Prepared in cooperation with Douglas County, Nevada

Precipitation and Runoff Simulations of the Carson Range and Pine Nut Mountains, and Updated Estimates of Ground-Water Inflow and the Ground-Water Budget for Basin-Fill Aquifers of Carson Valley, Douglas County, Nevada, and Alpine County, California

Scientific Investigations Report 2007–5205

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

Cover: Looking west from Ambrosetti Pond towards the Carson Range. Photograph taken by Laurie Bonner, U.S. Geological Survey, October 27, 2004.

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By Anne E. Jeton and Douglas K. Maurer

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Contents

Figures

Tables

Conversion Factors, Datums, and Abbreviations and Acronyms

Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
acre-foot per day (acre-ft/d)	0.01427	cubic meter per second (m^3/s)
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer [$(m^3/s)/km^2$]
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

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

ET	Evapotranspiration
GIS	Geographic Information System
HRU	Hydrologic Response Unit
MMS	Modular Modeling System
m.y.	Million years
PDSI	Palmer Drought Severity Index
PRMS	Precipitation-Runoff Modeling System
RMSE	Root mean square error
USGS	U.S. Geological Survey

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Precipitation and Runoff Simulations of the Carson Range and Pine Nut Mountains, and Updated Estimates of Ground-Water Inflow and the Ground-Water Budgets for Basin-Fill Aquifers of Carson Valley, Douglas County, Nevada, and Alpine County, California

By Anne E. Jeton and Douglas K. Maurer

Abstract

Recent estimates of ground-water inflow to the basin-fill aquifers of Carson Valley, Nevada, and California, from the adjacent Carson Range and Pine Nut Mountains ranged from 22,000 to 40,000 acre-feet per year using water-yield and chloride-balance methods. In this study, watershed models were developed for watersheds with perennial streams and for watersheds with ephemeral streams in the Carson Range and Pine Nut Mountains to provide an independent estimate of ground-water inflow. This report documents the development and calibration of the watershed models, presents model results, compares the results with recent estimates of ground-water inflow to the basin-fill aquifers of Carson Valley, and presents updated estimates of the ground-water budget for basin-fill aquifers of Carson Valley.

The model used for the study was the Precipitation-Runoff Modeling System, a physically based, distributed-parameter model designed to simulate precipitation and snowmelt runoff as well as snowpack accumulation and snowmelt processes. Geographic Information System software was used to manage spatial data, characterize model drainages, and to develop Hydrologic Response Units. Models were developed for

- Two watersheds with gaged perennial streams in the Carson Range and two watersheds with gaged perennial streams in the Pine Nut Mountains using measured daily mean runoff,
- Ten watersheds with ungaged perennial streams using estimated daily mean runoff,
- Ten watershed with ungaged ephemeral streams in the Carson Range, and
- A large area of ephemeral runoff near the Pine Nut Mountains.

Models developed for the gaged watersheds were used as index models to guide the calibration of models for ungaged watersheds.

Model calibration was constrained by daily mean runoff for 4 gaged watersheds and for 10 ungaged watersheds in the Carson Range estimated in a previous study. The models were further constrained by annual precipitation volumes estimated in a previous study to provide estimates of ground-water inflow using similar water input. The calibration periods were water years 1990–2002 for watersheds in the Carson Range, and water years 1981–97 for watersheds in the Pine Nut Mountains. Daily mean values for water years 1990–2002 were then simulated using the calibrated watershed models in the Pine Nut Mountains. The daily mean values of precipitation, runoff, evapotranspiration, and ground-water inflow simulated from the watershed models were summed to provide annual mean rates and volumes for each year of the simulations, and mean annual rates and volumes computed for water years 1990–2002.

Mean annual bias for the period of record for models of Daggett Creek and Fredericksburg Canyon watersheds, two gaged perennial watersheds in the Carson Range, was within 4 percent and relative errors were about 6 and 12 percent, respectively. Model fit was not as satisfactory for two gaged perennial watersheds, Pine Nut and Buckeye Creeks, in the Pine Nut Mountains. The Pine Nut Creek watershed model had a large negative mean annual bias and a relative error of -11 percent, underestimated runoff for all years but the wet years in the latter part of the record, but adequately simulated the bulk of the spring runoff most of the years. The Buckeye Creek watershed model overestimated mean annual runoff with a relative error of about -5 percent when water year 1994 was removed from the analysis because it had a poor record. The bias and error of the calibrated models were within generally accepted limits for watershed models, indicating the simulated rates and volumes of runoff and ground-water inflow were reasonable.

The total mean annual ground-water inflow to Carson Valley computed using estimates simulated by the watershed models was 38,000 acre-feet, including ground-water inflow from Eagle Valley, recharge from precipitation on eolian sand and gravel deposits, and ground-water recharge from precipitation on the western alluvial fans. The estimate was in close agreement with that obtained from the chloride-balance method, 40,000 acre-feet, but was considerably greater than the estimate obtained from the water-yield method, 22,000 acre-feet. The similar estimates obtained from the watershed models and chloride-balance method, two relatively independent methods, provide more confidence that they represent a reasonably accurate volume of ground-water inflow to Carson Valley. However, the two estimates are not completely independent because they use similar distributions of mean annual precipitation.

Annual ground-water recharge of the basin-fill aquifers in Carson Valley ranged from 51,000 to 54,000 acre-feet computed using estimates of ground-water inflow to Carson Valley simulated from the watershed models combined with previous estimates of other ground-water budget components. Estimates of mean annual ground-water discharge range from 44,000 to 47,000 acre-feet. The low range estimate for ground-water recharge, 51,000 acre-feet per year, is most similar to the high range estimate for ground-water discharge, 47,000 acre-feet per year. Thus, an average annual volume of about 50,000 acre-feet is a reasonable estimate for mean annual ground-water recharge to and discharge from the basin-fill aquifers in Carson Valley.

The results of watershed models indicate that significant interannual variability in the volumes of ground-water inflow is caused by climate variations. During multi-year drought conditions, the watershed simulations indicate that ground-water recharge could be as much as 80 percent less than the mean annual volume of 50,000 acre-feet.

Introduction

Rapid population growth (+49 percent from 1990 to 2000; Economic Research Service, 2003) and changing land use in Carson Valley, Douglas County, Nevada, is creating an increasing demand for potable water and concern over the continued availability of water to sustain future growth. Water- and land-use changes may alter the distribution and magnitude of ground-water recharge and discharge and consequently may alter flows in the Carson River, affecting water users downstream of Carson Valley, who depend on sustained river flow (fig. 1). As competition grows for limited water resources, water managers increasingly rely on the ground-water system to supply future water demand. Management of ground-water resources relies on reasonably accurate recharge rates, an important component of the ground-water budget; however, the commonly used methods to estimate recharge are limited by the scale of application (Cherkauer, 2004). A watershed-scale method for estimating ground-water recharge and other ground-water budget components uses process-based models that compute distributed water budgets for individual watersheds—a scale useful and familiar to water managers (Ely, 2006).

