochemical oxygen demand	Cadmium µg/L	Calcium mg/L	Carbon dioxide mg/L	Carbonate ion (CO_3^{2-}) mg/L	Chloride mg/L
1/5/00	15:32:00	210	*ND	*ND	120	256	-	*ND	75.9	3	0	39.5
6/13/00	13:35:00	184	-	-	-	224	-	-	61.5	1	0	32
1/31/01	13:10:00	244	*ND	*ND	144	298	*ND	*ND	79.2	4	0	42
5/3/01	14:55:00	81	181	*ND	55.3	99	*ND	*ND	26.7	2	0	*ND
1/22/02	17:00:00	238	-	-	-	290	*ND	-	75	3	0	48.2
6/26/02	10:15:00	202	-	-	-	246	-	-	71.1	2	0	31.5

Date Sampled	Chromium µg/L	Copper µg/L	Dissolved Solids mg/L	Hardness Ca + Mg mg/L	Hydroxide mg/L	Iron µg/L	Lead µg/L	Magnesium mg/L	Manganese µg/L	Mercury µg/L	Nitrogen, Nitrite (NO_2) + Nitrate (NO_3) as N mg/L	pH
1/5/00	5	*ND	326	272.1	0	*ND	*ND	20.1	12	*ND	0.7	8.21
6/13/00	-	-	266	219.7	0	-	-	16.1	-	-	0.3	8.47
1/31/01	*ND	*ND	372	280.7	0	*ND	*ND	20.2	45.9	*ND	1.04	8.1
5/3/01	*ND	*ND	134	92.7	0	78.1	*ND	6.33	17.9	*ND	0.32	7.93
1/22/02	-	-	-	274.4	0	-	-	21.2	-	-	*ND	8.23
6/26/02	-	-	314	251.5	0	-	-	18	-	-	0.3	8.4

Date Sampled	Phosphorus as P mg/L	Potassium mg/L	Selenium µg/L	Silver µg/L	Sodium mg/L	Specific conductivity µmho/cm	Sulfate as SO_4 mg/L	Total Suspended Solids (TSS) mg/L	Turbidity NTU	Zinc µg/L
1/5/00	*ND	2.66	*ND	*ND	24.9	580	28.3	0	2.29	*ND
6/13/00	0.035	2.42	-	-	19.4	456	24.9	4	1.73	-
1/31/01	0.024	2.74	*ND	*ND	24.6	646	36.9	0	1.45	*ND
5/3/01	0.041	1.02	*ND	*ND	8.08	195	*ND	*ND	7.56	*ND
1/22/02	0.042	3.1	-	-	29.3	636	34	*ND	1.53	-
6/26/02	0.022	2.54	-	-	22.6	535	23.1	*ND	1.95	-

*ND = Non-detect (below detection limit)
- = No data

Faults

Major faults, such as the Wasatch fault zone, likely influence ground-water flow in both bedrock and basin fill. Fractured zones preferentially transmit water parallel to the fault, and fine-grained gouge zones inhibit flow across the fault (Caine and others, 1996). Several warm springs north of the study area near the mouth of Ogden Canyon are located near the Wasatch fault zone in fractured footwall rocks of the Farmington Canyon Complex, including Ogden Hot Spring. These springs may reflect relatively rapid upward ground-water flow parallel to the Wasatch fault zone in the fractured footwall, with impermeable gouge zones at depth limiting fluid flow across the fault zone (Yonkee and Lowe, 2004).

Basin-fill Aquifers

Occurrence: The most important ground-water resources of the east shore area occur in unconsolidated to semiconsolidated Quaternary basin-fill deposits (Feth and others, 1966; Clark and others, 1990). These deposits consist of overall coarser grained alluvial and lacustrine sediments near the mountain front, and overall finer grained lacustrine and fluvial sediments westward away from the mountains (Feth and others, 1966; Bolke and Waddell, 1972; Clark and others, 1990). Deeper ground water in the aquifer system is predominantly confined, but unconfined conditions exist locally in primary recharge areas, which form a narrow band along the Wasatch Range front (figure 14) (Anderson and others, 1994); this area of unconfined conditions is widest at the mouth of Weber Canyon. Two principal aquifers, the Sunset and Delta, have been delineated in the central part of the Weber Delta district (figures 7 through 13; plate 2) (Feth and others, 1966). The Delta aquifer is the primary source of ground water in the Weber Delta district, and is composed mostly of coarse-grained, pre-Lake Bonneville fluvial and deltaic sediments (Clark and others, 1990). The top of the Delta aquifer is 500 to 700 feet (150–200 m) below the land surface in the eastern part of the Weber Delta subdistrict, and the aquifer is about 50 to 800 feet (15–240 m) thick (figures 7 through 13; plate 2) (Feth and others, 1966). The shallower Sunset aquifer has a lower permeability and is used to a lesser extent as a source of ground water. The top of this aquifer is 200 to 400 feet (60–120 m) below the land surface in the Weber Delta subdistrict, and it is about 50 to 200 feet (15–60 m) thick (figures 7 through 13; plate 2) (Feth and others, 1966). Fine-grained confining intervals overlie both aquifers west of the mountain front. A shallow unconfined aquifer is commonly within Quaternary surficial deposits above the upper confining beds (Clark and others, 1990). Tertiary basin-fill deposits deeper than about 1500 feet (450 m) are typically more lithified, less permeable, and contain poorer quality water, and thus are not considered an important ground-water source (Clark and others, 1990).

The observation well and infiltration ponds for this study are in the easternmost, unconfined part of the east shore aquifer system, where the Sunset and Delta aquifers cannot be distinguished, and are in the erosional canyon formed by the Weber River (figure 8; plate 1). The canyon bottom is below the base of the eastward projection of the Sunset aquifer (cross sections A and B, plate 2). Water from the infiltration basins percolates downward into the undifferentiated east shore aquifer system and, over time, will likely migrate westward into the confined part of the Delta aquifer.

Shallow aquifers provide water to wells 50 to 150 feet (15–46 m) deep in the Roy area. Hydraulic head is higher in this local aquifer than it is in the Delta aquifer (Feth and others, 1966). Typically, deeper confined aquifers in the study area have higher hydraulic head than shallow unconfined aquifers. In the Syracuse area, the shallow aquifer has hydraulic connection with deeper aquifers, which results in similar hydraulic head in both.

Recharge and discharge: Recharge to the Weber Delta subdistrict aquifer system includes channel seepage from losing stretches of streams; seepage from irrigation ditches, irrigated fields, lawns, and gardens; direct infiltration of precipitation; and subsurface inflow from bedrock of the Wasatch Range (table 2). Seepage from the Weber River and subsurface inflow from bedrock along the mountain front are probably the dominant recharge sources.

Most recharge takes place in the primary recharge area along the mountain front (figure 14), especially near the mouth of Weber Canyon (Anderson and others, 1994). A large flood in 1952 may have significantly raised ground-water levels in the Weber Delta subdistrict aquifer system (Lowe and others, 2004).

Discharge from the Weber Delta subdistrict aquifer system includes flow to gaining stretches of streams and to small springs, water-well withdrawal, evapotranspiration from shallow ground water, and ground-water flow to Great Salt Lake (table 2). Water-well withdrawal and flow to gaining streams and springs are the main discharge components (Clark and others, 1990).

Ground-water flow: Ground-water flow in the Weber Delta subdistrict aquifer system is generally westward from recharge areas near the Wasatch Range toward Great Salt Lake (Feth and others, 1966). Feth and others (1966) estimated the horizontal hydraulic gradient in the Delta aquifer to be about 5 feet per mile (1 m/km) in most areas, and the horizontal hydraulic gradient in the Sunset aquifer to be about 10 feet per mile (2 m/km) in most areas. These values are likely lower and more spatially variable now due to continued local lowering of ground-water levels since the time of their report (figure 2b). The vertical hydraulic gradient in the system is generally downward

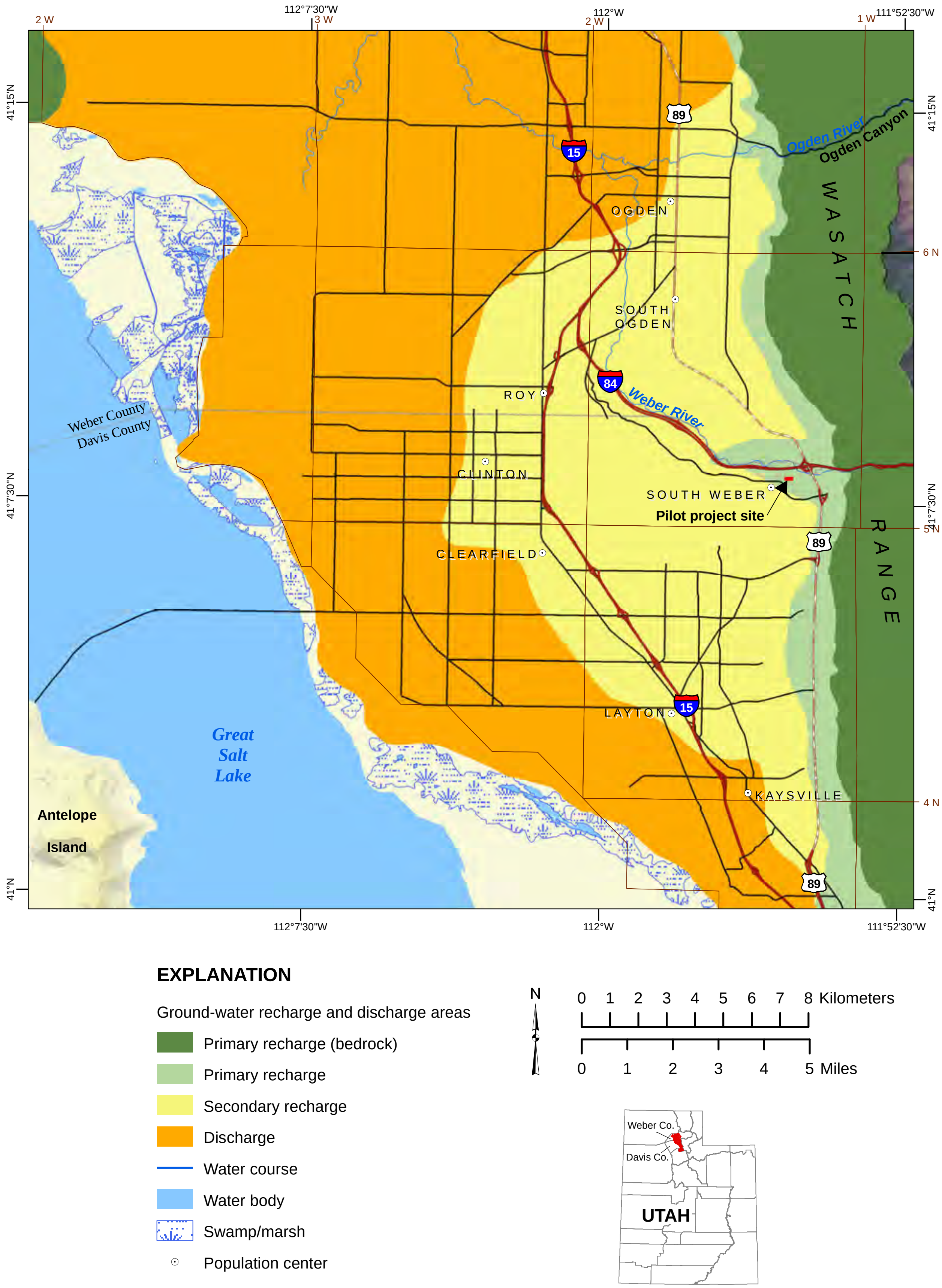


Figure 14. *Recharge and discharge areas in the east shore area of Great Salt Lake, Davis and Weber Counties, Utah (from Anderson and others, 1994).*

***Table 2.** Hydrologic budgets for the Weber Delta District.*

Recharge type	Feth and others (1966)[a] (km^3/yr)	Feth and others (1966)[a] (acre-feet/yr)	Gates (1995)[b] (km^3/yr)	Gates (1995)[b] (acre-feet/yr)	Clark and others (1990)[c] (km^3/yr)	Clark and others (1990)[c] (acre-feet/yr)
Channel seepage [d]	~ 0.025 [f]	~21,000 [f]	0.052	43,000	No separate estimate	
Other seepage [e]	0.007	6,000	0.007	6,000	No separate estimate	
Direct infiltration	0.012	10,000	0.008	7,000	No separate estimate	
Subsurface inflow	0.036	30,000	0.064	53,000	No separate estimate	
TOTAL	~ 0.084	~70,000	0.131	109,000	0.130	107,000
Discharge type						
Flow to streams, springs	~ 0.023[g]	~19,000[g]	0.070	58,000	0.045	38,000
Water-well withdrawal	0.030	25,000	0.030	25,000	0.060	50,000
Evapotranspiration	0.007	6,000	0.008	7,000	0.007	6,000
Flow to Great Salt Lake	0.025	20,000	0.023	19,000	0.018	15,000
TOTAL	~0.084	~70,000	0.131	109,000	0.131	109,000

[a] representative of time period 1953–1956 with well withdrawal for 1954; probably represents non-steady state conditions
[b] representative of time period 1953–1956, with values adjusted to approximate steady state conditions based on estimates of overall hydrologic budget for time period 1969-1984
[c] representative of time period 1969–1984, based on modeling study with values adjusted for water removal from storage
[d] includes losing stretches of stream channels and seepage from canals
[e] includes irrigated fields, lawns, and gardens
[f] approximate value, varies substantially between years
[g] adjusted to maintain water balance with total discharge = total recharge

in recharge areas near the mountain front, and generally upward where confined conditions are prevalent west of the mountain front, but vertical flow is probably relatively slow through low-permeability confining beds west of the mountain front (Clark and others, 1990).

Aquifer characteristics: Transmissivity values for confined parts of the east shore aquifer system in the Weber Delta subdistrict range from about 11,000 to 60,000 feet squared per day (1400–3700 m^2/d), based on four aquifer tests conducted between 1944 and 1956 (table A1; Feth and others, 1966, table 8). Transmissivity values for unconfined parts of the aquifer system near the mountain front range from 4000 to 5300 feet squared per day (370-500 m^2/d), based on two aquifer tests conducted between 1944 and 1956 (table A1; Feth and others, 1966, table 8). Elastic storage coefficients for the confined part of the east shore aquifer system range from about 2 x 10^{-3} to 7 x 10^{-5}, based on tests conducted between 1944 and 1956 (Feth and others, 1966, table 8). Specific yields, related to dewatering of pore space, are likely in the range of 0.25 to 0.07, based on observed porosities and limited recharge tests (Feth and others, 1966).

Storage: The amount of potentially available ground water in the entire Weber Delta district was estimated by Clark and others (1990) to be about 37 million acre-feet (45 km^3), based on an average specific yield of 0.11 for an aquifer thickness of 1500 feet (450 m), which includes the entire thickness of Quaternary basin fill. Feth and others (1966) estimated the total amount of potentially available water from the Sunset and Delta aquifers in the central part of the district to be about 3 million acre-feet (4 km^3), based on a specific yield of 0.07 and a combined thickness of 400 feet (120 m) for coarse-grained intervals observed in wells; about 100,000 acre-feet (0.1 km^3) of this total was estimated to be available before dewatering of these principal aquifers would begin. These estimates are clearly too high for the present-day situation, due to continual lowering of water levels in both aquifers.

Water-level changes: Ground-water levels in the Weber

Delta district generally rise in the spring during net recharge and decline in the summer; seasonal water-level declines are greatest near the mountain front and in areas of greatest water-well density (Clark and others, 1990). Long-term water levels in the east shore aquifer system have declined overall, probably related to increased withdrawals from wells for municipal and industrial use (figures 2a, 2b, and 3) (Clark and others, 1990). From 1953 to 1985, water levels declined an average of 27 feet (8 m) for wells located in the confined part of the aquifer system, with a maximum drop of 50 feet (15 m) near the principal pumping center for the aquifer system (figure 2a) (Clark and others, 1990). During the same time period, water levels in the unconfined part of the aquifer system declined as much as 40 feet (12 m) in wells at the mouth of Weber Canyon (figure 2a) (Clark and others, 1990). From 1985 to the present, water levels in most of the confined part of the east shore aquifer system declined 10 to 20 feet (3–6 m) and water levels in the unconfined part declined as much as 46 feet (14 m) (figure 2b).

Water quality: Ground-water quality in the Weber Delta subdistrict is generally high, and includes calcium-magnesium-bicarbonate, sodium-chloride, and mixed types (Smith and Gates, 1963; Feth and others, 1966; Bolke and Waddell, 1972; Clark and others, 1990). The calcium-magnesium-bicarbonate type occurs south of central Ogden City and includes the WRBASR pilot project study area, and generally contains less than 300 mg/L total TDS (Feth and others, 1966, figure 14). Mixed-type waters exist between the Ogden River and central Ogden City, and contain from 500 to 1000 mg/L TDS (Smith and Gates, 1963, figure 8; Feth and others, 1966, figure 14). The sodium-chloride type exists north of the Ogden River, and contains from 500 mg/L TDS at the mouth of Ogden Canyon to more than 2000 mg/L TDS (Smith and Gates, 1963, figure 8; Feth and others, 1966, figure 14).

Concentrations of organic solvents, such as toluene and trichloroethane, that exceed ground-water quality standards (U.S. EPA, 2002) have been identified on and near Hill Air Force Base, southwest of the WRBASR project study area, and are currently being remediated (Dalpias and others, 1989). The contamination is only in the upper aquifer system. Ground water from the Delta aquifer currently meets all U.S. EPA ground-water quality standards.

Ground-water quality data from Smith (1961, table 3), Smith and Gates (1963, table 4), Feth and others (1966, table 9), Bolke and Waddell (1972, table 2), Plantz and others (1986, table 5), and Clark and others (1990, table 13) do not indicate that tested wells in the WRBASR project study area have exceeded U.S. EPA (2002) ground-water quality standards. However, wells in sections 29 and 30, T. 5 N., R. 1 W., Salt Lake Base Line and Meridian, immediately to the west of the study area had moderately high nitrate concentrations, with respective maximum values of 5.0 and 7.4 ppm (Bolke and Waddell, 1972, table 2).

PROJECT DESIGN AND IMPLEMENTATION

Planning and Site Preparation

Any entity or person wishing to conduct an artificial recharge and/or ASR project must obtain the necessary permits from the Utah Department of Environmental Quality, Division of Water Quality (DWQ) and from the Utah Department of Natural Resources, Division of Water Rights. Specific regulations are available from these agencies. The type and duration of the required permits vary with the design and goals of each project and are considered on an individual basis. The general rule of thumb is that the chemical quality of artificially introduced water must be equal to or higher than that of the existing ground water. The application process and requirements for injection wells are more detailed and stringent than those for infiltration basins. For the WRBASR project, the WBWCD filed for a temporary change-of-use permit from the Division of Water Rights, and the project qualified for "permit-by-rule" status. Other infiltration-basin projects may or may not meet the qualifications for permit-by-rule status.

The WBWCD purchased approximately 12 acres (5 hm^2) of a former gravel pit to be used for the infiltration basins (figures 15 and 16; plate 1). The upper ~30 feet (10 m) of unconsolidated material had been removed from the pit during a prior operation, and the pit had subsequently been sold to a private party. An irrigation canal operated by the South Weber Diversion Canal Company is located along the north boundary of the property, providing easy access to Weber River water for the recharge experiments. Infiltration basins were constructed on site, using off-road heavy machinery, by leveling the ground and forming approximately 3-foot-high (1 m) berms around the basin perimeters. The WBWCD also constructed a diversion structure on the canal and a weir box to measure total flow diverted. The structure diverts water from the canal and through the weir box to a sedimentation basin. Gates in the southwest corner of the sedimentation basin allow water to flow to the two adjacent infiltration basins. A third infiltration basin was later constructed adjacent to the southwestern basin.

The U.S. Bureau of Reclamation well-drilling crew installed a new observation well adjacent to and downgradient from the infiltration basins (figure 15; appendix C) to allow measurement of ground-water levels and collection of water-chemistry samples. The well was drilled to a total depth of 301 feet (92 m) and intercepted a low-permeability, fine-grained layer at 116 feet (35 m) depth. The low-permeability layer had some naturally occurring perched water, and the main water table was encountered at 231 feet (70 m) depth.

During the recharge experiments, project personnel monitored the diversion structure and weir box daily for both

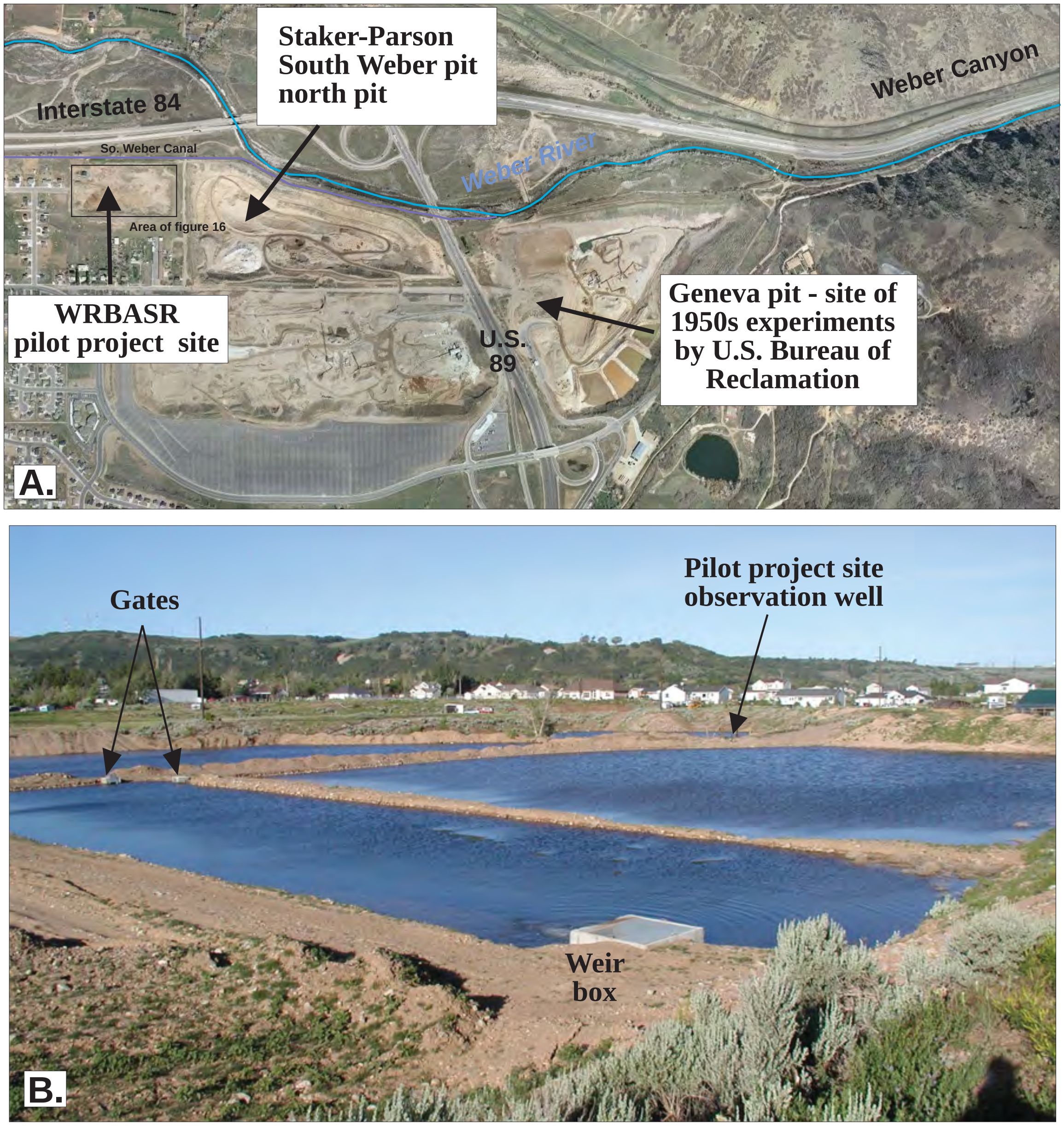


Figure 15. *Photographs of the WRBASR pilot project infiltration site. A. Aerial photograph of infiltration site and adjacent areas before development. B. View southwest of the sedimentation basin (foreground) and infiltration basins 2 and 3 (see figure 16 for schematic plan map).*

flow and debris buildup (table D1). The levels in each infiltration basin were also checked and recorded daily. Staff from the WBWCD and UGS took daily measurements of the ground-water levels and weekly samples for ground-water quality from the monitoring well.

Charles Bishop (then with UGS) estimated from local climate data that from April 19 to May 22, 2004, the infiltration ponds lost about 0.625 acre-feet (770 m^3) of water to evaporation, about 0.3% of the water diverted from the irrigation canal during that time. Evaporative loss was likely larger during the summer months. We consider the volume of infiltrated water to be slightly less than the amount of water diverted into the basins and, therefore, do not correct for evaporative loss when estimating infiltration rates and amounts.

First Recharge Experiment

From March 19 to July 2, 2004, approximately 800 acre-feet (1 hm^3) of water was diverted from the canal into the infiltration ponds (figure 17a; table D1). Infiltration rates were approximately 0.5 to as much as 1.42 cubic feet per second (cfs) per acre (0.03 to 0.10 m^3/s/hm^2) during the first half of the infiltration experiment, and 0.0 to 0.75 cfs per acre (0 to 0.06 m^3/s/hm^2) near the end; about 9 acre-feet per day (0.11 hm^3/d) infiltrated into the subsurface during most of the experiment (figure 17b).

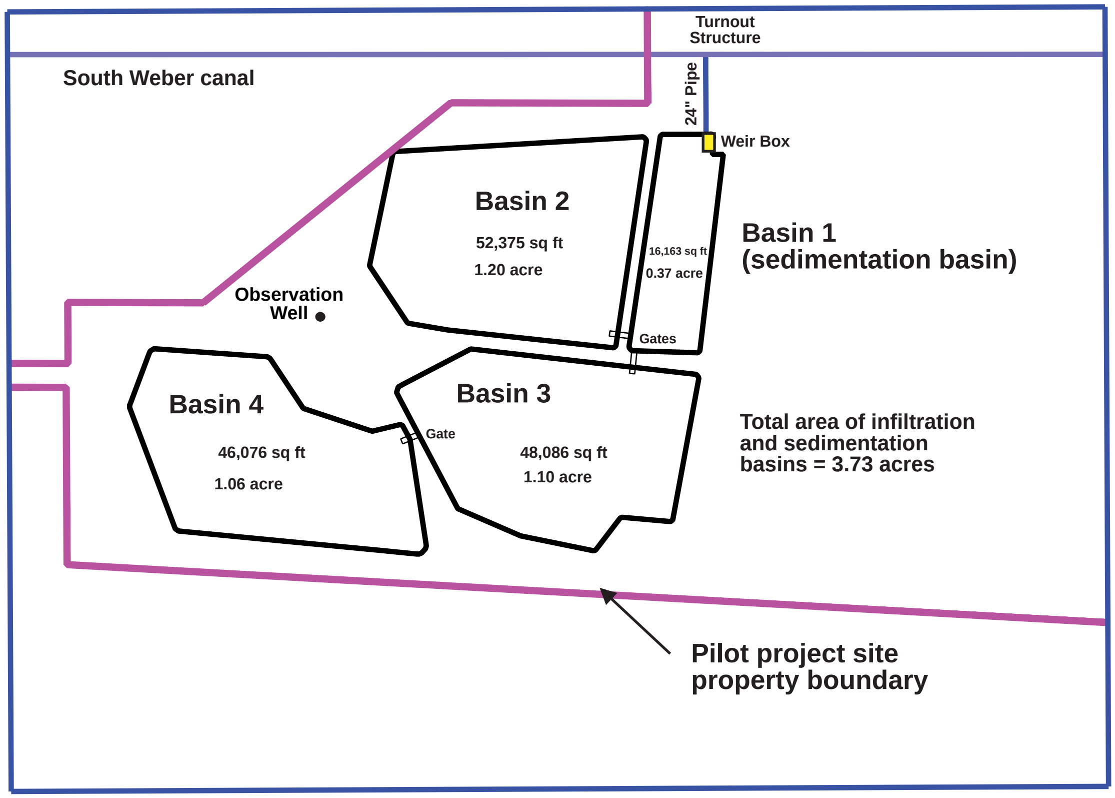


Figure 16. *Schematic diagram showing diversion structures and locations of infiltration basins at the WRBASR pilot project site.*

Diversion of canal water into the basins was terminated on July 2, 2004, due to the seepage of ground water into the Staker-Parson South Weber quarry, about 0.25 mile (0.4 km) east of the infiltration basins. The seepage was first observed on June 17, 2004. Project members from the WBWCD, Utah Division of Water Resources, UGS, and Weber State University monitored the seepage area, installed a makeshift flume to measure flow, marked the outer limit of surface wetting, and installed three shallow piezometers to estimate the local water-level gradient near the outflow area. The seepage occurred above a ~1-foot-thick (0.3 m) layer of clayey silt exposed at about 4360 feet (1329 m) elevation, about 30 feet (10 m) above the lowest level of the pit. The top of the fine-grained layer encountered by the observation well is at 116 feet (35 m) depth, and 4377 feet (1334 m) elevation. The observation well is about 1355 feet (413 m) west of the exposures in the north pit. Based on their similar composition and elevations, we interpret the fine-grained layers in the gravel pit and observation well to be the same layer. Total surface flow on the pit floor was estimated at 15 to 20 gallons per minute (57–76 L/min) at its maximum.

Measured infiltration rates decreased by about 30% during the first recharge experiment (figure 17b; table D1). The most likely causes of this decrease were clogging of pore space in the sand and gravel deposits of the infiltration-basin floors by fine-grained particles that settled out of the water, and gas generation in the soil (Bouwer, 2002). Algal growth in the ponds during the later stages of the infiltration experiment, after the onset of summer temperatures, also likely contributed to the clogging. Physical and biological clogging of this nature is the primary problem associated with artificial recharge by surface spreading (Bouwer, 2002). Although the sedimentation basin was designed to allow fine-grained particles to settle out of the water before it entered the infiltration ponds, not all sediment was removed.

After the first recharge experiment ended and the ponds dried, we examined the deposits left on the infiltration basin floors to evaluate the effectiveness of the sedimentation basin and the possible role of clogging by fine-grained sediment in reducing infiltration rates. The UGS measured and sampled along ten transects in the four basins (figure 18). All samples were described in the field, and 18 samples were collected and analyzed in the lab (table D2) using a 40X binocular microscope. Sampling intervals were approximately 10 to 15 feet (3–5 m) for the sedimentation basin, and 30 feet (10 m) for the infiltration basins (figure 18). Figure 18 shows the thickness range of sediment, and table D2 presents detailed descriptions for each sample.

Most samples are in the form of “mudcracks,” dominantly composed of silt and fine sand rather than clay (mud).

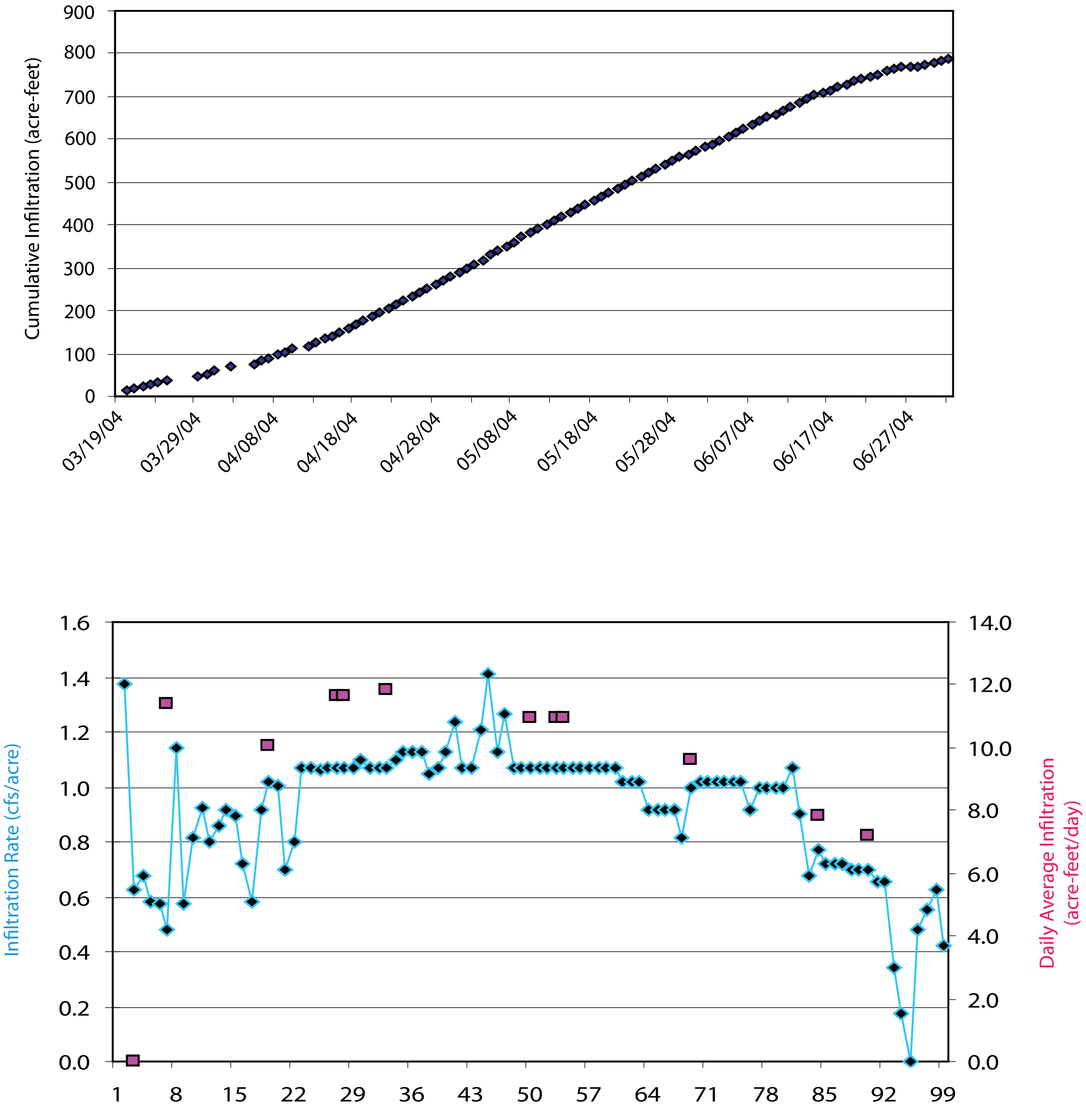


Figure 17. *Diversion and infiltration plots for the WRBASR pilot project first recharge experiment. A. Cumulative diversion, March 19 to July 2, 2004. B. Approximate infiltration rates for the same time period shown in A.*

The size and distribution of the mudcracks decrease from basin 1 to basins 2, 3, and 4. For basins 2 and 3, we noted some areas with artificial ridges (possibly generated during excavation of the pit) having a thin veneer of crust or rind on ripple marks and are adjacent to troughs containing mudcracks (¼ to ½ inch thick [6–13 mm]).

The distribution of visible surficial deposits on the infiltration basin floors seems negligible compared to the substantial decrease in infiltration rates observed during the first recharge experiment. Perhaps other factors in addition to these deposits, such as clogging of pore space by very fine, poorly visible particles, gradual compaction under the weight of the overlying water in the basins, or gas generation immediately below the land surface contributed to the decrease in infiltration rates.

Second Recharge Experiment

The infiltration-basin floors were scraped and leveled before the second recharge experiment began, to break up the fine-grained sediment deposited during the first experiment and dust that may have accumulated on the basin floors afterward. The scraping also loosened surface deposits that may have been compacted by the weight of overlying water during the first experiment.

During the second recharge experiment, approximately 450 acre-feet (0.55 hm^3) of water was diverted into the infiltration ponds from March 17 to May 23, 2005 (figure

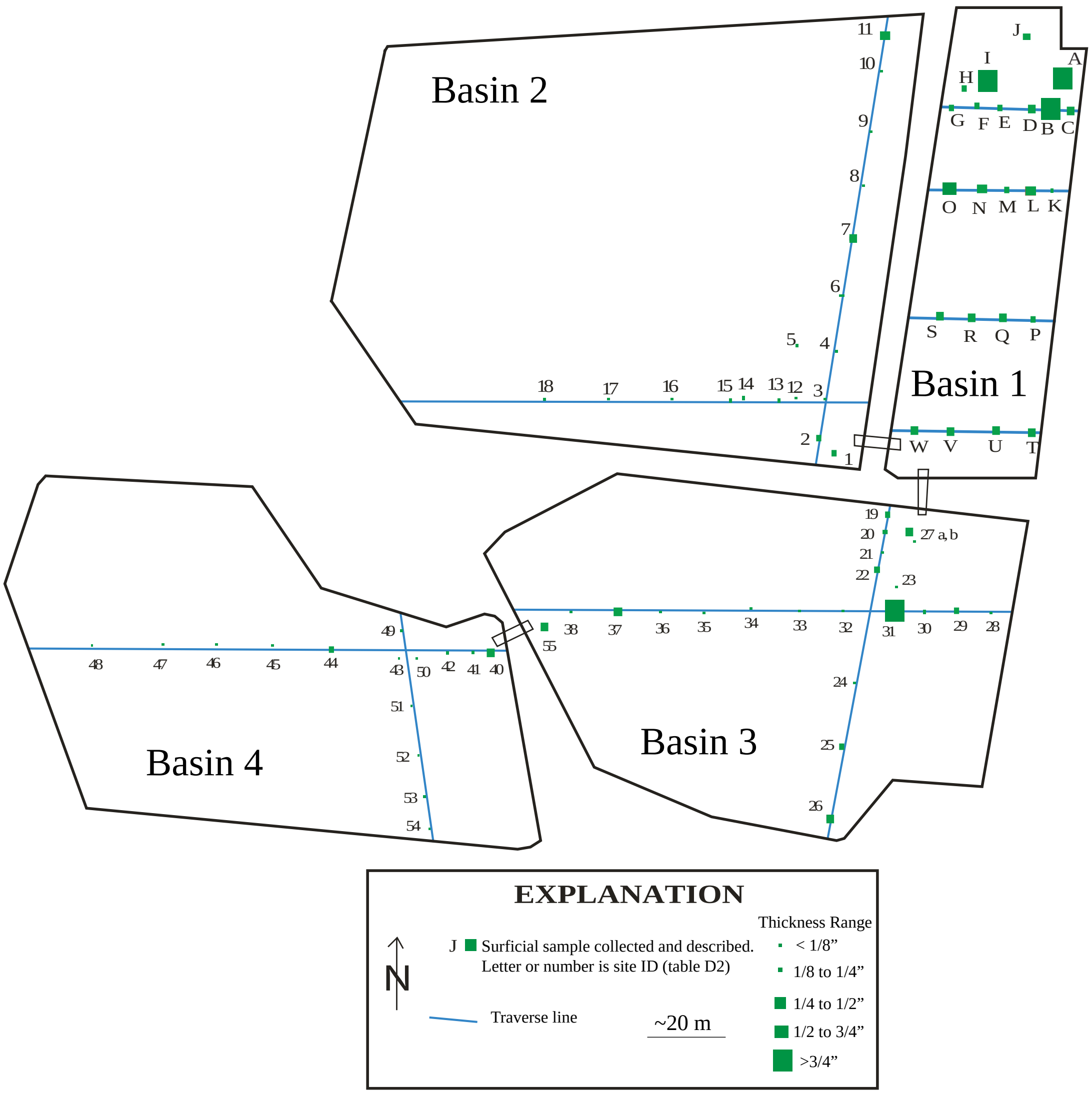


***Figure 18.** Locations and thickness ranges of samples from the infiltration basins.*

19a). In mid-May, sufficient water pooled at the bottom of the north pit of the Staker-Parson South Weber quarry to disrupt their operations, so diversion of canal water into the infiltration basins ceased. By mid-August the Staker-Parson pit had dried, so diversion from the canal to the infiltration basins resumed and 250 acre-feet (0.31 hm^3) was diverted from August 17 to October 11 and from October 25 to 31, 2005 (figure 19a). Infiltration rates varied considerably during the second recharge experiment, and generally were higher than during the first experiment (figure 19b).

Third Recharge Experiment

The WBWCD conducted a third recharge experiment during summer 2006, after funding from the U.S. Bureau of Reclamation expired and the working group ceased to meet (D. Hess, Weber Basin Water Conservancy District, written communication, November 30, 2006). Diversion from the irrigation canal into the infiltration basins occurred continuously from June 23 to September 24, 2006, and intermittently thereafter until November 1. Flow through the diversion gate ranged from about 3 to 6.6 cfs (0.1–0.2 m^3/s) and averaged 4.6 cfs (0.1 m^3/s), and estimated infiltration rates are about 0.2 to 1.1 acre-feet per day (247–1360 m^3/d). The total estimated amount of infiltrated water was about 1130 acre-feet (1.4 hm^3), substantially more than the previous two years. We are unsure why infiltration increased during the third year, but speculate that (1) a greater volume of pore water below the site at the beginning of infiltration increased the effective permeability by lowering effective stress, and/or (2) water infiltrated during the first two recharge experiments dissolved secondary minerals in pore spaces and on mineral grains and clasts in the vadose zone, resulting in increased permeability.

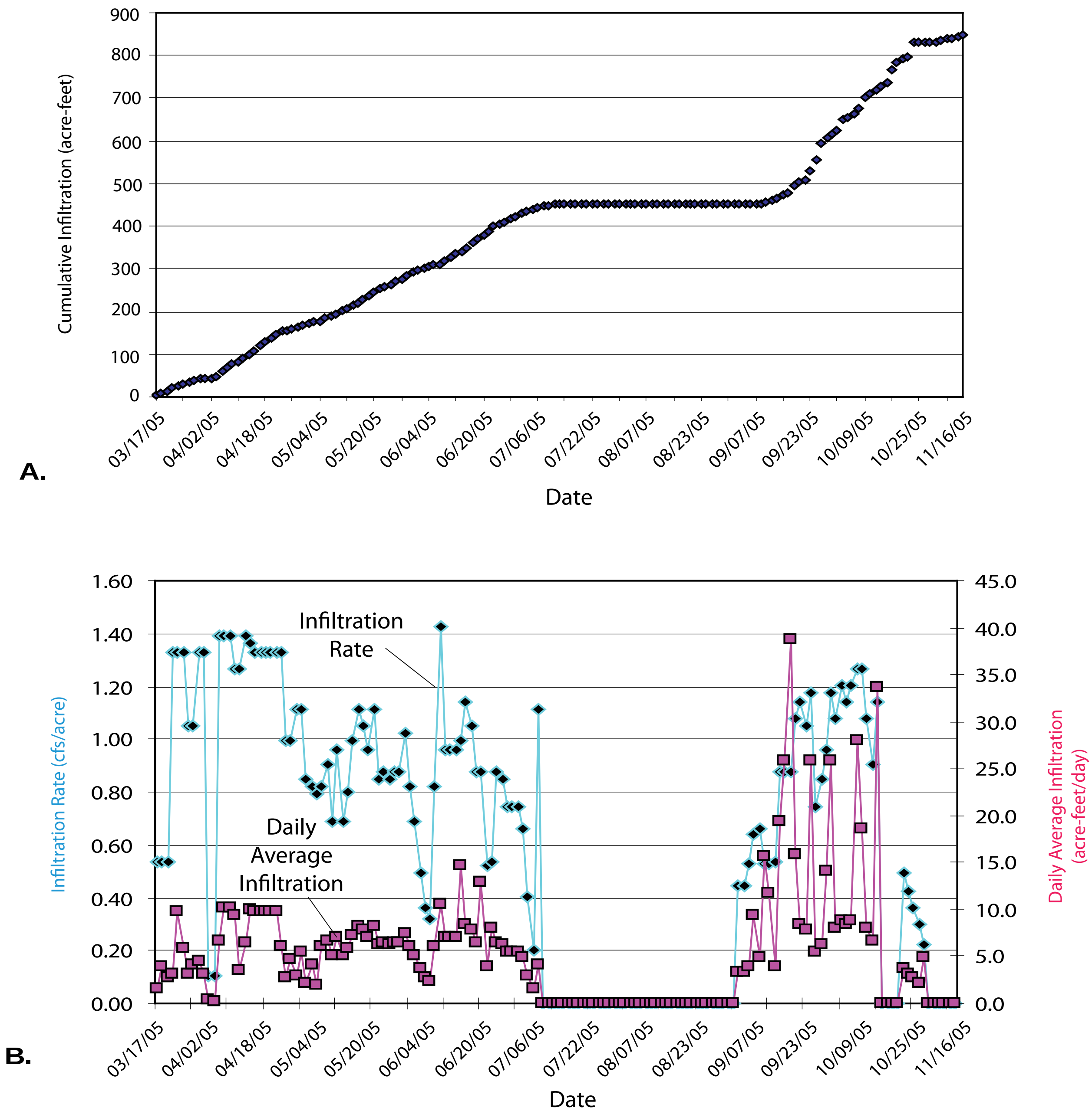


Figure 19. *Diversion and infiltration plots for the WRBASR pilot project second recharge experiment. A. Cumulative diversion, March 17 to October 31, 2005. B. Approximate infiltration rates for the same time period shown in A.*

WATER LEVELS AND CHEMISTRY

Introduction

We collected baseline water-level and chemical data monthly for about one year prior to and after the recharge experiments, and daily water-level measurements and weekly chemical sampling during the recharge experiments. Data-collection tasks included measuring water levels in wells, and collecting and analyzing water-quality samples from wells and from the Weber River. During the first recharge experiment we monitored and sampled 14 water wells, including the pilot project site observation well, for water-level changes and water quality from June 2003 to February 2005. During the second recharge experiment, we measured water levels in and sampled water from the WRBASR observation well daily from March to September 2005. We also sampled the water well in the Staker-Parson South Weber quarry for water quality during July 2004 and August 2005, and obtained a total of 34 surface-water-quality samples from the Weber River from January 2003 to September 2005.

Water-Level Measurements

Monthly Water Levels

Ground-water levels change in response to a variety of factors, including well pumping, precipitation, barometric pressure, irrigation and lawn watering, and changing river stages. These factors result in both short-term fluctuations and long-term trends in ground-water levels. To characterize the natural short-term fluctuations and identify long-term trends in the Delta aquifer, we measured and recorded water levels, air-line pressures, and transducer water levels periodically in twelve wells screened at various depths in the Delta aquifer, and in the ASR site observation well.

Figures 20 through 31 show data for wells surrounding the pilot project site (see plate 1 for locations). During the first recharge experiment we monitored the wells monthly, from July 2003 to October 2005, although from time to time we could not obtain measurements due to problems such as transducers being off line, no access to a well, and/or equipment failure.

Figures 20 through 23 show changes in water level in Hill Air Force Base (HAFB) wells 9, 2, 3, and 6, respectively (table A1 and plate 1). With respect to the location of the pilot project observation well, HAFB9 (well 72; table A1 and plate 1) is about 1.6 miles (2.6 km) west-southwest, HAFB2 (well 47) is about 3.0 miles (4.8 km) west-northwest, HAFB3 (well 46) is about 3.0 miles (4.8 km) west-northwest, and HAFB6 (well 52) is about 3.4 miles (5.5 km) west-northwest. All of these wells are south of the Weber River. HAFB9 produces from the lower Delta aquifer, whereas HAFB wells 2, 3, and 6 produce from the upper part of the Delta aquifer.

The HAFB wells are pumped periodically, and interpretation of the water-level data is challenging. Additionally, 2003 and 2004 were drought years during which water levels declined. Water levels fluctuate seasonally by different amounts in each well, reflecting different hydrologic settings and possibly spatial variability in recharge rates and/or storage characteristics of the aquifer. Water levels are generally highest in the winter and spring when the wells are pumped less and recharge is occurring, and decline during the summer due to pumping, reaching their lowest levels in the early fall. In wells not affected by pumping, rising water levels indicate recharge of the aquifer.

The magnitude of seasonal fluctuations may be as much as 35 feet (11 m) in HAFB9, and 5 to 10 feet (1.5–3 m) in HAFB wells 2, 3, and 6. HAFB9 shows at least 30 feet (10 m) of drawdown during pumping (figure 20). During the winter months, a general trend of increasing water levels exists due to less overall pumping. HAFB2 is less affected by pumping and is probably not pumped as much as the other wells; it shows a 6-foot (2 m) seasonal water-level change (figure 21). HAFB3 shows as much as 10 feet (3 m) of seasonal water-level change, as much as 15 feet (4.6 m) of drawdown associated with pumping, and recovery of water levels in the winter months (figure 22). HAFB6 shows seasonal water-level fluctuations similar to those observed in HAFB wells 3 and 9 (figure 23).

Figure 24 shows water levels in the Valley Nursery well (well 49; table A1 and plate 1), located about 0.75 mile (1.2 km) north of the pilot project site, and north of the Weber River. This well is pumped several hours daily throughout the spring and summer months. The well produces from the lower part of the Delta aquifer. The time-series plot (figure 24) shows that water levels are lower in high-use periods and higher in low-use periods. Figure 25 shows water levels for the Uintah Highlands City well (well 39; table A1 and plate 1), located about 1 mile (1.6 km) north of the site. We first accessed the Uintah Highland City well February 2004, and subsequently had periodic access. We measured water levels there with an electric tape; these levels remained consistent.

Daily Water Levels

First recharge experiment: We measured water levels in nine wells daily before, during, and after the first recharge experiment. Daily monitoring of the ASR, Valley Nursery, and South Weber City wells (wells 118, 49, and 68, respectively; table A1 and plate 1) began March 8, 2004, and daily monitoring of the Weber District 3, Laytona, Fairfield, South Weber District 2, Clearfield 1, and Clearfield 2 wells (wells 36, 87, 32, 65, and 84, respectively; table A1 and plate 1; all owned by Weber River Basin Water Conservancy District) began March 17, 2004. Diversion of water from the South Weber canal to the infiltration basins began March 19, 2004.

Water levels in the ASR site observation well increased only slightly while the infiltration experiment proceeded, and began to decline soon after infiltration ceased (figure 26). During the first recharge experiment, water levels in wells within about 1.5 miles (2.4 km) of the pilot project site (figures 27, 28, and 29) and the WRBWCD #3 and Laytona wells (figures 29 and 30) decreased, whereas water levels in wells on Hill Air Force Base showed variable levels but increased overall (figures 20 through 23).

