U.S. Department of the Interior
U.S. Geological Survey

Ground-Water Flow and Numerical Simulation of Recharge from Streamflow Infiltration near Pine Nut Creek, Douglas County, Nevada

Water-Resources Investigations Report 02–4145

Prepared in cooperation with the
CARSON WATER SUBCONSERVANCY DISTRICT

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(Back of Cover)

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By Douglas K. Maurer

U.S. GEOLOGICAL SURVEY

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Carson City, Nevada
2002

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
acre	4,047	square meters
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per mile ($ft^3/s/mi$)	0.02832	cubic meter per second per mile
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per year (ft/yr)	0.3048	meter per year
foot squared per day (ft^2/d)	0.1894	meter squared per day
gallons per minute (gal/min)	3.7854	liters per minute
gallons per day (gal/d)	0.003785	cubic meter per day
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Temperature: Degrees Celsius (^oC) can be converted to degrees Fahrenheit (^oF) by using the formula $^oF = [1.8(^oC)]+32$. Degrees Fahrenheit can be converted to degrees Celsius by using the formula $^oC = 0.556(^oF-32)$.

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929, formerly called “Sea-Level Datum of 1929”), which is derived from a general adjustment of the first-order leveling networks of the United States and Canada.

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By Douglas K. Maurer

ABSTRACT

Ground-water flow and recharge from infiltration near Pine Nut Creek, east of Gardnerville, Nevada, were simulated using a single-layer numerical finite-difference model as part of a study made by the U.S. Geological Survey in cooperation with the Carson Water Subconservancy District. The model was calibrated to 190 water-level measurements made in 27 wells in December 2000, and in 9 wells from August 1999 through April 2001. The purpose of this study was to estimate reasonable limits for the approximate volume of water that may be stored by recharge through infiltration basins, and the rate at which recharged water would dissipate or move towards the valley floor.

Measured water levels in the study area show that infiltration from the Allerman Canal and reservoir has created a water-table mound beneath them that decreases the hydraulic gradient east of the canal and increases the gradient west of the canal. North of Pine Nut Creek, the mound causes ground water to flow toward the northern end of the reservoir. South of Pine Nut Creek, relatively high water levels probably are maintained by the mound beneath the Allerman Canal and possibly by greater rates of recharge from the southeast. Water-level declines near Pine Nut Creek from August 1999 through April 2001 probably are caused by dissipation of recharge from infiltration of Pine Nut Creek streamflow in the springs of 1998 and 1999.

Using the calibrated model, a simulation of recharge through a hypothetical infiltration basin covering 12.4 acres near Pine Nut Creek applied 700 acre-feet per year of recharge over a six-month period, for a total of 3,500 acre-feet after 5 consecutive years. This recharge requires a diversion rate of about 2 cubic feet per second and an infiltration rate of 0.3 foot per day. The simulations showed that recharge of 3,500 acre-feet caused water levels near the basin to rise over 70 feet, approaching land surface, indicating 3,500 acre-feet is the maximum that may be stored in a 5-year period, given the basin location and surface area used in the simulations. Greater amounts probably could be stored if separate infiltration basins were installed at different locations along the Pine Nut Creek alluvial fan, applying the recharge over a larger area. The water-table mound resulting from recharge extended 7,000 feet north, west, and south of the infiltration basin.

After recharge ceased, water levels near the center of the mound declined rapidly to within 20 feet of initial levels after 2 years, and within 10 feet of initial levels after 7 years. The recharge mound dissipates laterally across the modeled area at decreasing rates over time. A water-level rise of 1 foot moved westward towards the valley floor 660 feet from peak conditions after 1 year, and averaged 550 feet, 440 feet, and 330 feet per year for the periods 1–4, 4–7, and 7–10 years, respectively, after recharge ceased.

Simulations of subsequent pumping from hypothetical wells near the infiltration basin were made by applying pumping near the basin beginning 1 year after recharge of 3,500 acre-feet ceased. Pumping was applied over a 6-month period for 4 years from one well at 400 acre-feet per year, withdrawing 1,600 acre-feet or 45 percent of that recharged, and from two wells totaling 800 acre-feet per year, withdrawing 3,200 acre-feet or 90 percent of that recharged. Pumping of 1,600 acre-feet caused water-levels near the infiltration basin to decline only slightly below initial levels. Pumping of 3,200 acre-feet caused water-levels near the infiltration basin to decline a maximum of 30 feet below initial levels, with smaller declines extending laterally in all directions for 4,000 feet from the pumping wells. Water-level declines are a result of pumping at a rate sufficient to withdraw the majority of the water recharged through the infiltration basin. Although the declines may affect water levels in nearby domestic wells, the simulations show that water levels recover quickly after pumping ceases and would recover more quickly with continued use of the infiltration basin for recharge.

INTRODUCTION

Continued population growth in the Carson River basin has increased the need for water storage for municipal supply. Currently no significant facilities exist for surface-water storage in the Carson River basin upstream from Lahontan Reservoir (fig. 1). Funding and environmental issues have blocked construction of dams for surface-water storage in the upper Carson River basin. Water rights to streamflow of the Carson River, held by City and County agencies, are currently unused because of the lack of storage facilities. Subsurface storage of water by augmenting the natural recharge of aquifers is a potentially cost-effective alternative to surface storage that could be developed with less environmental impact.

The Carson River basin covers 3,980 mi^2 in eastern California and western Nevada and consists of five valleys designated and managed as separate hydrographic areas bounded by bedrock narrows, yet linked by the Carson River (fig. 1). Numerous alluvial fans, formed by streams tributary to the Carson River, surround the margins of these valleys. The alluvial fans provide potential sites for infiltration basins and subsurface storage of water that later could be extracted by wells for municipal supply.

The coarse-grained, well-sorted sediments of stream channels on the alluvial fans are conducive to recharge by infiltration. Water that percolates to the water table creates recharge mounds of variable vertical and lateral extent that will, with time, dissipate and move downgradient towards the valley floor. The rates at which ground water moves from beneath alluvial fans to the valley floor are not well known and depend on the hydraulic gradient and the hydraulic conductivity of aquifer materials. A numerical ground-water flow model can be used to simulate ground-water mounding beneath an infiltration basin and estimate reasonable limits for the approximate volume of water that may be stored and the rate at which recharged water would dissipate or move towards the valley floor.

In 1999, work began on a cooperative study, funded by the U.S. Geological Survey and the Carson Water Subconservancy District, to determine the potential for augmenting recharge at a pilot infiltration site. A pilot infiltration site was selected on an alluvial fan near the mouth of Pine Nut Creek, on the eastern side of Carson Valley (fig. 2). The site was selected because it is near the Allerman Canal where surface-water flow of the Carson River could be diverted, it is upgradient from municipal wells of the towns of Gardnerville and Minden, and previous work by Maurer and Peltz (1994, sheet 3) indicated high potential for recharge through infiltration beds. The Pine Nut Creek alluvial fan is similar to other fans deposited by many perennial and ephemeral streams tributary to the Carson River. The hydrologic setting near Pine Nut Creek also is similar to many basins in western Nevada with through-flowing rivers which have distribution canals for irrigation around the perimeter of the valley near the toe of alluvial fans.

Instrumentation to monitor infiltration rates, changes in soil moisture, and changes in ground-water levels beneath the streambed of Pine Nut Creek were installed near the site from July 1999 through March 2000. In 2001, work began on the development of a numerical model of the ground-water flow system near Pine Nut Creek. The study area for the numerical model lies east of Gardnerville, Nevada, covering about 36 mi^2 (fig. 2).

Purpose and Scope

This report describes the simulation of ground-water flow near the infiltration site at Pine Nut Creek. Available data on streamflow, water levels, and aquifer properties near the alluvial fan of Pine Nut Creek were compiled and used to construct a numerical model of the ground-water flow system. The model was used to simulate recharge from a hypothetical infiltration basin near the infiltration site at Pine Nut Creek, and subsequent pumping from hypothetical wells near the infiltration basin at two different rates.

Streamflow data consisted of indirect measurements of Pine Nut Creek flow in 1999 at three sites along Pine Nut Creek, and streamflow measurements of the Allerman Canal at two sites in March 2001. Water levels were measured periodically from August 1999 through April 2001 in 9 wells near Pine Nut Creek, including 3 wells installed for this study, and in 27 wells in the study area in December 2000. Slug tests completed in the three wells installed for the study were used to estimate the hydraulic conductivity of aquifer materials.

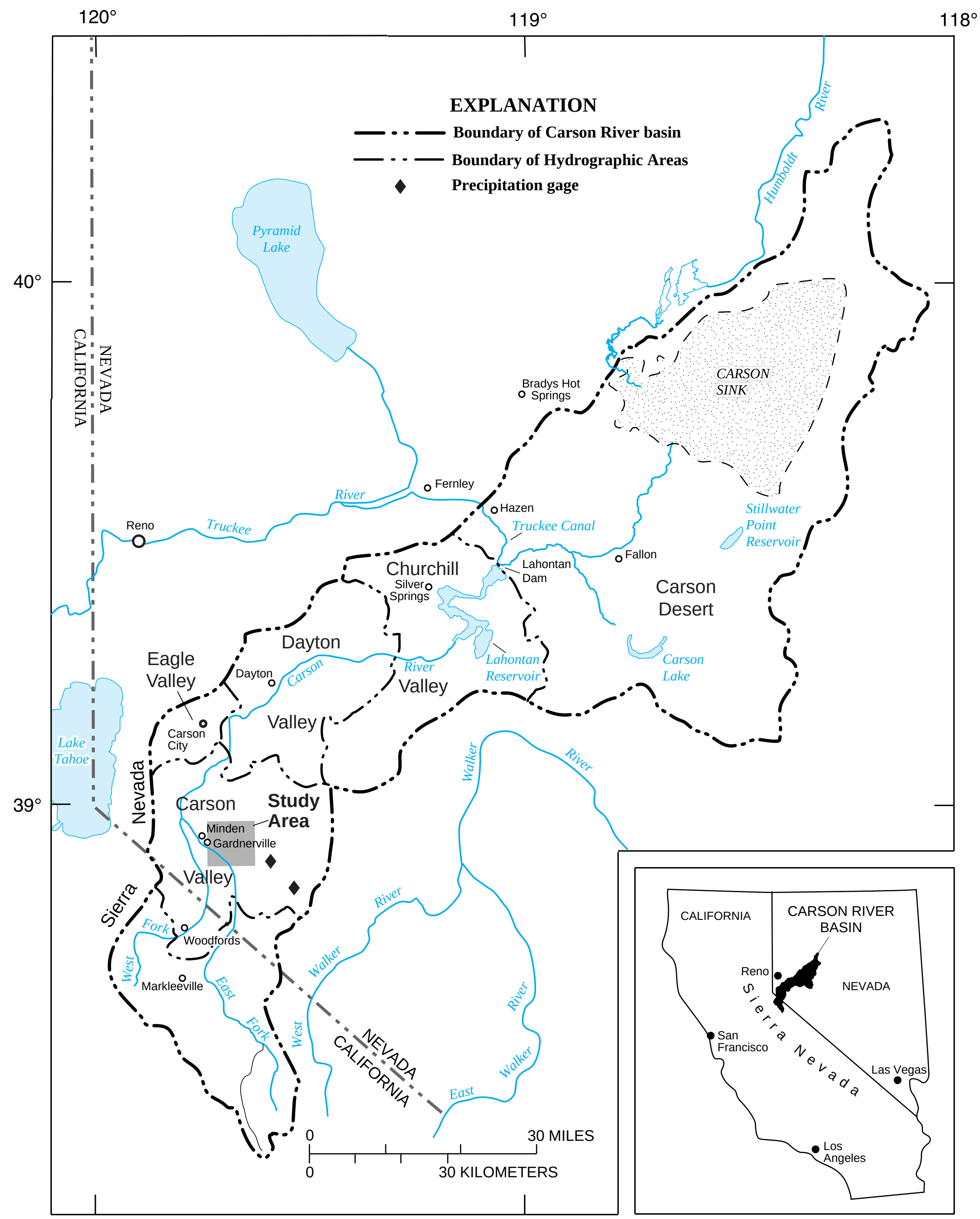
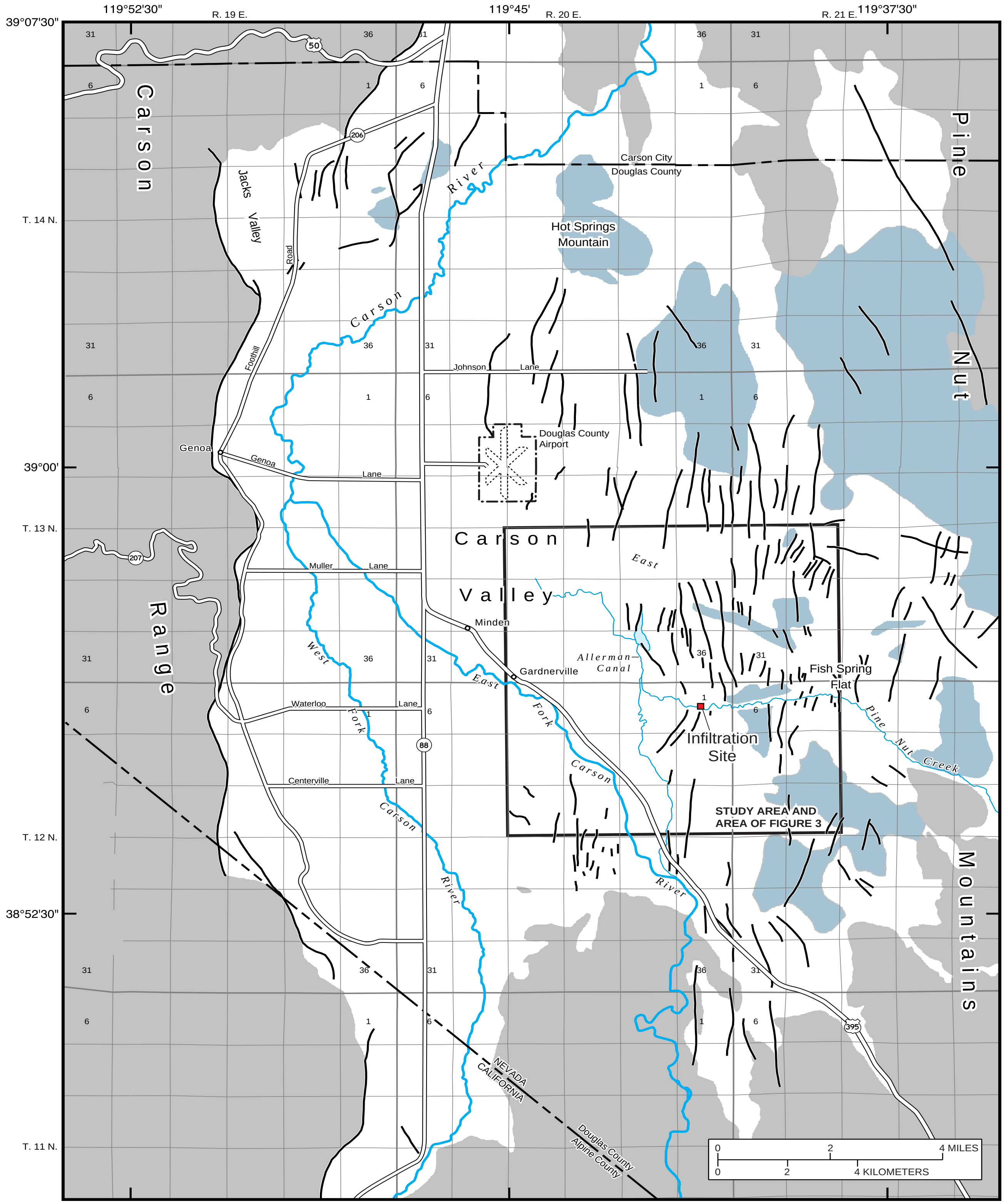


Figure 1. Locations of Carson River basin, Carson Valley, Pine Nut Creek study area, and precipitation gages in the Pine Nut Creek watershed.



Base from U.S. Geological Survey digital data, 1:100,000, Smith Valley and Carson City, 1979-85
Universal Transverse Mercator projection
Zone 11

Geology from Armin and others (1983), Moore (1969), Pease (1980), and Stewart and Noble (1979); generalized and modified by Maurer (1981)

EXPLANATION

- Quaternary unconsolidated sediments
- Tertiary semiconsolidated sediments
- Cretaceous granitic and Triassic/Jurassic metamorphic rock
- Fault

Figure 2. Geographic and geologic features of Carson Valley, and locations of Pine Nut Creek study area and infiltration site.

Acknowledgments

The author thanks Ray Gray and Mike Ferrell for allowing access to their private land for installation of wells and other instrumentation; Dawn Patterson of Douglas County Utilities for providing map information; Carl Rushmeyer and Joe Mackey of Douglas County Utilities, Robert Spellberg of the Gardnerville Ranchos General Improvement District, and Tom Brooks of the Carson Valley Golf Course for providing water-level and pumpage data; and numerous well owners surrounding the study area for access to their private wells for water-level measurements.

METHODS

Well Installation and Water-Level Measurements

Three wells were installed for the study (fig. 3) using air-rotary methods while driving 6-in. steel casing to hold the borehole open. The boreholes were drilled to about 30 ft beneath the water table, and a string of 2-in. diameter PVC casing screened over a 15-ft interval at the bottom of the borehole. The PVC screen and casing was attached to 2-in. diameter, thin-walled aluminum tubing. The PVC screen and casing was installed below the water table, while the portion constructed of aluminum was installed in the unsaturated portion of the borehole to allow for measurements of changes in soil moisture. The 6-in. steel casing was withdrawn in 20-ft sections followed by installation of a sand pack in the annulus around the screens, bentonite grout in the annulus above the screened interval to the top of the water table, and closed-cell polyurethane foam in the annulus above the water table adjacent to the aluminum tubing. The wells were developed by pumping and surging until discharged water was clear.

Water levels were measured manually in wells installed for the study and in 34 domestic wells in the study area. Water-level measurements in domestic wells were recorded only after water levels had become static after pumping had stopped. For wells within 1.5 mi of Pine Nut Creek, measuring points were surveyed to the nearest 0.1 ft. For other wells, land surface altitude was estimated from 1:4,800-scale topographic maps with 5-ft contour intervals (Genge Aerial Surveys, 1977) and considered accurate to within ±2.5 ft.

Slug Tests

Slug tests were made to estimate the transmissivity of aquifer materials near Pine Nut Creek. The tests were completed by lowering a solid cylinder below static water level in wells installed for the study to create a rise in water level. The following decline in water levels was recorded at 1-second intervals using a pressure transducer set at a constant depth below static water level sufficient to allow lowering of the cylinder. After the water level returned to static, the cylinder was removed to lower the water level, again recording the rise in water levels. Recorded water levels were analyzed using the Bouwer and Rice (1976) method to obtain estimates of the transmissivity of aquifer materials adjacent to the well screen.

