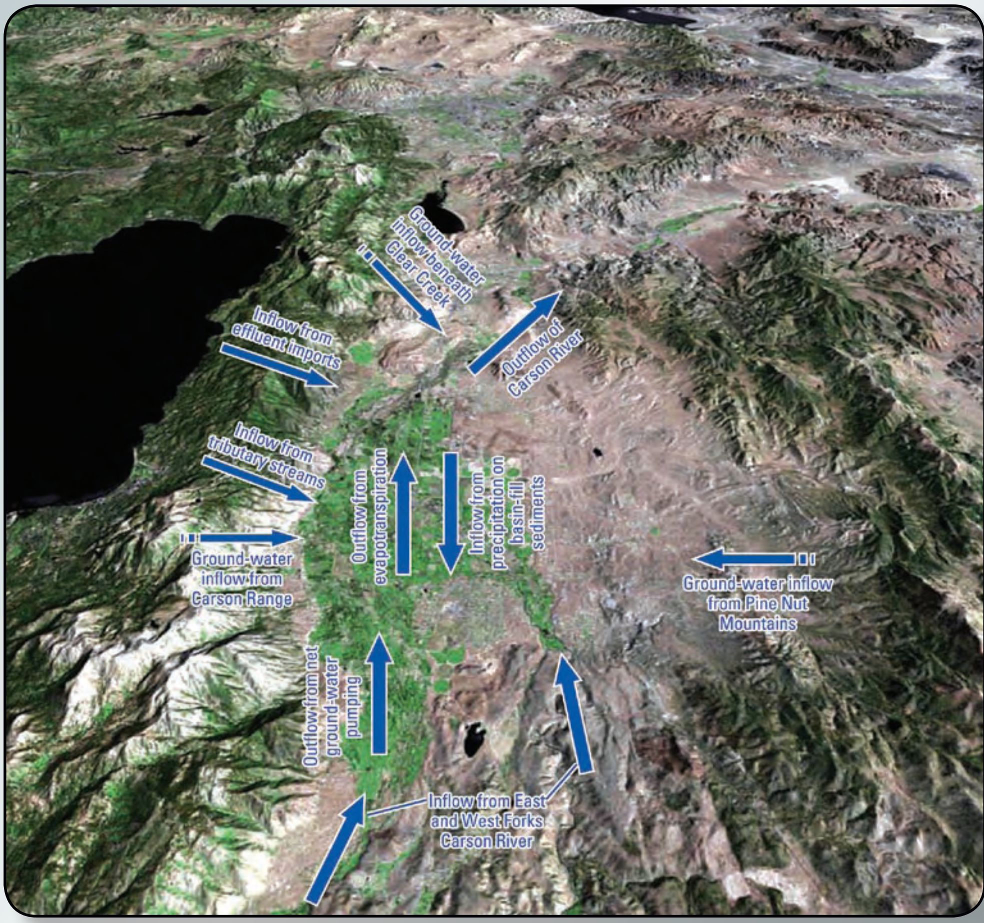
Prepared in cooperation with Douglas County Nevada

Water Budgets and Potential Effects of Land and Water-Use Changes for Carson Valley, Douglas County, Nevada, and Alpine County, California



Scientific Investigations Report 2006–5305

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

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By Douglas K. Maurer and David L. Berger

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U.S. Geological Survey

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Suggested citation:
Maurer, D.K., and Berger, D.L., 2007, Water budgets and potential effects of land and water-use changes for Carson Valley, Douglas County, Nevada, and Alpine County, California: U.S. Geological Survey Scientific Investigations Report 2006-5305, 64 p.

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Conversion Factors, Datums, and Abbreviations and Acronyms

Multiply	By	To obtain
acre	4,047	square meter
acre	0.4047	hectare
acre	0.4047	square hectometer
acre	0.004047	square kilometer
acre-foot (acre-ft)	1,233	cubic meter
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per day (acre-ft/d)	0.01427	cubic meter per second
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per mile (ft/mi)	0.1894	meter per kilometer
foot per year (ft/yr)	0.3048	meter per year
gallon per day (gal/d)	0.003785	cubic meter per day
inch (in.)	2.54	centimeter
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square foot (ft^2)	929.0	square centimeter
square foot (ft^2)	0.09290	square meter
section (640 acres or 1 square mile)	259.0	square hectometer
square mile (mi^2)	259.0	hectare
square mile (mi^2)	2.590	square kilometer

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

Conversion Factors, Datums, and Abbreviations and Acronyms—Continued

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations and Acronyms

Abbreviations or Acronyms	Meaning
DCSID	Douglas County Sewer Improvement District
ET	evapotranspiration
GIS	Geographic Information System
IVGID	Incline Village General Improvement District
m.y.	million years
mg/L	milligrams per liter
MGSD	Minden-Gardnerville Sanitation District
PDSI	Palmer Drought Severity Index
STPUD	South Tahoe Public Utility District

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Water Budgets and Potential Effects of Land- and Water-Use Changes for Carson Valley, Douglas County, Nevada, and Alpine County, California

By Douglas K. Maurer and David L. Berger

Abstract

To address concerns over continued growth in Carson Valley, the U.S. Geological Survey, in cooperation with Douglas County, Nevada, began a study in February 2003 to update estimates of water-budget components in Carson Valley. Estimates of water-budget components were updated using annual evapotranspiration (ET) rates, rates of streamflow loss to infiltration and gain from ground-water seepage, and rates of recharge from precipitation determined from data collected in 2003 and 2004 for the study and reported in the literature. Overall water budgets were developed for the area of basin-fill deposits in Carson Valley for water years 1941–70 and 1990–2005. Water years 1941–70 represent conditions prior to increased population growth and ground-water pumping, and the importation of effluent. A ground-water budget was developed for the same area for water years 1990–2005.

Estimates of total inflow in the overall water budget ranged from 432,000 to 450,000 acre-feet per year (acre-ft/yr) for water years 1941–70 and from 430,000 to 448,000 for water years 1990–2005. Estimates of total inflow for both periods were fairly similar because variations in streamflow and precipitation were offset by increases in imported effluent. Components of inflow included precipitation on basin-fill deposits of 38,000 acre-ft/yr for both periods, streamflow of the Carson River and tributaries to the valley floor of 372,000 acre-ft/yr for water years 1941–70 and 360,000 acre-ft/yr for water years 1990–2005, ground-water inflow ranging from 22,000 to 40,000 acre-ft/yr for both periods, and imported effluent of 9,800 acre-ft/yr for water years 1990–2005 with none imported for water years 1941–70. Estimates of ground-water inflow from the California portion of Carson Valley averaged about 6,000 acre-ft/yr and ranged from 4,000 to 8,000 acre-ft/yr. These estimates compared well with a previous estimate of ground-water inflow across the State line.

Estimates of total outflow in the overall water budget were 446,000 acre-ft/yr for water years 1941–70, and 439,000 to 442,000 acre-ft/yr for water years 1990–2005. Variations in ET and outflow of the Carson River were offset by an increase in net ground-water pumping for water years 1990–2005. Components of outflow include ET of 151,000 acre-ft/yr for water years 1941–70 and 146,000 acre-ft/yr for water years 1990–2005, streamflow of the Carson River of 293,000 acre-ft/yr for water years 1941–70 and 278,000 acre-ft/yr for water years 1990–2005, and net ground-water pumping of 2,000 acre-ft/yr for water years 1941–70, and 15,000 to 18,000 acre-ft/yr for water years 1990–2005. The decreased average flows for water years 1990–2005 compared to water years 1940–71 were likely the result of dry conditions from 1987 to 1992 and 1999 to 2005. The large volumes of inflow and outflow of the Carson River dominate the overall water budget.

Estimates of ground-water recharge for water years 1990–2005 ranged from 35,000 to 56,000 acre-ft/yr, and total sources of ground-water discharge ranged from 41,000 to 44,000 acre-ft/yr. Components of ground-water recharge included ground-water inflow from the Carson Range and Pine Nut Mountains (22,000 to 40,000 acre-ft/yr), ground-water recharge from streamflow (a minimum value of 10,000 acre-ft/yr), and secondary recharge of pumped ground water that returns to the water table (3,000 to 6,000 acre-ft/yr). Components of total ground-water discharge included ground-water ET from native phreatophytes, riparian vegetation, and non-irrigated pasture grasses (11,000 acre-ft/yr); ground-water discharge to streamflow of the Carson River (15,000 acre-ft/yr), and net ground-water pumping (15,000 to 18,000 acre-ft/yr).

Changes in land use between water years 1941–70 and 1990–2005 have decreased ET by about 5,000 acre-ft/yr. Increased application of effluent for irrigation between those years has decreased the use of surface water and ground water for irrigation by about 9,500 acre-ft/yr. The total decrease, about 15,000 acre-ft/yr, was approximately equal to the net ground-water pumping of 15,000 to 18,000 acre-ft/yr. The decrease in ET and in the use of streamflow and ground water for irrigation would tend to increase outflow of the Carson River from Carson Valley, offsetting the decrease in outflow caused by ground-water pumping without changes in land use predicted by previous studies of water budgets for Carson Valley.

Introduction

Rapid population growth and development in Carson Valley, west-central Nevada, is causing concern over the continued availability of water resources to sustain such growth into the future. As population growth continues, ground-water pumping will increase, land presently used for agriculture will be urbanized, and the effects of these changes on ground-water recharge and discharge are uncertain. These changes may affect outflow of the Carson River and, in turn, water users downstream of Carson Valley, who depend on sustained river flow (fig. 1).

In the early 1980s, the U.S. Geological Survey (USGS) estimated water-budget components for Carson Valley (Maurer, 1986). Major water-budget components included inflow from precipitation and from infiltration of streamflow, and outflow from evapotranspiration (ET) by plants and from ground-water seepage to the Carson River. Since that time, additional data have been collected on precipitation at stations in the Pine Nut Mountains and the Carson Range, and on streamflow from perennial streams tributary to the valley floor. In addition, new methods and instrumentation have been developed to estimate ET using micrometeorological measurements (Duell, 1990), to estimate recharge from precipitation using soil-chloride data and the chloride-balance method (Allison and Hughes, 1983; Dettinger, 1989), and to estimate rates of streamflow loss to infiltration and gain from ground-water seepage using streambed-temperature data (Constantz and Stonestrom, 2003).

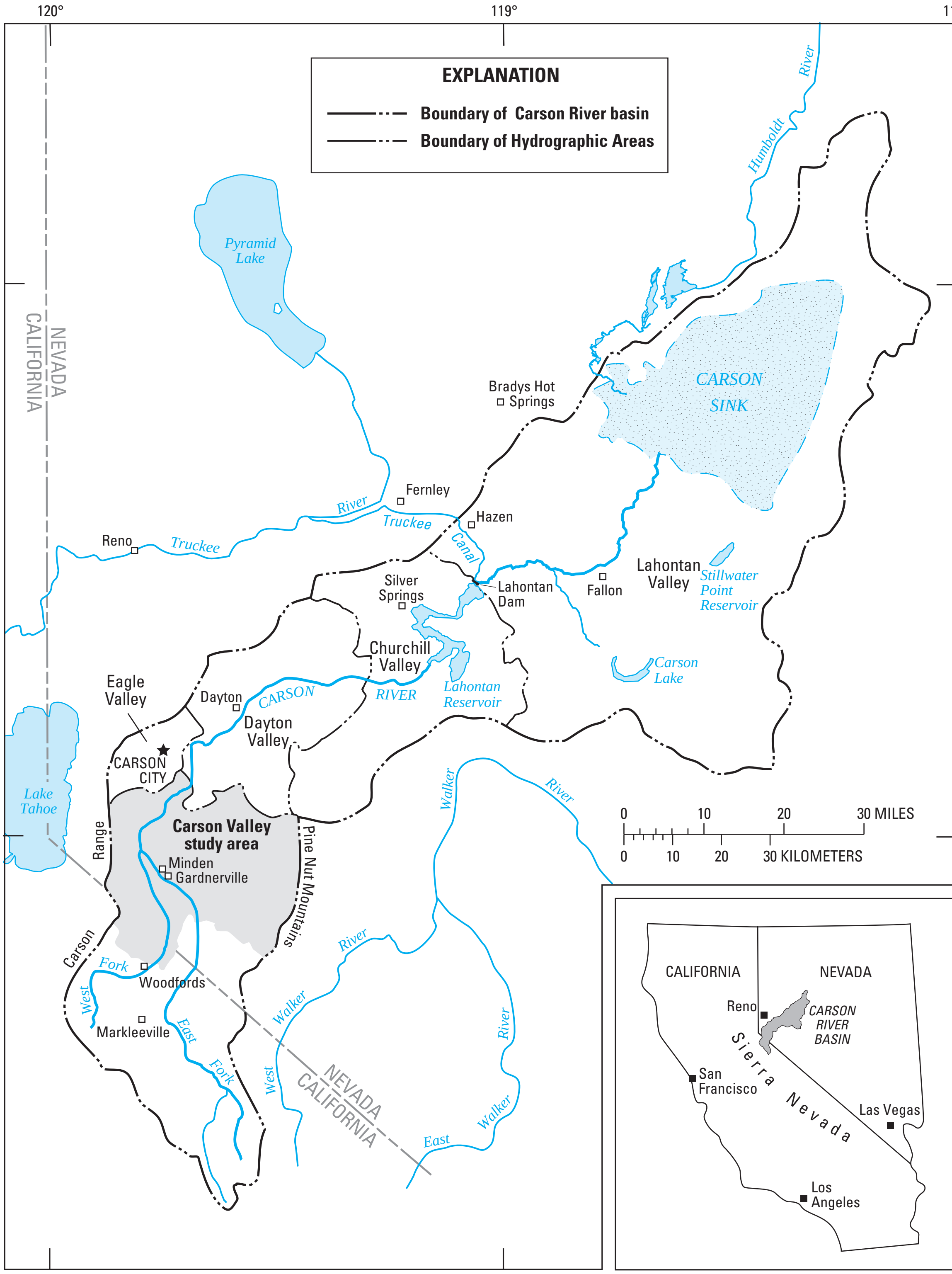
To address concerns over continued growth, in February 2003 the USGS, in cooperation with Douglas County, Nev., began a study to update estimates of water-budget components in Carson Valley. As part of the study, three reports have been published. The first two used precipitation and streamflow data to develop updated estimates of the distribution of precipitation in Carson Valley (Maurer and Halford, 2004), and updated estimates of streamflow tributary to the floor of Carson Valley (Maurer and others, 2004). The third report used ET, soil-chloride, and streambed-temperature data collected in 2003 and 2004 to provide estimates of ET from various types of vegetation and land use, estimates of recharge from precipitation on the northern and eastern sides of the valley, and estimates of the location and rates of streamflow losses and gains from streams and irrigation ditches on the valley floor (Maurer and others, 2006).

A final phase of work to address concerns over continued growth and to determine the potential effects of changes in land and water use involves the development of a numerical ground-water flow model of Carson Valley. This work is currently underway as a cooperative study between the USGS and the Carson Water Subconservancy District. The model is planned to be used to evaluate and potentially refine estimates of water-budget components presented in this report, and to estimate the effects of changes in land and water use.

Purpose and Scope

The purposes of this report are to present updated estimates of water-budget components for Carson Valley and to evaluate the potential effects of changes in land and water use on water-budget components. Estimates of water-budget components were updated using annual ET rates, rates of streamflow loss to infiltration and gain from ground-water seepage, rates of recharge from precipitation, estimates of streamflow from perennial streams, volumes of streamflow into and out of Carson Valley, volumes of effluent imported into Carson Valley, and annual ground-water pumping. Overall water budgets were developed for the area of basin-fill deposits of Carson Valley for water years 1941–70 and for 1990–2005. A ground-water budget was developed for the same area for water years 1990–2005. Estimates of water-budget components were compared with previous estimates and the uncertainty of the estimates was evaluated.

The potential effects of land-use changes on water-budget components were evaluated using examples of existing changes and application of ET rates to estimate changes in ET volumes and potential changes in Carson River outflow from Carson Valley.



Base from U.S. Geological Survey digital data, 1:100,000, 1988.
Universal Transverse Mercator projection, zone 11.
North American Datum of 1983 (NAD 83).

Figure 1. Location of the Carson River Basin and the Carson Valley Hydrographic Area, Nevada and California.

Geographic Setting

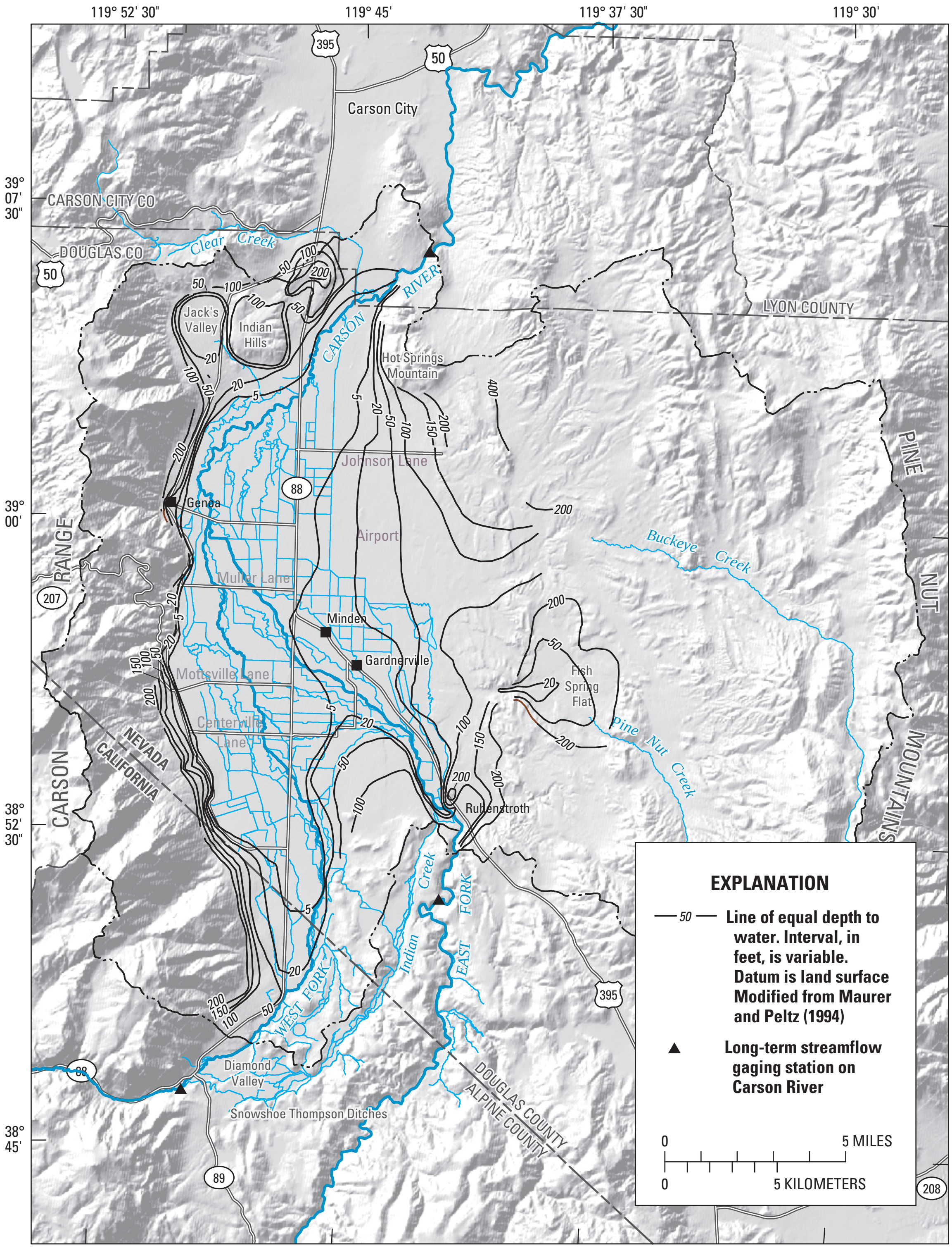
Carson Valley primarily is in Douglas County, Nevada, about 4 mi south of Carson City, Nevada's capital (fig. 1). The southern end of the valley extends about 3 mi into Alpine County, California (fig. 1). The floor of the valley is oval-shaped, about 20 mi long and 8 mi wide, and slopes from about 5,000 ft above sea level at the southern end to about 4,600 ft at the northern end. The Carson Range on the western side of the Sierra Nevada rises abruptly from the valley floor with mountain peaks ranging from 9,000 to 11,000 ft, whereas, the Pine Nut Mountains on the eastern side rise more gradually to peaks ranging from 8,000 to 9,000 ft.

The major towns in the valley are Minden and Gardnerville with populations of 2,800 and 3,400, respectively (fig. 2; U.S. Census Bureau, 2003). The subdivisions Gardnerville Ranchos south of Gardnerville and Johnson Lane and Indian Hills north of Minden are growing rapidly, with populations of 11,000, 4,800, and 4,400, respectively (U.S. Census Bureau, 2003). In addition, development is increasing along the eastern and western sides of the valley, and on the valley floor on land that historically has been agricultural. Douglas County as a whole has grown from a population of about 28,000 in 1990 to 41,000 in 2000, an increase of 49 percent (Economic Research Service, 2003).

For purposes of this study, the boundary of the Carson Valley study area was delineated as a subarea of the entire Carson Valley Hydrographic Area (figs. 2 and 3). The study area was selected to include only those parts of the hydrographic area connected by permeable aquifer materials capable of transmitting ground water to aquifers beneath the floor of Carson Valley. Along the southern boundary, the headwaters of the West and East Forks of the Carson River were not included in the study area because bedrock underlies the points where the West and East Forks of the Carson River cross the study area boundary, restricting ground-water inflow (fig. 3). The study area boundary (figs. 2 and 3) covers 253,570 acres, or about 396 mi^2.

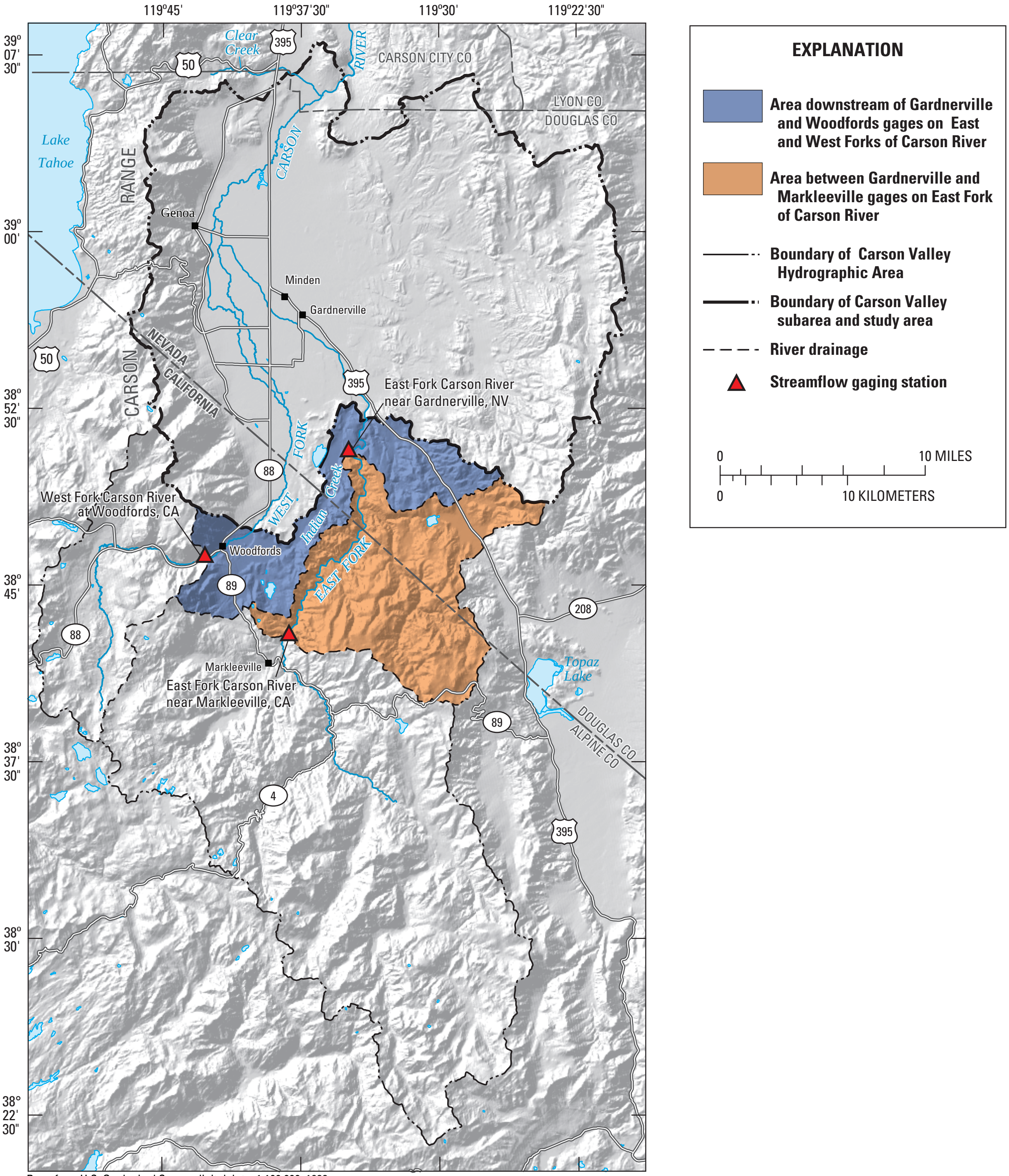
The valley floor is covered with native pasture grasses, crop lands of primarily alfalfa, and near the northern end of the valley, phreatophytes such as greasewood, rabbitbrush, and big sage. The distribution of these types of vegetation and other types of land use on the floor of Carson Valley were delineated for this study on a land-use map (fig. 4). The land-use map was developed using imagery collected in July 2004 by the Carson Valley Conservation District (BAE SYSTEMS Advanced Technologies, Inc., 2004). The imagery collected had a nominal ground sampling area of about 3 ft^2 and was digitized on screen to determine the distribution and areas of vegetation and land-use types. The initial map was field checked during the summer of 2005 and updated to include changes from July 2004 when the imagery was flown. The areas of selected vegetation and land-use types, and of selected geologic units listed in this report were calculated using Geographic Information System (GIS) software. Areas determined from the imagery were considered approximations only, because it was not feasible to field check all digitized polygons. In addition, the map and areas should be considered a snapshot in time because of the rapidly changing land use in Carson Valley.

At altitudes above the valley floor on the western side of the valley, bitterbrush and sagebrush cover steep alluvial fans, and manzanita and ponderosa pine cover the slopes of the Carson Range. Alluvial fans and foothills of the Pine Nut Mountains on the eastern side of the valley are covered with sage and rabbitbrush, and pinyon and juniper are found on the Pine Nut Mountains.



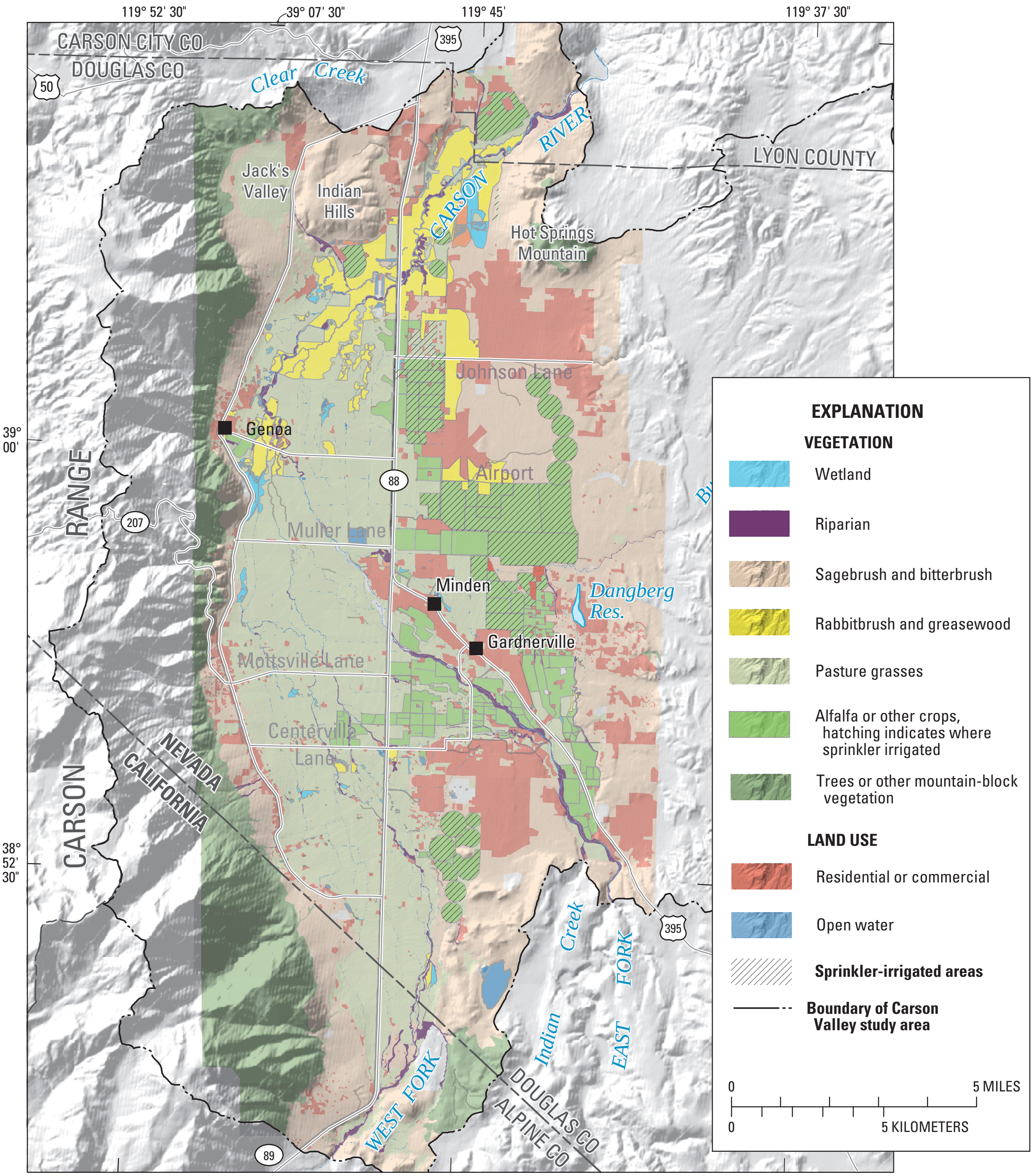
Base from U.S. Geological Survey digital data, 1:100,000, 1988.
Universal Transverse Mercator projection, zone 11.
North American Datum of 1983 (NAD 83).

Figure 2. Location of the Carson Valley study area and depth to water, Nevada and California, June 2005.



Base from U.S. Geological Survey digital data, 1:100,000, 1988.
Universal Transverse Mercator projection, zone 11.
North American Datum of 1983 (NAD 83).

Figure 3. Areas of the Carson Valley Hydrographic Area not included in study area, and used to estimate water budgets in previous investigations and Carson Valley study area.



Base modified from U.S. Geological Survey digital data, 1:100,000, 1988. UTM projection, zone 11. Shaded-relief from 30-meter DEM: sun illumination from northwest at 30 degrees above horizon.

Vegetation and land use imagery from the Carson Valley Conservation District (BAE SYSTEMS Advanced Technologies, Inc., 2004)

Figure 4. Vegetation and land use on the floor of Carson Valley, Nevada and California, 2005.

Geologic Setting

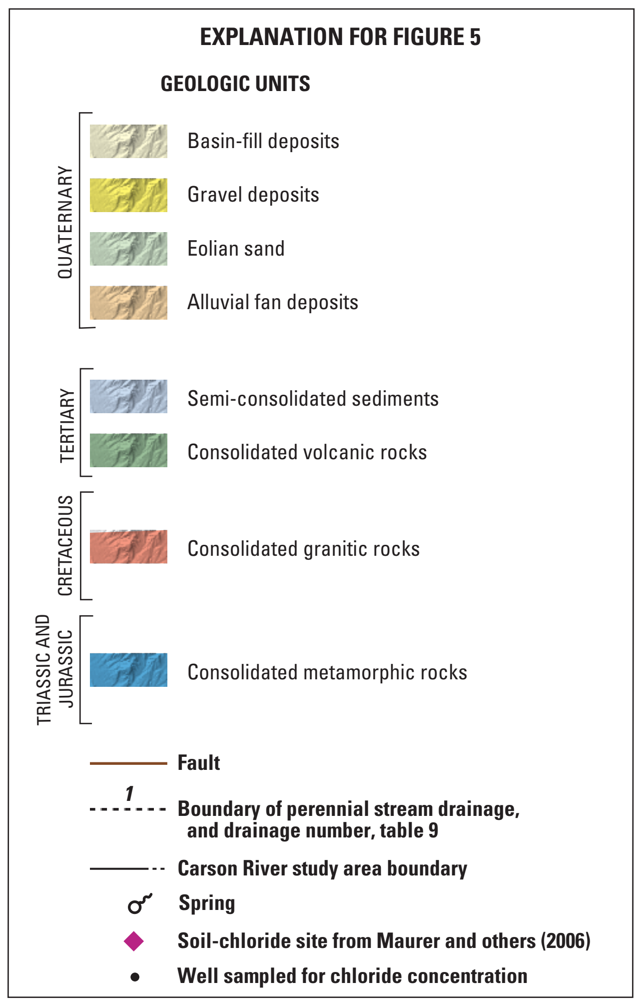
The distribution of geologic units in Carson Valley is shown in figure 5. The geologic units of Stewart and Carlson (1978) were grouped into metamorphic rocks of Jurassic to Triassic age, granitic rocks of Cretaceous age, volcanic rocks of Tertiary age, semi-consolidated sediments of Tertiary age, and alluvial fan, gravel, eolian sand, and basin-fill sediments of Quaternary age.