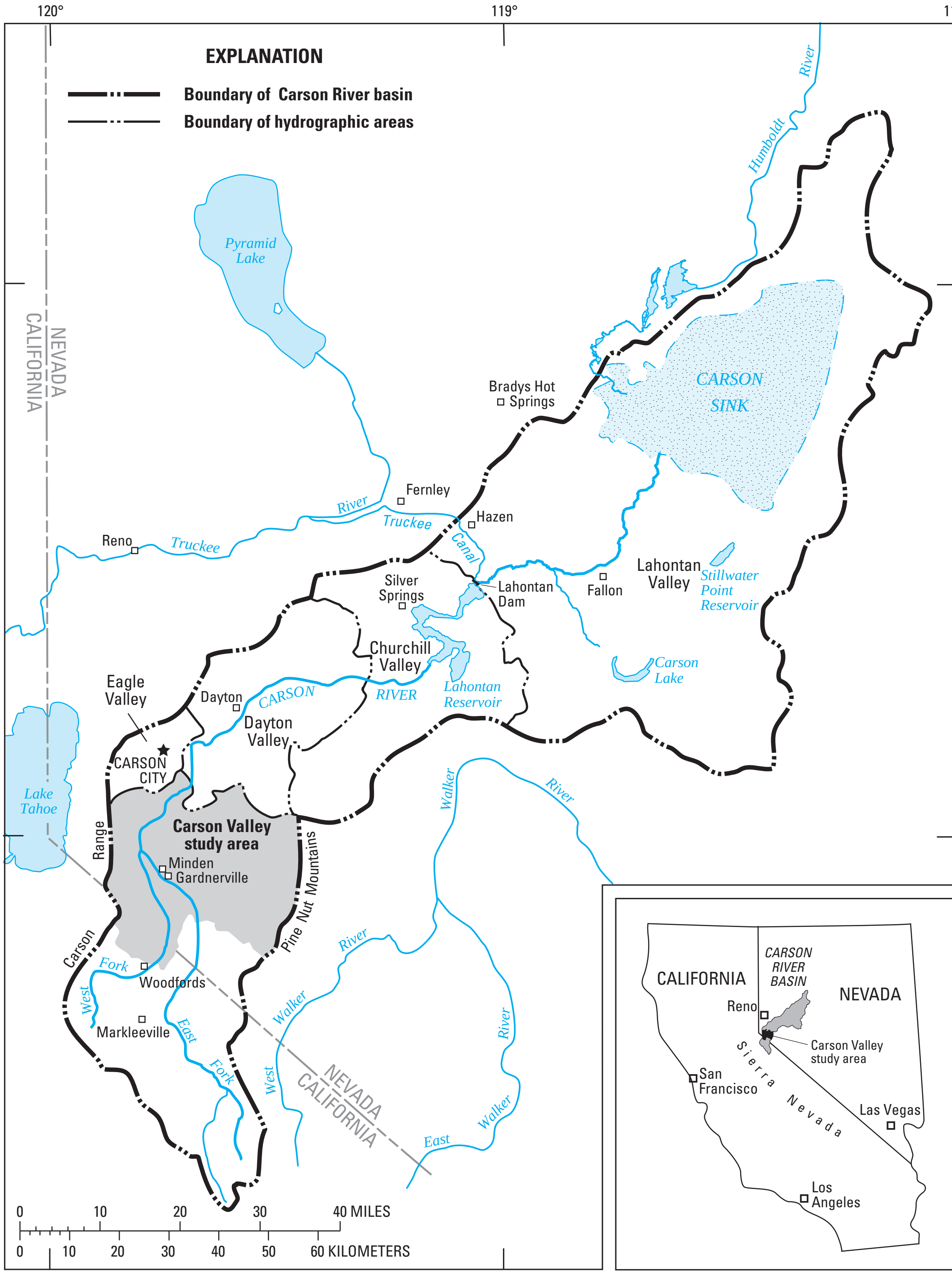
The U.S. Geological Survey (USGS) recently made estimates of water-budget components for basin-fill aquifers beneath the floor of Carson Valley (Maurer and Berger, 2007). A major water-budget component included ground-water inflow to the basin-fill aquifers of Carson Valley from the Carson Range and Pine Nut Mountains. Ground-water inflow was estimated to range from 22,000 acre-ft/yr using a water-yield method to 40,000 acre-ft/yr using a chloride-balance method (Maurer and Berger, 2007, p. 38).

Because of the relatively large range in these estimates and uncertainties in each method noted by Maurer and Berger (2007, p. 55), the U.S. Geological Survey, in cooperation with Douglas County, Nevada, and the Carson Water Subconservancy District, began a study in 2006 to update ground-water-budget estimates for Carson Valley using watershed models. Results of the models provide independent estimates of ground-water inflow to basin-fill aquifers underlying Carson Valley, and ephemeral runoff tributary to Carson Valley, both major components of the ground-water budget for Carson Valley.

The estimates of ground-water inflow simulated by the models provide information to update estimates of mean annual ground-water recharge to basin-fill sediments of Carson Valley. The estimate of mean annual ground-water recharge provides an estimate of the perennial yield of the basin-fill aquifers, defined by the Nevada Division of Water Planning (1992, p. 73) 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."

Perennial yield typically is 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 authors of these publications point out that the ultimate results of ground-water pumping are to increase, or induce, ground-water recharge, decrease ground-water discharge, or some combination of the two.



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 areas, Nevada and California.

Additionally, they state that streams and wetlands may be affected by ground-water pumping long before pumping reaches the volume of perennial yield. Prudic and Wood (1995, p. 10) have shown that in Carson Valley, pumping increases recharge through water losses from channels of the Carson River and irrigation ditches, and decreases ground-water discharge to the Carson River. These effects are caused by the hydraulic connection between the aquifer and surface-water flow created by the permeable sediments and shallow depth to water beneath much of the valley floor.

Bredehoeft (1997) and Sophocleous (1997) both note the utility of ground-water flow models to quantify the changes in recharge and discharge caused by pumping. Such a model is currently being developed for the basin-fill aquifers of Carson Valley by the USGS in cooperation with the Carson Water Subconservancy District. Results of the watershed modeling also provide a means to spatially and temporally distribute estimates of ground-water recharge near the boundaries of the numerical ground-water flow model. The model will provide a useful tool for the State Engineer and water planners to evaluate the ultimate effects of different ground-water management options on the water resources of Carson Valley.

Purpose and Scope

This report documents the development and calibration of precipitation-runoff models for watersheds with perennial streams, and for watersheds with ephemeral streams in the Carson Range and Pine Nut Mountains and presents estimates of ground-water inflow to basin-fill aquifers of Carson Valley based on the model results. The model results were compared with previous estimates of ground-water inflow to Carson Valley, and used to update the ground-water budget for basin-fill aquifers of Carson Valley.

The precipitation-runoff models were developed using the Precipitation-Runoff Modeling System (PRMS: Leavesley and others, 1983) within the Modular Modeling System (MMS: Leavesley and others, 1996). Input data used in the models were daily precipitation and daily minimum and maximum air temperature from four National Weather Service Stations and one Natural Resources Conservation Service high-altitude station, land-cover and soils data, and slope, aspect, and altitude. Model output consisted of runoff, evapotranspiration, and ground-water inflow.

The precipitation-runoff models were calibrated against measured runoff for water years 1990–2001 and 1990–2002 for two gaged watersheds with perennial streams in the Carson Range, and for water years 1981–97 for two gaged watersheds with perennial streams in the Pine Nut Mountains. Runoff and ground-water inflow from 10 ungaged watersheds with perennial streams in the Carson Range were simulated using the model parameters from the calibrated models having similar bedrock geology for water years 1990–2002. The models of watersheds with ungaged perennial streams were calibrated against runoff estimated in an earlier study. The precipitation-runoff models were calibrated to match the full period of record for each respective watershed rather than using separate calibration and verification periods. This allowed for a direct comparison to the mean annual water budget values estimated from earlier studies.

Additionally, 11 watersheds with ungaged ephemeral streams were modeled, 10 in the Carson Range and 1 large aggregated area on the east side of Carson Valley, using the model parameters from the calibrated models of watersheds with gaged perennial streams having similar bedrock geology. For brevity, in the remainder of the report, the modeled watersheds will be referred to as perennial and ephemeral watersheds, although the term actually applies to the streams themselves. Simulated ground-water inflow and ephemeral runoff were used to update estimates of ground-water inflow from the Carson Range and Pine Nut Mountains. The updated estimates of ground-water inflow were combined with previous estimates of other ground-water recharge components, to obtain an updated ground-water budget for basin-fill aquifers of Carson Valley.

Geographic Setting

Carson Valley is primarily in Douglas County, Nevada, about 4 mi south of Carson City, Nevada's capital (figs. 1 and 2). The southern end of the valley extends about 3 mi into Alpine County, California (fig. 2). The floor of the valley is oval-shaped, about 20 mi long and 8 mi wide, and slopes from an altitude of about 5,000 ft 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 in altitude from 9,000 to 11,000 ft, whereas, the Pine Nut Mountains on the eastern side rise more gradually to peaks ranging in altitude from 8,000 to 9,000 ft.