DESCRIPTION OF STUDY AREA

Geographic Setting

The study area is on the eastern side of Carson Valley, about 25 mi south of Carson City and east of Gardnerville, Nevada (figs. 1 and 2). The infiltration site is on an alluvial fan near the mouth of Pine Nut Creek, where the creek emerges from a narrow canyon cut through a low ridge separating Carson Valley from Fish Spring Flat to the east (fig. 3). The alluvial fan slopes from an altitude of about 5,000 ft above sea level near the base of the ridge to about 4,850 ft where it merges with the floor of Carson Valley. West of the ridge, the channel of Pine Nut Creek meanders across a 1,000-ft wide flood plain incised 10 to 20 ft into the alluvial fan (fig. 3). The headwaters of Pine Nut Creek are about 10 mi to the southeast in the Pine Nut Mountains, which rise to altitudes of 9,200 to 9,400 ft.

Average annual flow of Pine Nut Creek at a discontinued gaging station about 8.5 mi upstream from the study area was 1.27 ft^3/s, or 920 acre-ft, for the period of record 1980–97 (Bonner and others, 1998, p. 147). The highest monthly mean flows at the gage were about 2 ft^3/s from March through May, and an instantaneous peak flow of 165 ft^3/s occurred in March 1986. Streamflow recorded at the gage is lost to infiltration downstream, with flow often ending near the mouth of the canyon separating Carson Valley from Fish Spring Flat (fig. 3).

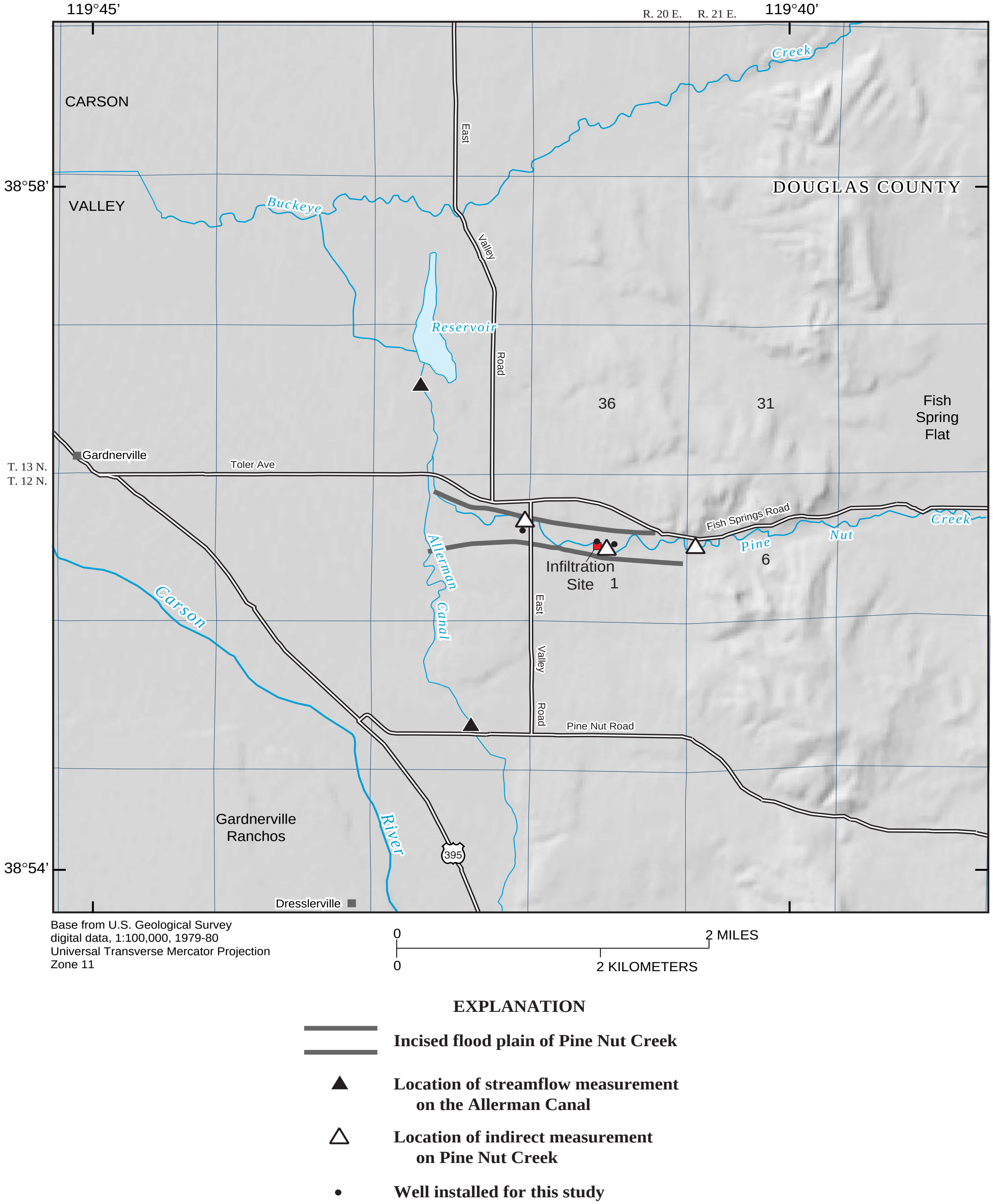


Figure 3. Locations of the incised flood plain of Pine Nut Creek, the infiltration site, two streamflow measurement sites along the Allerman Canal, three indirect measurement sites along Pine Nut Creek, and three wells that were installed for this study.

The channel of Buckeye Creek crosses the northern part of the study area. Annual flow of Buckeye Creek at a discontinued gaging station about 9 mi upstream from the study area was 0.89 ft^3/s, or 645 acre-ft, for the period of record 1980–97 (Bonner and others, 1998, p. 148). At the gaging station, no flow was recorded for many days in most years, and flow of the creek extends to the study area only during the most extreme flood events.

The Allerman Canal, a major distribution canal for irrigation supply on the eastern side of Carson Valley, diverts surface-water flow of the Carson River to a reservoir northwest of the infiltration site (fig. 3). Irrigated fields growing alfalfa, onions, and garlic lie west of the Allerman Canal, whereas east of the canal, open land covered with sagebrush is being developed for residential use. As altitude increases in the Pine Nut Mountains, pinon pine and juniper become the dominant land cover.

Carson Valley lies in the rain shadow of the Sierra Nevada, and average annual precipitation (1961–90) is 8.13 in. near Minden, Nevada (fig. 2; Owenby and Ezell, 1992, p. 16). Monthly precipitation in the upper part of the Pine Nut Creek watershed (fig. 1) has been recorded at two storage gages operated by the National Resource and Conservation Service and Douglas County personnel from water years (October through September) 1984–2000; however, complete monthly data sets for the two gages are only available for water years 1989–2000. Average annual precipitation from 1989 to 2000 is 15 in. at the lower gage (altitude 6,200 ft) and 16.6 in. at the upper gage (altitude 7,200 ft; Dan Greenlee, National Resource and Conservation Service, written commun., October 2000). Most precipitation occurs as snow from November through May, with occasional summer thunderstorms. Temperatures range from a normal maximum of about 90 ^{o}F in July and August, to a normal minimum of about 16 ^{o}F in December and January (Owenby and Ezell, 1992, p. 12).

Geologic Setting

During the Cretaceous period, 66–138 million years ago (Ma), the granitic magma of the Sierra Nevada pluton was intruded into sedimentary and volcanic rocks of the Triassic and Jurassic periods (138–240 Ma). The intrusion resulted in granodioritic, metavolcanic, and metasedimentary rocks which formed the Carson Range of the Sierra Nevada and the Pine Nut Mountains (fig. 2), and underlie the floor of Carson Valley (Pease, 1979, p. 2–4: Moore, 1969, p. 18). Basin and range faulting, which produced the present topography, began about 17 Ma (Stewart, 1980, p. 110), uplifting the Carson Range and the Pine Nut Mountains, and down-dropping the floor of Carson Valley. Concurrent with the faulting, mostly fine-grained sediments which have become semi-consolidated were deposited from 5 to 15 Ma during the Tertiary period (2–66 Ma). These sediments are exposed mainly on the eastern side of the valley (fig. 2), but dip towards the west and probably are present beneath the entire valley. Throughout the Quaternary period (present day to 2 Ma), unconsolidated sediments deposited by streams and debris flows have formed alluvial fans adjacent to the mountain blocks. The Carson River has deposited a thick sequence of well-sorted sand and gravel alternating with flood-plain sediments of silt and clay on the valley floor.

The mountain blocks bounding Carson Valley are western-tilted structural blocks (Stewart, 1980, p. 113), with Carson Valley occupying the down-dropped western edge of the Pine Nut Mountain block (Moore, 1969, p. 18). A steep, well-defined normal fault creates a 5,000 ft escarpment of the Carson Range on the west, whereas a diffuse fault zone is found on the eastern side of the valley near the infiltration site, dividing the Pine Nut Mountain block into several smaller blocks (fig. 2). Continued westward tilting is shown by recent faulting along the base of the Carson Range (Pease, 1979, p. 15) and by displacement of the Carson River to the extreme west side of the valley (Moore, 1969, p. 18).

HYDROGEOLOGY OF THE STUDY AREA

Description of Sedimentary Deposits

Sedimentary deposits near the study area include Tertiary-age sediments forming the ridge between Carson Valley and Fish Spring Flat, alluvial fan and stream channel deposits west of the ridge, and fluvial deposits adjacent to the Carson River.

The Tertiary-age sediments vary in their degree of compaction (Pease, 1979, p. 4), and predominantly are semi-consolidated tuffaceous clay with isolated lenses of sand and gravel. The lenses of sand and gravel are the main water-bearing layers supplying ground water to wells completed in the Tertiary-age sediments, and probably transmit small amounts of ground-water flow through the sediment (Maurer, 1986, p. 20). Tertiary-age sediments are exposed on the ridge east of the infiltration site and probably are present at shallow depths along the entire length of the ridge (fig. 2). Near the ridge, drillers' logs describe clay layers from 100- to 200-ft thick alternating with relatively thin layers of sand and gravel. West of the ridge, thick units of clay have not been encountered as described in the drillers' logs of wells as deep as 400 ft. Thus, alluvial fan and stream channel deposits west of the ridge, considered to be the main aquifer through which flow takes place in the modeled area, probably have an average thickness of about 400 ft. Tertiary-age sediments, thought to transmit minimal ground-water flow, probably are present at depths greater than 400 ft beneath the alluvial fan of Pine Nut Creek.

Alluvial fan sediments west of the ridge and north and south of Pine Nut Creek, as described in drillers' logs, predominantly consist of layers of coarse sand, gravel, and cobbles, from as much as 30- to 100-ft thick, alternating with layers of clay from 10-ft to as much as 60-ft thick. The coarse-grained sediments are well-sorted stream channel deposits that may extend laterally 50 to 100 ft, mixed with poorly sorted debris-flow deposits that may extend hundreds of feet laterally. Near Pine Nut Creek, sediments are similar except clay layers generally are less than 10-ft thick or are not present. Sediments in the channel of Pine Nut Creek at the three wells drilled for the study consisted of poorly sorted silty sand, gravel, and cobbles with minor clay layers less than 1-ft thick. Sediments near the channel of the Carson River are described as a mixture of boulders, gravel, and coarse to fine sand, with some layers having abundant clay.

Streamflow Infiltration

The hydrologic system near the infiltration site is dominated by streamflow infiltration from the Allerman Canal and reservoir, and Pine Nut Creek. The Allerman Canal flows year round, with rates varying from less than 10 ft^3/s during winter months to 50 and over 150 ft^3/s from mid-April through mid-October when the reservoir is actively used for water storage (Dave Wathen, Office of the Federal Watermaster, written commun., January 2001). During winter months, the canal flows across the floor of the reservoir and no active storage is maintained.

Seepage losses from the Allerman Canal have been reported to range from about 1 ft^3/s/mi during summer months to 0.5 ft^3/s/mi during winter months (Dennis Jensen, Office of the Federal Watermaster, oral commun., December 2000). To assess this estimate of seepage, streamflow measurements along a 2.6 mi reach of the canal spanning the mouth of Pine Nut Creek were made in March 2001, when total flow was about 9 ft^3/s and there were no diversions for irrigation (fig. 3). If the seepage rate is assumed to be 0.5 ft^3/s/mi, the reach measured should have lost about 1.3 ft^3/s. However, the measurements showed no measurable loss of flow. If it is assumed that the streamflow measurements were accurate to within 10 percent of total flow, a loss greater than 0.9 ft^3/s should have been measurable. This indicates that the flow loss during measurements in March was less than 0.9 ft^3/s over the 2.6 mi reach, or less than about 0.3 ft^3/s/mi. Flow losses from the canal may be greater during summer months because stage in the canal is 3–4 ft higher than in winter months. However, ground-water levels near the canal (well 1, fig. 5*B*) show little change over time, indicating that recharge from canal seepage is relatively constant. Measurements of flow losses from the canal were not practical during the summer because of the numerous irrigation diversions from the canal. Similarly, measurements of losses from the reservoir during the summer were not possible because inflow and outflow rates changed daily and measurements of changes in reservoir storage were not available. Flow losses from evapotranspiration from the canal and reservoir probably are minimal compared to seepage losses.

During spring months of wet years, Pine Nut Creek flows completely across the alluvial fan and into the Allerman Canal. Local residents reported flow in the creek from about March through May or June in 1998 and 1999 (Ray Gray, resident near Pine Nut Creek, oral commun., December 2000). High flow that covered large parts of the Pine Nut Creek flood plain was reported during a winter storm in February 1986 and in the spring of 1995 (Dennis Jensen, Office of the Federal Watermaster, oral commun., December 2000; A.T. Spence, resident near Pine Nut Creek, oral commun., December 2000).

Annual precipitation greater than 20 in. at the upper Pine Nut precipitation gage probably is required to produce flow across the fan. In 1995, 1998, and 1999, the annual precipitation measured at the uppermost gage in the Pine Nut Mountains (fig. 1) was about 26, 24, and 25 in., respectively (Dan Greenlee, Natural Resources Conservation Service, written commun., October 2000). The only years of record with precipitation greater than 20 in. at the upper gage (period of record 1989–2000) when flow occurred across the fan are 1995, 1998, and 1999. It is likely that flow of Pine Nut Creek across the fan also took place in 1982 and 1983, years when annual precipitation at Minden, Nevada, was 200 and 170 percent of normal, respectively (Maurer, 1986, p. 64), although flow during those particular years has not been confirmed. If there was flow in 1982 and 1983, flow of Pine Nut Creek extended across the entire fan 5 years out of the 17-year period (1982–99) for an average recurrence interval from 3 to 4 years. However, during years of extreme drought conditions (1986–95) flow may not occur for periods of up to 9 years.

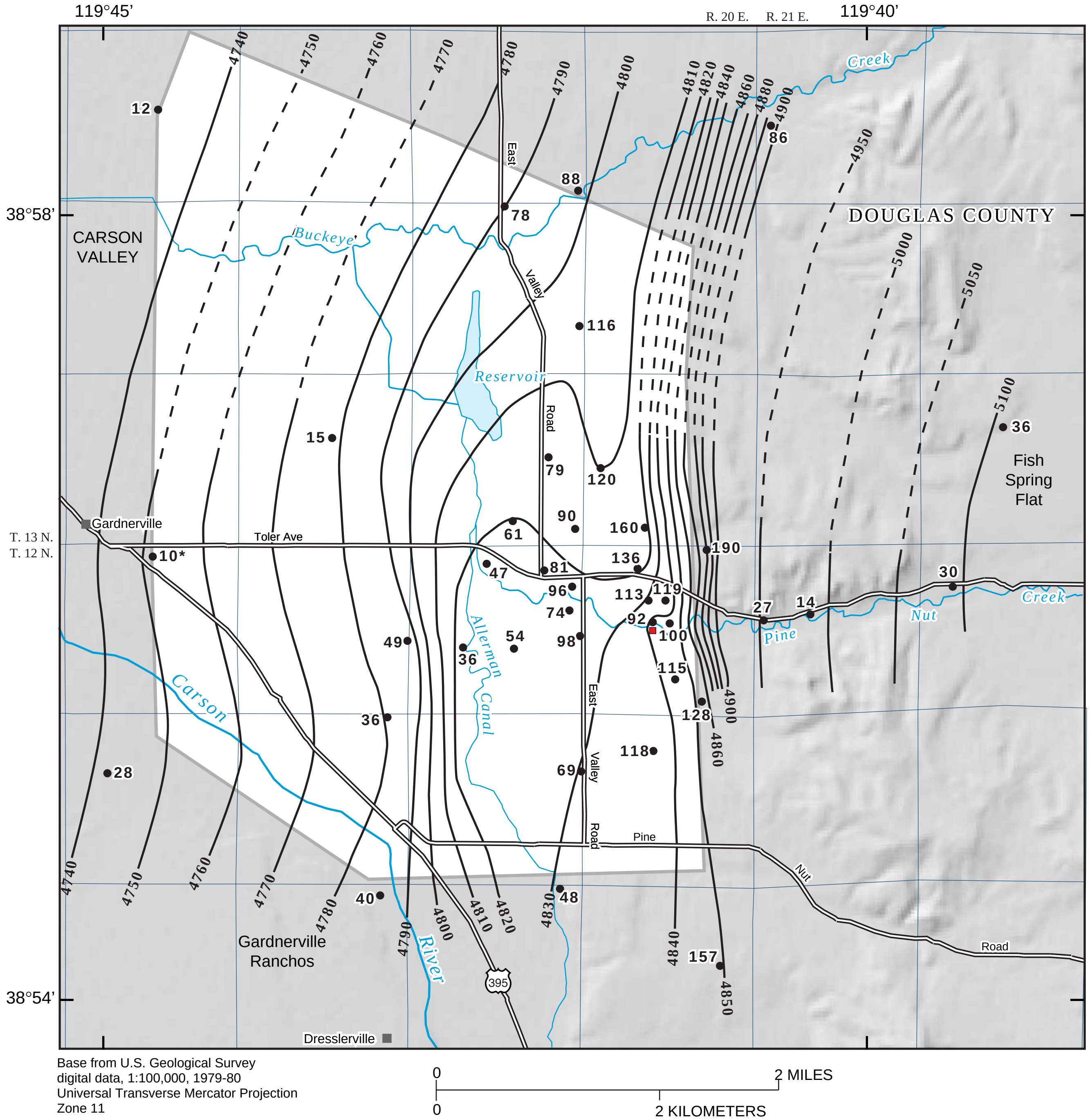
Direct measurements of flow in Pine Nut Creek near the infiltration site have not been made, but indirect estimates of flow were made using water marks from flow in 1999. The water marks used were mineral and algae deposits on culverts and cobbles in the stream channel and represented base flow of the creek over a 2 to 3 month period. Indirect measurements were made at three sites along Pine Nut Creek using the slope conveyance method and the depth of flow and slope of culverts at the upstream site, and three surveyed cross-sections and slope at the two downstream sites (fig. 3). The indirect estimates of flow ranged from 3 to 4 ft^3/s at the base of the ridge of Tertiary-age sediments to 2 ft^3/s near the infiltration site, a stream channel length of 2.8 mi, to 1 ft^3/s where the creek crosses East Valley Road (Glen Hess, U.S. Geological Survey, written commun., June 2000), a stream channel length of 2.2 mi. From these estimates, the stream loss along the channel was from 0.7 to 0.4 $ft^3/s/mi$ from the top of the alluvial fan to the infiltration site, and about 0.4 $ft^3/s/mi$ downstream from the site. Observed streamflow by the author in May 1999, just upstream of the point where flow enters the Allerman Canal, was less than about 0.5 ft^3/s. This indicates that the total flow loss across the alluvial fan in 1999 was about 3 ft^3/s.