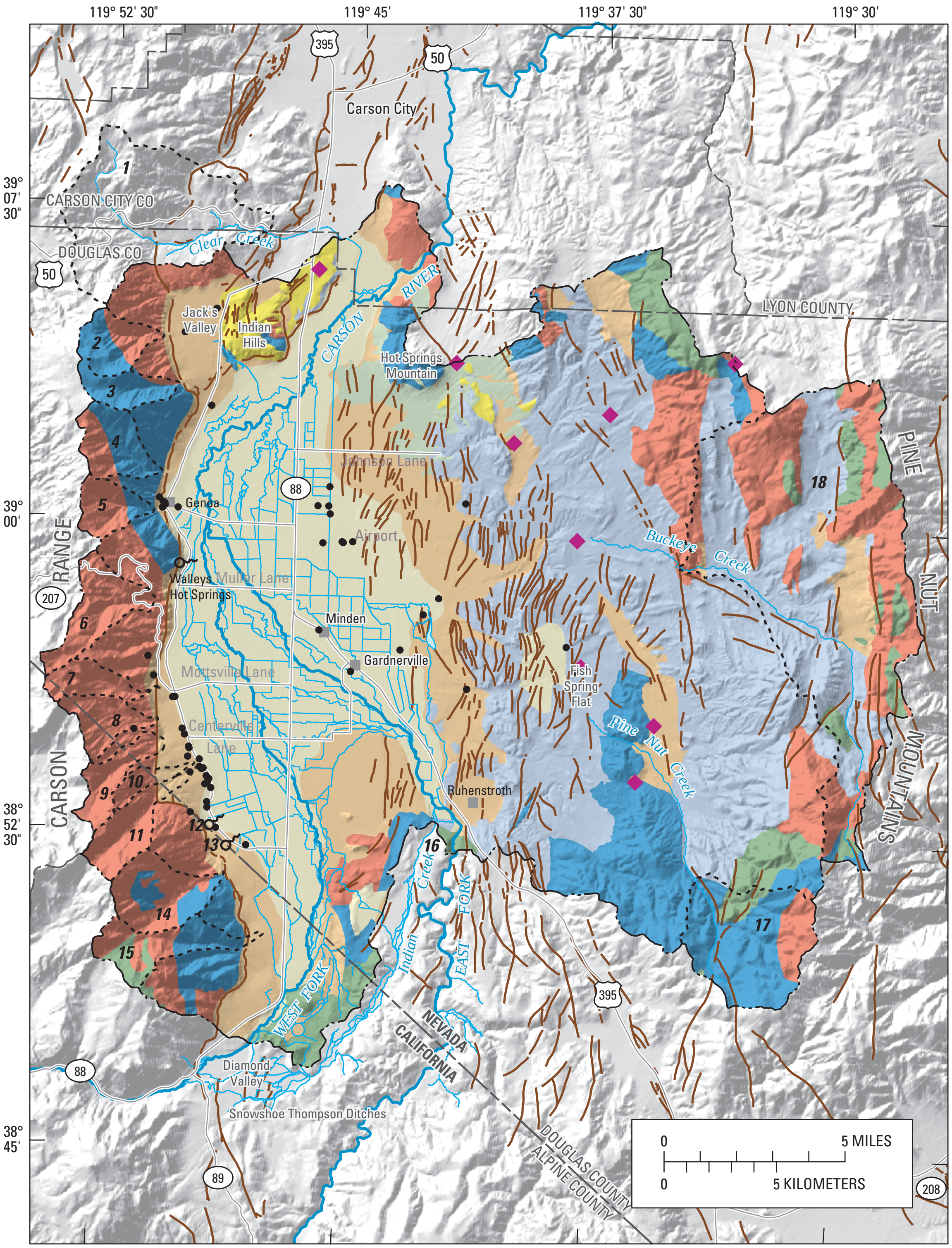
During the Cretaceous Period, 63 to 138 million years (m.y.) ago, the granitic magma of the Sierra Nevada pluton intruded into sedimentary and volcanic rocks of the Triassic and Jurassic Periods (138 to 240 m.y. ago). The resulting granodioritic and metavolcanic and metasedimentary rocks form the bulk of the Carson Range of the Sierra Nevada and the Pine Nut Mountains (fig. 5), and underlie the floor of Carson Valley (Moore, 1969, p. 18; Pease, 1980, p. 2). Basin and range faulting, which produced the present topography in Carson Valley, took place from 10 to 7 m.y. ago (Muntean, 2001, p. 9), uplifting the Carson Range and the Pine Nut Mountains, and down-dropping the floor of Carson Valley.

Contemporaneous with the faulting, volcanic rocks and sediments were deposited during the Tertiary Period and the sediments have become semi-consolidated. The volcanic rocks are exposed primarily on the extreme northeastern and southeastern ends of the valley (fig. 5). The semi-consolidated sediments are exposed primarily on the eastern side of the valley, but dip towards the west and probably are present beneath the entire valley. Geologic units mapped by Stewart and Carlson (1978) as older Quaternary alluvium on the eastern side of the valley likely are underlain by the Tertiary sediments at depths of 100 ft or less and, for this reason, are grouped with the Tertiary sediments on figure 5. The semi- consolidated Tertiary sediments vary in their degree of compaction (Pease, 1980, p. 14), and in their lithology, varying from fine-grained and tuffaceous siltstone with isolated lenses of sandstone and conglomerate, to sandstone and conglomerate (Muntean, 2001, p. 18-31). The coarser grained parts of the Tertiary sediments are exposed primarily on the southeastern part of the valley at the base of the Pine Nut Mountains (Muntean, 2001, p. 19). The aggregate thickness of the Tertiary sediments is estimated to exceed 3,000 ft (Muntean, 2001, pl. 5).

Throughout the Quaternary Period (present day to 2 m.y. ago), unconsolidated sediments (fig. 5) have been deposited on the valley floor by the Carson River and by tributary streams surrounding the valley. Unconsolidated sediments deposited by the Carson River generally are well-sorted sand and gravel, interbedded with fine-grained silt and clay from over-bank flood deposits. Unconsolidated sediments deposited by tributary streams are coarse- to fine-grained, poorly sorted deposits that form alluvial fans at the base of the mountain blocks.

The mountain blocks bounding Carson Valley are west-tilted structural blocks (Stewart, 1980, p. 113), with the 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 along the Carson Range on the west, whereas a diffuse fault zone is found on the eastern side of the valley, dividing the Pine Nut Mountain block into several smaller blocks (fig. 5). Continued westward tilting is shown by recent faulting along the base of the Carson Range (Pease, 1980, p. 15) and by displacement of the Carson River to the extreme western side of the valley (Moore, 1969, p. 18). A gravity survey by Maurer (1984) indicates the depth to consolidated bedrock beneath the western half of Carson Valley is as great as 5,000 ft.





Base modified from U.S. Geological Survey digital data, 1:100,000, 1988. UTM projection, zone 11. Shaded-relief from 30-meter DEM: sun illumination from northwest at 30 degrees above horizon.

Base geology from Stewart and Carlson (1978) at 1:250,000 scale, modified from geologic mapping by Stewart (1999) at 1:100,000 scale; by Armin and John (1983), Stewart and Noble (1979) at 1:62,500 scale; and by dePolo and others (2000), Garside and Rigby (1998), and Muntean (2001) at 1:24,000 scale. Faults from U.S. Geological Survey (2003).

Figure 5. Geologic units and faults in Carson Valley, drainage areas or location of perennial streams and springs, and wells from which samples were analyzed for chloride content.

Hydrologic Setting

Carson Valley lies in the rain shadow of the Sierra Nevada, with annual precipitation at the town of Minden averaging 8.4 in/yr (period of record 1971–2000, National Oceanic and Atmospheric Administration, 2002, p. 12). In contrast, the top of the Carson Range receives about 40 in/yr and the top of the Pine Nut Mountains receives from 15 to 18 in/yr (Maurer and Halford, 2004, p. 35). From 1987 to 1992 and from 1998 to 2005, conditions were dry with annual precipitation considerably less than average (fig. 6*A*). The Palmer Drought Severity Index (PDSI, National Oceanic and Atmospheric Administration) is based on long-term weather conditions and provides a cursory indication of regional meteorological wet or dry periods (fig. 6*B*; National Oceanic and Atmospheric Administration, 2006). The PDSI indicates dry conditions have dominated western Nevada since about 1999.

The hydrology of Carson Valley is dominated by flow of the Carson River. The East and West Forks of the Carson River enter from the southern parts of the valley and flow northward to join near Genoa. The combined flow continues north to leave the valley southeast of Carson City (fig. 2). Flow of the Carson River is diverted across the valley floor through a network of canals and ditches for flood irrigation of crops and native pasture grasses. Thirteen perennial streams drain the Carson Range, whereas only two perennial streams, Buckeye and Pine Nut Creeks, drain the Pine Nut Mountains Valley (Maurer and others, 2004).

Streamflow entering Carson Valley in the East and West Forks of the Carson River, and streamflow leaving the valley in the Carson River near Carson City has been gaged during a common period of record from 1940 to 2005 (stations 10309000, 10310000, and 10311000, respectively). Average annual flow at these three gaging stations was determined for different periods (table 1). Average flow at these stations for

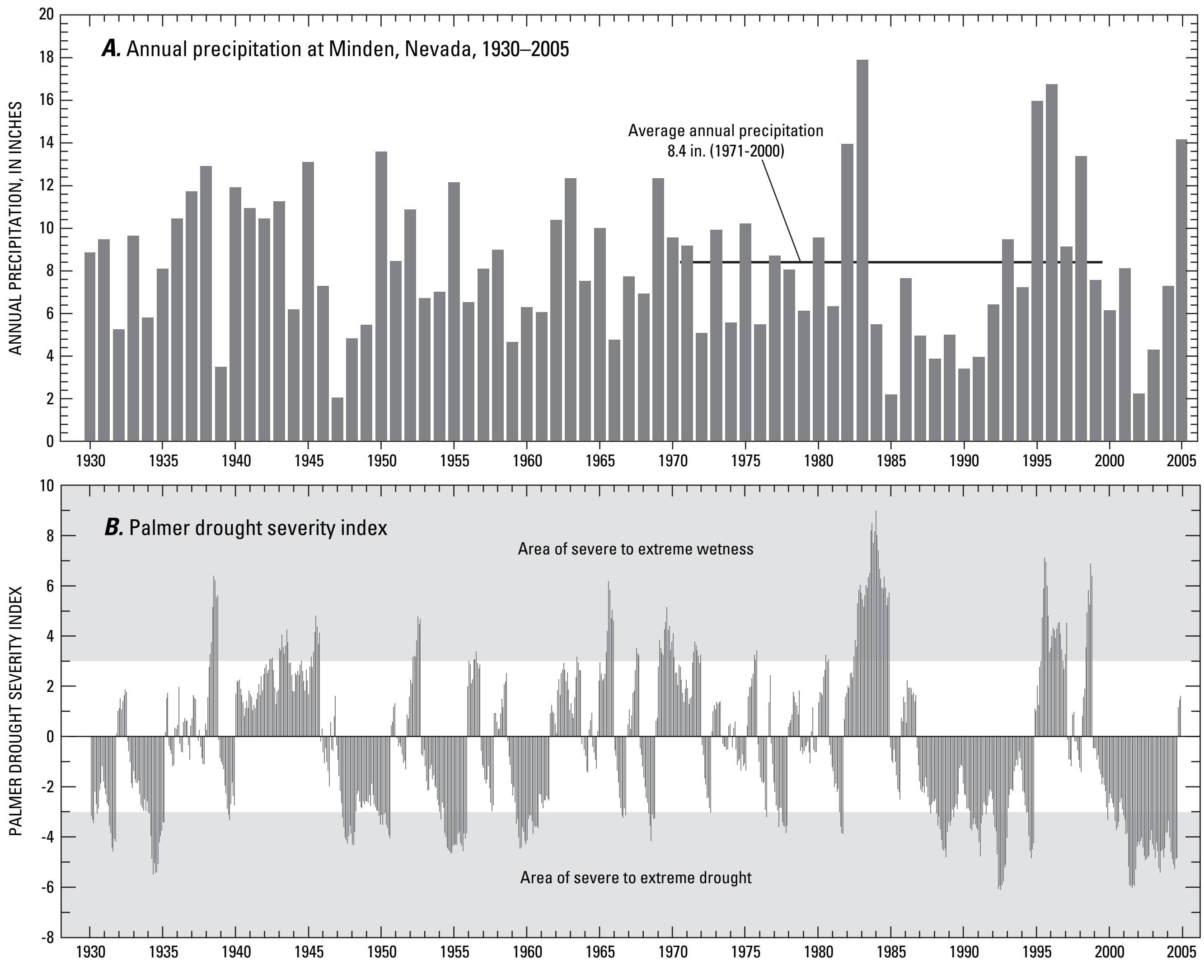


Figure 6. Annual precipitation at Minden, Nevada, for period of record (1930–2005) and average annual precipitation (1971–2000), and Palmer drought severity index (1930–2005) for western Nevada.

Table 1. Average annual flow of the East and West Forks Carson River and the Carson River near Carson City for selected water years, Nevada and California.

Water years	Average annual flow					
	East Fork Carson River near Gardnerville		West Fork Carson River near Woodfords		Carson River near Carson City	
	Station 10309000 (acre-feet)	Percentage of difference, 1940-2005	Station 10310000 (acre-feet)	Percentage of difference, 1940-2005	Station 10311000 (acre-feet)	Percentage of difference, 1940–2005
[1] 1940–2005	265,330	0	75,600	0	293,900	0
[1] 1941–1970	265,950	0.2	75,430	-0.2	292,660	-0.4
[1] 1971–2000	272,380	2.7	78,740	4.1	311,150	5.9
[2] 1990–2002	257,000	-3.1	75,150	-0.6	287,300	-2.2
[1] 1990–2005	256,240	-3.4	73,350	-3.0	277,850	-5.5

[1] From U.S. Geological Survey database.

[2] From Maurer and others (2004, p. 14).

water years 1941–70 was very similar to that for the entire common period of record, whereas average flow for water years 1971–2000 was about 3 to 6 percent greater than the common period of record. Average flows for water years 1990–2002 and 1990–2005 range from 0.6 percent less for the West Fork Carson River to almost 6 percent less for the Carson River near Carson City, than for water years 1940–2005.

Infiltration of surface water through streambeds and ditches and beneath flood-irrigated fields maintains a shallow water table beneath much of the valley floor where depth to ground water is less than 5 ft below land surface (fig. 2; Maurer and Peltz, 1994, sheet 2). Depth to water beneath alluvial fans on the western side of the valley quickly increases to greater than 200 ft within 1 mi of the valley floor, whereas depth to water on the eastern side of the valley reaches 200 ft about 3 mi from the valley floor (fig. 2).

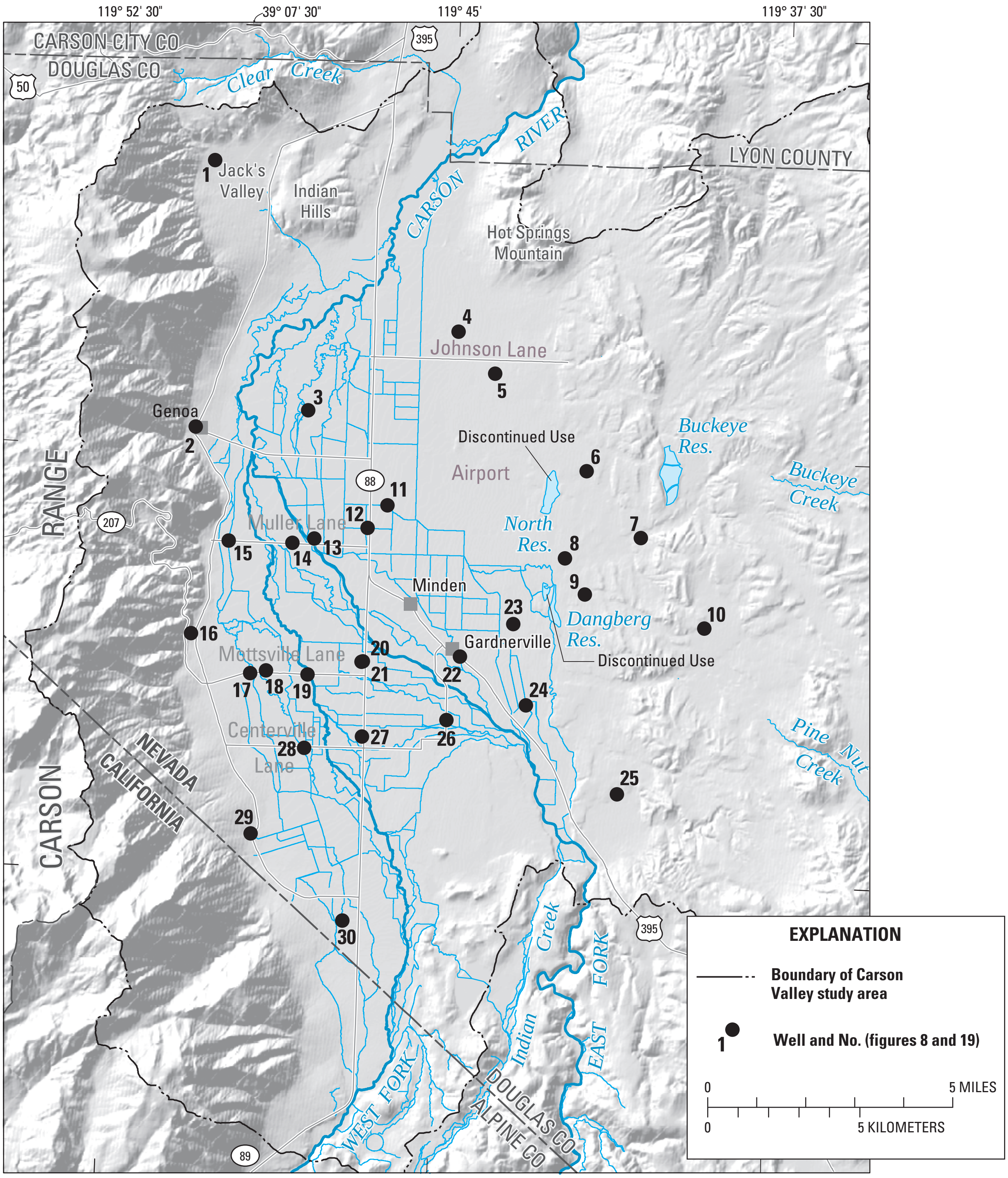
Ground water flows from the west and east towards the Carson River and then northward (Berger and Medina, 1999). Along the main axis of the valley, ground-water gradients range from about 100 ft/mi in the southwestern part of the valley to about 5 ft/mi in the northern part of the valley. Beneath alluvial fans on the western side of the valley, the ground-water gradient is eastward at about 100 ft/mi, whereas on the eastern side of the valley, gradients are westward and range from 20 to 100 ft/mi (Maurer, 1986, p. 18).

The consolidated granitic and metamorphic bedrock surrounding and underlying Carson Valley are relatively impermeable to ground-water flow, although some wells produce sufficient water from fractures for domestic use. In the semi-consolidated Tertiary sediments, lenses of sand and gravel are the primary water-bearing units, and probably transmit most ground water through the unit. Unconsolidated sediments that form alluvial fans surrounding the valley and that underlie the flood plain of the Carson River are the principal aquifers in Carson Valley (Maurer, 1986, p. 17).

Confined conditions and artesian flow are found in aquifers beneath the valley floor at depths of 200 to 300 ft below land surface (Maurer, 1986, p. 17). Inspection of drillers' logs has shown that a valley-wide confining unit is not present (Dillingham, 1980, p. 40). Confined conditions are likely the result of discontinuous clay beds 30 to 40 ft thick present at depths of 200 to 300 ft in scattered locations beneath the valley floor. Confined conditions and artesian flow is encountered at shallower depths, less than 100 ft, on the westernmost side of the valley floor. Here, confined heads may result where wells penetrate the toes of coarse-grained alluvial fans that have been buried by fine-grained flood-plain deposits of the Carson River (Maurer, 1986, p. 17).

As part of the overall study of Carson Valley water budgets, water levels have been measured in about 70 wells beginning about December 2004 (selected wells in fig. 7). The USGS has measured some of these wells since 1977, and many were measured during the study by Maurer (1986) in the early 1980s with continued measurements at various times through 2004.

Water levels along the western side of Carson Valley show seasonal fluctuations of 5 to 25 ft during the early 1980s when water levels were measured monthly (fig. 8*A*, wells 2 and 16), and longer term fluctuations in response to wet and dry periods (see fig. 6) of 5 to 30 ft. Similarly, shallow wells on the valley floor show both seasonal and longer term fluctuations of smaller magnitude, ranging from 2 to about 8 ft, although data from dry years of the late 1980s and from wet years of the late 1990s are not available for many of these wells (fig. 8*B*). From 1980 to 2006, water levels have fluctuated but overall show no long-term change. Water levels may change temporarily in response to seasonal and annual variations in recharge, but over time, if water levels do not show rising or declining trends, the aquifer is said to be in a state of dynamic equilibrium (Theis, 1940, p. 277).

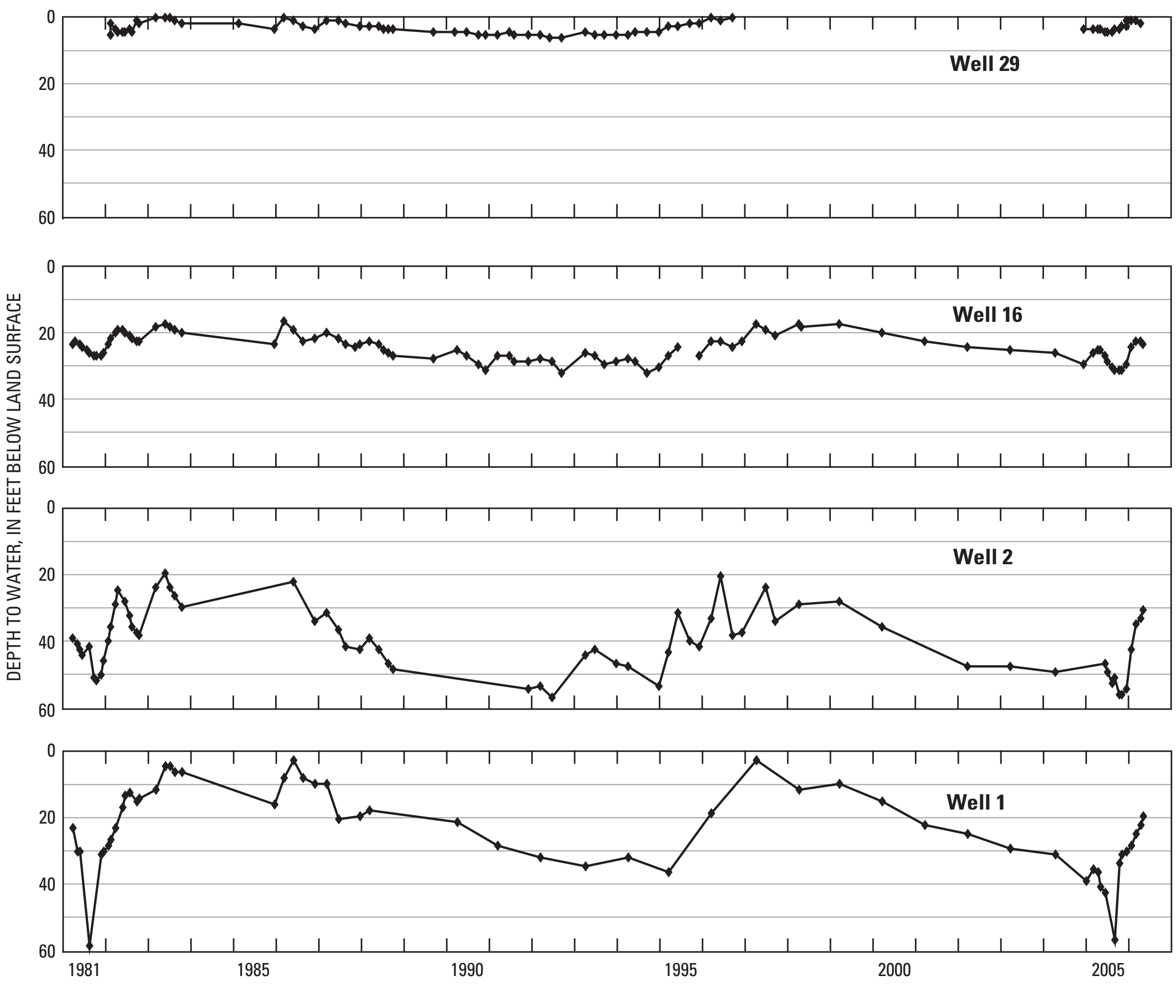


Base modified from U.S. Geological Survey digital data, 1:100,000, 1988. UTM projection, zone 11. Shaded-relief from 30-meter DEM: sun illumination from northwest at 30 degrees above horizon.

Figure 7. Locations of selected wells where water levels have been measured, Nevada, 1981–2006.

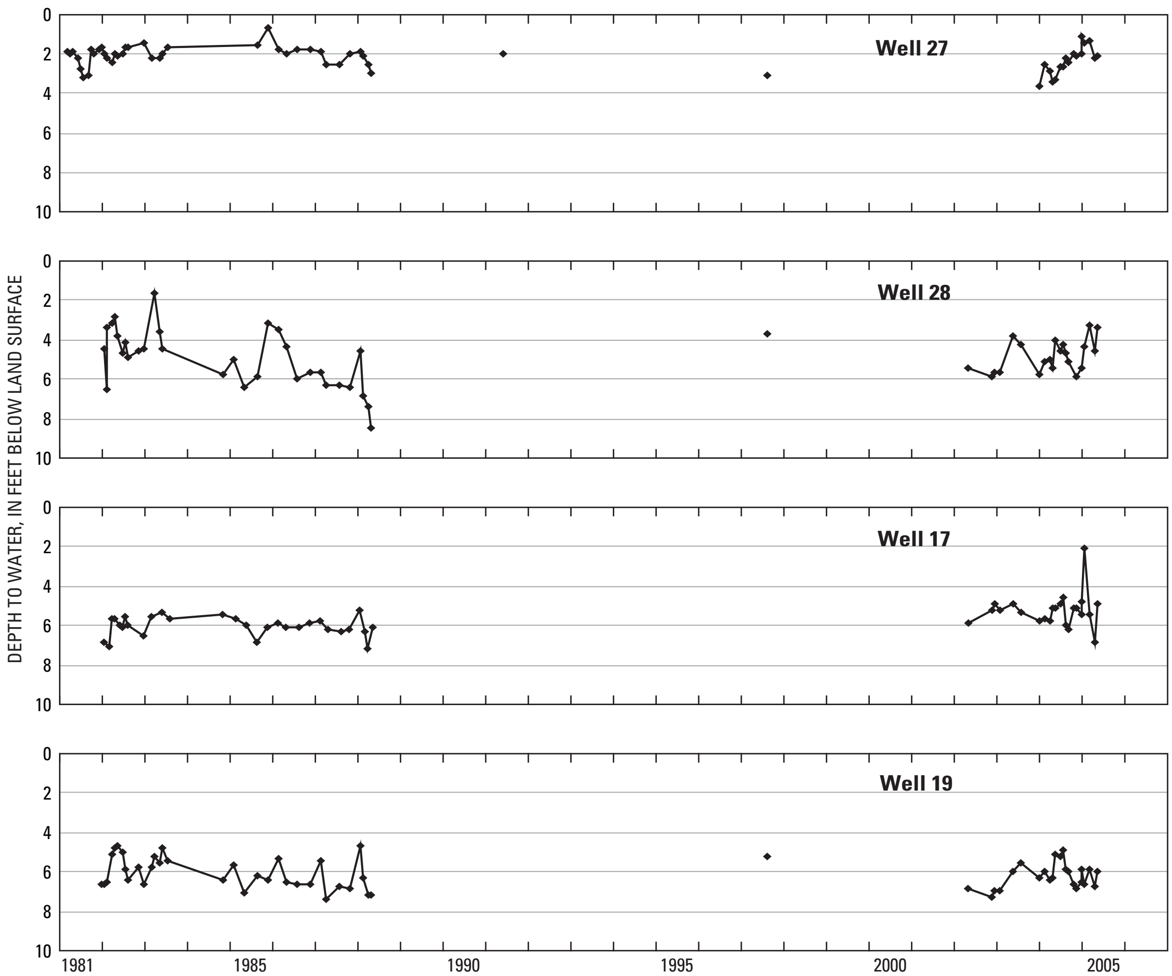
Water levels in deep flowing artesian wells fluctuate from about 5 to almost 20 ft above land surface (negative values in terms of depth below land surface, fig. 8*C*) in winter months and from 10 to 20 ft below land surface in response to summer pumping, with water levels in 2005 similar to those during the dry years of the early 1990s (fig. 8*C*). Water levels in deep irrigation wells (fig. 8*D*) in 2005 also are similar to those of the early 1990s, however, water levels in 2004 are somewhat lower than in the early 1990s. This may be the result of more severe drought conditions prior to 2004 than in the early 1990s (fig. 6*B*), or a response to increased pumping.

Water levels in wells near the valley floor show little long-term rise or decline from 1977 to 2006, suggesting that this part of Carson Valley is in a state of approximate dynamic equilibrium. However, on the eastern side of Carson Valley in areas of increased population growth supplied largely by individual domestic wells (fig. 8*E*), water levels show long-term water-level declines. Water levels in the Johnson Lane area (well 5) have declined about 5 ft lower than during the early 1990s, whereas water levels in Fish Spring Flat (well 10) and Ruhenstroth subdivisions (well 25) have declined about 10 ft. These areas are relatively distant from land irrigated with surface water and recharge is limited to ground-water inflow from the Pine Nut Mountains. Wet conditions during water year 2006 may cause water levels in these areas to rise as increased recharge from the Pine Nut Mountains moves westward.



A. Wells on the western alluvial fan

Figure 8. Water-level fluctuations in selected wells in Carson Valley, Nevada, 1981–2006. Location of wells are shown in figure 7.



B. Shallow wells on the valley floor

Figure 8.—Continued.

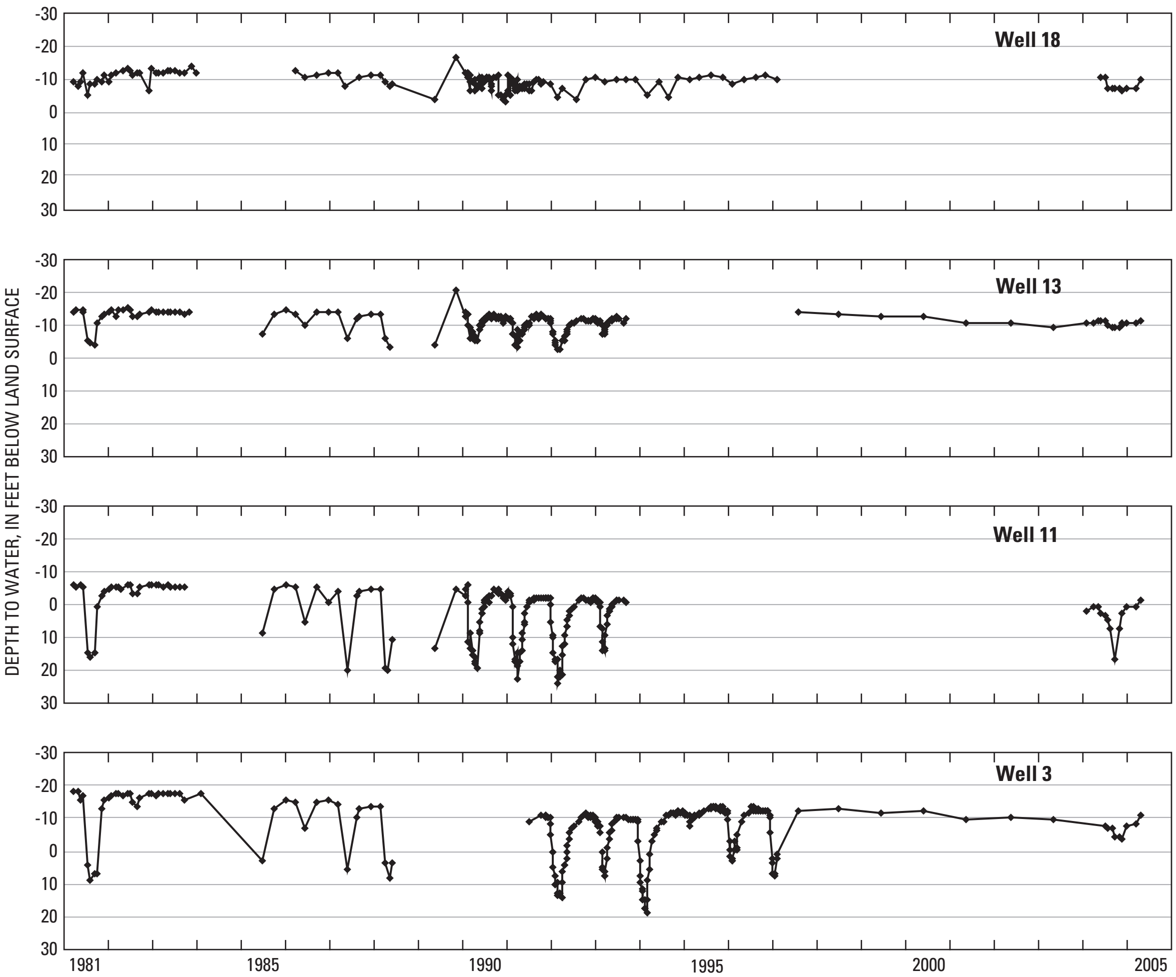
Previous Investigations

The most recent study that delineates the major water-budget components for Carson Valley was Maurer (1986), which includes estimates of ET, leakage from the Carson River and irrigation ditches to the water table and seepage from the water table back to the Carson River and irrigation ditches, ground-water recharge, and subsurface inflow. Estimates of the annual volumes of these components on the basis of a best-fit steady-state numerical model simulation are most clearly reported by Prudic and Wood (1995, p. 9) and summarized in table 2. In comparison, ground-water pumping in the early 1980s was relatively small and ranged from about 15,000 acre-ft/yr in dry years to about 7,000 acre-ft/yr in wet years (Maurer, 1986, p. 62–63).