The Valley Nursery well was pumped regularly during this period and shows a general decrease in water levels (figure 27). The South Weber City well was also pumped regularly during this period and also shows a decreasing trend (figure 28). Additionally, the Weber District well 3 was pumped regularly during the infiltration experiment and shows the greatest drawdown of all the monitored wells (figure 29). The Laytona well was not pumped during the

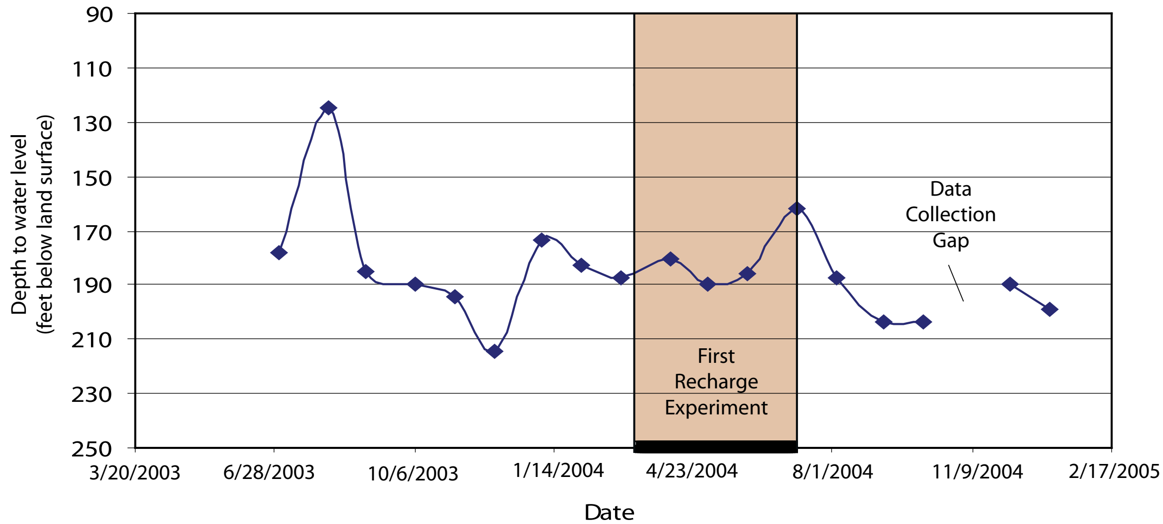


Figure 20. *Water levels measured in Hill Air Force Base well 9 (well 72; table A1 and plate 1).*

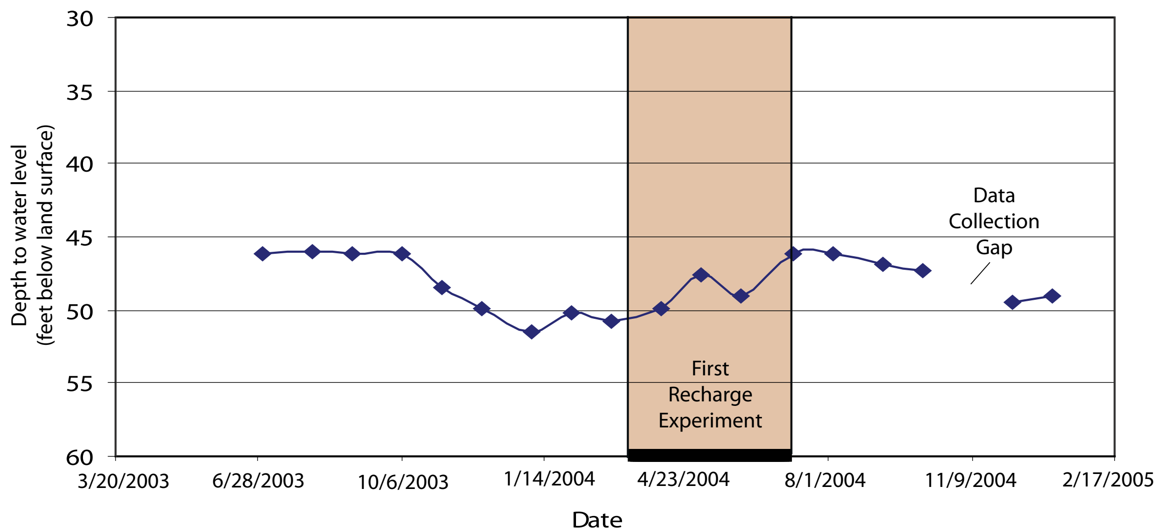


Figure 21. *Water levels measured in Hill Air Force Base well 2 (well 47; table A1 and plate 1).*

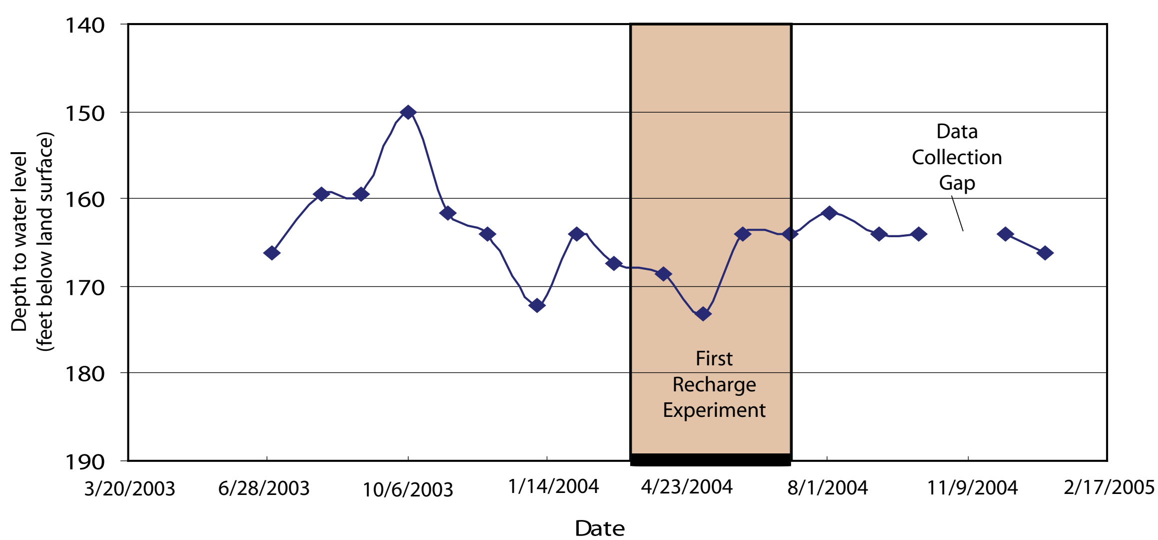


Figure 22. *Water levels measured in Hill Air Force Base well 3 (well 46; table A1 and plate 1).*

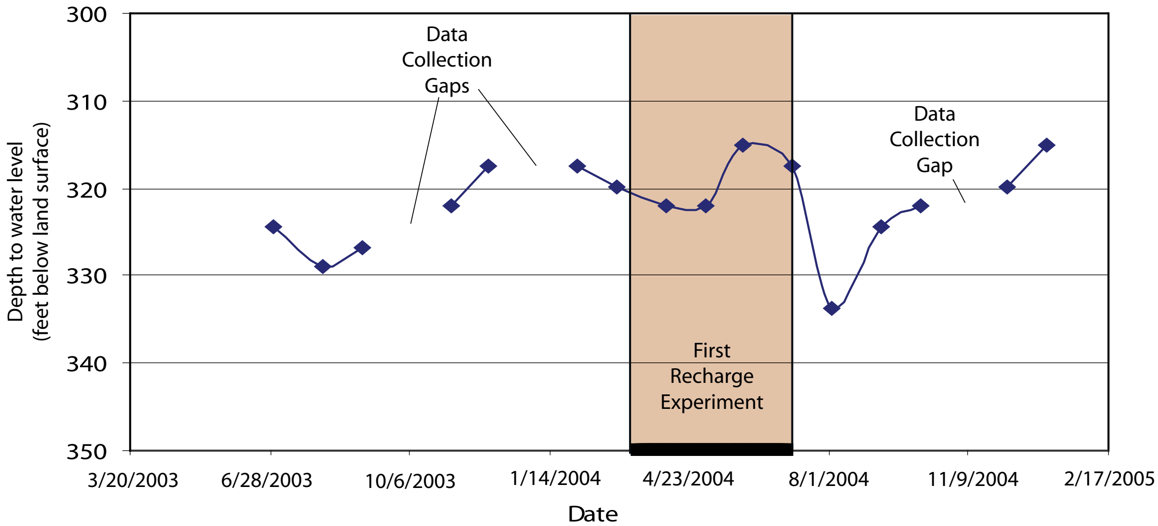


Figure 23. *Water levels measured in Hill Air Force Base well 6 (well 52; table A1 and plate 1).*

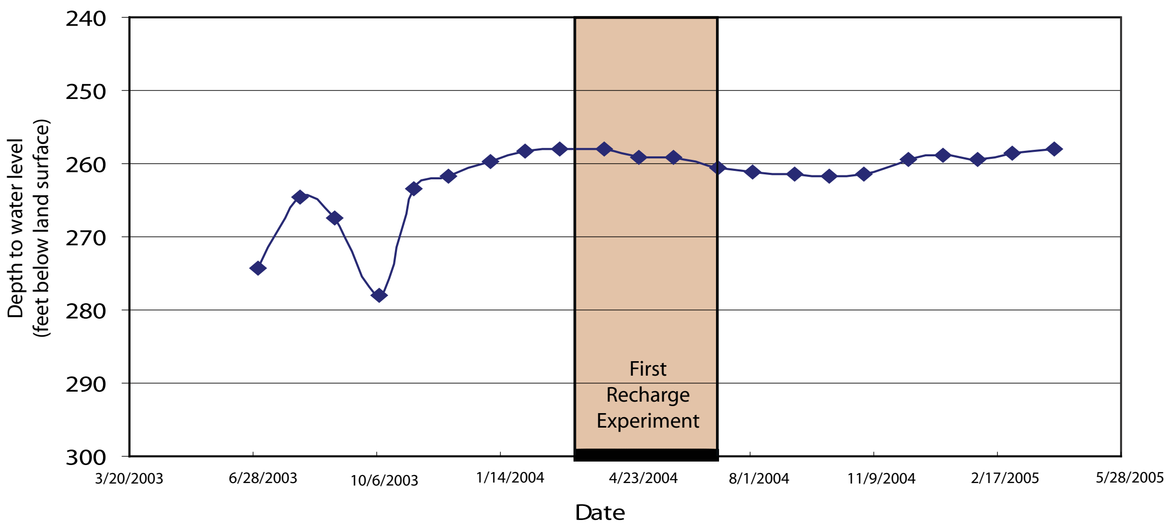


Figure 24. *Water levels measured in the Valley Nursery well (well 49; table A1 and plate 1).*

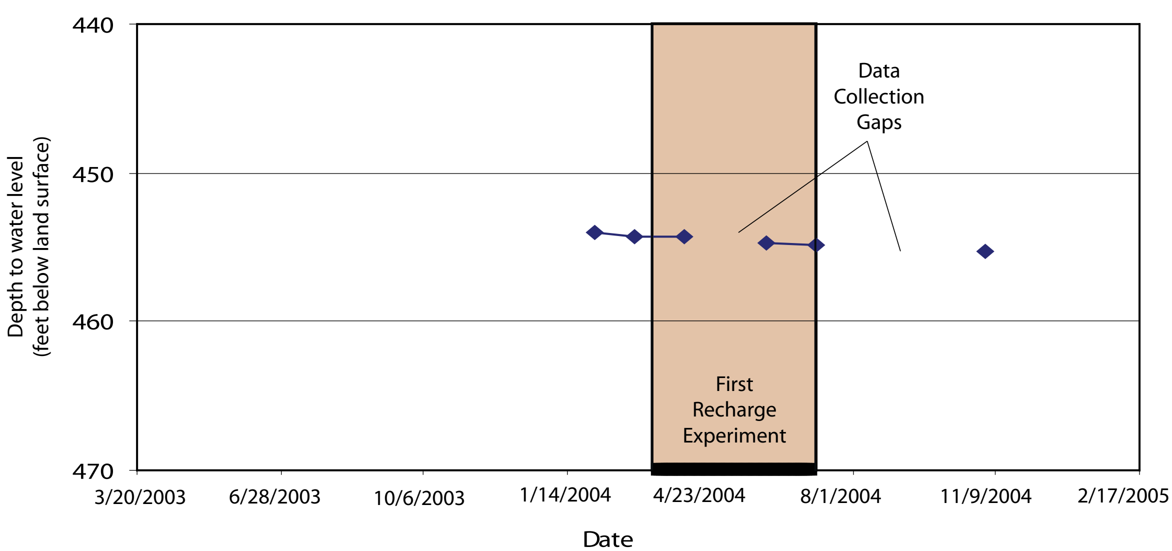


Figure 25. *Water levels measured in the Uintah Highland City well (well 39; table A1 and plate 1).*

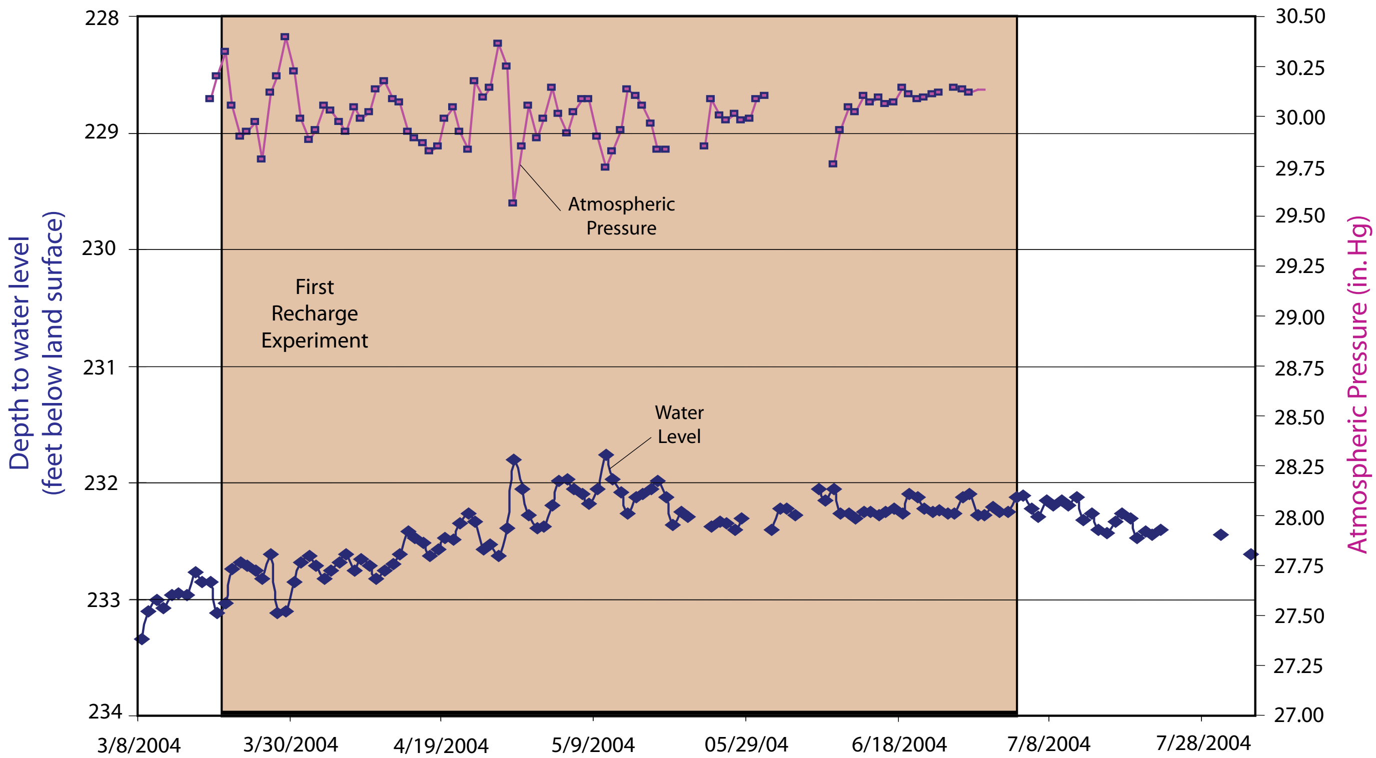


***Figure 26.** Daily water-level measurements for the WRBASR observation well (well 118; table A1, plate 1) for the first recharge experiment.*

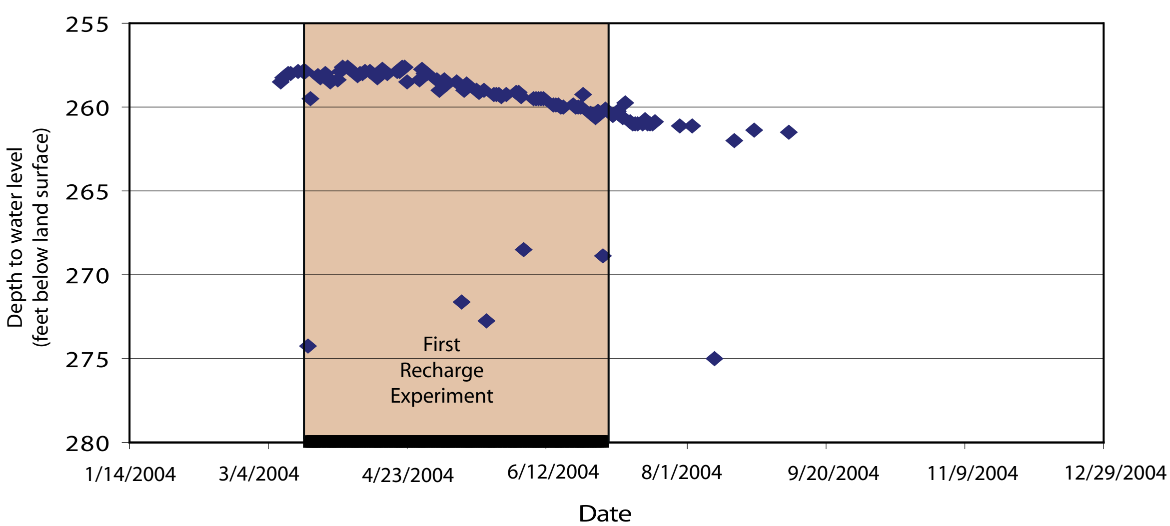


***Figure 27.** Daily water levels measured in the Valley Nursery well (well 49; table A1, plate 1).*

filling of the infiltration basins and shows a decreasing trend (figure 30). This probably indicates seasonal decline of ground-water levels.

Second recharge experiment: During the second recharge experiment, we measured water levels daily in the WRBASR observation well only; we did not measure water levels in the other wells. At the beginning of the second recharge experiment, the water level in the WRBASR observation well was 232.0 feet (70.71 m), and rose to its maximum level of 222.1 feet (67.69 m) 113 days after the experiment began (figure 31). The water level in the WRBASR observation well rose by a greater amount, but more slowly, than during the first recharge experiment (compare figures 26 and 31), although diversion and infiltration rates were similar (compare figures 17 and 19).

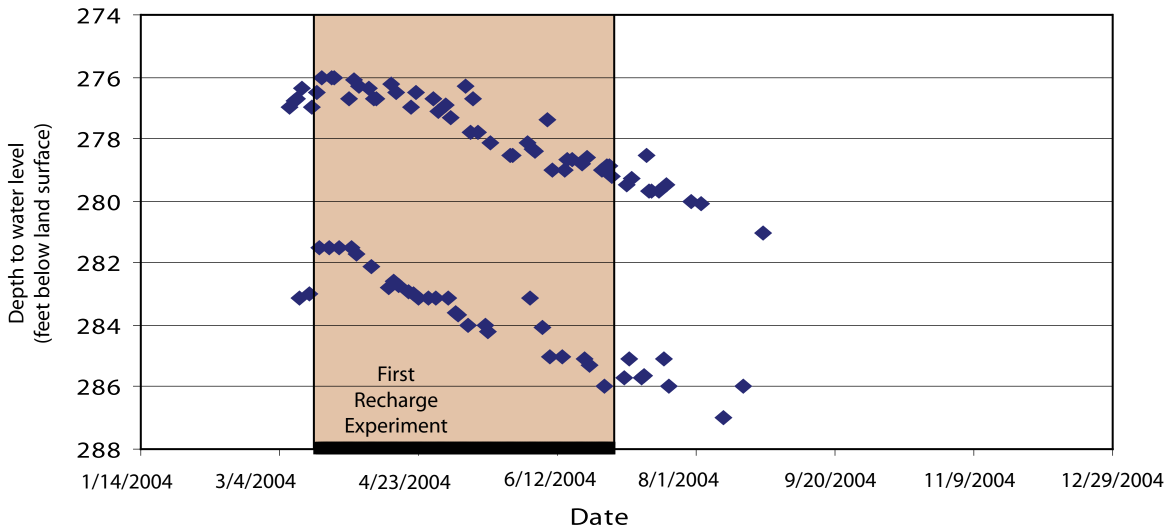


Figure 28. *. Daily water levels measured in the South Weber City well (well 61; table A1, plate 1). Values are bimodal due to pumping.*

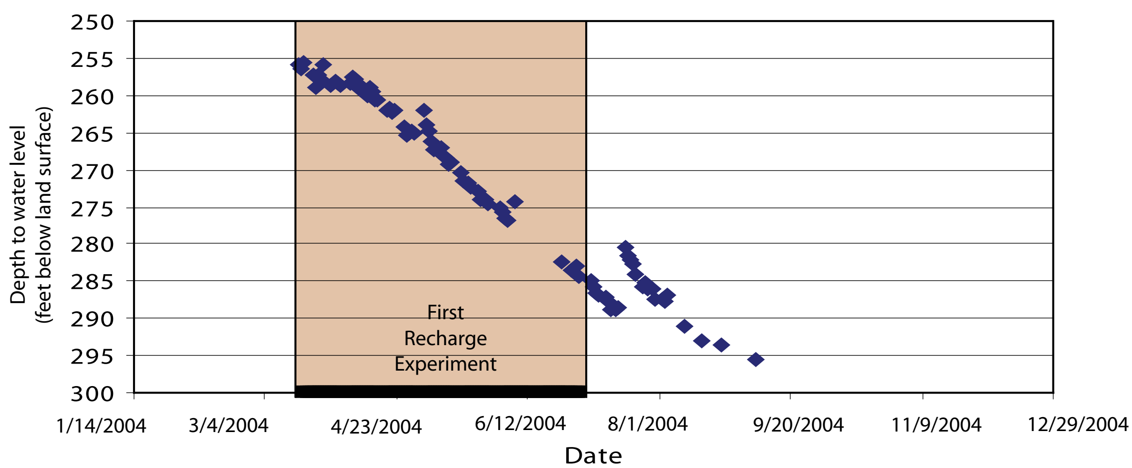


Figure 29. *Daily water levels measured in the WRBWCD Weber District well 3 (well 36; table A1, plate 1).*

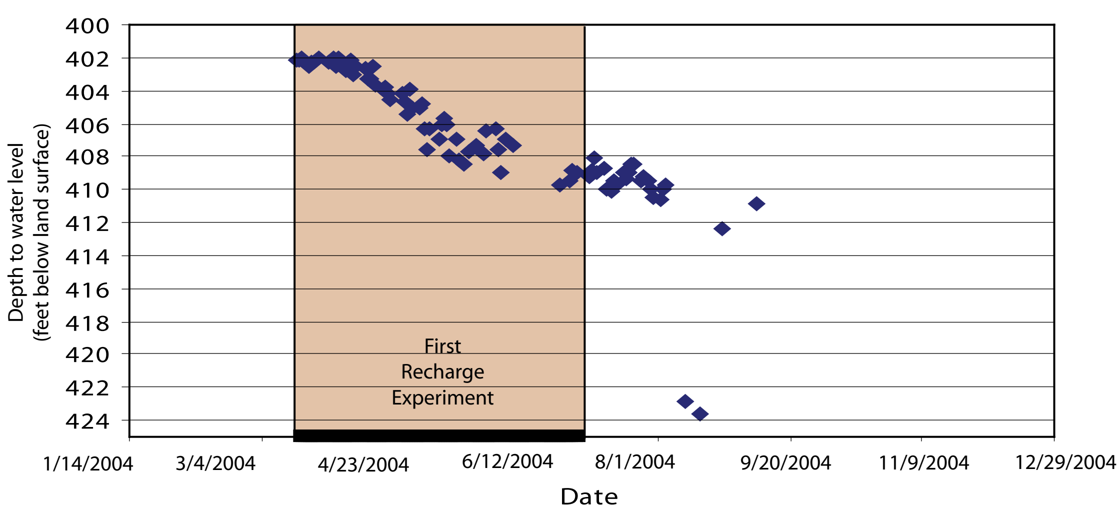


Figure 30. *Daily water levels measured in the WRBWCD Laytona well (well 87; table A1, plate 1) from March 2004 to August 2004, and weekly measurements through September 2004.*

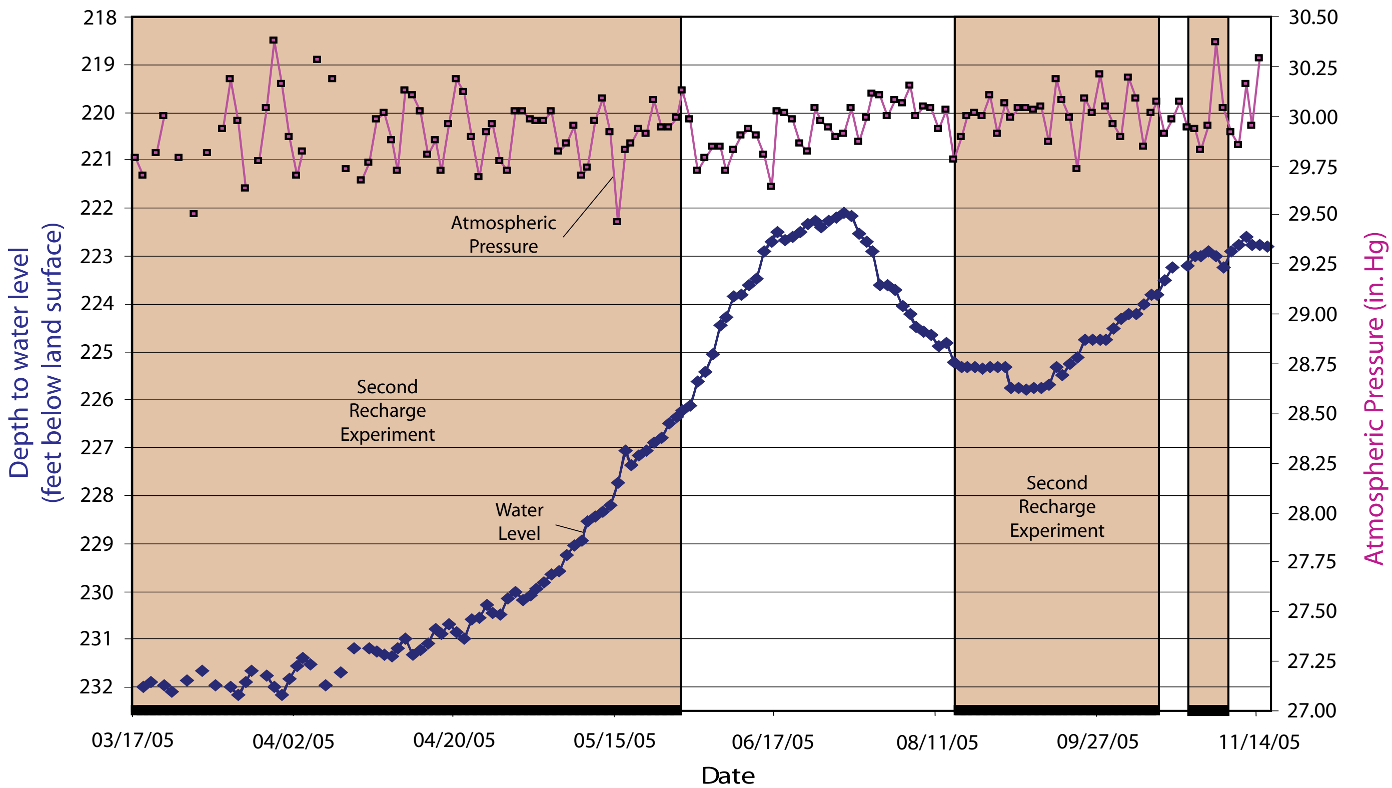


Figure 31. *Daily water-level measurements for the WRBASR observation well (well 118; table A1, plate 1) for the second recharge experiment.*

Atmospheric pressure: Changes in local atmospheric pressure can cause fluctuations in the static head of a confined aquifer; an increase in atmospheric pressure lowers the water level in the well, and a decrease in pressure causes a rise. We used barometric records from the Forest Park weather station in Layton, Utah, to evaluate the effect of atmospheric pressure on water levels at the ASR site observation well. Water-level changes in deep wells are normally out of phase with surface atmospheric pressure changes, due to the slow movement of air through the unsaturated zone. At the pilot project site, the barometric pressure and water levels are roughly in phase, perhaps reflecting the relatively high connectivity of pore spaces in the sand and gravel deposits at the site (figures 26 and 31).

Water Quality

Introduction

We analyzed water-quality samples from 14 wells and the Weber River from June 2003 to January 2005 and from March to October 2005 to assess the effects of infiltrated water on local ground-water quality. Two sites in the Staker-Parson South Weber gravel quarry were evaluated for water quality during part of July 2004. We collected 34 surface-water samples from the Weber River, spanning both recharge experiments.

Sampling and Analytical Methods

All water samples were collected in clean plastic bottles and sealed immediately. The Weber Basin Water Quality laboratory performed all chemical analyses. Analytical methods and results are presented in appendix E. Water samples from wells were collected from sampling ports located within several feet of the well head. Prior to sampling, the well casings and sampling ports were purged of stagnant water by allowing water to flow through the ports for several minutes.

Results

General: Using the methods described in appendix E, we established a quantitative relationship between specific conductance, which is measured readily in the field, and total dissolved solids, which was measured in the laboratory (figure 32). The regression line is fairly well constrained, and can be used to provide reasonably accurate estimates of total-dissolved-solids concentrations for samples from the study area.

Ground-water and Weber River water quality in the study area is generally good, and the water is suitable for most uses (figures 33 through 41; table E3). Weber River water and ground water in the Delta aquifer generally contain less than 500 mg/L total dissolved solids. Water from sev-

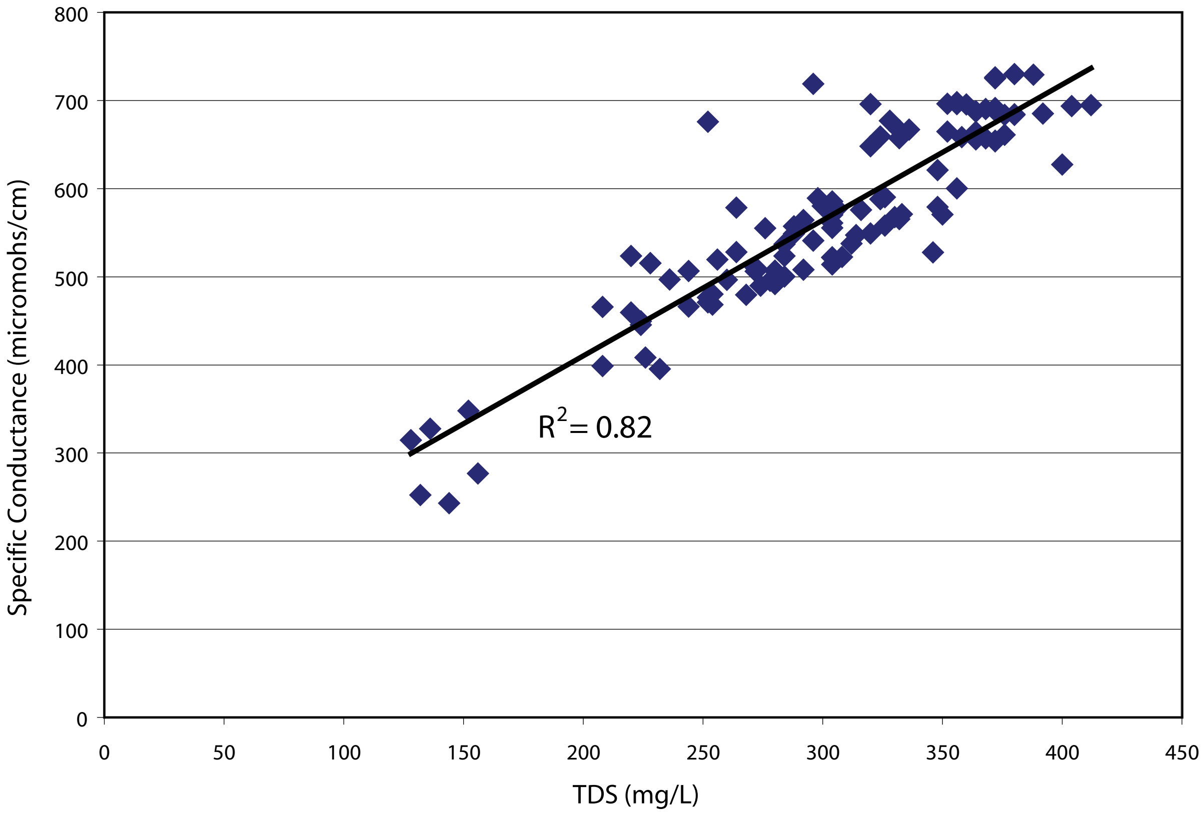


Figure 32. *Specific conductance versus total-dissolved-solids concentration data for wells and river samples in Weber and Davis Counties, Utah. Based on Hem's (1985) equation for estimating TDS from specific conductance: KA=S, where K=specific conductance, S=TDS, and A ranges from 0.55 to 0.96; for this study we used A=0.5.*

eral wells can be classified as Class IA, or Pristine, according to the Utah Division of Water Quality Board's ground-water quality classification scheme (table 3). Weber River water and ground water in the Delta aquifer in the study area is dominantly calcium-magnesium-bicarbonate type (figure 33).

Nitrate, typically associated with human activities, has been identified in negligible amounts in ground water in the study area (table E3). Nitrate concentration in ground water was analyzed and reported as nitrate-as-nitrogen. The Utah ground-water quality (health) standard for nitrate-as-nitrogen is 10 mg/L. Nitrate-as-nitrogen concentrations range from 0.0 to 1.6 mg/L for wells in the study area. No water samples from wells exceeded the ground-water quality standard for nitrate.

Water-quality samples from the Weber River: Prior to the recharge experiment, we evaluated Utah Division of Water Quality STORET data for the Weber River, obtained about 4 miles (6.4 km) east of the mouth of Weber Canyon (table 1). Water-quality data showed no constituents exceeding ground-water quality standards for the 2000–02 sampling period.

We obtained 33 water samples from the Weber River at the bridge at Highway 89, except during February 2004, when one Weber River sample was obtained at the Uintah Bridge (figures 34, 35, and 36). Water samples from the Weber River were also collected at the diversion site for the South Weber City canal used to convey water to the infiltration site. Samples were analyzed for the following constituents: NO_3+NO_2, TDS, Ca, Na, bicarbonate, CO_2, CO3, Cl, Fe, K, SO_4, Mg, temperature, pH, Cu, and Pb (table E3). Nitrate concentration in river water was analyzed and reported as nitrate-as-nitrogen.

Total-dissolved-solids concentration values were below 500 mg/L (figure 34), and no primary ground-water quality standard was exceeded; the secondary standard for iron was exceeded seven times during the spring of 2004 and once in November 2004. Total-dissolved-solids concentration remained relatively constant between 250 and 400 mg/L, except from March 30, 2004, to July 2004, when TDS averaged between 100 and 250 mg/L. These seasonal decreases in TDS are likely due to increased flow from snowmelt, based on comparing the data shown on figure 34 with discharge records for the Weber River east of the study area (figure 35).

The samples plot as a calcium-magnesium-bicarbonate type water (figure 36). Nitrate-as-nitrogen concentrations

Table 3. *Ground-water quality classes under the Utah Water Quality Board's total-dissolved-solids- (TDS) based classification system (modified from Utah Division of Water Quality, 1998).*

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

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

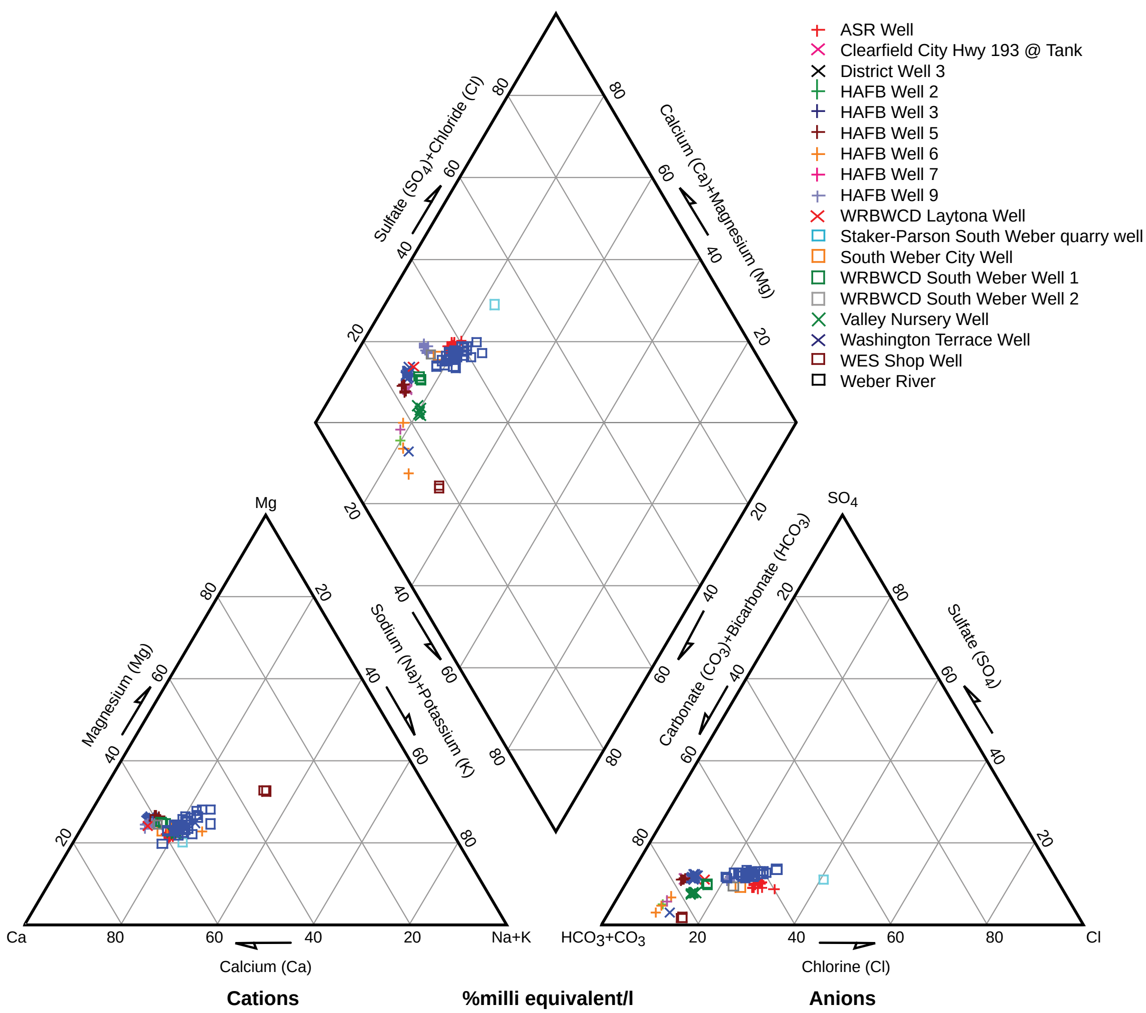


Figure 33. *Piper plot showing all water-quality data collected for the ASR project, 2003 to 2005.*

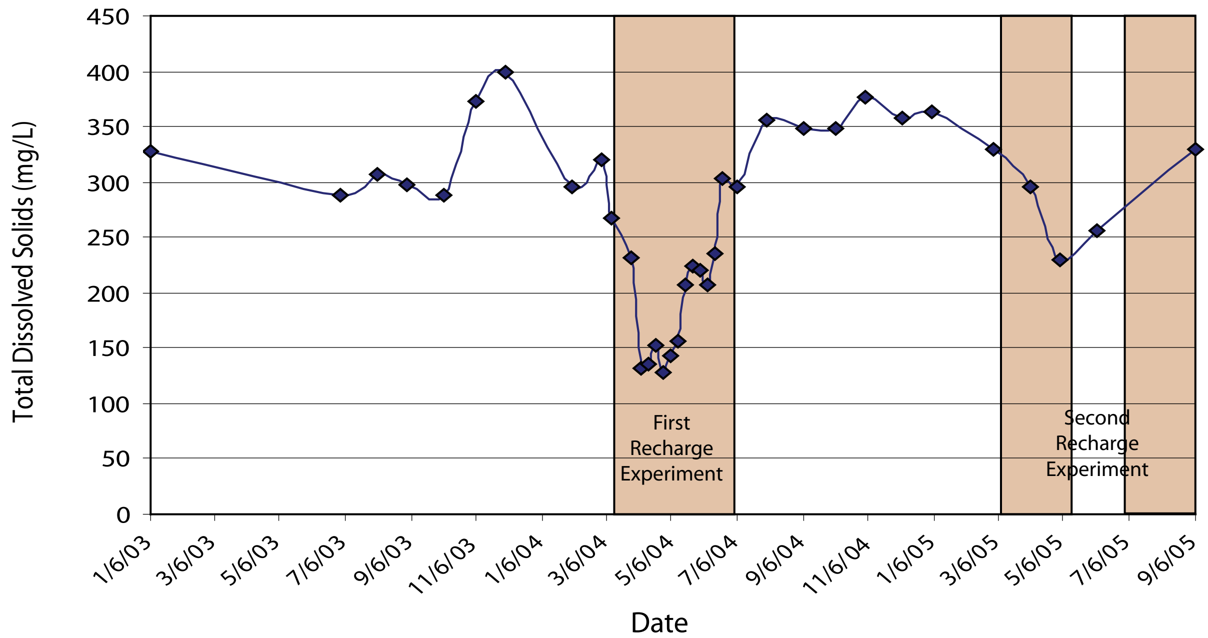


Figure 34. *Total-dissolved solids concentrations for samples from the Weber River, 2003 to 2005.*

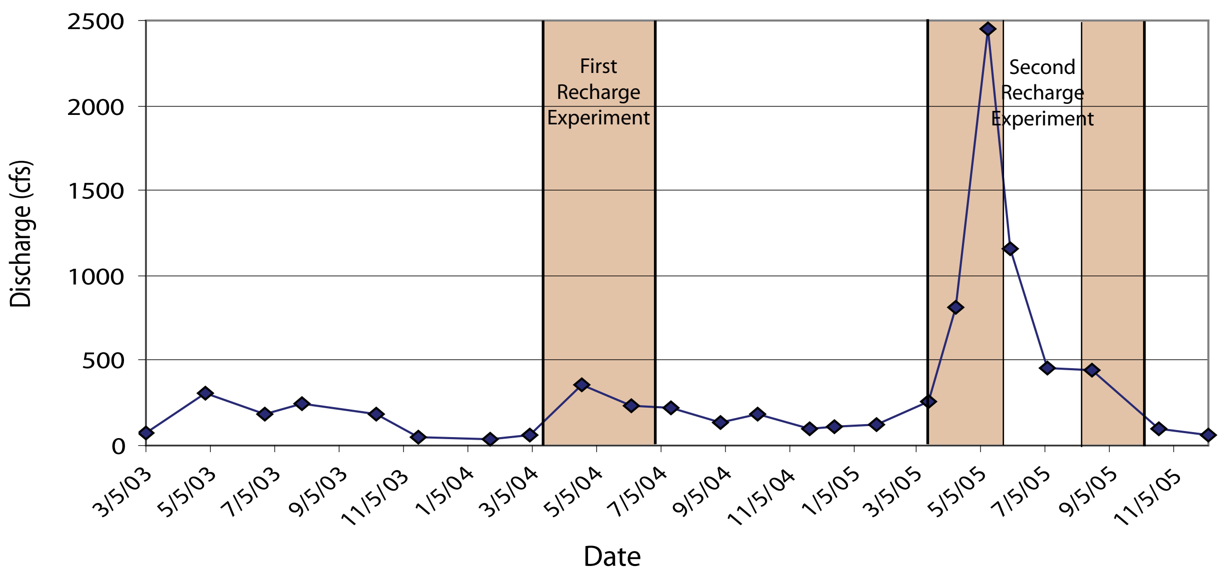


Figure 35. *Flow records for the Weber River at the Gateway gauge, 1.8 miles (2.9 km) east of the WRBASR pilot project site. Data are from the U.S. Geological Survey (2006).*

ranged from 0.12 to 0.97 mg/L (table E3). No samples exceeded the ground-water quality standards (table E3). Ground-water quality exceeded the secondary EPA standard for iron (300 µg/L) from Weber River water over seven sampling intervals from July 2003 to November 2004, ranging from 339 to 3662 µg/L (table E3). Various measured constituents show a pronounced decrease in concentration from March 30, 2004, to July 2004 and during April and May 2005, as observed for TDS analyses (figure 37).

Water-quality samples from wells: The chemical type and quantity of dissolved solids in ground water is influenced by the Weber River, the primary source of recharge, and local geology. Ground water with low total-dissolved-solids concentrations is likely due to the high quality of water in the Weber River and in the local crystalline basement source rock. Water from shallow wells, especially in irrigated areas, may contain higher dissolved salts derived from return irrigation flow, but this is not the case in the study area.

Water samples from wells were collected and analyzed quarterly for the following constituents: NO_3+NO_2, TDS,

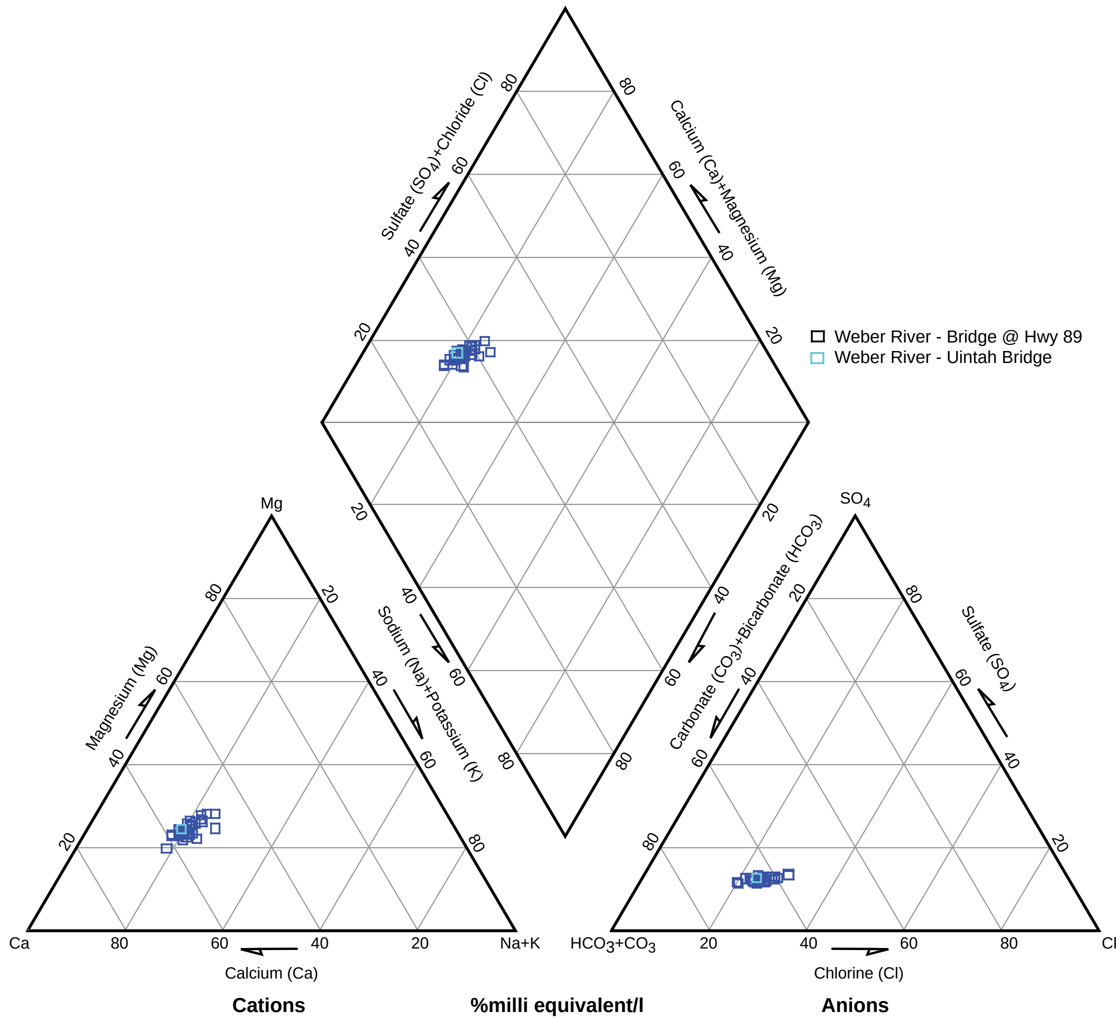


Figure 36. *Piper plot showing water-quality data for the Weber River collected 2003 to 2005.*

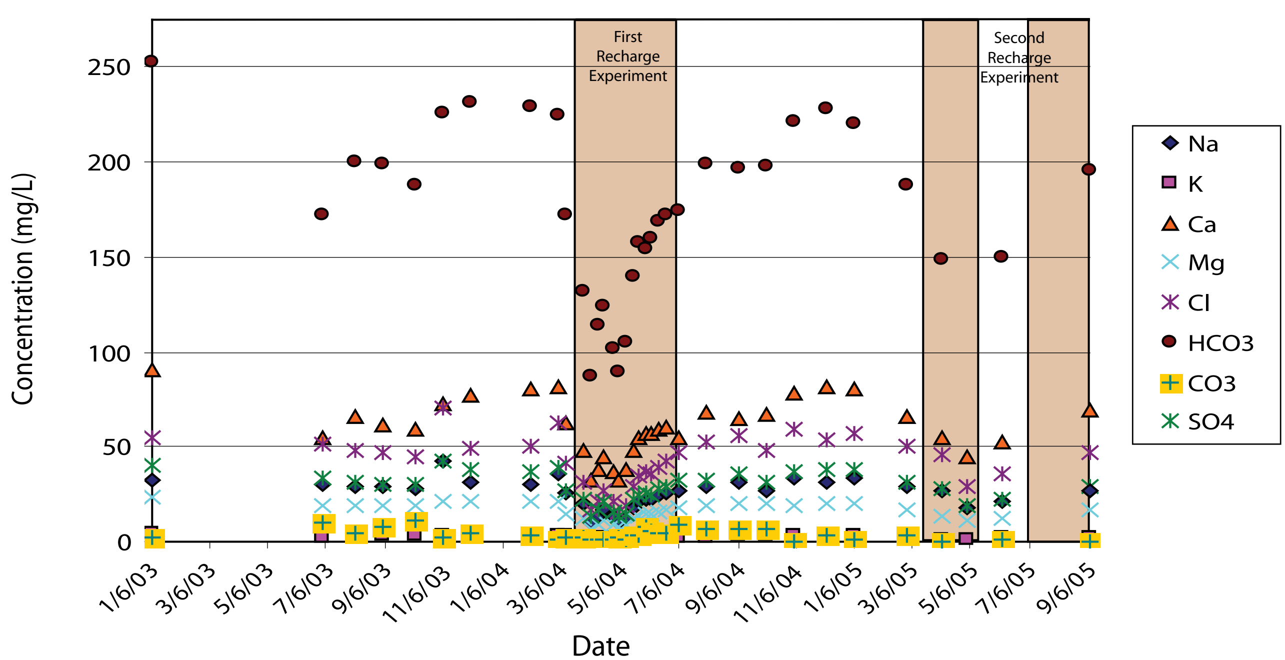


Figure 37. *General chemistry of Weber River water, 2003 to 2005.*

Ca, Na, bicarbonate, CO_2, CO_3, Cl, Fe, K, SO_4, Mg, temperature, pH, Cu, and Pb. Additionally, water samples from the pilot project observation well were collected and analyzed monthly during the experiment.

Total-dissolved-solids concentrations of water from all wells ranged from about 225 to 400 mg/L (figure 38; table E3), and did not display the sharp decrease in TDS during spring runoff that was observed in Weber River water (compare figures 34 and 38). The TDS values from the observation well were consistently higher than those from the other sampled wells (figure 38). The observation well displayed slight but discernable decreases in TDS during spring runoff during both 2004 and 2005. Possible reasons for the differences between the observation well and the other wells monitored are considered in the Discussion section of this report.

Ground water from the wells is a mixed calcium-magnesium-bicarbonate type (figures 39 and 40). The concentrations of analyzed chemical constituents in samples from the observation well remained relatively constant during the sampling period (figure 41). Lead concentrations in water from the Clearfield City well exceeded the primary EPA standard (15 µg/L) in the October 2003 sample (table E3). Samples from six wells (June 2003 to November 2004 for the Valley Nursery, Clearfield 1, HAFB6, Washington Terrace, WES Shop, and south Weber City wells) exceeded the secondary standard for iron (table E3). No constituents in samples from the observation well exceeded ground-water quality standards.

HIGH-PRECISION GRAVIMETRY

Introduction

Repeated high-precision gravity surveys can provide inexpensive monitoring of subsurface reservoir changes, such as the ground-water recharge from the WRBASR pilot project. The repeated measurements yield differences in gravity, which are used to infer reservoir properties or changes of state. The challenge is to implement a measurement and analysis technique that is sufficiently accurate to reveal changes in a desired time frame; in the case of the WRBASR pilot project, the objective was to track reservoir changes over a 17-month period that included pre-infiltration baseline data and the first two recharge experiments.

The subsurface reservoir changes inferred from gravity changes can provide insight into processes of geologic or engineering interest; for example, changes in storage in ground-water aquifers (Pool and Eychaner, 1995; Chapman and others, 2008; Gettings and others, 2008), natural seasonal mass changes (Goodkind, 1986; Keysers and others, 2001), steam-field changes in exploited geothermal fields (Allis and Hunt, 1986; Sugihara, 1999, 2001), or combined mass and elevation changes on volcanic or tectonic systems (Jachens and others, 1981; Arnet and others, 1997; Battaglia and others, 1999; Jousset and others, 2000; Ballu and others, 2003). The applicability of repeat gravity data is controlled by the precision of the gravity and Global Positioning System (GPS) measurements, which determine the minimum resolvable elevation and mass changes.

Multiple techniques exist for high-precision gravity-data acquisition and analysis (Whitcomb and others, 1980; Dragert and others, 1981; Jachens and others, 1981; Allis and Hunt, 1986; Andres and Pederson, 1993; Hunt and Kissling, 1994; Battaglia and others, 1999; Keysers and others, 2001; Sasagawa and others, 2003; Gettings and others, 2008). The WRBASR pilot project used the technique of Gettings (2005), which combines an automated gravimeter and rapid-static differential GPS measurements. We used a Scintrex CG-3M automated gravimeter, which allows statistical treatment of a time-series of gravity data at each station. The time-series analysis is combined with multiple station loops in a survey to handle instrument drift and random noise, which is the major challenge in high-precision gravity measurements. The results of this work are summarized here and by Chapman and others (2008).

Gravity changes may reflect changes in mass and/or elevation. To accurately determine mass change in a subsurface reservoir from repeated gravity measurements, station elevations must be monitored during the gravity experiment so that changes in gravity due to elevation changes can be subtracted from the measurements. Subsidence of stations during gravity monitoring has also been addressed in previous work (e.g., Arnet and others, 1997; Battaglia and others, 1999), but such data were derived using conventional leveling techniques, although Arnet and others (1997) also included a comparison with rapid-static GPS. Leveling is accurate but often prohibitively expensive for large station networks. The development of high-precision, rapid GPS measurements provides a method of monitoring ground deformation during the gravity campaigns without the expense of a separate leveling study. For the WRBASR pilot project, we used two Trimble 4700 GPS receivers to monitor possible ground-elevation changes during the gravity campaigns.

Gravimetry Project Data

Station Network

A network of 30 stations was installed around the WRBASR pilot project site prior to the start of the first recharge experiment, to provide temporal and spatial coverage of ground-water changes during and after infiltration (figure 42). Station WKRP, located about 6 miles (9 km) east of

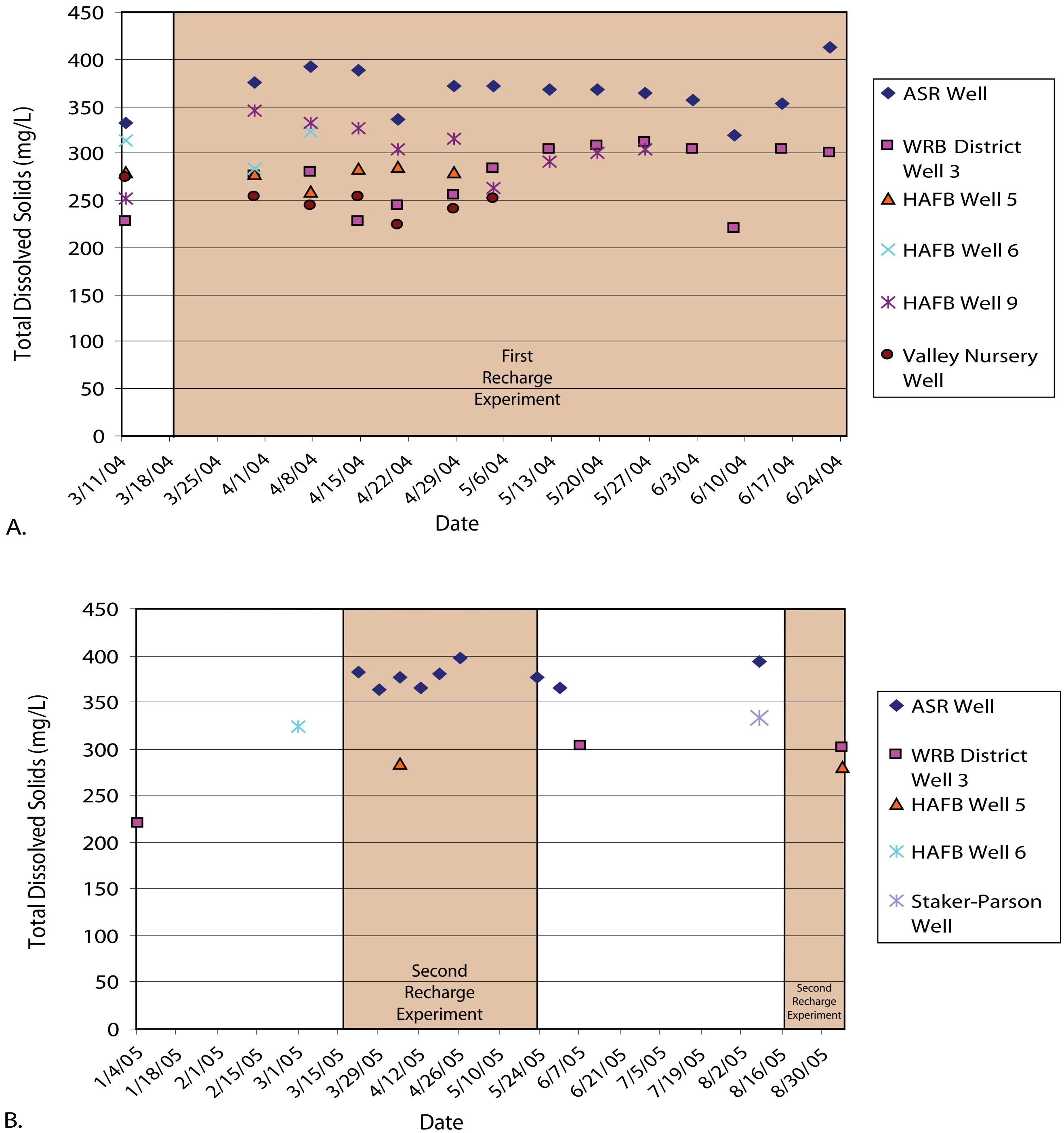


Figure 38. *Total-dissolved-solids concentrations of well-water samples from the WRBASR study area. A. Data from the first recharge experiment. B. Data from the second recharge experiment.*

the project site in Weber Canyon, was used as a reference station. Where possible, gravity stations were established on existing cement pads to reduce cost and impact. Three stations—WRP01, WRP27, and WRP28—were installed in soft ground by cementing a 12-inch-diameter (31 cm) paving stone around a 4-foot-long (1.2 m) rod of rebar driven to ground level. This provided a stable, level platform for the gravimeter and a good benchmark for GPS measurements to track possible ground deformation.

Data Acquisition and Processing

Occupation of the entire station network required two consecutive field days each for gravity and GPS measurements. Gravity and GPS measurement campaigns were split between two crews to allow complete measurement of the entire network in two days. GPS measurements were done monthly, and gravity measurements were made bi-weekly to improve reservoir tracking. The GPS data

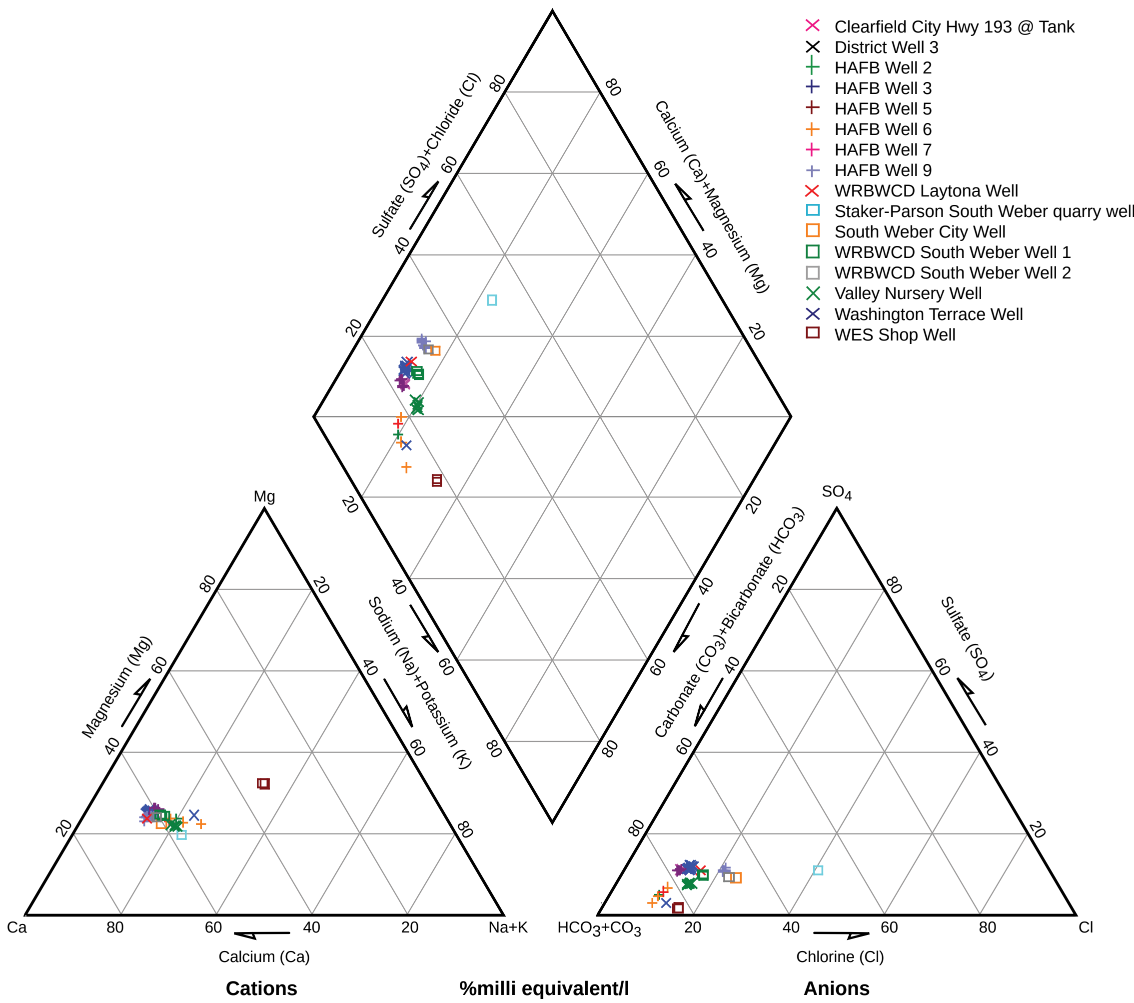


Figure 39. *Piper plot showing water-quality data for wells excluding the ASR observation well, 2003 to 2005.*

indicated no significant ground motion during the study, so the small differences in timing between GPS and gravity measurements are unimportant.