Ground-Water Flow

The depth to water below land surface is an important factor for subsurface storage of water, because this thickness limits the amount of water that may be stored in the unsaturated zone above the water table. East of the infiltration site, the depth to water is almost 200 ft near the western side of the ridge separating Fish Spring Flat from Carson Valley (fig. 4). Beneath the channel of Pine Nut Creek, depth to water varies from about 100 ft near the infiltration site to about 70 ft west of East Valley Road. North and south of Pine Nut Creek, depth to water decreases from over 100 ft west of the ridge to about 50–60 ft east of the Allerman Canal. West of the Allerman Canal, depth to water decreases from almost 50 ft to as little as 10 ft along the western model boundary.

Water-level altitudes measured in December 2000 are contoured to show the configuration of the water table and determine the directions of ground-water flow in the study area (fig. 4). Ground water moves in a direction perpendicular to the contours of water-level altitude.The water-table gradient may be calculated from the vertical change in altitude, divided by the horizontal distance over which the change takes place. The water-table gradient dips toward the west near the base of the ridge of Tertiary-age sediments at a gradient of 0.04. Between the ridge and the Allerman Canal, the gradient is much flatter, about 0.002, and north of Pine Nut Creek the gradient dips toward the north. West of the Allerman Canal, the gradient is about 0.03 dipping toward the west, decreasing over a small distance to about 0.05 on the floor of Carson Valley.

The water-table configuration indicates that infiltration from the Allerman Canal and reservoir is important in controlling the rate and direction of ground-water flow in the study area. Infiltration from the canal and reservoir has created a water-table mound beneath them that decreases the gradient immediately east of the canal, and increases the gradient immediately west of the canal. The mound north of Pine Nut Creek causes ground water to flow toward the northern end of the reservoir and has created a trough east of the canal (fig. 4). The trough indicates that ground-water flow through the ridge from the east is relatively small north of Pine Nut Creek. South of Pine Nut Creek, relatively high water levels probably are maintained by the mound beneath the Allerman Canal and possibly by greater rates of recharge from the southeast. High-altitude areas of the Pine Nut Mountains are more closely adjacent to the study area southeast of Pine Nut Creek, whereas north of Pine Nut Creek, high-altitude areas of the Pine Nut Mountains are separated from the study area by Fish Spring Flat (fig. 2).



EXPLANATION

Area of model

4770 — — — **Water-level altitude contour** In feet above sea level, interval variable. Dashed where inferred

● 10* **Well** Number is depth to water, in feet below land surface. Asterisk indicates location of well measured for hydrograph in figure 7

Infiltration site

Figure 4. Area of model, location of wells including depth to water, and water-level altitude, December 2000.

Water levels in wells near Pine Nut Creek declined over the period of measurement, with greater declines generally in wells nearest to the creek (wells 3, 6, 7, and 8; figs. 5*A* and *B*). Early in the year 2000, water-level altitudes were higher in wells 7 and 8 than in wells 5 and 6 north of the creek and in well 9 south of the creek (fig. 5*B*). Throughout the period of measurement, water-level altitude at well 3 within the flood plain of Pine Nut Creek (fig. 3) was higher than at wells 2 and 4, north and south of the creek, respectively. The water-level declines in domestic wells (all wells except 3, 7, and 8) may have been partially in response to increased pumping rates during summer months. Water levels measured in domestic well 1, near the Allerman Canal, declined only about 3 ft, possibly because water levels were partially maintained by seepage from the canal. These water-level declines probably are caused by the dissipation of recharge from Pine Nut Creek during periods of high infiltration in the springs of 1998 and 1999.

SIMULATION OF GROUND-WATER FLOW

The numerical modeling program MODFLOW (McDonald and Harbaugh, 1988) was used to simulate ground-water flow in an area of about 13 mi^2 (fig. 6). As applied for this study, the program uses a block-centered, finite-difference method to simulate ground-water flow through porous sediments in a horizontal grid. Flow between cells in the grid is controlled by user-specified transmissivity values. Model input is in the form of individual modules describing active cells, boundary conditions, aquifer properties, recharge, streamflow, and well discharge using arrays or lists of row and column cell location. Hydraulic head is calculated from specified inflows and outflows, and flow between each model cell.

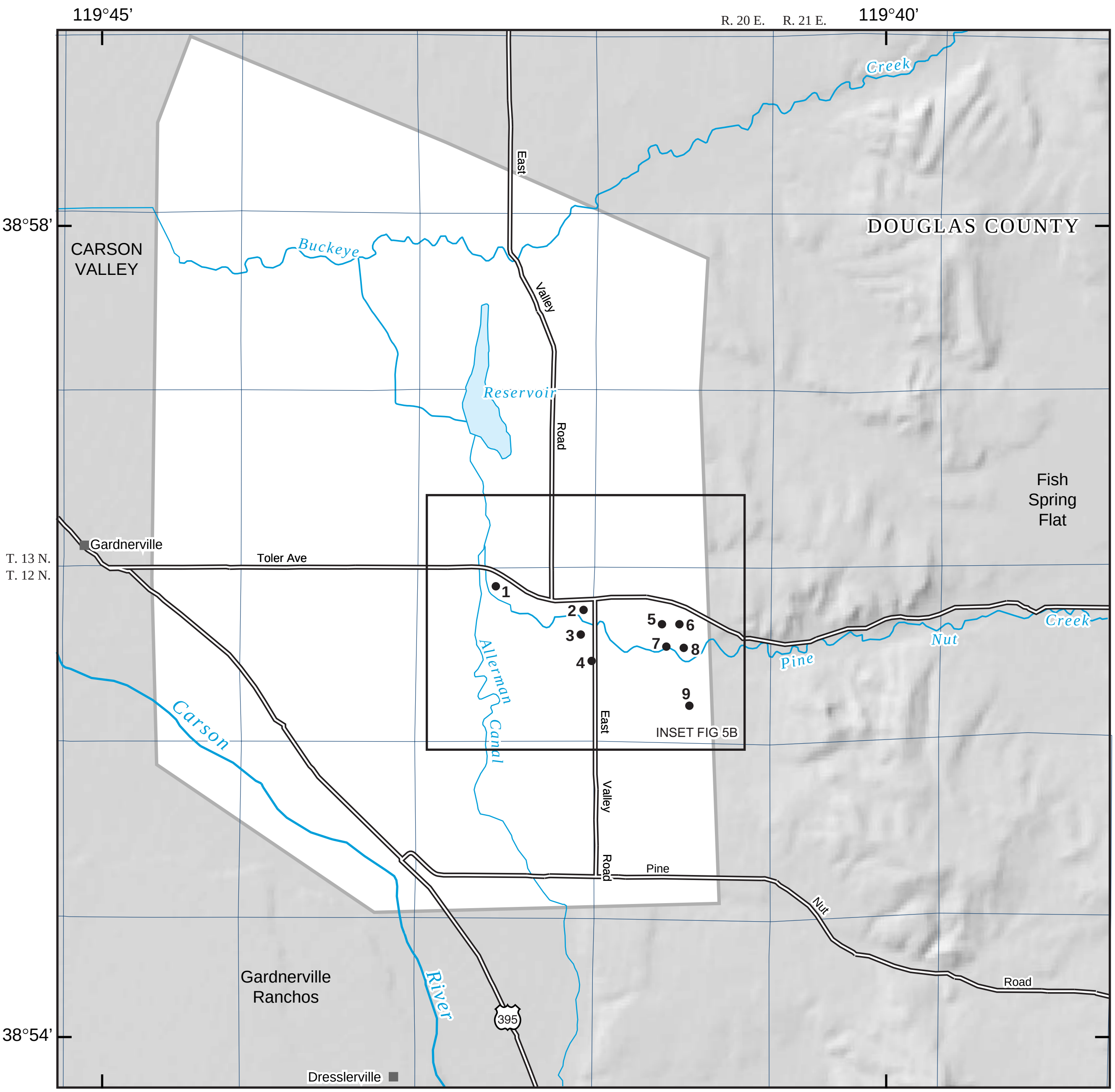
Description of Ground-Water Flow Model

The model simulated steady-state and transient ground-water flow near Pine Nut Creek as a confined aquifer system. The model grid was oriented along a north-south axis, roughly parallel to the base of the ridge separating Carson Valley from Fish Spring Flat and generally perpendicular to ground-water flow direction from the east (fig. 6). Lateral boundaries of the model were selected along the base of the ridge, at approximately right angles to water-level contours on the north and south sides of the study area, and along the western side of the study area where depth to water is shallow and relatively constant. The simulated area was discretized into 162 rows and 104 columns, having cells that were 164 ft x 164 ft (fig. 6). The cell size was selected to allow simulation of infiltration beds within the flood plain of Pine Nut Creek (fig. 3). Development within the flood plain is limited, making it a more likely area for obtaining easements to construct infiltration basins.

The alluvial-fan sediments were simulated as a single model layer because the available data do not support the added complexity of vertically discretizing the aquifer. The base of the sediments is uncertain, but, as discussed previously, are described by drillers' logs to be at least 400-ft thick near the mouth of Pine Nut Creek. Low permeability sediments of Tertiary age are present beneath this depth. Thus, the single model layer was assigned a uniform thickness of 400 ft, representing alluvial-fan sediments overlying relatively impermeable Tertiary-age sediments. No measurements of anisotropy were available and a lateral anisotropy ratio of 1:1 was used for simulation. Values of aquifer hydraulic properties were assigned to the center of each cell (defined as a node) based partially on values estimated from three slug tests.

Recharge from streamflow infiltration of Pine Nut Creek, the Allerman Canal and reservoir, and the Carson River was simulated as specified fluxes using a river module for MODFLOW (Prudic, 1989). The module calculates the exchange of flow between a surface-water body and the ground-water system using the difference in altitude between the water table in the cell and a specified streambed altitude and stage for the surface-water body, and a specified streambed conductance. Available water-level data near Pine Nut Creek and the Allerman Canal and reservoir indicate that the streambeds and stream stages are sufficiently higher than the water table so that the surface-water bodies are separated from the water table by an unsaturated zone. For this reason, streambed altitude for these surface-water bodies was specified at an arbitrary point far above the water-table altitude, along with an arbitrary stream stage of 3.28 ft. Subsurface flow through the unsaturated zone was not simulated. Available data near the Carson River do not clearly indicate whether the river is disconnected from the water table. Therefore, streambed altitude for the Carson River was specified to be equal to land surface altitude as determined from 1:24,000 scale topographic maps, along with an arbitrary stream stage of 3.28 ft.

A



EXPLANATION

Area of model

1 ● **Well** Well location and number

Figure 5. (A) Locations of nine selected wells near Pine Nut Creek where water levels were measured from August 1999 through April 2001, and **(B)** water-level fluctuations in nine wells measured from August 1999 through April 2001.

B

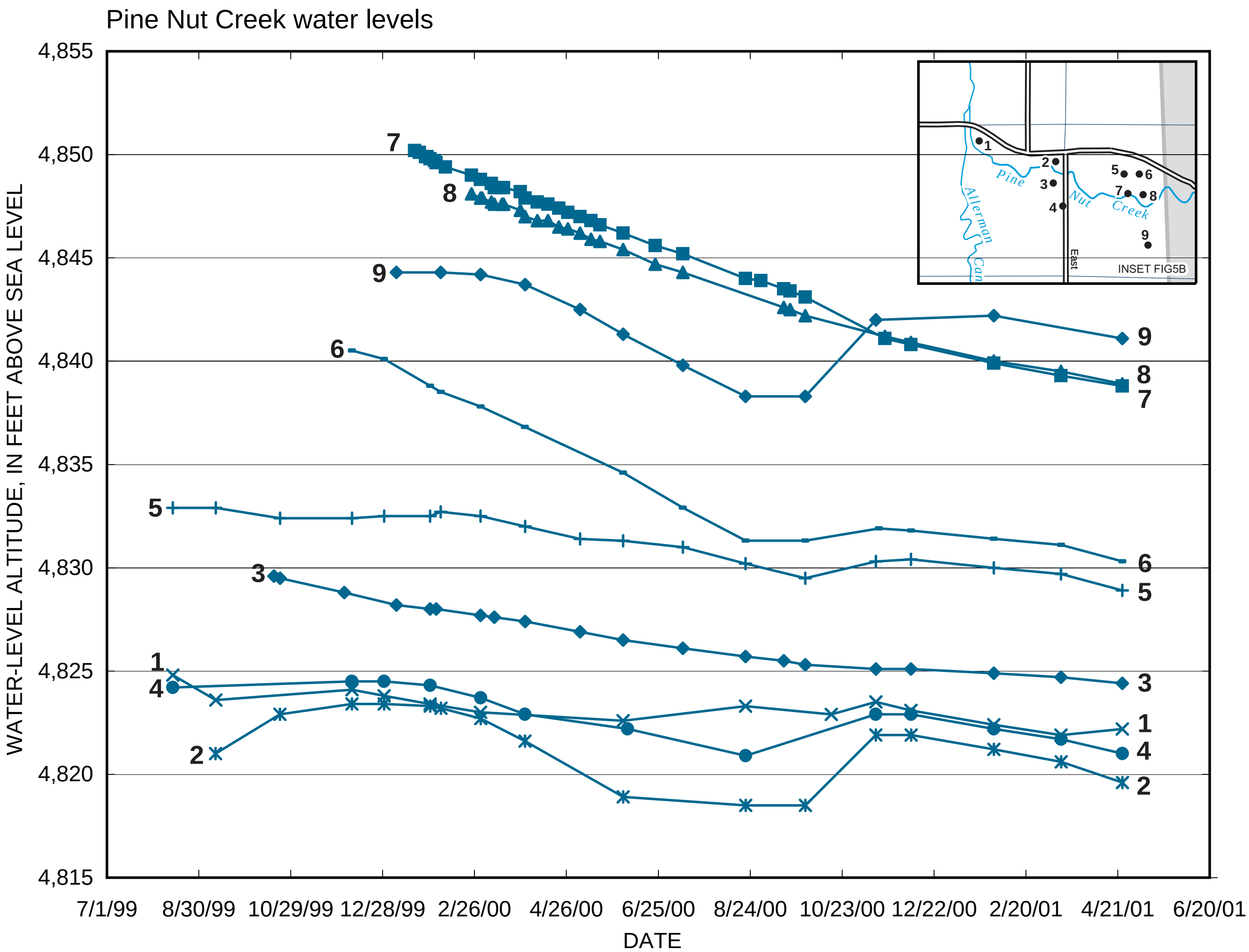
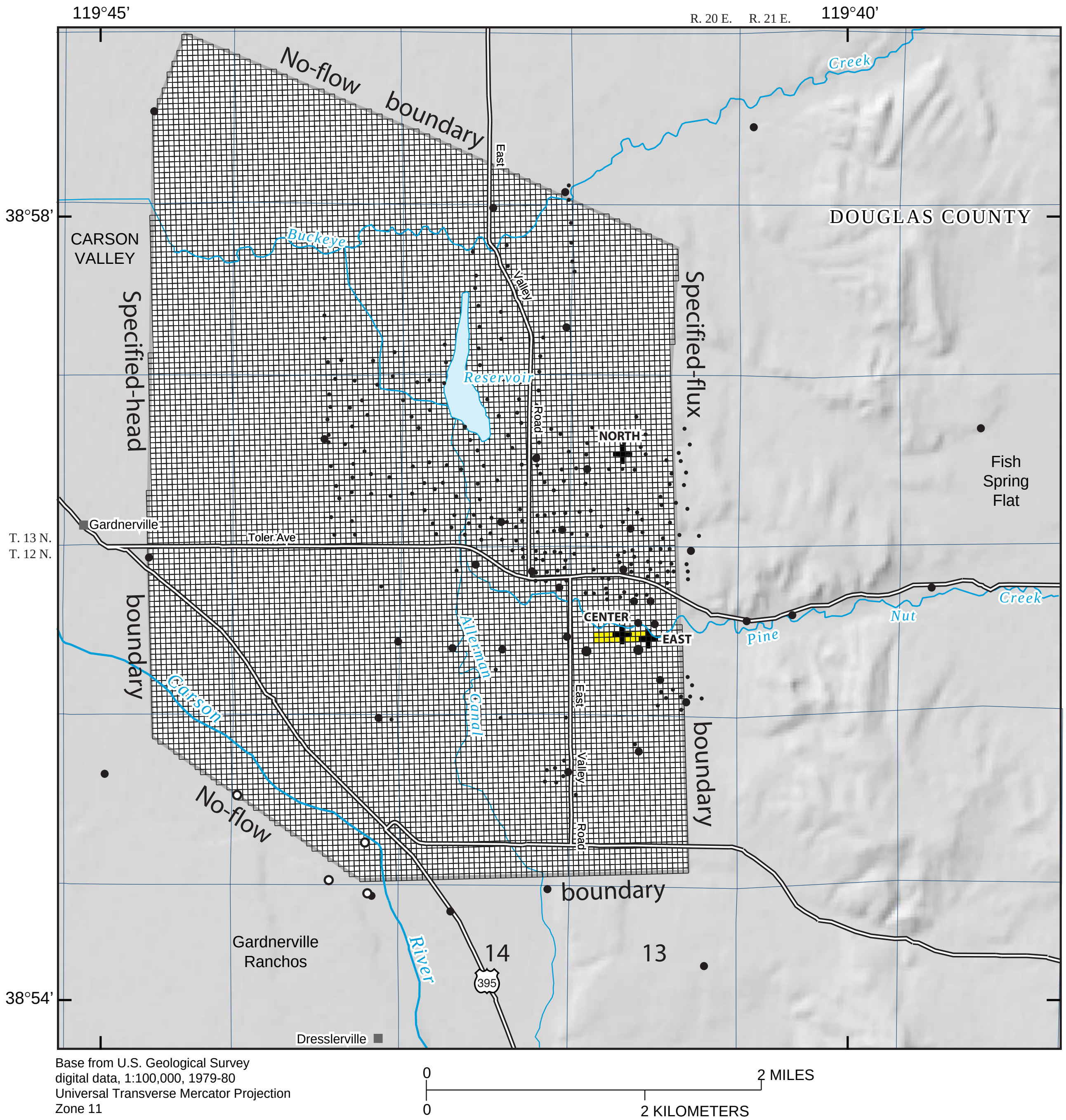


Figure 5. Continued.