Table 2. Estimates of average annual ground-water recharge and discharge based on best-fit steady-state simulation for the basin-fill aquifer in Carson Valley, Nevada.

[Summarized from Prudic and Wood, 1995, p. 9]

Water-budget component	Estimated volume (acre-feet per year)
Recharge	
From precipitation	47,000
Subsurface inflow	55,000
Leakage from Carson River and irrigation ditches	105,000
Total	207,000
Discharge	
Evapotranspiration (ET)	149,000
Seepage to Carson River and irrigation ditches	58,000
Total	207,000



C. Artesian wells on the valley floor

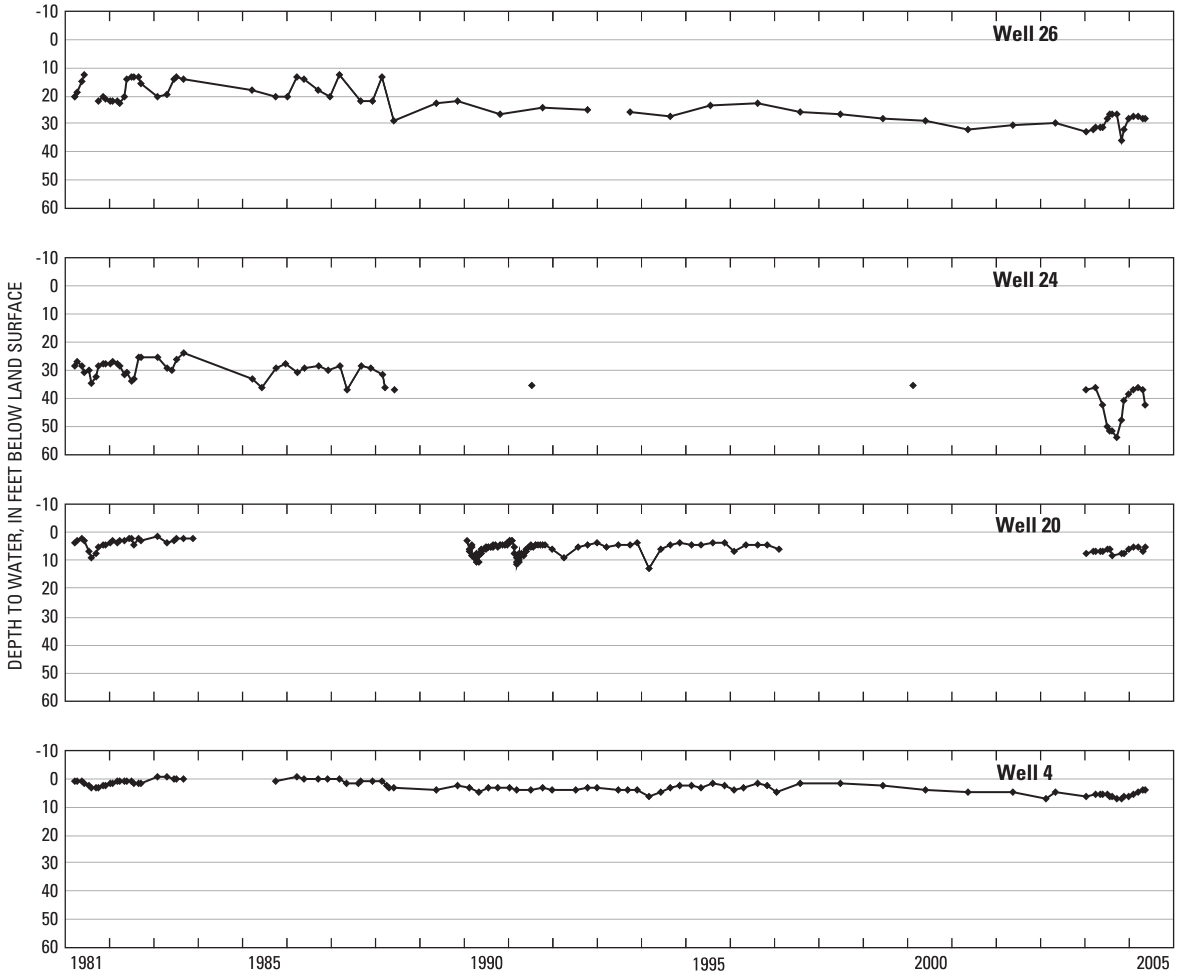
Figure 8.—Continued.

Evapotranspiration

The largest water-budget component is ET, or the discharge of ground water by native plants and irrigated crops, and evaporation from bare soil. Early studies used the term consumptive use which usually did not include estimates of evaporation. The earliest estimate of consumptive use in Carson Valley was made by Piper (1969, p. 7–8). He used estimates of surface-water runoff and gaged outflow of the Carson River to derive a volume of 77,200 acre-ft/yr for the depletion of surface water from consumptive use by plants. To this volume, he added 41,000 acre-ft/yr of annual precipitation on the area in Carson Valley at altitudes less than 4,800 ft, to obtain a total consumptive use of 118,000 acre-ft/yr. From estimates of the areas of native meadows and xerophytic vegetation prior to large-scale irrigation in Carson Valley, Piper (1969) estimated the increased consumptive use from irrigation to total 45,000 acre-ft/yr. Rabbitbrush, greasewood, pasture grasses, alfalfa, willow, and cottonwood are considered to be phreatophytic plants, meaning that their roots tap the water table, whereas plants such as bitterbrush and sagebrush are xerophytic, meaning that their roots do not tap the water table.

Walters and others (1970) applied an annual estimate of 2.5 ft for consumptive use by irrigated plants to derive a total of 110,000 acre-ft/yr. For native vegetation, consumptive use was estimated to be 24,000 acre-ft/yr, for a total consumptive use of 134,000 acre-ft/yr.

For the Nevada portion of Carson Valley, Glancy and Katzer (1976, p. 66) estimated 2,800 acre-ft of annual evaporation from surface-water bodies, and 80,000 acre-ft that included annual ET by crops and phreatophytes along with water consumptively used by ground-water pumping. The estimate of 80,000 acre-ft/yr was derived as the amount required to balance estimates of other components of inflow and outflow.



D. Deep irrigation wells near the valley floor

Figure 8.—Continued.

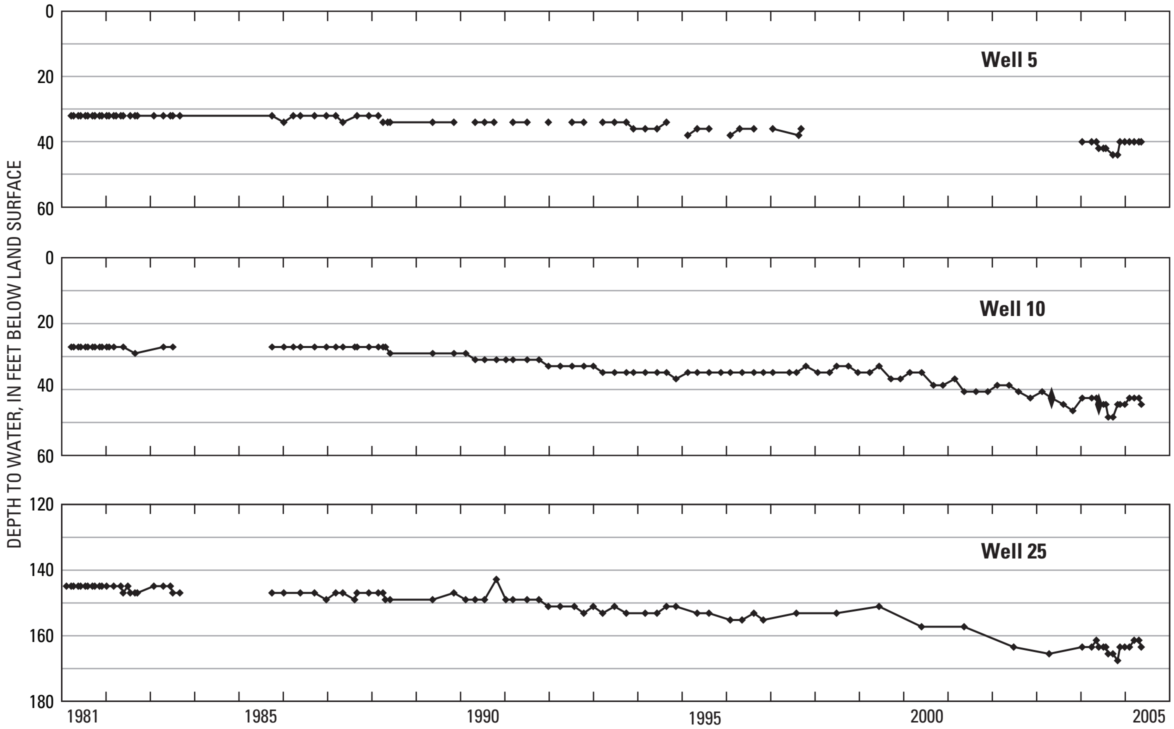
Spane (1977, p. 91) estimated annual ET to range from about 209,000 acre-ft in 1973, and 235,000 acre-ft in 1974. The estimates were based on mapped acreages of irrigated pasture and alfalfa, natural flood plain and phreatophytic vegetation, free-water surfaces, residential, and xerophytic vegetation. He used modified monthly pan-evaporation data and crop coefficients to obtain the total values.

Maurer (1986, p. 60) reported the total outflow from evaporation and ET was about 170,000 acre-ft/yr. This volume included 148,000 acre-ft/yr from phreatophytes and croplands, 2,800 acre-ft/yr from open-water evaporation, and 23,000 acre-ft/yr from xerophytic plants. The volume of 148,000 acre-ft/yr from phreatophytes and croplands was derived from a numerical ground-water flow model. The model applied maximum rates of ET ranging from 0.4 ft/yr in areas of sparse rabbitbrush, to 4.0 ft/yr in areas of irrigated pasture and alfalfa (Prudic and Wood, 1995, p. 7). The rates applied in the numerical model are a maximum where the water table is near land surface and decrease linearly to zero where the depth to water is equal to or greater than 35 ft (Maurer, 1986, p. 54).

Prudic and Wood (1995, p. 9), using the steady-state numerical ground-water flow model developed by Maurer (1986), reported annual ET from phreatophytes and irrigated crops to be 149,000 acre-ft/yr; slightly greater than that reported by Maurer (1986) due to differences in numerical rounding.

Leakage from and Seepage to Carson River and Irrigation Ditches

The interactions between ground water and surface water represent the next largest water-budget component. Previous estimates of leakage to ground water from the Carson River and irrigation ditches are sparse. Estimates of ground-water discharge by seepage to the Carson River and ditches are



E. Wells on the eastern side of the valley.

Figure 8.—Continued.

limited to those obtained from numerical modeling. Glancy and Katzer (1976, p. 34–35) discuss and present a hydrograph showing the monthly difference between surface-water inflow and outflow of the Carson River. The hydrograph shows that river outflow from Carson Valley is greater than inflow from November to March when ET is minimal, whereas inflow is greater than outflow from March to September when ET is greatest and when streamflow is applied for irrigation recharges the ground-water system. However, no volumetric estimates of net flow losses or gains were made. Spane (1977, p. 32–34) noted similar variations and calculated net losses of 52,000 and 58,000 acre-ft/yr in 1973 and 1974, respectively. Based on shallow water-level altitudes, Spane (1977, p. 144) stated that the Carson River gains flow along its entire length through Carson Valley, with the exception of the East Fork Carson River above Gardnerville, where streamflow is lost to infiltration.

Estimates of infiltration of surface water were made by Maurer (1986) and Prudic and Wood (1995) using a numerical ground-water flow model. Maurer (1986, p. 59–60) reported that the net annual infiltration of surface water from the Carson River was 44,000 acre-ft, with flow lost on the eastern and southern parts of the valley, and flow gained over the remainder of the valley floor. Using the same model, Prudic and Wood (1995, p. 9) reported average annual leakage from the Carson River and irrigation ditches was 105,000 acre-ft/yr, and average annual seepage from ground water back to the Carson River was 58,000 acre-ft/yr. The difference, 47,000 acre-ft/yr, is slightly greater than the net loss reported by Maurer (1986, p. 60), due to differences in numerical rounding. Prudic and Wood (1997, p. 10–11) describe losing streams and ditches near the southern end of the valley, and gaining streams and ditches at the northern end of the valley.

Ground-Water Recharge

Estimates of recharge have been made by many studies in Nevada using the empirical method described by Maxey and Eakin (1949, p. 40). The method assumes that increasing percentages of precipitation becomes recharge for increasing amounts of annual precipitation, and was developed initially for 13 closed basins in eastern Nevada where precipitation is the sole source of water for recharge. The distribution of precipitation used was that of Hardman (1936). The method was later modified (Eakin, 1960, p. 12) by relating precipitation to altitude, and using altitude zones in place of the original precipitation zones. Subsurface inflow from the mountain blocks is assumed to be included in the estimate of recharge (Glancy and Katzer, 1976, p. 49).

Application of the Maxey-Eakin method involves many uncertainties. Descriptions of the method do not clearly state if recharge from infiltration of streamflow is included in the resulting estimate of recharge. However, inclusion of recharge from streamflow is implied when Eakin and Maxey (1951, p. 81) justify a larger amount of recharge to Ruby Valley, Nev., because the steep slopes in the basin "favor a high percentage of runoff to the area of recharge." The exact "area of recharge" is not explicitly stated in descriptions of the method, and because the method was developed for entire basins, the accuracy of the method when applied to smaller portions of a basin is uncertain. The original recharge percentages have been modified by many workers for various reasons, including Glancy and Katzer (1976, p. 47–48) for Carson Valley, to account for greater amounts of precipitation. Glancy and Katzer (1976, p. 47) also state that the method only provides an estimate of potential recharge, because in areas like Carson Valley, where the water table is shallow and runoff from tributary streams joins the Carson River, not all estimated recharge reaches the ground-water reservoir. The accuracy of the method is uncertain when applied to precipitation distributions different than that originally used to develop the method (Maurer, 1997, p. 23). In addition, the method only provides an estimate of the total ground-water recharge to a basin, with no information on the areal distribution of recharge. The areal distribution of recharge is needed to evaluate the potential effects of ground-water pumping and changes in land use, and for development of numerical ground-water flow models.

Recharge from precipitation in Carson Valley has been estimated by several studies using the Maxey-Eakin method. All studies applied different recharge percentages and none explicitly stated if recharge included infiltration of streamflow. Recharge was first estimated (Nevada State Engineer, 1971, table 3, p. 5) to be 25,000 acre-ft/yr for the Nevada portion of the valley, and 3,000 acre-ft/yr was estimated for inflow from the California portion of the valley. The estimate included a note that part of the estimated recharge may be rejected with actual recharge being "somewhat" smaller (Nevada State Engineer, 1971, p. 40). Vasey-Scott Engineering (1974, p. 10–11) estimated that recharge was 27,400 acre-ft/yr for that part of the valley downstream of the Woodfords gaging station on the West Fork Carson River, and the Gardnerville gaging station on the East Fork Carson River (fig. 3). Glancy and Katzer (1976, p. 48) estimated 41,000 acre-ft/yr, and included the area downstream of the Markleeville gaging station on the East Fork Carson River (fig. 3). Using a precipitation distribution derived from 43 stations in eastern California and western Nevada, and including the Clear Creek drainage (fig. 3), Spane (1977, p. 143) obtained an estimate of 51,000 acre-ft/yr. Using Spane's (1977) distribution of precipitation and not including the Clear Creek drainage, Maurer (1986, p. 35–36) obtained an estimate of 47,000 acre-ft/yr, and cautioned that the value was only a crude estimate of recharge from the mountain blocks surrounding the valley.

Subsurface Inflow and Outflow

Estimates of subsurface inflow to Carson Valley are sparse. Vasey-Scott Engineering (1974, p. 11) cited a volume of 3,000 acre-ft/yr, reported by the Carson River Basin Council of Governments, for subsurface inflow to Carson Valley from "upstream areas"; the exact location of these areas is unclear. Glancy and Katzer (1976, p. 51) estimated subsurface inflow across the State line from the portion of Carson Valley in Alpine County to be 7,000 acre-ft/yr, and estimated inflow beneath the channel of the East Fork Carson River at the State line to be 150 acre-ft/yr. Maurer and Thodal (2000, p. 33) estimated that 400 acre-ft/yr of subsurface flow enters Carson Valley beneath Clear Creek on the northern end of the valley. Maurer and Thodal (2000, p. 34) also estimated that 2,500 acre-ft/yr could flow beneath the ridge separating the upper part of the Clear Creek drainage and Jacks Valley into Carson Valley, but note that such flow is not confirmed. Maurer (1986, p. 60) estimated subsurface inflow from the mountain blocks surrounding Carson Valley to range from 37,000 to 57,000 acre-ft/yr, but considered 37,000 acre-ft/yr to be the more reasonable volume. The volume of subsurface flow (55,000 acre-ft/yr) reported by Prudic and Wood (1995, p. 9) includes leakage from small perennial and ephemeral streams.

Subsurface outflow from Carson Valley to the Dayton Valley Hydrographic Area likely is small. Glancy and Katzer (1976, p. 51) estimated 15 acre-ft/yr of subsurface flow beneath the channel of the Carson River at the gaging station near Carson City (fig. 2), a negligible volume for purposes of evaluating the water-budget components of Carson Valley. Maurer (1997, p. 31) noted a lack of water-level data east of Hot Springs Mountain that would confirm a hydraulic gradient from that area towards the Dayton Valley Hydrographic Area, but also noted that water levels in wells near the Carson River were lower than river stage; indicating subsurface flow across the divide and toward the river is minimal.

Water-Budget Components

Two types of water budgets were developed for Carson Valley. The first type, an overall water budget, summarizes sources of inflow to and outflow from the valley and represents the available water resources of Carson Valley. The second type, a ground-water budget, summarizes sources of ground-water recharge and discharge and provides an estimate of the perennial yield of Carson Valley. Both types of water budgets were estimated for that part of Carson Valley underlain by Quaternary basin-fill deposits, the principal source of water for irrigation, municipal, and domestic water use (fig. 5). The area underlain by basin-fill deposits is the location of discharge of water by ET and the exchange of water between the surface-water irrigation system and basin-fill aquifers.

Overall water budgets were developed for two time periods, water years 1941–70, and water years 1990–2005. Water years 1941–70 represent conditions prior to increased population growth and ground-water pumping, and the importation of effluent. Water years 1990–2005 represent conditions under increased population growth that has caused changes in land and water use, increased ground-water pumping, and the application of effluent for irrigation. A ground-water budget was developed for water years 1990–2005, representing conditions under increased growth. Estimates for the ground-water budget components used an analysis of mean daily surface-water inflow to Carson Valley, including perennial streams tributary to the valley floor, and surface-water outflow from Carson Valley for water years 1990–2005. Mean daily surface-water data were not available for perennial streams tributary to the valley floor for water years 1941–70 and a ground-water budget was not developed for that period.

Components of the overall water budget and the ground-water budget are shown graphically in figures 9 and 10. Components of the overall water budget supplying inflow to basin-fill sediments in Carson Valley include streamflow of the East and West Forks of the Carson River and perennial streams tributary to the valley floor, precipitation on basin-fill deposits; ground-water inflow from the Carson Range, the Pine Nut Mountains, and beneath Clear Creek; and effluent imported from the Lake Tahoe basin (fig. 9). Components of outflow in the overall budget include streamflow of the Carson River, ET, and net ground-water pumping.

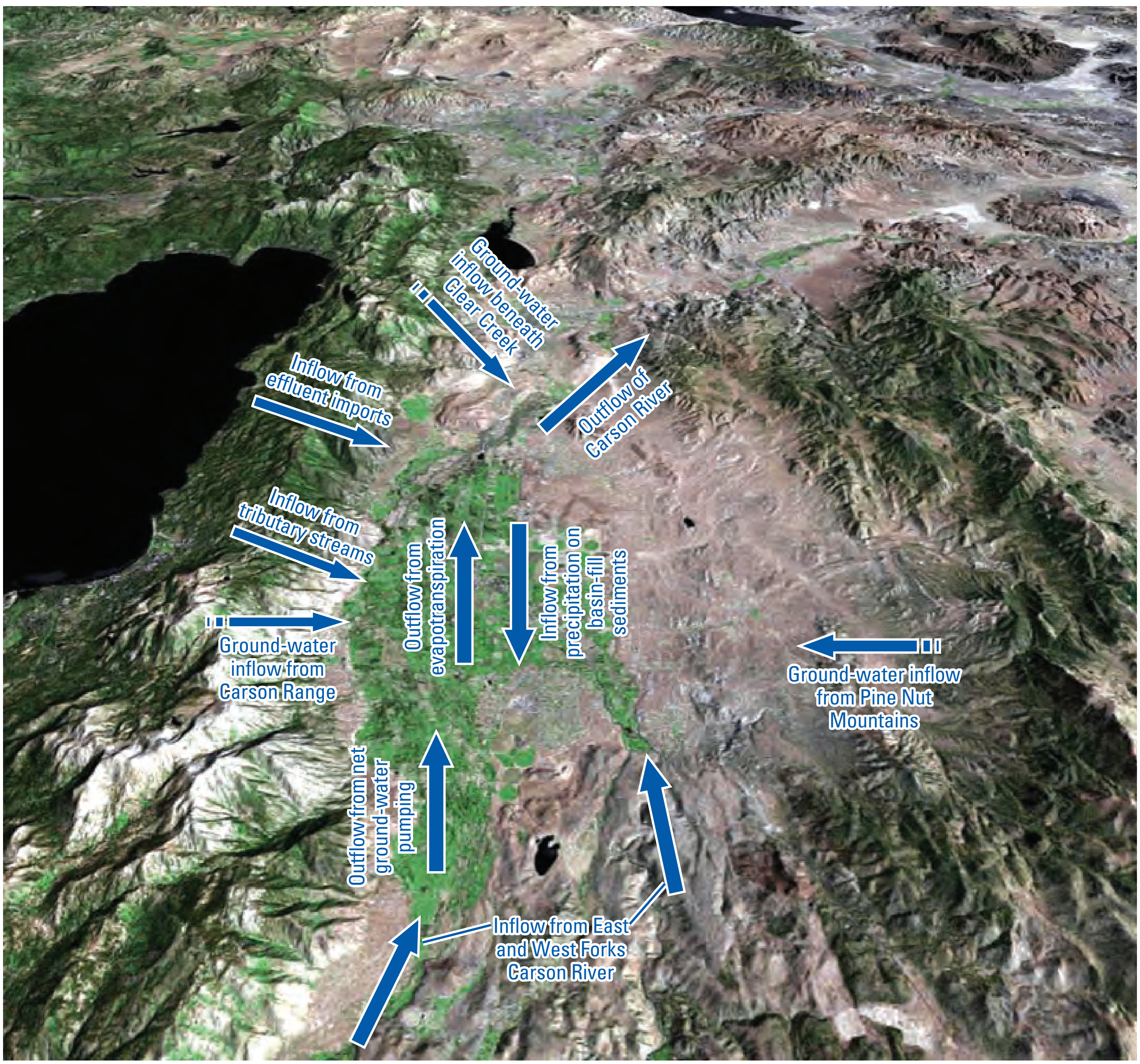


Figure 9. Conceptual diagram of overall water-budget components for Carson Valley.

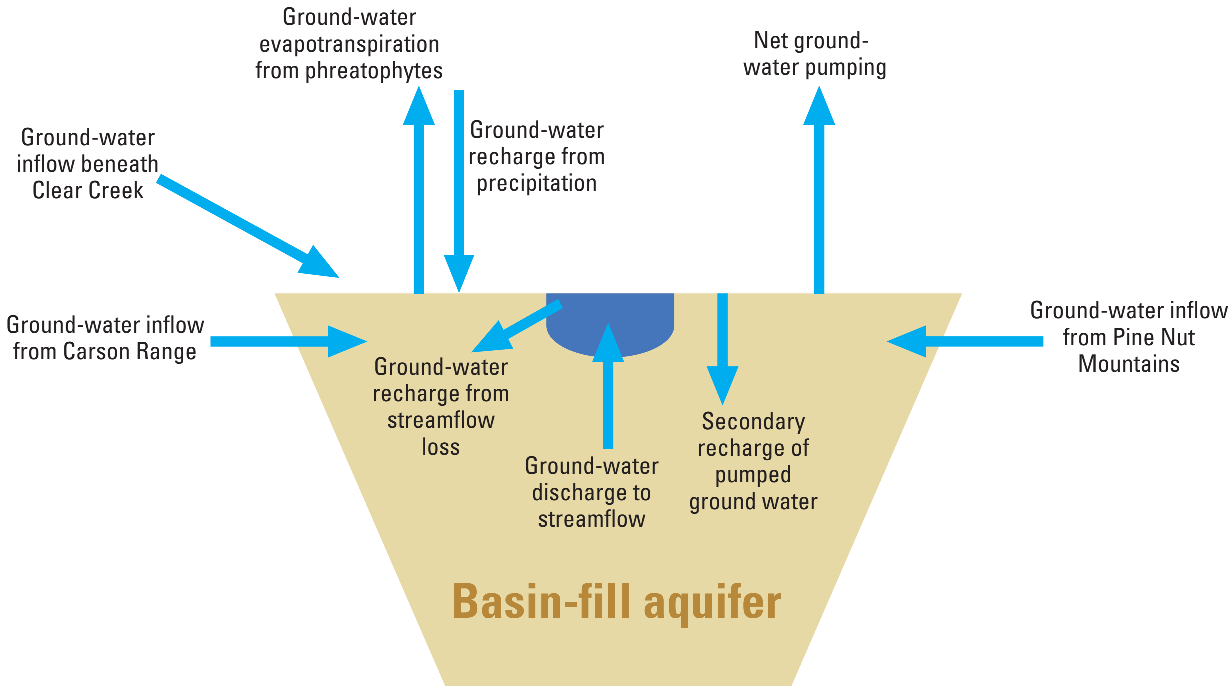


Figure 10. Conceptual diagram of ground-water budget components for Carson Valley.

The Maxey-Eakin method was not used to estimate ground-water recharge in this study because of the many uncertainties in application of the method, as discussed previously. Instead, the ground-water budget was divided into separate components that could be estimated with varying amounts of uncertainty. A ground-water budget often contains large inherent uncertainties because ground-water recharge cannot be directly measured.

Components of the ground-water budget supplying recharge to basin-fill sediments include ground-water inflow from the Carson Range and western alluvial fans, the Pine Nut Mountains and eastern alluvial fans, and beneath Clear Creek; recharge from precipitation on Quaternary eolian sand and gravel deposits and on the western alluvial fans; recharge from streamflow losses, and secondary recharge of pumped ground water that percolates to the water table (fig. 10). Ground-water inflow is not strictly defined as recharge because such flow does not cross the water table (Freeze and Cherry, 1979, p. 211). However, for purposes of this report, which is focused on water budgets for the basin-fill aquifers in Carson Valley, ground-water inflow entering basin-fill aquifers beneath Clear Creek and from the mountain blocks and alluvial fans were considered ground-water recharge. Sources of ground-water discharge from basin-fill aquifers include ground-water ET from non-irrigated phreatophytes: rabbitbrush and greasewood, riparian vegetation, and non-irrigated pasture grasses; ground-water discharge as seepage into the Carson River; and net ground-water pumping.

Surface-Water Inflow to and Outflow from the Floor of Carson Valley

Streamflow of the East and West Forks of the Carson River is gaged upstream of the Carson Valley boundary (fig. 2). Flow losses or gains likely are small along the East Fork Carson River between the gage and the Carson Valley boundary and there are no diversions of streamflow. Streamflow from the West Fork Carson River is diverted between the gage and the Carson Valley boundary to the Snowshoe Thompson Ditches 1 and 2 for irrigation in Diamond Valley (fig. 2). The diversions have been recorded by the Federal Watermaster's Office since about 1993. Total diversions to the Snowshoe Thompson ditches averaged about 5,900 acre-ft/yr for the 11-year period for water years 1993–2003, with 3,600 acre-ft/yr diverted to Ditch 1 and 2,300 acre-ft/yr diverted to Ditch 2 (David Waltham, Federal Watermaster's Office, written commun., 2004).

Return flow from Snowshoe Thompson Ditch 1 drains to Indian Creek, which enters Carson Valley about 1 mi west of the East Fork Carson River near the southeastern boundary of the study area. About one-half of the return flow from Snowshoe Thompson Ditch 2 also may drain to Indian Creek and about one-half may enter the study area's southwestern boundary downstream of Diamond Valley near the California State line (Donald Callahan, Federal Watermaster's Office, oral commun., December 2005). The volume of return flow entering Carson Valley from Diamond Valley is not known. Streamflow of Indian Creek was gaged near the downstream end of Diamond Valley and averaged about 7,500 acre-ft/yr for water years 1987–91 (station 10309030). This volume is greater than the average flow diverted to Snowshoe Thompson Ditches 1 and 2 for water years 1993–2003. Although data are not available for diversions to the Snowshoe Thompson ditches for 1987–91, this indicates that streamflow losses through Diamond Valley likely are minimal.

Streamflow also is diverted for irrigation of land near the West Fork between the gage and the study area boundary, and return flows enter the river upstream of the boundary. Consumptive use of these diversions is likely offset by inflow from unmeasured springs located near the West Fork about 0.5 mi downstream of Woodfords. In addition, the springs suggest that the nearby reach of the West Fork may gain flow. The volume of streamflow gain and spring flow is unknown (Donald Callahan, Federal Watermaster's Office, oral commun., December 2005), but, along with return flow from Snowshoe Thompson Ditch 2, the volume of streamflow would tend to offset reductions in flow from the diversions. For purposes of the overall water budget, the decrease in inflow to Carson Valley from West Fork diversions between the gage and the boundary is assumed to be negligible relative to the total volume of inflow.

In addition to flow in the East and West Forks of the Carson River, two perennial streams cross the study area boundary, Indian and Clear Creeks (sites 16 and 1, respectively, table 3, fig. 5). Indian Creek was gaged near the study area boundary for 4 complete water years from 1995 through 1998 (station 10309035), a period of above average streamflow. Average flow for that period was 8,480 acre-ft/yr (Preissler and others, 1999, p. 143). The average flow entering Carson Valley from Indian Creek for water years 1940–2005 was estimated by multiplying 8,480 acre-ft/yr by 0.6, the ratio of average annual streamflow in the West Fork Carson River for water years 1940–2005 to that for water years 1995–98. The resulting flow for Indian Creek for water years 1940–2005 is about 5,100 acre-ft/yr. Streamflow of the West Fork Carson River for water years 1941–70 and 1990–2002 is only 0.2 to 0.6 percent less than that for water years 1940–2005 (table 1). Thus, the volume of 5,100 acre-ft/yr is a reasonable estimate for inflow of Indian Creek during those periods as well.

Streamflow from Clear Creek enters Carson Valley near the northwestern boundary and is gaged about 2 mi upstream of the boundary. Flow at the gage averaged 4,210 acre-ft/yr for water years 1990–2002 (Maurer and others, 2004, p. 14). Maurer and Thodal (2000, p. 13) developed a relation between streamflow at the gage and flow at the Carson Valley boundary, based on measurements of flow losses from 1996 to 1998. Applying that relation to flow of Clear Creek for water years 1990–2002, flow from Clear Creek that enters Carson Valley is about 3,400 acre-ft/yr. Clear Creek also drains the Carson Range and because of the similarity of average annual streamflow for the West Fork Carson River for water years 1940–2005, 1941–70, and 1990–2002, 3,400 acre-ft/yr is a reasonable average annual volume for streamflow of Clear Creek for those periods.

Maurer and others (2004) estimated daily mean flow of perennial streams in the study area draining the Carson Range and Pine Nut Mountains (fig. 5, table 3, drainages 2–15, 17–18) for water years 1990–2002. Flow of perennial streams was estimated using the gaged flow of Daggett (site 6), Fredericksburg Canyon (site 15), Pine Nut (site 17), and Buckeye (site 18) Creeks, and Miller Spring (site 12). Flow from 10 other perennial but ungaged creeks was estimated using multivariate regressions of more than 400 individual discharge measurements against selected continuously gaged streams in and near Carson Valley (Maurer and others, 2004, p. 8).