The major towns in the valley are Minden and Gardnerville (fig. 2) with populations of 2,800 and 3,400, respectively (U.S. Census Bureau, 2003). Three 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 has grown from a population of about 28,000 in 1990 to 41,000 in 2000, an increase of 46 percent (Economic Research Service, 2003).

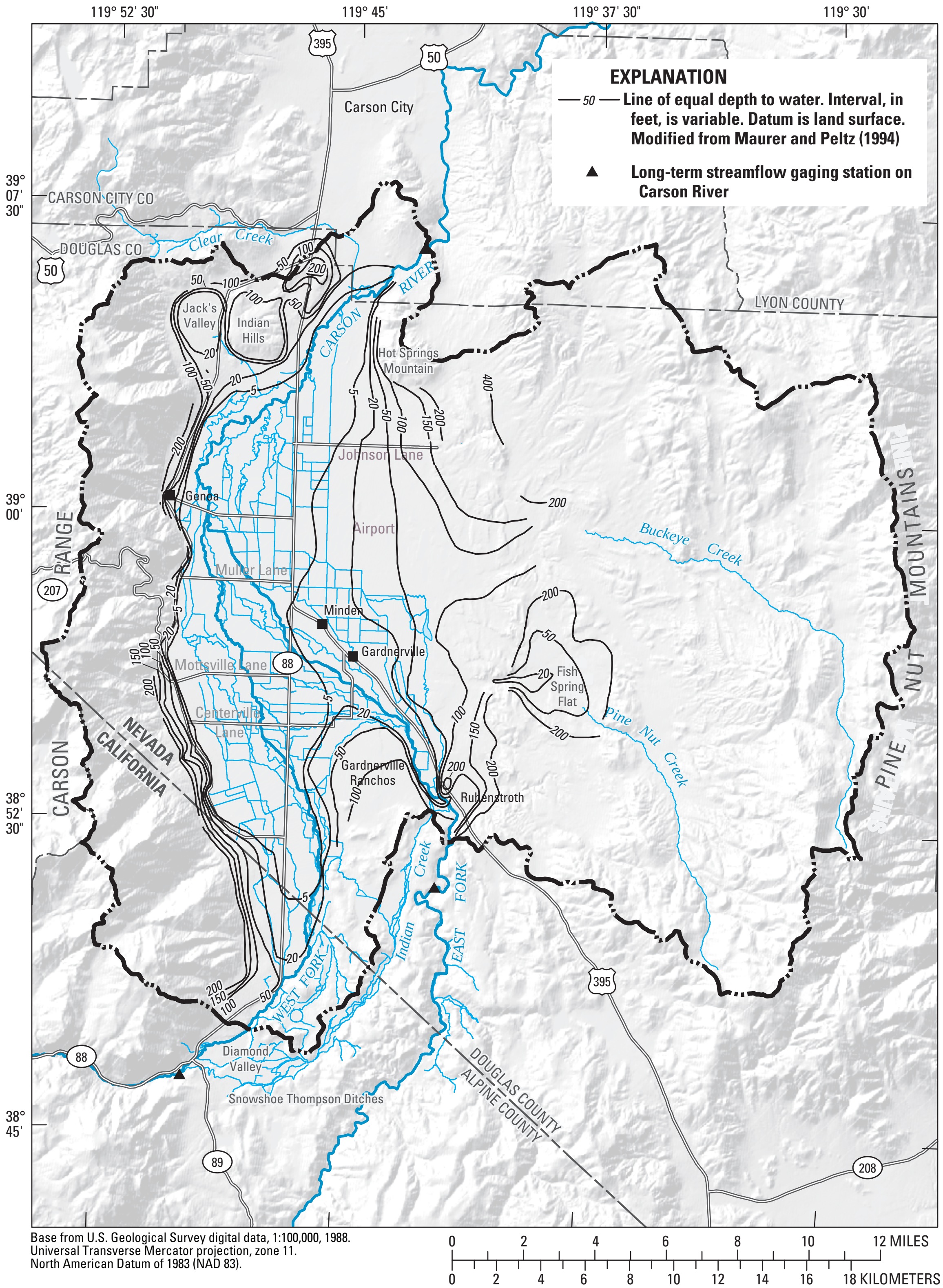


Figure 2. Location of the Carson Valley study area and depth to water table, Nevada and California, June 2005.

The Carson Valley study area is a subarea of the entire Carson Valley Hydrographic Area and includes the portion of the hydrographic area underlain by permeable materials capable of transmitting ground water to aquifers beneath the floor of Carson Valley (figs. 1 and 2). 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. The study area boundary covers 253,570 acres, or about 396 mi^2.

The valley floor is covered with native pasture grasses, croplands of primarily alfalfa, and near the northern end of the valley, phreatophytes such as greasewood, rabbitbrush, and big sage. 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 grow at high altitudes on the Pine Nut Mountains.

Geologic Setting

The distribution of surficial geologic units in Carson Valley is shown in figure 3. The geologic units of Stewart and Carlson (1978) were grouped into unconsolidated alluvial fan, gravel, eolian sand, and basin-fill deposits of Quaternary age, volcanic rocks and semiconsolidated sediments of Tertiary age, granitic rocks of Cretaceous age, and metamorphic rocks of Triassic to Jurassic 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. 3), and underlie the floor of Carson Valley (Moore, 1969, p. 18; Pease, 1980, p. 2). The Tertiary semiconsolidated sediments are exposed on the eastern side of the valley and likely also underlie Quaternary basin-fill sediments beneath the valley floor. Basin and Range faulting took place from 10 to 7 m.y. ago, producing the present topography of Carson Valley by uplifting the Carson Range and Pine Nut Mountains and downdropping the floor of Carson Valley (Muntean, 2001, p. 9).

The mountain blocks bounding Carson Valley are west-tilted structural blocks (Stewart, 1980, p. 113), with the valley occupying the downdropped western edge of the Pine Nut Mountains 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 Mountains block into several smaller blocks (fig. 3). Evidence of continued westward tilting is demonstrated 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 that the depth to consolidated bedrock beneath the western half of Carson Valley is as great as 5,000 ft.

EXPLANATION FOR FIGURE 3

Surficial Geologic Units

Quaternary

Basin-fill deposits

Gravel deposits

Eolian sand

Alluvial fans

Tertiary

Semiconsolidated sediments

Volcanic rocks

Cretaceous

Granitic rocks

Triassic and Jurassic

Metamorphic rocks

Boundary of Carson Valley study area

6u 12g **Boundary of perennial watershed and No.**—“u” indicates ungaged watershed, “g” indicates gaged watershed