Ground-water discharge by wells was simulated using the average annual volume of pumping at municipal wells in and near the modeled area as determined from records supplied by Douglas County, the Gardnerville Ranchos General Improvement District, and the Carson Valley golf course. Pumpage from domestic wells was assumed to be 1,000 gal/d per well. The maximum pumpage allowed for domestic wells by the State of Nevada is 1,800 gal/d per well, and average use reported by Maurer (1997, p. 27) in nearby areas is about 500 gal/d per well. Given the large size of lots near the Pine Nut Creek area, an average pumping rate of 1,000 gal/d per well was used. Aerial photographs taken in 1999 were used to determine the approximate location of 267 domestic wells in the modeled area, and pumping was applied to the model cell at each well location (fig. 6).

Municipal pumpage takes place at four wells near the southwestern boundary of the model (fig. 6). The southwestern boundary was selected to lie directly over the westernmost well and at the centroid of the three remaining wells to maintain the simulation of no-flow along the boundary (fig. 6). The westernmost well is pumped at an average rate of about 700 acre-ft/yr. Only 350 acre-ft/yr of pumpage was simulated because only half of the well is in the model domain. Pumpage from the remaining three wells totaled 1,300 acre-ft/yr and was simulated as a composite withdrawal from the cell at the bend in the model boundary. Only 430 acre-ft/yr of pumpage was simulated because only a third of the composite well is in the model domain. Under this scheme, conditions of no-flow are maintained along the boundary, given the assumption that symmetrical cones of depression form around the pumping wells. All pumping was simulated at constant rates throughout the simulations because data for the seasonal distribution of domestic pumping were not available.



Base from U.S. Geological Survey
digital data, 1:100,000, 1979-80
Universal Transverse Mercator Projection
Zone 11

EXPLANATION

- **Area of model**
- **Hypothetical infiltration basin**
- **Model grid** Cell size 164 feet by 164 feet
- **Well** Hypothetical withdrawal
- **Well** Municipal
- **Well** Domestic
- **Observation point**

Figure 6. Conditions at model boundaries, and locations of model grid, municipal and domestic wells, hypothetical infiltration basin and pumping wells, and three observation points within the model grid where changes in simulated water levels are calculated.

Boundary and Initial Conditions

The upper boundary of model layer 1 is the water table. However, the aquifer was simulated as a confined system and changes in the wetted thickness of the aquifer were not simulated (layer 1 had a uniform transmissivity). This was done to simplify the calibration process and because the range of water-table fluctuations typically are less than 20 ft, which is small relative to the total thickness of the alluvial aquifer (400 ft). The lower boundary is simulated as a no-flow boundary because, as discussed previously, poorly permeable Tertiary-age sediments likely underlie the alluvial aquifer beneath about 400 ft. The eastern boundary of the model is defined as a specified-flux boundary, the north and south boundaries are defined as no-flow boundaries because water flows parallel to them, and the western boundary is defined as a specified-head boundary (fig. 6). Along the southern model boundary, low hills present in sections 13 and 14 (T. 12 N., R. 20 E., fig. 6) probably are underlain by poorly permeable Tertiary-age sediments at shallow depths. This also indicates that the southern boundary is a no-flow boundary.

Inflow across the eastern boundary was divided into three parts: (1) flow through the ridge of Tertiary-age sediments north of Pine Nut Creek, (2) flow through the canyon beneath the channel of Pine Nut Creek, and (3) flow through the ridge south of Pine Nut Creek. Water levels discussed previously indicate that the modeled area adjacent to the ridge north of Pine Nut Creek could receive less inflow through the ridge than the area south of the creek. Ground-water flow through the ridge takes place through fine-grained Tertiary-age sediments that have a low hydraulic conductivity, whereas flow through the canyon is through stream-channel deposits that could have a hydraulic conductivity similar to or greater than those of the alluvial fan deposits.

The distribution of hydraulic head for the western boundary was determined by linear extrapolation between water levels measured in wells near the northwest and southwest corners of the model (fig. 4). Along this boundary, depth to water generally is less than 10 ft, and water levels measured in the well near the southwestern boundary from the mid-1970’s through 2000 show seasonal and annual fluctuations of 3 to 5 ft, but for most of the time period have averaged about 7 ft below land surface (fig. 7). In recent years, a nearby irrigation ditch has been replaced by a pipe, probably resulting in reduced infiltration and recharge, and declining water levels from about 1997 to 2000. Water levels have changed very little over a 30-year period along the western boundary which indicates that a constant, specified-head boundary is reasonable.

Initial water levels were estimated by simulating the first stress period in a transient model as steady state (the storage coefficient for each model cell was set to zero), representing average annual conditions. A single initial water-level distribution was not used during calibration because changes in recharge estimates changed the steady-state water levels. Steady-state recharge rates for the reservoir and Pine Nut Creek were specified at 50 and 17 percent, respectively, of their periodic rates determined from initial transient simulations. These percentages were used because the reservoir is active each year for approximately 6 months, which is one-half, or 50 percent, of an annual stress period, and because recharge from Pine Nut Creek was simulated to occur during a 6-month period once every 3 years, which is one-sixth, or 17 percent, of an annual stress period.

Model Calibration

Calibration is the attempt to reduce the difference between model results and measured data by adjusting model input. Calibration was accomplished in this study by adjusting input values of recharge until an acceptable calibration criterion was achieved. The “goodness” or improvement of the calibration generally is based on the differences between simulated and measured ground-water levels and stream discharges. Simulated water levels and discharges from a calibrated, deterministic ground-water model commonly depart from measured water levels and discharges, even after a diligent calibration effort. The discrepancy between model results and measurements (model error) commonly is the cumulative result of simplification of the conceptual model, grid scale, and the difficulty in obtaining sufficient measurements to account for all spatial variation in hydraulic properties and recharge throughout the model area.

The ground-water flow model was calibrated to 190 water-level measurements in 27 wells. The data contains a synoptic water-level survey that was measured in December 2000 (figs. 4 and 8), and periodic water levels measured in nine wells near Pine Nut Creek from August 1999 through April 2001 (figs. 5*B* and 8).

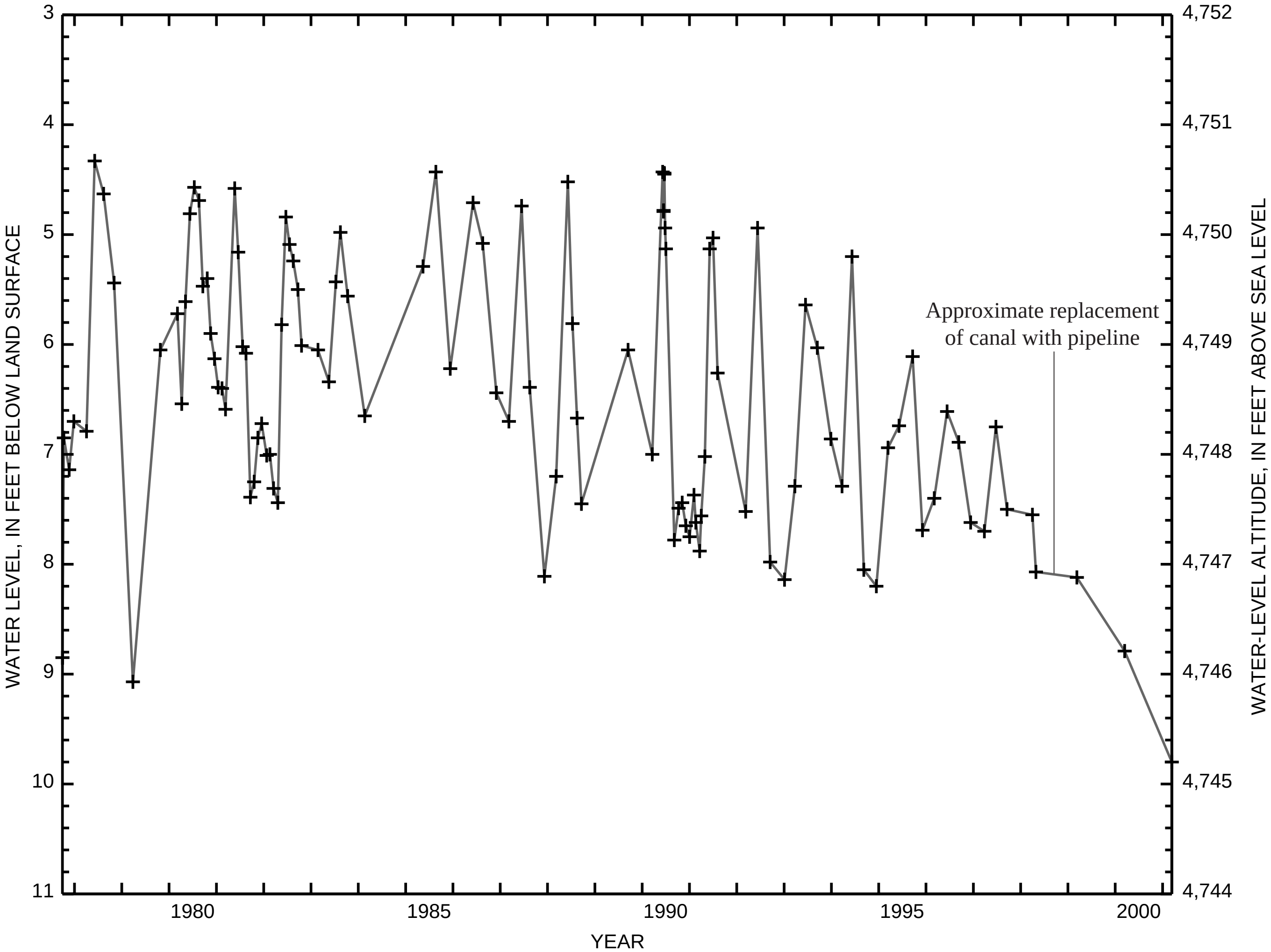


Figure 7. Water-level fluctuations from 1977 through 2000 near western boundary of the model. See figure 4 for well location.

Water levels measured during the synoptic survey represented conditions about 1.5 years after flow of Pine Nut Creek in two consecutive years, 1998 and 1999. The periodic water-level measurements represent conditions near Pine Nut Creek from 0.3 to 1.8 years after flow in the creek had ceased.

Calibration was constrained by assuming the transmissivity of the alluvial aquifer was known from slug tests completed in wells installed for the study. Transmissivity is equal to the hydraulic conductivity of aquifer materials, multiplied by the aquifer thickness. Values of hydraulic conductivity obtained from slug tests of the three wells installed for this study were about 1.8 ft/d at well 3, 1.7 ft/d at well 7, and 3.0 ft/d at well 8 (fig. 5*A*). Using the uniform thickness of 400 ft for the model, transmissivity near the channel of Pine Nut Creek may range from about 700 to 1,200 ft^2/d. Estimates of transmissivity made from the specific capacity of wells in the modeled area (Prudic, 1991, p. 11) range from about 10 to over 1,400 ft^2/d and average about 700 ft^2/d, although a large uncertainty is associated with these estimates. A transmissivity of 700 ft^2/d was assumed to be representative of most aquifer materials within the model boundary, and was assigned uniformly to cells throughout the model grid. A uniform transmissivity was assigned because available data were not sufficient to determine the spatial distribution of transmissivity and the associated uncertainty was thought to be less than the uncertainty of recharge estimates within the study area.

Calibration improvement was determined by decreases in sum-of-squares (SS) error, which is defined by

$$SS = \sum_{k=1}^{nwl} [\hat{h}_k - h_k]^2 \quad , \qquad (1)$$

where

$\hat{h}_k$ is the k^th simulated water level, in feet;

h_k is the k^th measured water level, in feet; and

nwl is the number of water-level comparisons.

Although the SS error serves as the objective function, root-mean-square (RMS) error is reported instead, because RMS error is more directly comparable to actual values and serves as a composite of the average and the standard deviation of a set. RMS error is related to the SS error by

$$RMS = \sqrt{\frac{SS}{nwl}} \ . \qquad (2)$$

Because measured water levels rarely coincide with the center of a cell, simulated water levels were interpolated laterally to points of measurement from the centers of surrounding cells. Simulated water levels were interpolated bilinearly because they were assumed to be part of a continuous distribution.

Model calibration was facilitated by a parameter estimation program (Halford, 1992). The parameter estimation process is initialized by using the model to establish the initial differences between simulated and measured water levels. These differences, or residuals, then are minimized by the parameter estimation program. To implement parameter estimation, the sensitivity coefficients (the derivatives of simulated water-level change with respect to changes in a particular parameter value) are calculated by the influence coefficient method using the initial model results (Yeh, 1986). Each parameter is changed a small amount and MODFLOW is used to compute new water levels for each perturbed parameter. The current arrays of sensitivity coefficients and residuals are used by a quasi-Newton procedure (Gill and others, 1981, p. 137) to compute the optimum parameter value for improving the model. The model is updated to reflect the latest parameter estimates and a new set of residuals is calculated. The entire process of changing a parameter value in the model, calculating new residuals, and computing a new value for the parameter is continued iteratively until model error or model-error change is reduced to a specified level or until a specified number of iterations are made.

Model calibration began with transient simulations to determine approximate rates of recharge from surface-water bodies and inflow through the eastern model boundary. Initial water levels for the transient model were estimated by simulating the first stress period as steady state followed by a 17-year transient simulation with uniform stress periods of 6 months. The 6-month stress periods were used to simulate time-varying recharge from the reservoir and Pine Nut Creek during spring and summer months. Infiltration from Pine Nut Creek occurs over periods of about 3 months, but finer temporal discretization was not warranted. The timing of recharge to the water table from infiltration of Pine Nut Creek is not well known, but probably is delayed and prolonged over a period longer than 3 months as it moves through the unsaturated zone. Recharge from the reservoir is approximated by the 6-month stress periods. Recharge from the Allerman Canal and the Carson River was simulated to be constant with time.

The transient model simulated four 3-year cycles to mitigate the effects of errors in the initial water-level distribution. During each 3-year cycle, recharge from Pine Nut Creek was specified in the spring–summer stress period of the third year. This represents an average recurrence interval of 3 years for flow of Pine Nut Creek across the alluvial fan (fig. 8). This scheme is considered to represent an average flow cycle for Pine Nut Creek, not a detailed simulation of its actual flow history, which is not well known. During a fifth 3-year cycle, recharge from Pine Nut Creek was specified in the last 2 consecutive years, representing flow conditions in 1998 and 1999 prior to available water-level measurements in the area and the calibration period. Following the fifth 3-year cycle, two additional years were simulated with no recharge from Pine Nut Creek, representing flow conditions in 2000 and 2001.

Initially, seven parameters were estimated during model calibration: recharge from (1) Pine Nut Creek, (2) the Allerman Canal, (3) the reservoir, and (4) Carson River; inflow through the eastern boundary (5) north and (6) south of Pine Nut Creek, and (7) specific yield (table 1). To minimize assumptions in estimating variable flow rates, model flows were kept constant in each stress period for inflow through the eastern boundary, well pumpage, and recharge from the Carson River and the Allerman Canal. Recharge

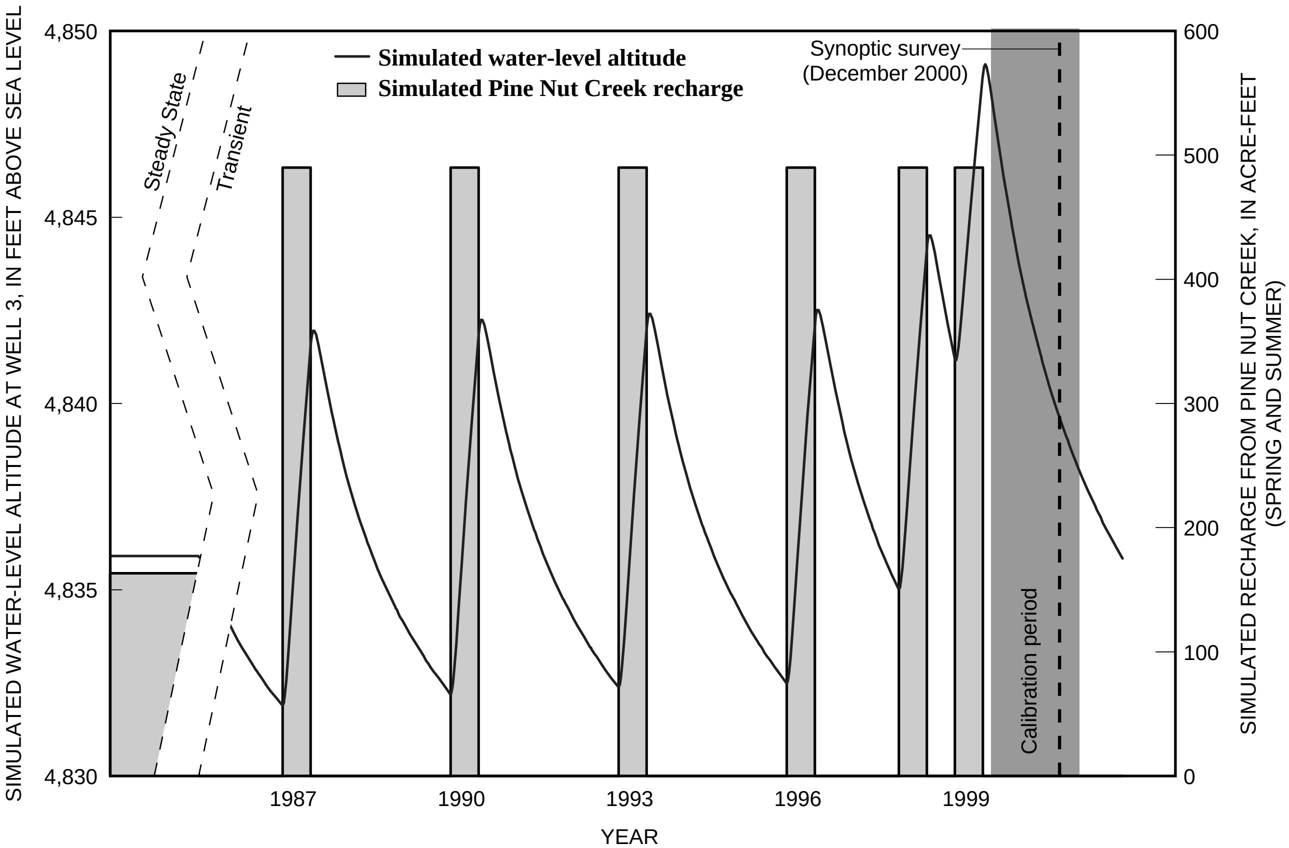


Figure 8. Timing of simulated recharge and simulated water-level altitude near Pine Nut Creek, model calibration period, and synoptic water-level measurements.

from the reservoir was simulated in each stress period representing spring and summer months, whereas recharge from Pine Nut Creek was varied as shown in figure 8.