Springs along Foothill Road also are tributary to the valley floor, however, data on their flow are sparse. Springs about 1 mi south of Jobs Canyon Creek (site 11) were called Benson Springs (site 13) by Maurer (1986, p. 16) and Jackson Springs by Nevada Division of Water Resources (Beutner and Squatrito, 1998). Maurer (1986, p. 16) estimated their combined flow to be 2,400 acre-ft/yr for water years 1981–83, and the average flow from five measurements by Beutner and Squatrito (1998) during water year 1997 totaled about 1,900 acre-ft/yr, about 1.55 times that of Miller Spring in water year 1997. Assuming that the flow of Benson/Jackson Springs varies similarly to that of Miller Spring, the average flow of Miller Spring for water years 1990–2002, 630 acre-ft/yr was multiplied by 1.55 to obtain an average flow for Benson/Jackson Springs of about 1,000 acre-ft/yr for 1990–2002. The flow of Walleys Hot Spring was estimated to be about 700 acre-ft/yr by Maurer (1986, p. 16) and was assumed to vary little. The total ungaged flow of Benson/Jackson and Walleys Hot Springs is estimated to be about 1,700 acre-ft/yr for water years 1990–2002 (table 3).

For water years 1990–2002, flow of perennial streams from the Carson Range to the valley floor, including Clear and Indian Creeks, totaled about 31,000 acre-ft/yr (table 3). As for Indian and Clear Creeks, flow of tributary streams from the Carson Range was assumed to vary similarly to that of the

Table 3. Average annual flow of perennial streams tributary to the floor of Carson Valley for water years 1990–2002, compared with average annual flow for wet water years 1995–97, and dry water years 1990–92, Nevada and California.

[**Site No.**: Location of sites are shown in figure 5. **Estimated average flow**: From Maurer and others (2004, p. 14), except as noted. **Average flow**: Determined from gaged flow for Daggett, Fredericksburg Canyon, Pine Nut, and Buckeye Creeks and Miller Spring, determined from daily flows estimated by Maurer and others (2004), except as noted. acre-ft/yr, acre-feet per year]

Site No.	Site name	Estimated average flow water years 1990–2002 (acre-ft/yr)	Average flow, in acre-ft/yr	
			Wet water years 1995–97	Dry water years 1990–92
	Carson Range			
1	Clear Creek	[1]3,400	[1]6,000	[1]1,790
2	Water Canyon Creek	1,900	3,100	950
3	James Canyon Creek	1,300	2,700	340
4	Sierra Canyon Creek	1,500	2,350	600
5	Genoa Canyon Creek	960	1,300	580
6	Daggett Creek	1,200	1,600	830
7	Mott Canyon Creek	1,700	2,100	1,300
8	Monument Creek	2,600	3,100	1,900
9	Stutler Canyon Creek	450	560	290
10	Sheridan Creek	1,300	1,900	600
11	Jobs Canyon Creek	1,700	2,500	760
12	Miller Spring	630	1,100	300
13	Benson/Jackson and Walleys Hot Springs	[2]1,700	[2]2,300	[2]1,180
14	Luther Creek	2,200	3,200	1,200
15	Fredericksburg Canyon Creek	2,890	5,300	1,200
16	Indian Creek	[3]5,100	8,700	[4]2,300
	Total – Carson Range (sites 1-16, rounded)	31,000	48,000	16,000
	Pine Nut Mountains			
17	Pine Nut Creek	670	1,200	300
18	Buckeye Creek	690	1,400	70
	Total – Pine Nut Mountains	1,360	2,600	380
	Total – Carson Valley (rounded)	32,000	51,000	16,000

[1] Gaged flow adjusted to obtain flow at study area boundary using relation from Maurer and Thodal (2000, p. 13).

[2] Flow estimated by multiplying flow of Miller Spring by 1.55—the ratio of flow at Miller Spring for water year 1997 to average flow for 1997 at Benson/Jackson Springs estimated from measurements by Beutner and Squatrito (1998), and adding an assumed constant flow of 700 acre-ft/yr for Walleys Hot Spring (Maurer, 1986, p. 16).

[3] Adjusted to obtain flow for water years 1990–92 by multiplying gaged flow for water years 1995–97 by 0.6—the ratio of flow of the West Fork Carson River for water years 1990–92 to 1995–98.

[4] Adjusted to obtain flow for water years 1990–92 by multiplying gaged flow for period of record (water years 1995–98) by 0.26—the ratio of flow of the West Fork Carson River for water years 1990–2002 to 1995–98.

West Fork Carson River and estimates for water years 1990–2002 also were reasonable volumes of inflow for water years 1940–2005 and 1941–70. However, flow of the West Fork Carson River was about 3 percent less for water years 1990–2005 than for water years 1940–2005 and 1990–2002. For this reason, total tributary inflow from the Carson Range estimated for water years 1990–2002 was decreased by 3 percent for water years 1990–2005, to obtain a representative volume of tributary inflow to the valley floor for that period (table 4). Flow of perennial streams from the Pine Nut Mountains in Buckeye and Pine Nut Creeks for water years 1990–92 totaled 1,360 acre-ft/yr, however, streamflow from the Pine Nut Mountains generally does not extend to the valley floor.

Flow of perennial streams tributary to the floor of Carson Valley varies considerably during extremely wet and dry periods. To illustrate the range in variability of this water resource, average flow of perennial streams was estimated for water years 1995–97 and 1990–92, representing wet and dry periods, respectively. The total flow volume of perennial streams tributary to the valley floor increased to about 51,000 acre-ft/yr during extremely wet periods and decreased to about 16,000 acre-ft/yr during extremely dry periods (table 3).

Flow estimates of streams tributary to the valley floor combined with flow of the East and West Forks of the Carson River results in a total surface-water inflow to Carson Valley of about 372,000 acre-ft/yr for water years 1940–71, and about 360,000 acre-ft/yr for water years 1990–2005 (table 4). The total surface-water outflow from Carson Valley is about 293,000 acre-ft/yr for water years 1940–71, and about 278,000 acre-ft/yr for water years 1990–2005. The decreased average flows for water years 1990–2005 compared to water years 1940–71 are likely the result of dry conditions from 1987 to 1992 and from 1999 to 2005.

Maurer and others (2006) showed that streamflow was lost to infiltration to the water table on the southern and eastern parts of the valley, whereas streamflow gains from seepage of ground water into the streambed of the Carson River and irrigation ditches takes place in the northwestern part of the valley. Streamflow gains and losses in the Carson Valley study area can be estimated using the difference between mean daily surface-water inflow to and outflow from Carson Valley. The total volume of the mean daily streamflow entering Carson Valley in the East and West Forks of the Carson River, Indian and Clear Creeks, and perennial streams and springs tributary to the valley floor was subtracted from mean daily streamflow leaving Carson Valley in the Carson River near Carson City for water years 1990–2002. The difference between surface-water inflow to and outflow from Carson Valley provides estimates of the volumes of streamflow gains and losses for the valley as a whole, and the periods of gains and losses during the year.

Gaged streamflow for the East and West Forks of the Carson River and the Carson River near Carson City, Daggett, Fredericksburg Canyon, and Clear Creeks, and Miller Spring are available, along with mean daily flows for ungaged perennial streams estimated by Maurer and others (2004) for water years 1990–2002. The mean daily flow for Benson/Jackson Springs was adjusted to water years 1990–2002 by multiplying mean daily flow of Miller Spring for water years 1990–2002 by 1.55, the ratio of flow recorded at Miller Spring in water year 1997 to flow estimated for Benson/Jackson

Table 4. Average annual surface-water inflow to and outflow from Carson Valley, Nevada and California, water years 1941–70 and 1990–2005.

[Average inflow data are from U.S. Geological Survey data base unless otherwise noted]

Water years	Average inflow, in acre-feet per year				Total average outflow (rounded, in acre-feet per year)
	East Fork Carson River near Gardnerville	West Fork Carson River near Woodfords	Tributary streams	Total (rounded)	Carson River near Carson City
1941–70	265,950	75,430	[1]31,000	372,000	293,000
1990–2005	256,240	73,350	[1,2]30,000	360,000	278,000

[1]Flow from table 3. Flow does not include flow of Pine Nut and Buckeye Creeks, which generally are not tributary to the valley floor.

[2]Flow for water years 1990–2005 decreased by 3 percent; the difference in average annual flow of West Fork Carson River between water years 1990–2002 and 1990–2005.

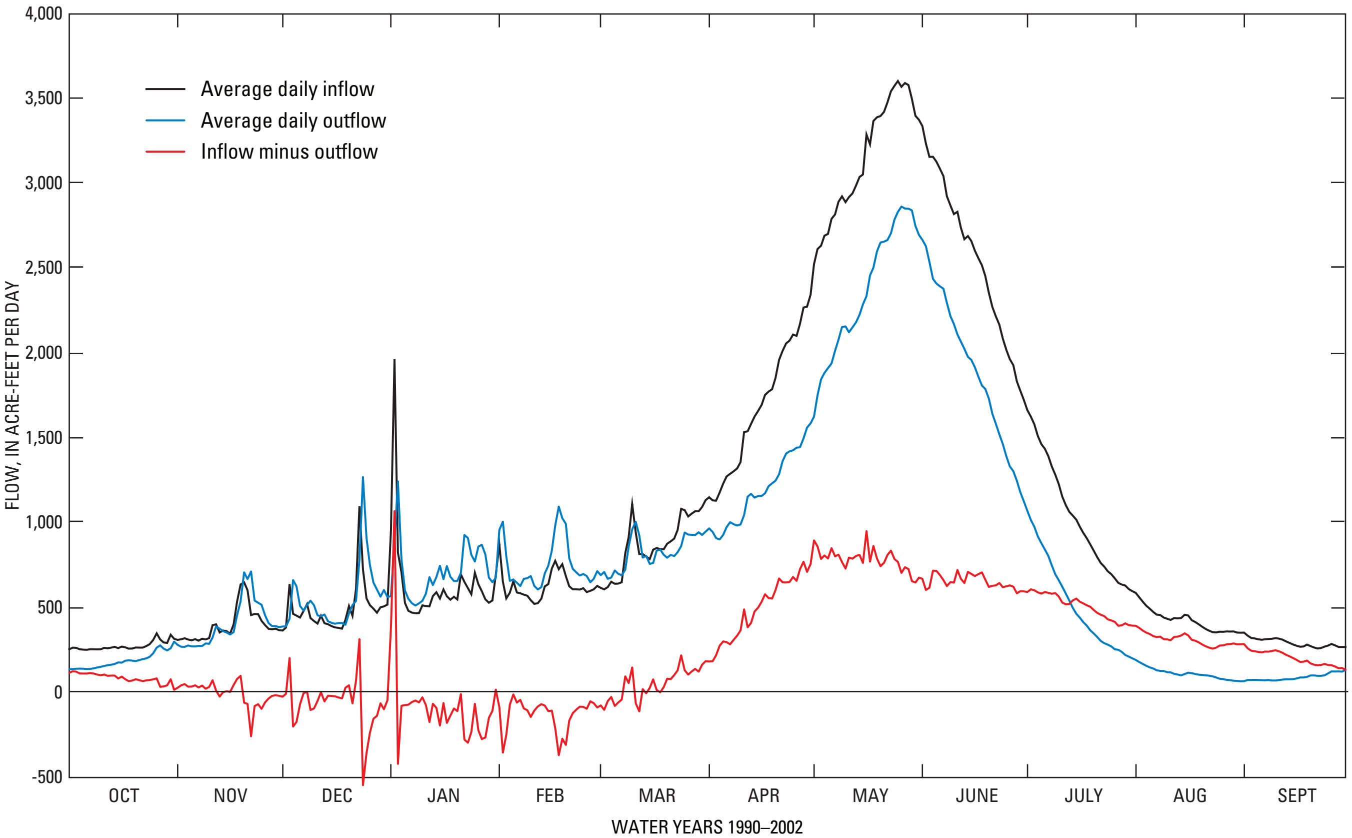


Figure 11. Mean daily surface-water inflow to and outflow from Carson Valley, and difference between inflow and outflow for water years 1990–2002.

Springs in water year 1997. The mean daily flow of Indian Creek for 1995–98 was adjusted by the ratio 0.6 of flow in the West Fork Carson River during 1995–98 to flow during 1990–2002, discussed previously. The mean daily flow of Clear Creek also was adjusted to provide estimates of flow at the Carson Valley boundary using the relation provided by Maurer and Thodal (2000, p. 13). Because streamflow from Pine Nut and Buckeye Creeks is lost to infiltration prior to reaching the valley floor, their streamflow was not included as flow tributary to the valley floor.

Close inspection of hourly flows recorded at the gaging stations on the Carson River shows that peak flows of the Carson River near Carson City lag from 16 to over 20 hours behind peak flows of the East and West Forks of the Carson River. Because mean daily flows were used to estimate streamflow gains and losses, the effect of the time lag depends on the time of day when peak flows occurred. Peaks flows on the East and West Forks of the Carson River that occurred from midnight to about 8 AM would be recorded at the gage near Carson City on the same day. In addition, the time lags between peak flows of ungaged perennial streams tributary to Carson Valley and the gage near Carson City are not known, but are likely less than 16 to 20 hours. For these reasons, unlagged mean daily inflow was subtracted from outflow, with the assumption that apparent streamflow losses caused by not considering a lag time were largely offset by streamflow gains on the following day.

Inflow to Carson Valley generally was greater than outflow from the valley from mid-March to mid-November (fig. 11). Outflow from Carson Valley was greater than inflow to the valley from mid-November through mid-March, except for short periods in December and January when the calculated mean daily flow was affected by large mean daily flows caused by floods. For water years 1990–2002, the volume of streamflow loss during summer months was about 89,000 acre-ft, and the volume of streamflow gain during winter months was about 16,000 acre-ft. For purposes of the ground-water budget, these volumes were assumed to be representative of water years 1990–2005.

Precipitation on Basin-Fill Sediments and Recharge from Precipitation on Quaternary Eolian Sand and Gravel Deposits and the Western Alluvial Fans

The distribution of average annual precipitation for Carson Valley was estimated by Maurer and Halford (2004, p. 35) using two independent methods, resulting in a range of 250,000 to 270,000 acre-ft/yr for the study area. Both methods used data collected from 14 stations in and near Carson Valley adjusted to a common period, 1971–2000. The 14 stations were located on the valley floor, on the western and eastern alluvial fans, and at higher altitudes in the Pine Nut Mountains and near the crest of the Carson Range. The estimate of 250,000 acre-ft/yr was obtained using a distribution of precipitation developed by Daly and others (1994) for the Western United States called Precipitation-elevation Regressions on Independent Slopes Model (PRISM). The PRISM distribution overestimated precipitation on the eastern side of the valley by 80 to 90 percent, and so, was adjusted to match measured average annual precipitation at the 14 stations (Maurer and Halford, 2004, p. 32). The estimate of 270,000 acre-ft/yr was obtained using two linear relations between annual precipitation and altitude, one for the western and one for the eastern side of Carson Valley. The distribution of annual precipitation in Carson Valley obtained using the two methods are applied elsewhere in this report and will be referred to as the linear relations and adjusted PRISM precipitation distributions. Estimates of annual precipitation on selected areas of Carson Valley obtained from the two methods and used in calculations in this report are shown in table 5. The volumes of precipitation on selected areas estimated from both methods were used in this report for comparison with other water-budget components to evaluate which method may provide the most reasonable estimate of annual precipitation.

Inflow from precipitation to basin-fill sediments in Carson Valley from the Carson Range and the Pine Nut Mountains, is included in estimates of streamflow from those areas. Similarly, inflow from precipitation is accounted for in estimates of ground-water recharge from precipitation on Quaternary gravel and eolian sand deposits and the western alluvial fans. Maurer and others (2006, p. 32) concluded that in areas of alluvial fans and Tertiary sediments on the eastern side of Carson Valley, precipitation does not percolate to the water table to become recharge. Thus, inflow from precipitation is limited to that which falls directly on the basin-fill deposits.

Average annual precipitation on Quaternary basin-fill deposits, including areas of pasture grasses in Jacks Valley, ranges from 37,000 to 39,000 acre-ft/yr from the linear relations and the adjusted PRISM distributions, respectively, for water years 1971–2000 (table 5). The volume of 38,000 acre-ft/yr represents an average for precipitation on Quaternary basin-fill deposits estimated using the two methods. Average annual precipitation at Minden was 8.4 in. for water years 1971–2000, 8.3 in. for water years 1941–70, and 8.7 in. for water years 1990–2005 (National Oceanic and Atmospheric Administration, written commun., 2005). The differences in average annual precipitation at Minden represent a decrease of about 1 percent for water years 1941–70 and an increase of about 5 percent for water years 1990–2005. Given the relatively small difference between the two periods, the volume of 38,000 acre-ft/yr was assumed to reasonably represent precipitation on basin-fill deposits for both periods.

Table 5. Average annual precipitation estimated using the linear relations and adjusted PRISM distributions for selected areas of Carson Valley, Nevada and California.

Location	Area (acres)	Precipitation, in acre-feet per year	
		Linear relations	Adjusted PRISM
Carson Range			
Perennial stream drainages	21,160	52,500	40,500
Ephemeral stream drainages	13,750	27,400	18,400
Total Carson Range	34,910	79,900	58,900
Western Quaternary alluvial fans	11,000	14,300	10,400
Total Carson Range and alluvial fans	45,900	94,200	69,300
Pine Nut Mountains			
Pine Nut and Buckeye Creeks	35,300	42,500	40,700
Eastern Quaternary alluvial fans and ephemeral stream drainages	100,500	88,500	91,300
Total – Pine Nut Mountains	135,800	131,000	132,000
Quaternary gravel deposits	3,100	2,500	2,900
Quaternary eolian sand deposits	4,500	3,200	3,800
Quaternary basin-fill deposits[1]	52,000	37,000	39,000
Rabbitbrush and greasewood	5,440	3,800	4,000
Non-irrigated pasture	1,400	980	1,000
Open water	1,690	1,200	1,300
Cottonwood and willow	1,420	1,000	1,100
Alluvial fans in California	3,920	6,200	5,000

[1] Includes area of pasture grasses in Jacks Valley.

Maurer and others (2006, p. 32) estimated recharge from precipitation at nine sites on the eastern side of Carson Valley using soil-chloride data collected from boreholes (fig. 5). Results showed that recharge from infiltration of precipitation at two sites near the northern end of Carson Valley was 0.04 ± 0.01 ft/yr on Quaternary gravel deposits capping Indian Hills, and 0.03 ± 0.01 ft/yr on Quaternary eolian sand deposits generally north and east of Johnson Lane (fig. 5; Maurer and others, 2006, p. 32). Recharge from infiltration of precipitation in these areas can be calculated from the estimated rates and the mapped areas of Quaternary gravel and eolian sand deposits, assuming that recharge rates estimated at the soil-chloride sites are applicable over their entire areal extent (table 6). The total estimated recharge from precipitation over the combined areas of gravel and eolian sand deposits is relatively small, ranging from about 200 to 300 acre-ft/yr (table 6).

The potential for recharge from infiltration of precipitation on the western alluvial fans may be evaluated using annual ET rates estimated by Maurer and others (2006) for the stands of bitterbrush and sagebrush that cover the fans, and the annual precipitation on the fans estimated by the linear relations and adjusted PRISM distributions (Maurer and Halford, 2004). ET from bitterbrush and sagebrush in water year 2004 was estimated to be 1.5 ft/yr at a site near the western end of Centerville Lane (fig. 2; Maurer and others, 2006, table 2). Assuming ET rates were similar for the entire area of the alluvial fans, a rate of 1.5 ft/yr results in an ET volume of about 16,500 acre-ft/yr. Estimates of annual precipitation on the western fans from both precipitation distributions were less than 16,500 acre-ft/yr (table 7). Streamflow may supply water for ET by vegetation near the stream channels, but for most of the fan area, precipitation is

Table 6. Estimates of annual ground-water recharge from precipitation in areas of Quaternary gravel and eolian sand deposits, Carson Valley, Nevada and California.

[**Area**: From table 5. **Estimated recharge rate**: From Maurer and others (2006, p. 32). **High and Low range recharge rates**: Uncertainty from Maurer and others (2006, p. 29)]

Quaternary deposits	Area (acres)	Estimated recharge rate (feet per year)	Estimated recharge (acre-feet)	High-range recharge rate (feet per year)	Estimated recharge (acre-feet)	Low range recharge rate (feet per year)	Estimated recharge (acre-feet)
Gravel	3,100	0.04	120	0.05	160	0.03	90
Eolian sand	4,500	0.03	140	0.04	180	0.02	90
Total recharge			260		340		180

Table 7. Estimates of average annual recharge from precipitation on western alluvial fans, compared to recharge from precipitation on Quaternary gravel and eolian sand deposits, Carson Valley, Nevada and California.

[**Area, Precipitation from linear relations,** and **Precipitation from adjusted PRISM**: Data from table 5. **Estimated recharge rate:** From Maurer and others (2006, p. 32). **Recharge as percentage of precipitation:** Annual recharge divided by annual precipitation from linear relations distribution, times 100. **Estimated recharge:** Estimated from recharge rate times area. **Estimated ET rate:** Annual precipitation from linear relations distribution minus estimated recharge divided by area. Shaded cells indicate rates used to estimate recharge. ET, evapotranspiration]

Quaternary deposits	Area (acres)	Precipitation, in acre-feet per year		Estimated recharge rate (feet per year)	Recharge as percentage of precipitation	Estimated recharge (acre-feet)	Estimated ET rate (feet per year)
		Linear relations	Adjusted PRISM				
Gravel	3,100	2,500	2,900	0.04	5	120	0.8
Eolian sand	4,500	3,200	3,800	0.03	4	140	0.7
Western alluvial fans	11,000	14,300	10,400	0.04	[1]3	440	1.3
				0.03	[1]2	330	1.3
					[2]5	700	1.2
					[2]4	570	1.2

[1]Estimated using recharge rate for Quaternary gravel and eolian sand deposits.

[2]Estimated using recharge as percentage of precipitation for Quaternary gravel and eolian sand deposits.

the only available source of water for ET. This suggests that recharge from precipitation may not take place on the fans, the volume of ET is overestimated, the volumes of precipitation are underestimated, or some combination of the latter two.

Precipitation estimated from the adjusted PRISM distribution is significantly less than that estimated from the linear relations on the western alluvial fans (table 7). As will be discussed in the following section, precipitation estimated using the adjusted PRISM distribution appears to underestimate precipitation on the Carson Range. The adjusted PRISM distribution likely underestimates precipitation on the western alluvial fans as well. For this reason, estimates of recharge from precipitation on the western alluvial fans will be made using precipitation estimated from the linear relations.

One possible cause for overestimation of ET is that vegetation at the site where ET was estimated may not be representative of the entire area of the western alluvial fans. Bitterbrush at the site is 6 to 7 ft tall and quite vigorous, with plant density estimated to be about 35 percent (Maurer and others, 2006, p. 10). Plant vigor and density in other areas of the western alluvial fans may be less than that at the ET site. The ET rate of 1.5 ft/yr is near the high range of ET rates reported for xerophytic vegetation elsewhere in Nevada (table 8).

It is reasonable to assume that some recharge from precipitation takes place on the western alluvial fans because precipitation is greater on the fans than at the soil-chloride sites. Bitterbrush and sagebrush also are the predominant types of vegetation at the soil-chloride sites (Maurer and others, 2006, p. 24), and soils on the western alluvial fans also consist of coarse-grained sand and gravel. Assuming that recharge from precipitation on the western alluvial fans does take place, recharge was estimated using rates determined from the soil-chloride sites on Quaternary gravel and eolian sand deposits and, for comparison, using recharge rates as a percentage of precipitation.

Estimated recharge from precipitation on the western alluvial fans may range 300 to 400 acre-ft/yr from application of rates estimated for the gravel and eolian sand deposits, 0.03 to 0.04 ft/yr, to the area of the western alluvial fans (table 7). The volumes of 300 to 400 acre-ft/yr range from 2 to 3 percent of the precipitation on the fans estimated using the linear relations distribution. ET rates for bitterbrush and sagebrush, calculated as the difference between precipitation and recharge and divided by the area of the fans, is about 1.3 ft/yr, assuming no runoff from the fans. These rates are somewhat less than the rate of 1.5 ft/yr estimated by Maurer and others (2006), but may be more reasonable average ET rates for the entire area of the alluvial fans. However, the volumes of 300 to 400 acre-ft/yr may be underestimated because precipitation rates are greater on the western alluvial fans than at the soil-chloride sites farther east.

Estimates of recharge on the western alluvial fans based on their greater rates of precipitation may be calculated using the percentage of precipitation that becomes recharge at the soil-chloride sites, from 4 to 5 percent (table 7). If 4 to 5 percent of the precipitation on the western alluvial fans is assumed to become recharge, recharge may range from 600 to 700 acre-ft/yr. The resulting ET rates for the fans calculated using these volumes is about 1.2 ft/yr, similar to those calculated using the direct application of the soil-chloride recharge rates. Because it is uncertain which method of estimating recharge on the western alluvial fans may be more reasonable, recharge from precipitation on the western alluvial fans is estimated to range from 300 to 700 acre-ft/yr.

Table 8. Annual evapotranspiration rates reported for selected types of xerophytic vegetation in various locations.

Vegetation type	Location	Reported evapotranspiration rate (feet per year)	Source
Xerophytic	Paradise Valley, Nev.	[1]0.75	Loeltz and others (1949, p. 35)
Xerophytic	North-central Nev.	[2]0.8–1.0	Berger (2000, p. 20)
Xerophytic	North-central Nev.	[1]1.0	Plume (1995, p. 55)
Xerophytic (upland desert)	Ruby Mountains, Nev.	[2]1.0	Berger and others (2001, p. 16)
Ponderosa Pine	Northern New Mexico	[1]1.5	Brandes and Wilcox (2000, p. 36)
Ponderosa Pine and bitterbrush	Eagle Valley, Nev.	[1]0.9–1.6	Maurer and Berger (1997, tables 8 and 9)
Lodgepole Pine	Colorado	[2]1.5	Bossong and others (2003, p. 36)
Pinyon and juniper	Tracy, Nev.	[1]1.0	Thodal and Tumbusch (2006, table 6)
Sagebrush	Tracy, Nev.	[1]1.0	Thodal and Tumbusch (2006, table 6)
Sagebrush and bitterbrush	Eagle Valley, Nev.	[1]0.8–1.1	Maurer and Berger (1997, tables 8 and 9)
Bitterbrush	Carson Valley, western alluvial fans	[2]1.5	Maurer and others (2004, p. 22)

[1]Estimated as residual from water balance.

[2]Estimated from micrometeorological measurements.

Ground-Water Inflow to Carson Valley

Ground-water inflow to Carson Valley was estimated for the Carson Range and western alluvial fans, and the Pine Nut Mountains and eastern alluvial fans. Ground-water inflow from the area beneath Clear Creek was estimated previously by Maurer and Thodal (2000, p. 33 and 34). For the water budgets, ground-water inflow to Carson Valley beneath Clear Creek was assumed to range from 400 to 2,500 acre-ft/yr and averaged about 1,400 acre-ft/yr.

Estimates of ground-water inflow from the Carson Range include subsurface inflow from the perennial drainages, infiltration of precipitation on the western alluvial fans, and infiltration of streamflow across the western alluvial fans. Estimates of ground-water inflow from the Pine Nut Mountains were limited to subsurface inflow from the drainages of Buckeye and Pine Nut Creeks and infiltration of streamflow on the eastern alluvial fans.

Ground-water inflow was estimated using two independent methods. The first method combines estimates of subsurface inflow from perennial stream drainages of the Carson Range and Pine Nut Mountains using a water-yield equation derived by Maurer and Berger (1997), with estimates of recharge from infiltration of precipitation and streamflow. This method will be referred to as the water-yield method. The second method is referred to as the chloride-balance method; discussed by Wilson and Guan (2004) and used in other locations throughout Nevada (Dettinger, 1989; Berger, 2005). Subsurface inflow estimated using the chloride balance method incorporates recharge from precipitation and infiltration of streamflow on the alluvial fans.

Subsurface Inflow from the Carson Range and Pine Nut Mountains

The high rate of precipitation on the crest of the Carson Range provides a likely source for subsurface inflow from the mountain blocks to basin-fill aquifers on the floor of Carson Valley. Maurer and Berger (1997, p. 32) estimated more than 3,000 acre-ft/yr of subsurface inflow from similar granitic, metamorphic, and volcanic rocks in mountain blocks surrounding the much smaller area of Eagle Valley (fig. 1). Wilson and Guan (2004, p. 113–115) note the high potential for mountain block recharge to basin-fill aquifers in other semiarid settings.

The potential for subsurface inflow from the mountain blocks may be estimated by comparing the annual runoff from perennial stream drainages determined by Maurer and others (2004, p. 14), to the annual precipitation that falls on the drainages. Runoff as a percentage of precipitation estimated from linear relations ranges from about 20 to 75 percent for the perennial stream drainages on the western side of Carson Valley with the exceptions of the Stutler Canyon and Sheridan Creeks (sites 9 and 10, respectively, table 9, fig. 5). The low percentage of runoff from Stutler Canyon Creek, 11 percent, compared to the high percentage of runoff from Sheridan Creek, 93 percent, suggests that subsurface flow may take place from the upper part of the Stutler Canyon Creek drainage to the Sheridan Creek drainage. The Sheridan Creek drainage is small and its source of flow is a series of springs that issue from the base of a ridge between the two drainages (fig. 5). Because the upper part of the Stutler Canyon drainage bends to the west of and lies higher than Sheridan Creek, subsurface flow between the two drainages appears likely. For this reason, these two drainages were combined for estimates of subsurface inflow.

Runoff as a percentage of precipitation estimated from the adjusted PRISM distribution ranges from about 30 to more than 100 percent for drainages on the western side of Carson Valley (table 9). The volume of runoff is greater than the volume of precipitation for the Monument Creek (site 8) drainage, suggesting that either runoff is overestimated or precipitation is underestimated. Because the estimate of runoff is based on many individual measurements of streamflow, the precipitation volume from the adjusted PRISM distribution is most likely underestimated.

Runoff from gaged perennial stream drainages in Eagle Valley underlain by similar metamorphic and granitic rocks was reported by Maurer and Berger (1997, p. 32) to range from about 20 to 30 percent of precipitation. Runoff as a percentage of precipitation estimated from the linear relations was close to this range for many of the perennial stream drainages in Carson Valley but ranges from 45 to 74 percent for Water Canyon (site 2), Mott Canyon (site 7), Monument (site 8), and Fredericksburg Canyon Creeks (site 15). The drainages of Water Canyon and Fredericksburg Canyon Creeks are underlain by mixtures of metamorphic and granitic rocks. However, the drainages of Mott Canyon and Monument Creeks are underlain entirely by granitic rocks, as are other drainages with lower percentages of runoff. Thus, the type of bedrock does not appear to explain the differences in the percentage of runoff from precipitation for drainages in the Carson Range.

The drainages of Mott Canyon and Monument Creeks have significantly less conifer cover than the other drainages, 36 and 18 percent, respectively (table 9). Less conifer cover likely reduces the amount of ET from those drainages, increasing the amount of runoff relative to the other drainages. Less conifer cover in these two drainage may be caused, in part, by the Autumn Hills fire which burned the lower half of the drainages in June, 1996 (Michael Wilde, U.S. Forest Service, written commun., 2006). However, streamflow measurements of Mott Canyon Creek, on which the estimate of annual runoff was based, were made prior to the fire from the late 1980s to 1996 (Maurer and others, 2004, p. 11).

Table 9. Drainage area and average annual flow of perennial streams, annual precipitation in drainages estimated from linear relations and PRISM distributions, runoff as a percentage of precipitation, and bedrock type and percentage of conifer cover for perennial stream drainages, Carson Valley, Nevada and California.

[**Runoff water years 1990–2002**: From Maurer and others (2004, p. 14). **Runoff as percentage of precipitation from linear relations** and **adjusted PRISM**: Runoff divided by precipitation, times 100. **Percentage of conifer cover**: Determined from Arc/Info coverage obtained from U.S. Forest Service (Kathy Braton, written commun., 2006). na, indicates not available]

Site No. (fig. 5)	Site name	Drainage area (acres, rounded)	Runoff water years 1990–2002 (acre-feet)	Linear relations		Adjusted PRISM		Bedrock type (see fig. 5)	Percentage of conifer cover
				Estimated annual precipitation (acre-feet)	Runoff as percentage of precipitation	Estimated annual precipitation (acre-feet)	Runoff as percentage of precipitation		
2	Water Canyon Creek	1,700	1,900	4,200	45	3,300	57	Metamorphic and granitic	67
3	James Canyon Creek	1,300	1,300	3,400	38	2,300	56	Metamorphic	67
4	Sierra Canyon Creek	2,000	1,500	4,900	31	4,000	37	Metamorphic and granitic	59
5	Genoa Canyon Creek	1,400	960	3,200	30	2,700	36	Granitic	73
6	Daggett Creek	2,400	1,200	5,600	21	4,300	28	Granitic	55
7	Mott Canyon Creek	1,300	1,700	3,300	52	2,500	67	Granitic	36
8	Monument Creek	1,500	2,600	3,500	74	2,500	102	Granitic	18
9	Stutler Canyon Creek	1,600	450	4,000	11	2,600	17	Granitic	52
10	Sheridan Creek	640	1,300	1,400	93	700	180	Granitic	46
9–10	Stutler Canyon and Sheridan Creeks combined	2,200	1,800	5,400	33	3,300	53	Granitic	49
11	Jobs Canyon Creek	2,000	1,700	5,500	31	3,900	44	Granitic	37
14	Luther Creek	2,800	2,200	7,200	30	5,700	38	Granitic	44
15	Fredericksburg Canyon Creek	2,400	2,900	6,400	45	5,800	50	Metamorphic and granitic	52
17	Pine Nut Creek	6,400	670	8,500	8	8,700	8	Metamorphic	na
18	Buckeye Creek	28,900	690	34,000	2	32,000	2	Granitic	na

Runoff is 2 and 8 percent of precipitation estimated from the linear relations for Buckeye (site 18) and Pine Nut (site 17) Creeks, respectively, on the eastern side of Carson Valley. These lower percentages may be caused by the low amounts of precipitation in the Pine Nut Mountains. The low amounts of annual precipitation do not provide sufficient water in excess of ET to produce runoff comparable to the western side of Carson Valley. Runoff as a percentage of precipitation estimated from the adjusted PRISM distribution for Buckeye and Pine Nut Creeks was similar to that estimated using the linear relations because the volumes of estimated precipitation were similar.