Gravity data were processed using the algorithms of Gettings (2005). Gravity changes were computed by comparing each measurement campaign to the average of all campaigns prior to March 19, 2004, when infiltration began. The scatter in the three pre-April campaigns indicates the natural variability and random noise across the network. Also, the average change in gravity of stations WRP16 through WRP22 and WRP26 is assumed to be zero over the period of the study. This assumption removes natural signals (due to precipitation, stream leakage, etc.) present across the network, enhancing the signal due to infiltration at the WRBASR pilot study area.

GPS data were processed using Trimble Geomatics Office software, in a post-processed, rapid-static mode. Both Trimble 4700 receivers were treated as rovers, using continuous GPS stations EOUT, Strawberry/Snow Basin, and NAIU, operated by the University NAVSTAR Consortium and National Oceanographic and Atmospheric Administration, as base stations.

Gravimetry Results

Temporal Gravity Changes

Figure 43 plots the gravity change at a selected set of stations over the period of the WRBASR pilot project, along with the total infiltrated mass during the project. Stations WRP01, WRP04, WRP27, and WRP26 are the three stations closest to, and the station farthest from, the infiltration site, respectively. Station WRP04, located on the observation well pad, is downgradient from the infiltration basins, and is therefore expected to show the first and largest gravity response to infiltration. Station WRP01 is close to the infiltration site, but upgradient, and therefore expected to show a delayed and reduced signal compared to WRP04. Station WRP27 is due north of the pilot project site, and therefore upgradient and farther removed than WRP01. Thus, the expected signal from infiltration is

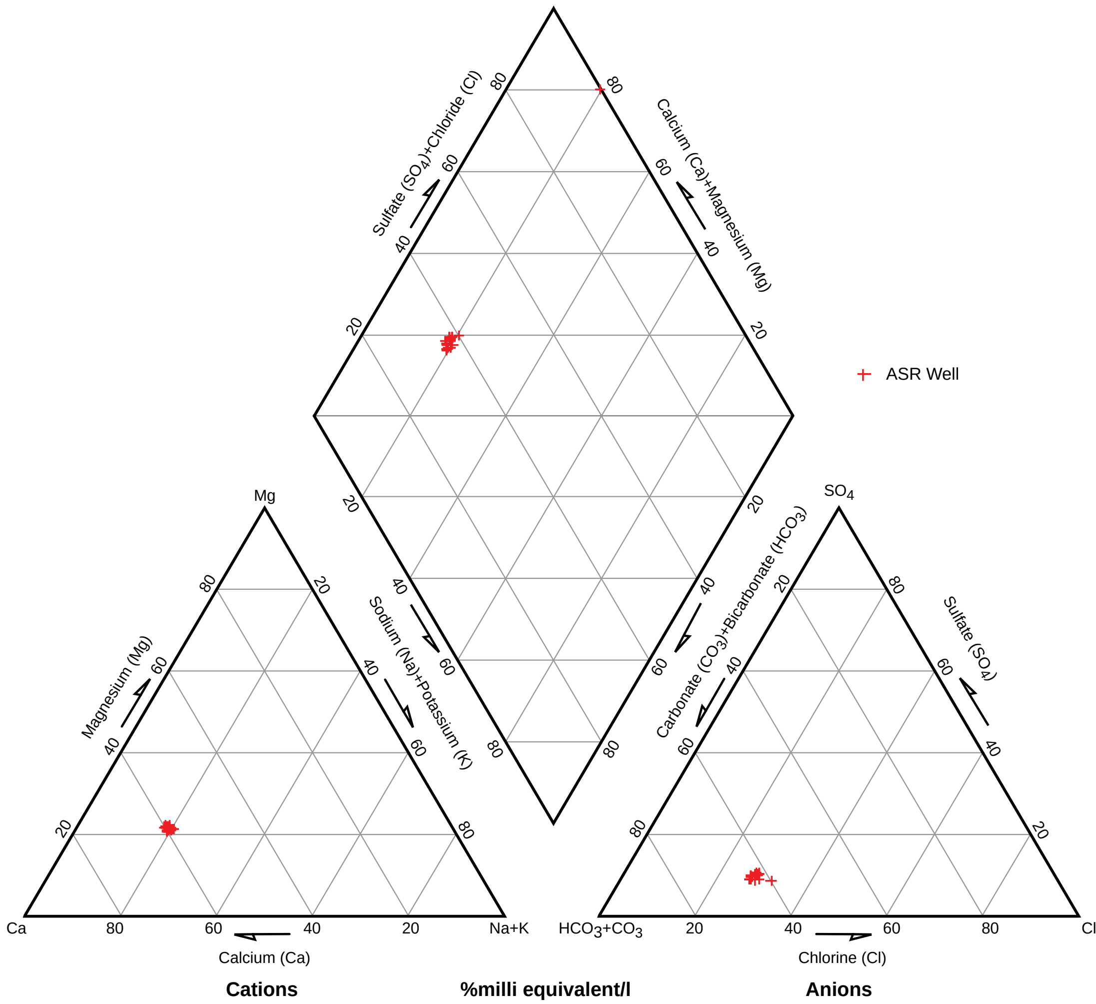


Figure 40. *Piper plot showing water-quality data collected for the ASR observation well, 2003 to 2005.*

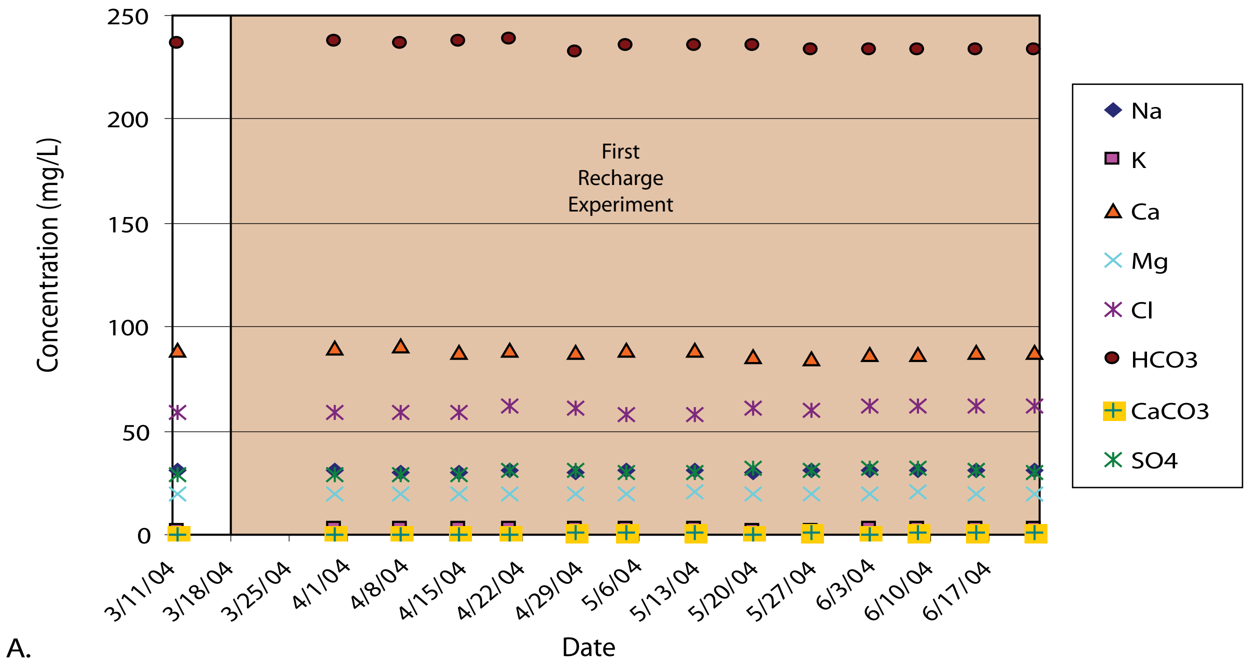
delayed compared to WRP01, and likely smaller. Note that station WRP27 was not installed until June 2004, near the peak of the infiltration signal. To make visual comparison of the WRP01, WRP04, and WRP27 time series easier, a shift of 80 μGal has been added to WRP27; this accounts for the delayed installation. However, this shift also means comparison between stations WRP27 and WRP01 or WRP04 can only be done based on the shape and magnitude of the signal decay after July 1, 2004.

The measured gravity changes are consistent with the expected signals; the first and largest signal was observed at WRP04, a smaller and delayed signal at station WRP01, and a similar shape of signal decay at WRP27. Station WRP26 shows variation of less than 10 μGal about zero, which results from the assumption that the far-field stations are stable (zero change). The small variation of WRP26 indicates that any signal greater than 10 μGal at the near-field stations is most likely due to infiltration associated with the pilot project, and not precipitation.

Note that gravity values did not decline to the original baseline during the winter of 2004–05. This indicates residual infiltration water that did not leave from the site after infiltration ceased. During the 2005 infiltration periods, stations near the site showed large, consistent increases coincident with infiltration. However, station WRP01 showed the largest peak signal, due to station WRP04 reaching an apparent saturation limit early in the infiltration. As in 2004, the gravity signals declined after the end of infiltration, although at a slower rate due to the intermittent infiltration throughout the summer and fall of 2005. Also note that station WRP26 was destroyed due to construction during the winter of 2004, and was replaced by WRP30 roughly 0.6 mile (1 km) southwest of WRP26.

Spatial Gravity Changes

In addition to comparing gravity change at selected sites through time, it is instructive to compare gravity changes for all stations at various times. Figure 44 shows eight such plots, with each bar on the plots representing a station; red bars indicate positive change, and blue negative. Each panel uses the average of the pre-infiltration sur-



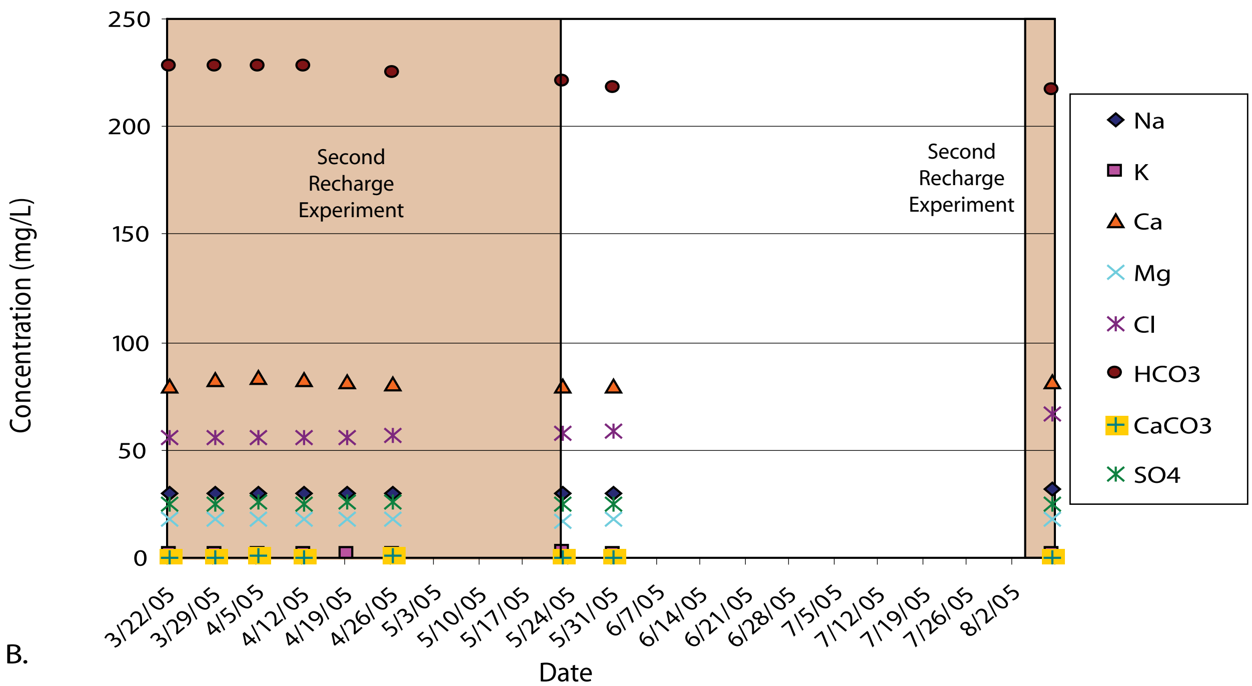


Figure 41. *General chemistry of samples from WRBASR observation well. A. Data from the first recharge experiment. B. Data from the second recharge experiment.*

veys for the zero baseline at each station, and is computed assuming the far-field stations are constant. This is identical to the assumptions used to produce figure 43. Figure 44A shows the gravity signals across the network one day prior to the start of infiltration. The small (<20 µGal), scattered changes at the stations indicate no coherent signal across the network.

After one month of infiltration, stations in and near the pilot project site displayed a clear gravity increase of 70 to 110 µGal. This large gravity increase was not present in the other near-field stations, which is expected considering typical flow rates in porous media. Just before the end of infiltration, the gravity increase from the experiment stabilized at the infiltration site, but also migrated to the south and slightly west (figure 44B). The stations with small or negative change are those used as the stable reference, so the residual changes at these stations provide a measure of the gravity change scatter due to local effects. These changes are small (<20 µGal) compared to

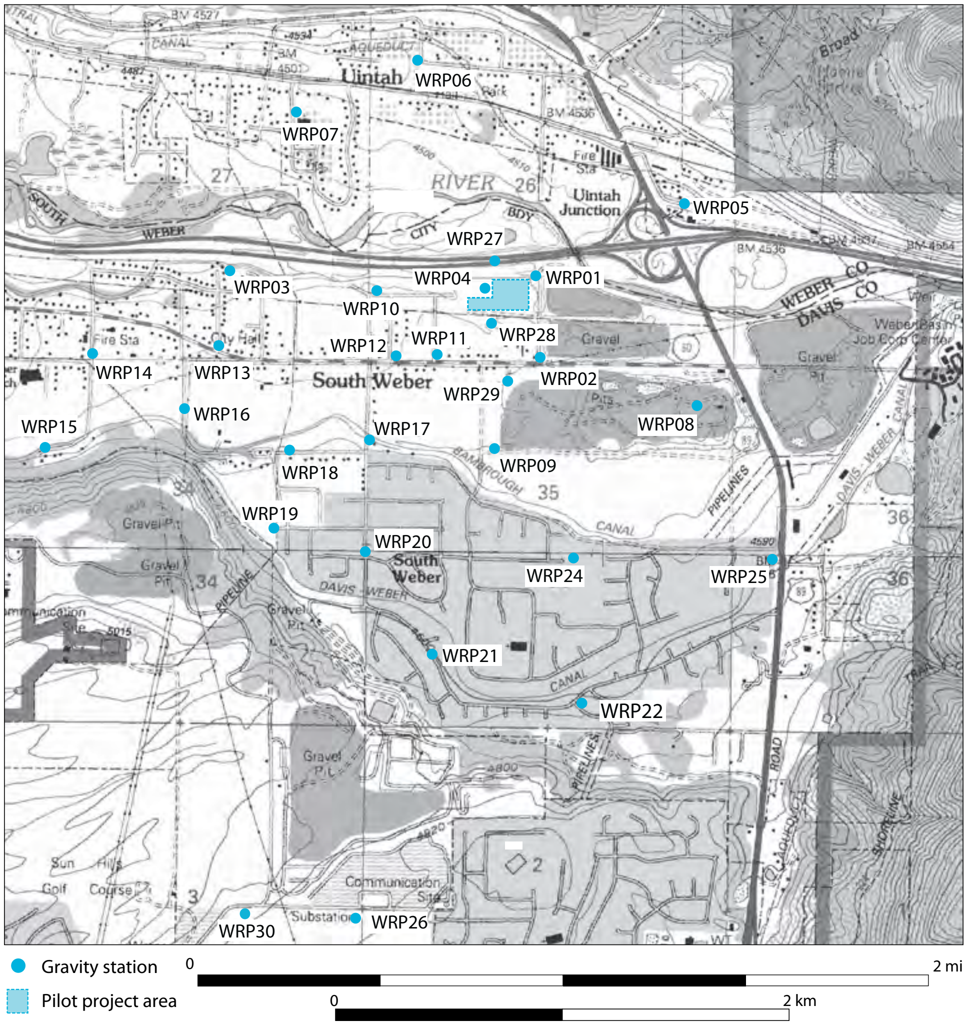


Figure 42. *Locations of gravity stations. Station WKRP (not shown) is ~6 miles (9 km) east of the infiltration site, up Weber Canyon, and is used as a reference station.*

the 100+ μGal signal near the site. Stations north of the Weber River also showed an increase in gravity, which may be due to infiltration from the river bed. If so, 20 to 40 μGal of the changes at the infiltration site could be due to natural recharge. This is possible, but not definite, as stations WRP10 and WRP12 did not show a 20 to 40 μGal increase, and both are near the Weber River.

About a month after diversion of water into the infiltration basins ceased, the increased gravity signal persisted at the infiltration site, and to the south (figure 44C). The gravity changes at the infiltration site were greatly reduced (80 μGal) from the peak value (110 μGal), but still eight times the estimated natural variation. Significant (>10 μGal), spatially coherent gravity increases also existed at stations south of the pilot project site, indicating the dominant local hydraulic gradient is to the south. Figure 44D shows the gravity changes at the end of the first year of the project, with a decreased, but still significant, excess mass under the infiltration site and stations to the south and west.

Figure 44E shows gravity changes just before the second recharge experiment began in April 2005. Note the significant (40 μGal) gravity increase (compared to values measured before the first recharge experiment) still present at the infiltration site. Based on the large signal at stations WRP05 to WRP07, at least part of the gravity increase is due to recharge from the Weber River. In the second year, gravity changes peaked at ~180 μGal at station WRP01, as shown in figure 44F. Note that station WRP04 slightly exceeded its previous peak value (140 vs. 110 μGal), but apparently quickly reached equilibrium. Station WRP01 peaked at almost twice the value of 2004, shortly before infiltration was suspended due to water leakage into the Staker-Parsons pit east of the infiltration site. This gravity change is consistent with major migration to the east from the site, causing the pit leakage; the infiltration mound locally reversed the regional hydraulic gradient.

Peak gravity changes quickly decreased after suspension of infiltration, but a signal exceeding 100 μGal was still present at the infiltration site in late June 2005 (figure

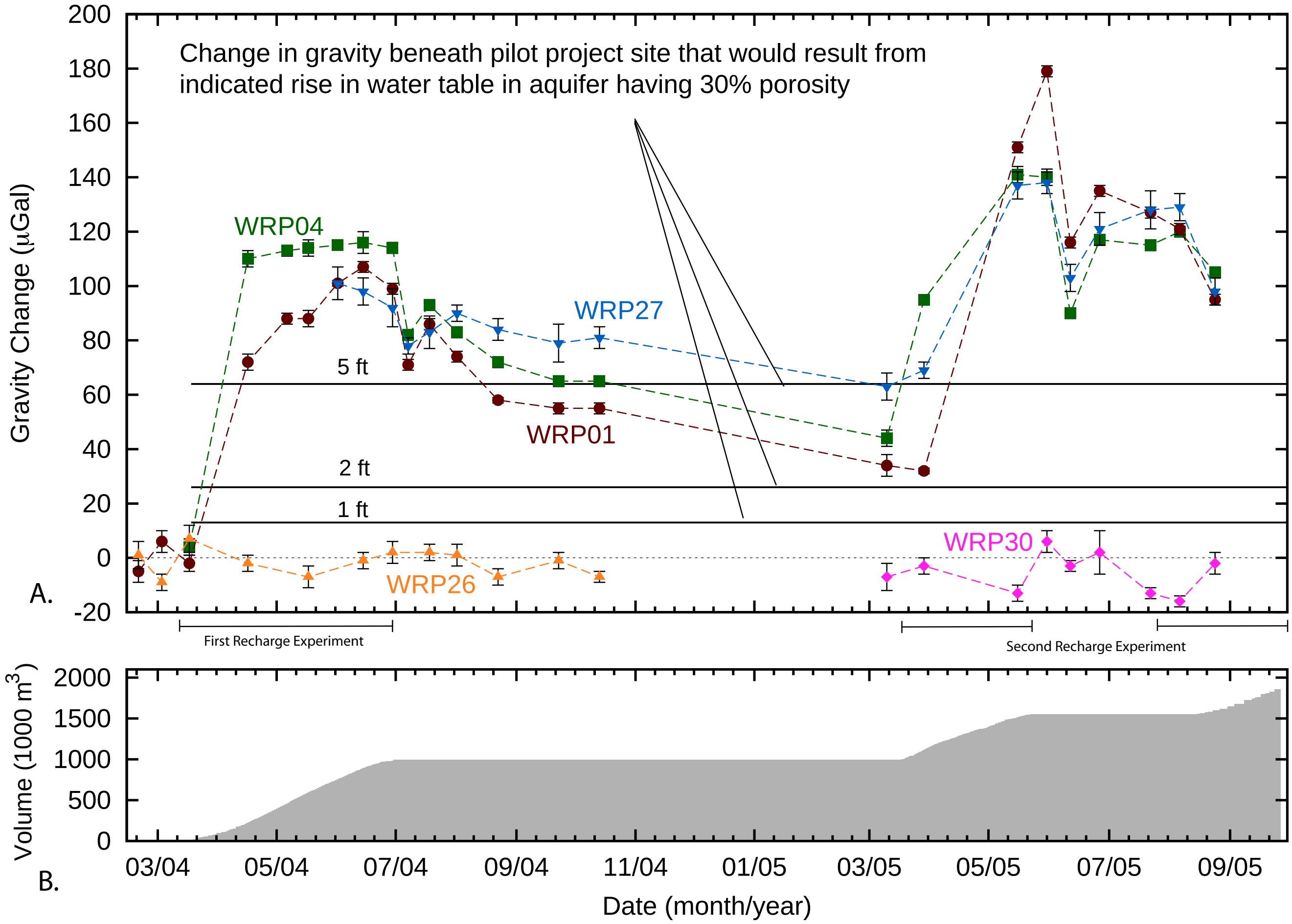


Figure 43. *Gravity changes at selected stations versus time and infiltration volume. A. Gravity changes for stations WRP01, WRP04, WRP26, WRP27, and WRP30 assuming the average of stations 16 to 22 and WRP26 (first recharge experiment) and WRP 30 (second recharge experiment) were constant in time. Stations WRP01, WRP04, and WRP26 use the average of all readings prior to March 19, 2004, as the zero baseline. A uniform shift of 80µGal has been applied to station WRP27 for comparison with other stations adjacent to the infiltration site. B. Cumulative infiltration, as measured by the diversion weir.*

44G). At the end of the second recharge experiment (figure 44H), the gravity signal at the infiltration site remained at ~100 µGal, and the signals at stations to the south and immediately west of the infiltration ponds were ~60 µGal. Up to ~40 µGal of this signal is likely due to infiltration from the Weber River, as shown by the signals at WRP05-WRP07, but there is still a clear indication of a mound of infiltrated water that resides below the infiltration site long after infiltration stops.

Estimating Excess Mass

Using a grid of gravity changes, it is possible to estimate the mass causing the gravity change ("excess mass"). The calculation relies on Gauss' Theorem for potential fields, which relates the magnitude of a causative body to the integral of the flux at a surface. By carefully contouring the gravity changes, it is possible to define a zero-change boundary, and sum the total gravity change over the area inside the boundary.

This sum, which is equivalent to the surface integral, can be converted to an equivalent mass source directly under the infiltration site. The magnitude of the estimated excess mass is then compared to the known infiltrated mass, as measured at the diversion weir. If the two estimates agree, then the gravity changes are measuring all the mass change due to the infiltration. However, due to the relatively sparse nature of the gravity network, any comparison beyond an order-of-magnitude (factor of ten) estimate is extremely difficult.

The excess mass calculated for the May 2004 campaign is equivalent to 750 acre-feet (0.92 hm^3) of water. The measured total infiltration volume up to that time is ~500 acre-feet (0.62 hm^3). The larger value from gravity is most likely due to the poor station density to the north of the infiltration site, which makes accurate contouring very difficult. Additional mass at the measurement site may also exist due to stream leakage, but this cannot be accurately determined without more near-river gravity stations or wells. Regardless, the agreement between estimated

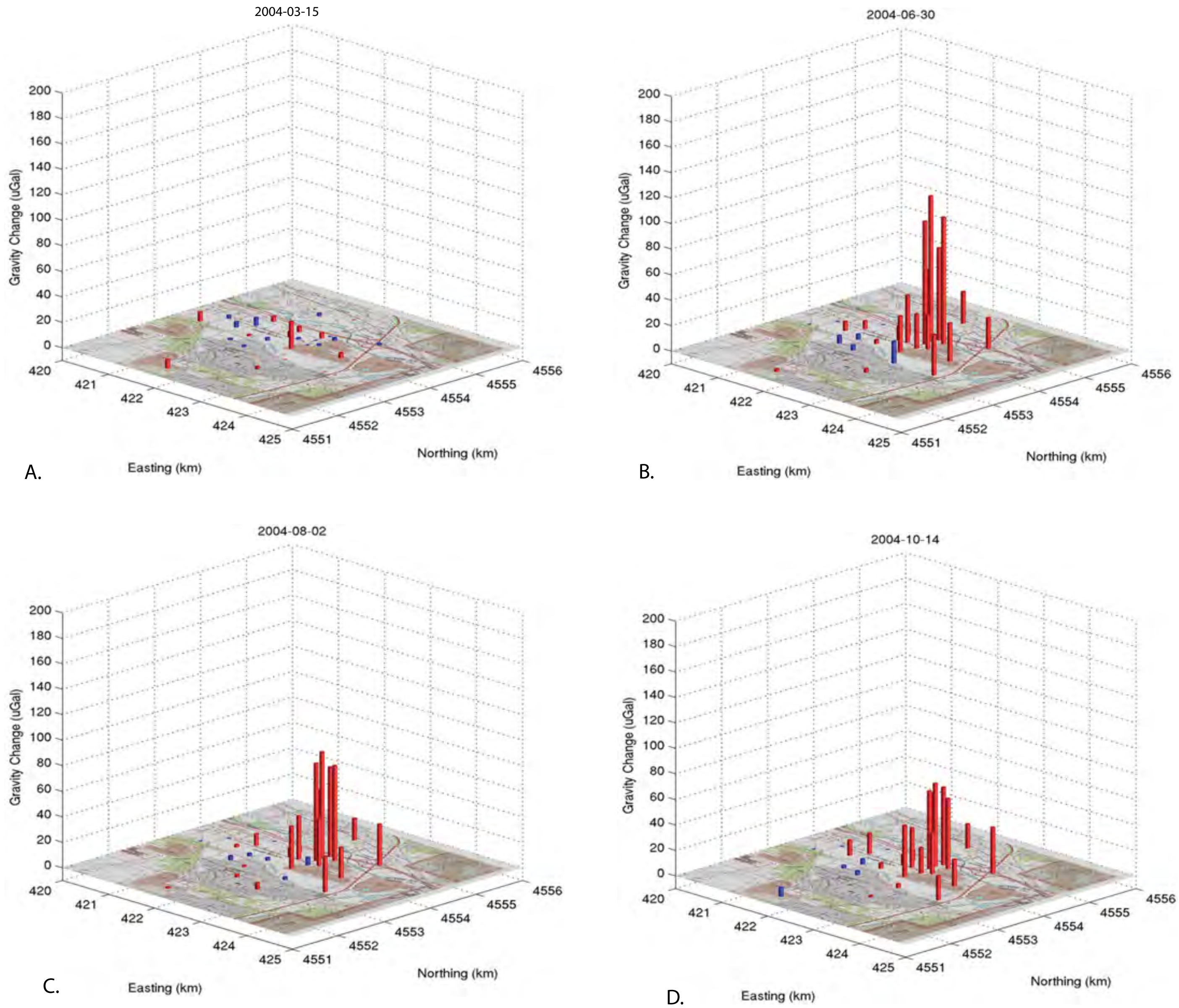


Figure 44. *Gravity changes across the station network for selected times, relative to the average of all pre-March 2004 surveys. Positive gravity changes are denoted by red bars, with height indicating magnitude of change. Negative gravity changes are shown in blue. A. Gravity changes a day before infiltration begins in March 2004. B. Gravity changes for 30 June 2004, showing the peak gravity signal at the infiltration site. C. Gravity changes as of 2 August 2004, approximately 1 month after the end of the first period of infiltration. D. Gravity changes at the end of the first recharge experiment, on 14 October 2004.*

excess mass and measured infiltration mass to within 50% is very good.

Conclusions

The extremely limited water-level information makes interpretation of the exact depth of ground-water infiltration difficult. Based on the minimal water-level changes observed in the WRBASR pilot project site observation well and the large gravity changes, the interpretation is that infiltrated water is reaching the low-permeability layer at 116 feet (35 m) depth below ground surface, which retards the downward flow. As a result, the infiltrated water builds a mound (leading to the gravity increase), which then flows along the low-permeability layer down the local hydraulic gradient. At the infiltration site, the gravity results indicate the local hydraulic gradient is predominantly to the south. The hydraulic gradient above the low-permeability layer may be influenced by the eastward slope of its upper surface, confirmed by its presence at lower elevation in the Staker-Parson north pit than at the observation well. This local perched gradient may differ from the regional hydraulic gradient in the main part of the aquifer below the low-permeability layer. Alternatively, the local south and east gradient below and near the pilot project site may be a minor permutation,

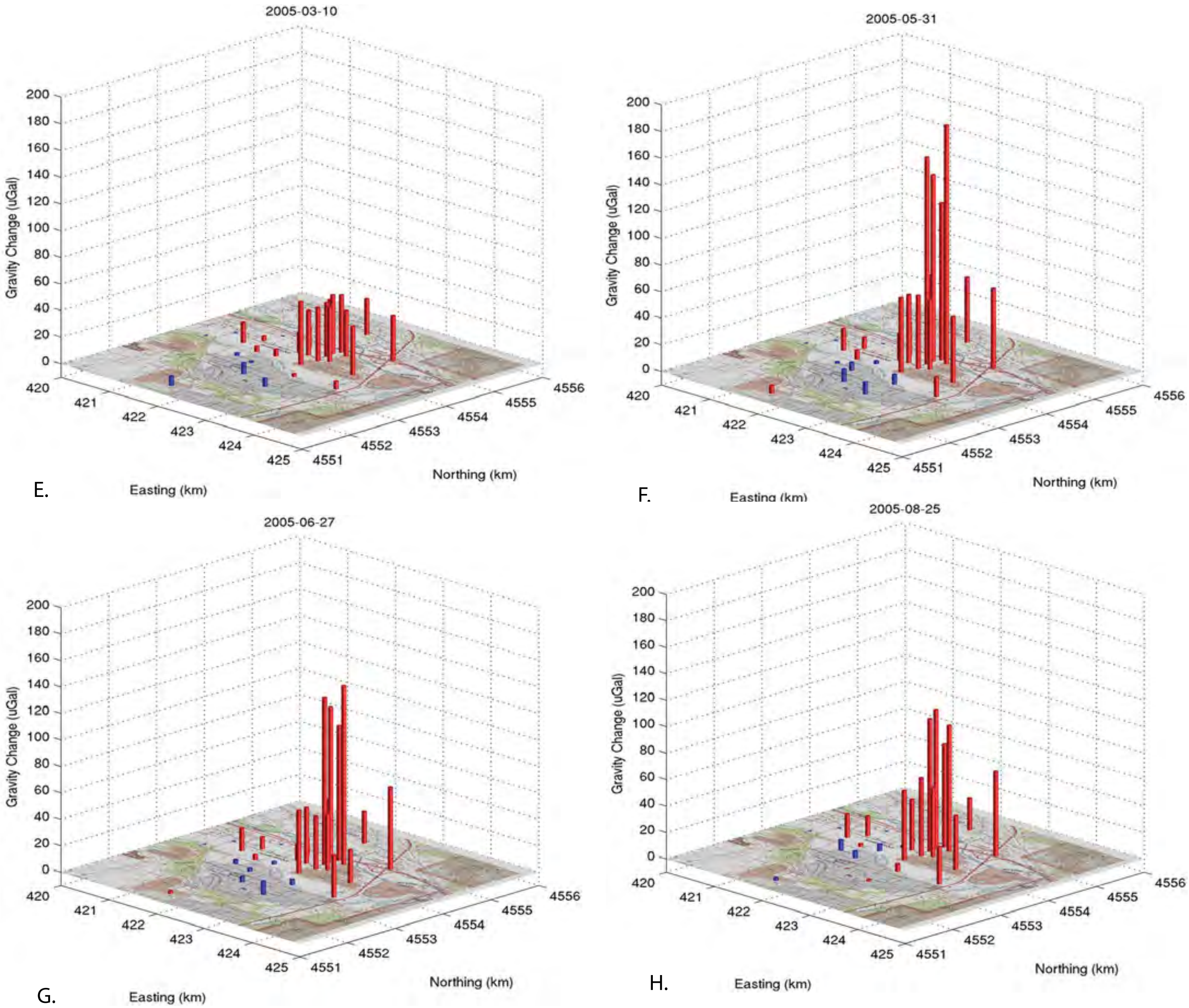


Figure 44. continued. *Gravity changes across the station network for selected times, relative to the average of all pre-March 2004 surveys. Positive gravity changes are denoted by red bars, with height indicating magnitude of change. Negative gravity changes are shown in blue. E. Gravity changes for 10 March 2005, the start of the second year of monitoring. F. Gravity changes as of 31 March 2005, at the peak signal of the second year. G. Gravity changes for 27 June 2005, approximately 1 month after the end of the second period of infiltration. H. Gravity changes for 25 August 2005, the end of the pilot project.*

due to deformation of the layer, within an overall west to southwest hydraulic gradient.

After the end of infiltration, the ground-water mound under the site continued to flow downgradient, leading to a decrease in gravity from the peak value at the site, and increasing gravity at the stations to the south. The lack of significant westward flow is interesting, as it is different from the results of the 1950s Bureau of Reclamation experiments which were located to the east of the WRBASR infiltration site. At the WRBASR infiltration site we observe (1) changes in gravity that clearly track infiltration volume in time, (2) spatial coherence of gravity changes that allow determination of local hydraulic gradients, and (3) estimates of the excess mass causing the gravity signal that agree reasonably well with the known infiltration mass.

GROUND-WATER FLOW MODEL

Introduction

Matyjasik and several of his students constructed a numerical model of the study area to better understand ground-water flow in the east shore aquifer system, and to evaluate the effects of our artificial recharge experiments on the ground-water flow system. The primary goals of the model were to simulate flow conditions in the direct vicinity of the recharge area from year 2004 on, and to allow prediction of the long-term effects of ongoing recharge. The model uses all available water-level and ground-water-withdrawal data for 1956–2005, and all available published geologic data. The model encompasses an area of 100,000 feet x 100,000 feet (30.5 x 30.5 km), between the Wasatch Range and Great Salt Lake and from Kaysville in the south to northern Ogden City in the north (figure 45). The three-dimensional numerical model MODFLOW, developed by the U.S. Geological Survey (McDonald and Harbaugh, 1984, 1988), was used to simulate ground-water flow, using visual MODFLOW as the interface. This portion of the report includes a description of input data in the model (some of which is described in the "Geologic and Hydrologic Setting" section of this report), a brief description of the model, and the results of the modeling.

General Description of the Numerical Computer Model

The northern and southern model boundaries are located where ground-water flow is almost directly westward from the mountain front toward Great Salt Lake. The western boundary represents the likely western margins of the Delta and Sunset aquifers below Great Salt Lake, and the eastern boundary coincides with the Wasatch fault zone. These boundaries are located far enough from the pilot project study area so that boundary conditions do not interfere with the flow system near the simulated artificial recharge. The model was constructed and calibrated using available geologic data, water levels, aquifer-test results, well pumping information, and climatic data. The calibrated transient flow model simulates the ground-water flow system over the past 50 years starting from January 1, 1956. Several data represent average conditions, and estimated data were used where the direct measurements were not available. The calibrated model was used to project changes in the flow system due to the artificial recharge in the next five years; however, future projections can be extended indefinitely. The simulations must be considered a simplification of the real ground-water flow system because the averaged input values do not represent exact conditions at all times. The model uses a series of rectangular cells ranging in size from 250 feet x 250 feet (76 x 76 m) in the direct vicinity of the pilot project site to 1000 feet x 1000 feet (305 x 305 m) in areas farther from the recharge area (figure 45). Input data in the model include (1) boundary conditions, including recharge, initial heads, and the spatial distribution of geologic layers, (2) hydraulic conductivity, and (3) specific storage values.

The model consists of six layers that represent, from shallowest to deepest, the shallow water-table aquifer (layer 1), the confined Sunset aquifer (layer 2), the confining layer between the Sunset and Delta aquifers (layer 3), the Delta aquifer (layers 4 and 6), and the low-permeability layer (layer 5) encountered below the recharge area (figures 46 and 47). The confining layers were distinguished in the model because of the possible changes in storage over the time of simulation caused by significant changes in hydraulic head.

Input Data

Surface Water

The average annual surface-water inflow to the study area includes 374,000 acre-feet (461 hm^3) (calculated from years 1955–2003) as measured in the Weber River at the Gateway gage, and 77,000 acre-feet (95 hm^3) in the Ogden River (calculated from years 1992–2003) (figures 48 and 49). Average annual flow in the Weber River measured at the Plain City gage in the west part of the study area is 346,000 acre-feet (427 hm^3). The Ogden River annual flow estimated by Feth and others (1966) was 160,000 acre-feet (197 hm^3), which included water in a pipeline from Pineview Reservoir. The estimated flows from specific ungaged perennial, intermittent, and ephemeral streams totals about 13,800 acre-feet (17 hm^3) per year, of which 10%, or 1380 acre-feet (1.7 hm^3), is estimated to recharge the aquifers (Feth and others, 1966). Other mountain-front streams are estimated to provide approximately 10% of the flow volume of the Weber River, as measured at the Plain City gage (Feth and others, 1966).

The seasonal fluctuation of Weber River flow is extremely large (figure 50). The largest mean monthly flows during wet years are about 10 times greater than during dry years. Peak discharge of the Weber River is from late April to early July, whereas the lowest discharge is during August through October (figure 50) (Federal Emergency Management Agency, 1982). The sum of flows measured in the Ogden and Weber Rivers measured near the mountain front is approximately 175 cfs (4.96 m^3/s) greater than the flow measured downgradient in the Weber River at Plain City, below the confluence. Part of this water is diverted to the Ogden-Brigham canal. An estimated 230,000 acre-feet (284 hm^3) of water enters the area directly from atmospheric precipitation, using an average atmospheric precipitation of 19.8 inches (50.3 cm) based on measurements in the years 1956-2004 (figure 51).

About 344,000 acre-feet (424 hm^3) of surface water annually leaves the study area in the Weber River. This volume is smaller than the measured flow at Plain City because it is reduced by about 30,000 acre-feet (37 hm^3) due to evapotranspiration from open water and marsh areas at the Ogden Bay Bird Refuge (Feth and others, 1966). The Ogden-Brigham canal carries about 10,000 acre-feet

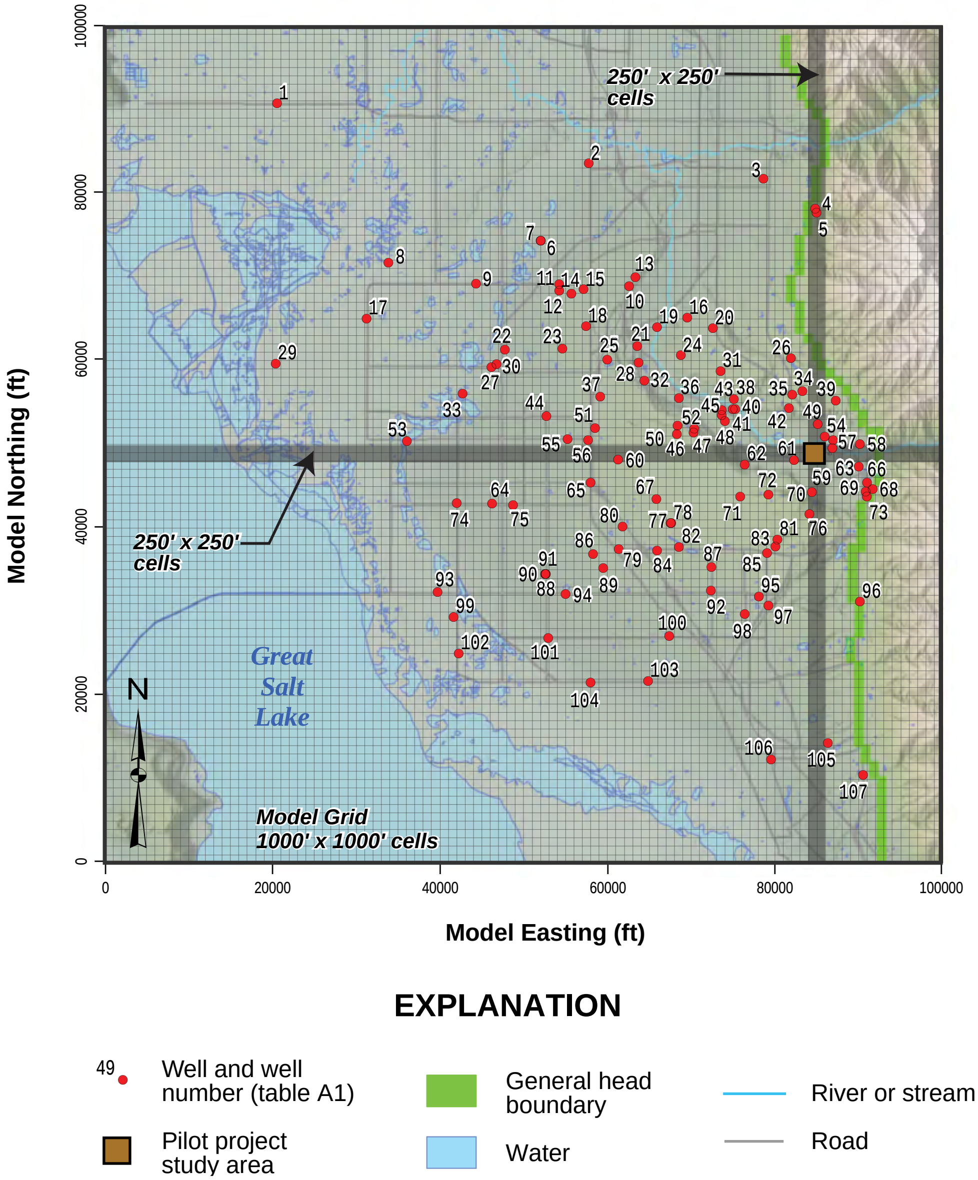


Figure 45. *Location, wells, and grid system used in the numerical model.*

(12.3 hm³) of water out of the study area. Water leaving the study area in drains and sloughs, including Howard Slough, Hooper Slough, Walker Slough, and Dixie Creek is about 20,000 acre-feet (24.6 hm³) per year. About 4300 acre-feet (5.3 hm³) of water annually reaches Great Salt Lake through the lower reaches of mountain-front stream channels, including three forks which emerge from Kays Creek and Holmes Creek (Feth and others, 1966).

Climate

As described in the Introduction to this report, the climate of the study area is temperate and semiarid. Precipitation increases from west to east. Generally, the normal annual precipitation ranges from less than 12 inches (30.5 cm) near Great Salt Lake to more than 20 inches (50.8) near the Wasatch Range front. The average annual precipitation for the entire area is about 23.8 inches (60.6 cm). Most of this precipitation occurs between September and May. The average potential evapotranspiration calculated for the study area based on air temperature is 45 inches (114 cm) (figure 52).

Ground Water

Occurrence: Ground water in the study area occurs chiefly in unconsolidated sediments composed of gravel, sand, and fine fractions, to a depth of more than 3000 feet (914 m) (Feth and others, 1966), as described in the Geologic and Hydrologic Setting section of this report. Ground water in the study area occurs in both shallow, unconfined aquifers and deeper, mostly confined aquifers. The unconfined aquifers contain local bodies of perched water. The major confined aquifers—the Sunset and Delta aquifers—are composed of relatively coarse sediments and are locally hydraulically interconnected. The Sunset and Delta

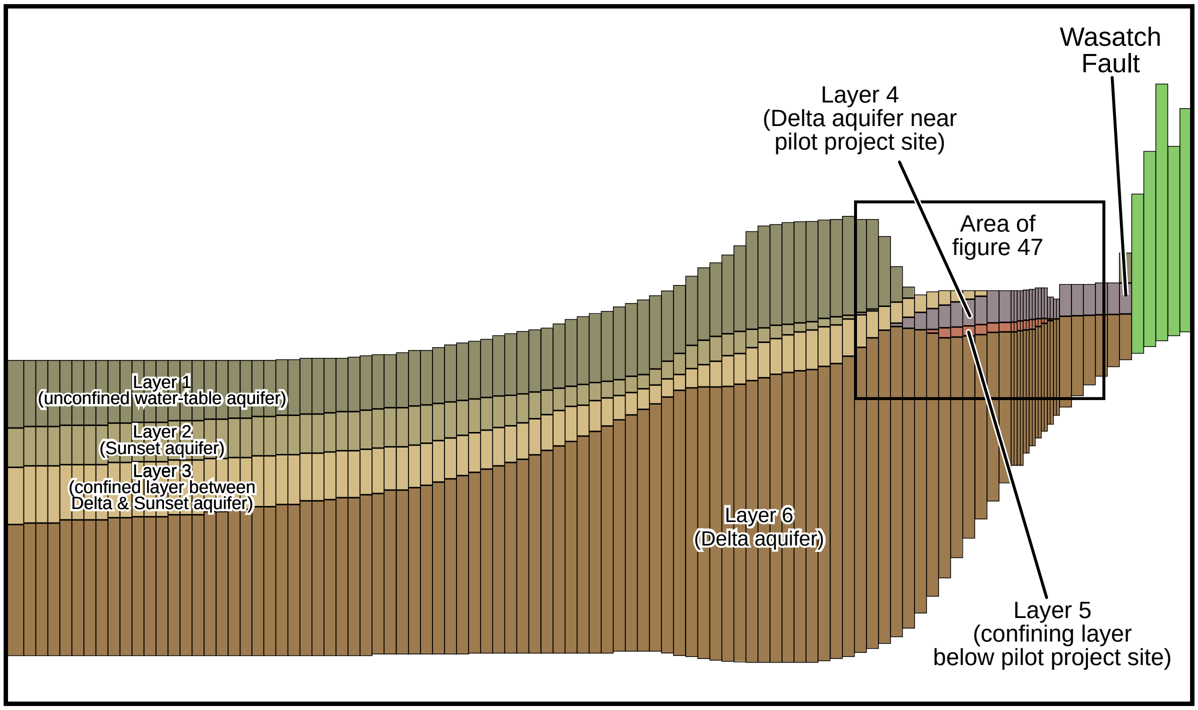


Figure 46. *East-west cross-sectional view of the study area model.*

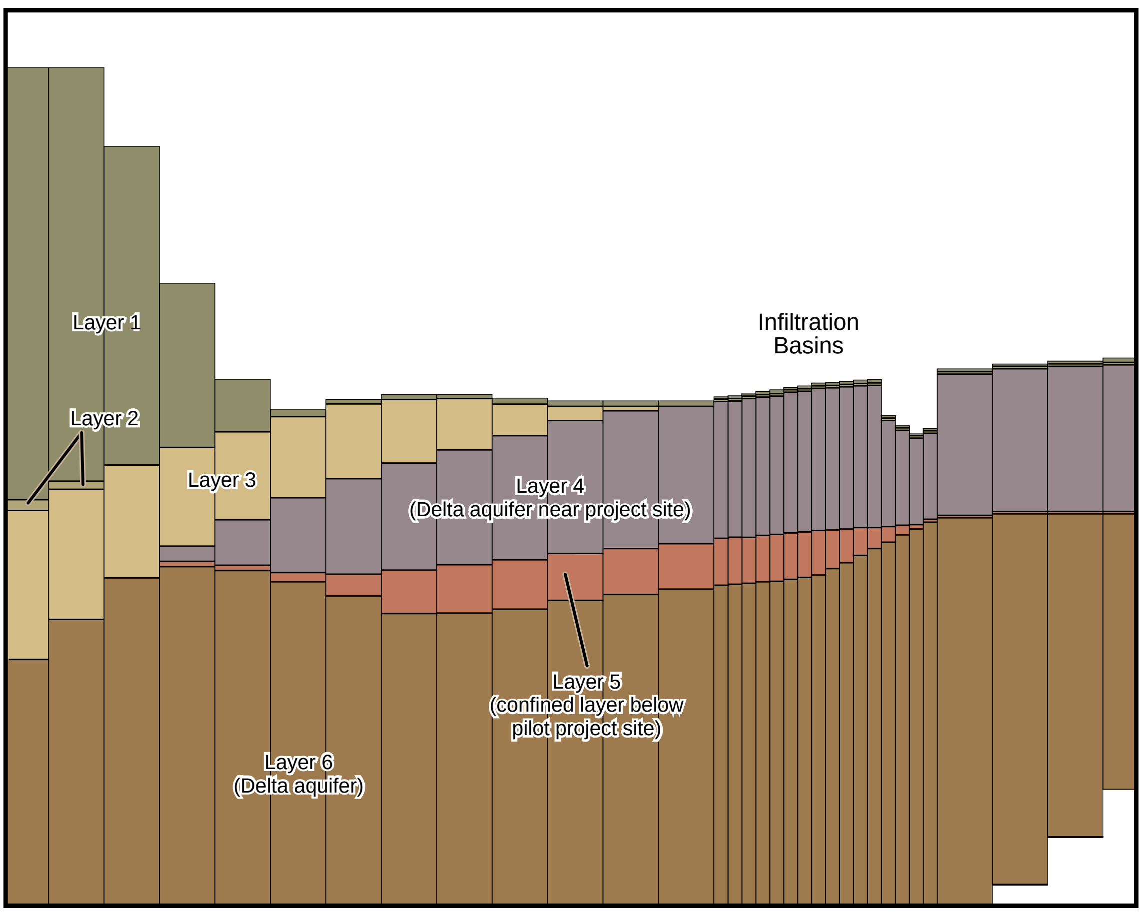


Figure 47. *East-west cross-sectional view of the model in the direct vicinity of the pilot project site.*

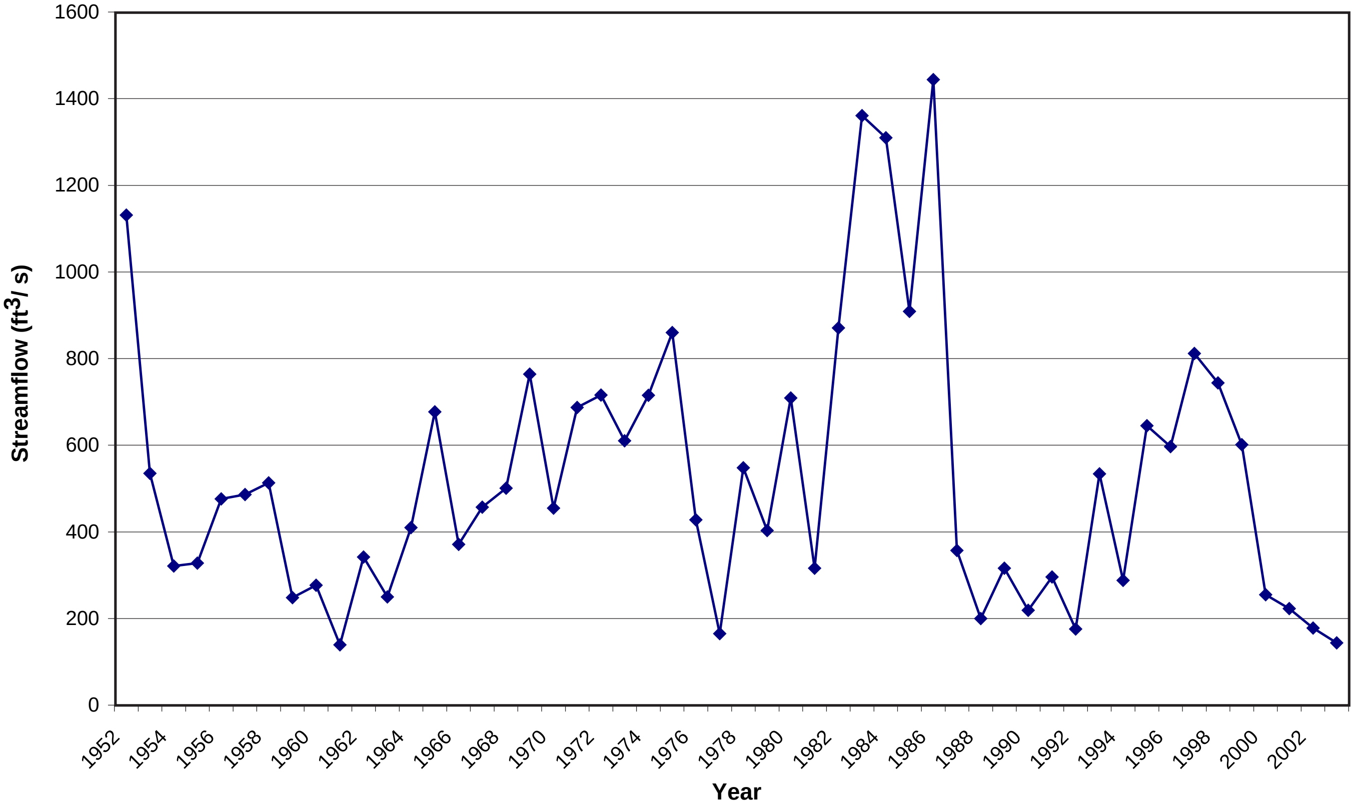


Figure 48. *Streamflow of Weber River at Gateway from 1952 to 2004 (data from U.S. Geological Survey, 2004).*

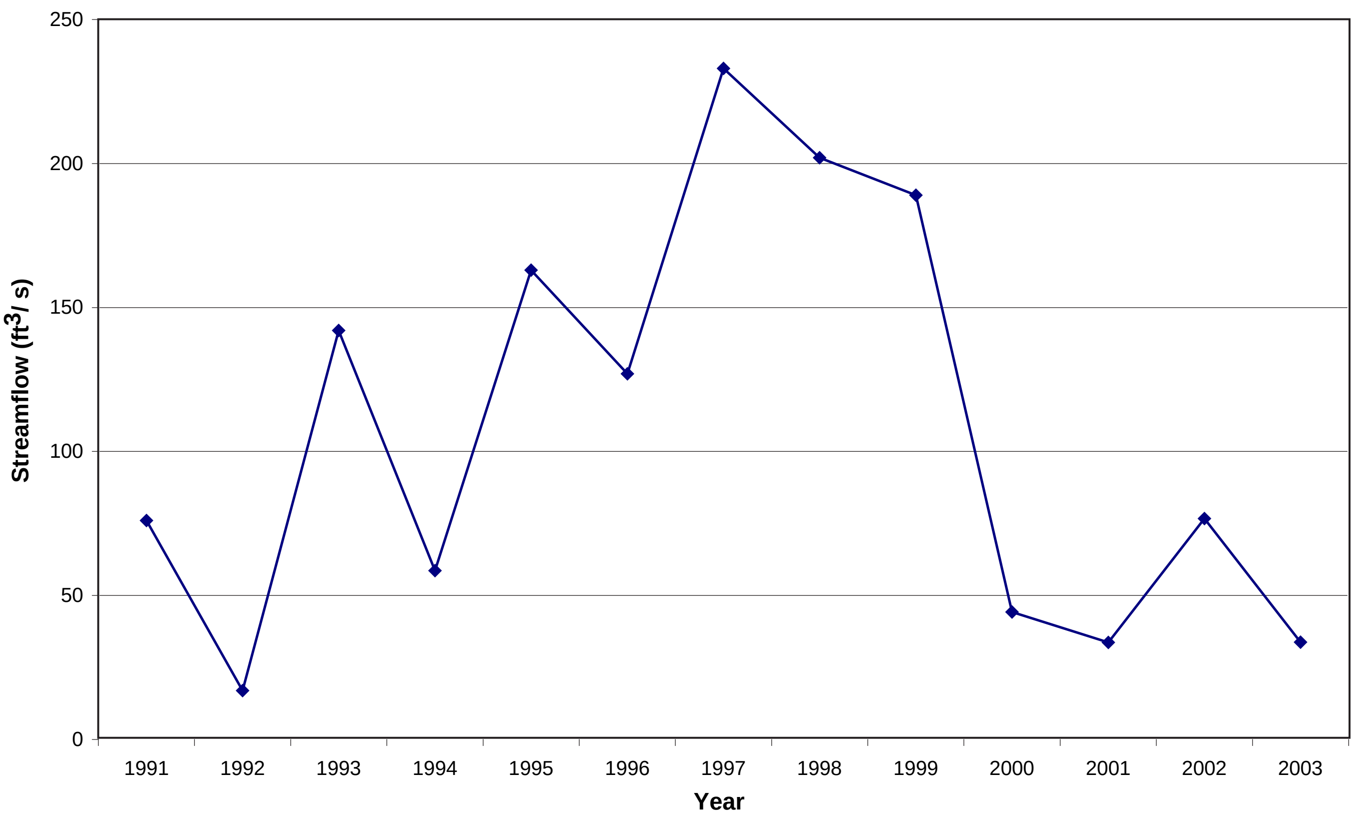


Figure 49. *Streamflow of Ogden River below Pineview near Huntsville from 1991 to 2003 (data from U.S. Geological Survey, 2004).*

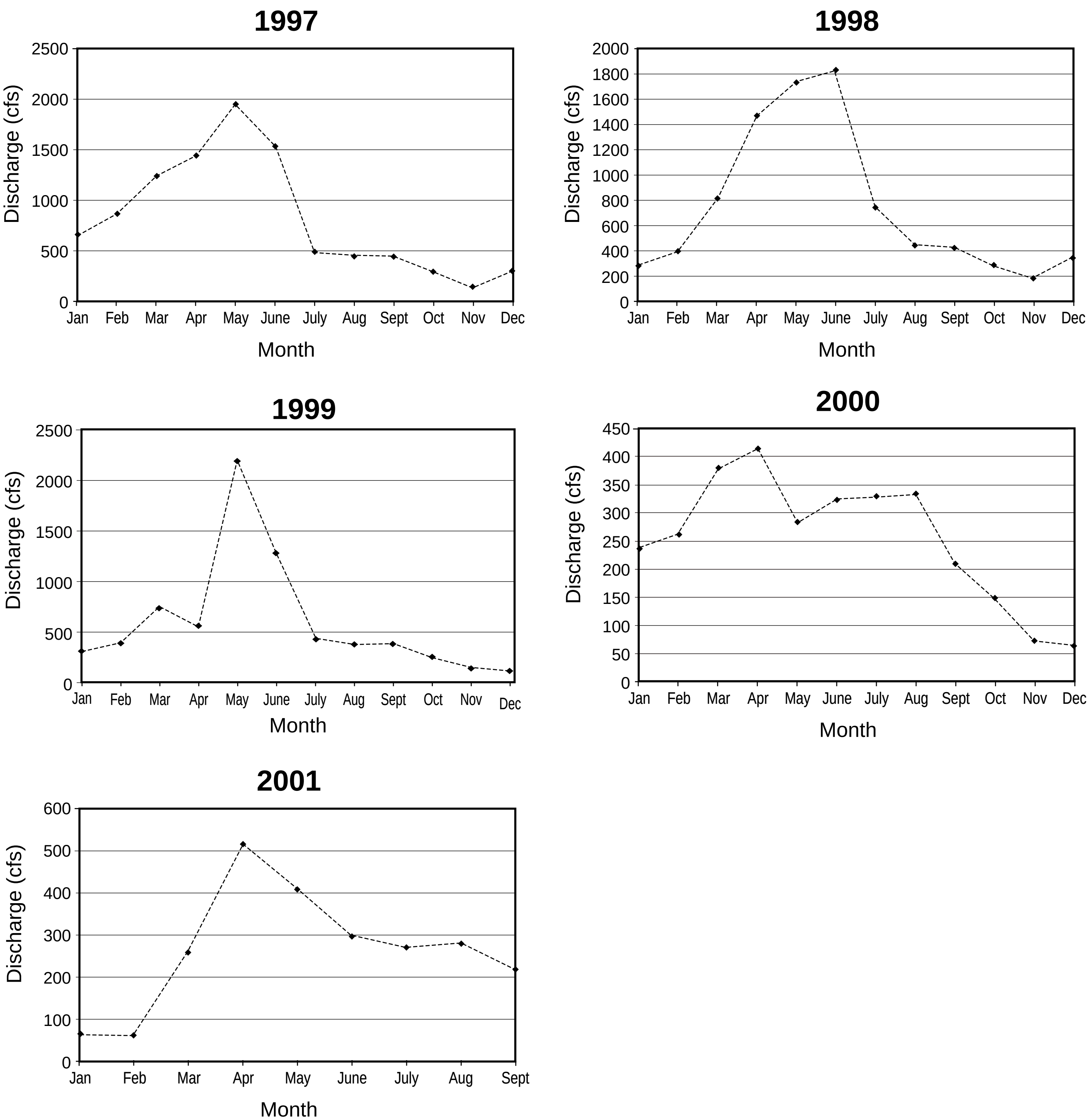


Figure 50. *Monthly hydrographs from 1997 to 2001 of Weber River at Gateway near the head of Weber Canyon just east of the study area (data from U.S. Geological Survey, 2004).*

aquifers are separated by predominantly fine-grained layers ranging up to 200 feet (60 m) thick, but are difficult to differentiate near Great Salt Lake, where they are composed of several thinner layers of variable permeability, and near the Wasatch Range, where the intervening fine-grained deposits are absent.