An estimate of the volume of streamflow infiltration from Pine Nut Creek was used as a limit to constrain results of the parameter estimation. From indirect measurements of Pine Nut Creek flow in 1999, discussed previously, flow lost to infiltration across the fan was about 3 ft^3/s. If flow lasted for about 3 months, as reported by local residents, recharge from infiltration of Pine Nut Creek was about 500 acre-ft. In extremely wet years, such as 1986 and 1995, flow of Pine Nut Creek covered a large part of its flood plain and greater volumes of water probably were recharged. Thus, the average recharge from Pine Nut Creek each time it flows across the fan could be somewhat greater than 500 acre-ft/yr (table 1). Initial parameter estimation simulations showed that the volume of 500 acre-ft/yr provided reasonable fits to measured water levels. During subsequent simulations, this volume was simulated at a fixed rate to allow estimation of the other six parameters.

An estimate of the volume of streamflow infiltration from the Allerman Canal was used as a limit to constrain results of parameter estimation. Measurements of flow lost to infiltration from the Allerman Canal showed that losses were less than 0.3 $ft^3/s/mi$ during winter months. The reach of the Allerman Canal within the model boundary is about 4.5 mi, resulting in a maximum loss over the 6-month non-irrigation period of about 500 acre-ft. Because infiltration losses probably are greater during the irrigation season when the stage of the canal is 3–4 ft higher, the annual flow loss from the canal could be somewhat greater than 1,000 acre-ft (table 1). The value of 1,000 acre-ft/yr for recharge from the Allerman Canal was used as a constraint for annual flow loss from the canal simulated by the model.

Table 1. Calibrated and alternative values of parameters estimated for the model. Values are averages for the simulation and include periods of flow and no-flow for Pine Nut Creek and the reservoir.

[Abbreviations: na, not available or applicable; ft, foot; ft^2/d, square foot per day; acre-ft/yr, acre-foot per year; acre-ft/event, acre-foot per event; RMS, root-mean-square error. Symbol: >, greater than]

Parameter	Estimated flow or value	Calibrated model[1]	Transmissivity halved (350 ft^2/d)	Transmissivity doubled (1,400 ft^2/d)	Five-year recurrence interval for Pine Nut Creek flow
Pine Nut Creek recharge steady-state, acre-ft/yr	na	170	110	170	130
Pine Nut Creek recharge transient, acre-ft/event [2]	> 500	490	320	500	800
Reservoir recharge steady-state, acre-ft/yr	na	30	20	70	30
Reservoir recharge transient, acre-ft/event [1]	na	60	20	70	40
Allerman Canal recharge, acre-ft/yr	>1,000	1300	890	2100	1300
Carson River recharge, acre-ft/yr	na	120	360	30	130
Eastern boundary inflow north part, acre-ft/yr	500 (combined north and south parts, and beneath Pine Nut Creek channel)	50	10	50	20
Eastern boundary inflow south part, acre-ft/yr		130	80	190	90
Eastern boundary inflow beneath Pine Nut Creek channel [3]		30	30	30	30
Specific yield	0.15	0.13	0.09	0.12	0.21
RMS, ft	na	2.7	2.5	3.8	2.3

[1] Calibrated model simulation used a transmissivity of 700 ft^2/d.
[2] An event is either flow of Pine Nut Creek or filling of the reservoir.
[3] Inflow beneath Pine Nut Creek channel is a fixed value and not estimated.

Approximations for the volume of ground-water inflow through the eastern boundary of the model can be made using Darcy's Law, which states that the flow is equal to the area of flow, multiplied by the hydraulic gradient and the hydraulic conductivity of aquifer materials through which flow takes place. Using this relation and units of square feet for area, a dimensionless hydraulic gradient, and feet per day for hydraulic conductivity, results in units of cubic feet per day for the estimate of flow. The eastern boundary of the model consists of 121 cells that are 164-ft wide and 400-ft thick, having an area of about 8×10^6 ft^2. The hydraulic gradient at the eastern boundary is about 0.04. If the hydraulic conductivity of the Tertiary-age sediments forming the ridge is an order of magnitude less than that of the alluvial fan sediments, or 0.2 ft/d, the resulting flow is about 64,000 ft^3/d. This results in an annual inflow of about 500 acre-ft/yr for ground-water flow through the eastern boundary of the model.

Ground-water flow beneath the canyon of Pine Nut Creek moves through an area about 600-ft wide. Based on drillers' descriptions of wells in the canyon, relatively coarse sediments are 100-ft thick, for a total area of about 60,000 ft^2. Using a hydraulic gradient of 0.04 and a hydraulic conductivity of 1.7 ft/d results in a flow of 4,100 ft^3/d, or about 30 acre-ft/yr.

The approximation of 500 acre-ft/yr for flow through the eastern boundary was used as a constraint for simulated volumes of inflow through the boundary (table 1). For parameter estimation, the estimated flow through the channel deposits was assigned a fixed value of 30 acre-ft/yr, and the relative volumes of inflow through cells north and south of Pine Nut Creek were calculated by the parameter estimation simulations.

The specific yield of sediments in the modeled area is not well known. Published values of specific yield for alluvium of large valleys range from about 0.03 to 0.10 for clay, 0.10 to 0.25 for silt, 0.25 to 0.33 for sand, and 0.19 to 0.33 for gravel and cobbles (Davis and DeWiest, 1966, p. 394). The poorly sorted texture of the alluvial fan sediments observed during drilling at Pine Nut Creek indicates that the average value of specific yield is likely to be toward the lower end of published values. A maximum value of 0.15 was used for evaluation of estimated parameters (table 1).

For the calibrated model, water levels simulated at locations where water levels have been measured had an RMS error of 2.7 ft (table 1). Simulated water levels representative of conditions from August 1999 through April 2001 approximated the 190 measured water levels within the modeled area (fig. 9). The areal distribution of simulated and measured water levels for the synoptic survey in December 2000 compares reasonably well with measured water levels (fig. 10). Simulated water levels did not exactly reproduce the mound in water levels beneath the Allerman Canal and reservoir north of Pine Nut Creek, but reproduced the gradient for ground-water flow towards the northwest from Pine Nut Creek. Cones of depression simulated near pumping wells along the southwestern boundary of the model indicate pumping water levels are about 50 ft below static water levels (fig. 10), which is reasonable based on information supplied by drillers' logs for the wells. Simulated water levels representative of conditions from August 1999 through April 2001 closely followed the generally declining water levels measured in nine wells near Pine Nut Creek (fig. 11).

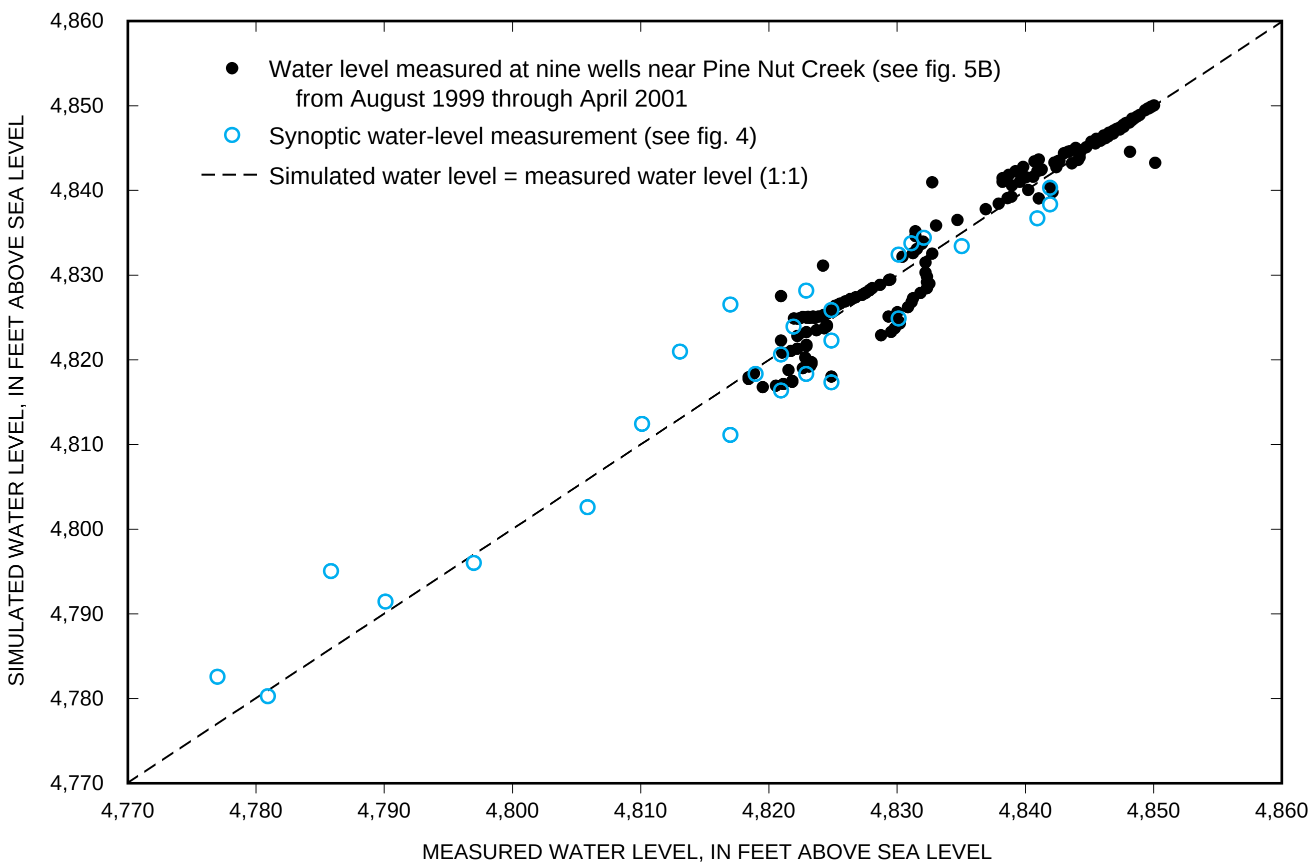
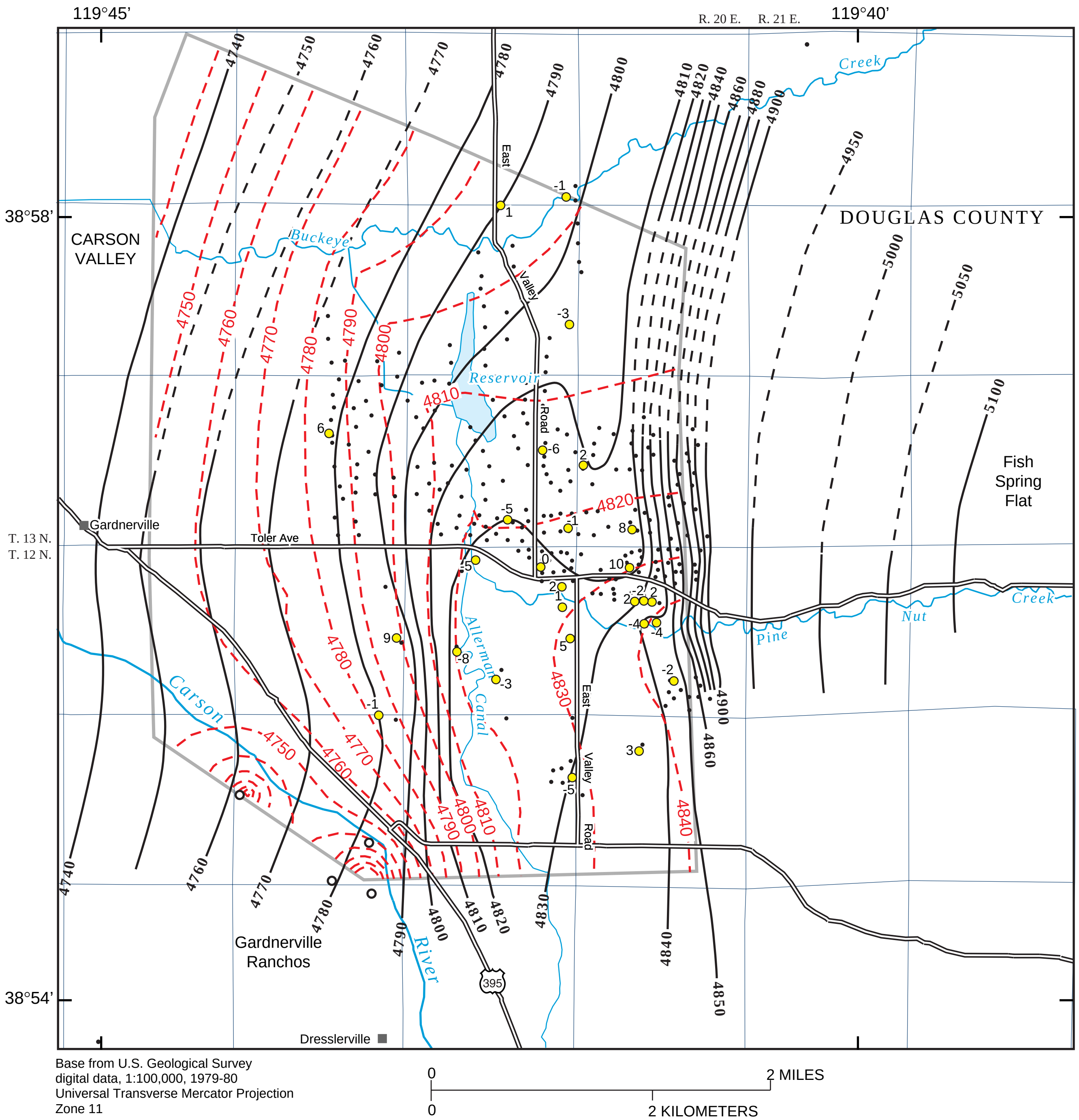


Figure 9. Comparison of simulated and measured water-level altitude, August 1999 through April 2001.



EXPLANATION

Area of model

4900 — **Contour of measured water-level altitude** Interval variable, dashed where inferred

4850 – – **Contour of simulated water-level altitude**

3 ● **Well** Number is difference, in feet, of simulated minus measured water-level altitude, December 2000

○ **Well** Municipal

• **Well** Domestic

Figure 10. Comparison of simulated and measured water-level altitude contours, and difference of simulated minus measured water-level altitude at selected wells, December 2000.

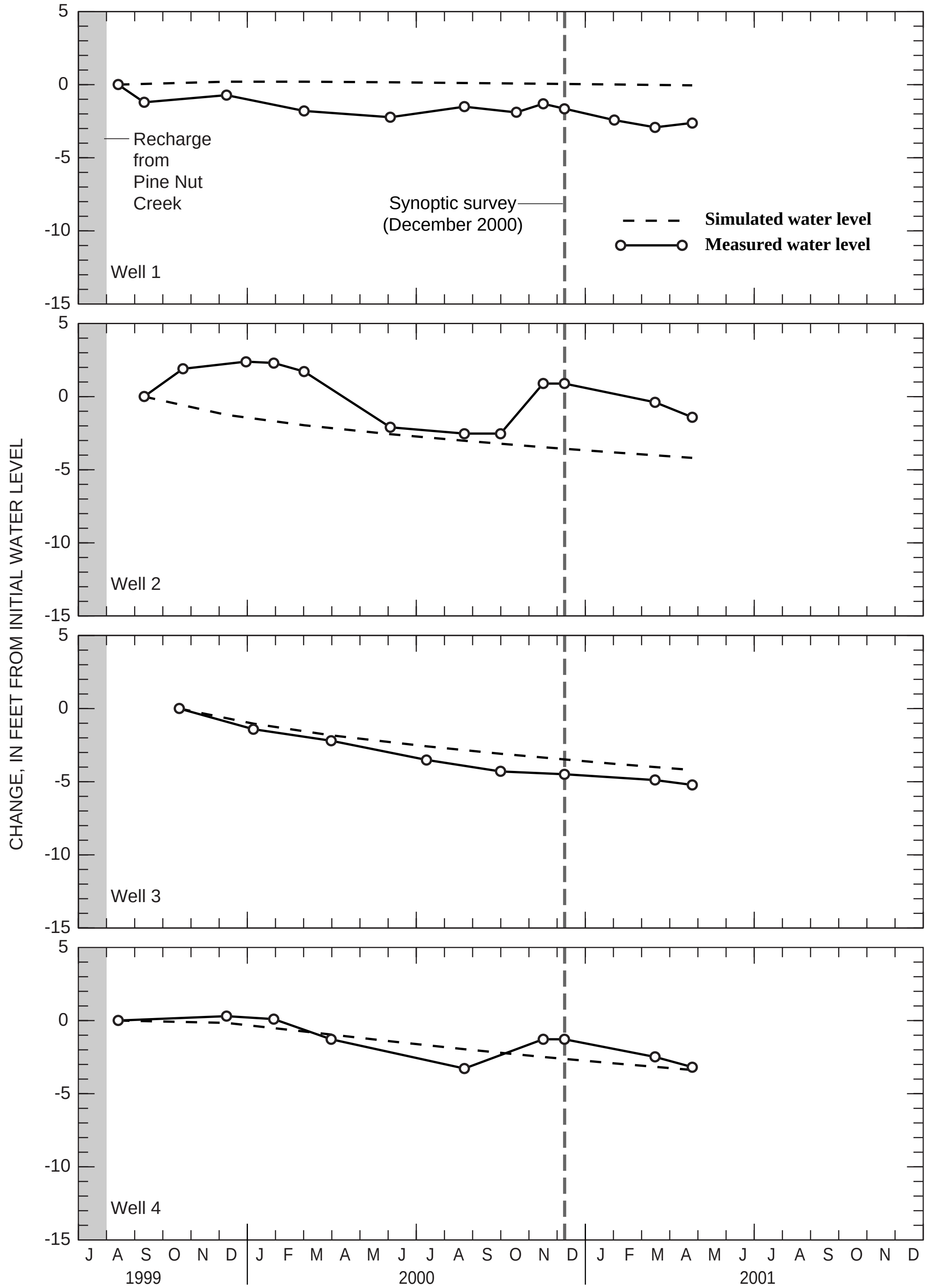


Figure 11. Comparison of simulated and measured water-level changes at wells 1–9 near Pine Nut Creek from August 1999 through April 2001. See figure 5 for well locations.