Water-Yield Method

Maurer and Berger (1997, p. 31 and 34) derived equations that predict runoff and water yield (the sum of runoff and subsurface flow) from annual precipitation for Eagle Valley, immediately north of Carson Valley and having a similar geologic setting and distribution of precipitation. Those equations were applied to drainages in Carson Valley to evaluate the estimates of precipitation and runoff, and estimate water yield and subsurface flow. Application of the equation predicting runoff from precipitation can be used to evaluate the precipitation estimates by solving the equation for precipitation using runoff determined for water years 1990–2002. This assumes that runoff estimates are more accurate than the estimates of precipitation.

Table 10. Drainage area and average annual flow of perennial streams, annual precipitation estimated from linear relations and adjusted PRISM distributions, and predicted annual flow and precipitation, Carson Valley, Nevada and California.

[**Runoff water years 1990–2002**: From Maurer and others (2004, p. 14). **Annual runoff**: Runoff in acre-feet divided by drainage area, and multiplied by 12 to obtain runoff, in inches. **Annual runoff predicted from precipitation**: Runoff estimated using equation from Maurer and Berger (1997, p. 31) from precipitation estimated from linear relations distribution. **Annual precipitation estimated from linear relations and adjusted PRISM**: Annual precipitation from table 9 divided by drainage area and multiplied by 12 to obtain precipitation, in inches. **Annual precipitation predicted from runoff**: Annual precipitation estimates using equation from Maurer and Berger (1997, p. 34) from annual runoff]

Site No. (fig. 5)	Site name	Drainage area (acres, rounded)	Runoff water years 1990–2002 (acre-feet)	Annual precipitation, in inches			Annual runoff, in inches	
				Estimated from linear relations	Estimated from adjusted PRISM	Predicted from runoff	From drainage area	Predicted from precipitation
2	Water Canyon Creek	1,700	1,900	30	23	33	13	9
3	James Canyon Creek	1,300	1,300	31	21	32	12	11
4	Sierra Canyon Creek	2,000	1,500	29	24	30	9	8
5	Genoa Canyon Creek	1,400	960	27	23	29	8	6
6	Daggett Creek	2,400	1,200	28	21	27	6	6
7	Mott Canyon Creek	1,300	1,700	29	23	34	15	8
8	Monument Creek	1,500	2,600	28	20	36	21	6
9–10	Stutler Canyon and Sheridan Creeks combined	2,200	1,800	29	21	30	10	8
11	Jobs Canyon Creek	2,000	1,700	33	23	31	10	14
14	Luther Creek	2,800	2,200	30	24	30	9	9
15	Fredericksburg Canyon Creek	2,400	2,900	32	29	33	14	12
17	Pine Nut Creek	6,400	670	16	16	19	1.3	0.6
18	Buckeye Creek	28,460	690	14	13	14	0.3	0.3

Application of the equation produces annual precipitation rates comparable to those estimated from the linear relations distribution, with the exception of Mott Canyon and Monument Creeks (table 10). For those drainages, precipitation estimated using the equation was greater than that estimated from the linear relations distribution. This indicates that runoff from those drainages is a greater proportion of precipitation than for the drainages used to derive the equation in Eagle Valley. For the remaining drainages, the precipitation rates estimated using runoff were similar to those estimated from the linear relations. This indicates that precipitation estimated from the linear relations was consistent with the distribution of precipitation used to derive the equation and estimate water yield and subsurface flow in Eagle Valley. Annual precipitation rates were all greater than those estimated using the adjusted PRISM precipitation distribution, further indication that the distribution underestimates precipitation in the Carson Range. The adjusted PRISM distribution may underestimate precipitation on the steep eastern slope of the Carson Range because of the relatively large 1.9 mi grid used to develop the original PRISM distribution (Daly and others, 1994).

Application of the equation used to estimate runoff from precipitation that was estimated from the linear relations distribution produces runoff rates that were comparable to those determined for the drainages in Carson Valley, again with the exceptions of Mott Canyon and Monument Creeks. The estimated runoff was considerably lower for Mott Canyon and Monument Creeks (table 10), indicating that runoff from Mott Canyon and Monument Creeks was greater than runoff from the drainages in Eagle Valley used to derive the equation. In part, this may be caused by the relatively small amount of conifer cover for those drainages compared to the other drainages in Carson Valley (fig. 12). However, some drainages in Eagle Valley used to derive the equations had conifer cover of 20 to 30 percent (Maurer and Berger, 1997, p. 34).

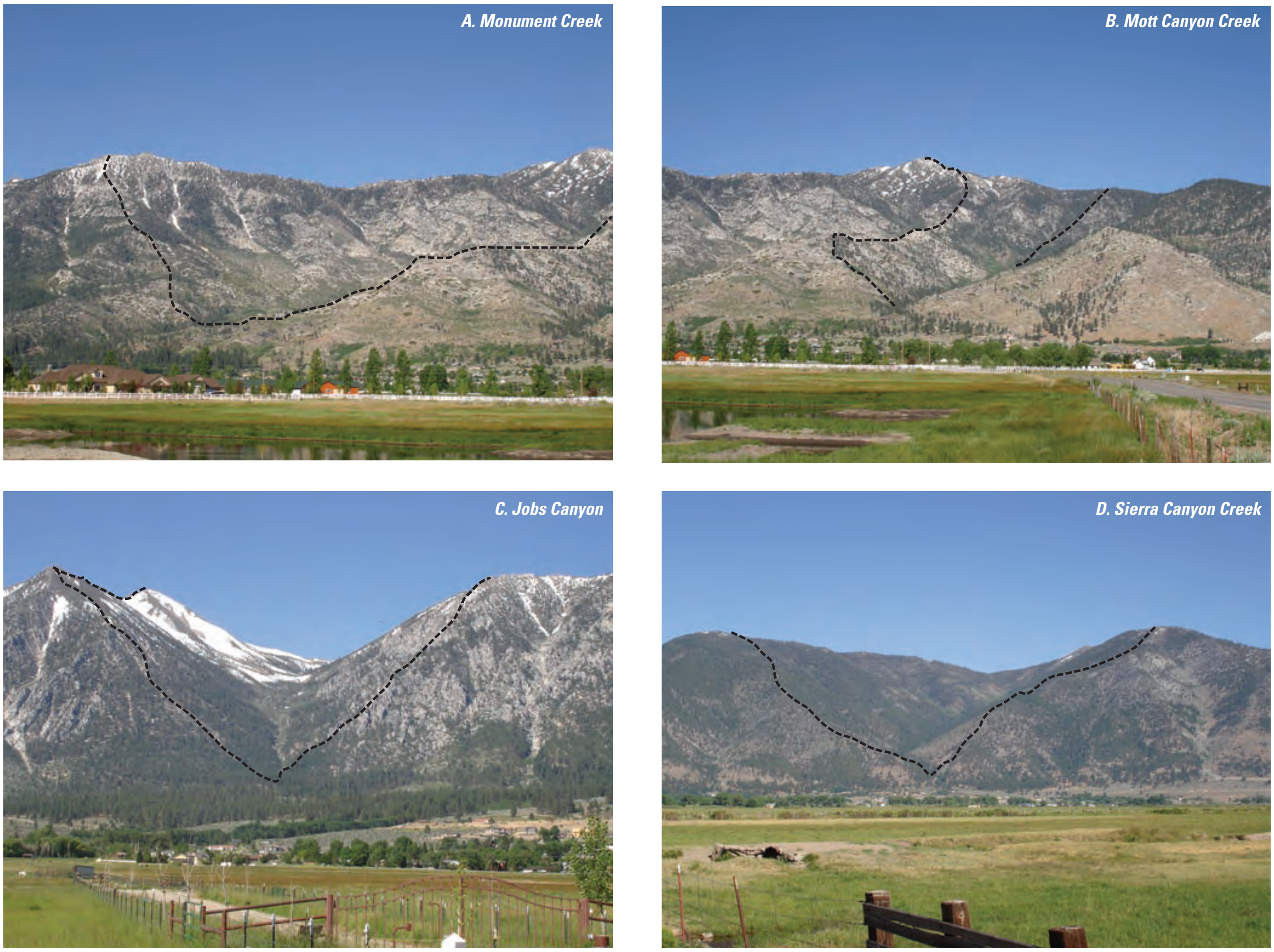


Figure 12. Comparison of Monument Creek and Mott Canyon Creek drainages to Jobs Canyon and Sierra Canyon Creek drainages.

Runoff was relatively greater from the Mott Canyon and Monument Creek drainages likely because the underlying bedrock is less permeable or fractured. The Mott Canyon and Monument Creek drainages are not incised as greatly into the mountain block as the other drainages (fig. 12) further suggesting more competent and less fractured bedrock underlying the drainages.

The equation used to estimate water yield from precipitation was applied to precipitation estimated from the linear relations distribution, The resulting estimates of water yield were less than the runoff for Water Canyon, Mott Canyon, Monument, and Fredericksburg Canyon Creeks (table 11). Runoff was greater than 45 percent of precipitation from these drainages (table 9), and subsurface flow is assumed to be negligible, likely because of relatively impermeable bedrock underlying the drainages. Ephemeral stream drainages generally are not deeply incised into the mountain blocks, similar to Mott Canyon and Monument Creeks. For this reason, subsurface flow from the ephemeral stream drainages also was assumed to be negligible.

Subsurface flow from the remaining drainages was calculated by subtracting runoff from the estimated water yield. In the Carson Range, estimates of subsurface flow totaled about 2,300 acre-ft/yr (table 11). In the Pine Nut Mountains, estimates of subsurface flow from Pine Nut and Buckeye Creeks totaled about 4,300 acre-ft/yr. The total estimated subsurface inflow to the floor of Carson Valley is about 6,600 acre-ft/yr. The general agreement between runoff and precipitation rates estimated using the equation from Maurer and Berger (1997) for most of the drainages indicates that the resulting estimates of subsurface flow are consistent with estimates made for Eagle Valley and are considered to be reasonable approximations for the perennial stream drainages in Carson Valley.

Table 11. Drainage area and average annual flow of perennial streams, estimated annual water yield and subsurface flow, ET rates, and ET as a percentage of precipitation, Carson Valley, Nevada and California.

[**Runoff water years 1990–2002:** From Maurer and others (2004, p. 14). **Estimated annual water yield**: Sum of runoff and subsurface ground-water inflow. Estimated using equation from Maurer and Berger (1997, p. 34) from precipitation estimated from linear relations distribution. **Estimated annual subsurface inflow**: Water yield minus runoff, assumed to be negligible where runoff is greater than estimated water yield. **ET rate**: Annual precipitation minus runoff and subsurface flow, divided by drainage area. **ET rate as percentage of precipitation**: Annual precipitation minus runoff and subsurface flow, divided by annual precipitation, times 100]

Site No. (fig. 5)	Site name	Drainage area (acres, rounded)	Runoff water years 1990–2002 (acre-feet)	Estimated annual water yield (acre-feet)	Estimated annual subsurface inflow, rounded (acre-feet)	Evapotranspiration	
						Rate (feet per year)	Rate as percentage of precipitation
2	Water Canyon Creek	1,700	1,900	1,570	0	1.4	55
3	James Canyon Creek	1,300	1,300	1,360	60	1.6	60
4	Sierra Canyon Creek	2,000	1,500	1,730	200	1.6	64
5	Genoa Canyon Creek	1,400	960	1,040	80	1.5	67
6	Daggett Creek	2,400	1,200	1,890	700	1.5	66
7	Mott Canyon Creek	1,300	1,700	1,200	0	1.2	48
8	Monument Creek	1,500	2,600	1,170	0	.6	25
9 and 10	Stutler Canyon and Sheridan Creeks combined	2,200	1,800	1,890	100	1.6	64
11	Jobs Canyon Creek	2,000	1,700	2,400	700	1.6	57
14	Luther Creek	2,800	2,200	2,730	500	1.6	62
15	Fredericksburg Canyon Creek	2,400	2,900	2,630	0	1.6	55
Total, Carson Range					2,300		
17	Pine Nut Creek	6,400	670	1,320	700	1.1	85
18	Buckeye Creek	28,900	690	4,240	3,600	1.0	87
Total, Pine Nut Mountains					4,300		
Total, Carson Valley					6,600		

The estimates of subsurface flow calculated using the water-yield equation from Maurer and Berger (1997) may be evaluated by combining the estimates with runoff, and subtracting the total from estimated precipitation to obtain a volume of water lost to ET. The ET volume divided by the precipitation volume and multiplied by 100 provides ET as percentage of precipitation. The volume of ET divided by the area of the drainage, provides an ET rate. The resulting rates and percentages can be compared with values reported in the literature.

ET rates were lowest, 0.6 to 1.2 ft/yr for Monument and Mott Canyon Creeks, respectively, but range from 1.4 to 1.6 ft/yr at the remaining drainages in the Carson Range (table 11). ET as a percentage of precipitation ranges from 25 to 48 percent at Monument and Mott Canyon Creeks, and from 55 to 67 percent at the remaining drainages in the Carson Range. The lower ET for Monument and Mott Canyon Creeks corresponds to the lower amount of conifer cover in the drainages. ET rates for Pine Nut and Buckeye Creeks were about 1 ft/yr and ET as a percentage of precipitation was 85 and 87 percent, respectively.

ET rates reported for Ponderosa Pine and pinyon and juniper in other areas are about 1.5 and 1.0 ft/yr, respectively (table 8). ET as a percentage of precipitation also is similar to studies reviewed by Wilson and Guan (2004, p. 120) in the Wasatch Mountains of Utah where ET was estimated to range from 44 to 53 percent of precipitation. However, ET averaged 83 percent of precipitation over 3 years where ET was estimated by micrometeorological measurements (Bossong and others, 2003, p. 37) for a forested watershed in Colorado. Brandes and Wilcox (2000, p. 966) listed ET calculated as the residual of precipitation minus runoff to range from about 80 to 95 percent of precipitation for three studies of watersheds vegetated by Ponderosa Pine in Colorado and Arizona.

Thus, ET rates calculated using the estimates of subsurface flow compare well with those reported in the literature, but ET as a percentage of precipitation appears to be somewhat lower for the Carson Range than found elsewhere. Uncertainty in estimates of ET as a percent of precipitation when calculated indirectly, and variation in ET over widespread locations may cause the differences.

Chloride-Balance Method

An alternative method of estimating subsurface inflow from the mountain blocks is application of the chloride-balance method recently summarized by Wilson and Guan (2004, p. 122) and used elsewhere in Nevada (Dettinger, 1989; Berger and others, 2005). This method assumes that chloride in precipitation is concentrated as water is lost to ET in the mountain block, and that mountain block recharge may be estimated using the following equation (Wilson and Guan, 2004, p. 122):

$$R = (C_p P - C_r R)/C_g \qquad (1)$$

where

- R is annual recharge, in acre-ft/yr,
- C_p is the chloride concentration of precipitation, in mg/L, including wet fall (precipitation) and dry fall (dust),
- P is the annual precipitation, in acre-ft/yr,
- C_r is the chloride concentration of runoff from the mountain block, in mg/L,
- R is the annual runoff from the mountain block, in acre-ft/yr, and
- C_g is the chloride concentration of ground water near the mountain front, in mg/L.

Assumptions in the method are that precipitation and dry fall are the only source of chloride and that chloride is conservative, the chloride deposition and precipitation rate have been constant over the period of ground-water residence time within the mountain block, and that the chloride concentration of ground water represents the mean value of ground water that has been recharged from the mountain block (Wilson and Guan, 2004, p. 123).

For the Carson Range, ground water near the toe of the western alluvial fans has been recharged by a combination of subsurface inflow from the Carson Range, and infiltration of streamflow and precipitation on the fans. Application of equation 1 using the chloride concentration of ground water near the toe of the fans provides an estimate of recharge from all three sources. Precipitation estimated from the linear relations distribution was used because precipitation estimated from the adjusted PRISM distribution likely was underestimated for the Carson Range. The chloride concentration of precipitation was estimated to be 0.5 mg/L based on analysis of 79 snow samples from the Sierra Nevada (Feth and others, 1964, p. 35). Data on the chloride concentration of runoff and ground water near the toe of the western alluvial fans were obtained from the water-quality database of the USGS (http://nwis.waterdata.usgs.gov/nv/nwis/qwdata).

The chloride concentration of ground water sampled from 23 wells near the toe of the western alluvial fans (fig. 5) ranges from 0.1 to 3.0 mg/L and averages 1.1 mg/L with a standard deviation of 0.7 mg/L. An additional potential source of water and chloride along the fans is leachate from septic tanks. The use of septic tanks is thought to have caused nitrate dissolved-solids concentrations to increase from 1985 to 2001 along the western side of Carson Valley (Rosen, 2003, p. 4). Along with nitrate, recharge of leachate from the septic tanks may supply an additional source of chloride to ground water at the toe of the fans. For many of the ground-water samples from the toe of the fans, nitrate concentrations also were analyzed and samples with nitrate concentrations greater than 1.0 mg/L were assumed to represent ground water recharged in part by septic tank leachate (Rosen, 2003, p. 2). Nitrate concentrations from a total of 75 samples from 23 wells were 1.0 mg/L or less and were used to calculate the average concentration of ground water near the toe of the western alluvial fans.

The chloride concentration of streamflow of the West Fork Carson River likely is representative of perennial streams draining the Carson Range. Eighty-five samples from the West Fork Carson River near Woodfords, collected from 1960 to 1994 ranged from < 0.1 mg/L (reporting limit) to 2.5 mg/L, and average 0.9 mg/L, with a standard deviation of 0.6 mg/L

A volume of 27,000 acre-ft/yr was obtained for subsurface inflow from the Carson Range using equation 1, and average chloride concentrations of precipitation, runoff, and ground water near the toe of the western alluvial fans (table 12). The chloride concentrations for runoff, ground water, and precipitation were varied over a reasonable range for measured values to assess the uncertainty in the estimate of subsurface inflow. A reasonable range for the chloride concentration of precipitation was determined by Maurer and others (2006, p. 29) to be 0.3 to 0.6 mg/L. Ranges for the chloride concentration of runoff and ground water of ±1 standard deviation were used, 0.6 and 0.7 mg/L, respectively. The volumes of precipitation estimated using the linear relations distribution and runoff are assumed to be reasonable, based on the application of equation for runoff from precipitation and water yield, as discussed previously. The resulting estimates of recharge from subsurface inflow have a considerable range; from about 9,600 acre-ft/yr for the low range of chloride concentration in precipitation to 73,000 acre-ft/yr for the low range in chloride concentration in ground water.

ET rates calculated from the difference in total precipitation minus runoff and estimated subsurface inflow, divided by the area of the Carson Range and western alluvial fans were used to evaluate the estimates of subsurface inflow from the chloride-balance method (table 12). ET calculated from estimates of subsurface inflow from 27,000 to 37,000 acre-ft/yr ranges from 1 to 0.8 ft/yr, near the low end reported in the literature for Ponderosa Pine and bitterbrush (table 8).

Table 12. Estimated ground-water inflow from the Carson Range and western alluvial fans using the chloride-balance method, Carson Valley, Nevada and California.

[**Annual runoff from perennial stream drainages**: Includes sites 2-11, 14, and 15, table 9. **Annual precipitation**: From table 5. **Estimated ground-water inflow**: Estimated using equation 1, $R = (C_p P - C_r R)/C_g$ (Wilson and Guan, 2004, p. 122). **ET rate**: Determined from volume of total precipitation minus runoff and estimated ground-water inflow, divided by total area of Carson Range and western alluvial fans, 94,200 acres. Shaded cells indicate chloride concentration varied from average values]

Annual runoff from perennial stream drainages (acre-feet)	Annual precipitation, in acre-feet				Chloride concentration (milligrams per liter)			Estimated ground-water inflow (rounded, acre-feet per year)	ET rate (feet per year)
	On perennial stream drainages (acre-feet)	On ephemeral stream drainages (acre-feet)	On western alluvial fans (acre-feet)	Total	Precipitation	Runoff	Ground water		
19,700	52,500	27,400	14,300	94,200	[1]0.5	[2]0.9	[3]1.1	27,000	1.0
					[4]0.3	0.9	1.1	9,600	1.4
					[4]0.6	0.9	1.1	35,000	0.9
					0.5	[5]0.3	1.1	37,000	0.8
					0.5	[6]1.5	1.1	16,000	1.3
					0.5	0.9	[7]0.4	73,000	0.02
					0.5	0.9	[8]1.8	16,000	1.3

[1] From Feth and others (1964, p. 35), average of 79 snow samples from the Sierra Nevada.

[2] Average of 85 samples from West Fork Carson River, 1960–94.

[3] Average of samples from 23 wells along toe of western alluvial fans, 1976–2004.

[4] Range of uncertainty in chloride concentration of precipitation determined by Maurer and others (2006, p. 32).

[5] Average concentration of runoff –1 standard deviation, 0.6 mg/L.

[6] Average concentration of runoff +1 standard deviation, 0.6 mg/L.

[7] Average concentration of ground water –1 standard deviation, 0.7 mg/L.

[8] Average concentration of ground water +1 standard deviation, 0.7 mg/L.

ET from subsurface inflow of 73,000 acre-ft/yr was 0.02 ft/yr, indicating that the value was greatly overestimated. ET from subsurface inflow estimates of 9,600 to 16,000 acre-ft/yr were 1.4 and 1.3 ft/yr, respectively, comparing well with reported values. Assuming ET rates for the Carson Range may range from 0.8 to 1.4 ft/yr, a reasonable range for ground-water inflow from the Carson Range and western alluvial fans estimated using the chloride-balance method and constrained by ET rates was from about 10,000 to 40,000 acre-ft/yr.

The uncertainty in estimates for recharge from the Carson Range was compounded by results of Feth and others (1964, p. 43) who noted that the chloride concentration of some springs in the Sierra Nevada were lower than the average concentration of precipitation. They suggest that chloride may be removed from solution by adsorption, limiting the use of chloride as a geochemical tracer (Feth and others, 1964, p. 67). However, they further point out that the chloride concentration of snow ranged from approximately 0 to 1.6 mg/L. Thus, the low chloride concentration of some springs may be explained by recharge of snow with low chloride concentration directly to the aquifer, with no concentration by ET (Feth and others, 1964, p. 45). Such a process may explain some of the low concentrations measured in both ground-water and surface-water samples in Carson Valley. The use of average chloride concentrations of runoff and ground water along the toe of the western alluvial fans was assumed to account for differences caused by direct recharge along localized flow paths.

The chloride balance method also was applied to the Pine Nut Mountains where ground water on the eastern side of the valley has been recharged by a combination of subsurface inflow from Pine Nut and Buckeye Creek drainages, and infiltration of ephemeral streamflow. Recharge from infiltration of precipitation was thought to be minimal on the eastern side of the valley.

The average chloride concentration of ground water near the eastern side of the valley floor was determined from a total of 89 samples collected from 21 wells during 1983–2006. As for the western side of the valley, samples with nitrate concentration greater than about 1 mg/L were not included in the average. Welch (1994, p. 41) notes a difference in ground-water chemistry for wells near the Johnson Lane area compared with other parts of Carson Valley, likely caused by differences in underlying bedrock. For this reason, samples from within about 2 mi of the Johnson Lane area also were not included in the average. The average chloride concentration of ground water was 5.9 mg/L, ranging from a minimum of 3.7 mg/L to a maximum of 10.0 mg/L, with a standard deviation of 1.4 mg/L (table 13). Streamflow from the Pine Nut Mountains is lost to infiltration before reaching the valley floor, so the term for the volume of runoff is reduced to zero in equation 1. Precipitation from both the linear relations and adjusted PRISM distribution were used to estimate the volume of precipitation. As for the Carson Range, the chloride concentration of precipitation was varied from 0.3 to 0.6 mg/L and the chloride concentration of ground water was varied by ± 1 standard deviation to evaluate the uncertainty of the recharge estimates.

The resulting estimates of ground-water inflow from the Pine Nut Mountains using average chloride concentrations were the same, 11,000 acre-ft/yr, respectively, from precipitation estimated by the adjusted PRISM and linear relations distributions. Varying the chloride concentration of precipitation resulted in a range of estimated recharge from 6,700 to 13,000 acre-ft/yr, whereas varying the chloride concentration of ground water resulted in a range from 9,000 to 15,000 acre-ft/yr. All estimates resulted in an ET rate of about 0.9 ft/yr, slightly less than that estimated for stands of pinyon and juniper and sage brush near Tracy, Nevada by Thodal and Tumbusch (table 8; Thodal and Tumbusch, 2006).

Infiltration of Streamflow on Western Alluvial Fans

Streams draining the mountain blocks may lose flow to infiltration as they cross the coarse-grained alluvial fans. Such losses are an important part of the water budget in many closed basins of Nevada (Meinzer, 1917, p. 78; Cohen, 1964, p. 44; Cooley, 1968). However, in many of those basins, the alluvial fans are much broader than those on the western side of Carson Valley and often streams become ephemeral before reaching the valley floor. On the western side of Carson Valley, most fans extend for distances of less than 1 mi, many streams are diverted near the top or middle of the alluvial fans into pipelines for irrigation application on the valley floor, and streamflow remaining after diversion continues across the alluvial fans to join the irrigation distribution system on the valley floor.

Available streamflow measurements indicate that streamflow losses to infiltration beneath perennial streams on the western side of the valley are small. Measurements were made to determine streamflow losses using standard flow-tracker and pygmy meters in the spring of 2005 on Jobs Canyon (site 11), Sheridan (site 10), and Barber Creeks (flow included with adjacent Sheridan Creek in table 3), which cross the longest reach of alluvial fan on the western side of

Table 13. Estimated ground-water inflow from the Pine Nut Mountains and eastern alluvial fans using the chloride-balance method, Carson Valley, Nevada and California.

[**Annual precipitation on perennial stream drainages and eastern alluvial fans from linear relations and adjusted PRISM**: From table 5. **Estimated ground-water inflow using linear precipitation distribution and adjusted PRISM precipitation distribution**: Estimated using equation 1, $R = (C_p P - C_r R)/C_g$ (Wilson and Guan, 2004, p. 122). **ET rate from linear relation and adjusted PRISM distributions**: Determined from volume of total precipitation minus estimated recharge, divided by total area of Pine Nut Mountains and eastern alluvial fans, 135,800 acres. Shaded cells indicate chloride concentration varied from average values]

Annual precipitation on perennial and ephemeral stream drainages and eastern Quaternary alluvial fans, in acre-feet		Chloride concentration (milligrams per liter)		Estimated ground-water inflow using linear precipitation distribution (rounded, acre-feet per year)	ET rate from linear relation distribution (feet per year)	Estimated ground-water inflow using adjusted PRISM precipitation distribution (rounded, acre-feet per year)	ET rate from adjusted PRISM distribution (feet per year)
Linear relations	Adjusted PRISM	Precipitation	Ground water				
131,000	132,000	[1]0.5	[2]5.9	11,000	0.9	11,000	0.9
		[3]0.3	5.9	6,700	0.9	6,700	0.9
		[3]0.6	5.9	13,000	0.9	13,000	0.9
		0.5	[4]4.5	15,000	0.9	15,000	0.9
		0.5	[5]7.3	9,000	0.9	9,000	0.9

[1] From Feth and others (1964, p. 35).

[2] Average of 89 samples from 21 wells on eastern side of Carson Valley, 1983–2006.

[3] Range of uncertainty in chloride concentration of precipitation determined by Maurer and others (2006, p. 32).

[4] Average concentration of ground water, –1 standard deviation, 1.4 mg/L.

[5] Average concentration of ground water, +1 standard deviation, 1.4 mg/L.

Carson Valley, about 1.1 mi (fig. 5). Two repeat measurements were made in quick succession at two times during the day at sites near the head, middle, and toe of the fan, with flow rates of about 2 ft^3/s at Jobs Canyon Creek and 1 ft^3/s for the combined flow of Sheridan and Barber Creeks. The average flow difference for all measurements showed that Jobs Canyon Creek gained about 10 percent from the head to mid-fan, and lost about 5 percent from mid-fan to the toe of the fan, for an overall gain of about 5 percent. Similarly, the average flow measurements for the combined flow of Sheridan and Barber Creeks showed a gain of about 38 percent from the head to mid-fan, and a loss of about 3 percent from mid-fan to the toe, for an overall gain of about 35 percent. The accuracy normally applied to flow-tracker and pygmy meter measurements is 5 percent, so the small measured gain for Jobs Canyon Creek may not be meaningful. The measured gain for the combined flow of Sheridan and Barber Creeks likely is meaningful. However, the magnitude of the gain, about 0.3 ft^3/s, is small and if it takes place year round, amounts to only about 200 acre-ft/yr.

Conditions on the Jobs Canyon Creek alluvial fan may not be representative of streamflow losses or gains across other alluvial fans on the western side of Carson Valley. However, measurements of streamflow losses or gains on other fans are difficult to accomplish because the streamflow of other perennial streams are all or partly diverted into pipelines relatively short distances downstream of the bedrock contact. For the purposes of this report, streamflow losses to infiltration and recharge to basin-fill aquifers beneath perennial streams on the western side of Carson Valley were assumed to be negligible. This is likely because, over time, infiltration losses have established a shallow water table beneath the streambed that limits infiltration losses. The gaged flow and individual measurements of perennial streams made since the early 1980s show that streamflow is maintained across the entire length of the alluvial fans even during extended droughts. This is not the case for ephemeral streams which flow for only short periods, and for perennial streamflow of Buckeye and Pine Nut Creeks draining the Pine Nut Mountains, which is lost to infiltration prior to reaching the valley floor.

Ephemeral streamflow is largely lost to infiltration during spring runoff and during large precipitation events. Such loss is supported by observations of a local rancher, who reported rapid infiltration losses from Water Canyon Creek. In 2004, streamflow of about 2 ft^3/s from Water Canyon, which had been completely diverted to a pipeline for more than a year, was temporarily diverted back to the stream channel. Streamflow in the channel was completely lost to infiltration within a few hundred feet, and after two weeks, flow did not extend more than about 1,000 ft from the point of diversion (Loren Mernock, Manager, Ascuaga Ranch, oral commun., 2004). Thus, ephemeral streamflow likely infiltrates to the water table to become ground-water inflow to Carson Valley. Inspection of stream channels in ephemeral stream drainages supports this conclusion, in that most do not have active channels. Their channels often are vegetated with stands of bitterbrush and sage with an understory of grasses (fig. 13).

Based on unit-area runoff from perennial stream drainages, estimated ephemeral streamflow from the Carson Range is about 8,000 acre-ft/yr (Maurer and others, 2004, p. 14). Maurer and others (2004, p. 18) reported that the uncertainty associated with estimates of ephemeral streamflow is large, about 50 percent, based on application of the range in unit-area runoff from perennial drainages. Thus, ephemeral streamflow from the Carson Range may range from about 4,000 to 12,000 acre-ft/yr. Estimated in a similar manner, ephemeral streamflow from the Pine Nut Mountains is about 3,600 acre-ft/yr and may range from about 1,800 to 5,400 acre-ft/yr (Maurer and others, 2004, p. 14). The total ephemeral streamflow from the Pine Nut Mountains including the flow of Pine Nut and Buckeye Creeks was about 5,000 acre-ft/yr, ranging from 3,200 to 6,800 acre-ft/yr.

Estimates of ephemeral streamflow to Carson Valley totaled about 13,000 acre-ft/yr and may range from 7,000 to 19,000 acre-ft/yr (table 14). Flow in ephemeral channels during extreme storms may reach the valley floor and join flow of the Carson River. Flow during such storms was assumed to be small because the flow takes place for very short periods. During most periods of ephemeral streamflow, the flow infiltrates to recharge alluvial fan sediments and becomes ground-water inflow to basin-fill sediments.

Table 14. Estimates of ephemeral streamflow and high and low range estimates ±50 percent average, Carson Valley, Nevada and California.

[Average ephemeral streamflow from Maurer and others (2004) and high and low ranges estimates from Maurer and others (2004, p. 18)]

Ephemeral streamflow	Ephemeral streamflow estimates, in acre-feet per year		
	Average	Low range	High range
Carson Range	8,000	4,000	12,000
Pine Nut and Buckeye Creeks[1]	1,360	1,360	1,360
Pine Nut Mountains	3,600	1,800	5,400
Subtotal, Pine Nut Mountains, rounded	5,000	3,200	6,800
Total, Carson Valley, rounded	13,000	7,000	19,000

[1]Flow is gaged, low and high range not varied.