Source of recharge: The ultimate source of ground water in the study area is precipitation, mostly in the form of snow on the Weber River and Ogden River drainage basins. Part of the runoff resulting from atmospheric precipitation contributes to ground-water recharge by either direct infiltration from streams or infiltration from canals and unused irrigation water. Part of the precipitation infiltrates directly to the ground-water table on the topographic benches along the mountain front. Surface waters on flatlands in the central and western parts of the study area contribute very little to recharge because of their

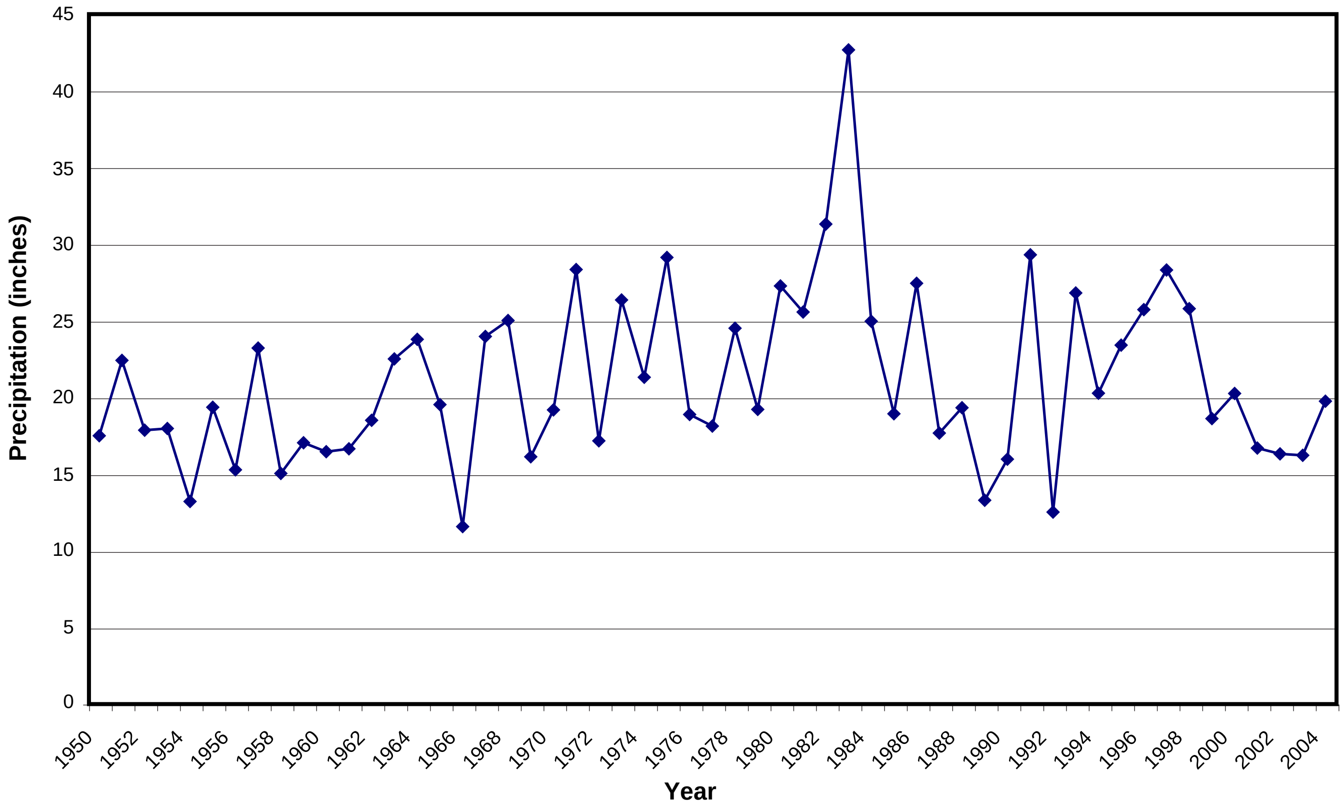


Figure 51. *Annual precipitation representative of the study area measured in Ogden Pioneer Powerhouse (PH) station (Western Regional Climate Center, 2005).*

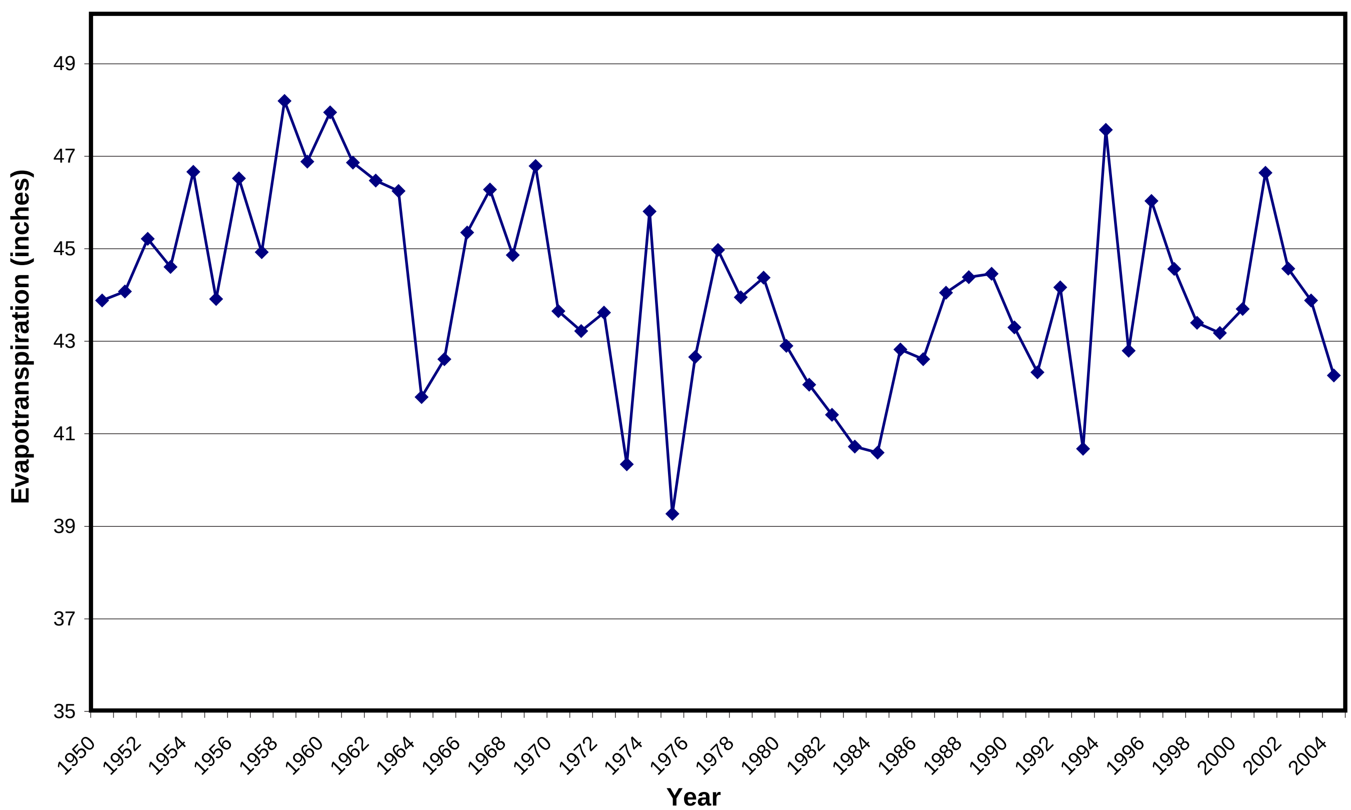


Figure 52. *Total average evapotranspiration of the study area (data from Utah Climate Center, Utah State University, written correspondence, 2005).*

high evapotranspiration. The main recharge area is composed of Weber Delta sediments from the mouth of Weber Canyon to about 1.5 miles (2.4 km) west of the mountains. Estimated recharge to the Delta aquifer, excluding mountain-front subsurface flow, is about 40,000 acre-feet (49 hm^3) per year, including 16,000 acre-feet (20 hm^3) average recharge from the Weber River, 2000 acre-feet (2.5 hm^3) from the Ogden River, 1380 acre-feet (1.7 hm^3) from mountain-front streams, 7000 acre-feet (8.6 hm^3) from direct precipitation, and 4000 acre-feet (4.9 hm^3) from irrigation seepage and canal losses to benchlands and floodplains (Feth and others, 1966).

The main source of recharging water to the unconsolidated aquifers is seepage from the Weber River within a distance of 1.5 miles (2.4 km) from the mountain front (figure 53). The average calculated loss to infiltration is 7% of the total discharge from the river (Feth and others, 1966). The loss to infiltration ranges from about 3% of the total discharge during high flow to about 20% of discharge during low flow (Clark and others, 1990). Losses during the period between March and June account for about one-half of the estimated total annual losses (Clark and others, 1990). Based on streamflow measurements provided by Feth and others (1966) and Clark and others (1990), recharge from the Weber River is about 12,000 to 38,000 acre-feet (15–47 hm^3) per year. In the principal recharge area just west of the mountains, the floodplain of the Weber River is underlain by coarse gravels and sands. Depth to the water table ranged from about 135 feet (41 m) in 1962 to about 175 feet (53 m) in 2003 (well [B-5-1]20ddd-2, figure 3). A trench dug across the Weber River for installation of a pipeline indicated that recharge occurs vertically downward below the river bed, because the recharge was so rapid that gravels in the recharge zone were dry. The recharge rate from the Weber River ranges from less than 100 cubic feet per second (2.8 m^3/s) to about 300 cubic feet per second (8.5 m^3/s) (figure 53). Seepage losses from the Ogden River are estimated to be about 3 cubic feet per second (0.08 m^3/s) or 2000 acre-feet (2.5 hm^3) per year, and fluctuate between 1% and 5% of the annual flow (Feth and others, 1966).

The slope of the potentiometric surface away from the mountains and toward Great Salt Lake suggests that the Wasatch Range is a linear source of recharge. Feth and others (1966) estimated recharge by underflow from the Wasatch Range is 25,000 acre-feet (30.8 hm^3). Evidence for ground-water flow within the mountain front was found during the drilling of the Gateway tunnel. The tunnel is 3.3 miles (5.3 km) long, and a significant inflow to the tunnel occurred during the drilling at a distance of 1100 feet (335 m) from its west portal. The flow measured in the tunnel during a period of two years, from 1953 to 1955, was between 180 and 580 gallons per minute (11-37 L/s). Estimated annual subsurface inflow from consolidated rock to basin fill is about 76,600 acre-feet (94.5 hm^3) (Clark and others, 1990). This flow was calculated from estimated values of transmissivity and hydraulic gradient.

Movement of ground water: Ground water in the study area generally flows westward from the Wasatch Range toward Great Salt Lake. Near the mountain front heads decrease with depth, indicating a downward vertical hydraulic gradient. Farther away from the mountain front water flows upward through confining layers. This upward flow has been decreasing over the years due to large-scale withdrawals of water from wells. Water levels in wells near South Weber and Hill Air Force Base have been declining, as detailed in the Geologic and Hydrologic Setting section of this report, resulting in an increased area where artesian conditions have changed to unconfined conditions.

Long-term fluctuations in confined aquifers: Based on our evaluation of records from the Utah Division of Water Rights and the WRBWCD, the first period of water-level decline in some wells occurred during the years 1953–61 and discharge from wells in 1956 was estimated to be about 25,000 acre-feet (30.8 hm^3). Wells in the Delta aquifer typically produce 200 to 2500 gallons per minute (12.6–157.8 L/s). A number of flowing wells are located west of (below) the 4300 foot (1311 m) topographic contour. The number of flowing wells in this area has decreased over the years. Flowing wells typically produced 1–80 gallons per minute (0.06–5 L/s) before 1960.

Boundary and Initial Conditions

No-flow boundaries are simulated by inactive cells surrounding the area of active cells. The Wasatch fault in layer 6 and Great Salt Lake in layer 1 are simulated by a general head boundary allowing flow across both boundaries depending on boundary properties. A no-flow boundary below layer 6 assumes no significant flow between layer 6 and deeper geologic layers. Recharge boundaries are used to simulate natural recharge to the uppermost layer in areas of primary recharge, mostly along the mountain front and in the eroded river valleys. No-flow boundaries occur at the northern and southern boundaries of the model area in all layers.

Ground-water withdrawal prior to 1956 was most likely balanced by natural recharge from infiltration of atmospheric precipitation, infiltration of Weber River and Ogden River water, and underflow from the mountain block. The initial, steady-state-condition model simulation was calibrated using average water level data from 1956. Ground-water withdrawals in the study area generally increased after 1956 (figure 54).

Hydraulic Parameters

All available information, including the results of aquifer pump tests and specific capacity tests, was used to esti-

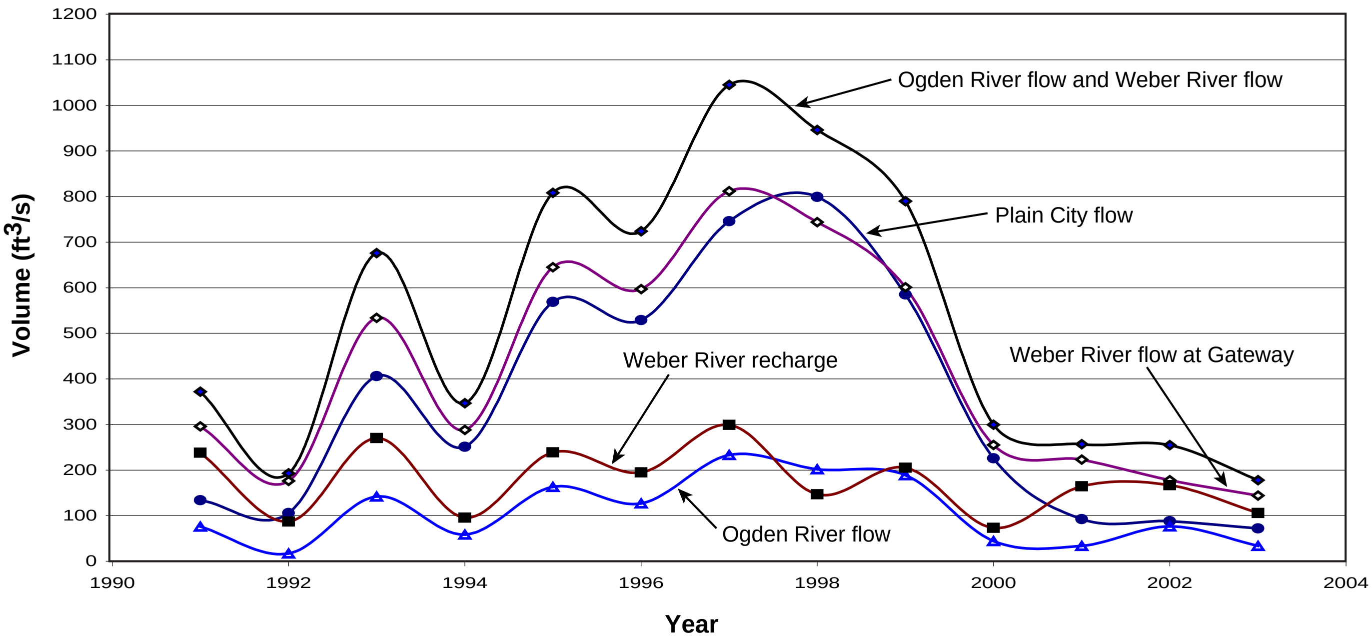


Figure 53. *Recharge from major streams in the study area in years 1991–2003, calculated in this study.*

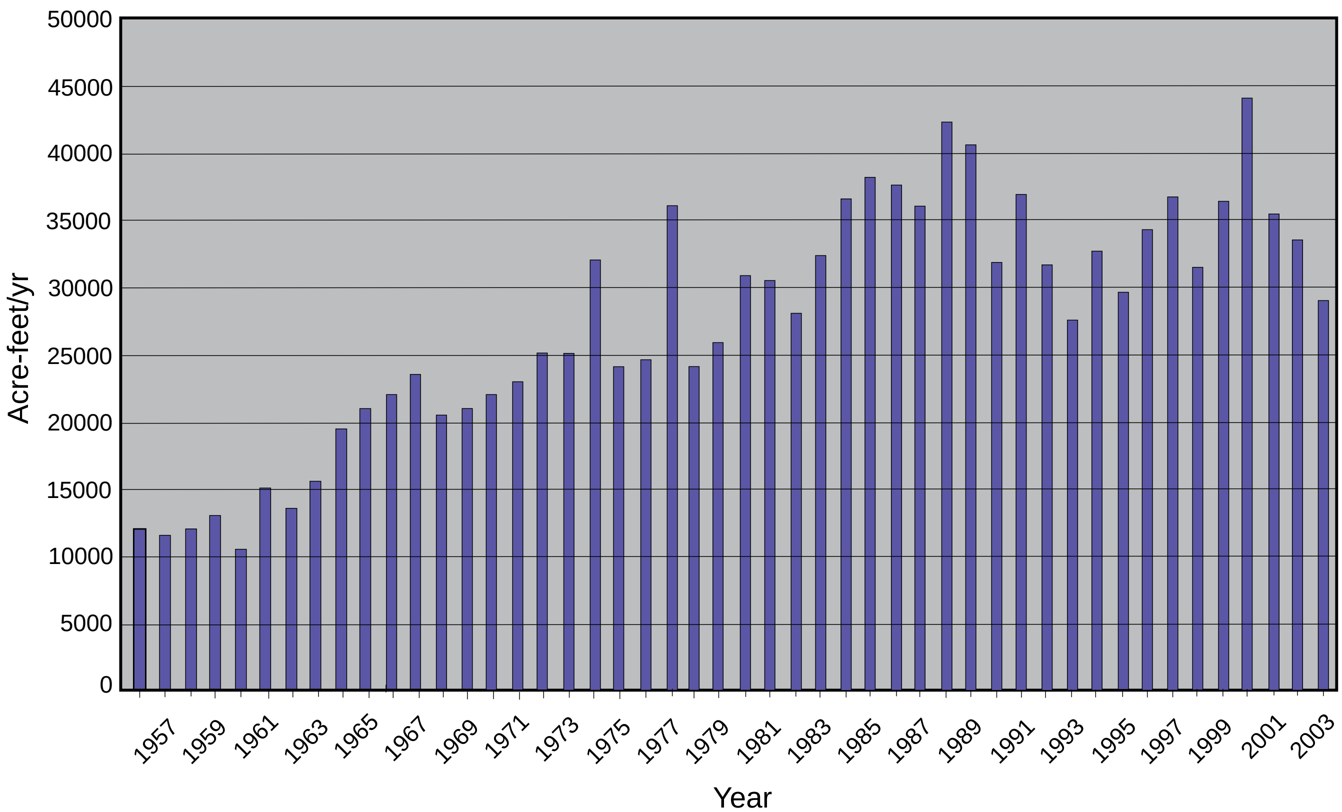


Figure 54. *Ground-water withdrawals in the study area between 1956 and 2003 (data from Utah Division of Water Resources, 2005, and Weber Basin Water Conservancy District, written communication, 2005).*

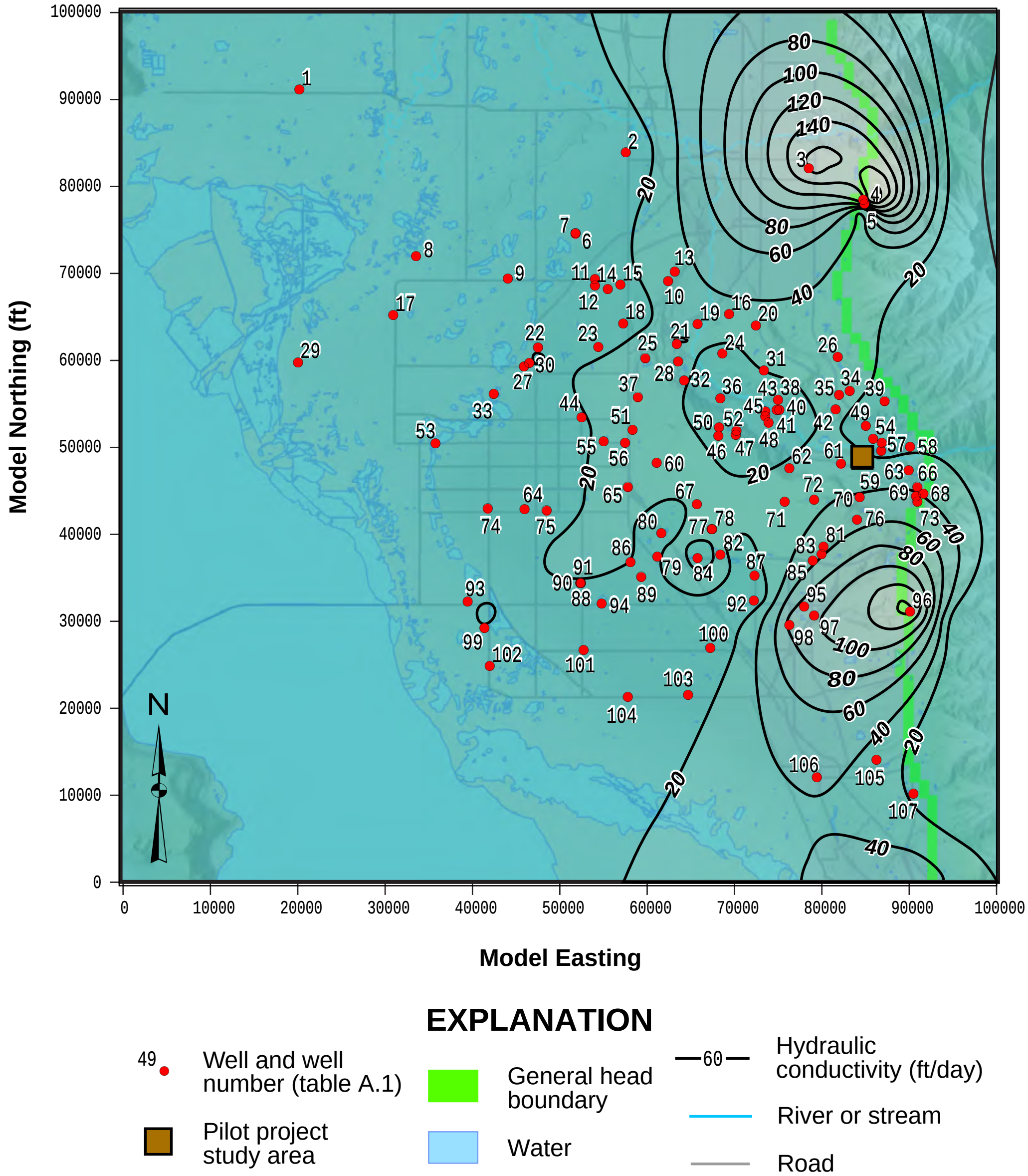


Figure 55. *Hydraulic conductivity of the Delta aquifer.*

mate the values of transmissivity, hydraulic conductivity, and storativity for the Delta and Sunset aquifers (table A1). Depending on the available data, transmissivity was calculated either through interpretation of transient flow data from the pumping aquifer tests or from specific capacity data. Transmissivity values for the two confined aquifers range from less than 1000 to more than 60,000 ft^2/day (90–7400 m^2/d) (table A1). The highest transmissivity values generally occur in the center of the valley and the thickest parts of the deltaic deposits. The smallest values occur in the western part of the study area where the aquifers contain more fine-grained sediments. The storativity of both aquifers, estimated from very limited aquifer-test data, range from $1x10^{-6}$ to $1x10^{-4}$ (table A1).

Hydraulic conductivity values for the Delta aquifer (model layers 4 and 6) range from 1 foot per day to more than 160 feet per day (0.3–49 m/d) (figure 55). Most of the Delta aquifer has hydraulic conductivity values ranging from 10 feet per day to 100 feet per day (3–33 m/d), and relatively larger hydraulic conductivities occur in the easternmost part of the model area (figure 55). Hydraulic conductivity values for the Sunset aquifer range from 1 foot per day to more than 350 feet per day (0.3–106 m/d) (figure 56). Most of the Sunset aquifer area has values between 10 feet per day and 100 feet per day (3–33 m/d).

In the absence of reliable data, layer 1 is assigned a uniform hydraulic conductivity value of 1 foot per day (0.3 m/d) because this represents the likely range of hydraulic conductivity values in the shallow unconfined aquifer. Layer 5 has a horizontal hydraulic conductivity of 3 feet per day (1 m/d), as calculated from observation-well cuttings, and a vertical hydraulic conductivity that is two orders of magnitude smaller. Because of the very small number of aquifer pump tests available to calculate specific storage precisely, a single value of $1x10^{-6}$ was used for the unconfined aquifers over the entire model area.

Model Results

Calibration

Model calibration proceeded by systematic variation of model parameters to achieve as close a match as possible between calculated and observed water levels in selected wells. Some parameters were considered well known and were held constant, including horizontal hydraulic conductivity values calculated from well-documented aquifer pump tests, well discharge, screened intervals in wells, and thickness of geologic layers from well logs. Aquifer parameters including hydraulic conductivity and storativity, and boundary conditions including recharge and general-head boundaries, that were considered less certain were altered during calibration. These parameters determine flow into the study area across the Wasatch fault zone and flow within the model aquifers to Great Salt Lake and across the western model boundary. The conductance term in general-head boundaries was adjusted during the steady-state calibration.

The calibration error was calculated as the mean error (ME)

$$\boldsymbol{ME}= \frac{1}{n}\sum_{1}^{n} |hm - hs|i$$

where *hm* is the measured value, *hs* is the simulated value, and *n* is the number of measurements.

Accurate calibration in the close vicinity of the recharge area during the simulated recharge experiments was the highest priority. The model was first calibrated to steady-state conditions, 50 years prior to the recharge experiments (January 1, 1956). Ground-water production at that time is not precisely known, because most pumping was from private wells that were not required to provide accurate real time pumping schedules. Other sources of significant uncertainty include (1) averaging of pumping schedules over five-year periods during times of relatively uniform stress conditions, and (2) assigning hydraulic parameters to geologic layers where no hydrogeologic data are available, such as confining layer 3 between the Sunset aquifer (layer 2) and the Delta aquifer (layers 4 and 6).

Transient-flow conditions were used to model declining water levels from 1956 to 2006 (figures 57 and 58). Figure F1 provides calculated ME values for wells having long-term observations, for the entire modeling period and during the recharge experiments. The average difference between observed and modeled values for wells within about 0.6 miles (1.0 km) of the infiltration basins is 3.7 feet (1.1 m). Modeled water levels are higher than observed values for five wells and lower than observed values for three wells. Wells farther from the recharge area have higher calibration errors due to less abundant geologic data.

Considering that observed water-level values were not collected continuously and cannot be easily correlated with the exact pumping schedules of production wells, and that the flow system is characterized by highly variable water levels with observed values changing by as much as 20 feet (6 m) between adjacent wells, we conclude that the calculated water-level values match observed values reasonably well and can be used to predict the effects of the recharge experiment on the flow system in the study area.

The model used reduced recharge values during the prolonged drought conditions from 1998 to 2005. These reduced recharge values corresponded with a measurable decline of the water table in the study area. Potentiometric-surface maps of the Delta aquifer from the calibrated numerical model for the years 1956, 1966, 1976, and 2004 show the continuous decline of hydraulic head in the study area (figures 59 through 62). Water in the Sunset aquifer generally flows from east to west and the hydraulic gradient is approximately 1×10^{-3} (Clark and others, 1990).

Simulation of Water Levels

Figures 63 and 64 show maps of the water table in the Delta aquifer in the vicinity of the pilot project site at the beginning of the recharge experiment in 2004 and in 2006 after two years of diversion, respectively. Figures 65 and 66 show the predicted hydraulic head and water table for the year 2016 for the entire study area and vicinity of the pilot project site, respectively. The model predicts water levels in the Weber Delta district to decline about 18 feet (5.5 m) during the next 10 years. As we discuss below, infiltration at the pilot project site at the rates and durations in the first two infiltration experiments will not measurably affect water levels in the Delta aquifer, but will improve flow to nearby wells.

Simulation of the Artificial Recharge

The model represents artificial recharge at the pilot project site by a recharge boundary in layer 6. The size of the recharge boundary corresponds to the size of the low-permeability zone in layer 5. The exact size of this zone is not known, but the size of the recharge boundary in layer 6 is consistent with the size of the water mound detected in the microgravity surveys (figure 44). In the model an additional recharge, representing the water infiltrated at the pilot project site of 33 million cubic feet (9.3×10^5 m^3), is added to the aquifer during the two-year-long experi-

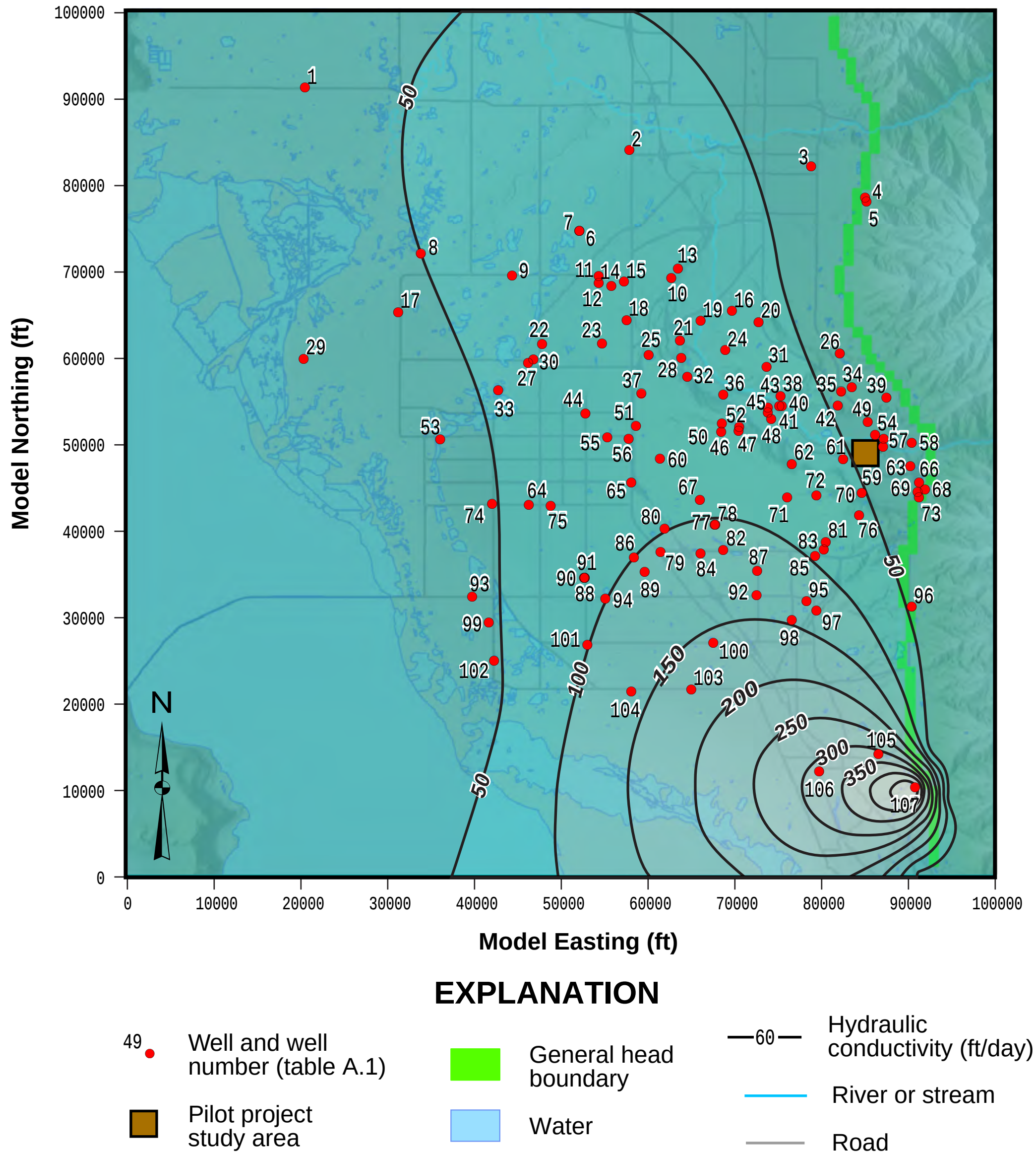


Figure 56. *Hydraulic conductivity of the Sunset aquifer.*

ment and spreads over an area of approximately 3.02 million square feet (2.8×10^5 m^2) to produce a water-level increase of 1.5 feet (0.5 m) in the pilot project observation well in the Delta aquifer below the recharge site. A smaller recharge boundary in layer 6 would result in a larger water-level increase in the observation well, whereas a larger boundary would result in a smaller water-level increase. Figures 67–69 present the simulated water levels in the Delta aquifer near the pilot project site after 100, 200, and 700 days, respectively, from the beginning of the water diversion.

The ground-water flow direction in the Delta aquifer changes only slightly due to the artificial recharge, because the amount of recharging water is relatively small compared to the entire amount of water flowing in the aquifer (figures 70 and 71). Examination of flow volume in the model shows that from the artificial-recharge site, 42% of the water volume flows across the southern boundary of the recharge area, 29% across the western boundary, 17% across the northern boundary, and 11% across the eastern boundary. Water that flows across the northern boundary changes flow direction to the west within the first 250-foot-wide (76 m) model block, increasing westward flow to 46.5% of the water volume. The flow across the southern boundary changes to southwest flow. Flow graphs representing all four recharge area boundaries are presented in figures 72 through 75. Figure 76 shows isochron lines representing the front of the recharging water, and figure 77 shows isochron lines representing the maximum peak of recharging water. Examples of time distribution of the recharge flow are presented for two distances, approximately 8500 feet (2600 m) and 12,000 feet (3600 m) from the recharge zone (figures 78 and 79).

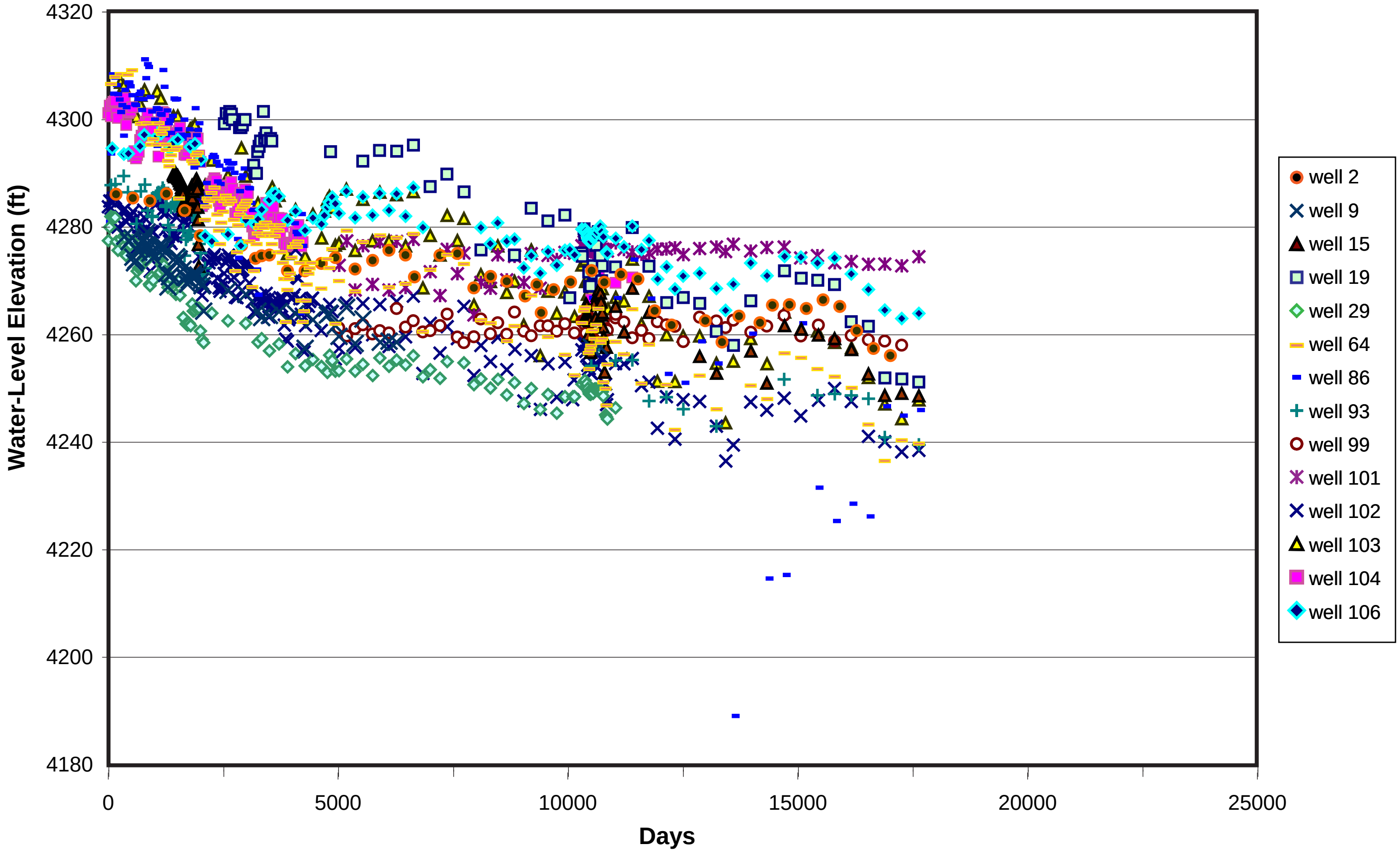


__Figure 57.__ Measured water levels in wells used in the model (data from U.S. Geological Survey, 2005).

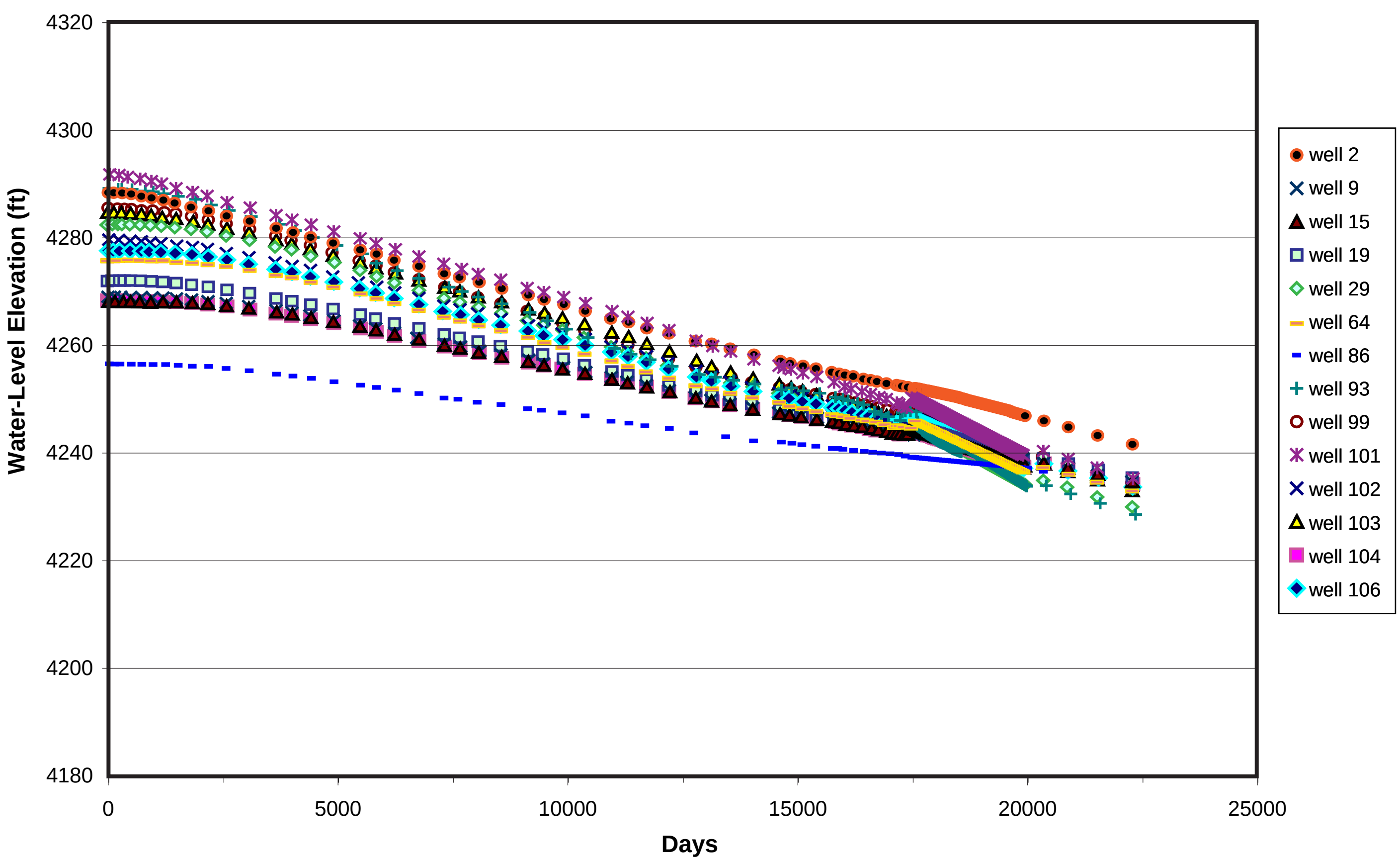


__Figure 58.__ Water levels calculated in the model.

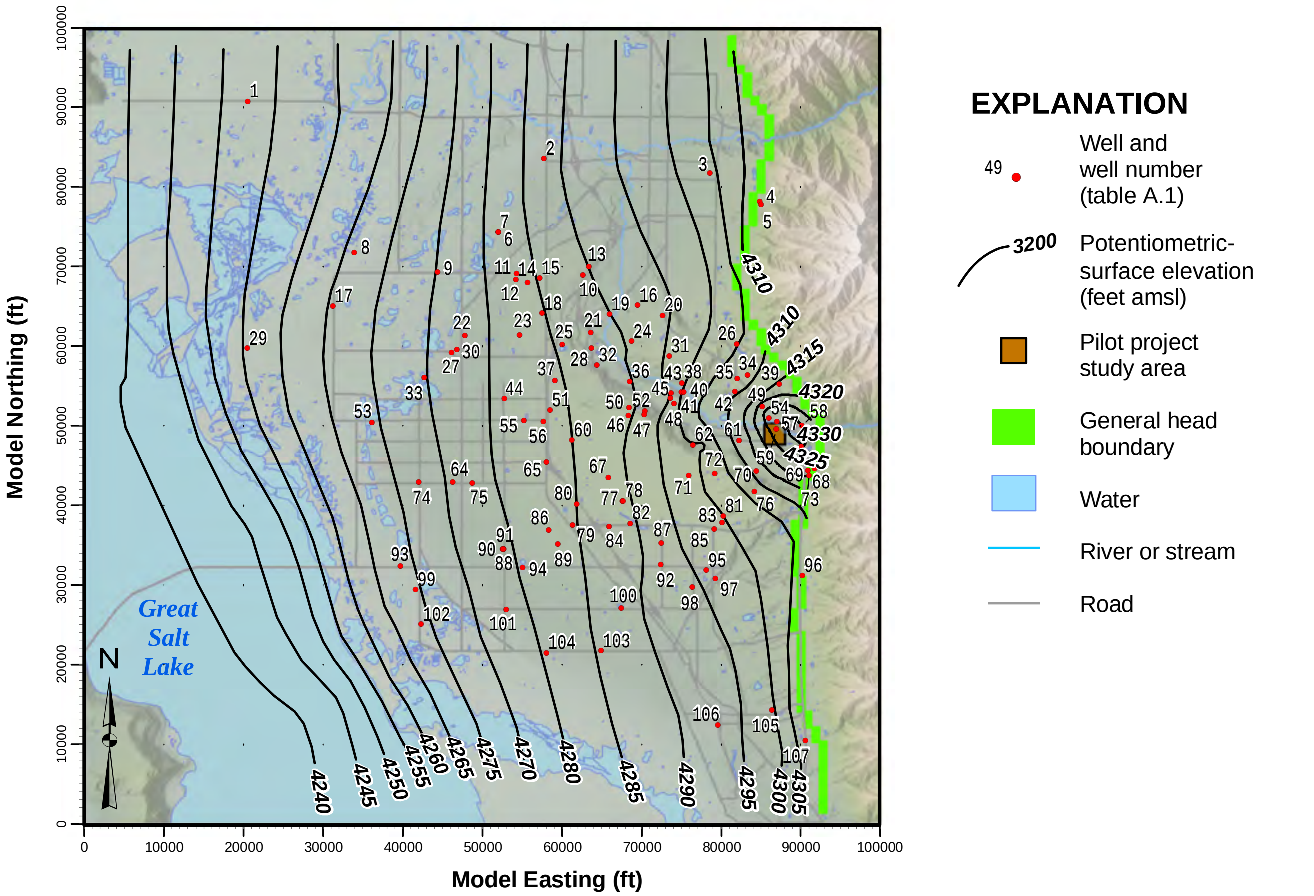


Figure 59. Modeled 1956 potentiometric surface of the Delta aquifer.

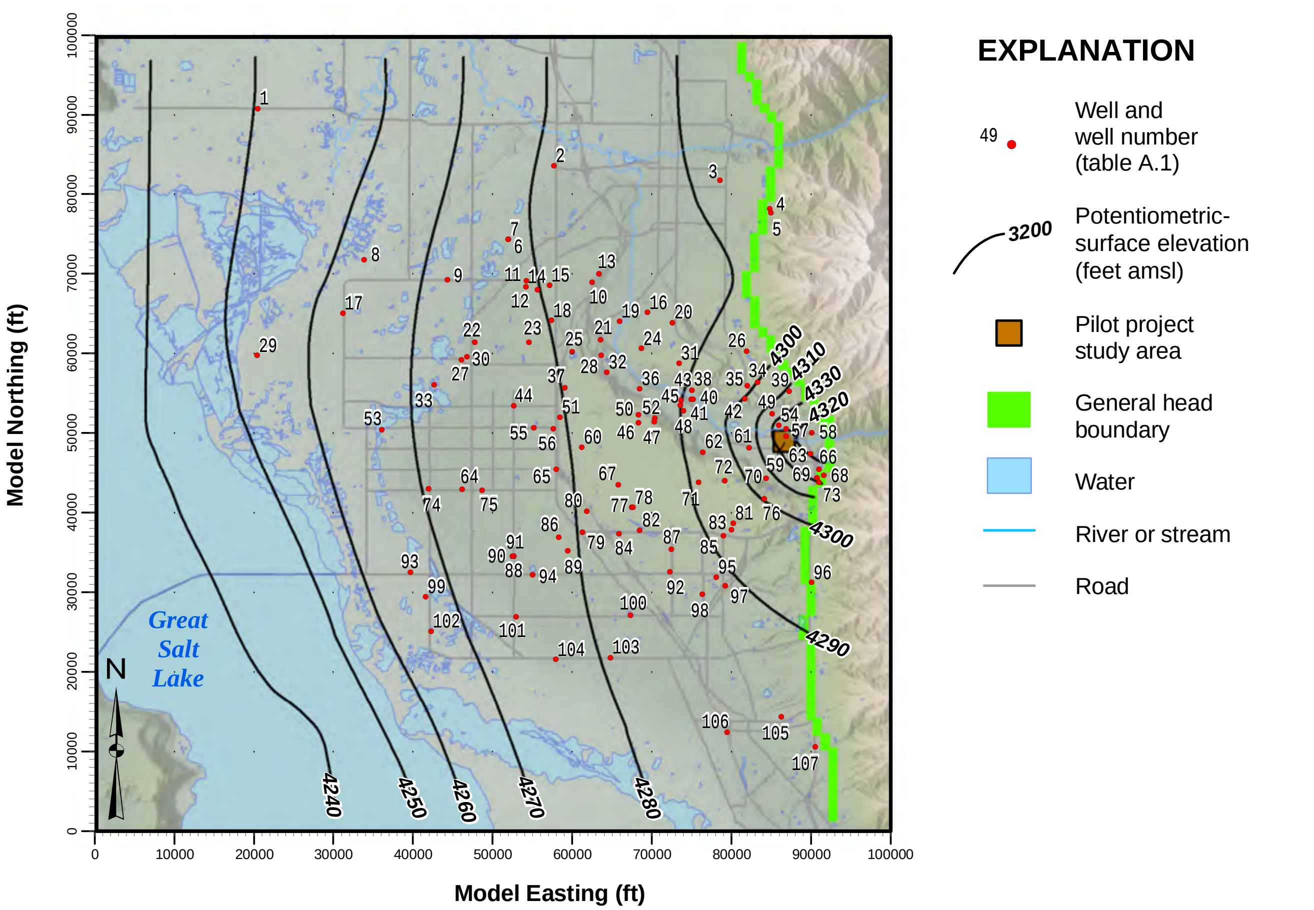


Figure 60. Modeled 1966 potentiometric surface of the Delta aquifer.