1e **Boundary of ephemeral watershed and No.**

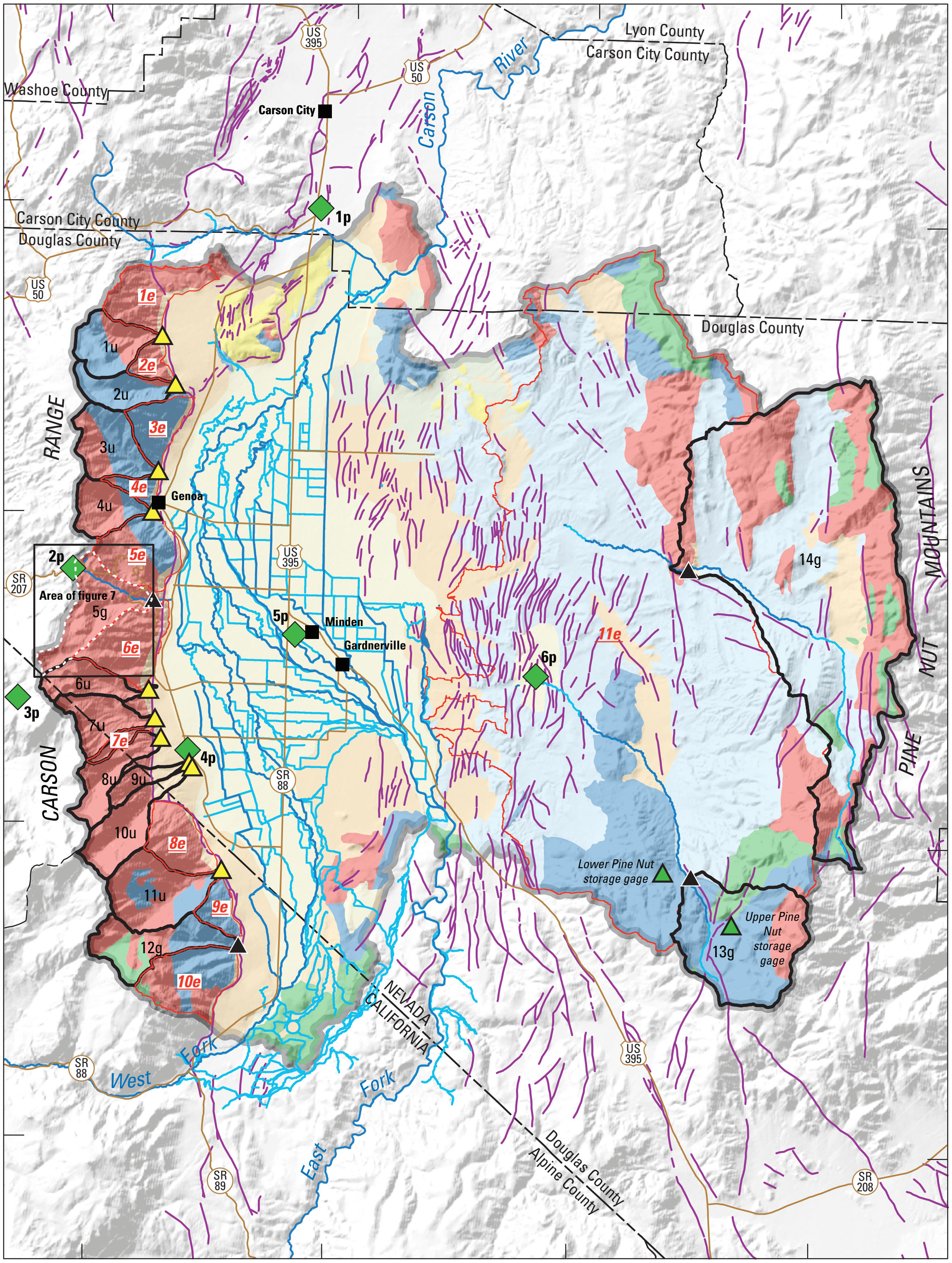
Fault—Dashed where approximately located

6p **Precipitation station and No.**

Runoff measurement site

Gaging station

Precipitation storage gage



Base from U.S. Geological Survey digital data, 1:100,000, 1988 Universal Transverse Mercator projection, zone 11.
Shaded-relief from 30-meter Digital Elevation Model: 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).

0 2 4 6 8 MILES
0 2 4 6 8 10 12 KILOMETERS

Figure 3. Surficial geologic units and faults in Carson Valley, perennial and ephemeral watersheds, and the locations of precipitation and runoff gaging or measurement stations used in watershed model development, Nevada and California.

Hydrologic Setting

Carson Valley lies in the rainshadow of the Carson Range, with annual precipitation at the town of Minden on the valley floor 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 1984 to 1992 and from 1999 to 2004, conditions were dry with annual precipitation less than average (fig. 4*A*). The Palmer Drought Severity Index (PDSI; National Oceanic and Atmospheric Administration, 2006) is based on long-term weather conditions and provides a cursory indication of regional meteorological wet or dry periods (fig. 4*C*). The PDSI indicates that the longest recorded period of severe to extreme drought conditions was from 1999 to 2004.

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 (fig. 2). The combined flow continues north to leave the valley southeast of Carson City. 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. Twelve perennial streams drain the Carson Range, their flow reaches the valley floor even during extended periods of drought (fig. 3; Maurer and Berger, 2007, p. 36). Only two perennial streams, Buckeye and Pine Nut Creeks, drain the Pine Nut Mountains and their flow only rarely reaches the valley floor, becoming ephemeral a short distance downstream of their gaging stations (fig. 3) Ten ephemeral watersheds also drain the Carson Range, and a large area of ephemeral runoff is present on the eastern side of the valley. However, runoff from these ephemeral watersheds has not been measured.

Infiltration of surface water through streambeds and ditches and beneath flood-irrigated fields maintains a shallow water table less than 5 ft below land surface beneath much of the valley floor (fig. 2). Depth to the water table 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 the water table on the eastern side of the valley reaches 200 ft about 3 mi from the valley floor (fig. 2).

Ground water flows downgradient from the Carson Range on the west and the Pine Nut Mountains on the east towards the Carson River on the valley floor. Beneath alluvial fans on the western side of the valley, ground water flows eastward and the gradient is about 100 ft/mi, whereas on the eastern side of the valley, ground water flows westward and the gradient ranges from 20 to 100 ft/mi (Maurer, 1986, p. 18). Beneath the valley floor, ground water flows toward the north and 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 (Berger and Medina, 1999). Maurer (1986, p. 18), Maurer (2002, p. 10), and Maurer and Berger (2007, p. 57) present water-level data that indicate ground water flows from semiconsolidated sediments on the eastern side of the valley towards the valley floor.

Unconsolidated sediments that form the 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). In the semiconsolidated Tertiary sediments, lenses of sand and gravel are the primary water-bearing units, and probably transmit most ground-water flow through the units. The consolidated granitic and metamorphic rocks forming the bulk of the Carson Range and Pine Nut Mountains are much less permeable to ground-water flow than other geologic units in Carson Valley. However, numerous wells have been drilled in the consolidated rocks that provide sufficient water for domestic use from fractured or weathered zones.

Components of the Ground-Water Budget for Basin-Fill Sediments of Carson Valley

The components of the ground-water budget for basin-fill sediments of Carson Valley were delineated by Maurer and Berger (2007, p. 20). The major component of ground-water recharge to basin-fill sediments is ground-water inflow from the Carson Range and Pine Nut Mountains (fig. 5). Ground-water inflow was estimated by Maurer and Berger (2007) from the perspective of the basin-fill aquifers beneath the floor of Carson Valley. For this reason, the term ground-water inflow was used to describe ground-water flow from watersheds in the Carson Range and Pine Nut Mountains. Ground-water inflow from the Carson Range includes inflow from perennial and ephemeral watersheds, and inflow from infiltration of