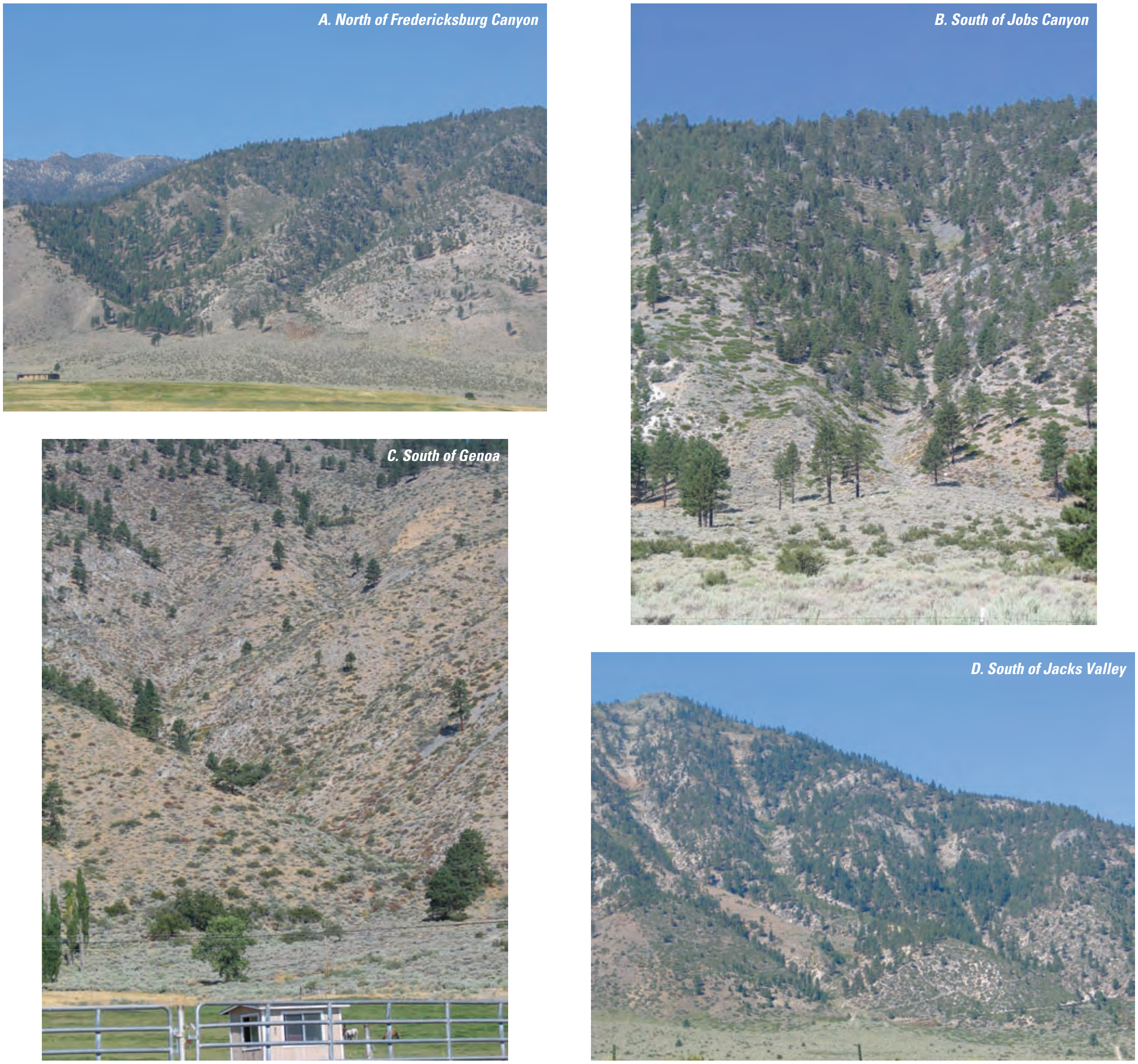


Figure 13. Examples of ephemeral stream drainages with no active channels.

The estimates of recharge from infiltration of streamflow and precipitation were combined with estimates of subsurface inflow from the perennial stream drainages to obtain the total ground-water inflow estimated using the water-yield method for comparison with that obtained using the chloride-balance method. The average estimate of ground-water inflow from the water-yield method was considerably less than that estimated using average chloride concentrations and the chloride-balance method for the Carson Range and western alluvial fans (table 15). Average estimates of ground-water inflow from both methods were similar for the Pine Nut Mountains and eastern alluvial fans. Differences in the low- and high-range estimates from the water-yield method largely were caused by the uncertainty in estimates of ephemeral streamflow. Total ground-water inflow to basin-fill sediments averaged 22,000 and 40,000 acre-ft/yr using the water-yield and chloride-balance methods, respectively, and low- and high-range estimates were from 15,000 to 58,000 acre-ft/yr including uncertainties.

Table 15. Estimates of ground-water inflow to Carson Valley, Nevada and California using the water-yield and chloride-balance methods.

Inflow source and method	Ground-water inflow estimates, in acre-feet per year		
	Average	Low range	High range
Clear Creek and northern Carson Valley			
Ground-water inflow from Eagle Valley[1]	1,450	400	2,500
Precipitation on Quaternary gravel and aeolian fan deposits[2]	250	200	300
Subtotal	1,700	600	2,800
Carson Range and western alluvial fans			
Precipitation on western alluvial fans[3]	500	300	700
Subsurface inflow from perennial stream drainages[4]	2,300	2,300	2,300
Infiltration of ephemeral streamflow[5]	8,000	4,000	12,000
Subtotal–water-yield method (rounded)	11,000	7,000	15,000
Ground-water inflow from chloride-balance method[6] (rounded)	27,000	10,000	40,000
Pine Nut Mountains and eastern alluvial fans			
Subsurface inflow from perennial drainages[4]	4,300	4,300	4,300
Infiltration of ephemeral streamflow[5]	5,000	3,200	6,800
Subtotal–water-yield method (rounded)	9,000	8,000	11,000
Ground-water inflow from chloride–balance method[7] (rounded)	11,000	6,700	15,000
Total for Carson Valley			
Total–water-yield method (rounded)	22,000	16,000	29,000
Total–chloride-balance method (rounded)	40,000	17,000	58,000

[1] From Maurer and Thodal (2000, p. 33–34).

[2] From table 7.

[3] From table 6.

[4] From table 11.

[5] From table 14.

[6] From table 12.

[7] From table 13.

The relative amounts of ground-water inflow from the California and Nevada portions of Carson Valley also is of interest to water planners in Douglas County (Daniel Holler, Douglas County Manager, oral commun., 2005). Estimates of ground-water inflow from the California portion of Carson Valley were made using estimates of streamflow from ephemeral stream drainages, precipitation on alluvial fans, and subsurface inflow from perennial stream drainages that lie within, or largely within, California (fig. 5).

Ephemeral stream drainages in the California portion of Carson Valley cover about 7,100 acres. The unit-area runoff from ephemeral stream drainages of the Carson Range was estimated to be 0.57 ft/yr by Maurer and others (2004, p. 17), resulting in runoff of about 4,000 acre-ft/yr from ephemeral stream drainages in California (table 16). The uncertainty associated with the unit-area runoff is about 50 percent (Maurer and others, 2004, p. 18) resulting in a range of 2,000 to 6,000 acre-ft/yr for ephemeral streamflow in California. Precipitation on alluvial fans in California from the linear relations distribution was about 6,200 acre-ft/yr (table 16). Applying rates of recharge from precipitation ranging from 0.03 to 0.05 ft/yr (see table 7) results in recharge estimates ranging from about 200 to 300 acre-ft/yr. Subsurface inflow estimated from Stutler Canyon, Sheridan, Jobs Canyon, Luther, and Fredericksburg Canyon Creeks totals about 1,300 acre-ft/yr (table 11). The combined estimates of ground-water inflow from the California portion of Carson Valley average about 6,000 acre-ft/yr and range from 4,000 to 8,000 acre-ft/yr (table 16). These estimates compare well with the estimate of 7,000 acre-ft/yr for ground-water inflow across the State line made by Glancy and Katzer (1976, p. 51).

Table 16. Estimates of annual ground-water inflow from the California portion of Carson Valley.

Inflow source and method	Ground-water inflow estimates, in acre-feet per year		
	Average	Low range	High range
Ephemeral streamflow[1]	4,000	2,000	6,000
Precipitation on alluvial fans[2]	250	200	300
Subsurface inflow from perennial stream drainages[3]	1,300	1,300	1,300
Total (rounded)	6,000	4,000	8,000

[1] Determined from application of unit-area runoff of 0.57 ft/yr (Maurer and others, 2004, p. 17) to 7,100 acres.

[2] Determined from application of recharge rates ranging from 0.03 to 0.05 ft/yr (table 7) to precipitation of 6,200 acre-ft/yr, estimated from linear relations distribution (table 5).

[3] From table 11, includes subsurface flow from Stutler Canyon, Sheridan, Jobs Canyon, Luther, and Fredericksburg Canyon Creeks. Low and high range not varied.

Effluent Imports

Effluent is imported to Carson Valley from Carson City and from three sources in the Lake Tahoe basin; the South Tahoe Public Utility District (STPUD) beginning in 1968, the Douglas County Sewer Improvement District #1 (DCSID), beginning in 1969, and Incline Village General Improvement District (IVGID) beginning in 1971. Beginning in 1988, Carson City began exporting effluent to Carson Valley for irrigation at the northern end of the valley. Total volumes imported have increased over time from about 3,000 acre-ft in the early 1970s to about 11,000 acre-ft/yr during the wet years of the mid-1900s, and decreased to about 8,600 acre-ft/yr in 2005 during dry years from 1999 to 2005. Average inflow of imported effluent for water years 1990–2005 is about 9,800 acre-ft/yr (table 17). For water years 1941–70, effluent imports to Carson Valley were negligible.

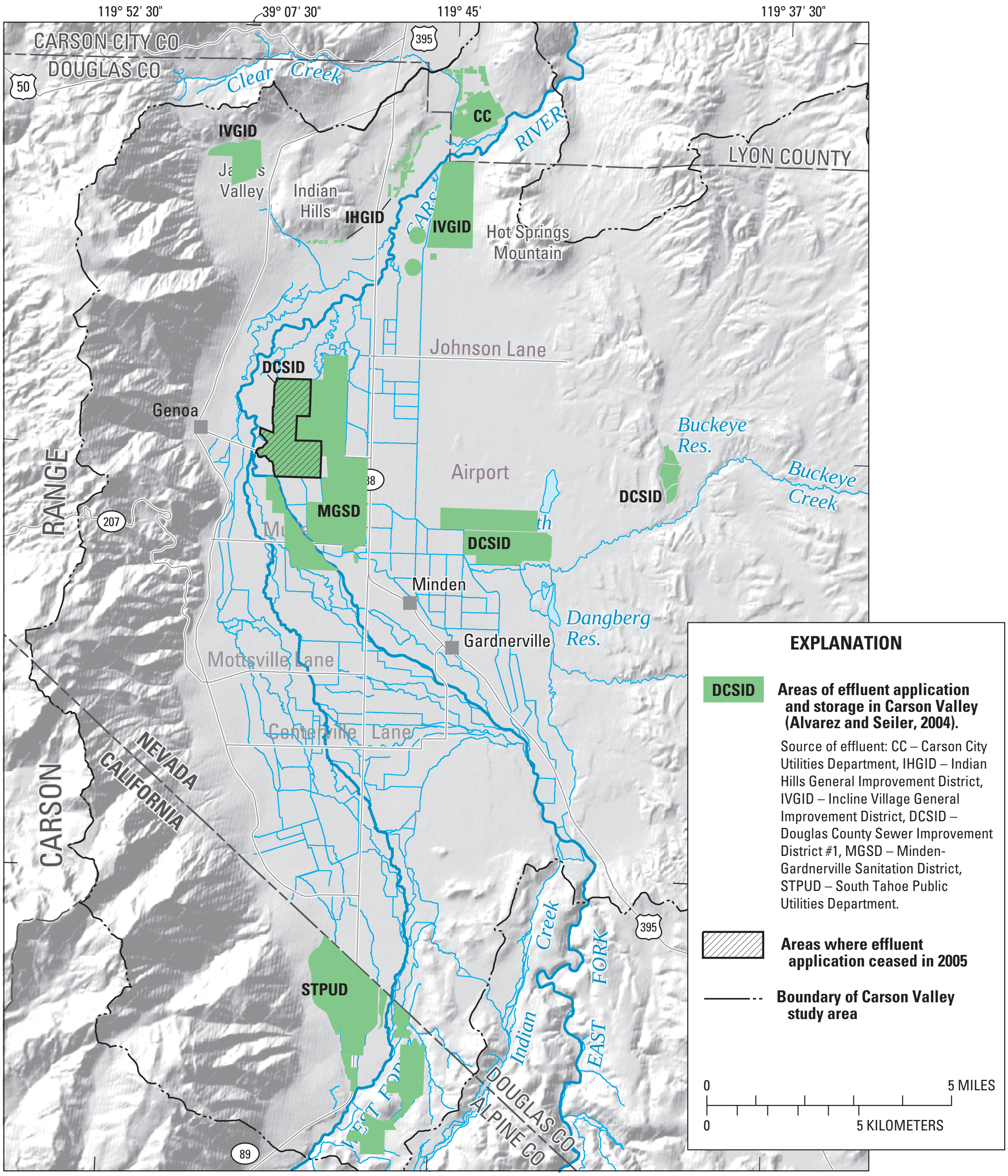
Effluent from the STPUD has been applied for irrigation in the Alpine County portion of southern Carson Valley since 1972 (fig. 14; Hal Bird, STPUD, written commun., 2005). Effluent from the DCSID (located at Zepher Cove, Nev.) has been imported to Carson Valley since 1968 (JWA Consulting Engineers, Inc. 2004, p. II-I). Effluent was discharged into Daggett Creek from 1968 to 1971 and into the Carson River immediately upstream of an irrigation diversion near Genoa Road from 1971 to 1981. Effluent was applied directly for irrigation along Genoa Road from 1981 to 1993. Beginning in 1993, the effluent was stored in a reservoir near the mouth of Buckeye Creek on the eastern side of Carson Valley and used for irrigation along Genoa Road, Muller Lane, and Stockyard Road (fig. 14). Effluent from the IVGID at Incline Village, Nev., has been exported to Carson Valley since 1971 (Harvey Johnson, IVGID, written commun., 2006). Effluent was discharged to the Carson River from 1971 to 1984 and used for irrigation in Jacks Valley. Beginning in 1984, wetlands were constructed north of Johnson Lane where effluent is stored and largely lost to evaporation with some used for irrigation near the wetlands and in Jacks Valley (fig. 14).

Based on data from the late 1990s up to 2004, about 80 percent of the imported effluent was applied for irrigation in Carson Valley, the remainder being lost to evaporation or infiltration beneath holding ponds (Hal Bird, STPUD, Harvey Johnson, IVGID; Kyle Menath, Carson City Utilities Department; Cindy Neissess, JWA Consulting Engineers, Inc., oral and written commun., 2006). Assuming this holds true for water years 1990–2005, the average volume applied for irrigation during that period was about 7,800 acre-ft/yr. In addition to imported effluent, about 1,700 acre-ft/yr of effluent generated within Carson Valley from the Minden-Gardnerville Sanitation District (MGSD) was applied for irrigation in 2005, however, records of the volumes applied prior to 2004 are not available (fig. 14; Frank Johnson, Minden-Gardnerville Sanitation District, written and oral commun., 2006). About

Table 17. Volumes of effluent imported to Carson Valley, Nevada and California, 1968–2005.

[**South Tahoe Public Utility District**: Data from Hal Bird, written commun., 2005, estimated 1972–96 by subtracting 600 acre-ft/yr from plant volumes. **Douglas County Sewer Improvement District #1**: Data from Kelvin Ikehara, written commun., 2005, estimated 1979–83. **Incline Village**: Data from Harvey Johnson, Incline Village General Improvement District, written commun., 2005, estimated 1972–74. **Carson City**: Data from Kyle Menath, Carson City Utilities Department, oral commun., 2005. **Abbreviations:** na, data for 1988–89 not available. –, Effluent not imported for years with no data]

Water year	Effluent imports by source, in acre-feet				Total imports (acre-feet)
	South Tahoe Public Utility District	Douglas County Sewer Improvement District #1	Incline Village	Carson City	
1968	1,280	–	–	–	1,280
1969	2,470	530	–	–	3,000
1970	2,640	543	–	–	3,183
1971	2,930	567	290	–	3,787
1972	2,695	722	300	–	3,717
1973	3,097	791	400	–	4,287
1974	3,178	992	500	–	4,669
1975	3,324	1,282	751	–	5,357
1976	3,252	1,456	745	–	5,454
1977	3,494	1,540	771	–	5,805
1978	4,292	1,903	1,005	–	7,199
1979	4,397	1,900	1,157	–	7,454
1980	3,752	1,950	1,354	–	7,056
1981	3,557	2,000	1,328	–	6,885
1982	4,948	2,050	1,435	–	8,433
1983	4,733	2,100	1,521	–	8,353
1984	4,208	2,260	1,351	–	7,820
1985	4,103	2,435	1,341	–	7,879
1986	4,496	2,590	1,438	–	8,525
1987	4,486	2,446	1,309	–	8,241
1988	4,371	2,386	1,355	na	8,113
1989	4,831	2,478	1,420	na	8,729
1990	4,609	2,423	1,456	1,568	10,056
1991	4,344	2,274	1,424	1,482	9,524
1992	4,336	2,269	1,460	1,416	9,481
1993	4,909	2,451	1,595	1,325	10,280
1994	4,428	2,517	1,549	1,506	9,999
1995	5,310	2,517	1,692	1,462	10,981
1996	5,433	2,529	1,722	1,450	11,134
1997	5,298	2,491	1,751	1,383	10,923
1998	4,660	2,496	1,618	1,289	10,063
1999	4,869	2,479	1,628	1,394	10,369
2000	4,367	2,331	1,571	1,579	9,848
2001	4,142	2,215	1,493	1,500	9,350
2002	4,127	2,063	1,472	1,476	9,138
2003	4,123	2,130	1,386	1,495	9,134
2004	3,716	2,064	1,428	1,464	8,673
2005	3,763	2,064	1,307	1,480	8,614
Average 1990–2005	4,527	2,332	1,535	1,454	9,848



Base modified from U.S. Geological Survey digital data, 1:100,000, 1988. UTM projection, zone 11. Shaded-relief from 30-meter DEM: sun illumination from northwest at 30 degrees above horizon.

Figure 14. Areas of effluent application and storage in Carson Valley, Nevada and California.

180 acre-ft/yr of effluent generated from Indian Hills was applied for irrigation of a golf course in 2005 (Andy Joyner, Indian Hills General Improvement District, written commun., 2006), and about 200 acre-ft/yr of effluent generated in the northern part of the valley was applied to the Incline Valley wetlands (Cathe Pool, Douglas County, written commun., 2006). Both of these sources of effluent were not applied for irrigation of pasture grasses or alfalfa. Thus, for water years 1990–2005, about 9,500 acre-ft/yr of effluent was applied for irrigation of pasture grasses or alfalfa and other crops in Carson Valley.

Ground-Water Pumping

Ground-water pumping in Carson Valley has increased 3-fold from the early 1970s as development has increased the demand for water (fig. 15). Estimates of annual ground-water pumping in Carson Valley have been made for only 4 years prior to 1981; 1965 by Harrill and Worts (1968, p. 14, 18, 24, and 26), 1968 and 1969 by Walters and others (1970, p. 42), and 1971 by Glancy and Katzer (1976, p. 56 and 59). The estimates made by Harrill and Worts (1968) were for all of Douglas County, and may be reasonable for Carson Valley, assuming pumping in the Topaz Lake and Lake Tahoe areas of Douglas County was minimal in 1965. From 1981 to 1986, estimates of annual pumping were made by USGS studies (Maurer, 1986, p. 62–63; Berger, 1987, p. 14; Berger, 1990, p. 9). These estimates were made using power consumption records and measurements of volume pumped per kilowatt/hour for irrigation pumping, pumping reported by municipalities, and domestic house counts. Since 1987, annual pumping estimates have been made by the Nevada Division of Water Resources and Water Planning in a publication titled "Carson Valley Groundwater Pumping Inventory." These estimates are made using data similar to USGS estimates for irrigation pumping including irrigated acreages, meters for municipal and other types of pumping where available, and well inventories for domestic pumping.

In the late 1960s and early 1970s, annual pumping ranged from less than 5,000 acre-ft/yr during years of above average precipitation (1969 and 1971) to about 10,000 acre-ft/yr during years of below average precipitation (1968) when ground water was pumped to supplement surface water for irrigation. In the late 1980s, annual pumping increased to about 20,000 acre-ft/yr during extended drought conditions, decreased to less than 20,000 acre-ft/yr during wet years from 1995 to 1998, and increased to greater than 30,000 acre-ft/yr in the dry year of 2004. Total pumping for water years 1990–2005 averaged about 24,000 acre-ft/yr.

As reported by Clark (2005, p. 2), pumping by manner of use is divided into irrigation, municipal, domestic, "other," commercial and stock water. Irrigation pumping has varied similarly to total pumping, increasing in dry years and decreasing in wet years, averaging about 9,100 acre-ft/yr for water years 1990–2005 (table 18). Municipal pumping has steadily increased from about 5,000 acre-ft/yr in the late 1980s to about 10,000 acre-ft/yr in 2004 and 2005. Similarly, domestic pumping has increased from about 1,400 acre-ft/yr in the mid-1980s to about 4,000 acre-ft/yr in 2005. Pumping in the "other" category has not changed significantly from 1987 to 2005 and averaged about 3,400 acre-ft/yr for water years 1990–2005. Pumping for the combined categories of commercial and stock use has decreased from about 500 acre-ft/yr in the late 1980s to about 150 acre-ft/yr in 2004 and 2005.

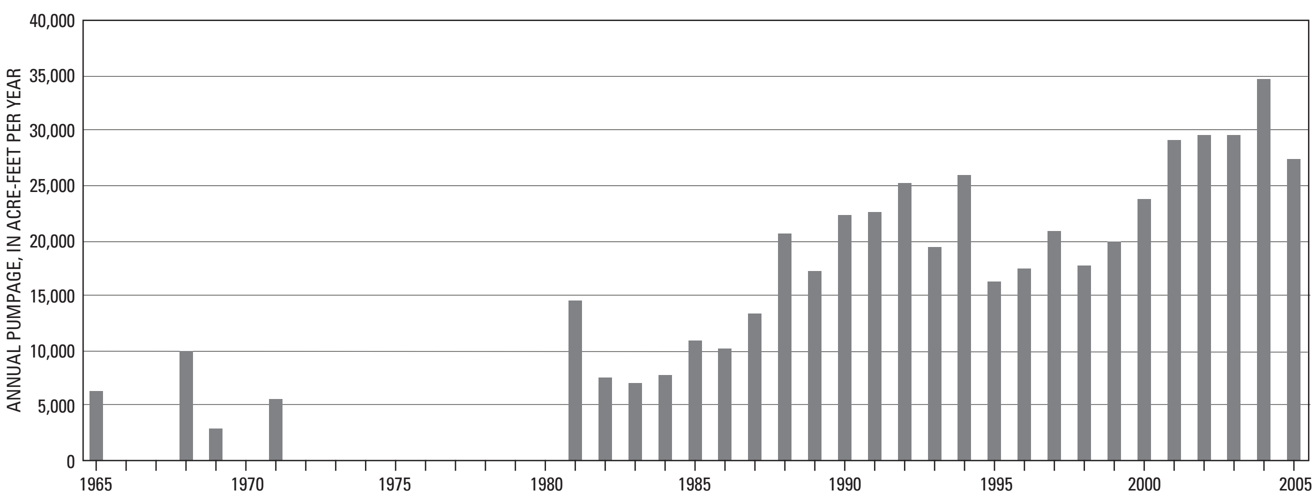


Figure 15. Annual ground-water pumping in Carson Valley, Nevada and California, 1965–2005.

Table 18. Annual ground-water pumping for selected water-use categories and estimates of net ground-water pumping, Carson Valley, Nevada and California.

[Pumping from 1987 to 2005 from Nevada Division of Water Resources, Carson Valley Groundwater Pumping Inventory. –, no data]

Water year	Irrigation	Municipal	Commercial	Stock	Domestic	Other	Total
[1]1965	5,000	970	400	–	190	–	6,560
[2]1968	–	–	–	–	–	–	10,000
[2]1969	–	–	–	–	–	–	3,000
[3]1971	5,000	590	–	–	–	–	5,590
[4]1981	–	–	–	–	–	–	14,500
[4]1982	–	–	–	–	–	–	7,400
[4]1983	–	–	–	–	–	–	7,000
[5]1984	2,800	3,400	–	–	1,300	200	7,700
[5]1985	5,700	3,500	–	–	1,400	200	10,800
[6]1986	3,400	3,500	–	–	1,400	1,900	10,200
1987	8,880	4,629	89	208	1,980	2,457	18,243
1988	10,124	5,348	58	370	2,144	3,165	21,209
1989	9,551	5,357	106	443	2,278	2,957	20,692
1990	10,387	5,642	148	447	2,400	3,050	22,074
1991	9,917	5,980	108	470	2,555	3,345	22,375
1992	11,833	7,021	171	234	2,656	3,209	25,124
1993	7,151	6,322	296	153	2,800	2,615	19,337
1994	12,465	7,058	150	122	2,960	3,298	26,053
1995	3,085	6,123	141	150	3,104	3,624	16,227
1996	3,883	6,740	97	133	3,187	3,498	17,538
1997	5,153	7,959	133	153	3,221	4,279	20,898
1998	4,031	6,597	90	155	3,312	3,398	17,583
1999	4,839	7,728	58	137	3,494	3,633	19,889
2000	8,678	8,435	74	123	3,593	2,974	23,877
2001	12,899	9,368	76	126	3,675	2,946	29,090
2002	11,137	10,967	81	119	3,744	3,566	29,614
2003	13,019	9,121	80	118	3,792	3,479	29,609
2004	17,150	9,887	63	114	3,918	3,428	34,561
2005	9,904	9,533	50	106	4,025	3,787	27,405
Average 1990–2005	9,096	7,780	114	179	3,277	3,383	23,828
Estimated return flow	[7]800					[10]2,368	[11]3,200
Secondary recharge		[8]2,000–4,800			[9]700		[11]3,000–6,000
Total return flow and secondary recharge							6,000–9,000
Net pumping[12]	8,200	3,100–6,000		179	2,577	1,015	15,000–18,000

[1] From Harrill and Worts (1968, p. 14, 18, 24, 26).

[2] From Walters and others (1970, p. 42).

[3] From Glancy and Katzer (1976, p. 56 and 59).

[4] From Maurer (1986, p. 62–63).

[5] From Berger (1987, p. 14).

[6] From Berger (1990, p. 9).

[7] Return flow estimated as 10 percent of that pumped for flood irrigation. About 1,200 acre-ft pumped for sprinkler irrigation in 2004 (James Asher, Beatty Agrodynamics, oral commun., 2006). Ground water pumped for flood irrigation was assumed to be about 8,000 acre-ft/yr 1990–2005.

[8] Secondary recharge estimated from 0.4 to 1.0 ft/yr from lawn watering and 40 percent lawn area (Maurer and Thodal, 2000, p. 21 and 26) for 12,000 acres of residential use.

[9] Secondary recharge estimated as 0.15 acre-ft/yr per septic tank (Maurer, 1997, p. 26) for 4,400 septic tanks (Dawn Patterson, Douglas County MAGIC, written commun., 2005).

[10] Return flow estimated as 70 percent flow through U.S. Fish Hatchery (Clark, 2005, p. 7).

[11] Rounded.

[12] Net pumping is average for 1990–2005 minus return flow and secondary recharge.

Ground water pumped for municipal use is partly removed from the hydrologic system by ET from lawn watering in summer months and by evaporation of effluent from holding ponds or by ET in areas where effluent is applied for irrigation. Ground water pumped for irrigation is partly consumed by ET, part may percolate to the water table, and part becomes return flow to the surface-water irrigation system. Ground water pumped for domestic use is partly lost to ET from lawn watering, part may percolate to the water table beneath lawns, and part returns to the water table by percolation beneath septic tanks. A large part of the ground water pumped for "other" use is for the U.S. Fish and Wildlife fish hatchery where no consumptive use takes place; the water passes through the facility to return to the irrigation system. The remaining water pumped for "other" uses, commercial use, and stock water is assumed to be lost to the hydrologic system.

The net volume of ground-water pumping was estimated from secondary recharge and return-flow rates reported in the literature. Using soil-chloride data, Maurer and Thodal (2000, p. 21 and 27) reported that secondary recharge (pumped ground water that percolates back to the water table) from lawn watering in Eagle Valley ranged from 0.4 to 1.0 ft/yr and that lawns cover about 40 percent of residential land. The land-use map for Carson Valley shows about 12,000 acres of residential use. Application of secondary recharge rates determined for Eagle Valley to 4,800 acres (40 percent of 12,000 acres) results in estimates of secondary recharge from municipal and domestic pumping ranging from 2,000 to 4,800 acre-ft/yr. Maurer (1997, p. 26) estimated that secondary recharge from septic tanks was about 0.15 acre-ft/yr per tank in the Dayton Hydrographic area, and data from Douglas County indicate effluent volumes of about 0.14 acre-ft/yr per lot in the northern part of the valley (Cathe Poole, Douglas County Utilities, written commun., 2006). A generalized estimate for effluent volume per domestic unit is 250 gal/d, or about 0.28 acre-ft/yr (Frank Johnson, Minden-Gardnerville Sanitation District, oral commun., 2006). A conservative value of 0.15 acre-ft/yr per septic tank was used to estimate secondary recharge from domestic pumping. The number of septic tanks in Carson Valley totals about 4,400 (Dawn Patterson, Douglas County Multi-Agency Geographic Information Center [MAGIC], written commun., 2006), thus, about 700 acre-ft/yr of the water pumped for domestic use may percolate back to the basin-fill aquifer. The combined secondary recharge from lawn watering in areas of residential use and from septic tanks ranges from about 3,000 to 6,000 acre-ft/yr (table 18).

Studies by Guitjens and others (1978, p. 14) in the 1970s indicate that from 30 to 50 percent of water applied for irrigation became return flow back to the surface-water irrigation system. Laser-leveling of fields and borders, begun in the 1980s, increased the efficiency of flood irrigation and likely reduced the amounts of return flow to 20 to 30 percent (Arlan Neil, Vada Hubbard, Natural Resources Conservation Service, oral commun., 2006). In addition, increasing costs for pumping of ground water also likely reduced the volumes of return flow from ground water pumped for irrigation. Because recent data are not available, return flow from application of ground water pumped for flood irrigation was assumed to be about 10 percent. Ground water pumped for sprinkler irrigation totaled about 1,200 acre-ft in 2004 (James Usher, Bently Agrodynamics, oral commun., 2006) with likely no return flow. Assuming this volume was similar for water years 1990–2005, ground water pumped for flood irrigation was about 8,000 acre-ft/yr. Applying a rate of 10 percent return flow to 8,000 acre-ft/yr pumped for flood irrigation results in a volume of about 800 acre-ft/yr (table 18). About 70 percent of the pumping in the "other" category is for the fish hatchery (Clark, 2005, p. 7), thus, about 2,400 acre-ft/yr of the volume pumped in the "other" category also becomes return flow. The average return flow for water years 1990–2005 totals about 3,200 acre-ft/yr.

The total volume of pumped ground water not consumptively used is from about 6,000 to 9,000 acre-ft/yr (table 18). Subtracting this from average annual pumping of about 24,000 acre-ft/yr leaves from 15,000 to 18,000 acre-ft/yr of net ground-water pumping for water years 1990–2005.

Net ground-water pumping for water years 1941–70 was difficult to accurately determine because data on ground-water pumping prior to 1970 are sparse. Pumping estimates for water years 1965, 1968, and 1969 averaged about 6,500 acre-ft/yr (table 18), however, this volume likely is greater than pumping in the 1940s and 1950s. The Nevada Division of Water Resources Driller's log database shows only four irrigation wells drilled prior to the 1950s, and 14 drilled from 1950 to 1960. Glancy and Katzer (1976, p. 59) estimate pumping for irrigation in Carson Valley in the 1970s ranged from 10,000 acre-ft/yr in dry years to 3,000 acre-ft/yr in wet years, and was about 5,000 acre-ft/yr in average years. Assuming pumping for irrigation was about 2,500 acre-ft/yr for water years 1941–70 and that about 40 percent became return flow, net irrigation pumping was about 1,500 acre-ft/yr. Harrill and Worts (1968, p. 7) and Glancy and Katzer (1976, p. 56) show the population of Carson Valley to be about 3,000 in 1965 and 1971, but estimates of pumping for municipal and domestic use for those years were considerably different; about 1,200 acre-ft/yr in 1965 (Harrill and Worts (1968, p. 18) and about 600 acre-ft in 1971 (Glancy and Katzer, 1976, p. 56). Assuming municipal and domestic pumping was considerably less from 1941 to the late 1960s, it may have averaged about 500 acre-ft/yr for water years 1941–70. Assuming that most of the volume pumped for municipal and domestic use was lost to the hydrologic system, and including net irrigation pumping of 1,500 acre-ft/yr, the total net pumping from 1941 to 1970 was estimated to be about 2,000 acre-ft/yr.

Evapotranspiration

Annual ET rates were estimated by Maurer and others (2006) using micrometeorologic measurements for vegetation types that included rabbitbrush and greasewood, flood-irrigated pasture grasses and alfalfa, and non-irrigated pasture grasses. ET rates were applied to mapped acreages of these vegetation types on the floor of Carson Valley (fig. 4) to obtain estimates of the annual volumes of ET.

The largest sources of ET in Carson Valley are from areas of pasture grasses, alfalfa, and rabbitbrush and greasewood (table 19). ET rates estimated by Maurer and others (2006, p. 22) for the water year 2004 include: 2.8, 3.2, and 4.4 ft/yr for three different stands of flood-irrigated pasture grasses; 1.7 ft/yr for non-irrigated pasture grasses; 3.1 ft/yr for flood-irrigated alfalfa where the depth to water was 3 to 6 ft below land surface; 3.0 ft/yr for flood-irrigated alfalfa where the depth to water was about 40 ft below land surface; and 1.9 ft/yr for rabbitbrush and greasewood. The highest rates for pasture grasses were obtained for a site where the depth to water ranged from 0 to 2 ft below land surface, compared to depths to water ranging from 2 to 5 ft below land surface at the two other stands of flood-irrigated pasture grasses, and 6 to 7 ft below land surface at the non-irrigated stand of pasture grasses (Maurer and others (2006, p. 9 and 22). Thus, the ET rate for pasture grasses likely is a function of the depth to water as previously noted by Nichols (2000, p. A10) for native phreatophytic shrubs and grasses.