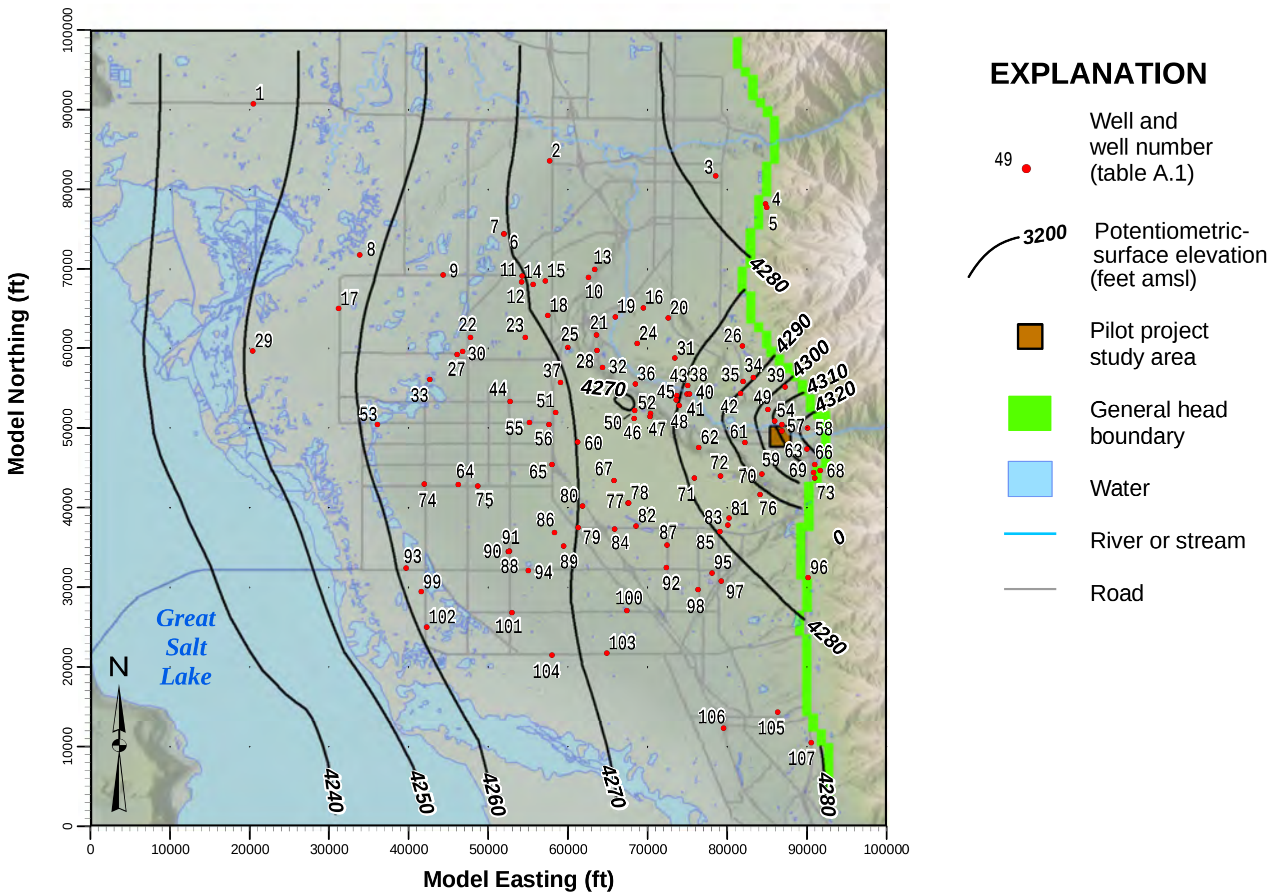


Figure 61. *Modeled 1976 potentiometric surface of the Delta aquifer.*

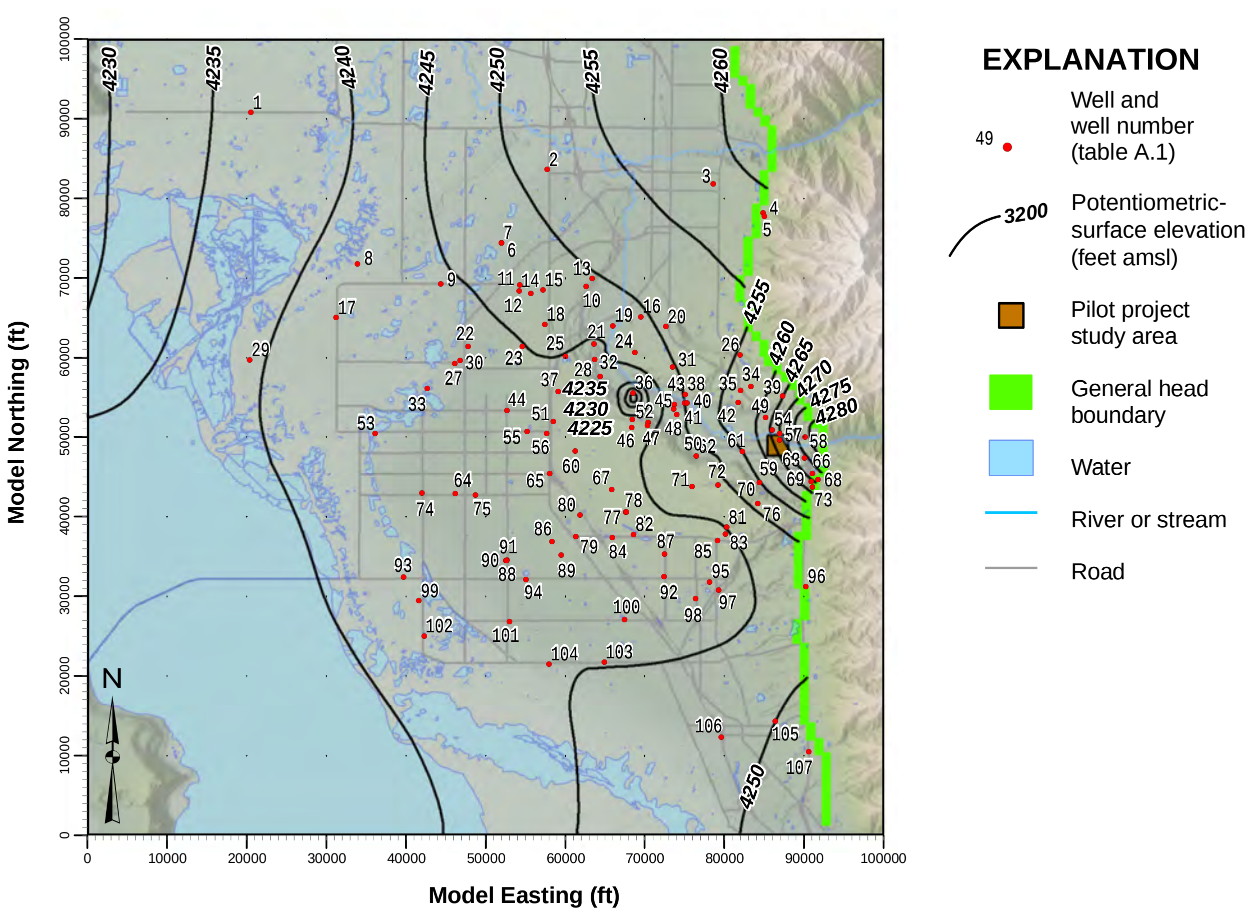


Figure 62. *Modeled 2004 potentiometric surface of the Delta aquifer.*

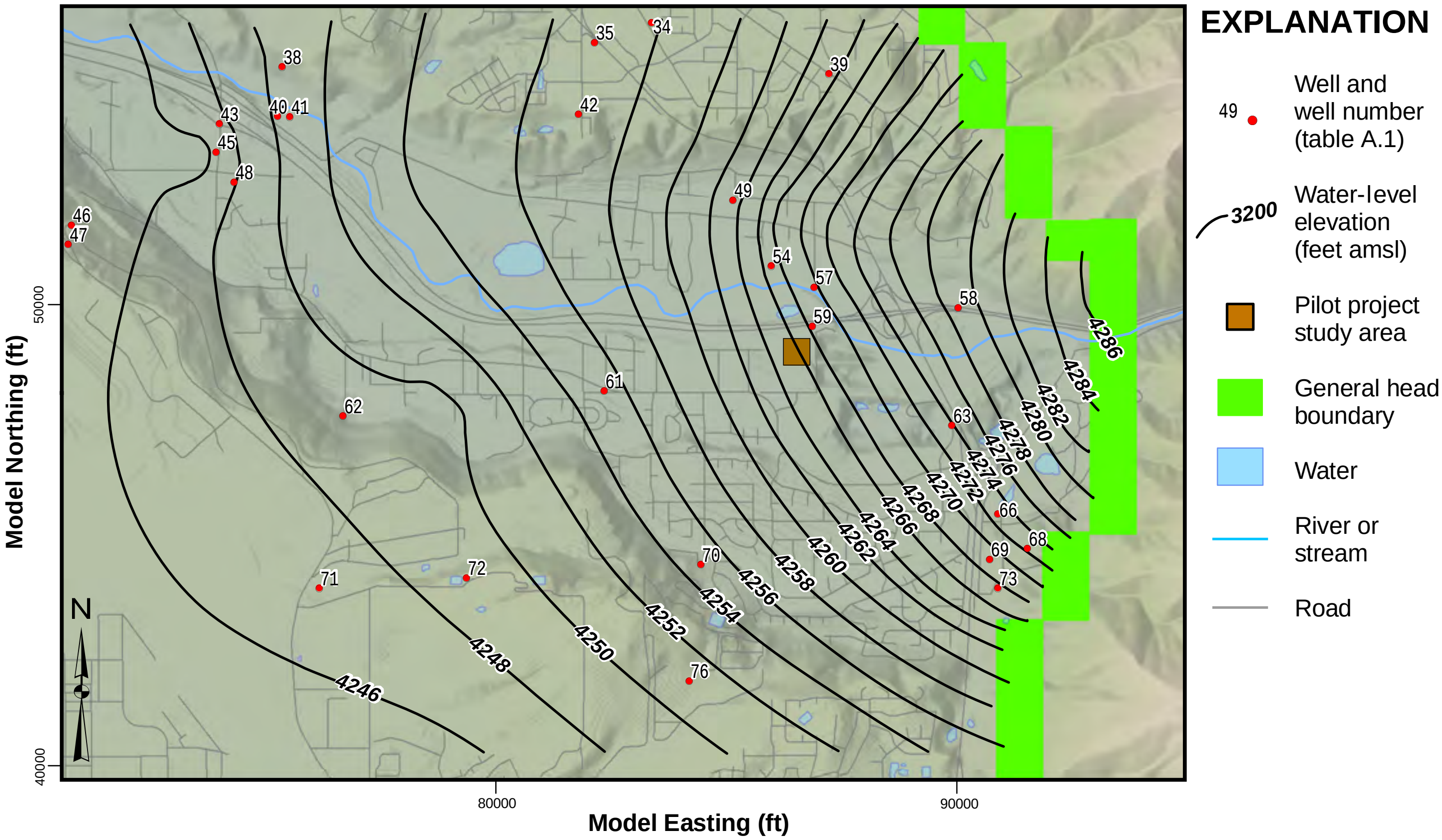


Figure 63. *Water-level elevation of the Delta aquifer in the vicinity of pilot project recharge site in 2004 at the beginning of the first recharge experiment.*

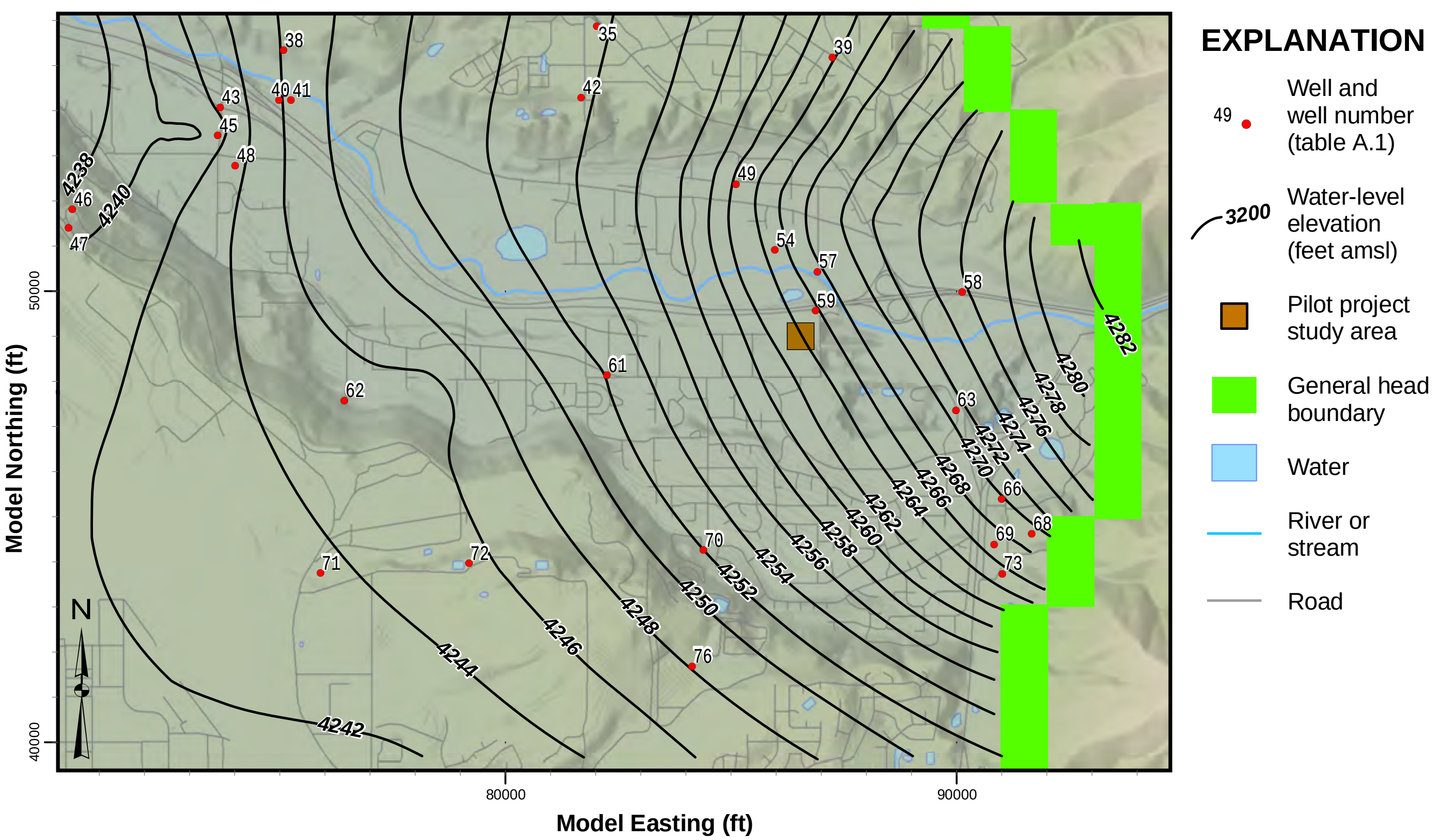


Figure 64. *Water-level elevation of the Delta aquifer in the vicinity of the pilot project recharge site in 2006 at the beginning of the second recharge experiment.*

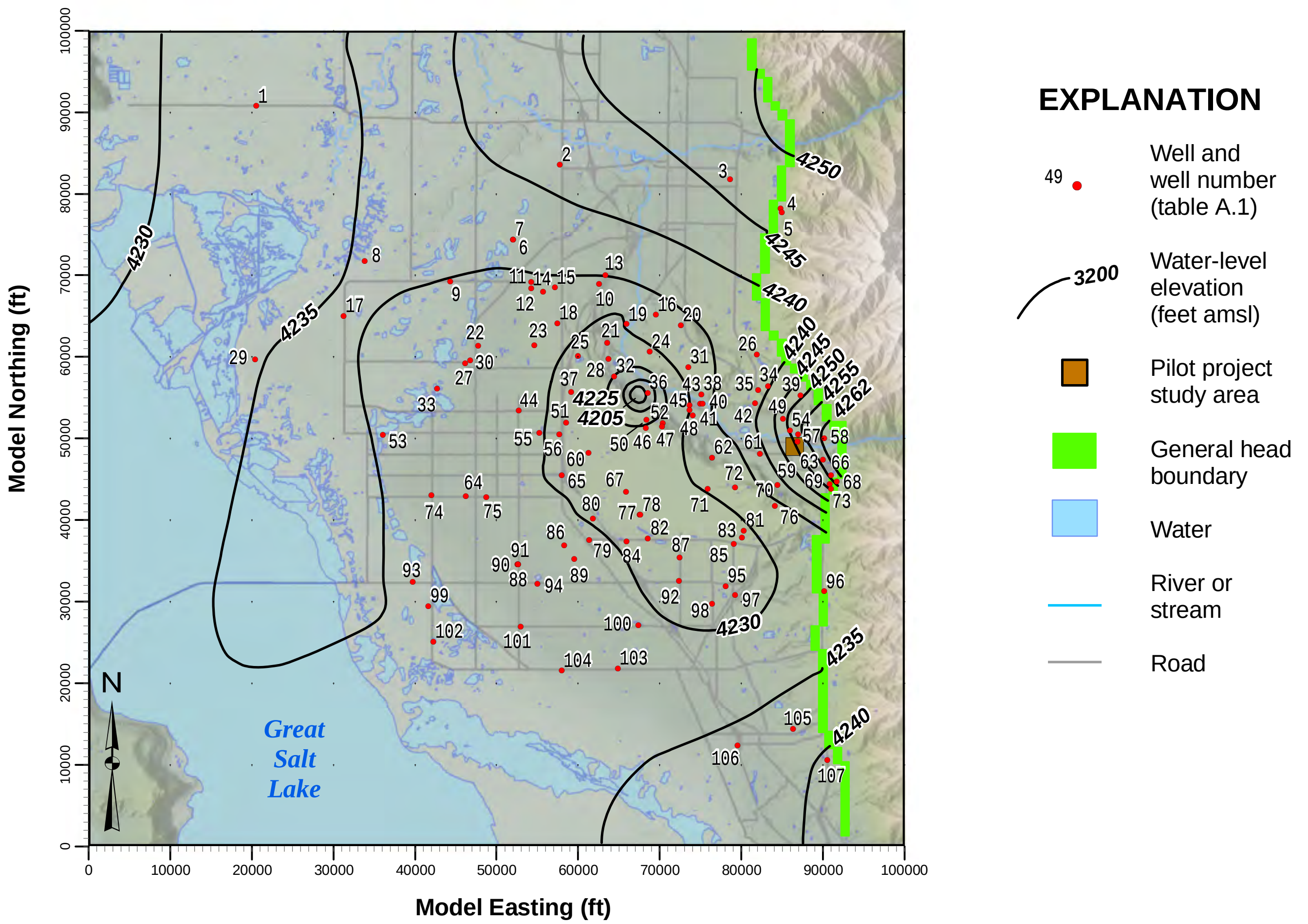


Figure 65. *Predicted water-level elevation in the Delta aquifer in 2016.*

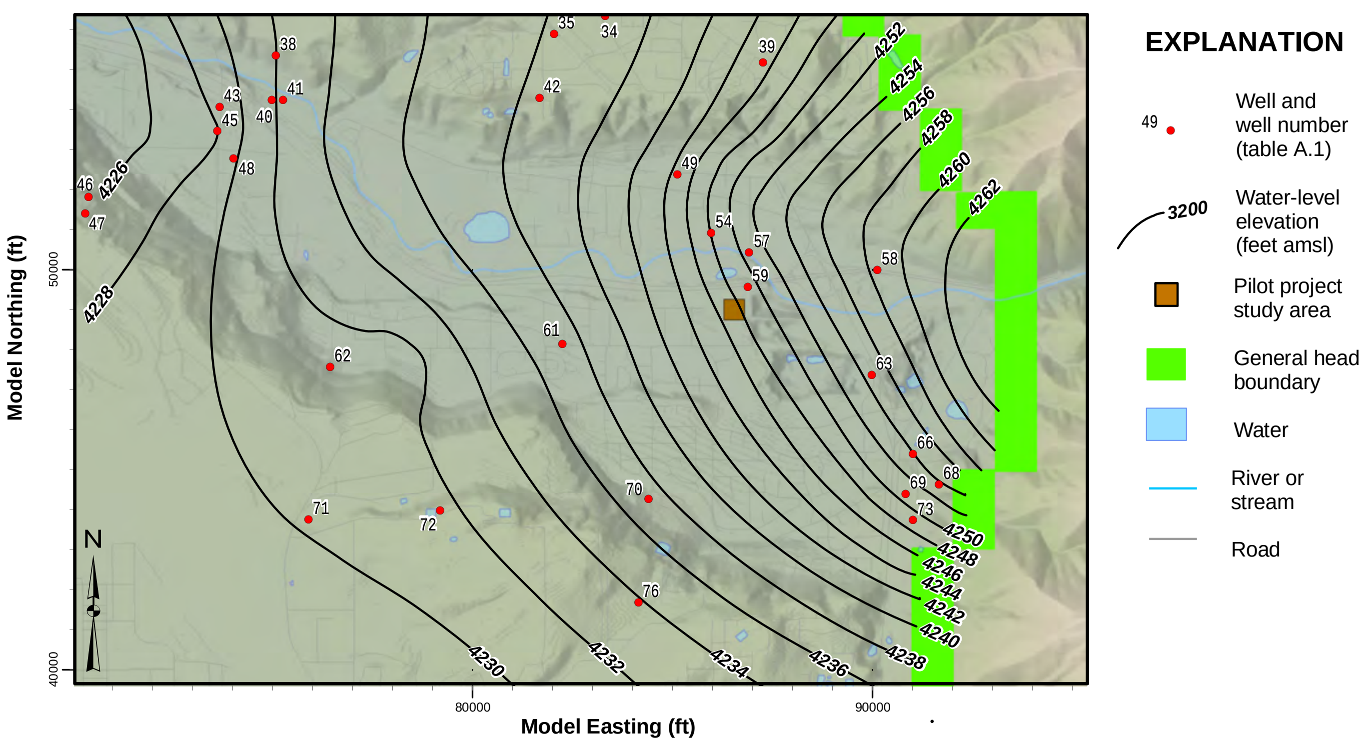


Figure 66. *Predicted water-level elevation in the Delta aquifer in the vicinity of the pilot project recharge site in 2016.*

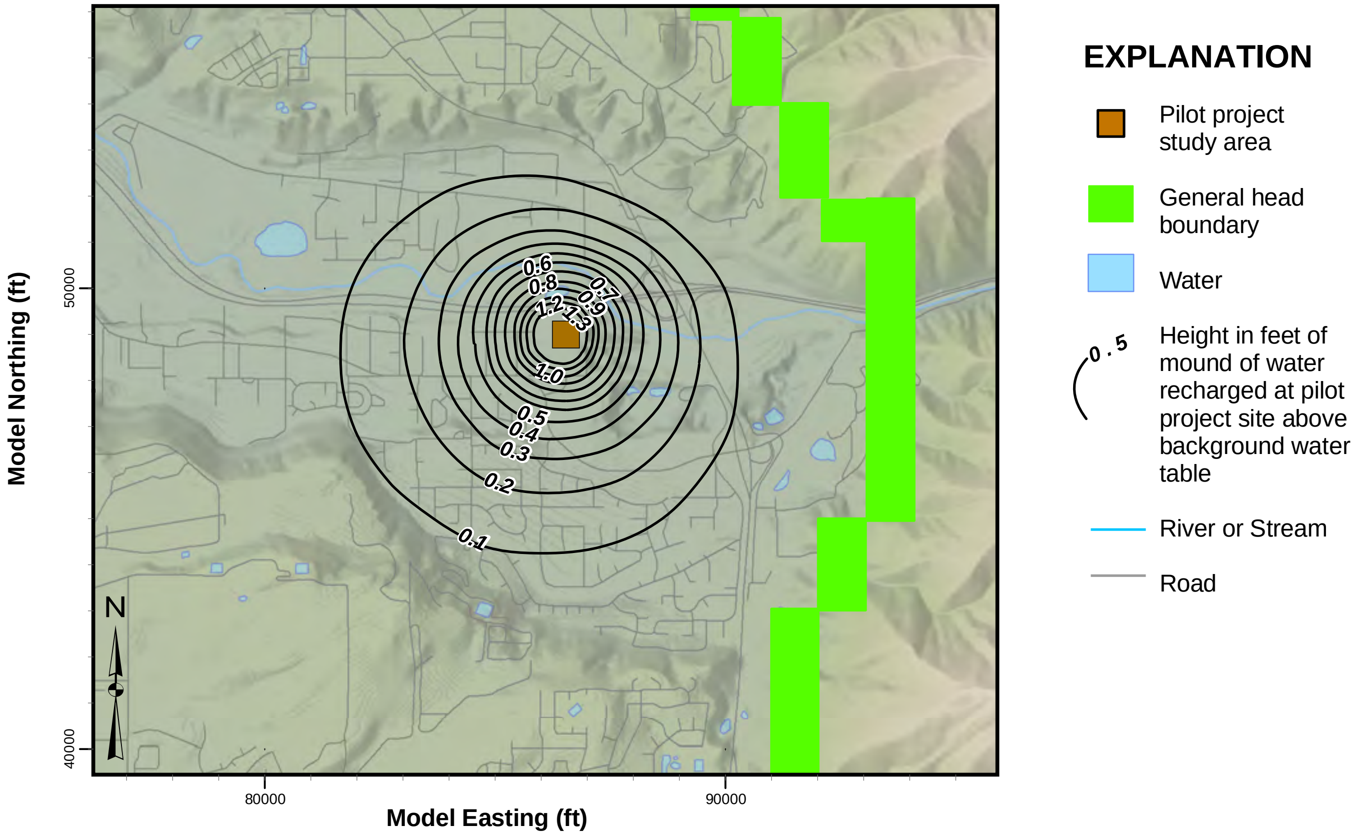


Figure 67. The mound of recharging water in the Delta aquifer after 100 days of continuous recharge. Contour interval 0.1 foot (0.03 m).

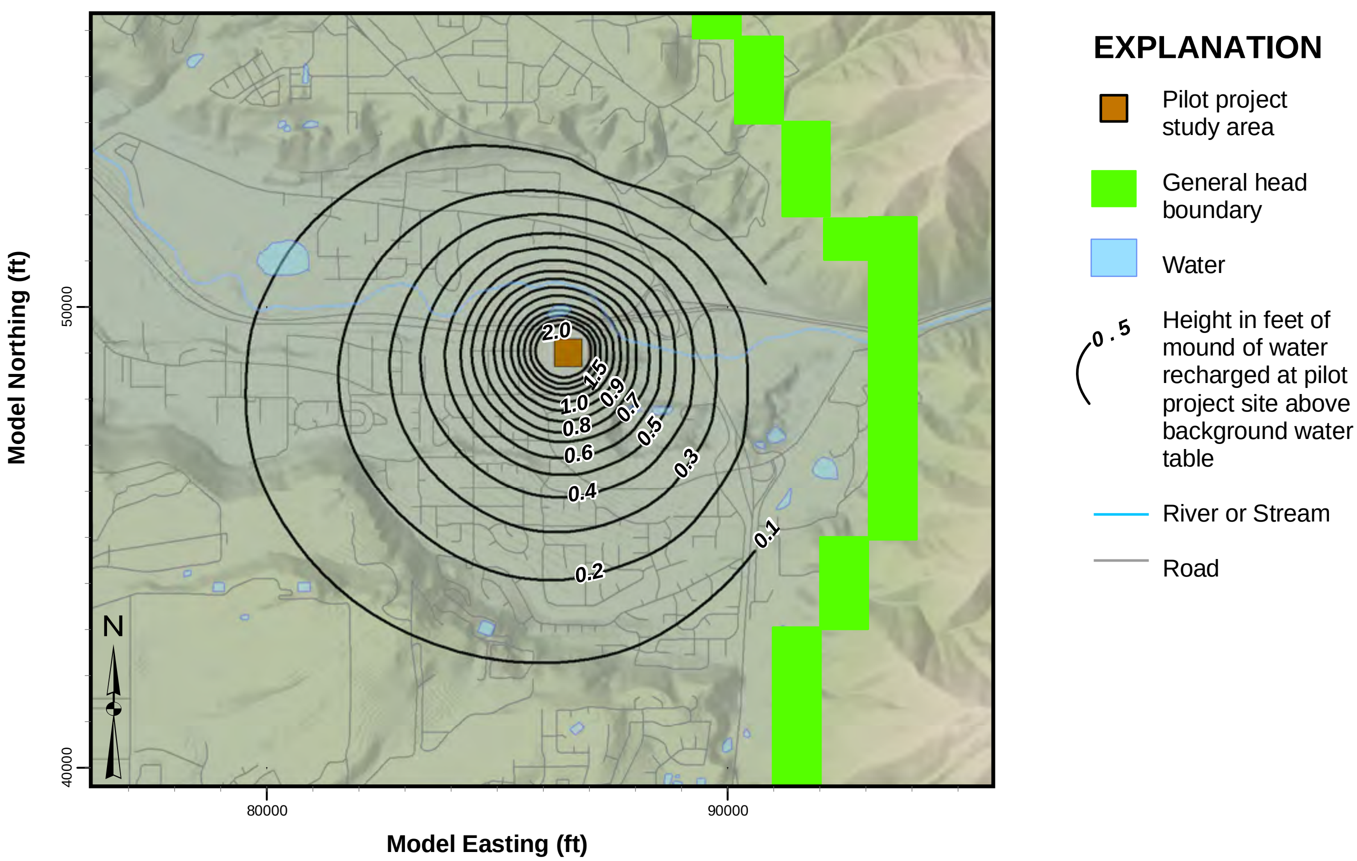


Figure 68. The mound of recharging water in the Delta aquifer after 200 days of continuous recharge. Contour interval 0.1 foot (0.03 m).

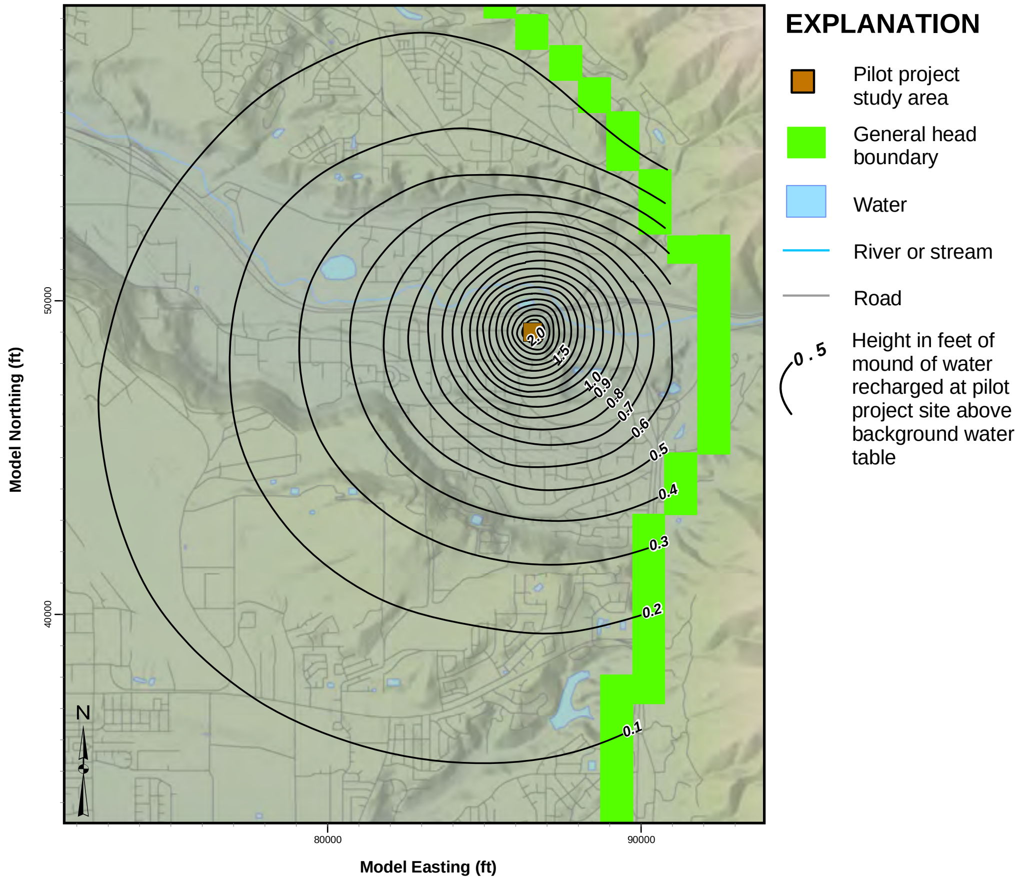


Figure 69. *The mound of recharging water in the Delta aquifer after 700 days of continuous recharge. Contour interval 0.1 foot (0.03 m).*

Predictive simulations were made for a 10-year period after the end of the artificial recharge experiment of 2004–06, assuming constant annual recharge from the pilot project site equal to that of the first two recharge experiments. Similarity between observed and calculated values in the model representing the years 1956–2004 permit confidence in the quality of predictive analysis for future years. The simulations estimate flow of recharging water accompanied by additional water-level declines caused by continued ground-water withdrawals from wells and assuming current ground-water withdrawal rates. They also assume continued less-than-normal naturally occurring recharge similar to drought conditions for the years 1998–2004. If weather patterns change in the future, the model can be modified by altering the natural recharge. Declining water levels over the entire simulation period indicate that any additional increase of ground-water withdrawals is likely to cause a significant decline in water levels. The model can be modified by changing withdrawal rates for each individual well or by adding any additional wells that might be used in the future.

The results of the flow model and predictive analyses presented here must be used with caution. The calibration and verification process does not lead to a unique description of hydrogeologic conditions. The model design depends on the "informed judgment" of the modeler where the data are of uncertain accuracy or are unavailable. The model can be updated and improved if new hydrogeologic data become available in the future. Predictive simulations in models such as ours are rarely accurate because the aquifers are subjected to a limited time and distribution of hydrodynamic stresses. To reduce this uncertainty the model represents 50 years of known hydrodynamic conditions to simulate changes in the flow system just 12 years into the future.

The amount of water introduced into the Delta aquifer at the pilot project site is relatively small compared with ground-water withdrawals and the total volume of ground-water flow in the Delta aquifer. Both human-caused and natural changes can easily alter the direction of ground-water flow in the Delta aquifer. Climatic fluctuations may also significantly alter ground-water flow patterns in the study area. The model allows for relatively easy representation of changing ground-water withdrawals and naturally occurring recharge, thus providing a flexible predictive tool for managing ground-water resources.

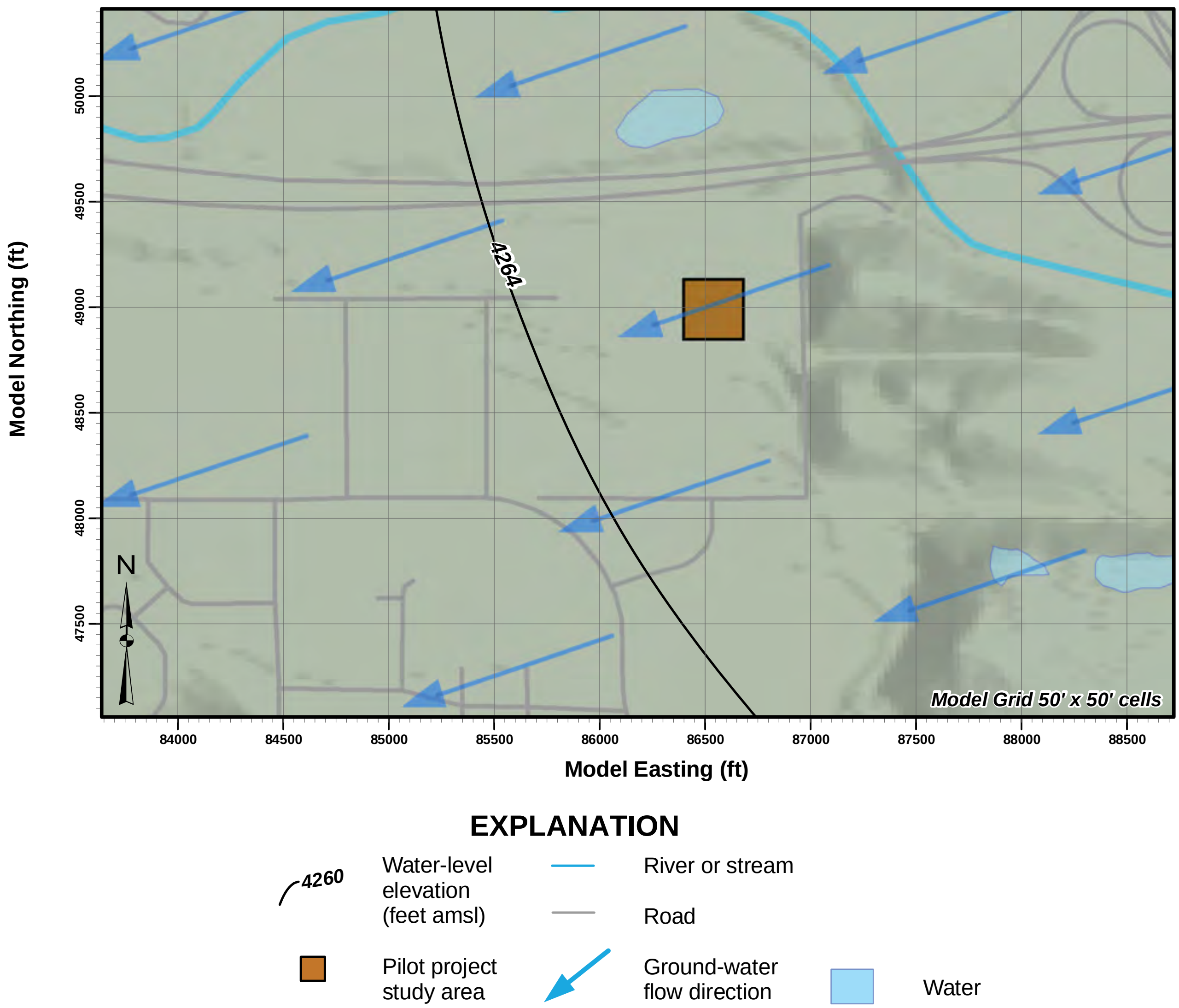


Figure 70. *Direction of ground-water flow in the Delta aquifer below the infiltration basins at the beginning of the recharge experiment.*

DISCUSSION

Fate of Infiltrated Water

The water level in the ASR observation well rose about 1 foot (0.3 m) during the first recharge experiment (figure 26). In contrast, water levels in the observation well for the experiments conducted by the U.S. Bureau of Reclamation in the 1950s rose over 30 feet (10 m) (Feth and others, 1966; Clyde and others, 1984). Although we recharged less water in our experiment than in those conducted by the Bureau of Reclamation, we expected to observe substantially greater water-level increases than those measured in our observation well. We believe that the fine-grained layer encountered by the observation well at 116 feet (35 m) depth is present beneath and beyond the entire pilot project site, as suggested by its presence in the north pit of the Staker-Parson South Weber gravel pit east of the site. This layer caused the infiltrated water to spread laterally over a larger area than the pilot project site, as confirmed by the microgravity study, and to flow downward more slowly than expected. As a result, water from the infiltration experiment entered the main aquifer over a large area, causing a relatively small water-level increase at any single location, including the observation well.

During the second recharge experiment, the water level in the ASR observation well rose about 10 feet (3 m) (figure 31). We interpret the greater response of the ground-water level below the confining layer beneath the pilot project site to reflect the presence of more water in pore spaces above the confining layer at the beginning of the second experiment. This extra water is likely a combination of incomplete drainage of water from the first recharge experiment and greater infiltration of Weber River water related to high flow during March 2005 compared to the previous year.

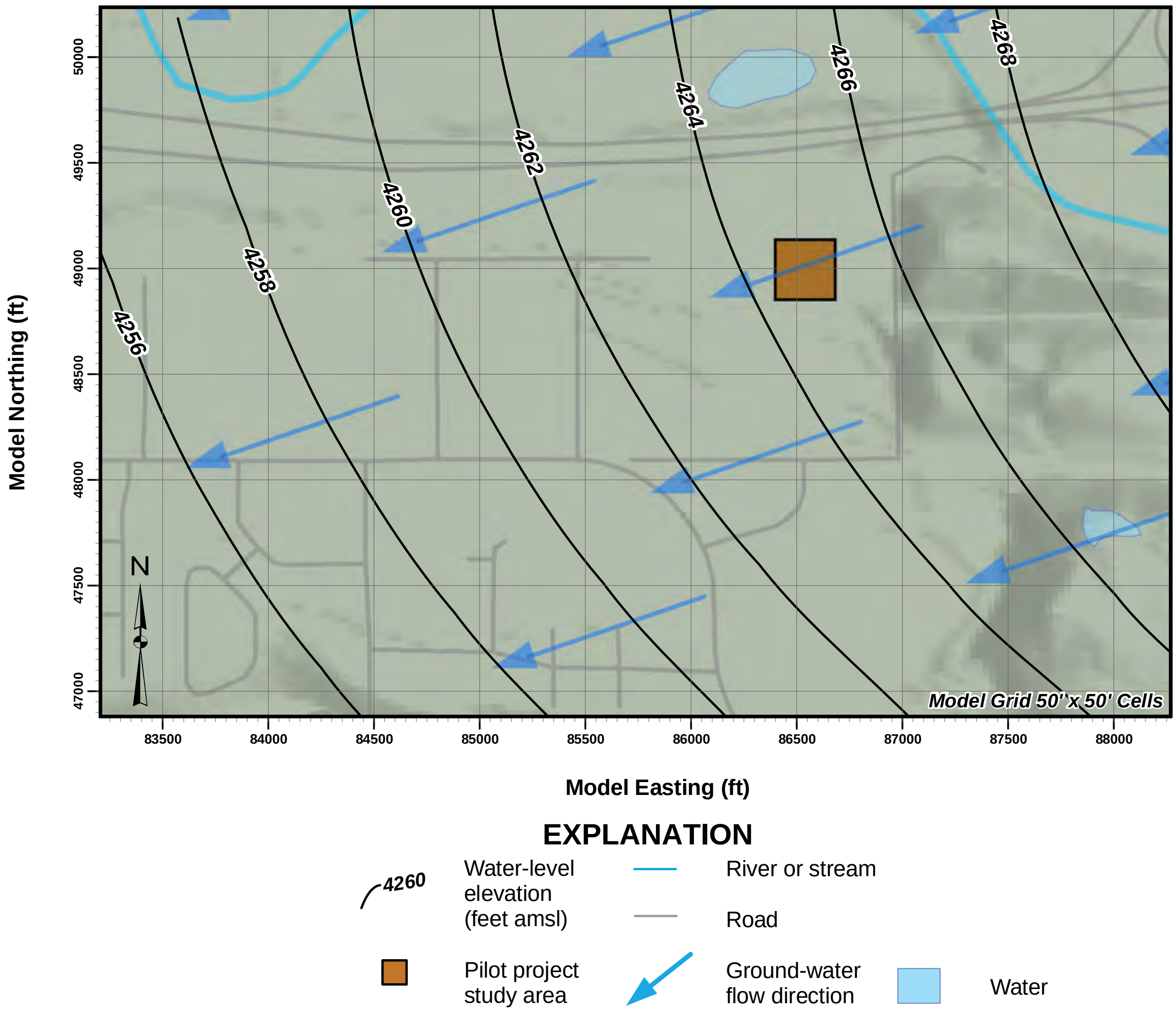


Figure 71. *Direction of ground-water flow in the Delta aquifer below the infiltration basins after 2 years of water diversion.*

Although we cannot quantify the water-level changes that would have occurred below the pilot project site without the infiltration experiment, all measured wells—including the WRBWCD Laytona well (figure 30), which was not pumped—showed steadily decreasing water levels during the time of infiltration. Water levels directly below the infiltration site, therefore, underwent a net positive increase compared to ground-water levels elsewhere in this part of the east shore aquifer system. If in the future we are able to install a new observation well that is screened both above the fine-grained layer and in the main aquifer, we will learn a great deal more about subsurface hydrologic processes associated with artificial recharge at this site.

The ground-water flow model predicts the movement of the artificially recharged ground water and changes to the Delta aquifer caused by the recharge experiments (figures 67–79). The addition of ground water infiltrated at the pilot project site likely caused water levels in wells about 5000 feet (1500 m) west to southwest of the infiltration basins to increase about 0.5 feet (0.15 m) about two years after the beginning of the first experiment (figure 69). As explained above, water levels in the Delta aquifer generally decline during the summer and fall months, so the change would be expressed as a slightly decreased rate of water-level decline. The maximum increase (or decreased rate of decline) in water levels in areas about 12,000 feet (3700 m) to the west and south of the infiltration basins will occur about 800 days (just over two years) after the beginning of the first recharge experiment (figure 79). Based on these calculations and considering the limitations on the rate, duration, and infiltration-basin area, artificial recharge at the pilot project site alone would have little effect on the long-term trend of decreasing water levels in the Delta aquifer. Significant expansion of the project in the future, most likely into the currently active gravel pits east of the pilot project site after their operations have ceased, provides the best hope for stabilizing or reversing

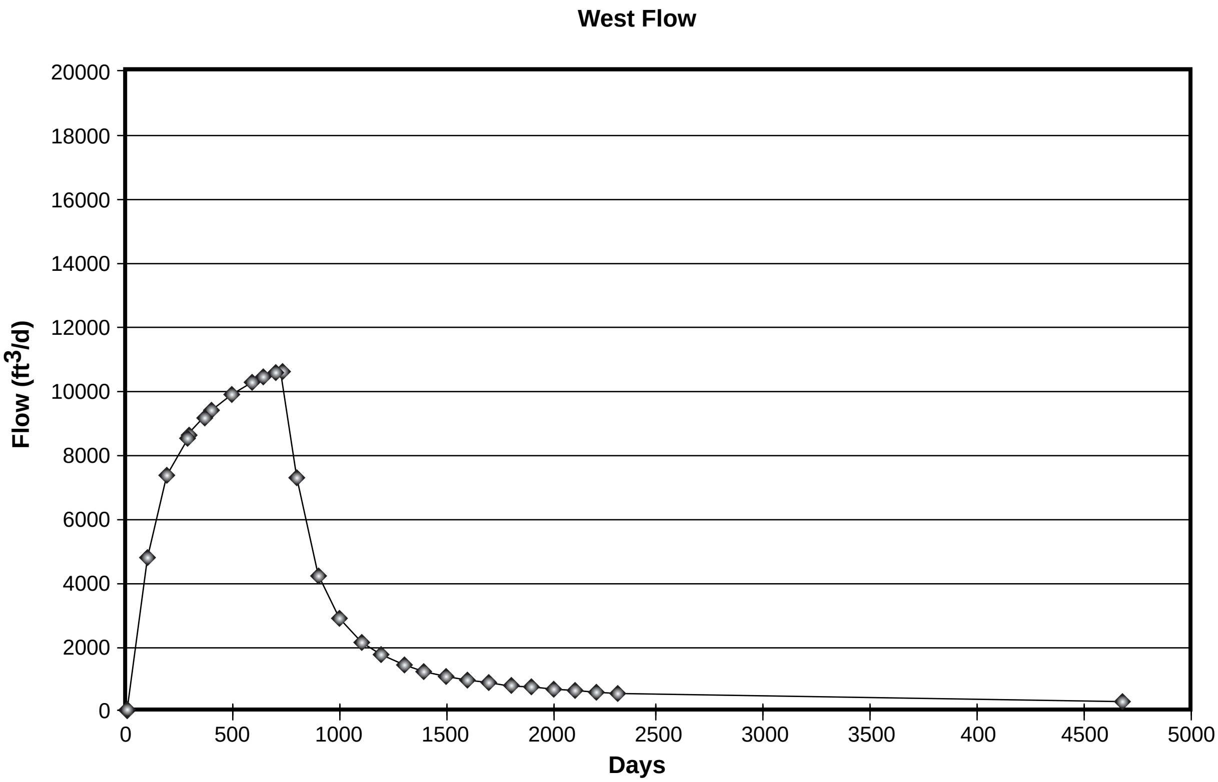


Figure 72. *Model-calculated flow rate from the pilot project site across the western margin of the model recharge boundary.*

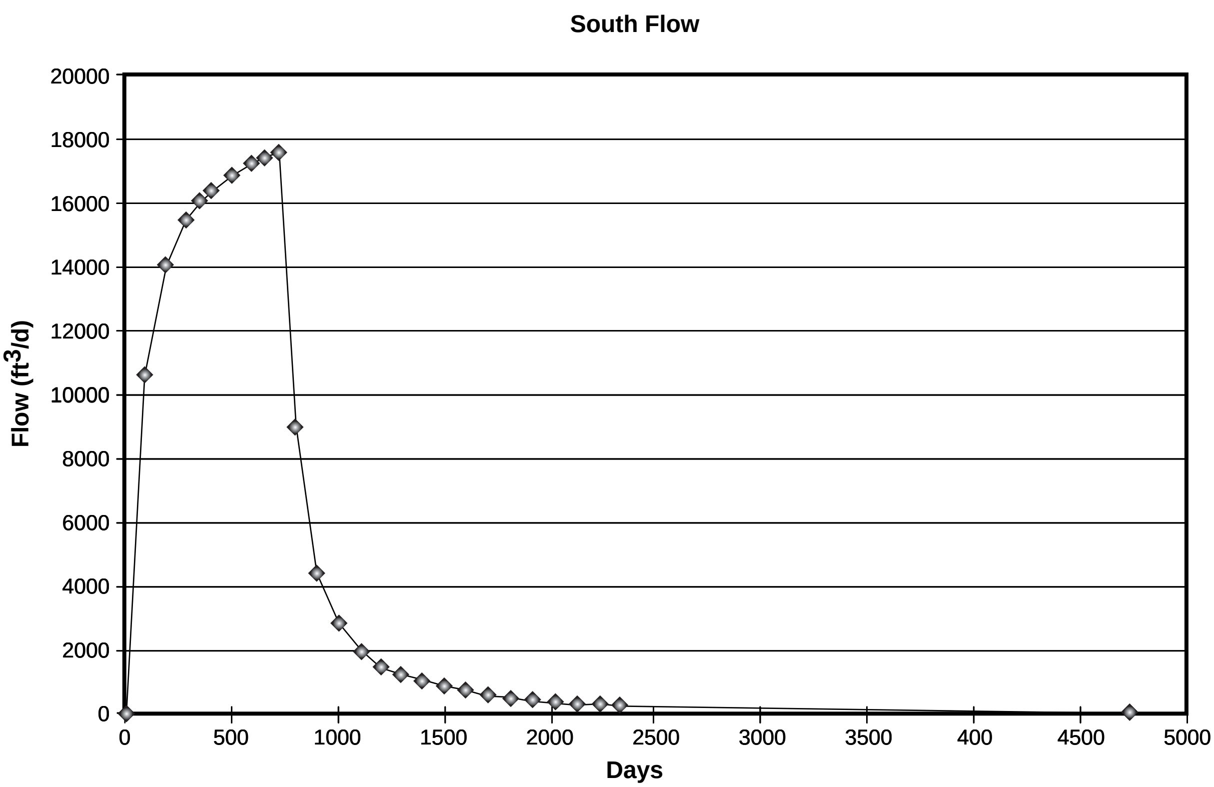


Figure 73. *Model-calculated flow rate from the pilot project site across the southern margin of the recharge boundary.*

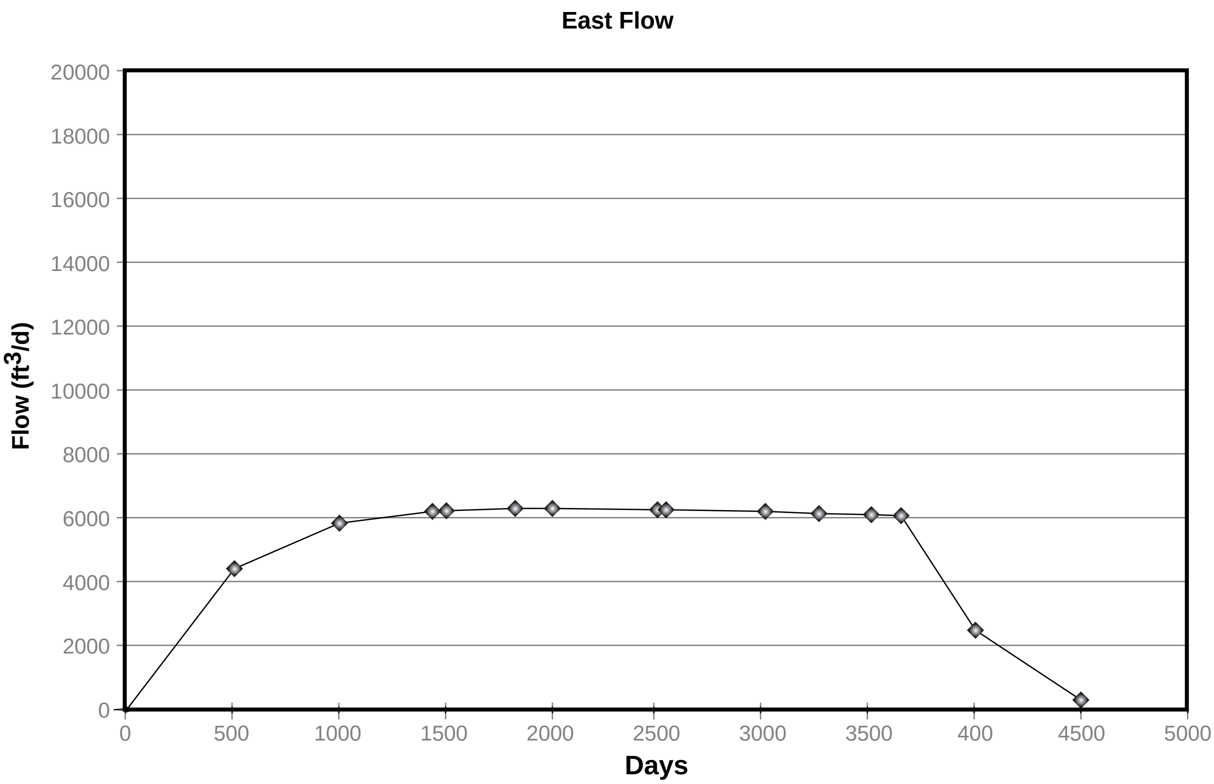


Figure 74. *Model-calculated flow rate from the pilot project site across the eastern margin of the recharge boundary.*

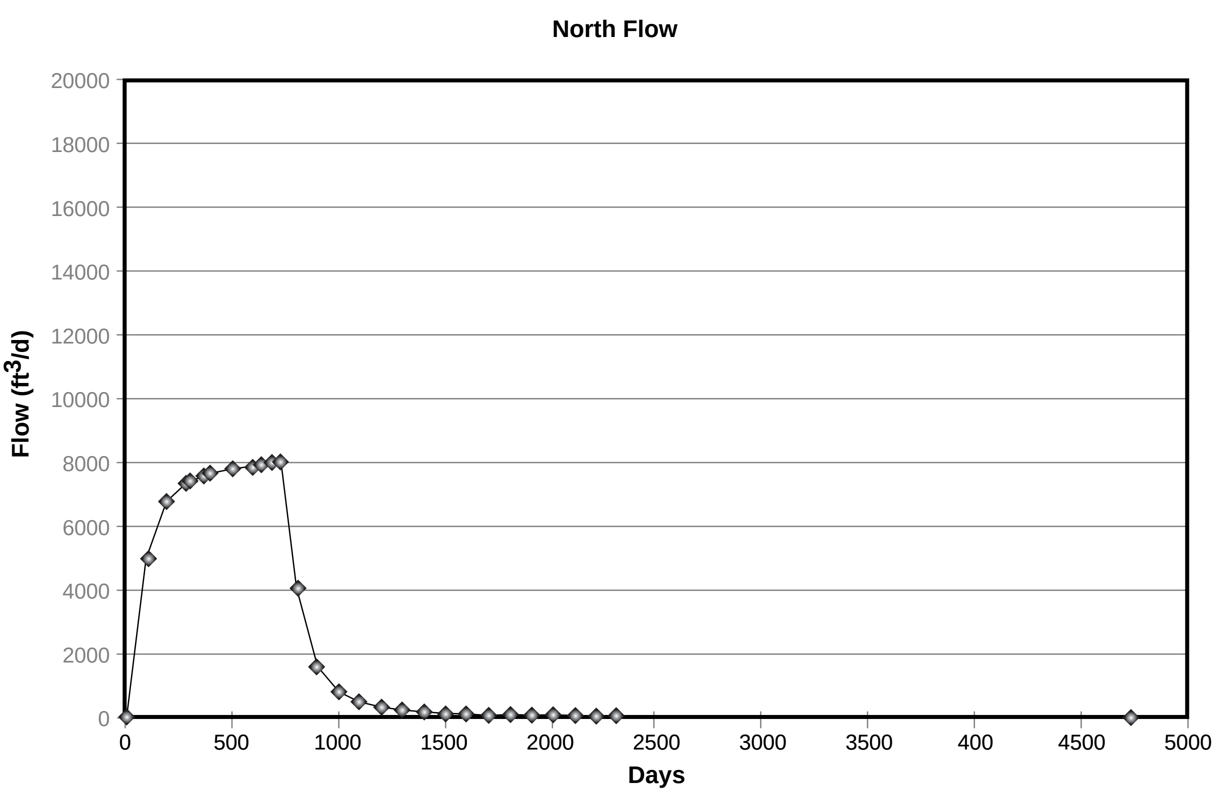


Figure 75. *Model-calculated flow rate from the pilot project site across the northern margin of the recharge boundary.*

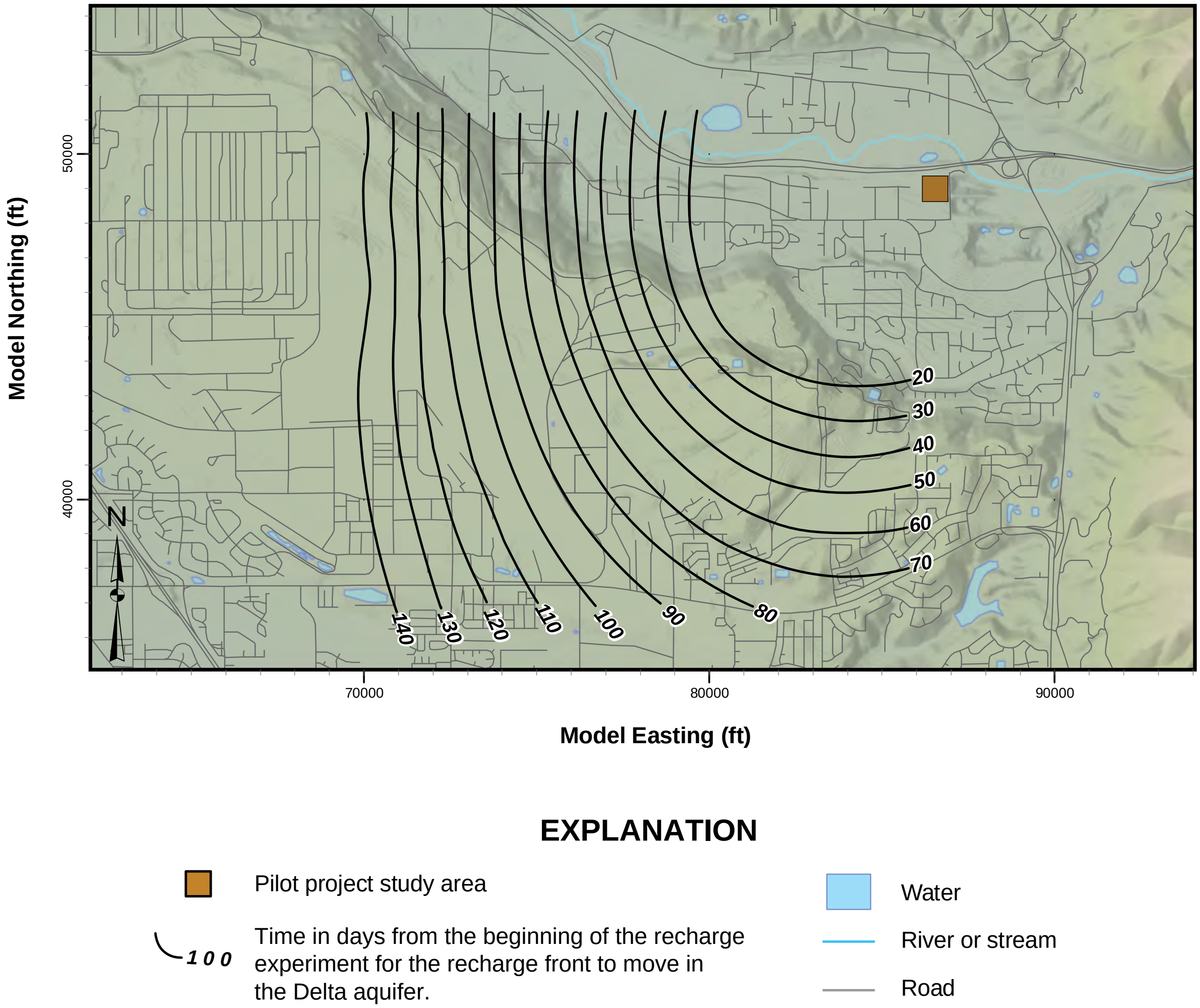


Figure 76. *Movement of the recharge front in the Delta aquifer.*

the current decreasing trend of ground-water levels.