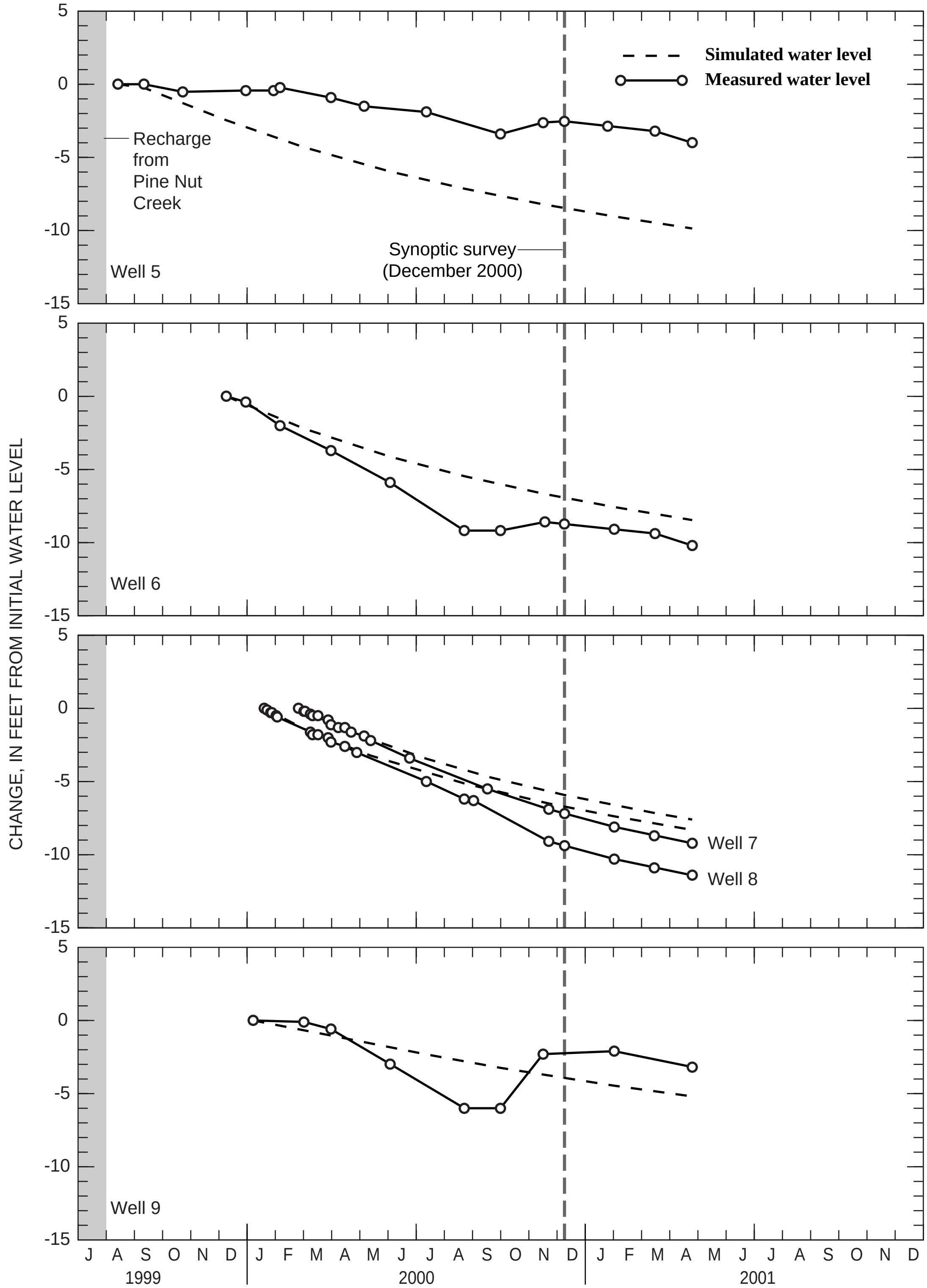


Figure 11. Continued.

Calibrated Model

The calibrated model provided reasonable estimates of model parameters and a good agreement between measured and simulated water levels. Under steady-state and transient conditions, rates of inflow along the eastern boundary, inflow and outflow along the western boundary, pumpage from wells, inflow beneath the channel of Pine Nut Creek, and recharge from the Allerman Canal and the Carson River are constant values (table 2). During transient conditions, recharge from Pine Nut Creek and the reservoir are simulated during spring–summer (6-month) stress periods, with recharge from Pine Nut Creek simulated every third year.

Table 2. Water budgets for modeled area of Pine Nut Creek for steady-state and transient conditions. Transient values are for peak flow conditions after simulated flow of Pine Nut Creek every 3 years for four cycles, followed by 2 consecutive years of Pine Nut Creek flow; and for conditions at the end of the simulation after 2 years of no Pine Nut Creek flow.
[Abbreviation: acre-ft/yr, acre-foot per year. Symbol: --, no flow from source]

Steady-state conditions			Transient conditions, peak flow			Transient conditions, end of simulation		
Flow source	Inflow (acre-ft/yr)	Outflow (acre-ft/yr)	Flow source	Inflow (acre-ft/yr)	Outflow (acre-ft/yr)	Flow source	Inflow (acre-ft/yr)	Outflow (acre-ft/yr)
Eastern boundary-North part	50	--	Eastern boundary-North part	50	--	Eastern boundary-North part	50	--
Eastern boundary-South part	130	--	Eastern boundary-South part	130	--	Eastern boundary-South part	130	--
Eastern boundary-beneath channel	30	--	Eastern boundary-beneath channel	30	--	Eastern boundary-beneath channel	30	--
Eastern boundary-Total	210	--	Eastern boundary Total	210	--	Eastern boundary Total	210	--
Western boundary	10	630	Western boundary	10	630	Western boundary	10	630
Pine Nut Creek	170	--	Pine Nut Creek	1,000	--	Pine Nut Creek	--	--
Allerman Canal	1,320	--	Allerman Canal	1,320	--	Allerman Canal	1,320	--
Reservoir	30	--	Reservoir	60	--	Reservoir	--	--
Carson River	120	--	Carson River	120	--	Carson River	120	--
Wells	--	1,230	Wells	--	1,230	Wells	--	1,230
			Storage	--	860	Storage	220	20
Total, rounded	1,860	1,860	Total, rounded	2,720	2,720	Total, rounded	1,880	1,880

The largest sources of water are recharge from the Allerman Canal, 1,320 acre-ft/yr, inflow along the eastern boundary, 210 acre-ft/yr, and recharge from the Carson River, 120 acre-ft/yr. Inflow along the eastern boundary includes130 acre-ft/yr from cells south of Pine Nut Creek, 50 acre-ft/yr from cells north of the creek, and 30 acre-ft/yr from cells beneath the channel of the creek (table 2). Sources of ground-water discharge are pumping by wells, 1,230 acre-ft/yr, and outflow along the western boundary, 630 acre-ft/yr. Municipal pumping induces 10 acre-ft/yr of inflow through the southernmost part of the western boundary.

Simulated recharge from Pine Nut Creek ranges from 0 when recharge from this source is not simulated to 1,000 acre-ft/yr during peak flow (transient) conditions, and averages 170 acre-ft/yr for steady-state conditions (table 2). Similarly, recharge from the reservoir ranges from 0 to 60 acre-ft/yr, and averages 30 acre-ft/yr. During peak flow conditions, recharge from Pine Nut Creek and the reservoir causes an increase in storage, and outflow from the model domain, of 860 acre-ft/yr.

At the end of the simulation, inflow from Pine Nut Creek and the reservoir are zero, because these sources are not active during the final stress period. As recharge from Pine Nut Creek and the reservoir dissipates, water levels near these sources decline, resulting in inflow from storage of 220 acre-ft/yr, and water levels downgradient rise, resulting in outflow to storage of 20 acre-ft/yr.

The water-budget rates simulated by the model are not necessarily exact measures of flow through the modeled area. Different rates could be simulated that also might provide a balance to the water budget and an acceptable match to observed water levels. Many of the simulated parameters are not exactly known or easily measured. However, the calibrated model provides a reasonable representation of the relative distribution of inflow and outflow through the modeled area that fits the constraints of measured water levels and available estimates of parameters based on field measurements. The model also is considered a reasonable tool with which to estimate the effects of recharge from a hypothetical infiltration basin and subsequent pumping of the recharged water.

Model Sensitivity

To determine how estimates of model parameters affect simulation results, each estimated parameter was varied independently by multiplying from 0.2 to 5 times the value estimated using the calibrated model. Model sensitivity is described in terms of RMS error difference in feet, between simulated and observed water levels for simulations where one parameter was changed while all others were kept at their calibrated values (fig. 12). The same 190 water-level measurements used for calibration were used to evaluate RMS error in all sensitivity analyses.

Model error was most sensitive to overestimation of recharge from the Allerman Canal and Pine Nut Creek (fig. 12). Overestimation of recharge from the Allerman Canal and Pine Nut Creek by 5 times their calibrated values resulted in RMS errors of about 160 and 80 ft, respectively. Overestimation of recharge along the eastern boundary resulted in a maximum RMS error of about 20 ft for recharge through cells south of Pine Nut Creek and about 4 ft for recharge through cells north of Pine Nut Creek. Underestimation of specific yield by 0.2 times its calibrated value resulted in RMS errors of about 7 ft. Overestimation of recharge from the Carson River and the reservoir resulted in RMS errors of more than 9 ft and about 4 ft, respectively.

Although transmissivity was not changed during model calibration, the value used directly affects the recharge rates estimated for infiltration from surface-water bodies and inflow to the model. To evaluate the effect of using a different transmissivity value on simulated water levels, transmissivity was varied by 0.2 to 5 times the value assigned during model calibration (fig. 12). Underestimation of transmissivity by 0.2 times its calibrated value resulted in RMS errors of almost 120 ft. The effect of transmissivity on estimated parameters was investigated by estimating the parameters listed in table 1 using two alternative models, one with a uniform transmissivity of half the calibrated value, and one with a uniform transmissivity double the calibrated value (table 1). Using the alternative models, RMS was minimized by adjusting the parameters with the parameter estimation program as was done during the model calibration.

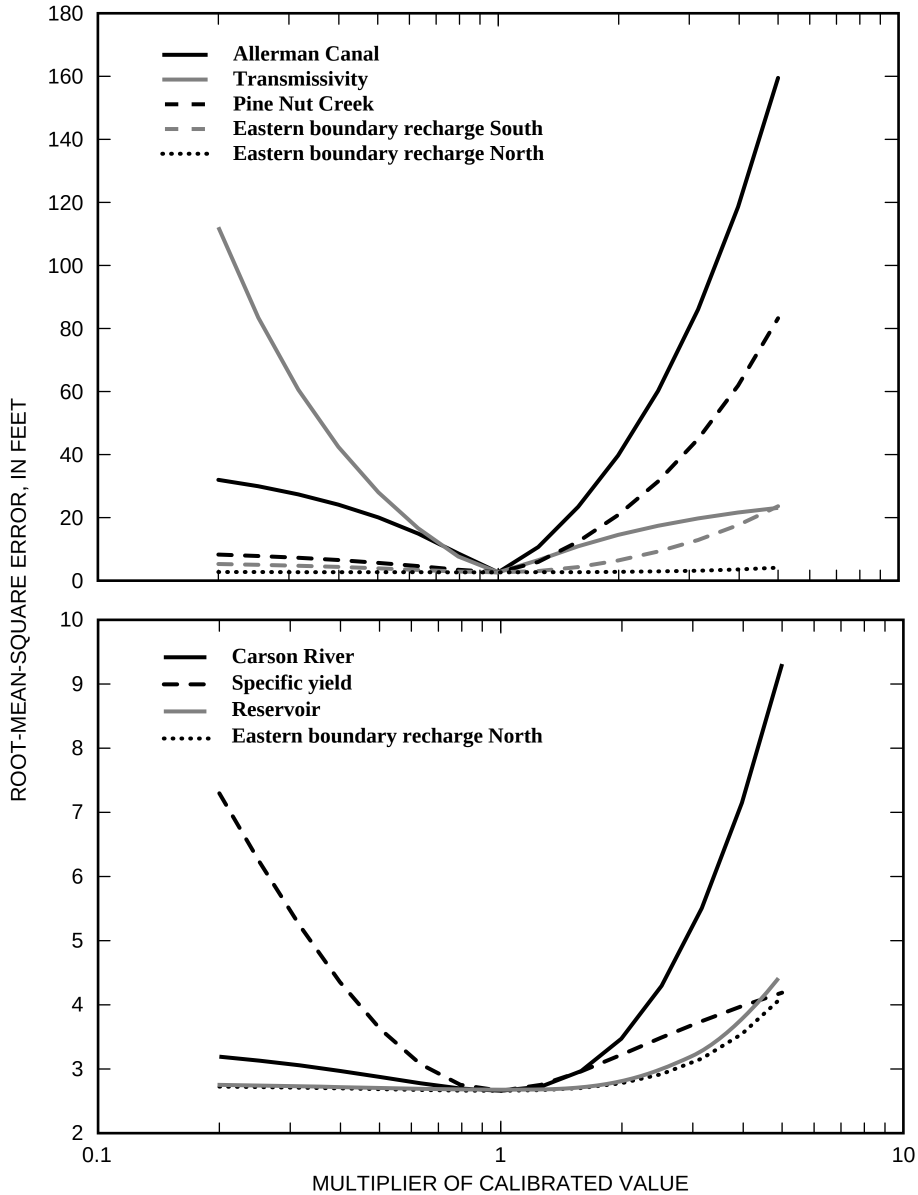


Figure 12. Model sensitivity to independent changes in calibration parameters in terms of RMS error between simulated and observed water levels.

Changing the transmissivity most greatly affected estimates of recharge from the Carson River and the Allerman Canal. Increasing transmissivity caused estimates of recharge from the river to decrease and recharge from the canal to increase, whereas decreasing transmissivity caused the opposite (table 1). Changes in transmissivity did not greatly affect estimates of recharge from the reservoir, inflow across the eastern boundary, or specific yield. These results also show that alternative combinations of parameters may provide an acceptable match to estimates of inflow and outflow, and measured water levels.

The frequency of Pine Nut Creek flow across the alluvial fan also is not well known, and does not necessarily occur at a recurrence interval of 3 years as was assumed for model calibration. To determine the sensitivity of the model by varying the recurrence interval, an alternative model was used where recharge from Pine Nut Creek was simulated at a recurrence interval of 5 years (table 1). Changing the frequency of Pine Nut Creek flow had little effect on parameter estimates except for increasing the specific yield to 0.21, which probably is an unreasonable value.

SIMULATION OF RECHARGE FROM A HYPOTHETICAL INFILTRATION BASIN

The calibrated model was used to simulate the hydrologic response of the ground-water flow system near Pine Nut Creek to recharge from a hypothetical infiltration basin located near the proposed infiltration site (fig. 6). A simulation was made where recharge through the infiltration basin was allowed to dissipate over time, followed by two simulations where the recharged water was pumped at two different rates from hypothetical wells located near the infiltration basin (fig. 6).

A base-line simulation was made using the calibrated model to provide a reference for predictive simulations of recharge through an infiltration basin and subsequent pumping. For the base-line simulation, 15 years were added to the calibration simulation, with the base-line year 0 corresponding to the end of the simulation period of the calibrated model. The base-line simulation used five 3-year cycles with recharge from Pine Nut Creek applied during the spring–summer stress period once every 3 years and recharge from the reservoir during the spring–summer stress period each year (fig. 13). This represents recharge to the ground-water flow system under natural conditions.

Figure 13 shows simulated changes in water-levels at three observation points in the modeled area; near the center of the area where the hypothetical infiltration basin will be simulated, just east of the basin, and about 5,000 ft north of the basin (observation points shown on fig. 6). In response to recharge from Pine Nut Creek, simulated water levels rose every 3 years by as much as 25 ft at the center observation point, about 15 ft at the east observation point, and did not change at the north point (figs. 6 and 13). Water levels near the creek declined after a 2.5 year period

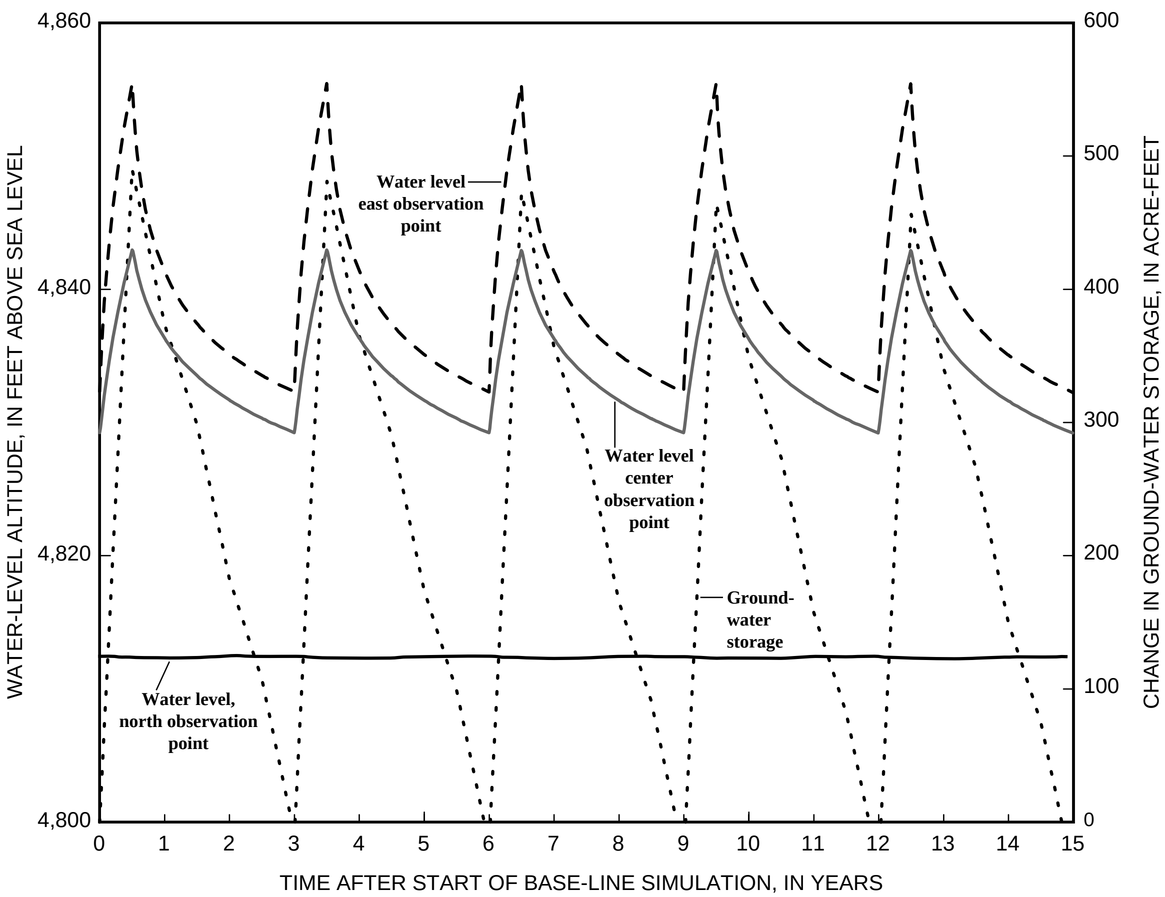


Figure 13. Simulated changes in ground-water storage and water-level altitude at three observation points from simulation of recharge from Pine Nut Creek once every three years. See figure 6 for observation point locations.

back to the level prior to recharge from Pine Nut Creek. Ground-water storage also increased every 3 years by 490 acre-ft, and decreased by about 490 acre-ft after 3 years without recharge from Pine Nut Creek (fig. 13). Results of the base-line simulation of natural conditions were subtracted from simulations applying recharge from the infiltration basin and subsequent pumping, to obtain net changes in water levels and ground-water storage.