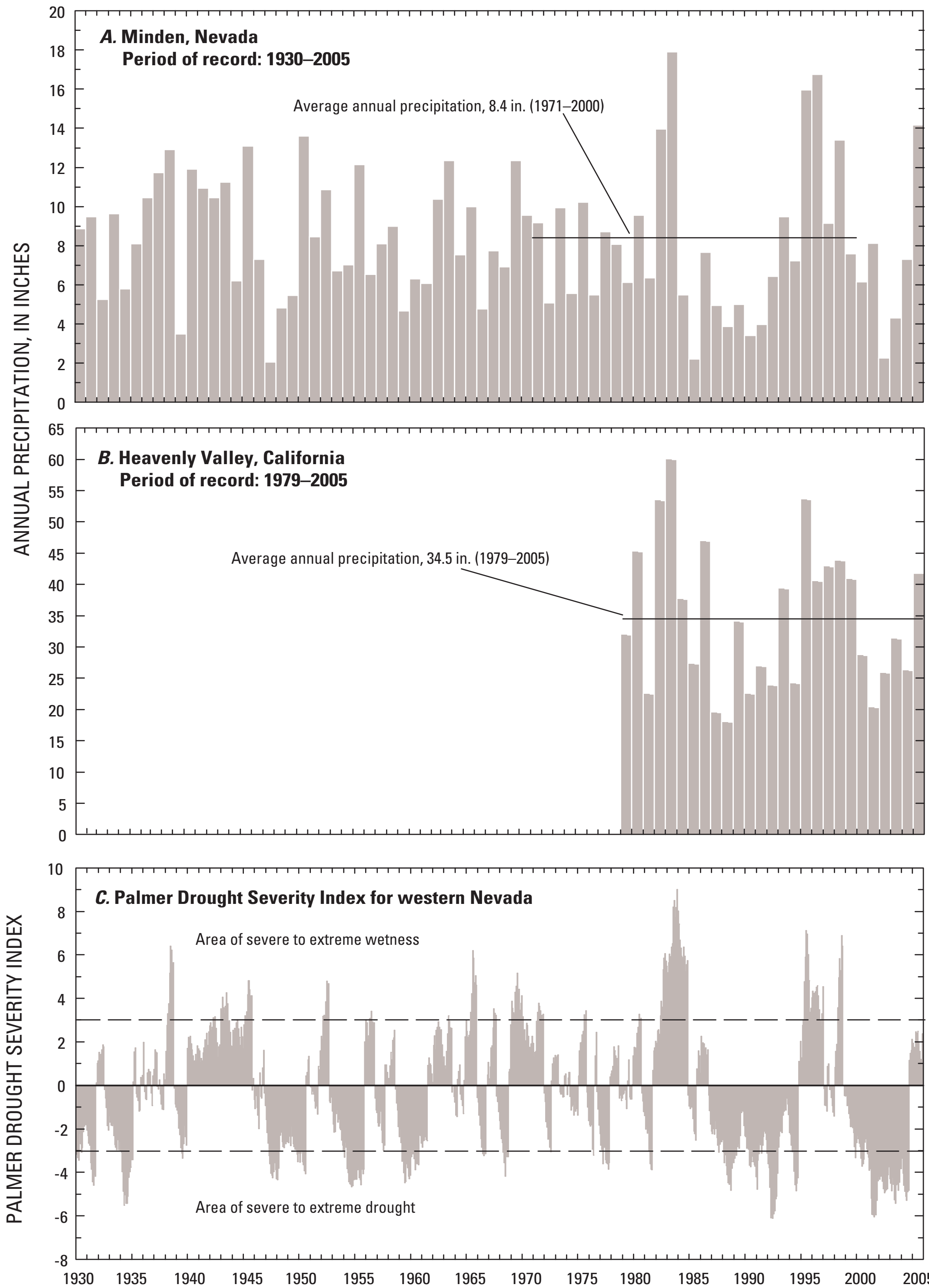


Figure 4. Annual precipitation at Minden, Nevada, and Heavenly Valley, California, and Palmer Drought Severity Index for western Nevada.

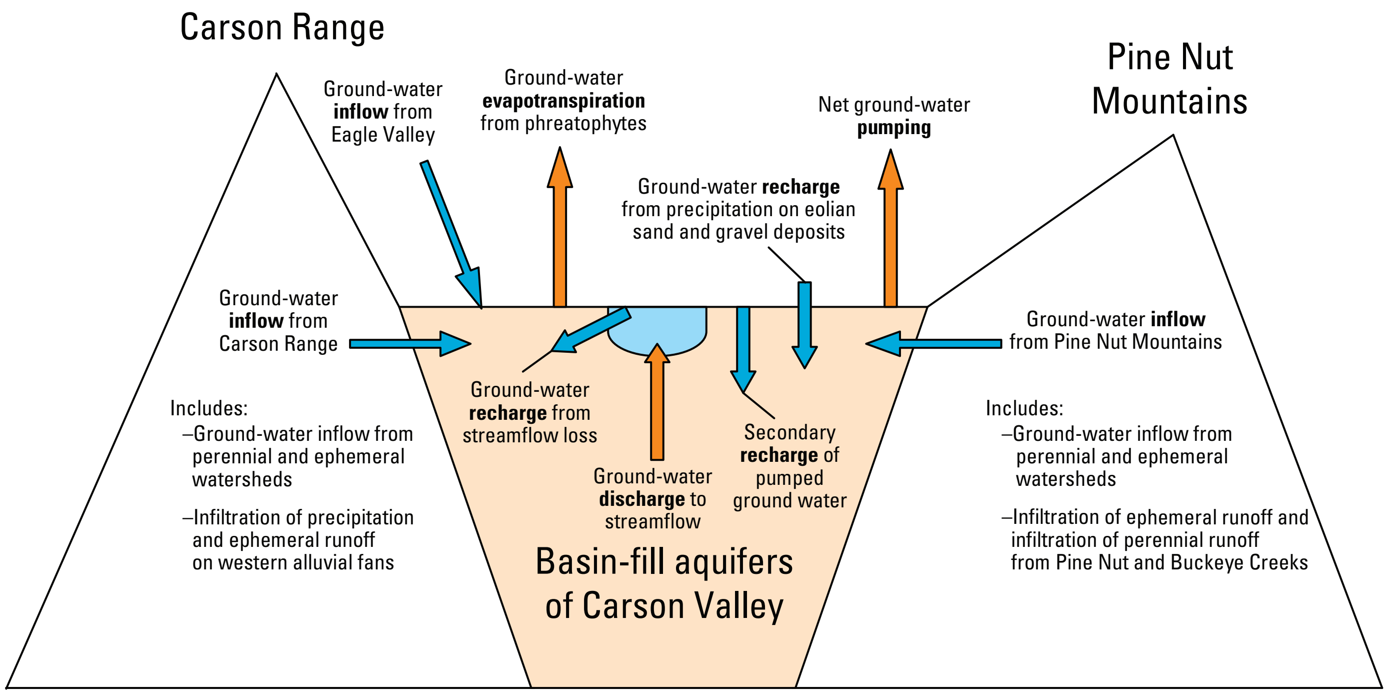


Figure 5. Components of ground-water recharge to and discharge from basin-fill aquifers of Carson Valley, Nevada and California.

precipitation and ephemeral runoff on the western alluvial fans. Maurer and Berger (2007, p. 36) concluded that infiltration of perennial runoff on the western alluvial fans was negligible. Ground-water inflow from the Pine Nut Mountains includes ground-water inflow from perennial and ephemeral watersheds, and ground-water inflow from infiltration of ephemeral runoff. The term ground-water inflow is used throughout this report to remain consistent with previous descriptions of ground-water movement into the basin-fill aquifers of Carson Valley.

Such ground-water inflow is not strictly considered ground-water recharge because the flow does not cross the water table (Freeze and Cherry, 1979, p. 211). However, for the purposes of this study, which is focused on the basin-fill aquifers of Carson Valley, ground-water inflow entering basin-fill aquifers from the mountain blocks was considered ground-water recharge.

Maurer and others (2006, p. 28) used soil-chloride data to show that recharge from precipitation does not take place at most locations on alluvial fans and semiconsolidated sediments on the eastern side of Carson Valley. The soil-chloride data showed that ground-water recharge from precipitation does take place on eolian sand and gravel deposits in the northern part of Carson Valley (fig. 3), although at relatively low rates.

Ground-water inflow to the basin-fill deposits of Carson Valley from the Carson Range and Pine Nut Mountains was estimated by Maurer and Berger (2007) using a water-yield method and a chloride-balance method. The water-yield method uses an equation developed for nearby Eagle Valley (Maurer and Berger, 1997, p. 34) that computes estimates of water yield, defined by Maurer and Berger (1997) as the sum of runoff and ground-water inflow, from annual precipitation. The equation was applied to precipitation estimates for each watershed made by Maurer and Berger (2007, p. 29) using the linear relations of Maurer and Halford (2004) to estimate water yield from the perennial watersheds. The estimates of runoff from the perennial watersheds by Maurer and others (2004, p. 14) were subtracted from the computed water yield to obtain estimates of ground-water inflow.