Figures 72 through 75 show that artificial recharge at the pilot project site and adjacent areas can positively affect water-supply issues without substantially altering water levels. During the first recharge experiment, ground-water flow outward from the infiltration basins through the southern model-recharge boundary was about 17,000 cubic feet (480 m^3) per day (figure 73), and flow through the western boundary was about 11,000 cubic feet (310 m^3) per day (figure 72). Although these flow rates gradually decline radially outward from the infiltration basins as the recharge mound disperses within the Delta aquifer, artificial recharge clearly increases ground-water flow rates within the aquifer and to individual wells. The effects of artificial recharge may not be manifested at current water-supply wells for at least two years after the beginning of any future artificial-recharge program (figures 76 through 79).

Ground-Water Chemistry

The Weber River, the ASR observation well, and nearby wells that we sampled have similar water chemistry; all are characterized as mixed calcium-magnesium-bicarbonate type (figure 33). The similarity between ground-water and surface-water chemistry is due to the fact that the Weber River is the dominant source of recharge to the Delta aquifer, as noted by Feth and others (1966). Total-dissolved-solids concentrations for Weber River water decreased markedly from March to June 2004 (figure 34). This trend was observed in muted form in the ASR observation well, but not in the other sampled water wells (figure 38); these wells maintained generally consistent total-dissolved-solids concentrations. The ASR observation well is very close to the Weber River, so the ground-water chemistry there has not completely equilibrated with the aquifer material. In contrast, the ground water we sampled from the other wells has resided in the Delta aquifer long enough to equilibrate chemically with the aquifer material, buffering the

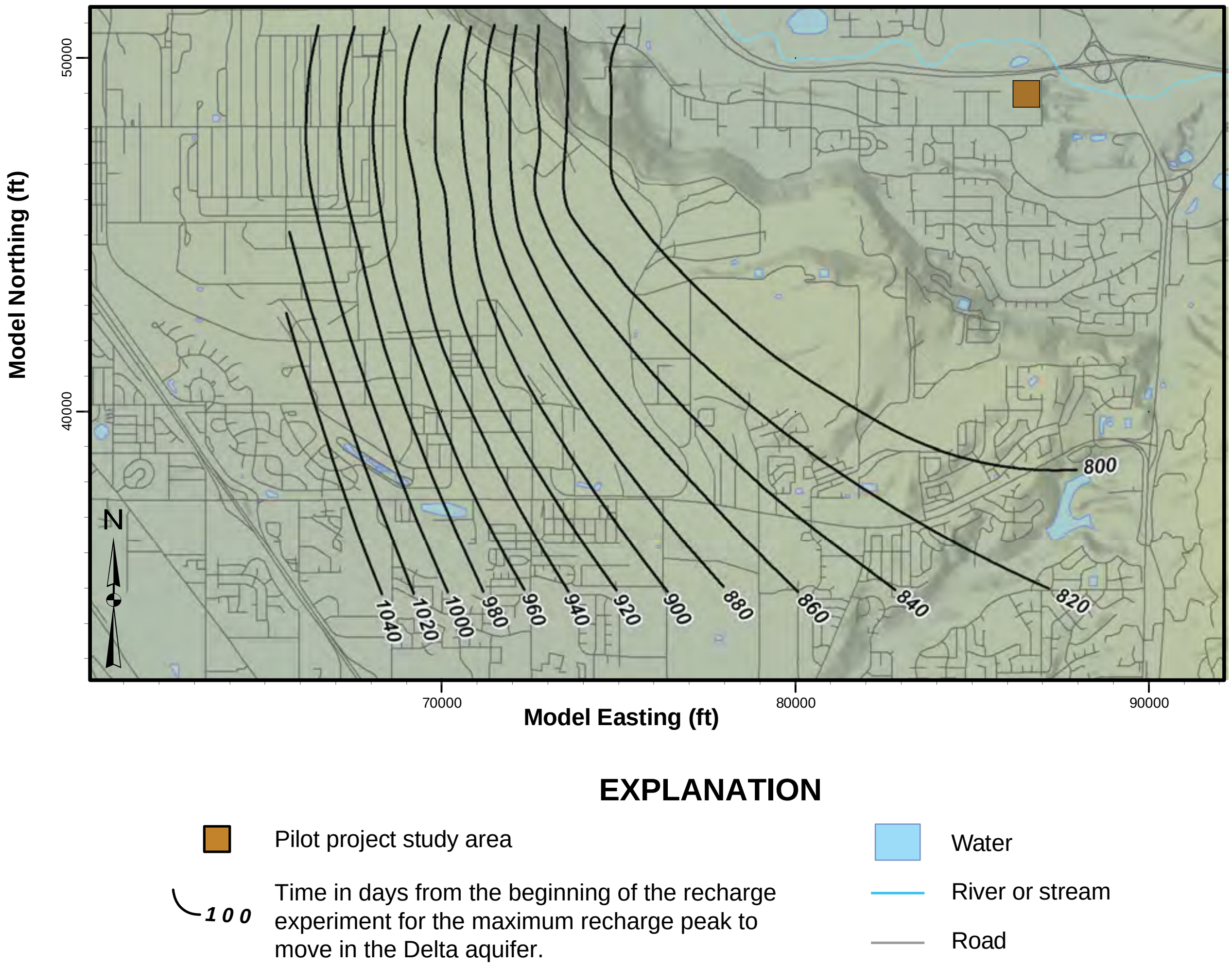


Figure 77. *Movement of the maximum recharge peak in the Delta aquifer.*

effects of short-term changes in Weber River water.

Ground water from the ASR observation well has slightly but consistently higher total-dissolved-solids concentrations than ground water in the other sampled wells and Weber River water (figure 38). The higher average TDS concentration of ground water from the ASR observation well may result from dissolution of chemical constituents in the vadose zone through which the infiltrated water must percolate before reaching the ground-water table. If so, the TDS measured in the observation well should gradually decrease with each infiltration experiment as readily dissolved constituents are progressively removed from the vadose zone.

Future of Artificial Recharge and ASR in the East Shore Area

Ground-water withdrawal from the east shore aquifer system will likely remain constant or increase slightly in the near future. Because ground-water levels in the east shore aquifer system have been declining for the past 50 years, average withdrawal clearly exceeds average recharge over the long term, and ground-water levels will likely continue to decline if the present imbalance is not changed. As we outlined in the Introduction section of this report, the area immediately west of Weber Canyon is an excellent location to perform artificial recharge, by virtue of the existence of a large supply of high-quality water from the Weber River and thick, permeable deposits that are physically contiguous with the Delta aquifer, a principal aquifer that is experiencing significant water-level declines. If performed in sufficient magnitude over a long time period, we believe that artificial recharge has the potential to stabilize ground-water levels in the Delta aquifer in the Weber Delta subarea. Although the Sunset and Delta aquifers are indistinguishable within about a mile of the mouth of Weber Canyon, we are confident that water infiltrated by artificial recharge in this area eventually enters the Delta aquifer because the canyon floor is below the elevation of the base of the Sunset aquifer to the west.

Artificial recharge at the WRBASR pilot project site in the future will likely be limited to about 1000 acre-feet per year (1 hm^3/yr), due to the relatively small size of the site, the presence of the fine-grained layer below the site that

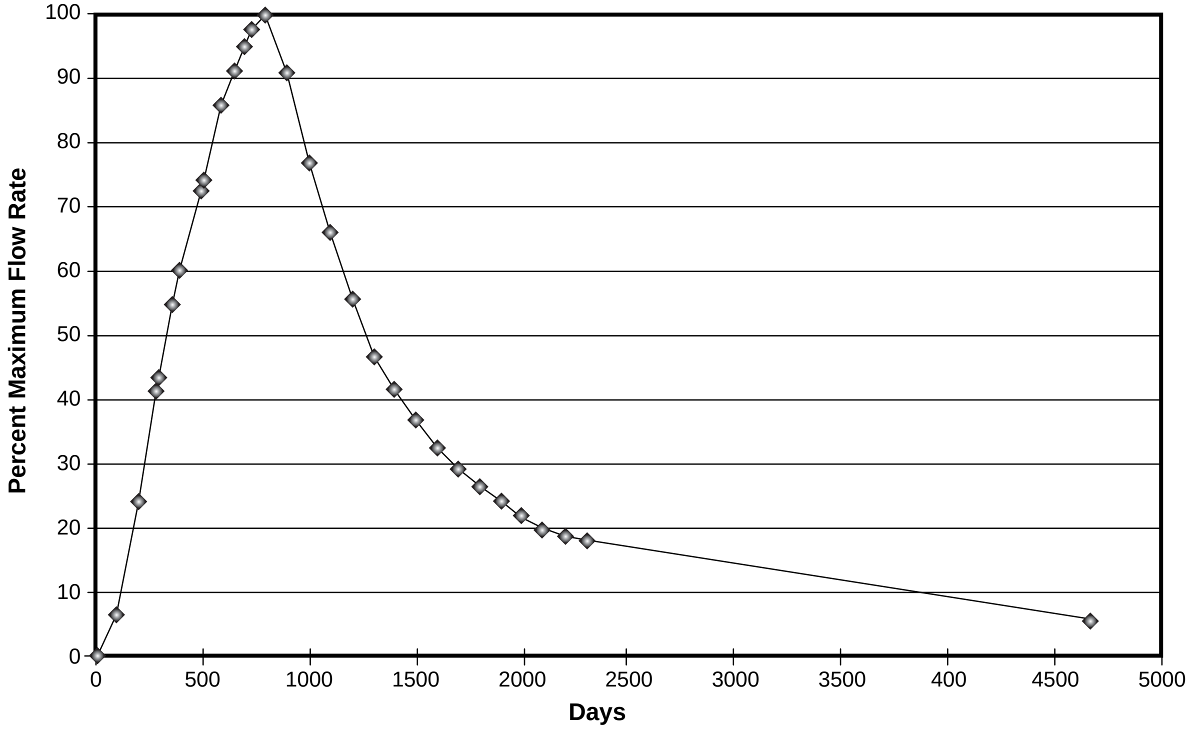


Figure 78. *Time distribution of the relative volumes of the recharge peak at a location 8500 feet (2591 m) downgradient from the pilot project site.*

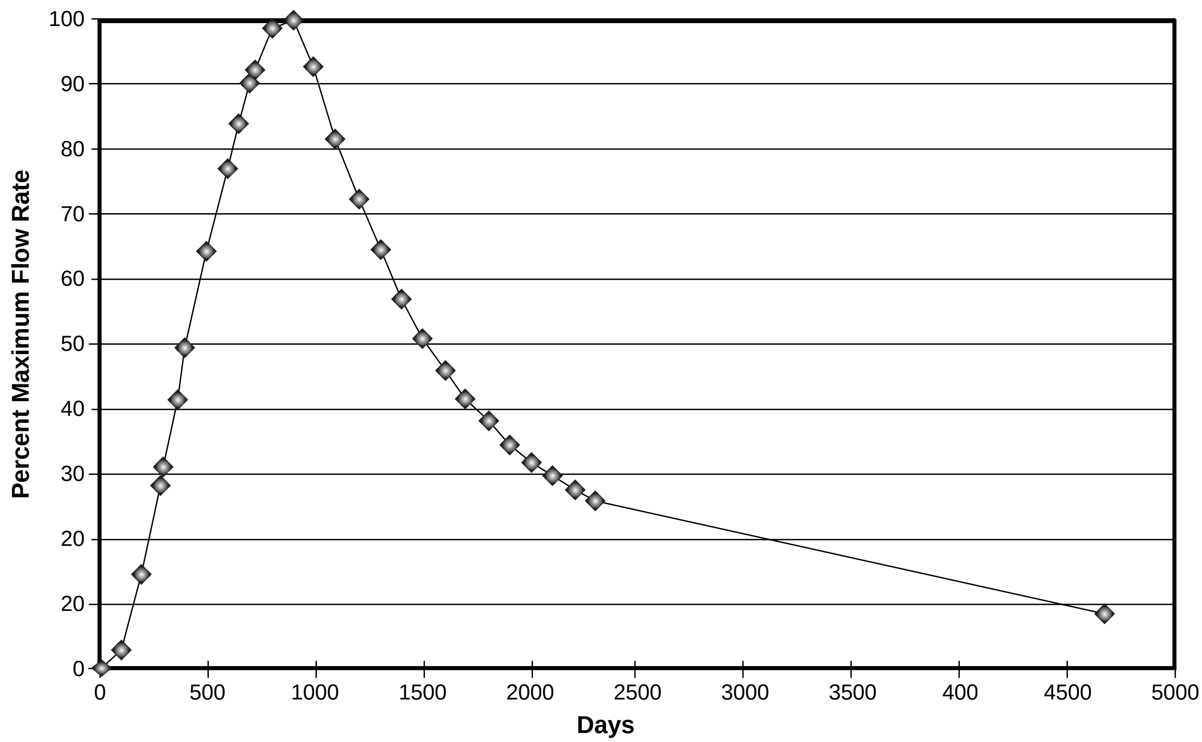


Figure 79. *Time distribution of the relative volumes of the recharge peak at a location 12,000 feet (3657 m) downgradient from the pilot project site.*

apparently substantially limits downward percolation of recharged water into the main part of the east shore aquifer system, and seepage of water infiltrated at the pilot project site into the north pit of the Staker-Parson South Weber quarry to the east. This amount of recharge will be helpful, but will not likely affect the large-scale decline in ground-water levels in the Delta aquifer.

The gravel pits east of the pilot project site (figure 15a) are better candidates for long-term, high-volume artificial recharge than the pilot project site because they contain fewer fine-grained layers and occupy a substantially larger area. The bottom of the north pit of the Staker-Parson South Weber pit is below the fine-grained layer that lies below the pilot project site. These pits are active and so are presently unavailable for artificial recharge. When operations in these pits cease, we hope that artificial ground-water recharge will receive strong consideration for use of the land. We recognize that such land-use decisions are complicated and require consideration of many different factors and interests, but ground-water supply will continue to be a challenging problem that must be addressed.

The ground-water flow model provides an excellent tool for planning and predicting the effects of future artificial recharge programs at the present pilot project site and/or the gravel pits to the east. The effects of various configurations and rates of artificial recharge and the resultant increased flow to existing water-supply wells can be calculated and weighed against the costs of implementation, and optimum program schedules or future well-drilling programs can be devised. The model, as currently constructed, accurately represents transient ground-water conditions in the east shore aquifer system. The predictive capacity of the model could be improved by incorporating new water-level and aquifer-test data if they become available in the future.

SUMMARY AND CONCLUSIONS

Ground-water levels in the east shore aquifer system of the Weber Delta subdistrict of the Weber Delta district have been steadily declining, locally by as much as 100 feet (30 m), during the past 50 years, due to increasing withdrawal of ground water by wells.

Several prior studies have shown that gravel pits at the mouth of Weber Canyon, where the Weber River enters the lowlands at the western boundary of the Wasatch Range, are excellent sites for infiltration of water diverted from the Weber River. Aquifer storage and recovery, as part of a conjunctive water-use program, can potentially help the water-supply problems in the area. The goal of this pilot project was to perform artificial recharge experiments that would lead to establishment of a long-term aquifer storage and recovery program involving substantial quantities of water by the Weber Basin Water Conservancy District near the mouth of Weber Canyon.

Two principal aquifers are present in the Weber Delta subdistrict—the Sunset (shallower) and Delta (deeper) aquifers, both composed of interbedded sand and gravel deposits. The Delta aquifer is the primary source of ground water in the area. The top of the Delta aquifer is 500 to 700 feet (150–200 m) below the land surface, and the aquifer is about 50 to 300 feet (15–60 m) thick. These two confined aquifers are separated by fine-grained deposits, are indistinguishable within about 1 mile (1.6 km) of the Wasatch Range front, and thin radially away from the mouth of Weber Canyon, which was the source of deposition of the Weber Delta.

The Delta aquifer is recharged primarily by infiltration from the Weber River within about 1.5 miles (2 km) of the mouth of Weber Canyon, and secondarily by westward underflow from bedrock aquifers in the Wasatch Range. Discharge is mainly by water wells for irrigation and domestic use, and secondarily by evapotranspiration, springs, and seepage along the eastern margin of Great Salt Lake.

A 12-acre (5 hm^2) plot of land, 1 mile (1.6 km) west of the mouth of Weber Canyon and just 0.25 mile (0.4 km) west of the Staker-Parson South Weber gravel pit, was selected as the pilot project site and was purchased by the Weber Basin Water Conservancy District. The District constructed a diversion structure on an irrigation canal along the north boundary of the property, and four basins having a total area of 3.7 acres (1.5 hm^2). Diverted water first spilled into a sedimentation basin to remove suspended matter, then into three infiltration basins. The U.S. Bureau of Reclamation well drilling team installed a 301-foot-deep (92 m) observation well at the pilot project site to obtain water-level and water-quality data before, during, and after the recharge experiments. The initial depth to water in the observation well was 231 feet (70 m).

Project personnel collected water-level and water-quality samples from wells in the vicinity of the pilot project site and water-quality samples from the Weber River before, during, and after the recharge experiments. All samples had high chemical quality. The pilot project recharge experiment included three periods of water diversion from the irrigation canal into the infiltration basins, one of which took place after the project team stopped collecting data. During the first recharge experiment, from March 18 to July 2, 2004, about 800 acre-feet (1 hm^3) of water was diverted into the infiltration basins. The water level in the observation well rose only about one foot (0.3 m) during the first recharge experiment. During the second recharge experiment, about 450 acre-feet (0.6 hm^3) of water was diverted and infiltrated from March 17 to May 23, 2005, and about 250 acre-feet (0.3 hm^3) of water was diverted and infiltrated from August 17 to October 31, 2005. The water level in the observation well rose 9.90 feet (3.00 m) during the second recharge experiment, conducted in spring and summer of 2005.

During the first two infiltration experiments, total-dissolved-solids concentrations in Weber River water decreased during spring runoff (late March to early July), then returned to normal values (~350 mg/L). Total-dissolved-solids concentrations in water wells in the area, including the pilot project site observation well, remained constant throughout the sampling period.

A high-precision gravity study was conducted to track the ground water infiltrated during the experiments. Gravity increased substantially below the infiltration site within a month after the beginning of the first recharge experiment. The area of increased gravity migrated to the east and south of the infiltration site. The infiltrated water encountered a low-permeability layer at 116 feet (35 m) depth, as documented in the observation well and in the north pit of the Staker-Parson South Weber pit, which retards the downward flow. The infiltrated water builds a mound (leading to the gravity increase) above this low-permeability layer, then flows laterally and slowly downward into the Delta aquifer.

A numerical ground-water flow model of the pilot project site and the surrounding east shore aquifer system was constructed using the three-dimensional numerical code MODFLOW, to calculate the effects of the infiltration experiments. The model accurately reproduces declining ground-water levels in the Weber Delta subdistrict over the past 50 years. The model includes diversion and infiltration data from the first two artificial recharge experiments, and is consistent with observed water-level changes in the pilot project site observation well and the size and movement of the mound of infiltrated water as estimated from the microgravity study.

Artificial recharge will need to occur at a substantially larger scale than that of the pilot project to stabilize or reverse downward-trending ground-water levels in the east shore area. Artificial recharge can, however, positively affect water-supply issues by increasing the flow to existing water-supply wells without substantially changing water levels.

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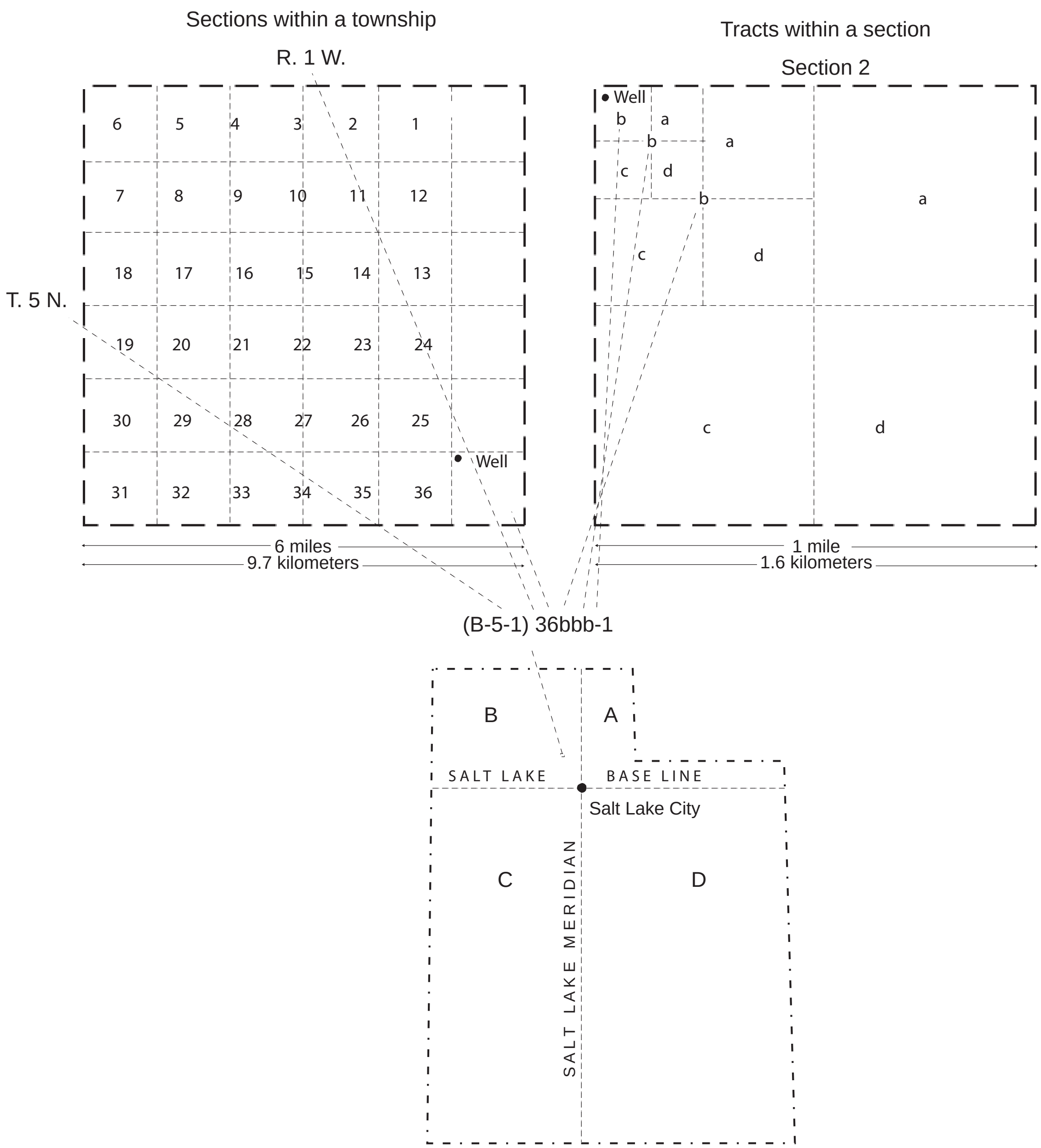
APPENDICES

APPENDIX A

RECORDS OF WATER WELLS AND WELL-NUMBERING SYSTEM



The numbering system for wells in this study is based on the Federal Government cadastral land-survey system that divides Utah into four quadrants (A–D) separated by the Salt Lake Base Line and Meridian. The study area is in the northwestern quadrant (B). The wells are numbered with this quadrant letter (B), followed by township and range, all enclosed in parentheses. The next set of characters indicates the section, quarter section, quarter-quarter section, and quarter-quarter-quarter section designated by letters a through d, indicating the northeastern, northwestern, southwestern, and southeastern quadrants, respectively. A number after the hyphen corresponds to an individual well within a quarter-quarter-quarter section. For example, the well (B-5-1)36bbb-1 would be the first well in the northwestern quarter of the northwestern quarter of the northwestern quarter of section 36, Township 5 North, Range 1 West (NW1/4NW1/4NW1/4 section 36, T. 5 N., R. 1 W.).

Figure A1. *Numbering system for wells in Utah - U.S. Geological Survey convention.*

Table A1*. Records of selected wells in study area.*

Well ID Number[1]	Owner	Well Name	Easting[2]	Northing[2]	Surface Elevation (ft)[3]	Well Depth (ft)[4]	Screened Interval (ft)[4]	Transmissivity (ft^2/d)[5]	Storativity[5]	Hydraulic Conductivity (ft/d)[5]
1	-	-	402714	4566940	4224	300	282-300	-	-	-
2	-	-	414019	4564591	4778	600	400-600	2010	3.9×10^{-4}	-
3	OGDEN CITY CORPORATION	WELL 23RD & VAN BUREN	420362	4563942	4415	583	-	-	-	-
4	OGDEN CITY CORPORATION	WELL NO.1	422249	4562824	5050	520	-	21,800	-	-
5	OGDEN CITY CORPORATION	WELL NO.2	422289	4562695	5050	510	-	2900	-	-
6	TAYLOR-WEST WEBER WID	BIG WELL	412233	4561810	4283	340	266-312	2	0.4	-
7	TAYLOR-WEST WEBER WID	SMALL WELL	412233	4561804	4283	340	273-312, 313-331	3520	0.023	-
8	-	-	406691	4561097	4222	83	-	-	-	-
9	-	-	409872	4560286	4259	546	-	-	-	-
10	OGDEN CITY	NORTH AIRPORT WELL	415670	4560419	4389	484	427-477	10,880	-	-
11	HOOPER WATER IMPROVEMENT DIST	WELL NO.2 40TH S.	412896	4560203	4252	430	390-400	7280	-	-
12	ROY CITY	4000 SOUTH WELL	413326	4559862	4480	970	885-945	13,440	-	-
13	OGDEN CITY	AIRPORT NO.2	415429	4560109	4401	507	439-487	-	-	-
14	HOOPER WATER IMROVEMENT DIST	WELL 2 REPLACEMENT	412875	4559972	4350	880	-	-	-	-
15	-	-	413781	4560006	4476	540	75-504?	-	-	-
16	UTAH BOARD WATER RESOURCES	WELL NO.1	417523	4558924	4495	450	-	9740	-	-
17	-	-	405862	4559054	4235	583	-		-	-
18	ROY CITY	4880 S. WELL	413847	4558671	4521	1108	950-1010	6220-9440	-	-
19	WEBER BASIN WCD	RIVERDALE WELL	416435	4558593	4367	730	570-600, 670-690, 710-720	32,200	2.5×10^{-4}	84.3
20	SOUTH OGDEN CITY	4800 S 390 E	418466	4558523	4662	784	-		-	-
21	RIVERDALE CITY	5190S 1050W NO.1	415705	4557904	4389	800	700-760	18,400	-	-
22	-	-	410886	4557874	4333	354	344-354?		-	-
23	ROY CITY	5175 SO 2425 W	412974	4557850	4495	1004	953-993	1720	-	-
24	WASHINGTON TERRACE	WELL NO.3	417271	4557553	4656	910	508-540, 795-855	15,130	-	-
25	RIVERDALE CITY	WELL NO 2	414603	4557450	4596	1085	940-1000, 1045-1065	60,000	7.5×10^{-7}	428.6
26	FLOREK, BJ	PRIVATE WELL	421289	4557396	4866	120	32-45		-	-
27	HOOPER WATER IMPROVEMENT DIST	WELLNO.1 5450 S.	410578	4557338	4612	807	247-310, 740-790	14,700	-	-
28	RIVERDALE CITY	RIVERDALE-GOLF	415729	4557311	4419	514	504-514	5950	-	-
29	-	-	402542	4557481	4234	649	-	-	-	-
30	-	-	410371	4557227	4286	978	-	-	-	-
31	WASHINGTON TERRACE	WELL NO.1	418703	4556963	4732	857	734-842	25,000	-	-
32	WEBER BASIN WCD	DIST. WELL NO 2	415933	4556652	4355	915	535-590, 690-795	42,000	-	-
33	FLADIE	PRIVATE WELL	409306	4556282	4254	547	537-547	1140	-	-
34	BYBEE, GRANT	PRIVATE WELL	421692	4556189	4830	23	-	-	-	-
35	RYUJIN, GEORGE	PRIVATE WELL	421301	4556059	4492	404	390-400	-	-	-
36	WEBER BASIN WCD	DIST. WELL NO.3	417174	4556007	4395	722	444-740, 820-841	14,000-22,400	-	-
37	ROY CITY	HILL FIELD WELL	414317	4556094	4611	560	530-560	22,880	1.3×10^{-6}	-
38	UNION PACIFIC RR	PRIVATE WELL	419179	4555925	4483	20		-	-	-
39	UINTAH HIGHLANDS IMP DIST	2559 S. COMBE	422890	4555823	4824	695	430-490, 585-605, 660-680	-	-	-
40	WINCHESTER, BRENT	PRIVATE WELL	419147	4555589	4483	190	180-190	<9000	-	-
41	NISTLER, RONALD	PRIVATE WELL	419228	4555585	4483	207	177-207	-	-	-
42	GIBBONS & REED	PRIVATE WELL	421187	4555576	4700	606	no screen	-	-	-
43	US BUREAU RECLAMATION	TEST HOLE NO.2	418748	4555544	4373	284	675-875	-	-	-
44	-	-	412357	4555415	4394	850	810-850	15,250	-	-
45	WEBER BASIN WCD	SO WEBER NO 1	418727	4555355	4735	1000	405-650, 712-752, 881-982	44,300	7.5×10^{-7}	148
46	HILL AIR FORCE BASE	WELL NO. 3	417738	4554871	4728	800	600-624, 720-787	-	-	-
47	HILL AIR FORCE BASE	WELL NO. 2	417712	4554744	4774	627	555-617	-	-	-
48	SPAULDING, LLOYD	PRIVATE WELL	418845	4555148	4459	193	160-?	-	-	-
49	VALLEY NURSERY	PRIVATE WELL	422226	4554978	4509	800	430-440, 720-800	-	-	-
50	HILL AIR FORCE BASE	WELL NO. 7	417126	4554996	4790	900	585-675	11,450	-	-
51	TOWN OF SUNSET	NEW WELL	414110	4554962	4550	759	-	-	-	-
52	HILL AIR FORCE BASE	WELL NO.6	417105	4554698	4665	900	654-?	-	-	-
53	HOOPER WATER IMPROVEMENT DIST	WELL NO.3	407275	4554588	4296	973	642-652, 664-700, 724-734, 810-820, 932-966	5970	-	-
54	CROFTS, DOUGLAS	PRIVATE WELL	422480	4554528	4509	186	164-165, 180-183	1430	-	-
55	CLINTON CITY	CLINTON WELL	413103	4554580	4480	937	847-917	-	-	336
56	SUNSET CITY WATER SYSTEM	CITY WELL	413848	4554513	4562	920	880-920	8075-9850	-	-
57	BYBEE, BRUCE	PRIVATE WELL	422767	4554378	4502	200	100-110		-	-
58	DANSIE, ROBERT	PRIVATE WELL	423742	4554226	4700	152	no screen	-	-	-
59	CLARENCE WATERFALL CO.	PRIVATE WELL	422751	4554113	4460	230	-	-	-	-
60	HILL AIR FORCE BASE	WELL NO. 8	414936	4553809	4679	900	740-760, 800-850, 860-880	11,100	-	-
61	SOUTH WEBER TOWN	WELL NO. 1	421334	4553697	4566	350	315-335	24,200	-	84.3
62	WEBER BASIN WCD	SO WEBER NO 2	419560	4553550	4515	1208	-		-	-
63	US BUREAU RECLAMATION	WELL	423688	4553428	4550	217	168-210	-	-	-
64	WEST POINT WATER SYSTEM	WELL NO.1	410334	4552251	4343	808	786-808	4540-6570	-	-

65	WEBER BASIN WCD	CLEARFIELD NO 1	413938	4552974	4567	995	911-941, 943-973, 974-985	38,600	-	-
66	KENNEDY, LEO	PRIVATE WELL	423991	4552824	4524	38	2-38	-	-	-
67	CLEARFIELD CITY	AT HILL AFB	416307	4552331	4767	1395	605-625, 645-685, 814-824, 870-950, 1246-1286	-	-	-
68	SMITH & PETTY	PRIVATE WELL	424189	4552588	4910	165	150-160	-	-	-
69	O'NEIL, BOB	PRIVATE WELL	423932	4552519	4762	520	no screen	-	-	-
70	WATER, CALVIN (?)	PRIVATE WELL	421971	4552508	4605	200	no screen	-	-	-
71	HILL AIR FORCE BASE	WELL NO. 4	419381	4552388	4813	730	584-623, 678-716	-	-	-
72	HILL AIR FORCE BASE	WELL NO. 9	420384	4552440	4916	1095	978-1018, 1075-1095	23,250	-	-
73	CHARLESWORTH, TERRY	PRIVATE WELL	423986	4552320	4865	119	111-119	-	-	-
74	WEST POINT WATER SYSTEM	WELL NO.2	409040	4552290	4313	1048	735-751, 823-871	-	-	-
75	WEST POINT WATER SYSTEM	WELL NO.3	411096	4552198	4367	865	802-840	11,400	-	-
76	DAVIS COUNTY LANDFILL	NDRD	421883	4551722	4890	510		-	-	-
77	HILL AIR FORCE BASE	WELL NO.5R	416819	4551458	4750	1500	970-1030, 1145-1245, 1315-1435	10,670	-	-
78	HILL AIR FORCE BASE	WELL NO. 5	416850	4551458	4754	805	610-800	-	-	-
79	CLEARFIELD CITY	750 E. 200 S.	414910	4550550	4487	668	-	-	-	-
80	-	-	415075	4551363	4554	730	701-725	-	-	-
81	LAYTON WATER SYSTEM	SANDRIDGE NO.2	420691	4550813	4779	957	555-590, 696-748, 765-795, 811-860, 919-947	-	-	107.4
82	CLEARFIELD CITY	RESERVOIR WELL	417108	4550582	4659	850	520-570, 695-705, 740-840	-	-	-
83	LAYTON WATER SYSTEM	SANDRIDGE NO.1	420621	4550563	4498	1007	690-840, 905-995	-	-	-
84	WEBER BASIN WCD	CLEARFIELD NO 2	416305	4550476	4503	902	675-875	61,600	0.73	-
85	-	-	420317	4550320	4501	990	672-797, 897-959	17,940	1.4×10^{-4}	107.4
86	CLEARFIELD CITY	FREEPORT NO.2	413996	4550360	4432	774	642-684	16,820	18	42.6
87	WEBER BASIN WCD	LAYTONA WELL	418290	4549833	4350	802	633-736, 739-745,750-768	31,850	9.8×10^{-10}	-
88	-	-	412262	4549674	4340	777	716-777	-	-	-
89	CLEARFIELD CITY	FREEPORT WELL NO.1	414347	4549842	4430	875	659-676, 756-768	14,900	3.35	47
90	SYRACUSE WATER SYSTEM	WELL NO.2	412217	4549670	4339	628	601-626	3940	-	-
91	SYRACUSE WATER SYSTEM	WELL NO.4	412246	4549671	4310	943	-	4760	-	-
92	LAYTON WATER SYSTEM	HILLFIELD WELL	418248	4548975	4310	707	582-700	-	-	25.6
93	-	-	408306	4549086	4240	622	614-622	-	-	-
94	SYRACUSE WATER SYSTEM	WELL NO.3	412974	4548940	4347	754	601-611, 704-734	7700	-	-
95	LAYTON WATER SYSTEM	SHOP WELL	420003	4548744	4367	1030	544-699, 819-900	26,400	1.2×10^{-8}	112
96	-	-	423665	4548500	4920	no log	-	-	-	
97	LAYTON WATER SYSTEM	CHURCH ST. WELL	420342	4548425	4778	930	560-720, 850-910	50,000	7.6×10^{-12}	250
98	LAYTON WATER SYSTEM	FORT LANE WELL	419462	4548109	4498	568	490-560	-	-	250
99	-	-	408869	4548164	4277	585	no screen	-	-	-
100	LAYTON WATER SYSTEM	GREENLEAF WELL	416712	4547351	4512	585	513-553, 560-570	3200	5×10^{-11}	25.6
101	-	-	412322	4547340	4280	600	no screen	-	-	-
102	-	-	409048	4546825	4227	600	580-600	-	-	-
103	EVANS	PRIVATE WELL	415921	4545725	4320	525	-	-	-	-
104	-	-	413824	4545681	4272	597	-	-	-	-
105	-	-	422429	4543371	4510	no log	-	-	-	-
106	-	-	420348	4542807	4323	350	-	-	-	-
107	LAYTON SUGAR COMPANY	PRIVATE WELL	423704	4542186	4580	300	195-298	40,000	-	-
108	HILL AIR FORCE BASE	WELL NO. 1	417627	4554823	4670	no log	-	-	-	-
109	ROY CITY	4800 SO 1980 W	414378	4556888	4550	561	-	-	-	-
110	BYBEE, BRUCE	PRIVATE WELL	419554	4556043	4760	200	-	-	-	-
111	UINTAH WARD LDS CHURCH	PRIVATE WELL	423055	4555670	4815	601	-	-	-	-
112	US BUREAU RECLAMATION	TEST WELL 3-A	420528	4553717	4495	350	-	-	-	-
113	US BUREAU RECLAMATION	TEST WELL 3-B	420531	4553742	4495	115	-	-	-	-
114	CLARENCE WATERFALL CO.	PRIVATE WELL	423451	4553463	4466	302	-	-	-	-
115	TOWN OF SUNSET	OLD WELL	414065	4554996	4550	505	-	-	-	-
116	LAYTON CITY CORPORATION	MALL WELL	418221	4547564	4390	505	-	-	-	-
117	OGDEN CITY CORPORATION	WELL (10")	415517	4560246	4455	536	-	-	-	-
118	ASR MONITOR WELL	MONITOR WELL	422471	4553960	4495	301	-	-	-	-
119	CLEMENTS	PRIVATE WELL	406698	4552393	4236	630	-	-	-	-
120	DAHL	PRIVATE WELL	405900	4552444	4225	693	-	-	-	-

Notes
1. ID number keyed to those shown in figures and text.
2. Easting and northing in meters, UTM NAD83.
3. Surface elevation from well-drillers' logs, or estimated from topographic maps, except wells 59 and 118 which were measured using high-precision GPS.
4. Data from well drillers' logs, available at <http://www.waterrights.utah.gov/>.
5. Data from well drillers' logs, pubications cited in the text, and/or calculated by M. Matyjasik.

Dash indicates data not available

APPENDIX B

DESCRIPTION OF GEOLOGIC UNITS SHOWN ON FIGURE 5

DESCRIPTION OF GEOLOGIC UNITS

Modified from Yonkee and Lowe (2004)

Quaternary

Quaternary map units are surficial deposits, grouped based on dominant depositional processes and their relationship to Bonneville lake-cycle stages (figure 6; table B1). Depositional process designators include lacustrine (l), deltaic (d), alluvial (a), and mass wasting (m). Relative-age designators include pre-Bonneville (5), Lake Bonneville transgressive (4), Lake Bonneville regressive (3), early to middle Holocene (2), and late Holocene (1).

Table B1. *Age (radiocarbon years B.P.) and elevation estimates for the principal shorelines of the Bonneville lake cycle (after Currey, D.R., unpublished data, and Oviatt and others, 1990, 1992; Oviatt, 1997).*

Shoreline	Phase	Elevation (ft)[1]	Age Estimate (10^3 years ago)
Stansbury	Transgressive	4419 – 4521	~ 21 – 20
Bonneville	Transgressive	5092 – 5335	~15 – 14.5
Provo	Regressive	4738 – 4931	~14.5 – 14
Gilbert	Regressive	4242 – 4301	~10.9 – 10.3

[1] Shoreline elevations are reported as ranges because the amount of post-Lake Bonneville isostatic rebound is geographically variable.

Lacustrine gravel bearing deposits, Bonneville transgressive (Qlg_4). This unit consists of moderately to well-sorted, medium- to thick-bedded, pebble- to cobble-clast gravel layers with minor to moderate amounts of sandy matrix interbedded with varying amounts of finer-grained intervals that increase in abundance away from the mountain front. Gravel clasts are mostly subrounded to rounded, but subangular clasts occur locally where alluvial-fan and landslide deposits were reworked along shorelines. Gravel-rich layers are best developed along the Bonneville shoreline (elevation 5210 feet [1590 m]).

Finer-grained intervals consist of thin-bedded silt, sand, and gravelly sand. This unit is exposed along the mountain front at elevations between the Provo and Bonneville shorelines, and grades westward into fine grained lacustrine deposits (Qlf_4) that lack gravel layers. This unit is locally greater than 200 feet (60 m) thick along the mountain front north of the mouth of Weber Canyon.

Lacustrine fine-grained deposits, Bonneville transgressive (Qlf_4). This unit consists of varying amounts of sand, silt, and clay, and includes both very fine grained intervals deposited in quiet, deep waters, and intervals deposited as delta bottomset beds. The very fine grained intervals are most abundant farther away from Weber Canyon and the mountain front, whereas bottomset deposits are more abundant near the mouth of Weber Canyon. The unit is well exposed within a series of 200-foot-high (60 m), 0.6-mile-long (1 km) ridges above the Provo shoreline (elevation 4800 feet [1460 m]) near the mouth of Weber Canyon. This unit may be up to 500 feet (150 m) thick near the mouth of Weber Canyon, including up to 300 feet (90 m) of deposits preserved in the subsurface; thickness appears to decrease to the north and west.

Deltaic deposits, Bonneville regressive (Qd_3). This unit consists mainly of sandy foreset and gravelly topset beds that form a large, gently west-sloping, composite delta deposited by the Weber and Ogden Rivers. The foreset deposits consist of interlayered beds of fine to medium, moderately to well-sorted sand, silt, and clay. The topset deposits consist mostly of clast-supported, subrounded to rounded, pebble and cobble gravel, with some gravelly sand; the gravel is moderately to well sorted, medium to thick bedded, and displays weak pebble imbrication and local channels. The topset gravels are up to 20 feet (6 m) thick. The foreset deposits are greater than 30 feet (9 m) thick in western parts of the Weber River delta, but are absent near the mouth of Weber Canyon east of the Provo shoreline (elevation 4800 feet [1460 m]) where the delta was incised into older lacustrine deposits.

The unit also includes gravels deposited as the Weber River incised into older deposits, forming multiple terraces between 100 and 300 feet (30 and 90 m) above the modern Weber River. These terraces are graded to various lower delta levels and regressive shorelines partly exposed to the west of the study area. The subrounded to rounded, pebble- to cobble-sized gravel is moderately to well sorted with some sandy matrix, medium to thick bedded, and displays pebble imbrication and local channels. Where exposed, the terrace gravels are up to 20 feet (6 m) thick.

Deltaic deposits, Bonneville transgressive (Qd_4). This unit consists mostly of clast supported, subrounded to rounded, pebble and cobble gravel and gravelly sand deposited as topset beds. The gravel is moderately to well sorted, medium to thick bedded, and exhibits weak pebble imbrication and contains local channels. These deposits cap small hilly areas at an elevation of about 5000 feet (1520 m) northwest of the mouth of Weber Canyon. The thickness of exposed topset beds in this unit is about 7 to 13 feet (2–4 m).

Stream alluvium, undivided (Qal). These deposits consist mainly of gravel, gravelly sand, and finer-grained overbank deposits along active stream channels and in inactive, low-level benches. The gravel is clast supported, mostly pebble to cobble sized, moderately to well sorted with some silty to sandy matrix, medium to thick bedded, and displays clast imbrication and channels. Clasts range from subangular to rounded, and are derived from mixed Paleozoic to Mesozoic sedimentary rock and Precambrian basement rock exposed in the Weber River drainage basin. Thin-bedded sand to silt comprise the overbank deposits. The undivided unit is mapped along the Weber River in Weber Canyon where separate alluvial deposits are too small to map separately. The deposits include minor matrix-supported debris-flow deposits along mountain stream channels, and are up to 40 feet (12 m) thick.

Stream alluvium, late Holocene (Qal_1). This unit consists mostly of gravel and some finer-grained overbank deposits along modern channels and recently active floodplains of the Weber River. The gravels have characteristics similar to those described for middle Holocene stream alluvium. The overbank deposits consist of thin bedded sand and silt. This unit is estimated to be about 10 to 20 feet (3–6 m) thick.

Stream alluvium, middle Holocene (Qal_2). This unit consists mostly of gravel and minor gravelly to silty sand forming benches about 10 to 30 feet (3–9 m) above the Weber Rivers active floodplain. The mostly pebble- to cobble-sized gravel is clast supported, moderately to well sorted with some silty to sandy matrix, medium to thick bedded, and displays clast imbrication and channels. Clasts range from subangular to rounded, and have mixed Paleozoic to Mesozoic sedimentary rock and Precambrian basement rock compositions, reflecting the wide variety of rock types in the Weber River drainage basin. Where exposed, the unit is less than 20 feet (6 m) thick.

Alluvial terrace deposits, early Holocene (Qat_2). This unit consists mainly of clast supported, pebble to cobble gravel and minor gravelly sand forming terraces found about 30 to 50 feet (9–15 m) above the modern Weber River. The terraces were deposited when the Weber River was graded to base levels below the Gilbert shoreline (elevation 4240–4245 feet [1292–1294 m] in the Roy quadrangle; Sack, 2003). The gravel is moderately to well sorted, medium to thick bedded, contains subangular to rounded clasts, and displays pebble imbrication and local channels. Where exposed, this unit is less than 20 feet (6 m) thick.

Alluvial-fan deposits, undivided (Qaf). This unit consists of complexly interlayered alluvial gravels and debris-flow deposits forming fan-shaped landforms. The alluvial gravels are typically clast supported, thin to thick bedded, moderately sorted, and contain angular to rounded, pebble to cobble clasts with variable amounts of sandy to silty matrix. The debris-flow deposits are typically matrix supported, unstratified, poorly to non sorted, and contain angular to subangular, pebble to boulder clasts; boulders can be up to 6 feet (2 m) in diameter. The undivided unit is mapped where relative age cannot be assigned based on morphologic and cross-cutting relations of the fans. These fan deposits, where exposed, are less than 30 feet (9 m) thick.

Alluvial-fan deposits, late Holocene (Qaf_1). These deposits comprise fan-shaped landforms that are graded to modern stream or local base levels, have relatively well-defined channels and levees, and, where the deposits are crossed by the Wasatch fault zone, exhibit fault scarps that are less than 10 feet (3 m) high. These alluvial fans also consist of interlayered gravel and debris-flow deposits. The alluvial gravels are a mixture of angular to subrounded and reworked, rounded clasts. The debris-flow deposits contain mostly angular clasts with an abundant fine-grained matrix. The larger boulder clasts are up to 6 feet (2 m) in diameter. These alluvial fans are probably less than 20 feet (6 m) thick.

Alluvial-fan deposits, middle and early Holocene (Qaf_2). These deposits comprise fan-shaped landforms that are slightly incised by modern streams, have moderately fresh channels and levees, and, where the deposits are crossed by the Wasatch fault zone, exhibit 10- to 30-foot-high (3–9 m) fault scarps. Like other alluvial fans, these deposits consist of complexly interlayered alluvial gravels and debris-flow deposits. The alluvial gravels are a mixture of angular to subrounded stream clasts and reworked, rounded lacustrine clasts, with variable amounts of sandy to silty matrix. The debris-flow deposits contain mostly angular clasts with abundant fine-grained matrix. These alluvial fans generally have exposed thicknesses of less than 20 feet (6 m).

Alluvial-fan deposits, Bonneville regressive (Qaf_3). These deposits comprise fan-shaped landforms that are graded to the Provo or other recessional shorelines, and that generally display subdued channels and levees; these alluvial fans are locally incised into transgressive alluvial fans (Qaf_4), but are incised by modern streams. Regressive fans also consist of complexly interlayered alluvial gravels and debris-flow deposits, like those described for undivided alluvial fans, but the gravels contain more rounded clasts derived from reworking of older lacustrine gravels. These fans generally have exposed thicknesses of less than 30 feet (9 m).

Alluvial-fan deposits, Bonneville transgressive (Qaf_4). These deposits comprise fan-shaped landforms having upper surfaces that are graded to the Bonneville shoreline, and that generally display subdued morphology and are deeply incised by modern streams. The deposits consist of complexly interlayered alluvial gravels and debris-flow deposits, like those described for undivided alluvial fans, but locally display increased rounding of clasts and decreasing amounts of fine-grained matrix near the Bonneville shoreline. These fan deposits grade locally into gravel-bearing lacustrine deposits (Qlg_4). These fans may be locally greater than 200 feet (60 m) thick, but fan thickness is difficult to determine.

Landslide deposits, undivided (Qms). This unit consists of unsorted, unstratified, clay- to boulder-rich diamicton and displaced bedrock blocks. Clasts in the deposits are generally angular and have compositions that reflect local source materials. This undivided unit is mapped above the Bonneville shoreline where age relations are uncertain. These deposits display distinct hummocky topography and local seeps, and are found mostly along steeper, north-facing slopes. Areas with indistinct hummocky topography that may be older landslides and hillslope colluvium are mapped as Qms?.

Landslide deposits, late Holocene (Qms_1). This unit includes landslides that have experienced recent movement reactivating parts of older landslides and typically have fresh scarps, local ground cracks, and distinctly hummocky surfaces. Deposits consist of sand, silt, and clay having disrupted bedding and local seeps, or clay- to boulder-rich diamicton, with clast and matrix compositions that reflect local source materials.

Landslide deposits, middle and early Holocene (Qms_2). This unit includes slides that developed mostly within finer-grained lacustrine and delta deposits, and slides along steeper slopes in the Wasatch Range that reactivated parts of older slides. Deposits consist mostly of sand, silt, and clay that have disrupted bedding and landslide-related faults (Feth and others, 1966). The former deposits exhibit hummocky topography, have subdued to moderately fresh head scarps, and locally form amphitheater-shaped regions. The latter deposits consist of clay- to boulder-rich diamicton with large bedrock blocks that have more distinctly hummocky topography compared to the older slides that they reactivated.

Landslide deposits, pre-Bonneville to Bonneville transgressive (Qms_5). These deposits are locally cut and reworked along the Bonneville shoreline, and the toes of the landslides are locally covered by thin lacustrine deposits, indicating they moved before Lake Bonneville rose to its highest level. However, parts of some of these landslides were likely active during the Bonneville transgression, and parts of some of these landslides may have been reactivated more recently. These deposits consist of clay- to boulder-rich diamicton with very large bedrock blocks that have been variably translated and rotated. These landslides have subdued hummocky topography and head scarps, and are found along steeper slopes above and near the Bonneville shoreline. The thicknesses of the deposits are likely highly variable. Areas that have randomly oriented bedrock blocks but lack distinct hummocky topography are mapped as Qms_5?.

Debris-flow deposits (Qmf). These deposits typically consist of matrix- to clast-supported, cobble to boulder gravel with variable amounts of sandy to clayey matrix. The deposits are generally poorly to non-sorted, non-layered, and locally exhibit rock levees and central channels. These deposits are present in some mountain canyons, and may contain multiple flows of various ages, including flows graded to the Bonneville or Provo shorelines, Holocene flows that are incised into older flows, and historically active flows. However, because individual flows are small relative to map scale and correlating ages of flows between canyons is difficult, all debris-flow deposits are grouped into one map unit. Debris-flow deposits are generally less than 30 feet (9 m) thick.

Talus (Qmt). These deposits consist of angular, pebble- to boulder-sized rock debris with little or no matrix. The talus forms scree slopes with little or no vegetation at the bases of cliffs and steeper bedrock slopes. The talus blocks have compositions that reflect the nearby bedrock sources. Talus deposits grade into colluvium that has been partly stabilized by vegetation. The thickness of the deposits is uncertain, but is probably less than 50 feet (15 m) in most areas.

Colluvium (Qc). Colluvium consists of variably clayey to sandy, pebble to boulder gravel and diamicton, that have moved and been deposited mostly by slope wash and creep. These deposits also include small areas of debris and alluvial cones, talus, landslides, alluvium, avalanche deposits, and bedrock exposures. Colluvial deposits are matrix to rarely clast supported, generally poorly to non-sorted, weakly to non-stratified, and contain angular to subangular clasts with variable amounts of sandy to clayey matrix. This unit is mapped along slopes in the Wasatch Range and some scarps of the Wasatch fault zone. The total thickness of colluvial deposits is probably less than 50 feet (15 m) in most areas.

Colluvium and alluvium, undivided (Qac). This unit includes hillslope colluvium and stream alluvium, with small areas of debris cones, landslides, and bedrock exposures. This unit consists of non-sorted, unstratified, clay- to boulder-rich diamicton, and moderately sorted, cobble gravel to sand with subangular to subrounded clasts deposited along channels and slopes near some ephemeral streams in the Wasatch Range. Modern channels are locally incised up to 20 feet (6 m) into these deposits, indicating a long history of accumulation and recent local erosion. These deposits are probably less than 50 feet (15 m) thick in most areas.

Artificial fill (Qf). This unit consists of debris that was excavated and reworked or imported into the area during construction of roads and railways along Weber Canyon. Smaller areas of fill and disturbed ground are not mapped.

Tertiary

Tertiary igneous dikes (Td). Two small igneous dikes (NE 1/4 section 24 and N 1/2 section 25, T. 5 N., R. 1 W., Salt Lake Base Line and Meridian) cross-cut rocks of the Farmington Canyon Complex. These dikes are non-foliated and are composed of hornblende, biotite, and plagioclase phenocrysts in a fine-grained, altered matrix.

Cretaceous

Chloritic gneiss, cataclasite, and mylonite (Kc). This unit consists of protoliths of the Farmington Canyon Complex that have undergone variable degrees of greenschist-facies alteration and deformation. The chloritic gneiss exhibits moderate to strong chlorite alteration, moderately to closely spaced fractures, some micaceous cleavage and fault and shear zones, and, locally, quartz-filled veins. The cataclasite exhibits extensive alteration, abundant angular fragments in a fine-grained, highly comminuted matrix, and widespread quartz veins. The mylonite exhibits extensive alteration and strong foliation defined by quartz ribbons and mica aggregates.

Neoproterozoic Farmington Canyon Complex

Granitic gneiss (Xfgh). This unit consists of medium- to fine-grained, strongly foliated granitic gneiss, composed of about 20 to 35 vol% quartz, 20 to 35 vol% plagioclase, 25 to 35 vol% K-feldspar, 3 to 15 vol% hornblende, 0 to 5 vol% biotite, and minor oxides and orthopyroxene. The plagioclase is partly altered to sericite and epidote, the K-feldspar is slightly altered to sericite, and the hornblende is partly altered to chlorite in some areas. The granitic gneiss is cut by coarse-grained granite and pegmatitic dikes composed of feldspar, quartz, and, in some dikes, minor hornblende and orthopyroxene. This unit is locally interlayered with the migmatitic gneiss (unit Xfm).

Migmatitic gneiss (Xfm). This unit consists of migmatitic, fine- to medium-grained, garnet- and biotite-bearing, quartzo-feldspathic gneiss. The migmatitic gneiss contains about 20 to 40 vol% quartz, 20 to 40 vol% K-feldspar, 20 to 40 vol% plagioclase, 0 to 20 vol% garnet, 0 to 20 vol% biotite, and minor oxides; some samples also contain up to 5 vol% hornblende and rare orthopyroxene. Locally, the plagioclase is partly altered to sericite and epidote, the K-feldspar is slightly altered to sericite, and the biotite and garnet are partly altered to chlorite. The unit exhibits a strong foliation defined by the preferred orientation of biotite and quartz aggregates. The gneiss is cut by widespread coarse-grained granitic to pegmatitic dikes composed mostly of coarse-grained feldspar and quartz, with rare orthopyroxene and minor garnet. This unit also contains widespread thin layers of amphibolite, bands of hornblende-bearing granitic gneiss, and local layers of biotite-rich schist.

Biotite-rich schist (Xfb). This unit consists mostly of layers of biotite-rich schist containing widespread sillimanite and garnet. The schist layers contain biotite and variable amounts of sillimanite, garnet, quartz, plagioclase, K-feldspar, and minor oxides. Locally, the biotite and garnet are partly altered to chlorite, and the plagioclase is partly altered to sericite and epidote. The unit exhibits a strong foliation that is partly defined by a preferred orientation of biotite, and local compositional layering is defined by alternating darker, biotite-sillimanite-rich bands and lighter, quartz-feldspar-rich bands. The schist is cut by widespread pegmatite pods, which consist of abundant quartz and feldspar, minor biotite, and garnet. This unit also contains some thin layers of amphibolite, quartz-rich gneiss, and granitic gneiss, and grades into migmatitic gneiss with decreasing biotite content.