The hypothetical infiltration basin was simulated by designating 20 model cells within the flood plain of Pine Nut Creek and south of the active stream channel, as active cells in the river module. The 20 cells cover an area of 12.4 acres. As was done for Pine Nut Creek, the streambed altitude of cells representing the infiltration basin was specified at an arbitrary point far above the water-table altitude, along with an arbitrary stream stage of 3.28 ft. By applying water through the river module, 100 percent of the water infiltrating through the basin provides instantaneous recharge to the ground-water system. This would not be the case for an active infiltration basin, where infiltrating water would take some period of time to move through the unsaturated zone to the water table, and water may be temporarily held within the unsaturated zone after infiltration. Measurements of changes in water levels and soil moisture during an actual infiltration event near the site would provide data to quantify the movement of water through the unsaturated zone.

As for the base-line simulation, predictive simulations were made by adding an additional 15 years to the calibration simulation, with the predictive year 0 corresponding to the end of the simulation period of the calibrated model. For the simulation of an operating infiltration basin, recharge was applied every spring–summer stress period for 5 consecutive years, along with cyclic recharge from Pine Nut Creek every 3 years. The total volume recharged from the basin each stress period (182.5 days) was 700 acre-ft, requiring a diversion rate of about 2 ft^3/s and an average infiltration rate of 0.3 ft/d over the 12.4 acre area of the basin. Although infiltration rates have not been determined for the flood plain of Pine Nut Creek, the value of 0.3 ft/d probably is reasonable. Infiltration rates determined for 10 active infiltration projects in Arizona averaged 1.6 ft/d (Martin and Swieczkowski, 1999, p. 208). After 5 years of recharge, a total of 3,500 acre-ft had been stored, and the resulting recharge mound was allowed to dissipate for a period of 10 years (fig. 14).

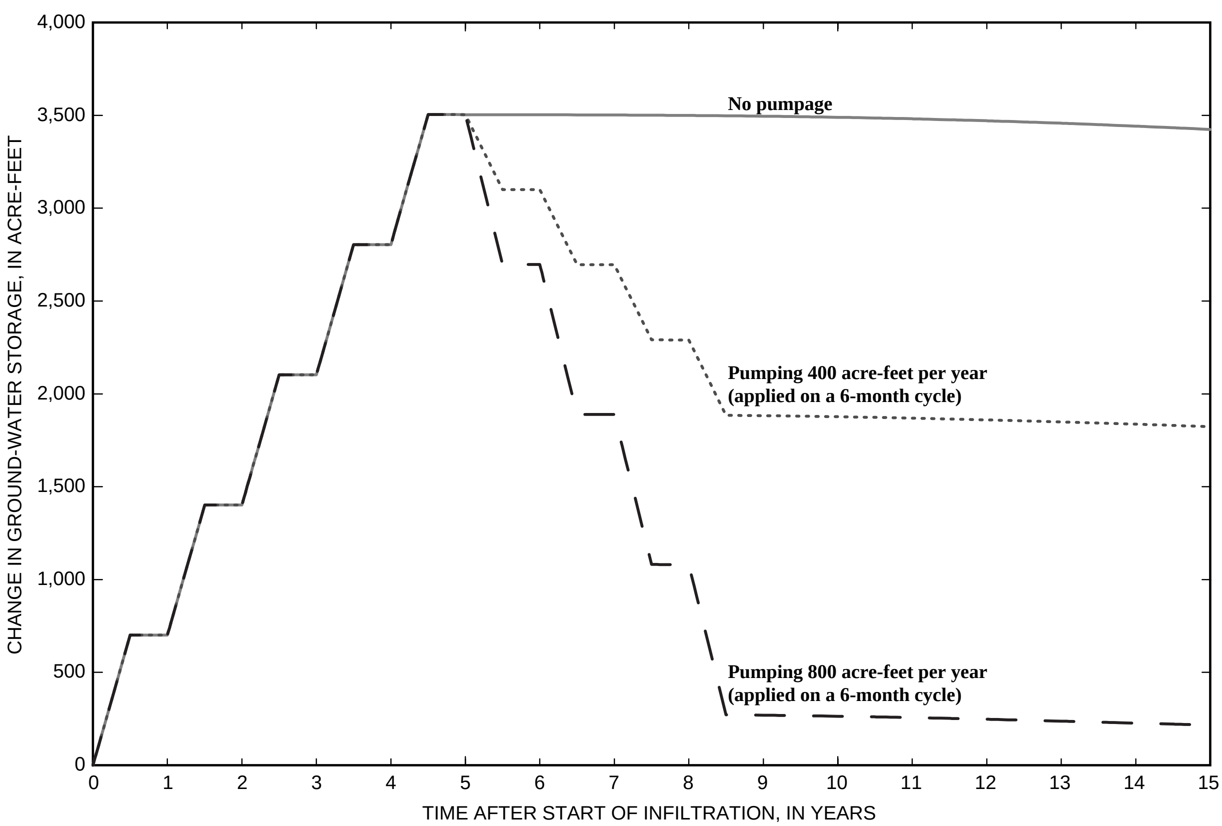


Figure 14. Simulated changes in ground-water storage from recharge from hypothetical infiltration basin and subsequent pumping at 400 and 800 acre-feet per year; pumpage applied on a 6-month cycle.

Simulated water levels rose more than 70 ft beneath the infiltration basin after 5 years of recharge (figs. 15 and 16). Water-level rises of more than 1 ft, representing the measurable extent of the recharge mound, extended about 7,000 ft north, west, and south of the infiltration basin (fig. 15). Near the center observation point, water levels rose a total of 76 ft after 5 years of recharge, whereas at the east observation point, water levels rose about 54 ft. At the north observation point, the maximum water level rise is about 6 ft, occurring about 3.5 years after the last period of recharge.

An additional simulation was made where the aquifer bottom was designated to be 400 ft below initial hydraulic heads of the baseline simulation, and unconfined conditions were specified. This was done to determine the effect of simulating the unconfined aquifer system as a confined aquifer on the calculated water-level changes. The resulting water-level rise beneath the infiltration basin was about 5 percent less than that simulated for confined conditions.

Simulated water-level rises along the southern no-flow boundary were from 1 to 3 ft. The water-level rises along the no-flow boundary, in part, violate the no-flow assumption. However, because it is likely that poorly permeable Tertiary-age sediments are present south of the boundary, the simulated water levels probably are realistic.

The increased water levels beneath the center of the infiltration basin are near land surface, indicating that, given the basin location and surface area used in the simulation, recharge of about 700 acre-ft/yr for 5 years is the maximum amount of water that could be stored. Greater amounts could probably be stored if separate infiltration basins were installed at different locations along the Pine Nut Creek alluvial fan, applying the recharge over a larger area.

After recharge ceased, water levels near the center and east observation points declined at similar rates. Water levels are about 20 ft greater than the initial level 2 years after recharge ceased, and 10 ft greater after about 7 years (fig. 16). Figure 17 shows how the recharge mound dissipates laterally with time (1, 4, 7, and 10 years) after cessation of recharge, in plan view and along a north-south cross section near the base of the alluvial fan. Ten years after cessation of recharge, water-level rises of more than 1 ft moved to the northern end of the reservoir, and about half way across the southwestern boundary of the model. The recharge mound dissipates at decreasing rates over time. A water-level rise of 1 ft moved westward towards the valley floor 660 ft from peak conditions after 1 year, and averaged 550, 440, and 330 ft/yr for periods 1–4, 4–7, and 7–10 years respectively after recharge ceased.

For the following two simulations, first one and then two hypothetical wells were pumped in spring–summer (6-month) stress periods only, representing the time when demand for municipal supply is greatest. Pumping started in the first spring–summer stress period following the last simulation of recharge from the infiltration basin and continued each spring–summer stress period, for 4 consecutive years. Pumping at the hypothetical wells was applied at a rate of 500 gal/min, a reasonably attainable rate for wells designed for municipal use, based on information from drillers' logs for existing wells near Pine Nut Creek.

In the first pumping simulation, pumping was applied only at the westernmost of the two hypothetical wells south of the infiltration basin (fig. 6), for a total volume during each 6-month stress period of about 400 acre-ft/yr. After four years of pumping, 1,600 acre-ft, or about 45 percent of the volume recharged was withdrawn (fig. 14). Water levels near the center and east observation points declined more rapidly than in the simulation without pumping (fig. 18). At the end of 4 years of pumping, water levels near the center observation point declined to about 1 ft below initial water levels prior to simulated recharge. The lateral extent of water-level declines below initial water levels is about 1,000 ft from the pumping well 4 years after cessation of recharge and at the end of pumping (see cross section, fig. 19). Three years after the end of pumping, water levels near the pumped wells had risen to above those prior to recharge as water remaining in the recharge mound dissipated laterally.

In the second pumping simulation, pumping was applied at both hypothetical wells at the rate of 500 gal/min each, in every spring–summer (6-month) stress period, for a total volume of 800 acre-ft/yr. After 4 years of pumping, 3,200 acre-ft, or about 90 percent of the volume recharged was withdrawn (fig. 14). Water levels near the center and east of the infiltration basin declined much more rapidly, to a maximum of about 30 ft below those prior to infiltration (fig. 18). However, water levels near the basin recovered quickly with declines of only 10 ft below initial levels after 1.5 years after pumping ceased. The lateral extent of water-level declines below the initial water levels is almost 4,000 ft from the pumped wells 4 years after the cessation of recharge and at the end of pumping (see cross section, fig. 20). Three years after the end of pumping, declines

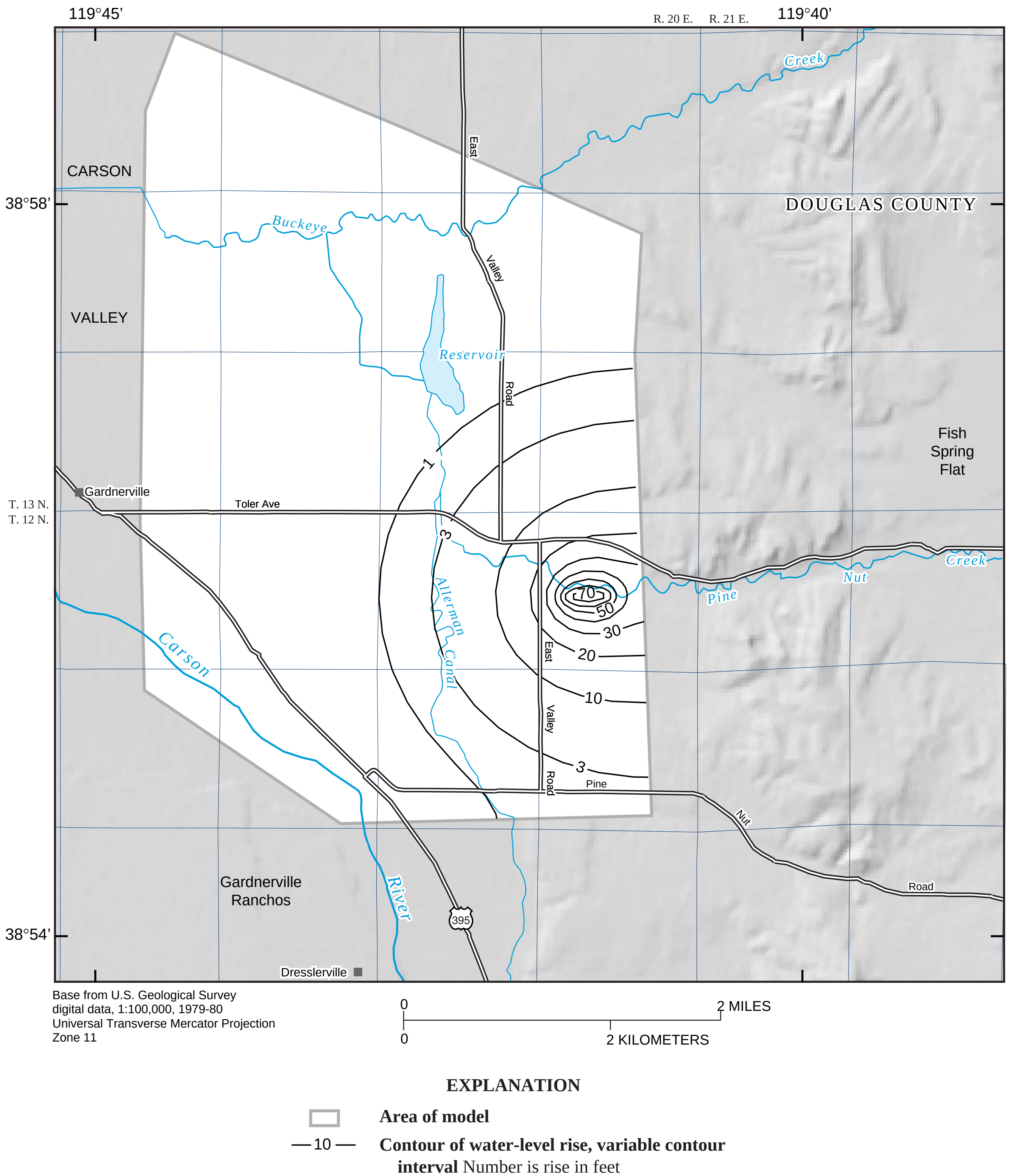


Figure 15. Peak of simulated water-level rise after five consecutive years of recharge applied to the hypothetical infiltration basin totaling 3,500 acre-feet.

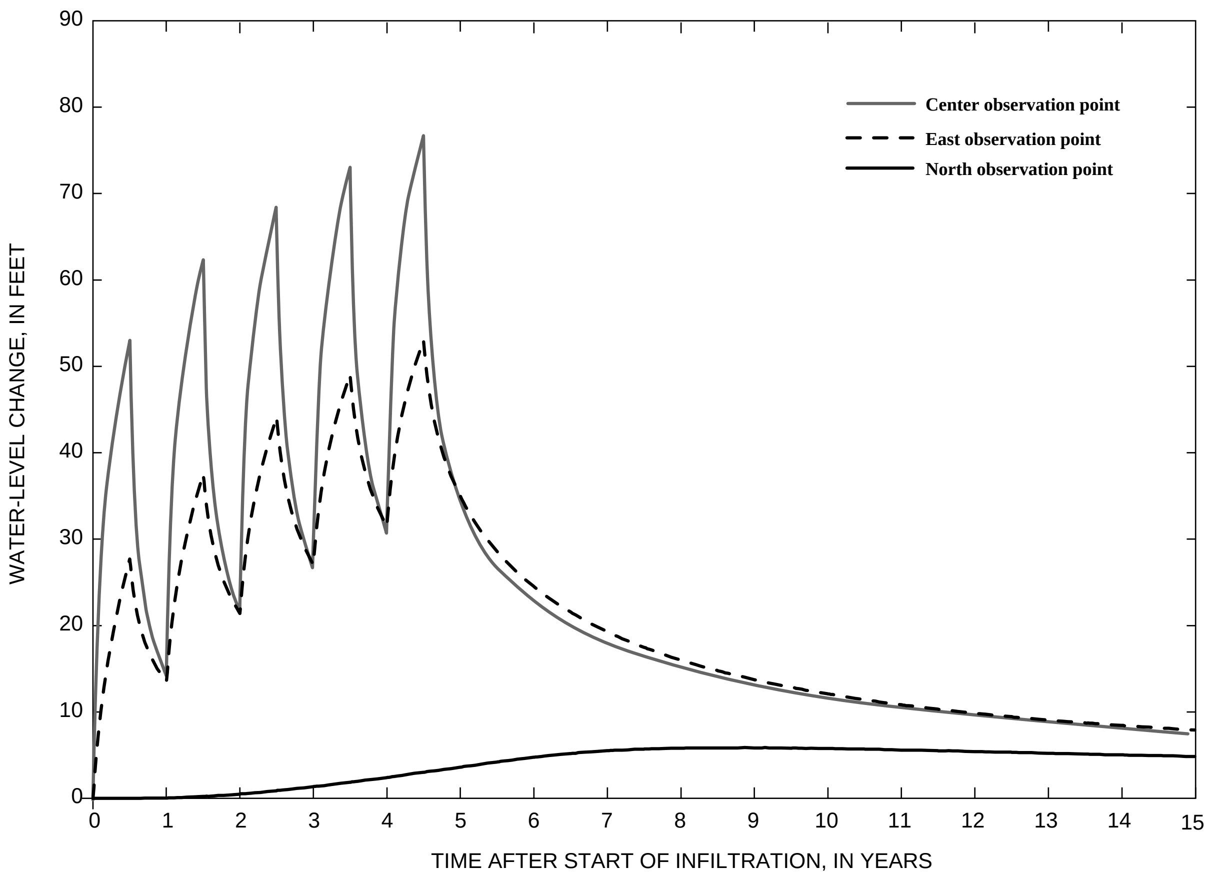


Figure 16. Simulated water-level changes at center, east, and north observation points from recharge applied to the hypothetical infiltration basin.

greater than the initial water levels extended about 7,500 ft from the pumping wells. Six years after the end of pumping, most of the recharge mound had been withdrawn or had dissipated, and water levels across the alluvial fan were within about 3 ft of their initial levels (figs. 18 and 20).

Water-level declines are a result of pumping at a rate sufficient to withdraw the majority of the water recharged through the infiltration basin. Although the declines may affect water levels in nearby domestic wells, the simulations show that water levels recovered fairly quickly after pumping ceased and would recover more quickly with continued use of the infiltration basin for recharge.

The simulations provide estimates of the volume of water that may reasonably be stored and the approximate time frame and pumping rates required for withdrawal of the majority of the recharged water near the infiltration site on the Pine Nut Creek alluvial fan. The geologic and hydrologic setting of the Pine Nut Creek alluvial fan is similar to that of alluvial fans throughout the Carson River basin and western Nevada. Although the detailed hydrologic setting and aquifer properties may be somewhat different, the simulations provide a starting point for evaluation of other potential sites for subsurface storage of water.

MODEL LIMITATIONS

The flow model addresses most questions about ground-water flow and water-level changes in the alluvial aquifer around Pine Nut Creek, but it cannot mimic the true system exactly. This model, or any other model, is limited by simplification of the surface- and ground-water systems into a conceptual model, the discretization effects, and difficulty in obtaining sufficient measurements to account for all of the spatial variation in hydraulic properties throughout the model area.