The estimates of ground-water inflow from the water-yield method were combined with estimates of inflow from infiltration of precipitation and ephemeral runoff on the western alluvial fans to obtain the total ground-water inflow to basin-fill aquifers in Carson Valley (Maurer and Berger, 2007, p. 38). Maurer and Berger (2007) assumed that ephemeral runoff is largely lost to infiltration and that infiltration of ephemeral runoff becomes ground-water inflow to the basin-fill aquifers of Carson Valley. The total ground-water inflow to the basin-fill deposits of Carson Valley estimated using the water-yield method was 22,000 acre-ft/yr (Maurer and Berger, 2007, p. 40).

The chloride-balance method uses a chloride mass-balance equation (Wilson and Guan, 2004, p. 122; Maurer and Berger, 2007, p. 34). The method assumes that chloride deposited from precipitation is concentrated in the subsurface as water is lost to evapotranspiration (ET) in the mountains and on alluvial fans. The masses of chloride deposited by precipitation and removed in runoff are determined from the chloride concentrations of precipitation and runoff multiplied by their mean annual volumes. The mass of chloride from precipitation minus the mass of chloride in runoff is divided by the chloride concentration of ground water in basin-fill aquifers to estimate ground-water inflow. The estimate includes ground-water inflow from perennial and ephemeral watersheds and from infiltration of runoff and precipitation on the alluvial fans when the chloride concentration of ground water near the toe of the alluvial fans is used (Wilson and Guan, 2004, p. 123). Ground-water inflow to Carson Valley estimated using the chloride-balance method was 40,000 acre-ft/yr (Maurer and Berger, 2007, p. 40).

Other components of ground-water recharge estimated by Maurer and Berger (2007) include ground-water inflow to the northern end of Carson Valley from Eagle Valley, ground-water recharge from precipitation on eolian sand and gravel deposits, ground-water recharge from streamflow of the Carson River and irrigation ditches, and secondary recharge of pumped ground water (fig. 5). Using streambed temperature data, and data on ground-water levels compared to stream stage, Maurer and Berger (2007, p. 51) showed that the Carson River and irrigation ditches generally lose flow to ground-water recharge on the southern and southeastern parts of Carson Valley, and gain flow from ground-water discharge on the western and northern parts of Carson Valley. Components of ground-water discharge estimated by Maurer and Berger (2007) include ground-water discharge by evapotranspiration (ET) of phreatophytes, ground-water discharge to streamflow, and net ground-water pumping.

Water-budget estimates by Maurer and Berger (2007) were representative of water years 1990–2005. The estimates of ground-water recharge from discharge to the Carson River, net ground-water pumping, and secondary recharge of pumped ground water were made from analyses of streamflow gains and losses, and data on annual pumping averaged over the period 1990–2005. The estimates of ET were based on a land-use map developed from imagery collected in 2004 and updated by field checks for 2005. Estimates of ground-water inflow used mean annual runoff for 1990–2002, and mean annual precipitation for 1971–2000.

In this report, water-budget components simulated by the watershed models are mean annual values representative of water years 1990–2002, the period for which measured and estimated daily mean runoff data were available for model calibration. The estimates were combined with other water-budget components estimated by Maurer and Berger (2007) for water years 1990–2005, under the assumption that the two periods have similar hydrologic conditions. Mean annual precipitation at Heavenly Valley, near the crest of the Carson Range averaged 33.29 in. for water years 1990–2002 and 33.26 in. for water years 1990–2005. Similarly, mean annual precipitation at Minden, Nev., on the floor of Carson Valley averaged 8.72 in. for water years 1990–2002 and 8.67 in. for water years 1990–2005; indicating only a small difference in mean annual precipitation during the two periods.

Description of Watershed Models

Models were developed for gaged and ungaged perennial-stream watersheds and ungaged ephemeral-stream watersheds in the study area. Watershed models for four gaged perennial watersheds were calibrated for this study; Daggett Creek (watershed 5g), Fredericksburg Canyon (watershed 12g), Pine Nut Creek (watershed 13g), and Buckeye Creek (watershed 14g; fig. 3, table 1). Models were then developed for the 10 ungaged perennial watersheds in the Carson Range (fig. 3 and table 1) having estimates of daily mean runoff from a previous study (watersheds 1u–4u and 6u–11u; Maurer and Berger, 2007).

Table 1. Major bedrock type, runoff as a percentage of precipitation, index model, and precipitation stations used for model development of perennial gaged and ungaged watersheds, Nevada and California.

[**Watershed No.:** "u" is ungaged, "g" is gaged. Locations are shown in figure 3. **Runoff efficiency:** Runoff as a percentage of precipitation from Maurer and Berger (2007, p. 29). **Index model**: Watershed model for gaged watershed used as index for models of ungaged watersheds. Abbreviations: –, indicates no index model used]

Watershed No.	Watershed name	Major bedrock type	Runoff efficiency (percent)	Index model	Altitude of precipitation station	
					Low	High
1u	Water Canyon	Metamorphic and granitic	45	Fredericksburg Canyon	Sheridan Acres	Daggett Pass
2u	James Canyon	Metamorphic	38	Fredericksburg Canyon	Sheridan Acres	Daggett Pass
3u	Sierra Canyon	Metamorphic and granitic	31	Daggett Creek	Sheridan Acres	Daggett Pass
4u	Genoa Canyon	Granitic	30	Daggett Creek	Sheridan Acres	Daggett Pass
5g	Daggett Creek	Granitic	21	–	Sheridan Acres	Daggett Pass
6u	Mott Canyon	Granitic	52	Fredericksburg Canyon	Sheridan Acres	Heavenly Valley
7u	Monument Creek	Granitic	74	Fredericksburg Canyon	Sheridan Acres	Heavenly Valley
8u	Stutler Canyon	Granitic	11	Daggett Creek	Sheridan Acres	Heavenly Valley
9u	Sheridan Creek	Granitic	93	Fredericksburg Canyon	Sheridan Acres	Heavenly Valley
10u	Jobs Canyon	Granitic	31	Daggett Creek	Sheridan Acres	Heavenly Valley
11u	Luther Creek	Granitic	30	Daggett Creek	Sheridan Acres	Heavenly Valley
12g	Fredericksburg Canyon	Metamorphic and granitic	45	–	Sheridan Acres	Heavenly Valley
13g	Pine Nut Creek	Metamorphic	8	–	Minden (1980–91) Fish Springs (1992–2002)	Minden (1980–91) Fish Springs (1992–2002)
14g	Buckeye Creek	Granitic	2	–	Minden (1980–91) Fish Springs (1992–2002)	Minden (1980–91) Fish Springs (1992–2002)

Models for the ungaged perennial watersheds were developed using the calibrated models for either the Daggett Creek or Fredericksburg Canyon watersheds as an index model, meaning that PRMS parameters of the index model were used in building the preliminary model for the ungaged watersheds. Selection of which gaged watershed model to use as an index model was based on the similarity between gaged and ungaged watersheds of (1) major bedrock type, and (2) runoff as a percentage of precipitation as determined by Maurer and Berger (2007, p.29). The Daggett Creek watershed is underlain by granitic bedrock and about 21 percent of precipitation becomes runoff (table 1), whereas the Fredericksburg Canyon watershed is underlain by a mixture of granitic and metamorphic bedrock and a relatively large amount, about 45 percent, of precipitation becomes runoff.

Finally, models were developed for ephemeral watersheds to estimate the quantity of ephemeral runoff tributary to Carson Valley and the potential for ground-water inflow from ephemeral watersheds. Models were developed for 10 of the larger ephemeral watersheds of the Carson Range (watersheds 1e–10e, fig. 3) and a large area near the Pine Nut Mountains where runoff is ephemeral (watershed 11e) Similar to the models developed for the ungaged perennial watersheds, either the Daggett Creek or Fredericksburg Canyon watershed models were used as index models for the ephemeral watershed models of the Carson Range. Because the volume of ephemeral runoff is uncertain, selection of the index model was based only on the bedrock type underlying the ephemeral watershed. The Buckeye Creek model (table 1) was used as an index model for the area of ephemeral runoff on the eastern side of the valley. The Buckeye Creek model was used rather than the Pine Nut Creek model because the overall geology underlying the Buckeye Creek watershed is more similar to that of the area of ephemeral runoff. It consists of a mixture of consolidated rocks, semiconsolidated sediments, and alluvial fans (fig. 3). Index model parameters were used for the ephemeral watershed models without adjustment, except for an adjustment of the precipitation correction factor as discussed in the section, “Runoff and Climate Data.”