The area of Carson Valley covered by pasture grasses generally corresponds to that part of the valley where depth to water is less than 5 ft below land surface (figs. 2 and 8). However, the depth to water changes seasonally and annually (fig. 8*B*), and the areal variation in depth to water is not known in sufficient detail to allow application of variable ET rates as a function of depth to water. For this reason, an annual ET rate of 3.0 ft/yr was applied to the entire area of pasture grasses, with the assumption that ET may be somewhat greater in parts of the valley with a shallow water table and somewhat less in parts of the valley with a deeper water table.

Table 19. Evapotranspiration for selected vegetation and land-use types, Carson Valley, Nevada and California, 2005 and 1979.

[**Area in 2005**: Estimated from imagery collected in 2004 and updated from field check in 2005 (fig. 8). **Area in 1979**: Estimated from aerial color infrared photography taken in 1979. – indicates non-irrigated pasture grasses not determined in 1979]

Vegetation/Land-use type	Area in 2005 (acres)	Estimated ET rate (feet per year)	Estimated ET volume in 2005 (acre-feet per year)	Area in 1979 (acres)	Estimated ET volume in 1979 (acre-feet per year)
Native phreatophytes (rabbitbrush and greasewood)	5,440	[1]1.9	10,000	[2]8,100	15,000
Irrigated pasture grasses	27,500	[1]3.0	83,000	[3]40,000	120,000
Irrigated alfalfa	11,500	[1]3.0	34,000		
Non-irrigated pasture grasses	[4]1,400	[1]1.7	2,400	–	–
Wetlands	[5]760	[1]4.4	3,300	500	2,200
Open water	[6]1,700	[7]5.0	8,500	1,700	8,500
Riparian vegetation (cottonwood and willow)	[8]1,420	[9]3.5	5,000	1,420	5,000
Total, rounded	49,700		146,000	52,000	151,000

[1] From Maurer and others (2006, p. 22).

[2] Includes 2,650 acres removed for agricultural, residential, and commercial use in 2005.

[3] Areas of irrigated pasture grasses and alfalfa combined, includes 2,200 acres removed for residential or commercial use in 2005 less 2,100 acres irrigated in 2005 that were not irrigated in 1979, and 900 acres of non-irrigated pasture grasses in 2005 that were irrigated in 1979.

[4] Includes 500 acres that were rabbitbrush and greasewood in 1979 and were non-irrigated pasture in 2005.

[5] Includes 250 acres of wetlands used for effluent discharge not present in 1979.

[6] Assumed to represent an annual average and to be similar in 1979 and 2005.

[7] From Huntington (2003, p. 55).

[8] Assumed to be similar in 1979 and 2005.

[9] From U.S. Geological Survey (2005), station 390653118583901.

The land-use map also included areas described as wetlands, riparian vegetation of cottonwood and willow, and open water (table 19). In areas classified as wetlands, the water table likely is within about 2 ft below land surface, and an ET rate of 4.4 ft/yr was applied. The rate of 4.4 ft/yr is similar to a rate of 4.2 ft/yr estimated for bulrush marshes in Ruby Valley, northeastern Nevada by Berger and others (2001, p. 16). An ET rate of 3.5 ft/yr was estimated for willow using micrometeorological measurements near Weber Reservoir, about 40 mi east of Carson Valley (U.S. Geological Survey, 2006, station 390653118583901). Reported ET rates for cottonwood and willow determined largely in Arizona and New Mexico range from about 4 to greater than 5 ft/yr (Unland and others, 1998, p. 541; Scott and others, 2000, p. 244; and Dahm and others, 2002, p. 837). ET rates for cottonwood and willow likely are less in northern Nevada than these reported rates because of the shorter growing season. For this reason, the rate estimated for willow near Weber Reservoir, 3.5 ft/yr was applied to areas of cottonwood and willow in Carson Valley. For open water, an estimated evaporation rate of 5.0 ft/yr was applied as determined by Huntington (2003, p. 55) for Washoe Valley, Nev. about 12 mi north of Carson Valley. The area of open water, as determined from the imagery collected in July 2004, likely changes during the year, greatly increasing during spring runoff when large areas of the valley floor are flooded, and greatly decreasing during winter months when evaporation rates are low and areas of open water are limited to the major ditches that provide stock water. The area of open water determined for July of a dry year was assumed to represent an approximate average annual area.

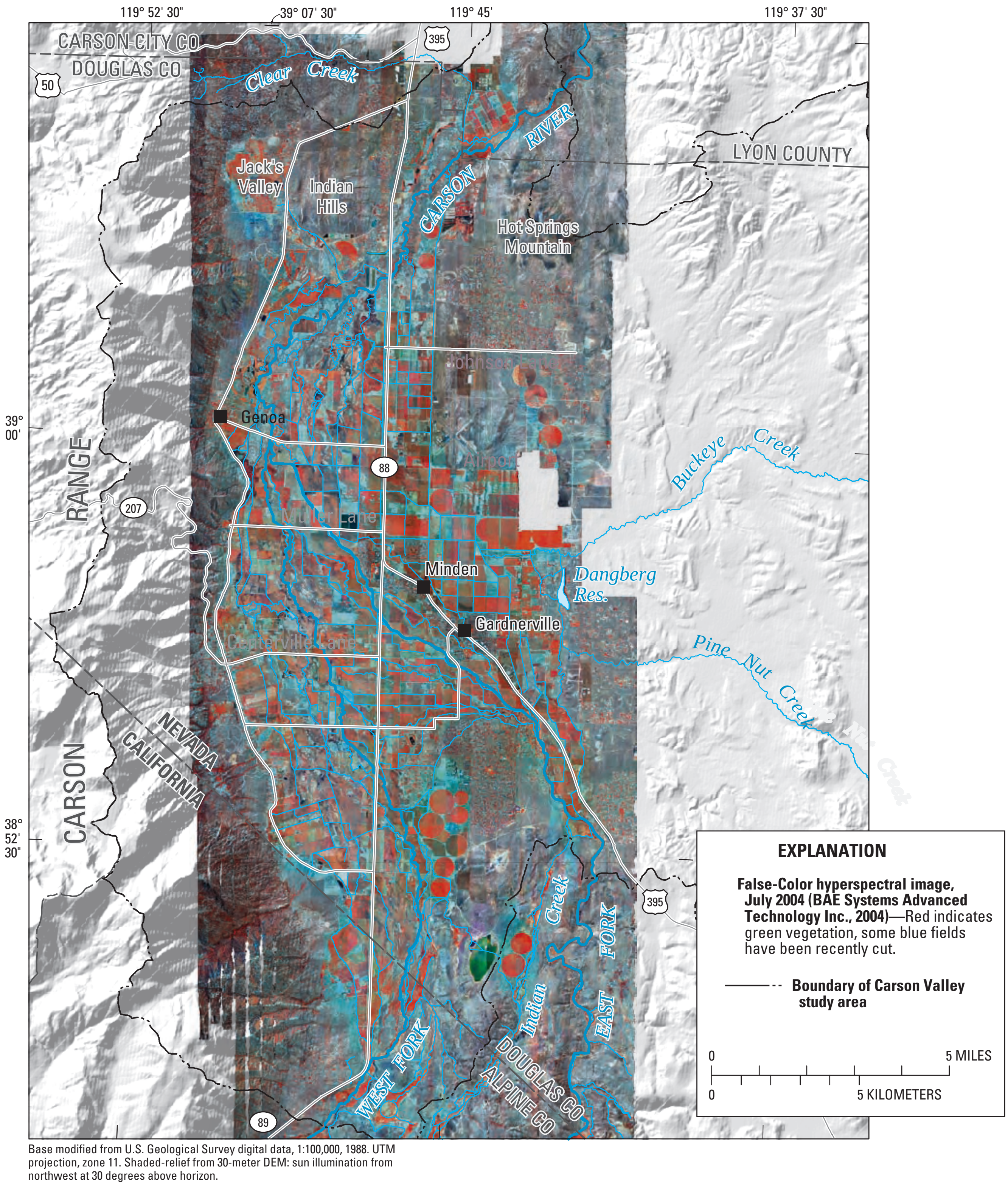
The resulting volumes of ET total about 146,000 acre-ft/yr from areas of native phreatophytes, irrigated alfalfa, irrigated and non-irrigated pasture grasses, wetlands, cottonwood/willow, and open-water bodies. This volume of ET is derived from precipitation, streamflow of the Carson River and streams tributary to the valley floor, shallow ground water, ground water pumped for irrigation, and effluent applied for irrigation.

The volume of ET for water years 1941–70 was estimated from changes in the acreage of irrigated lands and native phreatophytes determined from a comparison of color infrared aerial photography taken in 1979 with the imagery collected in 2004 and land-use map updated to 2005 (fig. 16*A* and 16*B*). For the comparison, geo-rectified digital images were overlain on the computer screen to delineate areas of land-use change. The color infrared photography is the earliest available imagery that could be used to determine actively irrigated lands. Information on the date and year of well constructions in Carson Valley (Mimi Moss, Douglas County MAGIC, written commun., 2006) shows about 800 parcels were developed from 1970 through 1978. Thus, the estimated changes in acreages represent minimum values.

Areas of rabbitbrush and greasewood in 1979 that had been removed for agricultural, residential, and commercial use in 2005 totaled about 2,650 acres reducing ET by about 5,000 acre-ft/yr (fig. 17; table 19). About 2,200 acres of irrigated alfalfa and pasture grasses in 1979 were replaced by residential or commercial use in 2005. However, the decrease in ET from irrigated land was mostly offset by an increase in irrigated lands south and east of the Douglas County airport, and near the northern end of the valley, totaling about 2,100 acres (fig. 17). The additional irrigated land generally was sprinkler irrigated rather than flood irrigated as was acreage removed from irrigation from 1979 to 2005. Application rates using sprinklers were about 3.5 ft/yr, somewhat greater than the ET rates determined from micrometeorologic measurements (James Usher, Bently Agrodynamics, oral commun., 2006). The additional 0.5 ft/yr likely is lost to evaporation to the atmosphere during sprinkler irrigation.

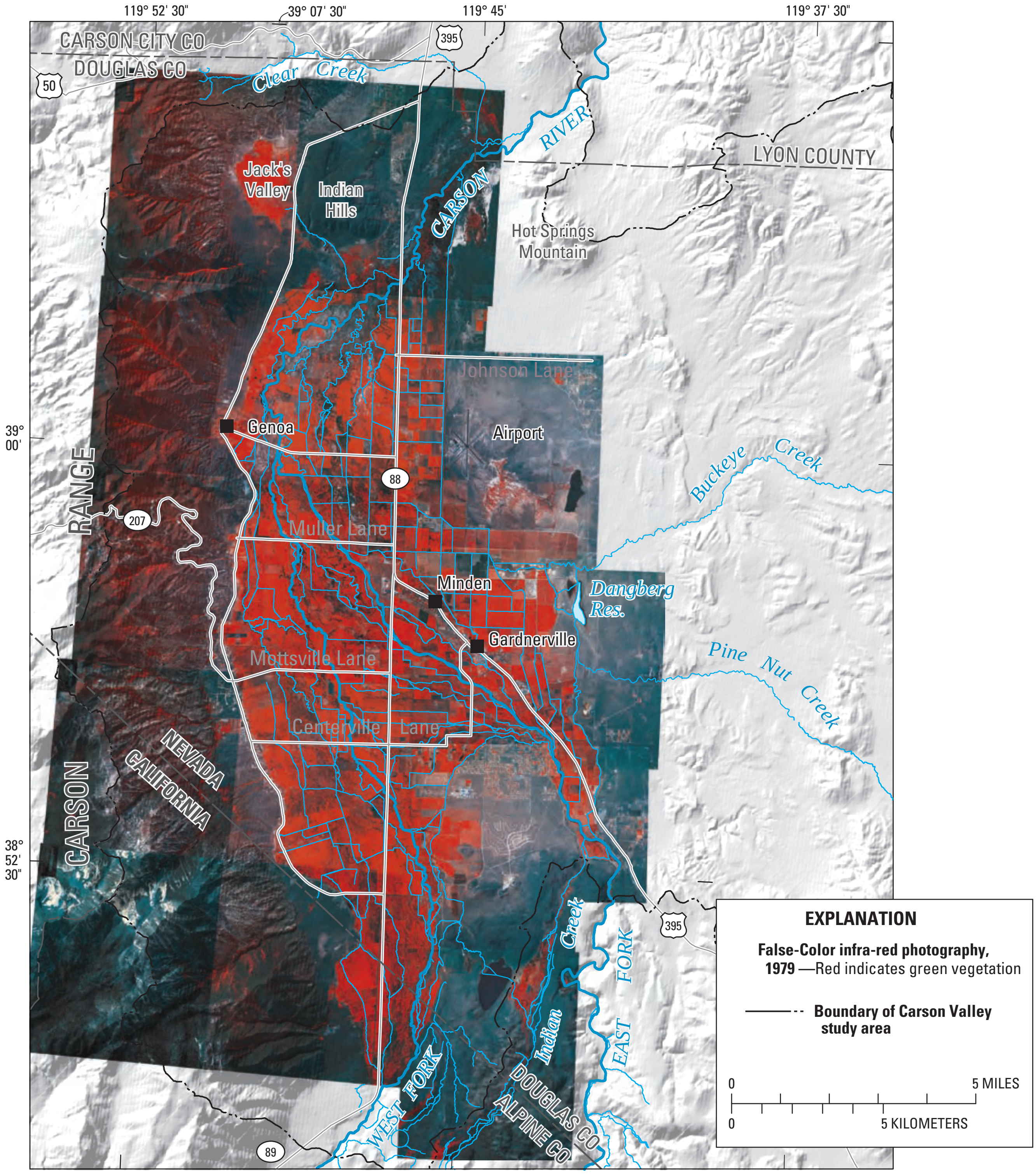
Other land-use changes include about 900 acres of non-irrigated pasture grasses in 2005 that were irrigated in 1979, about 500 acres of non-irrigated pasture grasses in 2005 replacing what was rabbitbrush and greasewood in 1979, and about 250 acres of wetland areas in 2005 that were covered by rabbitbrush and greasewood in 1979. Changes in open-water areas include a reservoir of about 60 acres that was present along Muller Lane in 2005 and not in 1979, however, two reservoirs of about 130 acres on the eastern side of the valley that were used in 1979 were not used in 2005. In addition, in 2005 numerous ponds were present on residential areas scattered across the valley floor that were not present in 1979. These changes in open-water areas were assumed to result in similar areas of open water for 1979 and 2005 because the aerial photography from 1979 is not of sufficient detail to discern small open-water areas. Similarly, detail is lacking to discern areas of riparian vegetation in 1979. Thus, areas of cottonwood and willow also were assumed to be approximately the same in 1979 and 2005.

Application of ET rates to the areas of vegetation in 1979 results in a somewhat greater volume of ET, about 151,000 acre-ft/yr. The difference in ET between the two periods was relatively small because the decrease in irrigated pasture grasses and alfalfa cause by land-use change was offset by the increase in irrigated alfalfa near the airport and the northern part of the valley. The greatest change in ET between 1979 and 2005 was not the overall volume, but the source of water that supplied ET. From 1990–2005, ET was supplemented by application of about 9,500 acre-ft/yr of imported effluent and effluent generated within Carson Valley, rather than streamflow of the Carson River or ground water pumped for irrigation.



A. Imagery collected in 2004

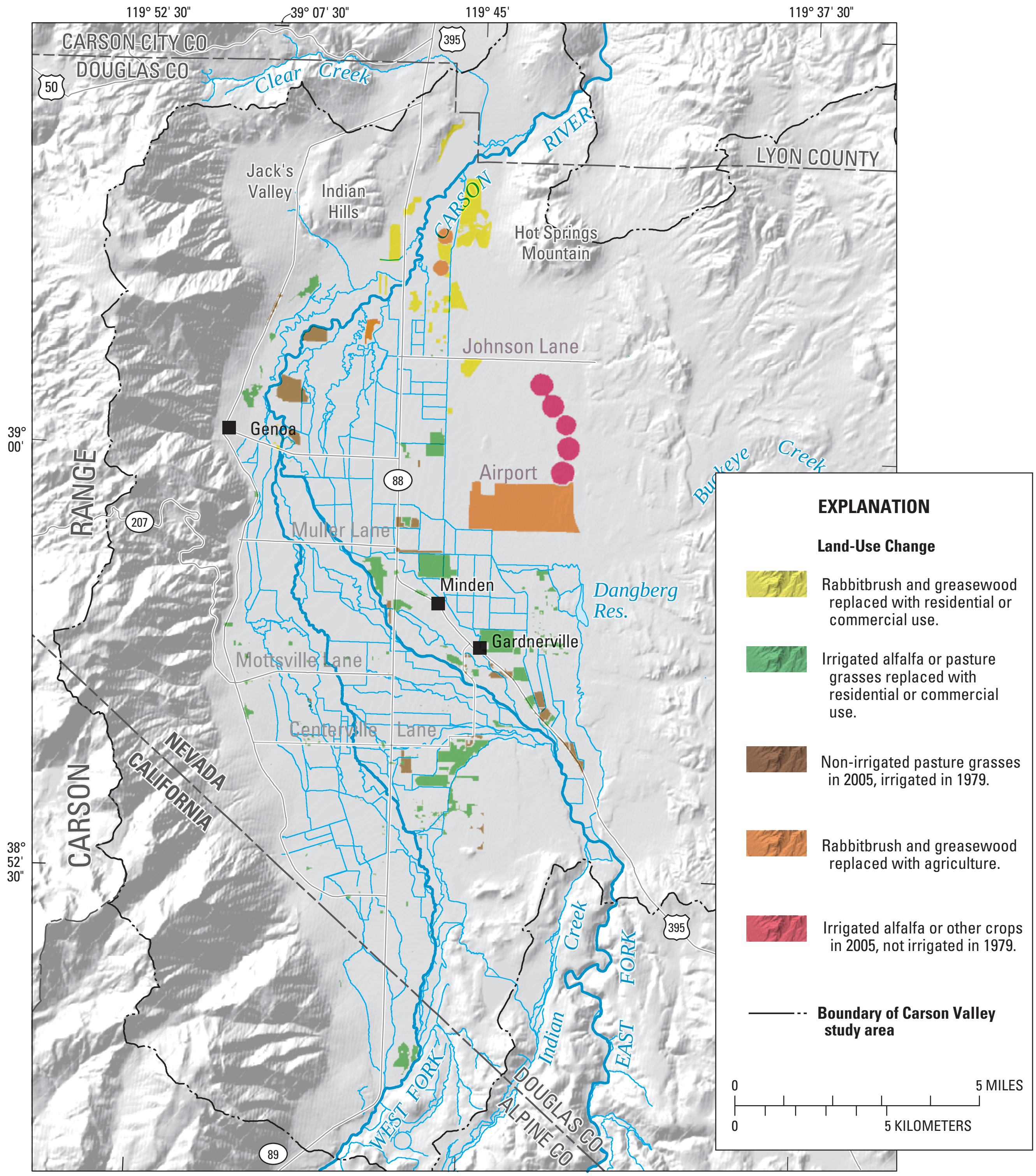
Figure 16. Color infrared aerial photography from 1979 compared to imagery collected in 2004, Carson Valley, Nevada and California.



Base modified from U.S. Geological Survey digital data, 1:100,000, 1988. UTM projection, zone 11. Shaded-relief from 30-meter DEM: sun illumination from northwest at 30 degrees above horizon.

B. Color infrared photography from 1979

Figure 16.—Continued



Base modified from U.S. Geological Survey digital data, 1:100,000, 1988. UTM projection, zone 11. Shaded-relief from 30-meter DEM: sun illumination from northwest at 30 degrees above horizon.

Figure 17. Changes in land use between 1979 and 2005, Carson Valley, Nevada and California.

ET from non-irrigated vegetation including rabbitbrush and greasewood, riparian vegetation, and non-irrigated pasture grasses is supplied only from precipitation and ground water. ET from irrigated pasture grasses and crops in Carson Valley is supplied by a combination of precipitation, ground water, and surface water applied for irrigation. The shallow depth to water over much of the valley floor makes it difficult to determine whether the plants use streamflow applied for irrigation as it percolates through the unsaturated zone, or the streamflow infiltrates to the water table, recharging the basin-fill aquifers, and the plant roots tap the ground-water system.

Data on the relative contribution of ground water and streamflow applied for irrigation to ET in Carson Valley consist solely of that collected during studies by the Department of Agriculture of the University of Nevada, Reno, in the 1970s (Guitjens and others, 1976; 1978). The studies included measurements of the volumes of water applied for irrigation of pasture grasses and alfalfa fields and the volumes of surface-water return flow, or runoff from the fields, at three locations in Carson Valley (fig. 18).

The studies showed that the net water lost to infiltration during the 1974 and 1975 irrigation seasons totaled 3.1 and 3.6 ft for alfalfa and pasture grass near the northern end of the valley, respectively, where the water table ranged from 4 to 7 ft below land surface. Net water lost to infiltration was 2.4 ft for pasture grass near the west-central part of the valley where the water table ranged from 0.2 to 3 ft below land surface, and was 8.5 ft for alfalfa and pasture grass near the southern end of the valley where the water table ranged from 4 to 20 ft below land surface and soils are sandy (Guitjens and others, 1978, p. 14). ET rates for alfalfa and pasture grasses used in this report range from about 3 to as much as 4.4 ft/yr where the water table is shallow, less than about 2 ft below land surface (table 17).

The difference between water lost to infiltration determined by Guitjens and others (1978) and ET rates used in this report was small for the fields near the northern end of the valley, indicating that most water applied for irrigation likely was consumed by ET. Near the west-central part of the valley, water lost to infiltration was less than ET, indicating that the crops were supported by shallow ground water (Guitjens and Mahannah, 1972, p. 14). However, the areas and rates of ground-water contribution to ET are not known. Near the southern end of the valley, water lost to infiltration is 3-5 ft/yr greater than that required for ET. This indicates that considerable volumes of water applied for irrigation may be lost to infiltration and supply ground-water recharge in flood-irrigated areas where the water table is relatively deep and soils are sandy. Irrigated areas where the water table is from 5 to 20 ft below land surface are relatively small near the southern end of the valley and mostly lie on the eastern side of the valley (figs. 2 and 4). Presently, land on the southern end of the valley where the study by Guitjens and others (1978) was conducted, and much land on the eastern side of the valley is irrigated by sprinkler application rather than flood irrigation, so recharge from infiltration of water applied for irrigation in these areas likely is small. Recharge from flood-irrigation on the eastern side of the valley may take place, but data are not available to make estimates of this potential source of recharge.

Because of the uncertainty in the relative contributions of surface water and ground water to ET, ET derived from sources known with reasonable accuracy were used to estimate ET from the combined sources of streamflow and ground water (table 20). All sources of ET except those derived from a combination of streamflow and ground water (ET from wetlands and irrigated crops and pasture grasses) total about 67,000 acre-ft/yr (table 20). Subtracting this volume from the total ET of 146,000 acre-ft/yr, results in a volume of about 79,000 acre-ft/yr for ET derived from a combination of streamflow and ground water.

Table 20. Sources and estimated annual volume of evapotranspiration from selected areas in Carson Valley, Nevada and California, water years 1990–2005.

Sources of ET	Estimated volume (acre-feet per year)
Total ET[1]	146,000
Ground-water ET from phreatophytes (rabbitbrush and greasewood)[2]	6,000
Ground-water ET from riparian vegetation (cottonwood and willows)[2]	4,000
Ground-water ET from non-irrigated pasture grasses[2]	1,000
Total ground-water ET	11,000
Open-water evaporation[2]	7,300
Effluent applied for irrigation[3]	9,500
Net ground water applied for irrigation[4]	8,200
Precipitation on basin-fill deposits[5]	31,000
Total (rounded)	67,000
Remainder (rounded)–Combined streamflow loss and ground water that supplies ET	79,000

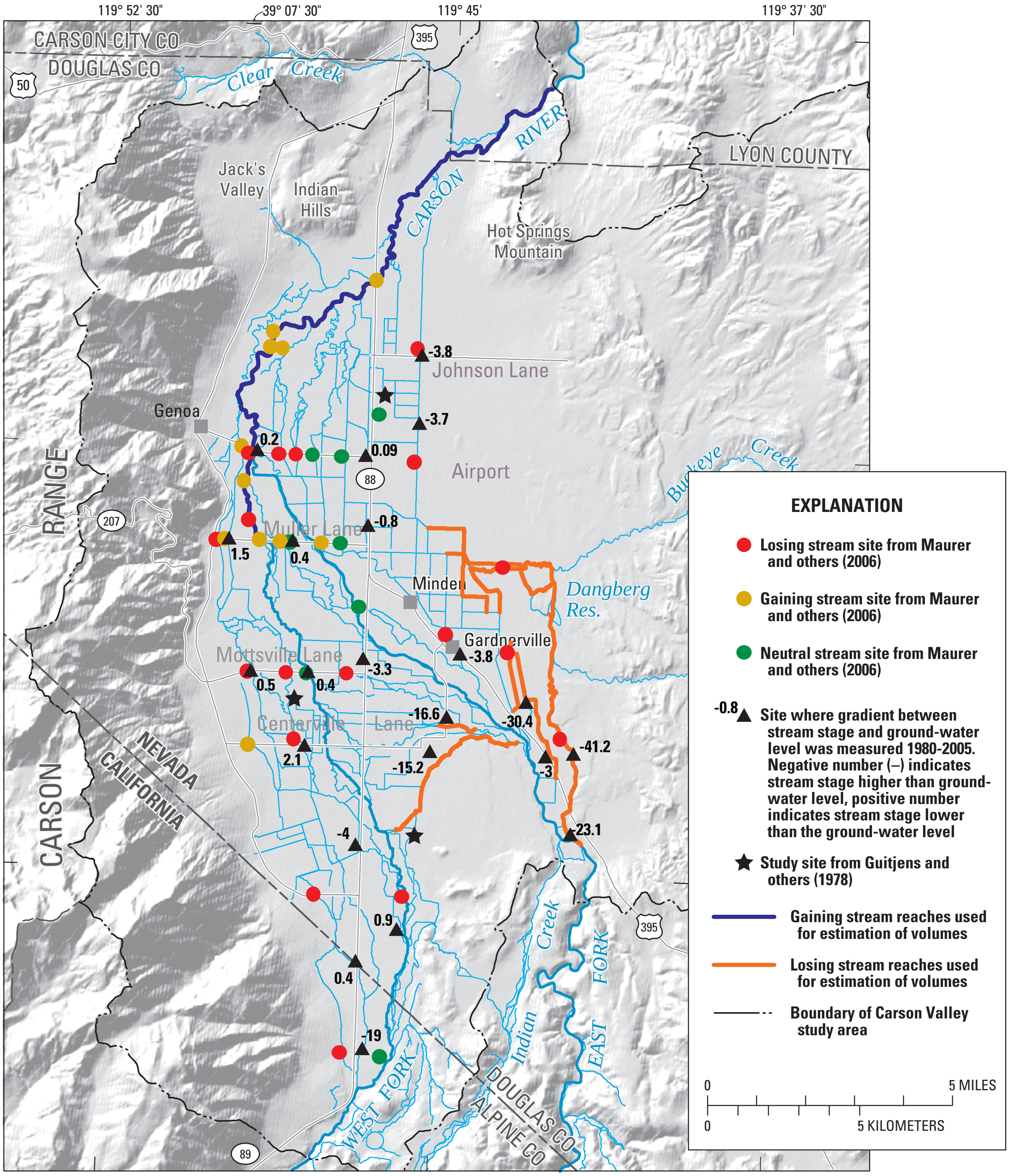
[1] From table 19.

[2] ET from table 19, minus precipitation from table 5, rounded.

[3] From written communications, Hal Bird, South Tahoe Public Utilities District, 2005; Cindy Neisess, JWA Consultants, 2005; Harvey Johnson, Incline General Improvement District, 2005; Kyle Menath, Carson City Utilities Department, 2005; and Frank Johnson, Minden-Gardnerville Sanitation District.

[4] From table 18.

[5] From table 5 minus precipitation on rabbitbrush and greasewood, riparian vegetation, and non-irrigated pasture grasses, totaling 7,000 acre-ft/yr.



Base modified from U.S. Geological Survey digital data, 1:100,000, 1988. UTM projection, zone 11. Shaded-relief from 30-meter DEM: sun illumination from northwest at 30 degrees above horizon.

Figure 18. Location of selected wells where ground-water levels adjacent to stream channels and stream stage have been collected, difference between ground-water altitude and altitude of stream stage, and location of gaining and losing stream sites, Carson Valley, Nevada and California.

Streamflow Losses to Infiltration and Streamflow Gains from Ground-Water Seepage on the Valley Floor

The locations of streamflow losses and gains from the Carson River and irrigation ditches and estimates of infiltration loss rates and seepage gain rates were made by Maurer and others (2006) using streambed-temperature data. That study showed that gaining and neutral reaches were found on the westernmost side of Carson Valley generally north of Muller Lane (Maurer and others, 2004, p. 34), South of Muller Lane, gaining sites generally were west of the West Fork Carson River. Losing reaches were found on the eastern side and southern end of the valley.

Measurements of ground-water levels in wells adjacent to stream channels relative to stream stage also provide data on the locations and potential rates of streamflow losses. These measurements were made at 23 sites in Carson Valley in the mid-1980s and in 2003–06 (fig. 18). However, many wells where measurements were made in the mid-1980s have been destroyed. For wells where data were collected only in the mid-1980s, the water-level difference for May 1985 is posted in figure 18. For wells where data were collected in the mid-1980s and in 2003–06, the average water-level difference for all measurements is posted in figure 18. By convention, a negative difference in water levels indicates stream stage is higher than the adjacent water table and streamflow loss to infiltration may take place. A positive difference indicates stream stage is lower than the adjacent water table and streamflow gain may take place from ground-water seepage into the streambed. The distribution of gaining and losing conditions shown by water-level differences is in general agreement with the distribution of gaining and losing stream sites determined from streambed-temperature measurements (fig. 18; Maurer and others, 2006, p. 34).

As shown in figure 18, stream stage ranges from 15 to 41 ft greater in altitude than adjacent ground-water levels in the southeastern part of Carson Valley. In the southeastern part of the valley, streamflow likely was lost to infiltration at greater rates than at sites near the center of the valley where water-level differences were negative (stream stage higher than ground-water level) and less than 1 ft. This is because the hydraulic gradient between the stream's stage and ground water that drives flow between the two was small. The remaining factor that controls the rate of infiltration is the hydraulic conductivity of the streambed materials, which may vary across the valley floor. Infiltration rates calculated from temperature data ranged from about 2 to 3 ft/d for sites on the eastern side of Carson Valley (Maurer and others, 2006, p. 40). Stream lengths and widths determined from the imagery used to develop the land-use map were used to calculate the surface area of major irrigation ditches where the depth to water was greater than about 20 ft (fig. 18) in the southeastern part of the valley. The total surface area of the ditches is about 1.6 million ft^2.

Application of infiltration rates from 2 to 3 ft/d to the area of 1.6 million ft^2 results in estimates of streamflow infiltration losses ranging from 18,000 to 26,000 acre-ft/yr. This calculation includes the assumption that losses take place only during the irrigation season from March through September, a period of 210 days. Although streamflow often is present in these ditches during winter months for stock water, stream stage is lower than during the irrigation season, and infiltration rates would accordingly be less. The infiltration losses of 18,000 to 26,000 acre-ft/yr represent a minimum range because infiltration losses in other ditches in Carson Valley also may take place. However, the loss rates likely are less because of the relatively small hydraulic gradient in other areas. In addition, the location of such losses is uncertain and likely change during the irrigation season and from wet years to dry years. For these reasons, estimation of streamflow losses to infiltration in the remainder of the valley was not attempted. The streamflow losses to infiltration through irrigation ditches in part supplies water for ET, and in part may supply recharge to basin-fill aquifers.

An estimate of ground-water recharge from streamflow can be made by subtracting the volume of ET from the combined sources of streamflow and ground water (79,000 acre-ft/yr, table 19), from the volume of streamflow loss during summer months estimated from the difference between mean daily inflow and outflow for water years 1990–2005 (fig. 11; 89,000 acre-ft/yr). The difference between the volume of streamflow loss during summer months and the volume of ET derived from the combined sources of streamflow and ground water is 10,000 acre-ft/yr. This volume provides an estimate of streamflow losses that do not supply ET and is a minimum estimate of ground-water recharge from streamflow losses, assuming that the contribution of ET from ground water is minimal.

Rates of streamflow gain based on streambed temperature data were reported by Maurer and others (2006, p. 43) to range from 0.1 to 1.0 ft/d for strongly gaining reaches. A gain rate of 0.3 ft/d was estimated for the Carson River in the northern part of Carson Valley based on streamflow measurements (Maurer and others, p. 43). Gaining sites along the southwestern part of the valley may receive flow from the ground-water system, but this flow may be lost to ET after downstream application for irrigation. Streamflow gains from ground-water discharge that actually leave Carson Valley likely are limited to those downstream from Muller Lane on the main stem and the West Fork Carson River. The East Fork of the Carson River north of Muller Lane was not considered to be gaining because there are no data to support gaining conditions, and gaining sites south of Muller Lane generally are found within about 1 mi from the mountain front.