The numerical model is based on a conceptualization of the natural surface- and ground-water flow system. Inherent in the conceptualization is the assumption that all sources of flow and stresses on the natural system are represented in the numerical model and accurately known. Because measurements of water levels were made over a short time period and measurements of streamflow are very limited, it is not known how completely or how accurately the numerical model simulates the natural system. In addition, the timing of natural events, such as the recurrence of Pine Nut Creek flow across the alluvial fan, is tentative.

The accuracy with which the height of the recharge mound is simulated by the model is affected by the lack of vertical discretization in the model, the assumption that 100 percent of the water infiltrated recharges the aquifer, and simulation of the unconfined ground-water system as a confined aquifer. The lack of vertical discretization will cause underestimation of mound height because fine-grained layers that might slow downward saturated flow within the mound are not simulated. The assumption that all the infiltrated water recharges the aquifer will cause overestimation of mound height because some part of the infiltrated water may be held in the unsaturated zone and not provide recharge to the aquifer for some period of time. Simulation of the unconfined system as a confined aquifer results in simulated water levels that are about 5 percent greater than would be simulated for an unconfined aquifer. Simulated water-level rises along the southern no-flow boundary, in part, violate the no-flow assumption. However, because of the likely presence of poorly permeable Tertiary-age sediments south of the boundary, the simulated water levels probably are realistic.

Lateral discretization of the study area into a rectangular grid of cells and vertical discretization into a single layer forced an averaging of hydraulic properties. Each cell represents a homogeneous block or some volumetric average of the aquifer medium. Discretization errors occur because the permeable zones in the aquifers are sand and gravel layers ranging from 30 to 100-ft thick, deposited along stream channels that may extend laterally 50 to 100 ft. These zones are probably smaller in 1 or 2 dimensions than the model cells that are 164 ft on a side and 400-ft thick. Due to the averaging of the hydraulic properties, the model cannot simulate the local effects on flow caused by aquifer heterogeneity.

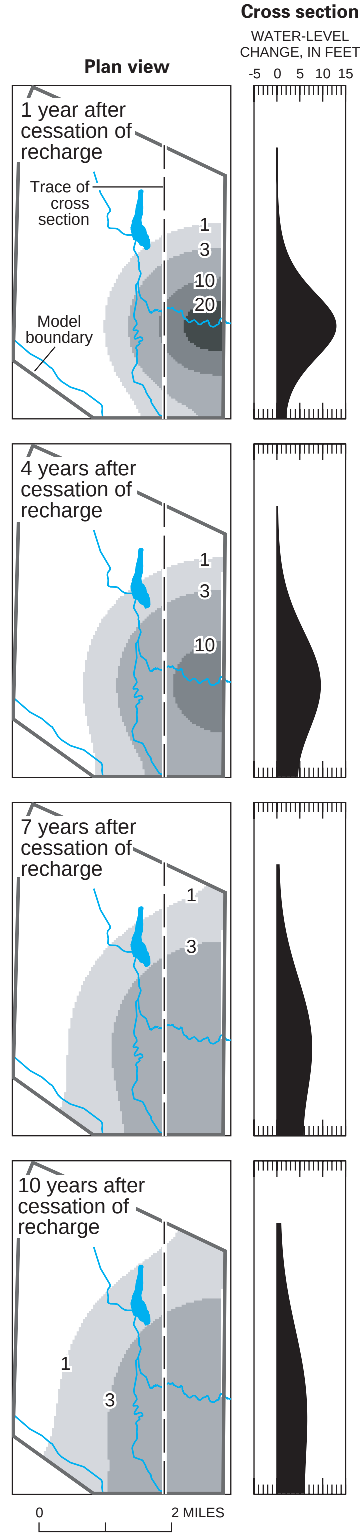


Figure 17. Plan view and cross sections along the base of the alluvial fan, showing simulated water-level changes at 1, 4, 7, and 10 years after cessation of recharge and no pumpage. Numbers in plan view indicate rise in water level in feet.

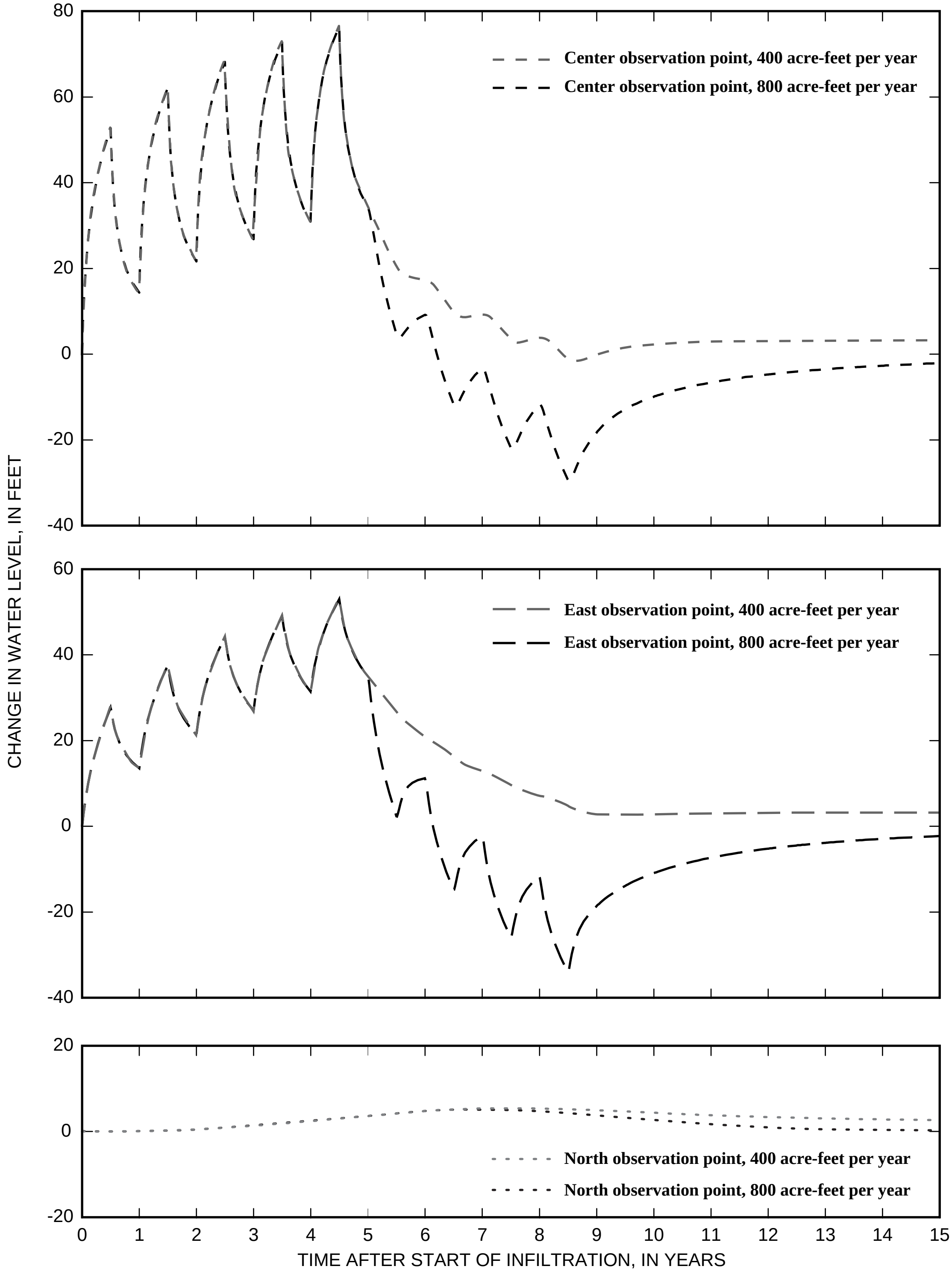


Figure 18. Simulated water-level changes at center, east, and north observation points from recharge applied to the hypothetical infiltration basin and subsequent pumping at 400 and 800 acre-feet per year.

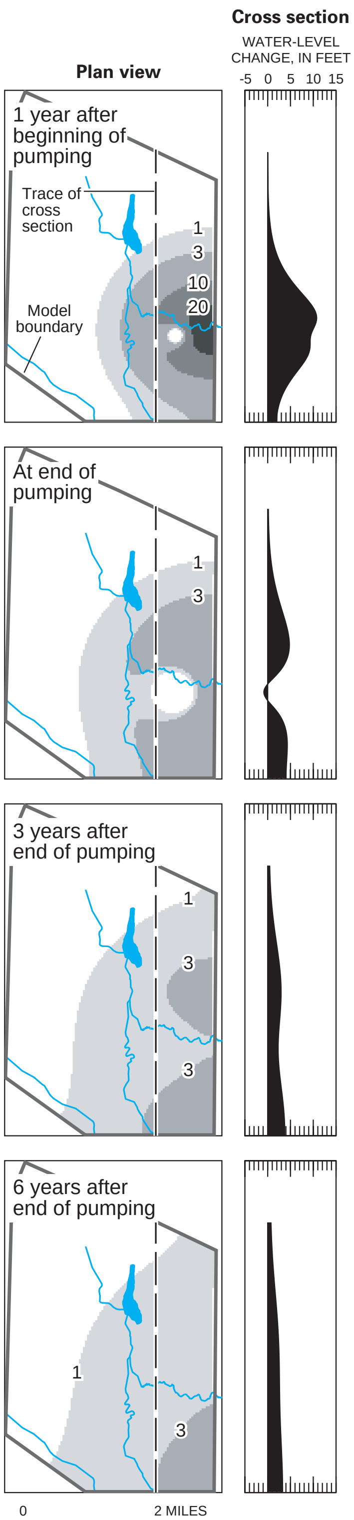


Figure 19. Plan view and north-south cross sections along the base of the alluvial fan showing simulated water-level change, after recharge of 3,500 acre-feet, 1 year after beginning of pumping, at end of pumping, and 3 years and 6 years after the end of pumping at 400 acre-feet per year. Numbers in plan view indicate rise in water level, in feet.

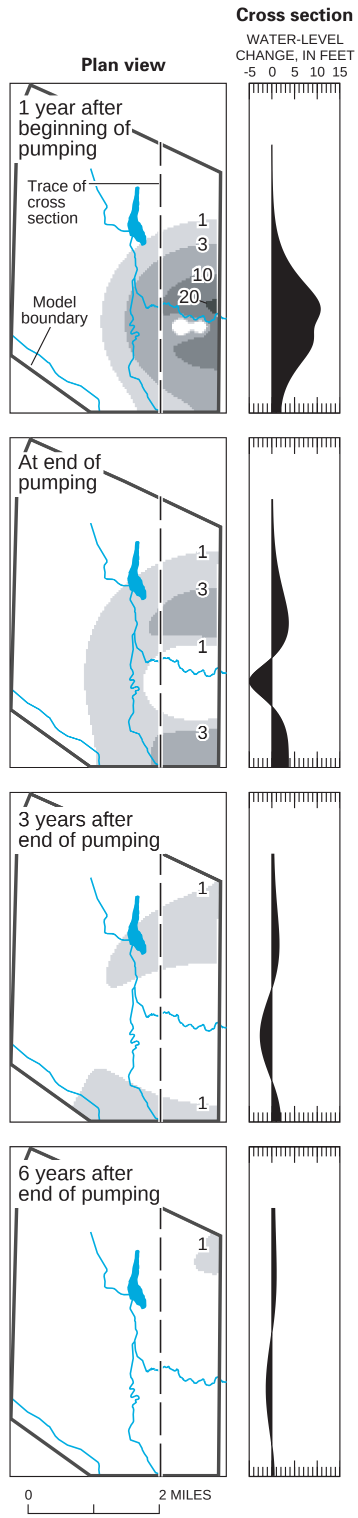


Figure 20. Plan view and north-south cross sections along the base of the alluvial fan showing simulated water-level change, after recharge of 3,500 acre-feet, 1 year after beginning of pumping, at end of pumping, and 3 years and 6 years after end of pumping at 800 acre-feet per year. Numbers in plan view indicate rise in water level, in feet.

The model of a heterogeneous aquifer system was simplified further by applying a uniform value of transmissivity to the modeled area. The lack of sufficient measurements to account for the spatial variation in hydraulic properties within the modeled area necessitated this simplification. Simplifying the model to this degree does not invalidate the model results; however, but does mean model results should be interpreted at scales larger than the volume of an individual grid cell.

The analysis of model sensitivity and application of alternate models showed that the calibrated model is not necessarily unique. Different rates could be simulated that also might provide a balance to the water budget and an acceptable match to observed water levels. Similarly, the simulation of variable rates for recharge through the Allerman Canal, the Carson River, and pumpage also could provide acceptable alternative models if more detailed data were available. However, the calibrated model provides a reasonable representation of the relative distribution of inflow and outflow through the modeled area that fits the constraints of measured water levels and available estimates of parameters based on field measurements. The model also is considered a reasonable tool with which to estimate the effects of recharge from a hypothetical infiltration basin and subsequent pumping of the recharged water.

SUMMARY AND CONCLUSIONS

Continued population growth in the Carson River basin has increased the need for water storage. Alluvial fans surrounding the floors of valleys along the Carson River provide potential sites for subsurface storage of currently unused surface-water rights to flow of the Carson River. However, the volumes of water that may be recharged and the rates at which recharged water would dissipate or move toward the valley floor are not well known. A numerical ground-water flow model can be used to simulate ground-water mounding beneath an infiltration basin and estimate reasonable limits on the approximate volume of water that may be stored and the rate at which recharged water would dissipate or move towards the valley floor.

In cooperation with the Carson Water Subconservancy District, the U.S. Geological Survey measured water levels at 27 wells, estimated hydraulic conductivity using data from slug tests of 3 wells, and developed a numerical ground-water flow model for an area of about 13 mi^2 east of Gardnerville, Nevada.

The study area is centered around an infiltration site selected on the east side of Carson Valley, on an alluvial fan near the mouth of Pine Nut Creek. The creek emerges from a narrow canyon cut through a low ridge separating Carson Valley from Fish Spring Flat to the east and meanders across a 1,000-ft wide flood plain incised 10 to 20 ft into the alluvial fan. Sedimentary units near the study area include Tertiary-age sediments forming the ridge between Carson Valley and Fish Spring Flat, alluvial fan and stream channel deposits west of the ridge, and fluvial deposits adjacent to the Carson River.

Measured water levels in the study area show that infiltration from the Allerman Canal and reservoir has created a water-table mound beneath them that decreases the gradient east of the canal and increases the gradient west of the canal. North of Pine Nut Creek, the mound causes ground water to flow toward the northern end of the reservoir. South of Pine Nut Creek, relatively high water levels probably are maintained by the mound beneath the Allerman Canal and possibly by greater rates of recharge from the southeast. Water-level declines near Pine Nut Creek from August 1999 through April 2001 probably are caused by dissipation of recharge from infiltration of Pine Nut Creek streamflow in the springs of 1998 and 1999.

Ground-water flow in an area of about 13 mi^2 was simulated with a single-layer, finite difference model extending from the water table to a depth of 400 ft, the maximum thickness of alluvial fan deposits penetrated by nearby wells. The model was calibrated to 190 water-level measurements made in 27 wells in December 2000, and in 9 wells from August 1999 through April 2001. Model calibration was facilitated by a parameter estimation program that estimated infiltration from Pine Nut Creek, the Allerman Canal and reservoir, and the Carson River, inflow through the eastern boundary, and specific yield. Because there was insufficient data to determine the spatial distribution of transmissivity within the modeled area, a constant transmissivity of 700 ft^2/d was assigned to cells throughout the model grid.

The calibrated model was used to simulate recharge from Pine Nut Creek once every 3 years to represent the ground-water flow system under natural conditions. Recharge from Pine Nut Creek caused water levels near the creek to rise as much as 25 ft, and caused ground-water storage to increase by 490 acre-ft. The simulation provided a comparison for estimating effects of recharge through a hypothetical infiltration basin and subsequent withdrawal of recharged water at two different rates.

Recharge of 700 acre-ft/yr through a hypothetical infiltration basin, covering 12.4 acres near the infiltration site, was simulated for 5 consecutive years, resulting in an increase in ground-water storage of 3,500 acre-ft. Such recharge requires a diversion rate of about 2 ft^3/s and an average infiltration rate of 0.3 ft/d.

The recharge caused water levels to rise over 70 ft near the infiltration basin, and water-level rises of more than 1 ft extending about 7,000 ft north, west, and south of the infiltration basin. The increase in water levels were near land surface beneath the infiltration basin, indicating that, given the basin location and surface area, 3,500 acre-ft is the maximum volume of water that could be stored. Greater amounts probably could be stored if separate infiltration basins were installed at different locations along the Pine Nut Creek alluvial fan, applying the recharge over a larger area.

After recharge ceased, water levels near the center of the mound declined rapidly to within 20 ft of initial levels within 2 years, and within 10 ft of initial levels within 7 years. The recharge mound dissipates laterally across the modeled area at decreasing rates over time. A water-level rise of 1 ft moved westward towards the valley floor 660 ft from peak conditions after 1 year, and averaged 550, 440, and 330 ft/yr for periods 1–4, 4–7, and 7–10 years respectively, after recharge ceased.

Two other simulations were made where hypothetical wells near the infiltration basin were pumped for 4 consecutive years. In the first pumping simulation, pumping was applied at one hypothetical well for 6 months, resulting in a total volume of about 400 acre-ft/yr and 1,600 acre-ft after 4 years of pumping, for withdrawal of about 45 percent of the volume recharged. After 4 years of pumping, water levels near the center of the infiltration basin declined to about 1 ft below initial water levels prior to simulated recharge. The lateral extent of water-level declines below initial water levels was about 1,000 ft from the pumped well during the last year of pumping.

In the second pumping simulation, pumping was applied at two hypothetical wells resulting in a total volume of 800 acre-ft/yr and 3,200 acre-ft after 4 years of pumping, for withdrawal of about 90 percent of the volume recharged. After 4 years of pumping, water levels near the basin declined a maximum of about 30 ft below those prior to recharge and the lateral extent of water-level declines below initial water levels was almost 4,000 ft from the pumped wells. Three years after the end of pumping, declines greater than initial water levels extended about 7,500 ft from the pumped wells.

Water-level declines are a result of pumping at a rate sufficient to withdraw the majority of the water recharged through the infiltration basin. Although the declines may affect water levels in nearby domestic wells, the simulations show that water levels recover fairly quickly after pumping ceases and would recover more quickly with continued use of the infiltration basin for recharge.

The simulations provide estimates of the volume of water that may reasonably be stored and the approximate time frame and pumping rates required for withdrawal of the bulk of the recharged water near the infiltration site on the Pine Nut Creek alluvial fan. The geologic and hydrologic setting of the Pine Nut Creek alluvial fan is similar to that of alluvial fans throughout the Carson River basin and western Nevada. Although the detailed hydrologic setting and aquifer properties may be somewhat different, the simulations provide a starting point for evaluation of other potential sites for subsurface storage of water.

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