Precipitation-Runoff Modeling System

Conceptually, perennial and ephemeral drainages such as those on the eastern and western sides of Carson Valley can be described in terms of a few key hydrologic processes that, working in combination, result in measured runoff variations (Beven, 2001). The model used in this study is the Precipitation-Runoff Modeling System (PRMS; Leavesley and others, 1983). PRMS is a process-based, distributed-parameter modeling system designed to analyze the effects of precipitation, climate, and land use on runoff and watershed hydrology (Leavesley and others, 1983).

The term “process-based” refers to the use of mathematical equations to simulate the physical processes of the various water-budget components. The term “distributed-parameter” refers to the representation of the watershed with spatially varying hydrologic characteristics, which is represented numerically as a collection of hydrologic response units (HRUs) that each have a unique set of physical-parameter values. The term “parameters” used throughout this report refers to quantities that define certain relatively constant characteristics of the watershed system. When evaluating the mathematical representation of the watershed, the independent variables are varied, while the parameters are held constant. The system may then be reevaluated or reprocessed with different parameter values, to simulate a system with different behavior.

The PRMS computer program is part of a larger modeling system, the Modular Modeling System (MMS) (http://wwwbrr.cr.usgs.gov/projects/SW_precip_runoff/software/software.shtml). MMS combines a library of modules that simulate separate components of the hydrologic system including water, energy and biochemical processes.

In distributed-parameter precipitation-runoff models, the hydrologic processes are parameterized to account for the spatial and temporal variability of basin characteristics. Although partitioning methods differ, the intent of distributed-parameter models is to better conceptualize hydrologic processes, to represent these processes at time and space scales similar to those in nature, and to reduce model input error, thereby improving overall model performance.

The spatial variability of land characteristics that affect runoff within watersheds is accounted for in the model by dividing the modeled area into Hydrologic Response Units (HRUs). A critical assumption is that the hydrologic response to uniformly distributed precipitation and simulated snowmelt is homogeneous within each HRU. HRUs are thus characterized by those physiographic properties that determine hydrologic response: altitude, slope, aspect, vegetation, soil, geology, and climate. HRUs may consist of noncontiguous or contiguous areas of similar properties. Water and energy balances reflecting physical and hydrologic characteristics and the climate conditions for that day are computed daily for each HRU. The HRU is indexed to one or more nearby climate stations and precipitation is adjusted within the PRMS model with monthly correction factors. Monthly temperature lapse rates and precipitation-correction factors are used to extrapolate measured daily air temperature and precipitation from nearby climate stations to individual HRUs, thereby accounting for spatial and altitude differences. The form of precipitation (rain, snow, or mixed) is dependent on relations between a specified snow-rain threshold temperature and minimum and maximum temperatures for each HRU.

Responses to climate events can be simulated in terms of water and energy balances, streamflow regimes, flood peaks and volumes, soil-water relations, and ground-water recharge (represented by the term ground-water sink in fig. 6). Ground-water recharge from the watersheds moves in the subsurface to become ground-water inflow to the basin-fill aquifers in Carson Valley.

The watershed system is conceptualized as a series of interconnected reservoirs, whose collective output produces the total hydrologic response (fig. 6). The water-budget components (rectangular boxes) denote the storage and collection of water and energy. Daily precipitation, daily maximum and minimum air temperature, and a surrogate for daily solar radiation are inputs that drive the model. The surrogate for solar radiation is estimated from daily temperature using a modified degree-day method and adjusted for slope and aspect. This method is appropriate for use in the study area because predominantly clear skies prevail on days without precipitation (Frank and Lee, 1966; Swift, 1976).

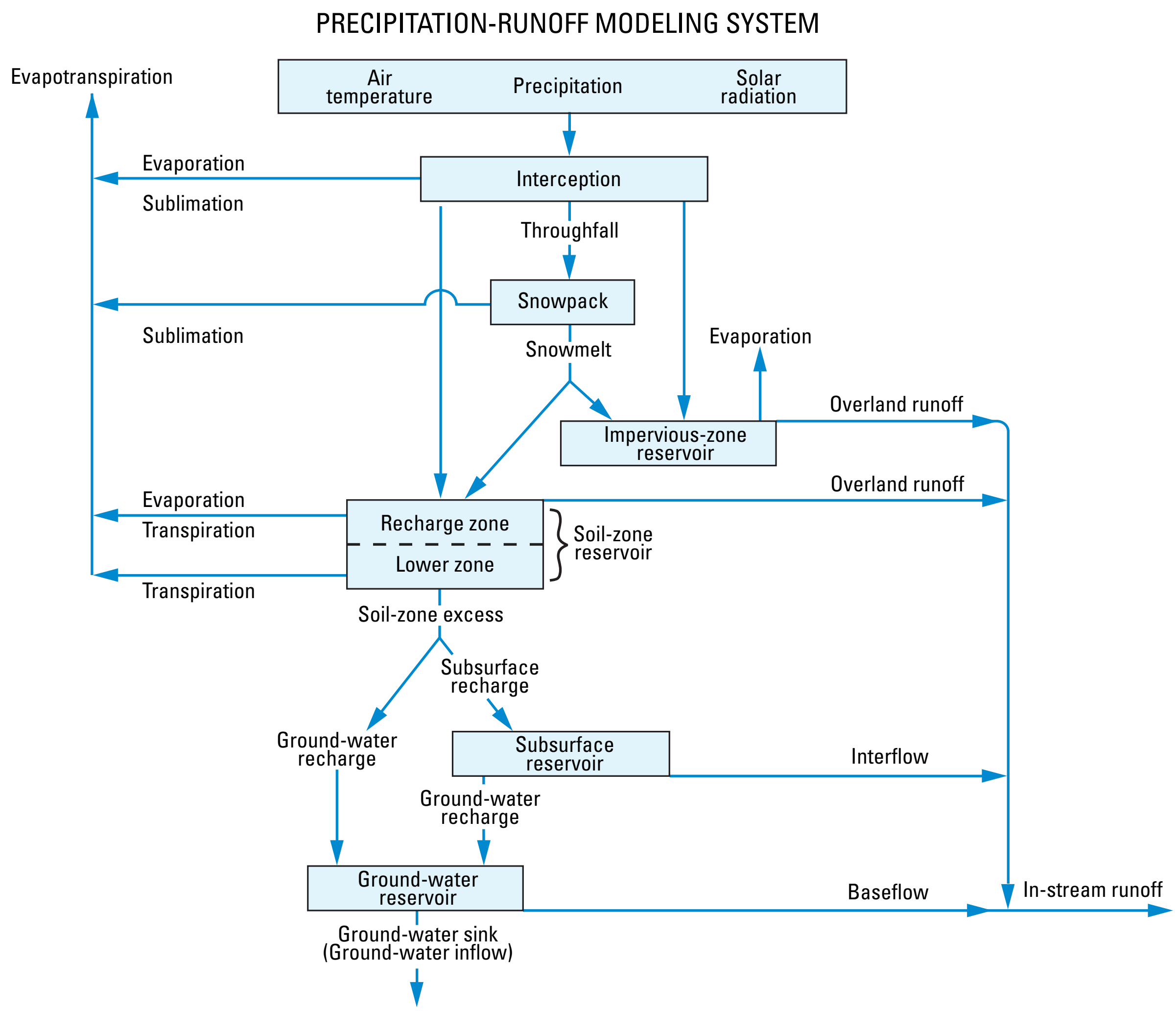


Figure 6. Schematic diagram of processes simulated by the Precipitation-Runoff Modeling System (modified from Leavesley and others, 1983).