APPENDIX C

LOGS OF OBSERVATION WELL

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

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

Well Identification

Non-Production Well: 0435001M00 RECEIVED WIN: 29129

Owner *Note any changes*

Weber Basin Water Conservancy District
2837 East Highway 193
Layton, UT 84040

MAR 1 5 2004
WATER RIGHTS
SALT LAKE

Contact Person/Engineer: ____________

Well Location *Note any changes*

N 972 E 1673 from the SW corner of section 26, Township 5N, Range 1W, SL B&M

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

Drillers Activity Start Date: Jan 26, 2004 Completion Date: March 3, 2004

Check all that apply: ☒ New ☐ Repair ☐ Deepen ☐ Clean ☐ Replace ☐ Public Nature of Use: Monitoring Well

If a replacement well, provide location of 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	35'	12"	Air rotary - Odex System	Air
35	143'	10"	" " " "	Air to 116', Air foam/water to 143'
143	301	8"	" " " "	Air

Well Log

DEPTH (feet) FROM	TO	WATER	PERMEABLE High	PERMEABLE Low	CLAY	SILT	SAND	GRAVEL	COBBLES	BOULDER	OTHER	ROCK TYPE	COLOR	DESCRIPTION AND REMARKS (e.g., relative %, grain size, sorting, angularity, bedding, grain composition density, plasticity, shape, cementation, consistancy, water bearing, ordor, fracturing, minerology, texture,degree of weathering, hardness, water quality, etc.)
0	17					x	x						brown	dry
17	30					x	x	x					"	"
30	40					x	x	x					"	"
40	50					x	x	x					"	"
50	60					x	x	x					"	"
60	65					x	x	x					"	"
65	75					x	x						"	moist
75	85					x	x						"	"
85	94	x		x		x	x						"	Wet, perched water table
94	103	x		x		x	x						"	" " " "

Static Water Level

Date Feb 23, 2004 Water Level 234.3 feet Flowing? ☐ Yes ☒ No

Method of Water Level Measurement Water Level Meter If Flowing, Capped Pressure ____________ PSI

Point to Which Water Level Measurement was Referenced Top of sounder tube Elevation 4495

Height of Water Level reference point above ground surface 3.5' feet Temperature 55 degrees ☐ C ☒ F

Construction Information

DEPTH (feet)		CASING			DEPTH (feet)		☐SCREEN	☐PERFORATIONS	☐OPEN BOTTOM
FROM	TO	CASING TYPE AND MATERIAL/GRADE	WALL THICK (in)	NOMINAL DIAM. (in)	FROM	TO	SCREEN SLOT SIZE OR PERF SIZE (in)	SCREEN DIAM. OR PERF LENGTH (in)	SCREEN TYPE OR NUMBER PERF (per round/interval)
270	0	Sched 80 PVC		6	270	300	0.040	6	sched 80 PVC
3.5	+1.5'	Steel casing	.365	10					

Well Head Configuration: 10" casing, turtle cap, 3/4" sounder tube Access Port Provided? ☒Yes ☐No

Casing Joint Type: threaded Perforator Used: ____

Was a Surface Seal Installed? ☒Yes ☐No Depth of Surface Seal: 140 feet Drive Shoe? ☐Yes ☒No

Surface Seal Material Placement Method: tremie

DEPTH (feet)		SURFACE SEAL / INTERVAL SEAL / FILTER PACK / PACKER INFORMATION		
FROM	TO	SEAL MATERIAL, FILTER PACK and PACKER TYPE and DESCRIPTION	**Quantity** of Material Used (if applicable)	GROUT DENSITY (lbs./gal., # bag mix, gal./sack etc.)
140	135	Pel Plug 3/8" Bentonite	4 5gal buckets	
135	11	BH high solids bentonite grout	22 50lb bags	14 gal/bag
11	0	Portland Cement	24 47lb bags	15 lb/gal

Well Development and Well Yield Test Information

DATE	METHOD	YIELD	Units Check One		DRAWDOWN (ft)	TIME PUMPED (hrs & min)
			GPM	CFS		
2/24/04	Air Jet developed	not meas.				
3/1/04	Pump Test	93	x		2.34	7 hrs

Pump (Permanent)

Pump Description: Grundfus 25S30-15 single phase Horsepower: 3 Pump Intake Depth: 270 feet

Approximate Maximum Pumping Rate: 30 gpm Well Disinfected upon Completion? ☐Yes ☒No

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

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

Name US BUREAU OF RECLAMATION, DRILL SHOP **License No.** 681
(Person, Firm, or Corporation - Print or Type)

Signature [signature] (Licensed Well Driller) **Date** Mar 12, 2004

WELL DRILLER'S REPORT ADDTIONAL DATA FORM
State of Utah
Division of Water Rights

Page ____ of ____

RECEIVED
MAR 1 5 2004
WATER RIGHTS
SALT LAKE
SC

Well Identification

Non-Production Well: 0435001M00

Owner *Note any changes*

Weber Basin Water Conservancy District
2837 East Highway 193
Layton, UT 84040

Contact Person/Engineer: ______________________

Well Location *Note any changes*

N 972 E 1673 from the SW corner of section 26, Township 5N, Range 1W, SL B&M

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

Well Log

DEPTH (feet) FROM	TO	WATER	PERMEABLE High	PERMEABLE Low	UNCONSOLIDATED CLAY	SILT	SAND	GRAVEL	COBBLES	BOULDER	OTHER	CONSOLIDATED ROCK TYPE	COLOR	DESCRIPTION AND REMARKS (e.g., relative %, grain size, sorting, angularity, bedding, grain composition density, plasticity, shape, cementation, consistancy, water bearing, ordor, fracturing, minerology, texture,degree of weathering, hardness, water quality, etc.)
103	116	xx		x		x	x						brown	Silty layer at 116' wet, perched water table
116	125					x	x						"	
125	135					x	x	x					"	
135	143					x	x	x					"	
143	148					x	x	x					"	dry to moist
148	158					x	x	x					"	" x "
158	170					x	x	x					"	" "
170	180					x	x	x					"	" "
180	190					x	x	x					"	" "
190	200					x	x	x					"	moist
200	209					x	x	x					"	"
209	219					x	x	x					dk brown	"
219	229					x	x	x					" "	"
229	239					x	x	x					brown	"
239	244					x	x	x					"	"
244	254					x	x	x					dk brown	"
254	264					x	x	x					" "	"
264	274	x		x		x	x	x					" "	moist to wet
274	284	x	x			x	x	x	x	x			brown	Cobbles and boulders at 282', water increasi
284	294	x	x			x	x	x	x	x			"	water increasing
294	301	x	x			x	x	x	x	x			dk brown	" "

Construction Information (con't)

DEPTH (feet)		CASING			DEPTH (feet)		☐SCREEN ☐PERFORATIONS ☐OPEN BOTTOM		
FROM	TO	CASING TYPE AND MATERIAL/GRADE	WALL THICK (in)	NOMINAL DIAM. (in)	FROM	TO	SCREEN SLOT SIZE OR PERF SIZE (in)	SCREEN DIAM. OR PERF LENGTH (in)	SCREEN TYPE OR NUMBER PERF (per round/interval)

DEPTH (feet)		SURFACE SEAL / INTERVAL SEAL / FILTER PACK / PACKER INFORMATION		
FROM	TO	SEAL MATERIAL, FILTER PACK and PACKER TYPE and DESCRIPTION	**Quantity** of Material Used (if applicable)	GROUT DENSITY (lbs./gal., # bag mix, gal./sack etc.)

Comments (con't)

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

Name US BUREAU OF RECLAMATION, DRILL SHOP **License No.** 681
(Person, Firm, or Corporation - Print or Type)

Signature [illegible] **Date** Mar 12, 2004
(Licensed Well Driller)

GEOLOGIC LOG OF DRILL HOLE NO. ARS-MW-1-04

SHEET 1 OF 3

FEATURE: Monitoring Well
LOCATION: Near west mouth of Weber Cyn.
BEGUN: 1/26/04 FINISHED: 3/3/04
DEPTH AND ELEV OF WATER
LEVEL AND DATE MEASURED: ▽ 230.8 (4264.20)2/23/04

PROJECT: Weber Basin
COORDINATES:
TOTAL DEPTH: 301.0
DEPTH TO BEDROCK: N/E

STATE: Utah
GROUND ELEVATION: 4495.0
ANGLE FROM HORIZONTAL: -90.0 AZIMUTH —
HOLE LOGGED BY: Ira Terry
REVIEWED BY:

NOTES

Drilled by:
USBR Provo Area Office Drill Crew, Brad Winters, driller

Drill Equipment:
Gus Pech Brat 22R truck mounted air rotary drill rig

Drilling method:
Drilled from 0.0' to 35' using 12" Odex drilling system and installed 12" temporary casing. Drilled from 35' to 143' using 10" Odex drilling system and installed 10" temporary casing. Drilled from 143' to 301' using 8" Odex drilling system and installed 8" temporary casing.

Drilling fluid:
The drillers used two 900 cfm Ingersol-rand air compressors to drill this hole. The hole was drilled with air from 0 to 116', used water and air foam from 116' to 143'. Stopped using air foam at 143' and switched back to using air only from 143' to 301'.

Drilling Character:
Good fast drilling to 116'. Odex hammer stopped working at 116' due to flowing sand and mechanical problems. Slow drilling from 116' to 143' due to mechanical problems with the hammer. Good fast drilling to 282'. Slow, hard drilling to 301' in cobbles and boulders.

Water Level:
Water level measured 2-23-04 at 230.8 from ground level. Casing stickup is 1.7'. Water level from top of casing is 232.5'.

Hole Completion:
Installed 6" diameter schedule 80 PVC, 0.040 slot screen from 300 to 270'. Installed schedule 80 PVC blank casing from 270' to the surface. All temporary 8, 10 and 12" steel casing was removed from the

DEPTH	GEOL UNIT SYMBOL	% CORE RECOVERY	SEISMIC VELOCITY (S-Wave) m/s	SEISMIC VELOCITY (P-Wave) m/s	WEATHERING	HARDNESS	ELEVATION	FLD CLASS/ LITH	CLASSIFICATION AND PHYSICAL CONDITION
									Note; All samples described below are field classifications. See note at bottom of log.
0-5							4490.0	(SP-SM)	0-5' about 95% coarse to predominantly fine sand; about 5% nonplastic fines; brown, dry. (FS-1)
5-10							4485.0	(SP-SM)	5-10' as at 0' except no coarse sand. (FS-2)
10-15							4480.0	(SP-SM)	10-15' as at 0'. (FS-3)
15-17							4478.0	(SP-SM)	15-17' as at 0'. (FS-4)
17-20							4475.0	(SP-SM)G	17-20' about 5% nonplastic fines; about 20% coarse to fine, angular (fractured) to subrounded gravel, gravel is fractured by drilling; about 70% coarse to fine, subangular to subrounded sand; brown, dry. (FS-5)
20-25							4470.0	(SP-SM)G	20-25' as at 17' (FS-6)
25-30							4465.0	(GP-GM)S	25-30' about 55% coarse to fine, subangular to subrounded gravel; about 45% coarse to fine, subangular to rounded sand; about 5% nonplastic fines; brown, dry. (FS-7)
30-35							4460.0	(GP-GM)S	30-35' as at 25' (FS-7)
35-40							4455.0	(SP-SM)	35-40' predominantly coarse to fine, angular (fractured) to subrounded sand; about 5% nonplastic fines; trace of fine gravel; brown, dry (FS-8)
40-45							4450.0	(GP-GM)S	40-45' about 60% coarse to fine angular (fractured) to well rounded gravel; about 35% coarse to fine angular (fractured) to rounded sand; about 5% nonplastic fines; brown, dry. (FS-9)
45-50							4445.0	(SP-SM)G	45-50' about 30% coarse to fine, angular (fractured) to rounded gravel; about 65% coarse to fine, angular (fractured) to rounded sand; about 5% nonplastic fines; brown, dry. (FS-10)
50-55							4440.0	(SP-SM)G	50-55' about 65% coarse to fine, angular (fractured) to subrounded sand; about 30% angular (fractured) to subrounded gravel; about 5% nonplastic fines; brown, dry. (FS-11)
55-60							4435.0	(SP-SM)G	55-60' about 65% coarse to predominantly fine sand; about 30% coarse to fine, angular (fractured) to subrounded gravel; about 5% nonplastic fines; brown, dry. (FS-12)
60-65							4430.0	(SP-SM)	60-65' about 85% fine sand; about 10% coarse gravel; about 5% nonplastic fines; brown, dry. (FS-13)
65-70							4425.0	(SP-SM)	65-70' about 90 to 95% fine sand; about 5 to 10% nonplastic fines; brown, moist. (FS-14).
70-73							4422.0	(SP-SM)	70-73' as at 65'. (FS-15)
73-77							4418.0	(SP-SM)	73-77' as at 65' (FS-16)
77-80							4415.0	(SP-SM)	77-80' as at 65' (FS-17)
80-85							4410.0	(SP-SM)	80-85' as at 65' (FS-18)
85-89							4406.0	(SP-SM)	85-89' as at 65' (FS-19)
89-94							4401.0	(SP-SM)	89-94' as at 65' except moist to wet; quick dilatancy (FS-20)
94-98							4397.0	(SP-SM)	94-98' as at 65' except moist (FS-21)
98-103								(SP-SM)	98-103' as at 65' except wet (FS-22)

Continued next page

COMMENTS:
N/E = Not encountered

Notes:
Odex drill cuttings are typically are not representative of the materials encountered. Any coarse material such as cobbles and boulders are pulverized in the hole before being air lifted to the surface. Samples are usually mixed and contain less fines than the material encountered. FS= field samples taken. All samples were given to Weber State University for analysis.

U.S. DEPARTMENT OF THE INTERIOR · BUREAU OF RECLAMATION

Date Plotted: 3/9/04 Time Plotted: 01:29 PM

GEOLOGIC LOG OF DRILL HOLE NO. ARS-MW-1-04

SHEET 2 OF 3

FEATURE: Monitoring Well
LOCATION: Near west mouth of Weber Cyn.
BEGUN: 1/26/04 FINISHED: 3/3/04
DEPTH AND ELEV OF WATER
LEVEL AND DATE MEASURED: 230.8 (4264.20)2/23/04

PROJECT: Weber Basin
COORDINATES:
TOTAL DEPTH: 301.0
DEPTH TO BEDROCK: N/E

STATE: Utah
GROUND ELEVATION: 4495.0
ANGLE FROM HORIZONTAL: -90.0 AZIMUTH: --
HOLE LOGGED BY: Ira Terry
REVIEWED BY:

NOTES

hole. Two feet of 10" steel casing standpipe was placed over the PVC. A 3/8" bentonite pellet plug was placed in the hole from about 140 to 135'. The hole was grouted using high solids bentonite grout from 135' to 11'. Portland cement from 11' to the surface. Used 40 50lb buckets of bentonite pellets, 20 50lb bags of BH high solids bentonite grout, and 21 47lb bags of Portland cement.

ELEVATION	FLD CLASS/ LITH	CLASSIFICATION AND PHYSICAL CONDITION
4392.0	(SP-SM)	
4388.0	(SP-SM)	103-107' as at 65' except saturated (FS-23)
4385.0	(SP-SM)	107-110' as at 65' except saturated (FS-24)
4379.0	(SM)	110-116' about 85% fine sand; about 15% nonplastic fines; brown, wet. (FS-25).
4378.0	S(ML)	At 116' about 60% nonplastic fines; about 40% fine sand; brown, saturated. (FS-26). The actual thickness of this zone is unknown, but it is thin.
4375.0	(SM)	(Note: Odex hammer stopped working at this depth due to flowing sands. Started to use water and air foam).
4370.0	(SM)	117-120' silt and sand; mostly fine sand; saturated, brown (poor sample) (FS-27)
4365.0	(SM)	120-125' as at 116-120' (FS-28) 125-130' as at 116-120' (FS-29)
4360.0	(SM)	130-135' as at 116-120' trace of fine gravel (FS-30)
4355.0	(SM)	135-140' as at 116'120' silt and fine sand, trace of coarse sand; brown; saturated (FS-31)
4352.0	(SP-SM)G	140-143' about 75% coarse to fine, subangular to subrounded sand; about 20% coarse to fine, angular (fractured) to subrounded gravel; about 5% nonplastic fines; brown, saturated. (FS-32)
4347.0	(SP-SM)G	143-148' about 65% coarse to predominantly fine sand; about 30% coarse to fine, subangular to subrounded gravel; about 5% nonplastic fines; brown; dry to moist. (Note: stopped using air foam at 143') (FS-33)
4342.0	(GP-GM)S	148-153' about 75% coarse to fine, subangular to subrounded gravel; about 20% coarse to fine, subangular to subrounded sand; about 5% nonplastic fines; brown, dry to moist. (FS-34)
4337.0	(GP-GM)S	153-158' as at 148' (FS-35)
4335.0	(GP-GM)S	158-160' as at 148' (FS-36)
4330.0	(GP-GM)S	160-165' as at 148' (FS-37)
4325.0	(GP-GM)S	165-170' as at 148' (FS-38)
4320.0	(GP-GM)S	170-175' as at 148' (FS-39)
4315.0	(GP-GM)S	175-180' as at 148' (FS-40)
4310.0	(GP-GM)S	180-185' as at 148' except moist (FS-41)
4305.0	(GP-GM)S	185-190' as at 148' (FS-42)
4300.0	(GP-GM)S	190-195' as at 148' (FS-43)
4295.0	(GP-GM)S	195-200' as at 148' except moist (FS-44)
4291.0	(GP-GM)S	200-204' about 55% coarse to fine, subangular to subrounded gravel; about 40% coarse to fine, subangular to subrounded sand; about 5% nonplastic fines; brown, moist. (FS-45)
4286.0	(GP-GM)S	204-209' about 50% coarse to fine, subangular to subrounded gravel; about 40% coarse to fine, subangular to subrounded sand; about 10% nonplastic fines; brown, moist. (FS-46)
4281.0	(GP-GM)S	209-214' about 55% coarse to fine, subangular to subrounded gravel; about 40% coarse to fine, subangular to subrounded sand; about 5% nonplastic fines; dark brown; moist. (FS-47)
4276.0	(GP-GM)S	214-219' about 75% coarse to fine, subangular to subrounded gravel; about 20% coarse to fine, subangular to subrounded sand; about 5% nonplastic fines; dark brown, moist (FS-48)
4271.0	(GP-GM)S	219-224' about 55% coarse to fine, subangular to subrounded gravel; about 40% coarse to fine, subangular to subrounded gravel; about 5% nonplastic fines; dark brown, moist.

Continued next page

GEOLOGIC LOG OF DRILL HOLE NO. ARS-MW-1-04

SHEET 3 OF 3

FEATURE: Monitoring Well
LOCATION: Near west mouth of Weber Cyn.
BEGUN: 1/26/04 FINISHED: 3/3/04
DEPTH AND ELEV OF WATER
LEVEL AND DATE MEASURED: 230.8 (4264.20)2/23/04

PROJECT: Weber Basin
COORDINATES:
TOTAL DEPTH: 301.0
DEPTH TO BEDROCK: N/E

STATE: Utah
GROUND ELEVATION: 4495.0
ANGLE FROM HORIZONTAL: -90.0 AZIMUTH: —
HOLE LOGGED BY: Ira Terry
REVIEWED BY:

NOTES	DEPTH	GEOL UNIT SYMBOL	% CORE RECOVERY	SEISMIC VELOCITY (S-Wave) m/s	SEISMIC VELOCITY (P-Wave) m/s	WEATHERING	HARDNESS	ELEVATION	FLD CLASS/ LITH	CLASSIFICATION AND PHYSICAL CONDITION
								4266.0	(SP-SM)G	(FS-49) 224-229' about 65% coarse to fine, subangular to subrounded sand; about 30% coarse to fine, subangular to subrounded gravel; about 5% nonplastic fines; moist, brown. (FS-50).
	230							4261.0	(SP-SM)	229-234' about 90% predominantly fine sand; about 5% coarse to fine, subangular to subrounded gravel; about 5% nonplastic fines; brown, moist. (FS-51)
	235							4256.0	(SP-SM)	234-239' about 95% fine sand; about 5% nonplastic fines; brown, moist. (FS-52)
	240							4251.0	(SP-SM)	239-244' about 90% predominantly fine sand; about 5% coarse to fine, subangular to subrounded gravel; about 5% nonplastic fines; brown, moist (FS-53)
	245							4246.0	(GP-GM)S	244-249' about 50% coarse to fine, subangular to subrounded gravel; about 45% coarse to fine, subangular to subrounded sand; about 5% nonplastic fines; brown, moist. (FS-54)
	250							4241.0	(SP-SM)G	249-254' about 65% coarse to fine, subangular to subrounded sand; about 30% coarse to fine, subangular to subrounded gravel; about 5% nonplastic fines; dark brown, moist. (FS-55)
	255							4236.0	(SP-SM)G	254-259' as at 249' (FS-56)
	260							4231.0	(SP-SM)G	259-264' as at 249' (FS-57)
	265							4226.0	(GP-GM)S	264-269' about 55% coarse to fine, subangular to subrounded gravel; about 40% coarse to fine, subangular to subrounded sand; about 5% nonplastic fines; brown, saturated. (FS-58)
	270							4221.0	(GP-GM)S	269-274' about 60% coarse to fine, subangular to subrounded gravel; about 35% coarse to fine, subangular to subrounded sand; about 5% nonplastic fines; brown, moist. (FS-59
	275							4216.0	(GP-GM)S	274-279' as at 269' except wet. (FS-60)
	280							4213.0	(GP-GM)S	279-282' as at 269' except saturated (FS-61)
								4211.0	(SP)cb	282-284' driller reported cobble and boulder size material with gravel and sand (FS-62). Approximately 50% gravel and 50 % sand. The amount oversize material is unknown.
	285, 290							4201.0	(SP)cb	284-294' as at 282' (FS-63)
	295							4196.0	(SP)	294-299' about 50% predominantly coarse sand; about 50% coarse to fine, angular (fractured) to subrounded gravel; brown to dark brown, wet. Driller reported cobbles and boulders in this interval. (FS-64)
	300							4191.0	(SP-SM)G	299-304' about 75% predominantly medium to coarse sand; about 20% coarse to fine, subangular to subrounded gravel; about 5% nonplastic fines. (FS-65)
	305									
	310									
	315									
	320									
	325									
	330									
	335									
	340									
	345									

BOR-ELEV WEBER.GPJ BOR_UTAH.GDT 3/9/2004 1:29:57 PM

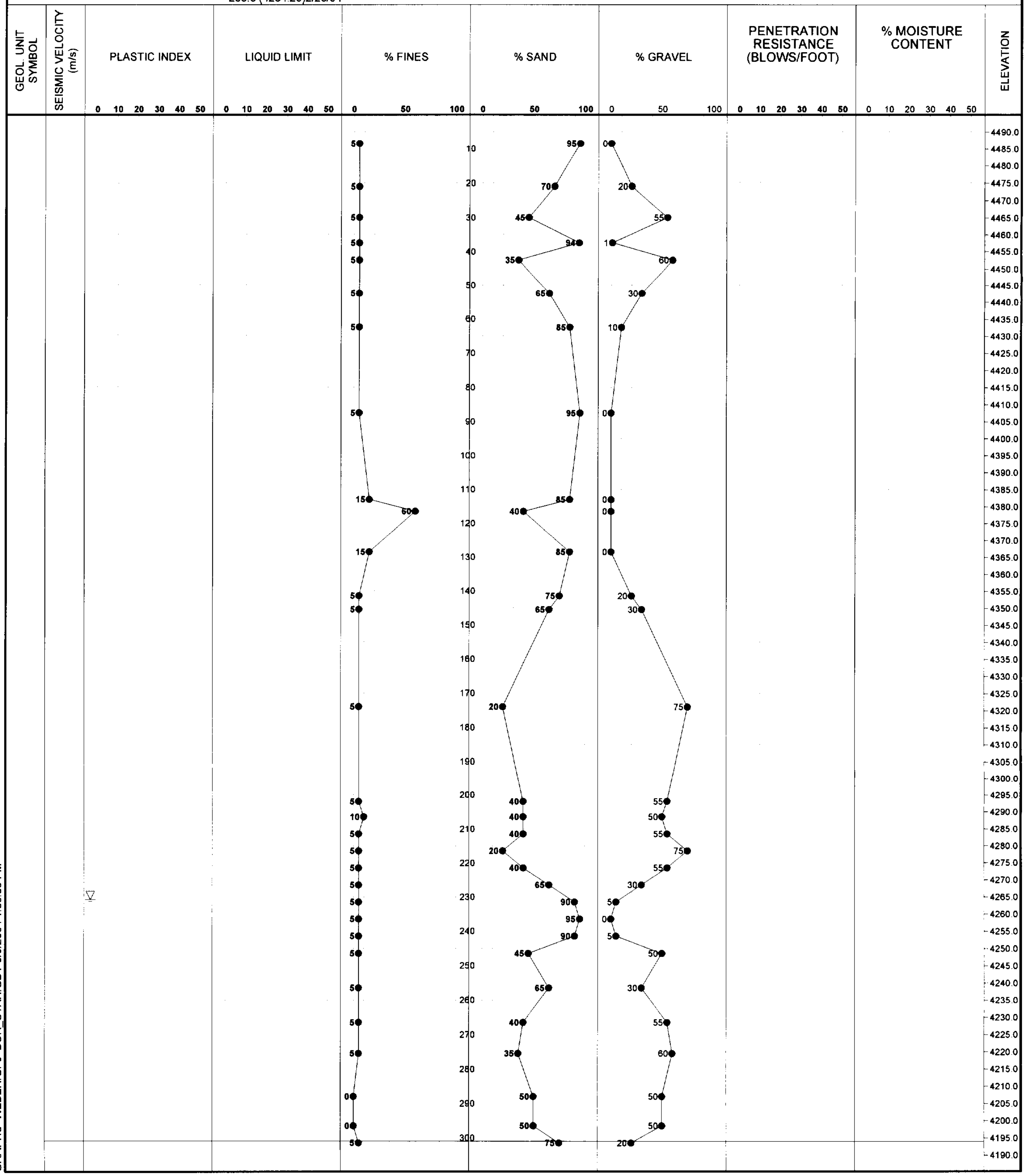
GRAPHIC SUMMARY OF DRILL HOLE ARS-MW-1-04

SHEET 1 OF 1

FEATURE: Monitoring Well
LOCATION: Near west mouth of Weber Cyn.
BEGUN: 1/26/04 FINISHED: 3/3/04
DEPTH AND ELEV OF WATER
LEVEL AND DATE MEASURED: ∇ 230.8 (4264.20)2/23/04

PROJECT: Weber Basin
COORDINATES:
TOTAL DEPTH: 301.0
DEPTH TO BEDROCK: N/E

STATE: Utah
GROUND ELEVATION: 4495.0
ANGLE FROM HORIZONTAL: -90.0 AZIMUTH: ---
HOLE LOGGED BY: Ira Terry
REVIEWED BY:



GRAPHS WEBER.GPJ BOR_UTAH.GDT 3/9/2004 1:30:35 PM

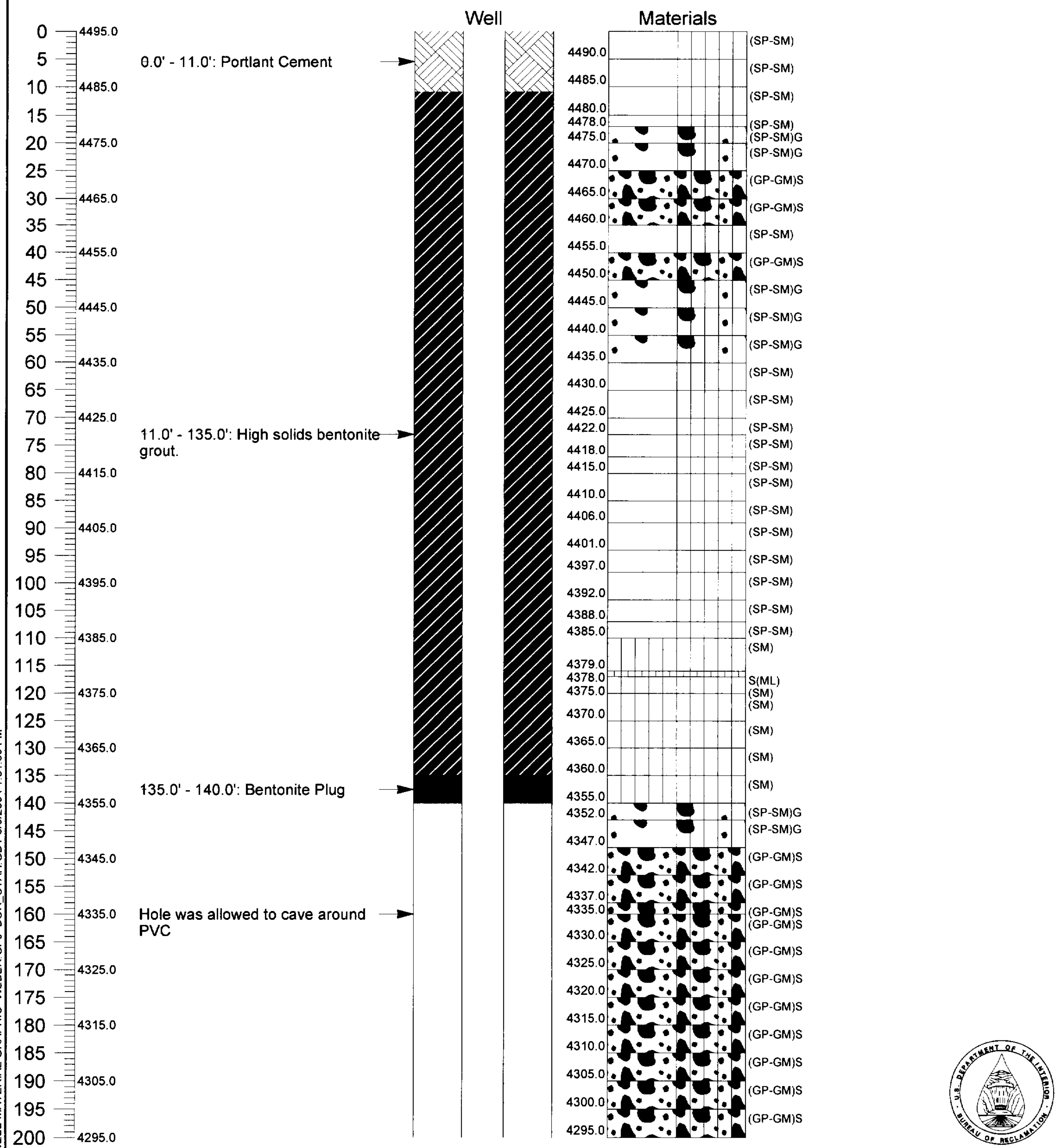
WELL COMPLETION LOG NO. ARS-MW-1-04

SHEET 1 OF 2

FEATURE: Monitoring Well
LOCATION: Near west mouth of Weber Cyn.
BEGUN: 1/26/04 FINISHED: 3/3/04
DEPTH AND ELEV OF WATER
LEVEL AND DATE MEASURED: ∇ 230.8 (4264.20)2/23/04

PROJECT: Weber Basin
COORDINATES:
TOTAL DEPTH: 301.0
DEPTH TO BEDROCK: N/E

STATE: Utah
GROUND ELEVATION: 4495.0
ANGLE FROM HORIZONTAL: -90.0 AZIMUTH: —
HOLE LOGGED BY: Ira Terry
REVIEWED BY:



WELL-MATERIAL GRAPHIC WEBER.GPJ BOR_UTAH.GDT 3/9/2004 1:31:09 PM

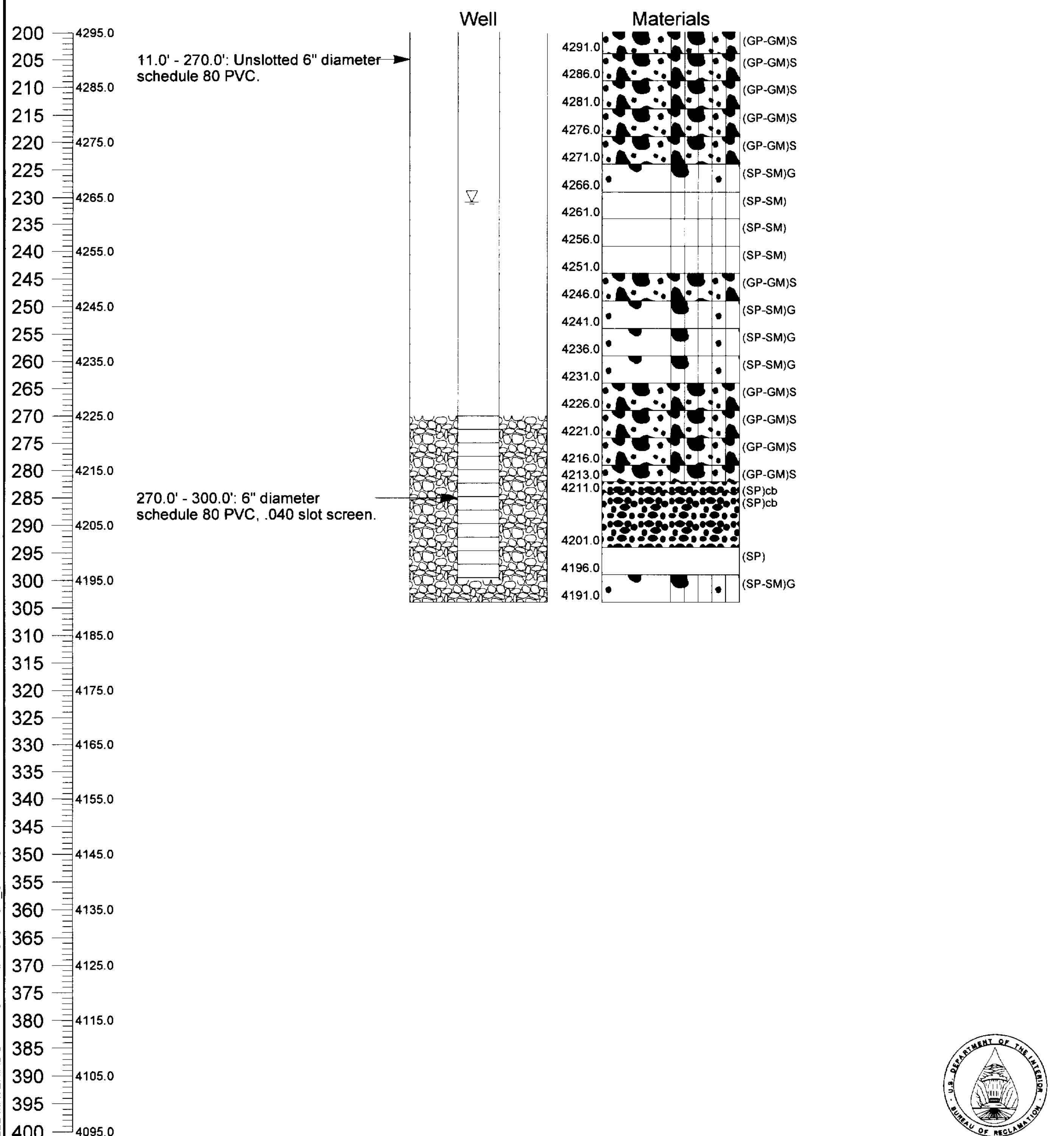
WELL COMPLETION LOG NO. ARS-MW-1-04

SHEET 2 OF 2

FEATURE: Monitoring Well
LOCATION: Near west mouth of Weber Cyn.
BEGUN: 1/26/04 FINISHED: 3/3/04
DEPTH AND ELEV OF WATER
LEVEL AND DATE MEASURED: ∇ 230.8 (4264.20)2/23/04

PROJECT: Weber Basin
COORDINATES:
TOTAL DEPTH: 301.0
DEPTH TO BEDROCK: N/E

STATE: Utah
GROUND ELEVATION: 4495.0
ANGLE FROM HORIZONTAL: -90.0 AZIMUTH: ---
HOLE LOGGED BY: Ira Terry
REVIEWED BY:



WELL-MATERIAL GRAPHIC WEBER.GPJ BOR_UTAH.GDT 3/9/2004 1:31:09 PM

APPENDIX D

RECORDS OF DIVERSION AND INFILTRATION AND LOG OF BASIN-FLOOR SAMPLE DESCRIPTIONS

Table D1. *Record of diversion of water and water levels in infiltration basins during pilot project. AF = acre-feet.*

DATE	DAY	FLOW (CFS)	INFILTRATION CFS/ACRE	AF/DAY	CUMULATIVE INFILTRATION (AF)	COMMENTS
3/19/04	1	6.00	-	-	-	Started flow into ponds 1 & 2
3/20/04	2	2.75	-	12.0	12.0	Adjusted river gate to reduce canal flow
3/21/04	3	3.05	-	5.5	17.5	
3/22/04	4	2.85	-	5.9	23.4	+2-3"from 3/21
3/23/04	5	2.56	-	5.1	28.5	+2-3" from 3/22
3/24/04	6	2.46	-	5.0	33.5	+2-3" from 3/23
3/25/04	7	1.91	1.3	4.2	37.7	Pond 2 level dropped 2" since 11am 3/24
3/29/04	11	1.66	-	10.0	47.7	1'9" pond 2 - Started water into pond #3 (south)
3/30/04	12	3.46	-	5.0	52.7	1'5.5" pond 2
3/31/04	13	3.68	-	7.1	59.8	2'1" pond 2
4/2/04	15	4.46	-	8.1	67.9	
4/5/04	18	3.46	-	7.0	74.9	
4/6/04	19	4.01	-	7.5	82.4	2'3" pond 2
4/7/04	20	4.01	-	8.0	90.4	2'1.5" pond 2
4/8/04	21	3.79	-	7.8	98.2	2'1" pond 2
4/9/04	22	2.56	-	6.3	104.5	
4/10/04	23	4.46	-	5.1	109.6	
4/12/04	25	3.57	-	8.0	117.6	
4/13/04	26	4.46	1.2	8.9	126.5	1'8.5" pond 2; 1'3" pond 3
4/14/04	27	4.35	-	8.8	135.3	1'10" pond 2; 10" pond 3
4/15/04	28	0.903	-	6.1	141.4	2'2"pond 2; 1'10" pond 3
4/16/04	29	4.69	-	7.0	148.4	2'0"pond 2; 8"pond 3; started flowing into pond 4
4/17/04	30	4.93	-	9.4	157.8	
4/18/04	31	4.69	-	9.4	167.2	
4/19/04	32	4.58	-	9.3	176.4	1'1" pond 2; 7"-pond 3; 2'9" pond 4
4/20/04	33	4.69	-	9.4	185.8	2'0" pond 2; 5.5" pond 3; 2'7.5" pond 4
4/21/04	34	4.69	1.3	9.4	195.2	2'3" pond 2; 5" pond 3; 2'6" pond 4
4/22/04	35	4.69	1.3	9.4	204.6	2'1/2" pond 2; 5" pond 3; 2'8" pond 4
4/23/04	36	4.69	-	9.4	214.0	1'11" pond 2; 51/2" pond 3; 2'6" pond 4
4/24/04	37	4.93	-	9.6	223.6	1'11" pond 2; 7" pond 3; 3'0" pond 4
4/25/04	38	4.69	-	9.4	233.0	1'11" pond 2; 51/2" pond 3; 2'8" pond 4
4/26/04	39	4.69	-	9.4	242.3	1'11" pond 2; 5" pond 3; 2'7" pond 4
4/27/04	40	4.69	1.4	9.4	251.7	1'11" pond 2; 5" pond 3; 2'7" pond 4

Table D1. *continued*

4/28/04	41	4.93	-	9.6	261.3	1'11" pond 2; 5" pond 3; 2'6" pond 4
4/29/04	42	4.93	-	9.9	271.2	1'5" pond 2; 5" pond 3; 2'51/2" pond 4
4/30/04	43	4.93	-	9.9	281.1	1'7" pond 2; 41/2" pond 3; 2'21/2" pond 4
5/1/04	44	4.93	-	9.9	290.9	1'6" pond 2
5/2/04	45	4.58	-	9.2	300.1	1'6" pond 2
5/3/04	46	4.69	-	9.4	309.5	1'8" pond 2; 5" pond 3; 2'4" pond 4
5/4/04	47	4.93	-	9.9	319.3	1'9" pond 2; 5" pond 3; 2'31/2" pond 4
5/5/04	48	5.42	-	10.8	330.2	1'9" pond 2; 41/2" pond 3; 2'3"; pond 4
5/6/04	49	4.69	-	9.4	339.5	1'8" pond 2; 5" pond 3; 2'3" pond 4
5/7/04	50	4.69	-	9.4	348.9	1'8" pond 2; 5" pond 3; 2'3"; pond 4
5/8/04	51	5.29	-	10.6	359.5	
5/9/04	52	6.17	-	12.3	371.8	
5/10/04	53	4.93	-	9.9	381.7	1'6" pond 2; 4" pond 3; 1'9" pond 4
5/11/04	54	5.54	-	11.1	392.8	1'7" pond 2; 51/2" pond 3; 2' pond 4
5/12/04	55	4.69	-	9.4	402.2	1'6" pond 2; 4" pond 3; 1'5" pond 4
5/13/04	56	4.69	-	9.4	411.5	1'51/2" pond 2; 41/2" pond 3; 1'6" pond 4
5/14/04	57	4.69	1.3	9.4	420.9	1'71/2" pond 2; 41/2" pond 3; 1'31/2" pond 4
5/15/04	58	4.69	-	9.4	430.3	
5/16/04	59	4.69	-	9.4	439.7	1'101/2" pond 2; 5" pond 3; 1'9" pond 4
5/17/04	60	4.69	1.3	9.4	449.1	1'9" pond 2; 5" pond 3; 1'6" pond 4
5/18/04	61	4.69	1.3	9.4	458.4	1'71/2" pond 2; 5" pond 3; 1'6" pond 4
5/19/04	62	4.69	-	9.4	467.8	1'71/2" pond 2 5" pond 3; 1'51/2" pond 4
5/20/04	63	4.69	-	9.4	477.2	1'7" pond 2; 5" pond 3; 1'6" pond 4
5/21/04	64	4.69	-	9.4	486.6	1'61/2" pond 2 5" pond 3; 1'5" pond 4
5/22/04	65	4.69	-	9.4	496.0	
5/23/04	66	4.69	-	9.4	505.3	
5/24/04	67	4.69	-	9.4	514.7	1'10" pond 2; 5" pond 3; 1'5" pond 4
5/25/04	68	4.46	-	8.9	523.6	1'101/2" pond 2; 5" pond 3 1'41/2" pond 4
5/26/04	69	4.46	-	8.9	532.6	1'10" pond 2; 5" pond 3; 1'31/2" pond 4
5/27/04	70	4.46	-	8.9	541.5	1'10" pond 2; 5" pond 3; 1'4" pond 4
5/28/04	71	4.01	-	8.0	549.5	
5/29/04	72	4.01	-	8.0	557.5	
5/30/04	73	4.01	-	8.0	565.5	
5/31/04	74	4.01	-	8.0	573.6	
6/1/04	75	3.57	-	7.1	580.7	1'9" pond 2; 61/2" pond 3; 1'3" pond 4
6/2/04	76	4.35	1.1	8.7	589.4	1'9" pond 2; 51/2" pond 3; 1'2" pond 4

Table D1. *continued*

6/3/04	77	4.46	-	8.9	598.3	1'81/2" pond 2; 51/2" pond 3; 111/2" pond 4
6/4/04	78	4.46	-	8.9	607.2	1'9" pond 2; 51/5" pond 3; 12" pond 4
6/5/04	79	4.46	-	8.9	616.2	1'8" pond 2; 5" pond 3; 101/2" pond 4
6/6/04	80	4.46	-	8.9	625.1	
6/7/04	81	4.46	-	8.9	634.0	
6/8/04	82	4.46	-	8.9	642.9	1'9" pond 2; 5" pond 3; 9" pond 4
6/9/04	83	4.01	-	8.0	650.9	1'10" pond 2; 6" pond 3; 81/2" pond 4
6/10/04	84	4.35	-	8.7	659.6	
6/11/04	85	4.35	-	8.7	668.3	
6/12/04	86	4.35	-	8.7	677.0	
6/13/04	87	4.35	-	8.7	685.7	
6/14/04	88	4.69	-	9.4	695.1	1'5" pond 2 41/2" pond 3; 1" pond 4
6/15/04	89	3.57	-	7.9	703.0	1'51/2" pond 2; 6" pond 3; 41/2" pond 4
6/16/04	90	2.95	-	5.9	708.9	1'6" pond 2; 6" pond 3; 41/2" pond 4
6/17/04	91	3.36	0.9	6.7	715.6	1'61/2" pond 2; 6" pond 3; 41/2" pond 4
6/18/04	92	3.15	-	6.3	721.9	1'6" pond 2; 6" pond 3; 2" pond 4
6/19/04	93	-	-	6.3	728.2	
6/20/04	94	-	-	6.3	734.5	
6/21/04	95	3.05	-	6.1	740.6	1'7" pond 2; 7" pond 3; 6" pond 4
6/22/04	96	-	-	6.1	746.7	
6/23/04	97	3.05	0.8	6.1	752.8	1'7" pond 2; 7" pond 3; 71/2" pond 4
6/24/04	98	2.85	-	5.7	758.5	1'61/2" pond 2; 61/2" pond 3; 6" pond 4
6/25/04	99	2.85	-	5.7	764.2	1'61/2" pond 2; 8" pond 3; 81/2" pond 4
6/26/04	100	1.5	-	3.0	767.2	
6/27/04	101	0	-	1.5	768.7	
6/28/04	102	2.09	-	0.0	768.7	2'6" pond 2; 1'6" pond 3; 2'6" pond 4
6/29/04	103	2.09	-	4.2	772.9	2'2" pond 2; 8" pond 3; 1'9" pond 4
6/30/04	104	2.75	-	4.8	777.7	Parsons pit = 6.38 gpm
7/1/04	105	2.75	-	5.5	783.2	1'81/2" pond 2; 8" pond 3; 1'1/2" pond 4 (Ppit=4.76 gpm)
7/2/04	106	0.972	-	3.7	786.9	1'8" pond 2; 9" pond 3; 1'3" pond 4
7/6/04	-	-	-	-	-	Parson's pit flow = 5gpm
7/9/04	-	-	-	-	-	Parson's pit flow = 5gpm
7/13/04	-	-	-	-	-	Parson's pit flow = 4gpm
7/28/04	-	-	-	-	-	Parson's pit flow = Approx. 1gpm at N&S seeps Not flowing at measurement point Saturated area has receded 3 to 8 feet (north seep)

Table D1. *continued*

Second Recharge Experiment						
3/17/05	1	0	0.54	-	5.45	Started flow into ponds 1 & 2
3/18/05	2	0	0.54	3.97	8.13	
3/19/05	3	0	0.54	-	11.32	increased to 5 cfs
3/19/05	-	0	1.33	5.86	21.1	
3/20/05	4	1.66	1.33	9.78	27	
3/21/05	5	1.66	1.33	-	30.07	
3/21/05	-	1.97	1.05	8.97	34.26	
3/22/05	6	2.37	1.05	-	38.74	
3/22/05	-	2.46	1.33	8.67	41.93	readjusted flow to 5 cfs
3/23/05	7	1.97	1.33	-	42.35	
3/23/05	-	1.97	0.11	3.62	42.64	reduced flow due to muddy river
3/24/05	8	2	0.11	-	49.26	increased to 5 cfs
3/24/05	-	3.25	1.39	6.9	59.51	only ponds 1&2
3/25/05	9	3.25	1.39	10.25	69.77	cut flow to pond 2
3/26/05	10	3.25	1.39	10.25	79.07	spill to pond 4
3/27/05	11	4.01	1.26	9.3	82.56	break in pond 2
3/28/05	12	4.23	1.26	-	88.97	steady rain
3/28/05	-	3.9	1.39	9.9	98.98	
3/29/05	13	4.35	1.36	10.02	108.76	light snow
3/30/05	14	2.75	1.33	9.78	118.54	snowing
3/31/05	15	3.15	1.33	9.78	128.32	closed pond 2
4/1/05	16	3.57	1.33	9.78	138.1	raised pond 2 0.2'
4/2/05	17	4.35	1.33	9.78	147.88	pond 2 0.3 open
4/3/05	18	4.01	1.33	9.78	153.99	
4/4/05	19	4.46	1.33	-	156.73	reduced flow, ponds full
4/4/05	-	4.23	0.99	8.85	161.44	pond 2 0.25 open
4/5/05	20	4.46	0.99	-	164.33	pond 2 0.3 open
4/5/05	-	4.69	1.11	7.61	169.78	
4/6/05	21	4.69	1.11	-	171.86	reduced flow, muddy river
4/6/05	-	4.01	0.85	7.53	175.9	
4/7/05	22	3.36	0.82	-	177.85	
4/7/05	-	4.23	0.8	5.98	183.9	
4/8/05	23	0	0.82	6.05	190.56	
4/9/05	24	0	0.91	6.66	195.64	
4/10/05	25	0	0.69	5.08	202.72	

Table D1. *continued*

4/11/05	26	0	0.96	7.08	207.8	increased flow
4/12/05	27	1.83	0.69	5.08	213.67	green algae growth starting
4/13/05	28	1.58	0.8	6.05	220.97	very windy
4/14/05	29	1.34	0.99	7.3	229.14	
4/15/05	30	1.11	1.11	8.17	236.88	
4/16/05	31	0.83	1.05	7.74	243.96	
4/17/05	32	0	0.96	7.08	252.13	
4/18/05	33	0	1.11	8.17	258.38	
4/19/05	34	0	0.85	6.25	264.82	
4/20/05	35	0	0.88	6.45	271.07	
4/21/05	36	0	0.85	6.25	277.52	
4/22/05	37	0	0.88	6.45	283.96	
4/23/05	38	-	0.88	6.45	291.48	
4/24/05	39	-	1.02	7.52	297.53	
4/25/05	40	-	0.82	6.05	302.61	
4/26/05	41	-	0.69	5.08	306.24	
4/27/05	42	-	0.49	3.63	308.9	
4/28/05	43	-	0.36	2.66	311.26	super turbid, opened gate 8 turns
4/29/05	44	-	0.32	2.36	317.31	
4/30/05	45	-	0.82	6.05	327.8	
5/1/05	46	-	1.43	10.49	334.88	
5/2/05	47	-	0.96	7.08	341.96	
5/3/05	48	-	0.96	7.08	349.04	
5/4/05	49	-	0.96	7.08	363.64	
5/5/05	50	-	0.99	14.6	372.03	5/5 & 5/6
5/7/05	52	-	1.14	8.39	379.76	
5/8/05	53	-	1.05	7.74	386.21	
5/9/05	54	-	0.88	6.45	399.1	
5/10/05	55	-	0.88	12.89	402.93	
5/12/05	57	-	0.52	3.83	410.87	5/11 & 5/12
5/13/05	58	-	0.54	7.93	417.31	5/13 & 5/14
5/15/05	60	-	0.88	6.45	423.56	
5/16/05	61	-	0.85	6.25	429.01	
5/17/05	62	-	0.74	5.45	434.47	
5/18/05	63	-	0.74	5.45	439.92	
5/19/05	64	-	0.74	5.45	444.8	

Table D1. *continued*

5/20/05	65	-	0.66	4.88	447.78	
5/21/05	66	-	0.4	2.98	449.27	
5/22/05	67	-	0.2	1.49	453.35	
5/23/05	68	-	1.11	4.09	453.35	shut down ASR at 12:00
5/24/05	70	-	0	0	453.35	
5/25/05	71	-	0	0	453.35	
5/27/05	73	-	0	0	453.35	
5/29/05	75	-	0	0	453.35	
5/30/05	76	-	0	0	453.35	
6/2/05	79	-	0	0	453.35	
6/3/05	80	-	0	0	453.35	
6/5/05	82	-	0	0	453.35	
6/6/05	83	-	0	0	453.35	
6/8/05	85	-	0	0	453.35	
6/9/05	86	-	0	0	453.35	
6/14/05	91	-	0	0	453.35	
6/16/05	93	-	0	0	453.35	
6/17/05	94	-	0	0	453.35	
6/21/05	98	-	0	0	453.35	
6/22/05	99	-	0	0	453.35	
6/23/05	100	-	0	0	453.35	
6/27/05	104	-	0	0	453.35	
6/28/05	105	-	0	0	453.35	
6/30/05	107	-	0	0	453.35	
7/1/05	108	-	0	0	453.35	
7/5/05	112	-	0	0	453.35	
7/6/05	113	-	0	0	453.35	
7/7/05	114	-	0	0	453.35	
7/14/05	121	-	0	0	453.35	
7/19/05	126	-	0	0	453.35	
7/20/05	127	-	0	0	453.35	
7/26/05	133	-	0	0	453.35	
7/27/05	134	-	0	0	453.35	
7/29/05	136	-	0	0	453.35	
8/1/05	139	-	0	0	453.35	
8/3/05	141	-	0	0	453.35	

Table D1. *continued*

8/5/05	143	-	0	0	453.35	
8/8/05	146	-	0	0	453.35	
8/9/05	147	-	0	0	453.35	
8/11/05	149	-	0	0	453.35	
8/12/05	150	-	0	0	453.35	
8/15/05	153	-	0	0	456.64	
8/17/05	155	-	0.45	5.45	459.94	Resumed ASR @ 12:30
8/18/05	156	-	0.45	3.29	463.84	
8/19/05	157	-	0.53	5.45	473.24	
8/21/05	160	-	0.64	4.7	478.12	
8/22/05	161	-	0.66	4.88	493.75	
8/26/05	165	-	0.53	3.91	505.48	
8/29/05	168	-	0.53	3.91	509.44	
8/30/05	169	-	0.54	3.97	528.78	
9/2/05	172	-	0.88	6.45	554.57	
9/6/05	176	-	0.88	6.45	593.24	
9/12/05	182	-	0.88	6.45	609.15	
9/14/05	184	-	1.08	7.95	617.54	
9/15/05	185	-	1.14	8.39	625.28	
9/16/05	186	-	1.05	7.74	651.16	
9/19/05	189	-	1.17	8.63	656.62	
9/20/05	190	-	0.74	5.45	662.86	
9/21/05	191	-	0.85	6.25	677.03	
9/23/05	193	-	0.96	7.08	702.91	
9/26/05	196	-	1.17	8.63	710.86	
9/27/05	197	-	1.08	-	719.71	
9/28/05	198	-	1.2	-	728.1	
9/29/05	199	-	1.14	-	736.95	
9/30/05	200	-	1.2	-	764.85	
10/3/05	203	-	1.26	-	783.46	
10/5/05	205	-	1.26	-	791.41	
10/6/05	206	-	1.08	-	798.08	
10/7/05	207	-	0.91	-	831.64	
10/11/05	211	-	1.14	-	831.64	
10/17/05	217	-	0	-	831.64	
10/18/05	218	-	0	-	831.64	

Table D1. *continued*

10/19/05	219	-	0	-	831.64	Opened gate at the River 6"
10/24/05	224	-	0	-	835.27	
10/25/05	225	-	0.49	-	838.4	Closed the gate DS of turnout, raised gate at river 2"
10/26/05	226	-	0.43	-	841.06	Raised river gate 3"
10/27/05	227	-	0.36	-	843.26	
10/28/05	228	-	0.3	-	848.2	
10/31/05	231	-	0.22	-	848.2	Closed River Gate completely
11/1/05	232	-	0	-	848.2	
11/4/05	235	-	0	-	848.2	
11/7/05	238	-	0	-	848.2	
11/9/05	240	-	0	-	848.2	
11/14/05	245	-	0	-	848.2	
11/16/05	247	-	0	-	-	

- No data.