Stream lengths and widths determined from the imagery used to develop the land-use map were used to calculate the area of the Carson River and the West Fork Carson River for reaches north of Muller Lane (fig. 18), resulting in an area of 5.65 million ft^2. Application of a gain rate of 0.3 ft/d to the stream area, and assuming that the rate of streamflow gain is constant throughout the year, results in a volume of about 14,000 acre-ft/yr.

As discussed previously, the outflow of the Carson River is a total of about 16,000 acre-ft/yr greater than inflow during the period from mid-November through mid-March (fig. 11). This volume represents the net streamflow gain for the valley as a whole during periods when precipitation rates are high and ET rates are low. However, temperature data collected by Maurer and others (2006) showed strongly gaining conditions in July, indicating that the northern reach of the Carson River may gain flow throughout the year. Despite such gains, the high rate of ET during summer months causes an overall loss of streamflow through the valley. Both methods of estimating streamflow gains by ground-water discharge produce similar volumes, from 14,000 to 16,000 acre-ft/yr. For purposes of the ground-water budget, 15,000 acre-ft/yr is assumed to represent a reasonable estimate for streamflow gains from ground-water discharge.

Water Budgets

The estimates of water-budget components developed in the previous section were compiled into overall water budgets for water years 1941–70 and 1990–2005, and a ground-water budget for water years 1990–2005. Components of the ground-water budget were compared to previous estimates, and the relative uncertainty of the components was discussed.

Overall Water Budget

Sources of inflow in the overall water budget include streamflow tributary to the floor of Carson Valley, precipitation on Quaternary basin-fill sediments, ground-water inflow from the mountain blocks and alluvial fans, and effluent imported from outside the basin. Sources of outflow include streamflow of the Carson River that leaves the valley, ET, and net ground-water pumping. Differences in streamflow, precipitation, effluent imports, and ground-water pumping for two periods, water years 1941–70 and 1990–2005, were determined from the long-term records and estimates of such data. Differences in ET for the two periods were estimated from application of differing ET rates to areas where land use has changed from agricultural or from phreatophytic vegetation (rabbitbrush and greasewood) to residential or commercial land use between the two periods (see section titled "Evapotranspiration"). The volumes of ground-water inflow for the two periods likely are not significantly different and the same estimates of ground-water inflow were used for each period.

The combined estimates of inflow, including the range in estimated ground-water inflow, total from 432,000 to 450,000 acre-ft/yr for water years 1941–70 and 430,000 to 448,000 acre-ft/yr for water years 1990–2005. Estimated volumes of inflow were similar for the two periods because a decrease in streamflow was offset by an increase in imported effluent (table 21). The combined estimates of outflow total 446,000 acre-ft/yr for water years 1941–70, and 439,000 to 442,000 acre-ft/yr, for water years 1990–2005. Again, decreases in ET and outflow of the Carson River were offset by the increase in net ground-water pumping. The greater volume of ground-water inflow using the chloride-balance method was closest to estimates of outflow; less than 1 percent of outflow for both periods. However, the lesser volumes of ground-water inflow estimated using the water-yield method also were relatively close, within 2 to 3 percent of outflow, for both periods. The large volumes of inflow and outflow of the Carson River dominate the overall water budget.

Table 21. Overall water budget, Carson Valley, Nevada and California, water years 1941–70 and 1990–2005.

Water-budget component	Estimated volumes (acre-feet per year)	
	Water years 1941–70	Water years 1990–2005
Sources of inflow		
Precipitation on basin-fill deposits[1]	38,000	38,000
Streamflow of Carson River and tributaries[2] (rounded)	372,000	360,000
Ground-water inflow[3]	22,000–40,000	22,000–40,000
Imported effluent[4]	0	9,800
Total	432,000–450,000	430,000–448,000
Sources of outflow		
Evapotranspiration[5]	151,000	146,000
Streamflow of Carson River[2]	293,000	278,000
Net ground-water pumping[6]	2,000	15,000–18,000
Total	446,000	439,000–442,000

[1] From table 5.

[2] From table 4.

[3] From table 15.

[4] From table 17.

[5] From table 19.

[6] From table 18.

The overall water budget illustrates that the major differences in the overall water budget for the two periods was the increased use of effluent for irrigation, increased net ground-water pumping, and changes in land use that replaced native phreatophytes and irrigated lands with residential or commercial land use. Application of 9,500 acre-ft/yr of effluent in water years 1990–2005 decreased the volume of streamflow and ground water applied for irrigation for that period compared to water years 1941–70 by 9,500 acre-ft/yr. Changes in land use for water years 1990–2005 reduced the annual volume of ET by about 5,000 acre-ft/yr. Combining that change with the application of 9,500 acre-ft/yr of effluent for irrigation resulted in an overall decrease of about 15,000 acre-ft/yr, approximately equal to the net ground-water pumping of 15,000 to 18,000 acre-ft/yr. The decrease in ET and in the use of streamflow and ground water for irrigation would tend to increase outflow of the Carson River from Carson Valley, offsetting the decrease in outflow caused by ground-water pumping without changes in land use predicted by Maurer (1986) and Prudic and Wood (1995).

Ground-Water Budget

Ground-water inflow from Eagle Valley and the Carson Range and Pine Nut Mountains was estimated to range from about 22,000 to 40,000 acre-ft/yr using average values for inflow estimates (table 15). The low-range estimate was obtained using the water-yield method and the high-range estimate was obtained using the chloride-balance method. Both volumes include an average estimate of 250 acre-ft/yr of recharge from precipitation on Quaternary eolian and gravel deposits in the northern part of the valley (table 6). However, the small volume of recharge is essentially lost in the rounding required to present values that include the uncertainty in the estimates. A minimum estimate of ground-water recharge from streamflow losses, 10,000 acre-ft/yr, was obtained from the difference between daily mean streamflow losses during summer months, and the volume of ET from the combined sources of streamflow and ground water. Estimates of secondary recharge of pumped ground water range from 3,000 to 6,000 acre-ft/yr. Estimates of total ground-water recharge to basin-fill sediments in Carson Valley, for water years 1990–2005, range from 35,000 to 56,000 acre-ft/yr (table 22).

Components of ground-water discharge include ground-water ET from native phreatophytes, riparian vegetation, and non-irrigated pasture grasses totaling 11,000 acre-ft/yr (table 20); ground-water discharge to streamflow of the Carson River of 15,000 acre-ft/yr, and net ground-water pumping of 15,000 to 18,000 acre-ft/yr (table 18). Estimates of total ground-water discharge from basin-fill sediments in Carson Valley, for water years 1990–2005, range from 41,000 to 44,000 acre ft/yr (table 22).

Table 22. Annual ground-water budget for basin-fill aquifer, Carson Valley, Nevada and California, water years 1990–2005.

[**Abbreviations**: acre-ft/yr, acre-feet per year; ft/d, feet per day; ft^2, square feet]

Source of recharge and discharge	Estimated average volume (acre-ft/yr)	Estimated low- and high-range volume (acre-ft/yr)
Ground-water recharge		
Ground-water inflow[1] and recharge from precipitation on Quaternary eolian sand and gravel deposits[2]	22,000 – 40,000	15,000 – 58,000
Ground-water recharge from streamflow[3]	10,000	10,000
Secondary recharge of pumped ground water [4]	3,000 – 6,000	3,000 – 6,000
Total	35,000 – 56,000	28,000 – 74,000
Ground-water discharge		
Ground-water ET from phreatophytic and riparian vegetation and non-irrigated pasture grasses[5]	11,000	
Ground-water discharge to streamflow[6]	15,000	
Net ground-water pumping[4]	15,000 – 18,000	
Total	41,000 – 44,000	

[1] From table 15.

[2] From table 6.

[3] Estimated from annual streamflow loss during summer months for water years 1990–2005, determined from the difference between mean daily inflow to and outflow from Carson Valley during summer months; 89,000 acre-ft/yr, minus the combined ET loss from streamflow and ground water, 79,000 acre-ft/yr (table 20). The volume of 10,000 acre-ft/yr represents a minimum value assuming minor ground-water contribution to ET.

[4] From table 18.

[5] From table 20.

[6] Estimated as the average of streamflow gain during winter months for water years 1990–2005 determined from difference between mean daily inflow to and outflow from Carson Valley; 16,000 acre-ft/yr, and streamflow gain estimated from application of a gain rate of 0.3 ft/day (Maurer and others, 2006, p. 43) to the area of the West Fork and Carson River north of Muller Lane to the study area boundary, 5,65 million ft^2; 14,000 acre-ft/yr.

The average low-range estimate for ground-water recharge was about 15 percent less than the low-range estimate of ground-water discharge, and the average high-range estimate was about 25 percent greater than the high-range estimate of ground-water discharge. Inclusion of the total range in uncertainty for the estimates of ground-water recharge estimated from the water-yield (15,000 to 29,000 acre-ft/yr) and chloride-balance methods (17,000 to 58,000 acre-ft/yr) resulted in estimates of ground-water recharge from 32 percent less than the estimates of ground-water discharge to 68 percent greater (table 22). For this reason, the average estimates of ground-water inflow were considered to provide a more reasonable range for estimates of ground-water recharge.

As stated previously, the ground-water budget summarizes sources of ground-water recharge and discharge and provides an estimate of the perennial yield of Carson Valley. The perennial yield of an aquifer is defined as: "The amount of usable water from a ground-water aquifer that can be economically withdrawn and consumed each year for an indefinite period of time. It can not exceed the natural recharge to that aquifer and ultimately is limited to the maximum amount of discharge that can be utilized for beneficial use." (Nevada Division of Water Planning, 1992, p. 73).

Perennial yield is typically used by the Nevada State Engineer to determine the maximum limit of ground-water pumping allowed in a ground-water basin. However, recent publications have noted the inadequacy of using perennial yield as a limit to protect water resources (Bredehoeft, 1997; Sophocleous, 1997). The publications point out that the ultimate results of ground-water pumping are to increase, or induce, additional recharge, to decrease ground-water discharge, or some combination of the two. Additionally, they state that streams and wetlands may be affected by ground-water pumping long before pumping reaches the volume of perennial yield. In Carson Valley this is especially true because of the close hydraulic link between the aquifer and surface-water flow created by the permeable sediments and shallow depth to water beneath much of the valley floor. Pumping causes both additional recharge to be induced through the channels of the Carson River and irrigation ditches, and a decrease in ground-water discharge to the Carson River (Prudic and Wood, 1995, p. 10.). Sophocleous (1997) and Bredehoeft (1997) both note the utility of ground-water flow models to quantify the changes in recharge and discharge caused by pumping.

Comparison with Previous Water-Budget Estimates

Comparison of water-budget components with previous estimates is somewhat hampered by the different areas included in the estimates. Estimates of ET for the overall budget, 146,000 acre-ft/yr (table 21), are quite similar to that determined using a steady-state numerical model, 149,000 acre-ft/yr, by Prudic and Wood (1995, p. 9; table 2), but was greater than previous estimates ranging from 80,000 acre-ft/yr (Glancy and Katzer, 1976, p. 66) to 134,000 acre-ft/yr (Walters and others, 1970), and less than the estimate of 235,000 acre-ft/yr by Spane (1977, p. 91). All previous estimates of ET and the estimate of ET in the overall budget were made for ET supplied by ground water, surface water, and precipitation. The estimate of ground-water ET from phreatophytes, riparian vegetation, and non-irrigated pasture grasses, 11,000 acre-ft/yr, (table 22) is considerably less than any previous estimate.

Estimates of ground-water recharge, including secondary recharge, total from 35,000 to 56,000 acre-ft/yr, and are greater than previous estimates of 27,400 acre-ft/yr (Vasey-Scott Engineering, 1974, p. 10–11), 28,000 acre-ft/yr (Nevada State Engineer, 1971, p. 5), similar to estimates of 41,000 acre-ft/yr (Glancy and Katzer, 1976, p. 48), 47,000 acre-ft/yr (Maurer, 1986, p. 35 and 36), and 51,000 acre-ft/yr (Spane, 1977, p. 143). Previous studies did not consider secondary recharge. Ground-water recharge simulated from precipitation and subsurface flow by a steady-state numerical model totaled 102,000 acre-ft/yr (Prudic and Wood, 1995, p. 9; table 2).

The volume of 10,000 acre-ft/yr (table 22) estimated for ground-water recharge from streamflow was a minimum value, assuming no contribution of ground water to ET, and was considerably less than estimates of streamflow loss of 52,000 to 58,000 acre-ft/yr (Spane, 1977, p. 14) the net infiltration of surface water, 44,000 acre-ft/yr (Maurer, 1986, p. 59 and 60) and the average annual leakage from the Carson River and irrigation ditches, 105,000 acre-ft/yr simulated by a steady-state numerical model (Prudic and Wood, 1995, p. 9; table 2). However, the estimate of 10,000 acre-ft/yr represents only that part of streamflow loss that contributes ground-water recharge and does not supply ET. The volume of streamflow loss estimated from application of infiltration rates to the areas of irrigation ditches on the southeastern part of the valley, 18,000 to 26,000 acre-ft/yr was less but of a similar magnitude to previous estimates of streamflow loss. Estimates of streamflow loss during summer months, 89,000 acre-ft/yr, (fig. 11) determined from the difference between mean daily inflow to and outflow from Carson Valley, was similar to that simulated by the numerical model.

Similarly, estimates of ground-water seepage to streamflow, 15,000 acre-ft/yr (table 22) was considerably less than that estimated by the steady-state numerical model, 58,000 acre-ft/yr (Prudic and Wood, 1995, p. 9). The estimate of 15,000 acre-ft/yr may represent a minimum value because it was calculated only for the main stem and West Fork of the

Carson River downstream of Muller Lane. Streamflow gains in the remainder of the valley were assumed to be lost to ET from downstream application of the water for irrigation.

Estimates of streamflow loss and gain presented in this report are considered to be approximations only because the application of appropriate rates of loss and gain is uncertain over large parts of the valley floor. A more appropriate tool for refining estimates of streamflow loss and gain is a numerical ground-water flow model using accurate altitudes for stream stage relative to ground-water levels adjacent to the streams and reasonable estimates for the hydraulic conductivity of the streambed materials.

Uncertainty of Water-Budget Components

The largest components of the overall water budget were the main-stem river flows of the East and West Forks of the Carson River and outflow of the Carson River, which are gaged near the study area boundaries. Uncertainties in the volumes of streamflow diversions and return flows across the study area boundary on the West Fork of the Carson River were small relative to the volume of streamflow in the Carson River.

The uncertainty of the gaged mainstem flows may be evaluated from the accuracy attributed to the records published for each water year. Records described as “excellent” means that 95 percent of the daily discharges are within 5 percent of their actual values; “good” within 10 percent; and “fair” within 15 percent. Records that do not meet these criteria are rated “poor.” Record descriptions for the mainstem gages range from “excellent” to “fair” from water years 1940 to 2005. However, Burkham and Dawdy (1968, p. 8–9) note that the uncertainty in annual flows may be less than that of the daily flows because of the compensating effects of errors in the daily flows. Anning (2002) presented methods for calculating standard errors of annual discharge, however, application of the methods is complex and beyond the scope of this study. Anning (2002, p. 37) estimated uncertainties ranging from about 8 to 14 percent for annual flows from a desilting basin on the Colorado River with annual flows ranging from about 200,000 to more than 300,000 acre-ft/yr, similar to the annual flows of the East Fork Carson River and the Carson River near Carson City (table 1). Assuming uncertainties are similar for the gaged Carson River flows, the uncertainty in annual flows may be from about 20,000 to 40,000 acre-ft/yr. Such volumes are of a similar, or greater, magnitude than many of the other water-budget components.

The next largest component of the overall water budget was ET. The accuracy of ET rates used in this report were estimated to be about 12 percent for irrigated pasture grasses and alfalfa and 20 to 30 percent for non-irrigated pasture grasses (Maurer and others, 2006, p. 23). Inaccuracies in the areas of land use to which the ET rates were applied may be present because it was not possible to field check all digitized polygons, however, these errors were considered to be small.

Uncertainty in the volume of precipitation on basin-fill sediments may be about 15 percent (Maurer and Halford, 2004, p. 37), or about 6,000 acre-ft/yr. The volumes of imported effluent are closely measured by the importing agencies. The volumes of ground-water pumping determined by the State Engineer’s Office from 1987 to 2005 were considered to be the best available estimates. However, estimates of pumping prior to the 1980s and for water years 1941–70 were considered approximations only. Estimates of the volumes of return flow from irrigation pumping and secondary recharge from lawn watering may be considerably in error.

The range for estimates of ground-water inflow indicates an uncertainty of 40 to almost 70 percent. The uncertainty includes the differences between estimates of subsurface inflow from perennial drainages, calculated using the water-yield method, combined with estimates of ephemeral streamflow lost to infiltration, and ground-water inflow calculated from the chloride-balance method. The estimates of subsurface inflow from perennial stream drainages appear to provide reasonable volumes compared to those determined for Eagle Valley where the method was developed, and provide estimates of ET that compare well with those reported in the literature (table 11). Estimates of ephemeral streamflow have an uncertainty of 50 percent and the uncertainty of chloride concentrations used in the estimates from the chloride-balance method results in a range of more than 50 percent (tables 12 and 13). However, inclusion of these uncertainties results in estimates of ground-water recharge that appear unreasonable (table 22). Development of watershed models for the Carson Range and Pine Nut Mountains could provide a more rigorous analysis of subsurface inflow and an independent check on the estimates of ground-water inflow. Such models use data on daily temperature and precipitation combined with vegetation cover, soils, altitude, slope, and aspect within the watershed to simulate runoff and provide an estimate of excess water that would become subsurface flow from the watershed. A cooperative study between the USGS and the Carson Water Subconservancy District to develop a ground-water flow model for Carson Valley includes the development of watershed models for the Carson Range and the Pine Nut Mountains. Work on the watershed models is planned to be completed in 2007.

The lack of data on the volumes of surface-water return flow from irrigation and the relative contribution of ground water and streamflow applied for irrigation to ET in Carson Valley make for considerable uncertainty in the estimate of ground-water recharge from streamflow. The estimate of ground-water recharge from streamflow represents a minimum value, assuming that ground-water contribution to ET from irrigated lands was minimal. Studies in the 1970s by Guitjens and others (1976 and 1978) indicate that ground water does supply water for ET to irrigated crops where the water table is shallow, however, the locations and rates were uncertain. The studies further indicate that ground-water recharge from flood irrigation could be significant where the water table is relatively deep and soils are sandy. Additional study that includes direct measurement of the volumes of streamflow or ground water applied for irrigation and the volumes of return flow from fields in areas having different soil types and depth to water is needed. Such data would allow refinement of the estimates of secondary recharge and net ground-water pumping for irrigation, and ground-water recharge from streamflow.

The estimate of ground-water discharge to streamflow was considerably less than previous estimates and is only approximate. Development of a numerical ground-water flow model for Carson Valley is planned and should provide a better tool to estimate the volumes of water exchanged between the surface-water and ground-water systems in Carson Valley.

Potential Effects of Land- and Water-Use Changes

The water-budget components of Carson Valley will be most greatly affected by: changes in land use from agricultural areas or areas of phreatophytic vegetation, to residential or commercial use; or changes in water use that include the increased application of effluent for irrigation, increased ground-water pumping, and changes in the configuration of the surface-water irrigation distribution system. With the exception of increased ground-water pumping, these changes will tend to decrease the volume of water lost to ET from streamflow of the Carson River and streams tributary to the valley floor and increase the volume of Carson River outflow from the valley. A numerical ground-water model would most accurately determine the net effect of these changes in land and water use.

Changes in water levels in wells on the eastern side of Carson Valley provide evidence of the effects of changes in the configuration of the irrigation distribution system. Water levels at wells 6, 8, and 9 (figs. 7 and 19) have declined about 20 ft from those in the early 1990s. The declines likely were caused by the discontinued use in 1997 of reservoirs about 1 mi from the wells which had been in use since the early 1900s (fig. 7). Infiltration from the reservoir maintained relatively high water levels in the surrounding area, which are continuing to decline in 2006. Conversely, water levels in a well near the mouth of Buckeye Creek on the eastern side of Carson Valley (well 7) have risen about 20 ft from those in the early 1990s, likely caused by infiltration losses from an effluent reservoir also about 1 mi to the northeast (figs. 7 and 19). Installation of a new ditch in the late 1990s near well 30 caused water levels to decline about 6 ft, and water levels at well 22 declined about 2 ft after flow from a nearby irrigation ditch was placed into an underground pipe. A change from agricultural use to residential use with some continued irrigation near well 23 (fig. 19) may be in part responsible for declines of about 10 ft, however, the well also is within 1 mi of a reservoir with discontinued use (fig. 7).

Discontinued use of the remaining reservoir on the eastern side of Carson Valley likely would cause water-level declines of a similar magnitude and over a similar area. Installation of deep ditches that act as drains, and lining or piping of small ditches also would likely cause water-level declines of 2 to 5 ft in areas relatively near the change.

Currently planned land-use changes in Carson Valley include as much as 350 acres where use would change from agricultural to residential or commercial use (Mimi Moss, Douglas County Planning, oral commun., 2005). The land-use change also is adjacent to a major irrigation ditch that currently is not planned to be piped but could be in the future. The decrease in irrigated land would result in a decrease in ET of about 1,000 acre-ft/yr, assuming an ET rate of 3.0 ft/yr. The canal is on the southeastern part of the valley where depth to water is greater than about 20 ft. The potential reduction in infiltration losses from the canal, assuming a loss rate of 2 ft/d and a canal width of about 10 ft, would be about 900 acre-ft/yr. The planned land-use changes likely would cause an increase in streamflow of the Carson River of about 2,000 acre-ft/yr from the decrease in ET and infiltration losses. The change in land use also is likely to increase the runoff of precipitation from impervious surfaces, however, the effect of this change depends on the use of the storm-water drainage. Along with the increase in flow of the Carson River, ground-water levels in the areas of land-use change likely would decline somewhat, however, it is difficult to predict the magnitude of the water-level declines and the area which may be affected without a detailed study of the area undergoing change.

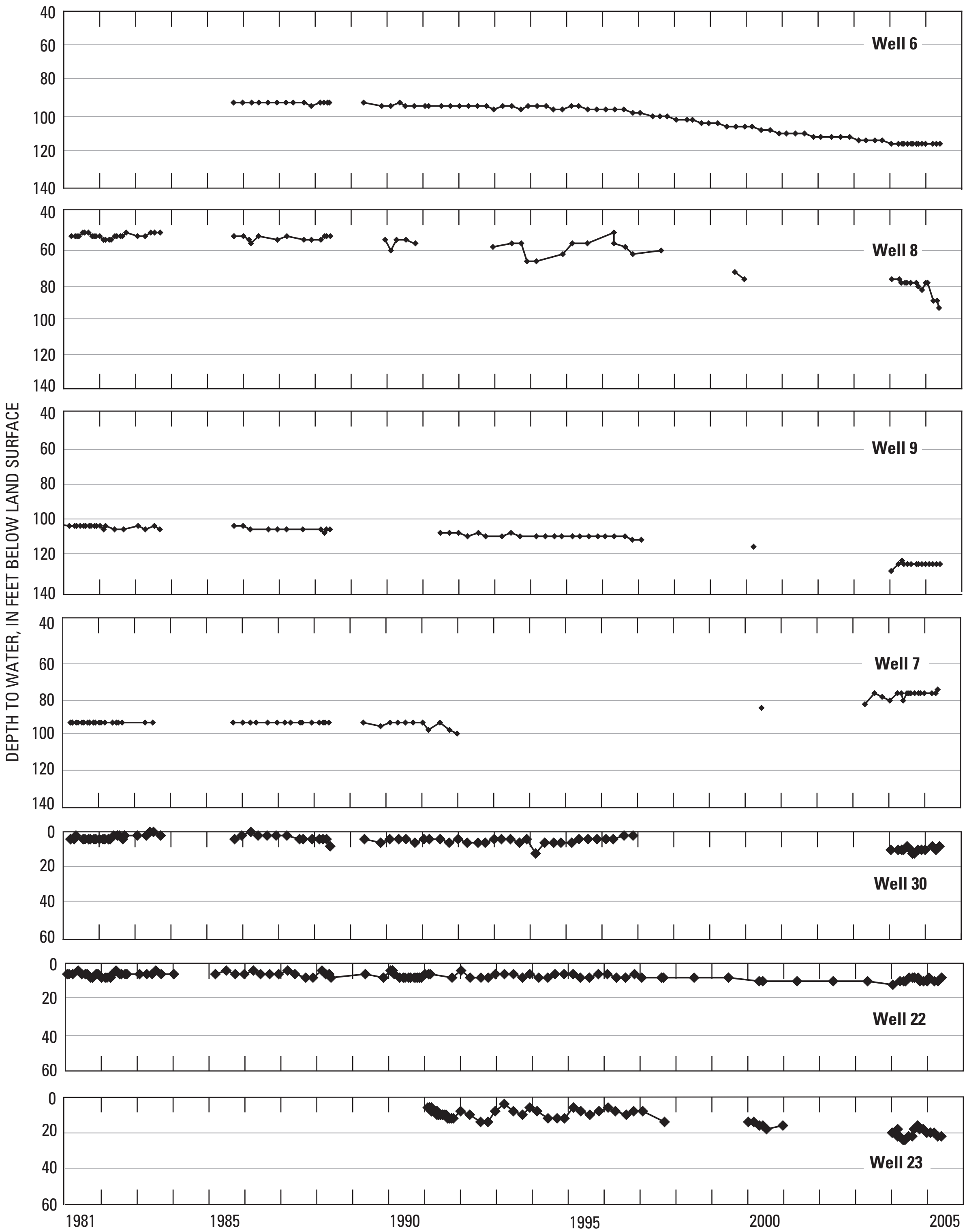


Figure 19. Water-level fluctuations in wells affected by changes in land and water use, Carson Valley, Nevada and California, 1981–2006.

Another potential land-use change is the development of 19-acre parcels on agricultural land (Mimi Moss, Douglas County Planning, oral commun., 2005). Irrigation ditches on these parcels would be maintained if downstream users are present, however, it is not certain that irrigation would continue. The effect of this type of development on the water budget depends on the location where irrigation is discontinued and the resulting vegetation that may replace the irrigated crops. If irrigation is discontinued on the valley floor where irrigated pasture grasses are present, the decrease in ET can be estimated from the area of discontinued irrigation, multiplied by 1.3 ft/yr, the difference between the ET rate of 3.0 ft/yr for irrigated pasture grasses and 1.7 ft/yr for non-irrigated pasture grasses. The decrease in ET caused by development in areas of native phreatophytes could be estimated in a similar manner, using an ET rate of about 1.9 ft/yr for the acreage removed. Land-use changes in areas currently without irrigated crops or pasture grasses, or without native phreatophytes, likely would have little effect on the overall water budget of Carson Valley.

Summary and Conclusions

To address concerns over continued growth in Carson Valley, the USGS, in cooperation with Douglas County, began a study in February 2003 to update estimates of water-budget components in Carson Valley, Nevada and California. The estimates of water-budget components were updated using annual ET rates, rates of streamflow loss to infiltration and gain from ground-water seepage, and rates of recharge from precipitation, determined from data collected in 2003 and 2004 for this study and reported in the literature. Overall water budgets were developed for the area of basin-fill deposits in Carson Valley for water years 1941–70 and for 1990–2005. A ground-water budget was developed for the same area for water years 1990–2005.

Annual ET rates were applied to areas of rabbitbrush and greasewood, bitterbrush, irrigated pasture grasses and alfalfa, non-irrigated pasture grasses, wetlands, open-water, and cottonwood and willow to determine the volumes of water discharged to the atmosphere. The areas covered by these types of vegetation were delineated from a land-use map of Carson Valley developed from imagery collected in July 2004 and used to estimate ET volumes for water years 1990–2005. Aerial photography from 1979 was used to estimate changes in land use between water years 1941–70 and 1990–2005 and estimate ET volumes for water years 1941–70.

Rates of streamflow loss and gain on the valley floor were applied to selected stream reaches to estimate ground-water recharge and discharge. The estimates of ground-water recharge and discharge were compared with the annual volumes of streamflow loss and gain determined from the long-term annual difference between mean daily inflow and outflow for water years 1990–2005.

Rates of recharge from precipitation were used to estimate recharge from precipitation on Quaternary gravel and eolian sand deposits, and the western alluvial fans. Estimates of ground-water inflow from the Carson Range and Pine Nut Mountains were derived from estimates of ephemeral streamflow, subsurface flow from perennial stream drainages estimated using a water-yield equation, referred to as the water-yield method, and the chloride-balance method.

The estimates of average inflow in the overall water budget total from 432,000 to 450,000 acre-ft/yr for water years 1941–70 and 430,000 to 448,000 acre-ft/yr for water years 1990–2005. The volumes were relatively similar, because variations in streamflow and precipitation are offset by imported effluent. Components of inflow included precipitation on basin-fill deposits of 38,000 for water years 1941–70, streamflow of the Carson River and tributaries to the valley floor of 372,000 acre-ft/yr for water years 1941–70 and 360,000 acre-ft/yr for water years 1990–2005, ground-water inflow ranging from 22,000 to 40,000 acre-ft/yr for both periods, and imported effluent of 9,800 acre-ft/yr for water years 1990–2005 with none imported for water years 1941–70. The flow of perennial streams tributary to the valley floor averaged about 32,000 acre-ft/yr for water years 1990–2005, but varies considerably, from 16,000 acre-ft/yr during dry years to 51,000 acre-ft/yr during wet years. Estimates of ground-water inflow from the California portion of Carson Valley average about 6,000 acre-ft/yr and range from 4,000 to 8,000 acre-ft/yr, comparing well with a previous estimate of ground-water inflow across the State line.

The estimates of outflow in the overall water budget total 446,000 acre-ft/yr for water years 1941–70, and 439,000 to 442,000 acre-ft/yr, for water years 1990–2005. Variations in ET and outflow of the Carson River were offset by the increase in net ground-water pumping for water years 1990–2005. Components of outflow include ET of 151,000 acre-ft/yr for water years 1941–70 and 146,000 acre-ft/yr for water years 1990–2005, streamflow of the Carson River of 293,000 acre-ft/yr for water years 1941–70 and 278,000 acre-ft/yr for water years 1990–2005, and net ground-water pumping of 2,000 acre-ft/yr for water years 1941–70, and 15,000 to 18,000 acre-ft/yr for water years 1990–2005. The decreased average flows for water years 1990–2005 compared to water years 1940–71 were likely the result of dry conditions from 1987 to 1992 and 1999 to 2005. The large volumes of inflow and outflow of the Carson River dominate the overall water budget.

Water levels in wells near the valley floor show little long-term rise or decline from 1977 to 2006, suggesting that this part of Carson Valley is in a state of approximate dynamic equilibrium. However, on the eastern side of Carson Valley in areas of increased growth and where recharge is limited to ground-water inflow from the Pine Nut Mountains, water levels show long-term water-level declines of 5 to 10 ft lower than during the previous dry period in early 1990s.

Wet conditions during water year 2006 may cause these water levels to rise as increased recharge from the Pine Nut Mountains moves westward.

Analyses of precipitation and ET for the overall water budget have shown that precipitation estimated using the adjusted PRISM distribution underestimates precipitation on the mountain blocks, and that the volume of precipitation estimated from the linear relations distribution, 270,000 acre-ft/yr, provides a reasonable estimate.

Estimates of ground-water recharge for water years 1990–2005 range from 35,000 to 56,000 acre-ft/yr, and sources of ground-water discharge range from 41,000 to 44,000 acre-ft/yr. Components of ground-water recharge include ground-water inflow from the Carson Range and Pine Nut Mountains ranging from 22,000 to 40,000 acre-ft/yr, ground-water recharge from streamflow, a minimum value of 10,000 acre-ft/yr, and secondary recharge of pumped ground water that returns to the aquifer of 3,000 to 6,000 acre-ft/yr. Components of ground-water discharge include ground-water ET from native phreatophytes, riparian vegetation, and non-irrigated pasture grasses totaling 11,000 acre-ft/yr; ground-water discharge to streamflow of the Carson River, 15,000 acre-ft/yr, and net ground-water pumping, 15,000 to 18,000 acre-ft/yr.

Changes in land use between water years 1941–70 and 1990–2005 have decreased ET by about 5,000 acre-ft/yr. The increased application of effluent for irrigation between those years has decreased the use of surface water and ground water for irrigation by about 9,500 acre-ft/yr. The total decrease, about 15,000 acre-ft/yr, was approximately equal to the net ground-water pumping of 15,000 to 18,000 acre-ft/yr. The reduction in ET and in the use of streamflow and ground water for irrigation would tend to increase outflow of the Carson River from Carson Valley, offsetting the decrease in outflow caused by ground-water pumping without changes in land use predicted by Maurer (1986) and Prudic and Wood (1995).

Acknowledgments

The authors thank Mimi Moss of Douglas County Community Development, Planning Division for providing information and assistance in developing land and water-use change scenarios, James Usher of Bently Agrodynamics for information on sprinkler application rates, Scott Clark of the Nevada Division of Water Resources for providing information on ground-water pumping, and Hal Bird of the South Tahoe Public Utilities Department, Harvey Johnson of the Incline Village General Improvement District, John Hastie and Kelvin Ikehara of the Douglas County Sewer Improvement District #1, Cindy Neisess of JWA Consultants, Kyle Menath of Carson City Utilities Department, and Frank Johnson of the Minden-Gardnerville Sanitation Department for providing information on the importation and application of effluent for irrigation.

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For more information concerning the research in this report, contact the
Director, Nevada Water Science Center
U.S. Geological Survey, 2730 N. Deer Run Road
Carson City, Nevada 89701
http://nv.water.usgs.gov

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Maurer and Berger

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SIR 2006–5305