Table D2. *Percentage log of basin-floor sample descriptions. See figure 18 for sample locations.*

Location: (B-5-1)26, Weber County, Utah
Geologist: Janae Wallace, Utah Geological Survey, 8/4/04

Site ID*	**PERCENTAGES**				**COMMENTS**
	unconsolidated				
	clay /silt	silt/ sand	evaporite	algal mat	
A **b1***	10	90	0	2-3 mm	dark brown clay, silt, and fine sand (this core sample shows fining up; mudcracks makeup the surface); sand is angular to rounded and dominantly fine with minor medium and coarse grains composed of quartz, feldspar, mica, and lithic fragments; calcareous; (5" thick)
B **b1**	tr	100	0	no	dark brown mudcrack sample; sample consists of fine sand and silt; sand is angular to rounded and consists of quartz, feldspar, mica, and lithic fragments; calcareous; (2" thick)
C **b1**	0	100	0	1-2 mm	light brown silt and fine sand; sand is angular to rounded and consists of quartz, feldspar, mica, mafic minerals, and lithic fragments; trace gravel; gastropods (whole and fragments); calcareous; (7" thick)
D **b1**	20	80	0	no	brown mudcrack sample; sample consists dominantly of silt with clay and fine sand; trace gravel; burrows; calcareous; (3/4" thick)
E **b1**	80	20	0	1 mm	dark brown mudcrack sample; sample consists of clay and silt with minor fine sand; calcareous; (1/2" thick)
F **b1**	80	20	0	1 mm	dark brown mudcrack sample; sample consists of clay and silt with minor fine sand; calcareous; (1/2" thick)
G **b1**	90	10	0	1 mm	brown mudcrack sample; sample consists dominantly of clay with minor silt and sand; calcareous; (<1/2" thick)
H **b1**	90	10	0	1 mm	brown mudcrack sample; sample consists dominantly of clay with minor silt and sand; calcareous; (<1/2" thick)
L **b1**	10	90	0	<1/2 mm	brown mudcrack sample; sample consists dominantly of silt with clay and fine sand; sand is angular to rounded and consists of quartz, feldspar, and rock fragments; burrows and ostracods; calcareous; (3/4" thick)
W **b1**	25	75	0	no	brown mudcrack sample; sample consists of clay, silt, and fine sand; sand is angular to rounded and consists of quartz, feldspar, and rock fragments; burrows; calcareous; (3/4" thick)
3 **b2**	0	50	50	no	pink-tan silt and white-pink finely crystalline evaporite (carbonate and/or gypsum?); calcareous; (<1 mm)
27a **b3**	0	50	50	no	pink-tan silt and white-pink finely crystalline evaporite (carbonate and/or gypsum?); calcareous; (<1 mm)
27b **b3**	10	90	0	no	light brown mudcrack sample; sample consists of silt and fine sand with minor clay; sand is angular to rounded and consists of quartz, feldspar, and rock fragments; ostracods; calcareous; (1/2" thick)

Table D2. *continued*

Site ID*	PERCENTAGES				COMMENTS
	unconsolidated				
	clay /silt	silt/ sand	evaporite	algal mat	
55 b3	10	90	0	no	brown mudcrack sample; sample consists dominantly of silt with find to medium sand and minor clay; sand is angular to rounded and consists of quartz, feldspar, and rock fragments; calcareous; (1/2" thick)
40 b4	tr	100	0	tr	light brown mudcrack sample; sample consists dominantly of fine to medium sand with minor silt and trace clay; sand is angular to rounded and consists of quartz, feldspar, mica, mafic minerals, and rock fragments; calcareous; (<1/2" thick)
in situ	0	100	0	no	orange-brown sand; sand is fine to coarse, angular to rounded, and consists of quartz, feldspar, mica and rock fragments; calcareous

Site ID	**COMMENTS**
J b1	1/2" mudcrack sample; less algal buildup
K b1	sandbar sample, less pronounced than near gate; 3" thick brown silt and sandy silt; gastropods; thin algal mat
M b1	1/2" thick mudcrack- one layer; no algal mat; subsurface is granule gravel
N b1	2-layer mudcrack, total thickness is 5/8" to 3/4"; top layer is 1/2", bottom layer is ~ 1/4" thick; substrate is coarse and medium sand and granule gravel; no algal mat
O b1	algal mat (~1mm) covering 1-layer mudcrack, ~1" thick
P b1	2-layer mudcrack, ~1 1/2" total thickness, layers are indiscernible; burrows
Q b1	mudcrack ~1"; plant material; organic; bird tracks; not as compact as previous samples
R b1	2-layer mudcrack, ~1" total thickness; top layer is 3/4", bottom layer is 1/4"; pebble substrate
S b1	2-layer mudcrack; no algal mat; top layer is ~ 1/2" thick, bottom layer ~ 1/4" thick; pebble substrate and fine to medium sand
T b1	1-layer mudcrack ~ 1" thick; sand substrate
U b1	2-layer mudcrack; less organic material; bird tracks; top layer ~1/2" thick, bottom layer ~1/8" thick; substrate is fine to medium sand
V b1	2-layer mudcrack; ~1" total thickness, top layer ~3/4" thick, bottom layer ~1/4" thick; dark organic material; pebble substrate

Table D2. *continued*

1 b2	1-layer mudcrack ~1/2" thick; no algal mat; this pond #3, mudcracks are smaller than pond #1 (spacing is closer)
4 b2	mudcrack with evaporite? crust/rind; 1/4" mudcrack, no algal mat
5 b2	evaporite? rind/crust on pebble substrate
6 b2	mudcrack with a silt crust; 1/4" mudcrack no algal mat; surrounded by pebbles and cobbles
7 b2	mudcrack range between 1/2" to 3/4"; some burrowing; no algal mat
8 b2	1/4" mudcrack; less prominent cracks, friable
9 b2	1/4" mudcrack; less prominent cracks; friable
10 b2	mudcrack 1/4" thick; boulder/cobble substrate
11 b2	1/8" mudcrack adjacent to bank of pond; boulder/pebble surrounding sample
12 b2	1/4" rind/crust silt and/or evaporite?
13 b2	1/4" mudcrack
14 b2	<1/4" mudcrack around some scattered pebbles
15 b2	<1/4" mudcrack adjacent to thin rind sample on silty ripple/ridges
16 b2	scant rind on 1/8" mudcrack surrounded by pebble, cobble, and granule gravel
17 b2	1/8" mudcrack; sparse gravel substrate
18 b2	1/8" mudcrack; sparse gravel substrate; adjacent to rippled ridges perpendicular to flow
19 b3	algal mat ~1mm over 1/8" mudcrack
20 b3	silt mudcrack, 1/8" thick; mudcracks are smaller in size/ spacing than basin 2
21 b3	<1/8" silt/evaporite? rind/crust; sporadic algal in the area covering sparse pebble and sandy substrate
22 b3	silt mudcrack 1/4" thick
23 b3	poorly developed mudcrack; mudcrack <1/8" thick; no algal mat
24 b3	<1/8" mudcrack, sporadic in distribution in the area; sparse pebble and sandy substrate
25 b3	1/4" mudcrack; sparse algal mat
26 b3	1/2" thick mudcrack with sparse, thin rind; shell fragments (gastropod?) and plant material; adjacent area has algal mat covering thin mudcrack with thin rind
28 b3	4 mm algal mat covering sand substrate

Table D2. *continued*

29 b3	silt mudcrack 1/8" to 1/4" thick; sandy substrate
30 b3	3 mm algal mat
31 b3	5/8" to 1" thick mudcrack with 1-2mm algal mat cover
32 b3	<1/8" thick mudcrack; fine sand with sparse scattered pebble substrate
33 b3	<1/8" thick mudcrack and thin cement rind between cobble substrate; thin algal layer
34 b3	<1/8" thick mudcrack; thin algal layer
35 b3	<1/8" thick mudcrack; thin algal layer; scattered pebble and sandy substrate
36 b3	<1/8" thick rind; no mudcrack; scattered pebble substrate; no algal mat
37 b3	1/4" to 1/2" thick mudcrack; no or sparse organic material
38 b3	2 mm algal mat on sandy and gravelly sand substrate
41 b4	thin, compact silt (<1/8" thick) on sandy substrate
42 b4	<1/8" thick mudcrack; organic; trace thin cement rind on surrounding substrate
43 b4	1 mm silt layer; no mudcrack; no algal mat
44 b4	1/8" silt mudcrack; surrounded by pebble/cobble substrate
45 b4	1 mm silt layer on <1/8" thick micro-mudcrack (e.g., much smaller in size than any others described)
46 b4	thin rind cement on sparse pebbles and ~1 mm thick silt layer
47 b4	<1mm silt layer on cobble and pebble substrate
48 b4	<1mm silt layer on cobble and pebble substrate
49 b4	~1mm silt layer on cobble and pebble substrate; no cement rind
50 b4	<1/2 mm silt layer on sand substrate
51 b4	<1/2 mm silt layer on pebble and cobble substrate
52 b4	sparse mudcracks; ~1 mm thick mudcrack on a compact, fine to medium sand substrate
53 b4	scant silt rind and cement on sand substrate
54 b4	2 mm algal mat on sand substrate

* b1 through b4 denote infiltration basin from which samples were observed and/or collected.
Microscopic analysis were performed for site IDs shown in bold.

APPENDIX E

ANALYTICAL METHODS AND WATER QUALITY RESULTS

ANALYTICAL METHODS

Establishment

The Weber Basin Water Quality Laboratory (WBWQL) maintains a quality system based on the regulatory required elements specified under:

- Utah Rule R444-14, Rules for the Certification of Environmental Laboratories, and
- National Environmental Laboratory Accreditation Conference (NELAC), July 2002 Standards.

Quality Policy Statement

WBWQL is committed to producing scientifically defensible analytical data and acceptable precision and accuracy for use in compliance with the Safe Drinking Water Act and Clean Water Act.

Essential Quality Control Procedures and Measures

Before water samples are analyzed, the analytical system must be in a controlled, reproducible state from which results of known and acceptable quality can be obtained. That state is verified through the use of Quality Control (QC) procedures to ensure accuracy, precision, selectivity, sensitivity, freedom from interference, and freedom from contamination. The QC procedures performed at WBWQL, where applicable, include:

- calibration and calibration verification,
- quality control samples,
- laboratory reagent blanks,
- laboratory fortified blanks,
- laboratory fortified matrix samples,
- duplicate samples,
- surrogates added to samples,
- analysis of proficiency testing samples,
- determination of Method Detection Limits (MDLs), and
- tracking and evaluation of precision and accuracy.

For specific analytical methods, other QC procedures are implemented as required by the method.

These QC procedures are performed and evaluated on a batch basis. An analytical batch is usually defined by the method. Batches range from 10 to 20 unknown samples and may not exceed 20 unknown samples. The samples in a batch are processed together, through each step of the analysis, to ensure that all samples receive consistent and equal treatment. Consequently, the results from the batch QC samples are used to evaluate the results from all samples in the batch.

WBWQL ensures that all quality control measures are reviewed and evaluated before data are reported. This is accomplished by a peer review system. This is documented through the QC Summary Form. Upon completion of each analytical run, a QC Summary Form is completed by the analyst performing the test. The peer reviewer verifies that the calibration standards, type of calibration, and sample set with associated QC samples were selected correctly. Once this review is completed, the peer reviewer signs the QC Summary Form indicating that the QC results have been reviewed and evaluated.

Methods Documentation

WBWQL has documented instructions on the use and operation of all relevant equipment, on the handling and preparation of samples, and for calibration and/or testing, where the absence of such instructions could jeopardize the calibrations or tests. All instructions, standards, manuals, and reference data relevant to the work of WBWQL is maintained up-to-date and is readily available to the staff.

Standard Operating Procedures (SOPs)

WBWQL maintains standard operating procedures that accurately reflect all phases of current laboratory activities such as assessing data integrity, corrective actions, handling customer complaints, and all test methods. These documents, for example, may be equipment manuals provided by the manufacturer, or internally-written documents. Each SOP clearly indicates the effective date of the document, the revision number and the signatures of the approving authority.

Laboratory Methods Manuals

WBWQL maintains an in-house methods manual for each accredited analytic or test method. These manuals may consist of copies of published or referenced test methods or standard operating procedures that have been written by WBWQL.

Test Methods

WBWQL uses appropriate test methods and procedures for all tests and related activities within its responsibility (including sample collection, sample handling, transport and storage, sample preparation, and sample analysis). These methods and procedures are consistent with the accuracy required, and with any standard specifications relevant to the calibrations or tests concerned.

When the use of specific test methods for a sample analysis are mandated or requested, only those methods are used. Table E1 lists all promulgated methods used by WBWQL for the Aquifer Storage and Recovery project. Table E2 lists non-promulgated methods used by WBWQL for the Aquifer Storage and Recovery project.

Table E1. *Promulgated methods used by WBWQL.*

Method	**Parameter**
EPA 120.1	Conductivity
EPA 150.1	pH
EPA 160.1	Residue, Filterable (Total Dissolved Solids)
EPA 200.9	Lead
EPA 300.0	Fluoride, Chloride, Nitrite, Bromide, Nitrate, ortho-Phosphate, Sulfate
SM 2320 B	Alkalinity
SM 3111 B	Copper and Iron
SM 4500-CO2 D	Forms of Alkalinity and Carbon Dioxide

Table E2. *Non-promulgated methods used by WBWQL.*

Parameter	**Method**
Sodium, Potassium, Calcium, Magnesium	Ion chromatography
Sum of Anions	Calculation
Sum of Cations	Calculation
Charge Balance Error	Calculation

Table E3. Results of chemical analyses of water samples from wells and the Weber River taken during the WRBASR pilot project.

			FIELD PARAMETERS			ANIONS							CATIONS				INORGANICS							METALS			
Sample			pH	Conductivity	Temp	F	Cl	NO_2	Br	NO_3	o-PO_4	SO_4	Na	K	Ca	Mg	Alk, T	Alk, Bicarb	Alk, Carb	Alk, Hydrox	CO_2, Free	CO_2, T	TDS	Pb, T	Cu, T	Fe, T	
Date	Location	ID		υmhos/cm	°C	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L $CaCO_3$	mg/L $CaCO_3$	mg/L $CaCO_3$	mg/L $CaCO_3$	mg CO_2/L	mg total CO_2	mg/L	μg/L	μg/L	μg/L	Comments
6/4/03	Valley Nursery Well	49	7.58	489.7	15.25	0.24	24.71	0.00	0.03	0.00	0.03	16.90	23.41	1.78	60.60	14.16	206.5	205.7	0.7	0.0	10.8	192.2	274	0	0	1210	Well was running
6/4/03	HAFB Well 2	47	7.41	558.0	11.23	0.15	19.24	0.00	0.03	0.52	0.05	12.54	27.45	2.03	70.90	18.00	268.5	267.8	0.6	0.0	20.8	256.8	326	0	0	0	Well was running
6/4/03	HAFB Well 6	52	7.50	547.4	11.36	0.17	18.17	0.00	0.03	0.00	0.02	7.55	35.24	2.52	64.99	16.94	275.0	274.2	0.8	0.0	17.3	259.0	314	0	0	1060	Had to start well to collect sample
6/4/03	HAFB Well 9	72	7.54	527.6	12.66	0.14	38.32	0.00	0.04	1.61	0.03	27.42	19.73	1.74	75.14	17.93	216.5	215.8	0.7	0.0	12.4	202.7	346	8.2	110	50	Had to start well to collect sample
6/4/03	Clearfield City Hwy 193 @ Tank	82	7.42	565.3	12.76	0.14	21.83	0.00	0.04	1.36	0.03	28.71	19.92	2.92	76.09	18.78	244.5	243.9	0.6	0.0	18.5	233.4	332	24	165	770	Well was running
6/4/03	HAFB Well 5	78	7.61	491.8	12.68	0.16	18.19	0.00	0.02	1.37	0.03	24.08	17.33	2.31	64.55	16.85	211.5	210.7	0.8	0.0	10.3	196.1	280	0	0	0	Well was running
6/5/03	South Weber Well 2	62	7.45	570.8	14.25	0.12	43.10	0.00	0.04	1.47	0.03	23.97	21.18	2.09	75.71	18.29	220.0	219.4	0.6	0.0	15.6	208.9	350	0	0	0	Well was running
7/1/03	Valley Nursery Well	49	7.73	480.2	15.36	0.27	23.81	0.00	0.03	0.00	0.02	16.45	23.40	1.52	60.06	13.72	205.5	204.4	1.0	0.0	7.6	187.9	254	0	52	1282	Well was running
7/1/03	HAFB Well 5	78	7.65	495.5	13.39	0.16	18.32	0.00	0.02	1.39	0.03	24.24	17.50	2.00	64.37	17.08	216.0	215.1	0.9	0.0	9.6	199.3	278	0	0	0	Well was running
7/1/03	Clearfield City Hwy 193 @ Tank	82	7.56	567.7	12.21	0.15	21.81	0.00	0.03	1.35	0.03	28.47	20.06	2.82	75.61	18.81	246.0	245.1	0.8	0.0	13.5	229.6	330	0	0	0	Well was running
7/1/03	Weber R-Bridge @ Hwy 89	ASR100	8.80	548.6	19.47	0.18	50.92	0.00	0.01	0.50	0.02	33.60	30.71	2.67	54.60	19.31	183.0	172.5	10.2	0.3	0.5	156.8	288	0	0	0	
8/5/03	Valley Nursery Well	49	7.43	466.3	15.85	0.26	22.85	Reject	Reject	Reject	0.00	15.75	23.18	1.20	57.87	13.57	199.5	199.0	0.5	0.0	14.8	190.1	244	0	67	1416	Well was running
8/5/03	HAFB Well 5	78	7.55	496.5	12.76	0.18	17.98	Reject	Reject	Reject	0.02	23.58	17.34	2.24	64.28	17.20	212.5	211.8	0.7	0.0	11.9	198.6	260	0	0	0	Well was running
8/5/03	HAFB Well 9	72	7.40	571.1	12.74	0.17	38.10	Reject	Reject	Reject	0.01	27.05	19.81	1.89	74.97	18.32	216.5	216.0	0.5	0.0	17.2	207.5	333	14.9	227	0	Well was running
8/5/03	Weber R-Bridge @ Hwy 89	ASR100	8.39	577.3	17.78	0.21	47.83	Reject	Reject	Reject	0.02	31.10	29.45	2.83	65.88	19.41	205.0	200.3	4.6	0.1	1.6	179.9	306	0	0	68	
8/6/03	South Weber Well 1	45	7.80	528.0	18.47	0.16	28.20	Reject	Reject	Reject	Reject	21.86	20.53	1.74	64.65	16.49	204.0	202.8	1.2	0.0	6.4	185.4	264	0	110	0	Well was running
8/6/03	District Well 3	36	7.90	555.0	14.45	0.15	21.70	Reject	Reject	Reject	Reject	25.84	17.09	1.76	68.61	17.74	217.0	215.4	1.6	0.0	5.4	195.7	276	0	0	0	Well was running
9/2/03	Valley Nursery Well	49	7.72	468.4	15.54	0.27	21.96	0.26	0.02	0.00	0.00	15.19	23.01	1.55	56.81	13.14	195.0	194.0	1.0	0.0	7.4	178.5	254	0	0	114	Had to start well to collect sample
9/2/03	HAFB Well 9	72	7.48	590.4	12.11	0.18	38.38	0.30	0.03	1.46	0.00	27.44	20.00	1.95	76.27	18.34	216.0	215.4	0.6	0.0	14.3	204.1	326	0	77	0	Well was running
9/2/03	Weber R-Bridge @ Hwy 89	ASR100	8.59	589.1	17.09	0.22	46.87	0.24	0.02	0.37	0.01	30.55	29.16	3.22	61.49	19.40	207.0	199.5	7.3	0.2	1.0	179.8	298	0	0	62	
9/2/03	South Weber Well 1	45	7.00	506.3	-	0.16	27.82	0.28	0.02	1.08	0.00	22.71	20.21	1.81	66.54	16.75	206.5	206.3	0.2	0.0	41.3	222.9	272	0	0	0	Well was running
9/2/03	District Well 3	36	6.90	506.9	-	0.16	21.60	0.29	0.00	1.23	0.00	25.98	17.20	1.65	69.05	17.62	214.5	214.3	0.2	0.0	54.0	242.6	280	0	0	0	Well was running
9/3/03	Washington Terrace Well	31	7.60	408.4	19.52	0.25	17.18	0.25	0.02	0.00	0.02	5.58	22.06	2.81	47.14	13.42	193.5	192.8	0.7	0.0	9.7	179.7	226	0	0	919	Had to start well to collect sample
10/7/03	HAFB Well 9	72	7.43	570.4	11.96	0.18	38.45	0.27	0.06	1.45	0.02	27.27	19.29	2.10	78.29	18.77	216.5	215.9	0.5	0.0	16.0	206.3	304	7.5	101	0	Well was running
10/7/03	Clearfield City Hwy 193 @ Tank	82	7.56	561.0	12.22	0.16	21.94	0.31	0.05	1.14	0.03	28.27	19.55	2.93	78.06	19.14	245.0	244.1	0.8	0.0	13.4	228.6	304	53.9	828	482	Well was running
10/7/03	Laytona Well	87	7.77	587.9	12.67	0.16	30.99	0.30	0.05	1.43	0.03	28.88	19.67	1.88	83.33	19.22	241.5	240.1	1.3	0.0	8.2	220.0	324	0	0	0	Well was running
10/7/03	WES Shop Well	95	7.76	659.1	16.83	0.42	33.70	0.35	0.06	0.00	0.02	5.06	46.07	14.42	47.50	27.53	299.5	297.9	1.6	0.0	10.4	273.2	324	0	0	3662	Well was running
10/7/03	Valley Nursery Well	49	7.70	449.3	15.13	0.24	21.57	0.24	0.05	0.00	0.01	14.39	22.44	1.58	57.12	13.43	193.0	192.1	0.9	0.0	7.7	177.1	224	0	0	1523	Had to start well to collect sample
10/7/03	Weber R-Bridge @ Hwy 89	ASR100	8.79	557.4	13.28	0.20	44.21	0.22	0.04	0.49	0.01	30.45	27.73	2.99	59.16	19.36	198.5	187.3	10.9	0.3	0.6	170.2	288	0	0	132	
10/7/03	South Weber Well 1	45	7.76	510.2	16.41	0.15	28.09	0.26	0.04	1.06	0.01	22.37	19.74	1.84	67.72	17.10	205.5	204.4	1.1	0.0	7.1	187.5	272	0	76	0	Well was running
10/7/03	District Well 3	36	7.86	508.8	14.12	0.15	21.68	0.27	0.02	1.22	0.00	25.86	16.56	1.96	70.93	18.04	215.0	213.5	1.5	0.0	5.9	194.4	354	0	0	0	Well was running
10/7/03	South Weber City Well	61	7.56	614.5	11.82	0.18	48.10	0.29	0.05	1.26	0.02	24.89	25.58	2.11	81.28	18.33	225.5	224.7	0.8	0.0	12.4	210.5	292	12.5	85	605	Had to start well to collect sample
11/4/03	HAFB Well 9	72	7.45	575.8	11.71	0.16	38.43	0.30	Reject	1.46	Reject	27.59	19.41	2.26	78.87	18.92	218.5	217.9	0.6	0.0	15.5	207.5	316	0	0	0	Well was running
11/4/03	WES Shop Well	95	7.62	664.9	16.37	0.38	33.94	0.38	Reject	0.00	Reject	5.58	46.24	13.55	48.19	27.68	301.0	299.8	1.2	0.0	14.4	278.7	352	0	0	1963	Well was running
11/4/03	Weber R-Bridge @ Hwy 89	ASR100	8.04	691.4	4.83	0.21	70.01	0.27	Reject	0.76	Reject	42.64	42.57	3.58	72.67	21.73	228.0	225.6	2.3	0.1	4.1	203.7	372	5	0	148	
12/2/03	Weber R-Bridge @ Hwy 89	ASR100	8.30	627.5	3.90	0.21	49.26	0.29	0.04	0.86	0.02	37.69	30.86	3.37	77.47	21.79	236.0	231.6	4.3	0.1	2.3	208.0	400	0	0	0	
1/6/03	HAFB Well 9	72	7.54	675.9	0.15	0.16	39.08	0.29	0.04	1.46	0.03	27.63	18.04	2.76	81.63	19.00	216.0	215.3	0.7	0.0	12.4	202.2	252	0	85	0	Well was running
1/6/03	District Well 3	36	7.55	515.5	13.13	0.15	22.26	0.28	0.18	1.21	0.02	26.17	16.35	2.15	71.76	18.03	215.5	214.8	0.7	0.0	12.1	201.4	228	0	0	0	Well was running
1/6/03	Weber R-Bridge @ Hwy 89	ASR100	7.90	677	0.10	0.22	54.73	0.32	0.03	0.97	0.02	40.25	32.51	4.10	90.82	23.26	254.0	252.1	1.9	0.0	6.3	229.0	328	0	0	0	
2/3/04	HAFB Well 9	72	6.07	578.4	11.95	0.15R	38.99R	0.36R	0.047R	1.5R	0.016R	27.26R	18.24R	3.03R	84.39R	19.59R	216.0	216.0	0.0	0.0	367.7	557.8	264	0	54	0	Well was running
2/3/04	District Well 3	36	7.79	515.6	13.58	0.13R	22.22R	0.40R	0.00	1.2R	0.026R	25.85R	16.36R	2.18R	72.15R	18.00R	216.0	214.7	1.2	0.0	7.0	196.4	228	0	0	0	Well was running
2/3/04	WeberR @ Uintah Bridge	ASR101	8.11	718.7	2.33	0.19R	50.16R	0.41R	0.032R	0.96R	0.013R	36.71R	30.05R	3.35 R	80.56R	21.03R	231.5	228.7	2.8	0.1	3.6	206.0	296	0	0	104	
3/2/04	HAFB Well 9	72	7.56	564.5	11.99	0.17	38.62	0.37R	0.045R	1.4R	0.062R	27.18	18.01	3.24	81.31	19.18	216.5	215.7	0.7	0.0	11.9	202.0	292	0	0	0	Well was running
3/2/04	District Well 3	36	7.65	506.7	13.66	0.13	21.77	0.31R	0.031R	1.2R	0.053R	25.81	16.71	1.95	72.04	18.28	216.5	215.6	0.9	0.0	9.7	199.8	244	0	0	0	Well was running
3/2/04	Weber R-Bridge @ Hwy 89	ASR100	7.77	647.9	3.66	0.20	62.32	0.43R	0.029R	.089R	0.035R	38.94	36.26	3.63	81.37	21.10	226.5	225.2	1.2	0.0	7.6	206.4	320	0	0	74	
3/11/04	ASR Well	118	7.39	657.4	11.81	0.17	59.15	0.45	0.05	1.50	0.062R	28.77	30.63	2.57	88.69	19.76	237.5	236.9	0.5	0.0	19.3	228.0	332	0	0	0	
3/11/04	ASR Well Field Duplicate	118	7.39	657.4	11.81	0.21	59.17	0.46	0.04	1.49	0.064R	28.75	30.86	2.74	87.77	19.85	236.5	235.9	0.5	0.0	19.2	227.1	332	0	0	0	
3/11/04	Weber R-Bridge @ Hwy 89	ASR100	8.06	479.5	2.86	0.19	41.11	0.20	0.00	0.92	0.064R	27.18	25.38	3.09	62.18	14.91	173.5	171.6	1.9	0.1	3.0	154.8	268	7.7	0	2197	
3/30/04	ASR Well	118	7.33	683.8	12.10	0.13	58.98	0.38	0.05	1.40	0.01	28.90	31.23	2.98	89.75	19.90	238.5	238.0	0.5	0.0	22.3	231.9	376	0	0	0	
3/30/04	ASR Well Field Duplicate	118	7.33	683.8	12.10	0.13	59.00	0.39	0.05	1.40	0.01	28.91	31.24	3.19	90.72	18.35	237.0	236.5	0.5	0.0	22.1	230.5	380	0	0	0	
3/30/04	Weber R-Bridge @ Hwy 89	ASR100	8.16	395.4	6.88	0.19	30.82	0.14	0.01	0.68	0.01	21.96	20.03	2.26	48.20	12.17	133.5	131.6	1.8	0.1	1.8	118.4	232	0	0	355	
4/6/04	HAFB Well 9	72	7.46	580.4	12.03	0.18	37.97	0.35	0.05	1.39	0.02	27.29	17.02	2.82	77.62	17.09	216.0	215.4	0.6	0.0	14.9	204.7	300	0	0	0	Well was running
4/6/04	Valley Nursery Well	49	-	-	-	0.28	22.72	0.25	0.04	0.21	0.03	17.51	22.38	2.10	61.65	14.04	201.5	-	-	-	-	-	240	0	0	0	Well was running
4/6/04	District Well 3	36	7.68	519.4	13.98	0.16	21.52	0.39	0.01	1.16	0.02	25.71	16.37	2.27	71.00	18.07	215.0	214.0	1.0	0.0	8.9	197.7	256	0	0	0	Well was running

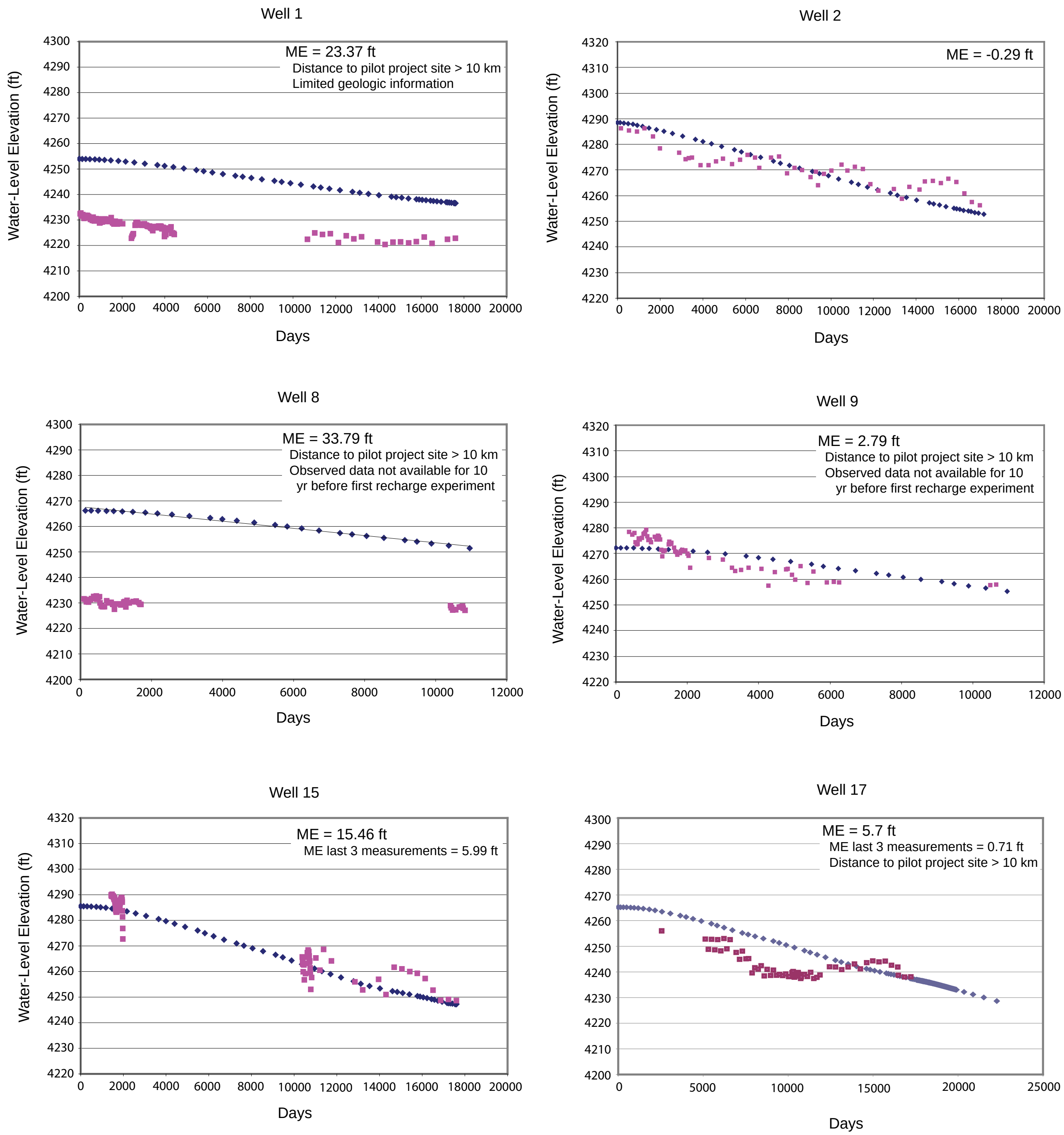
R=reject

			FIELD PARAMETERS			ANIONS							CATIONS				INORGANICS							METALS			
Sample Date	Location	ID	pH	Conductivity µmhos/cm	Temp °C	F mg/L	Cl mg/L	NO_2 mg/L	Br mg/L	NO_3 mg/L	o-PO_4 mg/L	SO_4 mg/L	Na mg/L	K mg/L	Ca mg/L	Mg mg/L	Alk, T mg/L $CaCO_3$	Alk, Bicarb mg/L $CaCO_3$	Alk, Carb mg/L $CaCO_3$	Alk, Hydrox mg/L $CaCO_3$	CO_2, Free mg CO_2/L	CO_2, T mg total CO_2	TDS mg/L	Pb, T µg/L	Cu, T µg/L	Fe, T µg/L	Comments
4/7/04	ASR Well	118	7.31	685.1	12.10	0.21	58.80	0.43	0.06	1.38	0.06	28.94	30.10	2.81	90.40	20.12	237.5	237.0	0.5	0.0	23.2	232.0	392	0	0	0	
4/7/04	ASR Well Field Duplicate	118	7.26	684.4	11.84	0.19	58.84	0.43	0.06	1.38	0.07	28.94	31.12	3.02	91.10	20.05	238.0	237.6	0.4	0.0	26.1	235.4	380	0	0	0	
4/7/04	Weber R-Bridge @ Hwy 89	ASR100	8.04	252.4	10.00	0.23	16.70	0.11	0.01	0.81	0.04	13.37	10.16	2.18	32.69	6.22	88.5	87.5	0.9	0.1	1.6	79.0	132	8.4	0	1636	
4/14/04	ASR Well	118	7.38	729.2	11.75	0.22	58.87	0.285 R	0.06	1.4R	0.06R	29.31	30.19	2.85	87.60	19.72	238.0	237.5	0.5	0.0	19.8	229.0	388	0	0	0	
4/14/04	ASR Well Field Duplicate	118	7.39	730.1	11.72	0.19	58.90	0.288 R	0.06	1.4R	0.06R	29.31	30.15	2.91	87.76	19.72	239.0	238.4	0.6	0.0	19.4	229.5	380	0	0	0	
4/14/04	Weber R-Bridge @ Hwy 89	ASR100	7.77	327.5	8.20	0.16	21.47	0 R	0.01	0.47R	0.033R	17.22	13.81	1.86	37.63	8.84	114.5	113.8	0.6	0.0	3.9	104.3	136	12.8	0	1935	
4/20/04	ASR Well	118	7.36	667	11.67	0.21	61.58	0.294 R	0.06	1.47R	0.02	30.79	30.80	2.63	89.02	19.64	239.0	238.5	0.5	0.0	20.8	230.9	336	0	0	0	
4/20/04	ASR Well Field Duplicate	118	7.38	666.4	11.57	0.21	61.47	0.295 R	0.06	1.47R	0.02	30.75	30.44	2.66	89.24	19.80	239.0	238.5	0.5	0.0	19.9	230.0	332	0	0	0	
4/20/04	Weber R-Bridge @ Hwy 89	ASR100	7.77	348.1	6.03	0.19	27.10	0 R	0.02	0.44R	0.02	20.92	17.02	1.93	44.65	10.84	125.0	124.3	0.7	0.0	4.2	113.9	152	0	0	442	
4/28/04	ASR Well	118	7.45	726.4	11.74	0.24	60.73	0.29	0.06	1.46	0.024R	30.57	29.60	2.89	87.95	20.02	233.5	232.9	0.6	0.0	16.5	221.8	372	0	0	0	
4/28/04	ASR Well Field Duplicate	118	7.43	725.3	11.66	0.23	60.55	0.30	0.06	1.45	0.01R	30.53	30.32	2.75	89.22	19.87	234.5	233.9	0.6	0.0	17.4	223.5	372	0	0	0	
4/28/04	Weber R-Bridge @ Hwy 89	ASR100	7.89	314.5	9.99	0.16	20.78	0.11	0.01	0.32	0.01 R	16.15	13.02	1.77	36.35	9.15	102.5	101.7	0.7	0.0	2.6	92.4	128	0	0	243	
5/4/04	HAFB Well 6	52	7.30	536.9	11.84	0.17	20.38	0 R	0.03	0.60 R	0.01	16.92	25.83	2.56	74.45	18.65	254.5	254.0	0.5	0.0	25.5	249.2	284	0	0	265	Well was running
5/4/04	Valley Nursery Well	49	7.74	470.8	20.62	0.25	23.57	0 R	0.04	0 R	0.02	16.94	22.44	2.13	62.73	14.49	204.5	203.4	1.1	0.0	7.4	186.9	252	0	0	911	Well was running
5/4/04	ASR Well	118	7.46	654.2	12.61	0.25	57.50	0 R	0.06	1.38R	0.01	29.52	30.66	3.06	88.72	20.03	236.0	235.3	0.6	0.0	16.3	223.7	372	0	0	0	
5/4/04	ASR Well Field Duplicate	118	7.46	653.7	11.98	0.26	56.98	0 R	0.05	1.39	0.03	29.38	31.21	2.85	89.06	20.09	236.0	235.3	0.6	0.0	16.3	223.7	372	0	0	0	
5/4/04	Weber R-Bridge @ Hwy 89	ASR100	8.42	242.9	10.22	0.14	16.01	0 R	0.01	0.28R	0.01	12.89	10.62	1.83	32.73	7.54	92.0	89.7	2.2	0.1	0.7	80.6	144	0	0	339	
5/12/04	ASR Well	118	7.45	656.8	11.78	0.27	57.64	0.00	0.06	1.37	0.03	29.53	30.98	3.09	88.77	20.34	236	235.4	0.6	0.0	16.7	224.1	368	0	0	0	
5/12/04	ASR Well Field Duplicate	118	7.49	655.9	11.64	0.27	58.48	0.00	0.06	1.39	0.03	30.04	30.50	2.90	88.58	19.88	237	236.3	0.7	0.0	15.3	223.5	364	0	0	0	
5/12/04	Weber R-Bridge @ Hwy 89	ASR100	8.12	276.7	8.12	0.16	18.85	0.00	0.01	0.35	0.02	14.29	12.30	1.58	37.52	8.83	107	105.6	1.0	0.1	2	100	156	0	0	190	
5/19/04	ASR Well	118	7.35	690.4	11.87	0.25	60.69	0.00	0.04	1.33	0.00	32.41	30.17	2.12	86.20	19.55	236	235.5	0.5	0.0	21	228.5	368	0	0	0	
5/19/04	ASR Well Field Duplicate	118	7.38	688.4	11.76	0.12	60.76	0.00	0.04	1.33	0.00	32.41	30.06	2.69	87.67	19.64	236	235.5	0.5	0.0	19.6	227.1	372	0	0	0	
5/19/04	Weber R-Bridge @ Hwy 89	ASR100	8.43	398.8	10.82	0.16	28.96	0.00	0.00	0.31	0.00	22.48	18.05	1.92	47.57	12.17	143.5	139.8	3.5	0.1	1	125.6	208	0	0	95	
5/26/04	ASR Well	118	7.43	687.7	11.74	0.27	60.42	0.00	0.05	1.33	0.01	30.55	30.86	2.38	84.74	19.55	234.5	233.9	0.6	0.0	17.4	223.5	364	0	0	0	
5/26/04	ASR Well Field Duplicate	118	7.49	687.5	11.72	0.25	59.72	0.00	0.05	1.32	0.00	30.34	30.49	2.60	86.07	19.62	235	234.3	0.7	0.0	15.2	221.7	364	0	0	0	
5/26/04	Weber R-Bridge @ Hwy 89	ASR100	8.28	445.5	8.47	0.23	34.46	0.00	0.00	0.39	0.00	24.40	21.23	1.70	55.14	13.72	161	158.1	2.8	0.1	1.7	142.1	224	0	0	50	
6/1/04	HAFB Well 9	72	7.56	585.4	12.11	0.17	38.74	0.00	0.04	1.44	0.00	29.52	19.09	2.24	77.00	18.57	213.5	212.8	0.7	0.0	11.7	199.3	304	0	0	0	Well was running
6/1/04	Weber R-Bridge @ Hwy 89	ASR100	8.70	459.4	13.52	0.18	37.09	0.00	0.00	0.33	0.00	26.06	22.72	1.75	56.65	14.22	161.5	154	7.3	0.3	0.6	139.3	220	0	0	124	
6/1/04	District Well 3	36	7.70	523.4	14.01	0.17	22.28	0.00	0.00	1.19	0.00	28.14	16.86	1.58	69.35	17.69	213.5	212.5	1.0	0.0	8.5	195.9	284	0	0	0	Well was running
6/2/04	ASR Well	118	7.19	698	12.24	0.20	61.90	0.00	0.05	1.24	0.00	31.73	30.59	2.75	86.43	19.78	233.5	233.2	0.3	0.0	30.1	235.4	356	0	0	0	
6/2/04	ASR Well Field Duplicate	118	7.38	695.4	12.06	0.20	61.92	0.00	0.05	1.24	0.00	31.75	30.42	3.04	87.00	19.50	233	232.5	0.5	0.0	19.4	224.2	360	0	0	0	
6/8/04	ASR Well	118	7.49	695.8	12.20	0.19	62.20	0.00	0.03	1.21	0.02	31.64	31.11	2.68	87.11	20.34	234.5	233.8	0.7	0.0	15.1	221.2	320	0	0	0	
6/8/04	ASR Well Field Duplicate	118	-	-	-	0.21	62.34	0.00	0.03	1.22	0.02	31.59	31.53	2.78	88.27	20.21	234.5	-	-	-	-	-	324	0	0	0	
6/8/04	Weber R-Bridge @ Hwy 89	ASR100	8.56	465.7	15.20	0.18	35.65	0.00	0.00	0.41	0.01	25.06	21.99	2.00	57.54	14.10	166	160.3	5.5	0.2	0.9	144.4	208	0	0	149	
6/15/04	ASR Well	118	7.48	696.1	11.90	0.23	62.39	0.00	0.05	1.17	0.012R	31.45	30.90	2.88	87.30	19.82	234.5	233.8	0.7	0.0	15.5	221.6	352	0	0	0	
6/15/04	ASR Well Field Duplicate	118	7.46	695.8	11.80	0.23	62.44	0.00	0.05	1.18	0.01R	31.50	31.19	2.57	88.68	19.71	234	233.4	0.6	0.0	16.2	221.9	356	0	0	0	
6/15/04	Weber R-Bridge @ Hwy 89	ASR100	8.45	496.8	13.60	0.19	39.68	0.00	0.01	0.41	0.021R	28.01	24.19	2.03	59.38	15.37	173.5	168.9	4.5	0.1	1.2	151.8	236	0	0	168	
6/22/04	ASR Well	118	7.43	694.7	11.90	0.31	61.75	0.00	0.05	1.20	0.01	29.82	31.15	2.62	88.05	19.68	234	233.4	0.6	0.0	17.3	223	412	0	0	0	
6/22/04	ASR Well Field Duplicate	118	7.46	693.7	11.80	0.27	61.65	0.00	0.04	1.20	0.01	29.83	31.16	2.76	88.45	19.70	234	233.4	0.6	0.0	16.2	221.9	404	0	0	0	Well was running
6/22/04	Weber R-Bridge @ Hwy 89	ASR100	8.39	513.9	14.40	0.26	42.23	0.00	0.02	0.38	0.01	28.88	25.85	1.97	60.65	16.75	176.5	172.4	4.0	0.1	1.4	154.9	304	0	0	158	
7/6/04	Weber R-Bridge @ Hwy 89	ASR100	8.71	540.9	16.80	0.21	47.49	0.00	0.02	0.12R	0.00	32.32	27.25	2.63	54.31	18.43	183.5	174.8	8.4	0.3	0.7	158.2	296	0	0	81	
7/6/04	District Well 3	36	7.74	522.2	14.10	0.14	22.23	0.00	0.00	1.17R	0.02	28.09	16.09	1.57	68.73	17.38	216.5	215.4	1.1	0.0	7.8	197.8	304	0	0	0	Well was running
7/7/04	Parsons-Po0ed H2O N of Pz		7.75	549.2	-	0.32	39.93	0.00	0.11	0.13	0.03	26.74	20.19	1.93	77.15	11.79	206	204.9	1.1	0.0	7.3	188.1	320	-	-	-	Parsons gravel pit
7/7/04	Parsons-Foil Flume SE of Pz		8.24	507.9	-	0.24	37.00	0.00	0.06	1.57	0.00	24.95	22.19	2.02	61.94	13.62	181.5	178.5	2.9	0.1	2.1	160.5	292	-	-	-	Parsons gravel pit
7/13/04	Parsons-Po0ed H2O N of Pz		8.00	555.3	-	0.31	39.38	0.00	0.06	0.10	0.02	24.02	19.50	1.65	77.21	12.35	205	203	1.9	0.1	4.1	183.6	304	-	-	-	Parsons gravel pit
7/13/04	Parsons-Foil Flume SE of Pz		8.39	476.5	-	0.26	36.18	0.00	0.04	1.29	0.00	22.82	22.07	2.24	53.79	13.34	165	161.2	3.7	0.1	1.3	144.8	252	-	-	-	Parsons gravel pit
8/3/04	HAFB Well 5	78	7.59	500.1	17.80	0.18	18.67	0.00	0.02	1.17	0.02	24.80	15.97	2.17	64.08	17.37	211.5	210.7	0.8	0.0	10.8	196.6	284	0	0	0	
8/3/04	Weber R-Bridge @ Hwy 89	ASR100	8.55	600.4	18.10	0.26	51.99	0.00	0.02	0.37	0.03	32.33	28.99	2.57	68.36	19.30	206	199.2	6.6	0.2	1.1	179.3	356	0	0	118	
8/3/04	District Well 3	36	7.57	522.4	14.20	0.15	22.81	0.00	0.00	1.22	0.02	27.00	16.06	1.33	70.35	17.40	215.5	214.7	0.7	0.0	11.6	200.8	308	0	0	0	
9/7/04	Weber R-Bridge @ Hwy 89	ASR100	8.55	621.1	13.90	0.27	55.48	0.00	0.00	0.40	0.00	35.86	31.27	2.91	64.55	19.80	203	196.3	6.5	0.2	1.1	176.7	348	0	0	59	
9/8/04	District Well 3	36	7.64	537.5	14.10	0.23	24.00	0.00	0.00	1.24	0.00	28.05	16.19	1.46	71.75	17.91	216.5	215.6	0.9	0.0	9.9	200	312	0	0	0	
10/5/04	Weber R-Bridge @ Hwy 89	ASR100	8.55	579	12.10	0.21	48.27	0.00	0.00	0.30	0.02	31.21	27.24	2.80	66.52	19.65	204.5	197.7	6.6	0.2	1.1	178	348	0	0	85	
10/5/04	District Well 3	36	7.69	521.7	13.90	0.16	23.46	0.00	0.00	1.23	0.03	27.87	16.16	1.97	70.58	18.21	218.5	217.5	1.0	0.0	8.9	200.7	304	0	0	0	
11/2/04	Weber R-Bridge @ Hwy 89	ASR100	7.06	660.9	3.91	0.23	58.86	0.00	0.00	0.74	0.06	36.49	33.60	3.22	77.91	19.54	221.5	221.3	0.2	0.0	38.5	233.3	376	0	0	648	
12/7/04	Weber R-Bridge @ Hwy 89	ASR100	8.14	658.3	2.10	0.21	54.11	0.00	0.00	0.88	0.02	37.75	31.26	3.12	81.99	20.26	231	228	3.0	0.1	3.3	205.3	358	0	0	62	
1/4/05	Weber R-Bridge @ Hwy 89	ASR100	7.89	664.4	3.33	0.21	57.13	0.00	0.00	0.84	0.02	38.35	33.25	2.94	80.15	19.79	222	220.4	1.6	0.0	5.7	200.4	364	0	0	78	
1/4/05	District Well 3	36	7.69	523.5	2.95	0.14	23.09	0.00	0.00	1.18	0.02	26.14	15.99	1.71	72.09	18.07	215.5	214.5	1.0	0.0	8.8	198	220	0	0	0	

R=reject

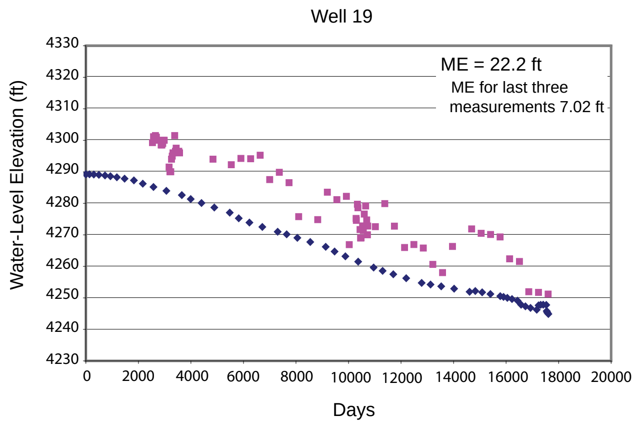
APPENDIX F

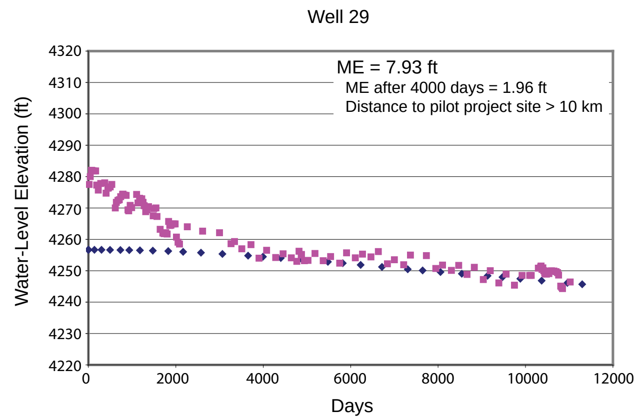
WATER-LEVEL CALIBRATION PLOTS FOR GROUND-WATER FLOW MODEL

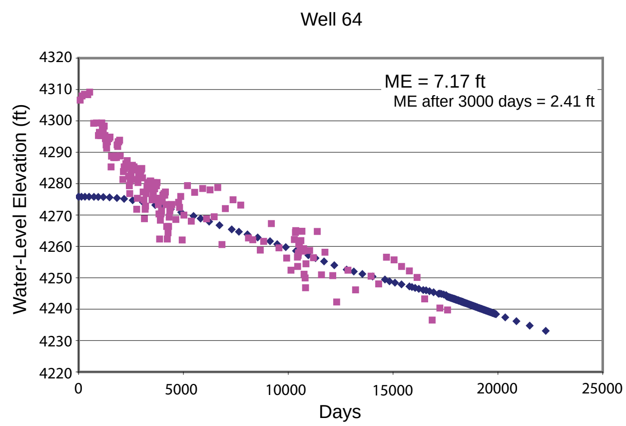


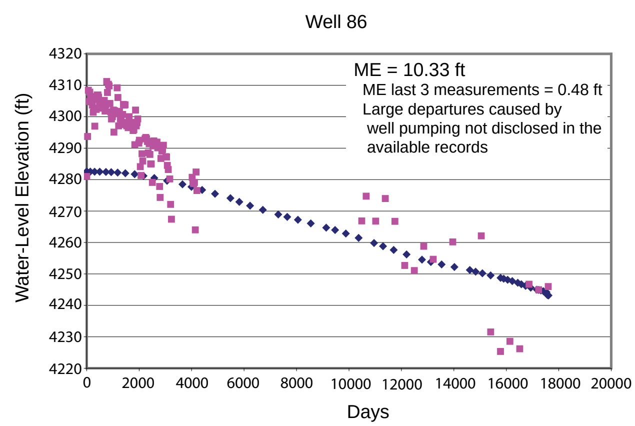
EXPLANATION

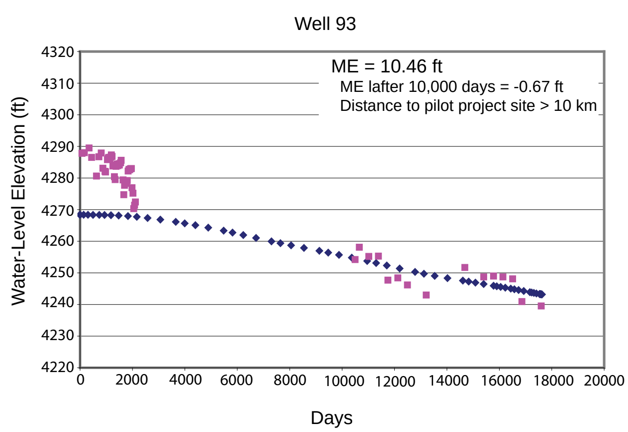
- Observed water level
- Modeled water level

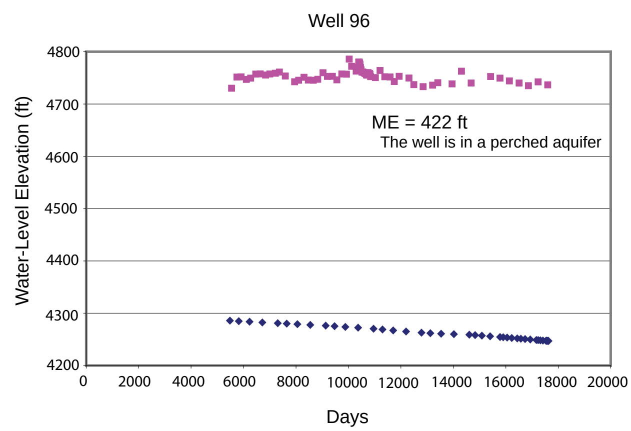






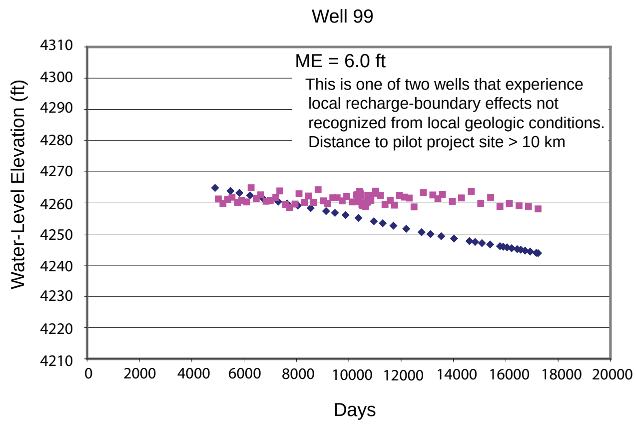


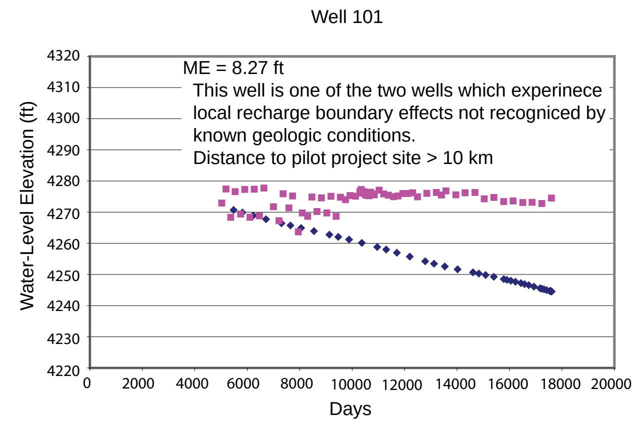


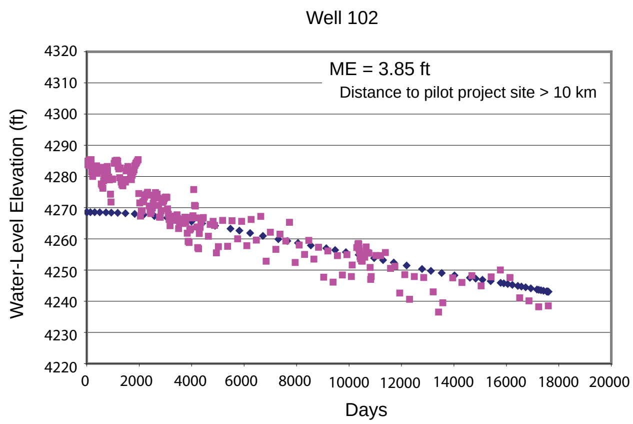


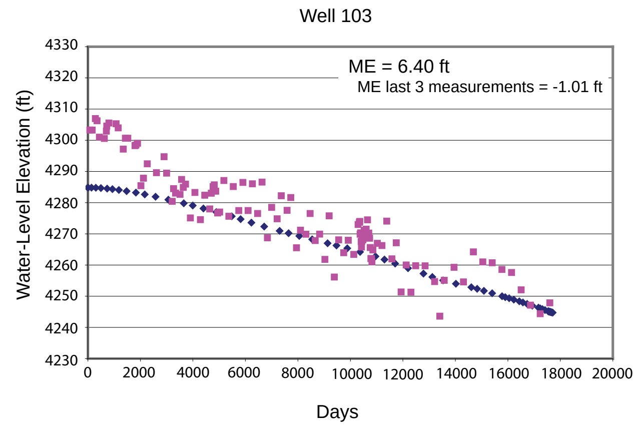
EXPLANATION

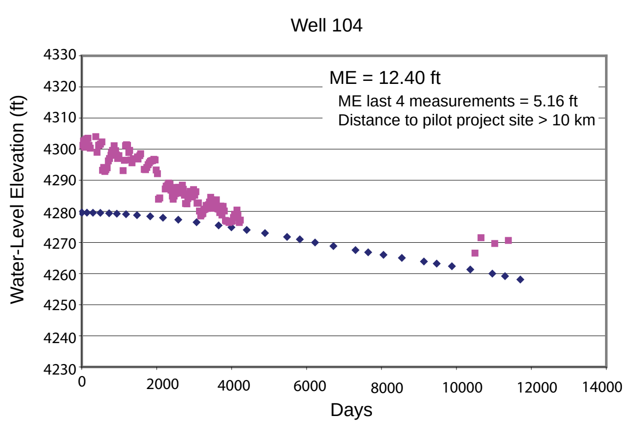
- ▪ Observed water level
- ◆ Modeled water level

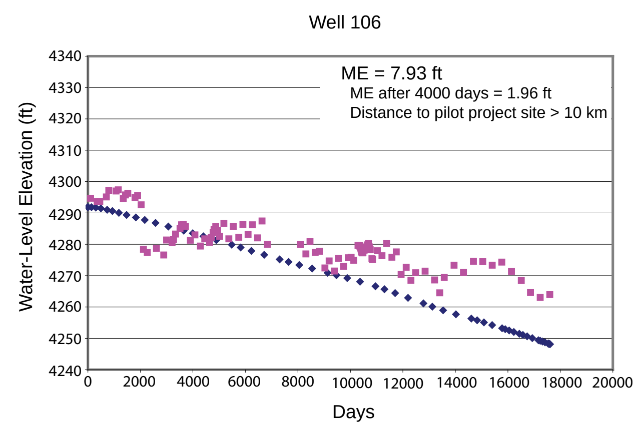












EXPLANATION

- ▪ Observed water level
- ◆ Modeled water level