Snowmelt is a significant component of the water budget for mountainous watersheds. Snowpack components of PRMS simulate the initiation, accumulation, and depletion of snow on each HRU. The snowpack is simulated both in terms of its water storage and as a dynamic-heat reservoir (Anderson, 1973; Obled and Rosse, 1977; Leavesley and others, 1983). A snowpack water balance is computed daily within each HRU, and a snowpack energy balance is computed each day and night. For moderate-altitude, snow-dominated watersheds such as in the Carson Range and the Pine Nut Mountains, the importance of seasonal differences in temperature and precipitation is reflected in snowpack accumulation and melt rates, and ultimately the timing of runoff.

Potential evapotranspiration (PET) was computed using a modified version of the Jensen Haise method (Jensen and Haise, 1963; Jensen and others, 1969) to account for forest canopies and changes in altitude and humidity. Annually simulated PET estimates were compared to regional PET values for verification (Farnsworth and others, 1982). PET is first satisfied in the model by vegetation canopy-interception storage, followed by sublimation (snowpack evaporation) and impervious-surface evaporation. When snow is present and there is no transpiration, sublimation is computed as a percentage of the total PET (PRMS assumes no sublimation when plants are transpiring). The remaining PET demand is satisfied by evaporation from the soil surface and soil-zone storage after transpiration begins. The transpiration period depends on the plant type and altitude zone contained within each HRU. For each year of simulation, a cumulative degree-day index is computed (using daily mean temperature) to determine the start of transpiration, allowing for earlier or later initiation of the transpiration period during warmer or cooler springs, respectively.

PRMS simulates the soil zone as a simplified two-layer system: a shallow, upper zone (called the recharge zone in figure 6) where water losses are from soil evaporation and transpiration, and a deeper, lower zone where the soil-moisture depletion is by transpiration, ground-water and subsurface recharge. In this study, the subsurface is defined as the unsaturated zone below the root zone and above the water table. The total soil profile depth for each HRU is defined as the average rooting depth of the dominant vegetation. Actual evapotranspiration (AET) losses from the soil zone are simulated as proportional to the remaining PET demand and the ratio of currently available soil moisture to the maximum water-holding capacity of the soil profile. In PRMS, infiltration into the soil-zone reservoir depends on the daily snowmelt or net rainfall rates (total precipitation minus canopy interception), soil field capacities, specified maximum infiltration rates (for snowmelt), and antecedent soil-moisture conditions (water in the soil zone prior to infiltration). Infiltration thresholds are defined depending on whether the water is derived from rain or snowmelt.

The subsurface reservoir represents the pathways that the soil-water excess takes in percolating through the shallow unsaturated zones to stream channels, arriving at the streams above the water table. Soil water in excess of field capacity is first used to satisfy recharge to the ground-water reservoir and is assumed to have a maximum daily limit. Once this limit is reached, further percolation of soil water is routed to the subsurface reservoir. Water can then be further allocated to the ground-water reservoir or routed directly to the stream channel from the subsurface reservoir (fig. 6). The latter is referred to as interflow and is computed as a non-linear rate using the storage volume of the subsurface reservoir and user-defined routing coefficients. Flow from the ground-water reservoir is the source of baseflow in the stream. Movement of ground water outside the modeled watershed is simulated by decreasing the ground-water storage. This portion of the water budget is referred to as a ground-water sink. In this study, the ground-water-sink flux represents ground-water inflow to the basin-fill aquifers of Carson Valley.

Runoff, as simulated by PRMS, is a summation of three components: (1) overland runoff from saturated soils or runoff from impervious surfaces, (2) interflow from the unsaturated zone below the root zone as described above, and (3) baseflow. A basic assumption in PRMS is that the runoff travel time, from the headwaters to the outlet of a defined model area (a tributary watershed, for example) is less than or equal to the daily time step, and thus daily runoff need not be explicitly routed along stream channels.

In PRMS, the ground-water reservoir can be thought of as a bucket from which water in storage is released at a rate that satisfies the baseflow component of the measured hydrograph (the seasonal runoff recessions). Baseflow is designed to respond more slowly to hydrologic fluctuations than interflow. The interflow component typically is represented in the stream hydrograph as the more immediate response to snowmelt, though less rapid than the overland flow component, which occurs when net precipitation or snowmelt exceed infiltration thresholds.

Model Development

The development of the PRMS model required delineating subbasins or watersheds for gaged and ungaged perennial and ephemeral watersheds, compiling daily time series of runoff and climate data, delineating HRUs, and computing initial index-model parameters for gaged watersheds. PRMS parameters of the index models were used in building the preliminary models for the ungaged perennial and ephemeral watersheds. While the HRU-dependent parameters were determined and computed for watershed-specific areas, the non-HRU dependent parameters were initially derived using the index model then transferred to the models of the ungaged and ephemeral watersheds. Parameters of particular relevance are those used in the routing of water through the soil zones and the shallow subsurface reservoir, the ground-water flow coefficients, and most importantly, those used for simulating ground-water inflow to the basin-fill aquifers of Carson Valley.

Index model parameters for the ungaged perennial watershed models were adjusted to closely match reconstructed runoff, whereas index model parameters were used without adjustment for the ephemeral watershed models, except for adjusting the precipitation correction factor, as discussed in the section, "Runoff and Climate Data." The modeling and calibration periods were restricted by the lengths of the climate and runoff records.

Basin Characterization and Delineation of Hydrologic Response Units

Geographic Information System (GIS) software, the Weasel Toolbox (Viger and Leavesley, 2006: http://wwwbrr.cr.usgs.gov/weasel/, accessed on November 1, 2005) was used to manage spatial data and to characterize model drainages and HRUs in terms of slope, aspect, altitude, vegetation-cover densities and types, and soil types and depths. Analyses of these characteristics provided estimates of spatially varying HRU-specific model parameters. Initial global model parameters, whose values apply over the entire basin, were quantified from PRMS parameter values for similar watershed studies in the region (Jeton and others, 1996; Jeton, 1999a and 1999b). The gaged and ungaged perennial watersheds are hydrographically defined basins, defined as land areas that drain to a downstream point, whereas the ephemeral watersheds are aggregated areas whose boundaries were arbitrarily defined outside of the Weasel Toolbox, and imported for use in HRU delineation.

A 10-meter digital elevation model (DEM) was used as the basis for computing the watershed boundary (U.S. Geological Survey, 1999). Other digital data include slope and aspect (derived from the 10-meter DEM), soils [1:250,000 State Soil Geographic (STATSGO) database; (U.S. Department of Agriculture, 1991)], and land cover for computing vegetation type and canopy density.

Preliminary HRUs were delineated as subbasin areas with more emphasis on hydrography than on other physical characteristics. These HRUs were further subdivided by altitude resulting in the final physiographic delineation of the HRUs. The final digital HRU data layer was intersected with measurements of altitude, slope, aspect, vegetation, and soils and averaged values were assigned to each HRU.

Figure 7 shows an example of HRU delineation and the distribution of slope, aspect, land cover, and land-surface altitude zones in the Daggett Creek watershed. The GIS-derived parameters are "static," meaning they are simulated as constant through time and are not adjusted during model calibration. Typically, watershed models are run using several years of daily climate data as model input and land cover and density are assumed to be constant over time. In the present study, however, vegetation-cover type and canopy density for the western and eastern sides of Carson Valley have undergone some changes attributed to recent wildfires. The vegetation data reflect conditions from 1998 to 2000, as mapped in the digital land-cover data sets, with some modifications made to the land cover for the eastern side of Carson Valley.

For the present study, the altitude (DEM) dataset was re-classified into 1,000-foot altitude bands and used to restrict the altitude range within a single HRU to about 1,000 ft (fig. 7*D*). Point precipitation and temperature measurements from climate stations at lower or higher altitudes than the HRUs were distributed to the HRU using orographic corrections based on the mean HRU altitude. Restricting the range in altitude within a single HRU decreases the magnitude of the orographic corrections.

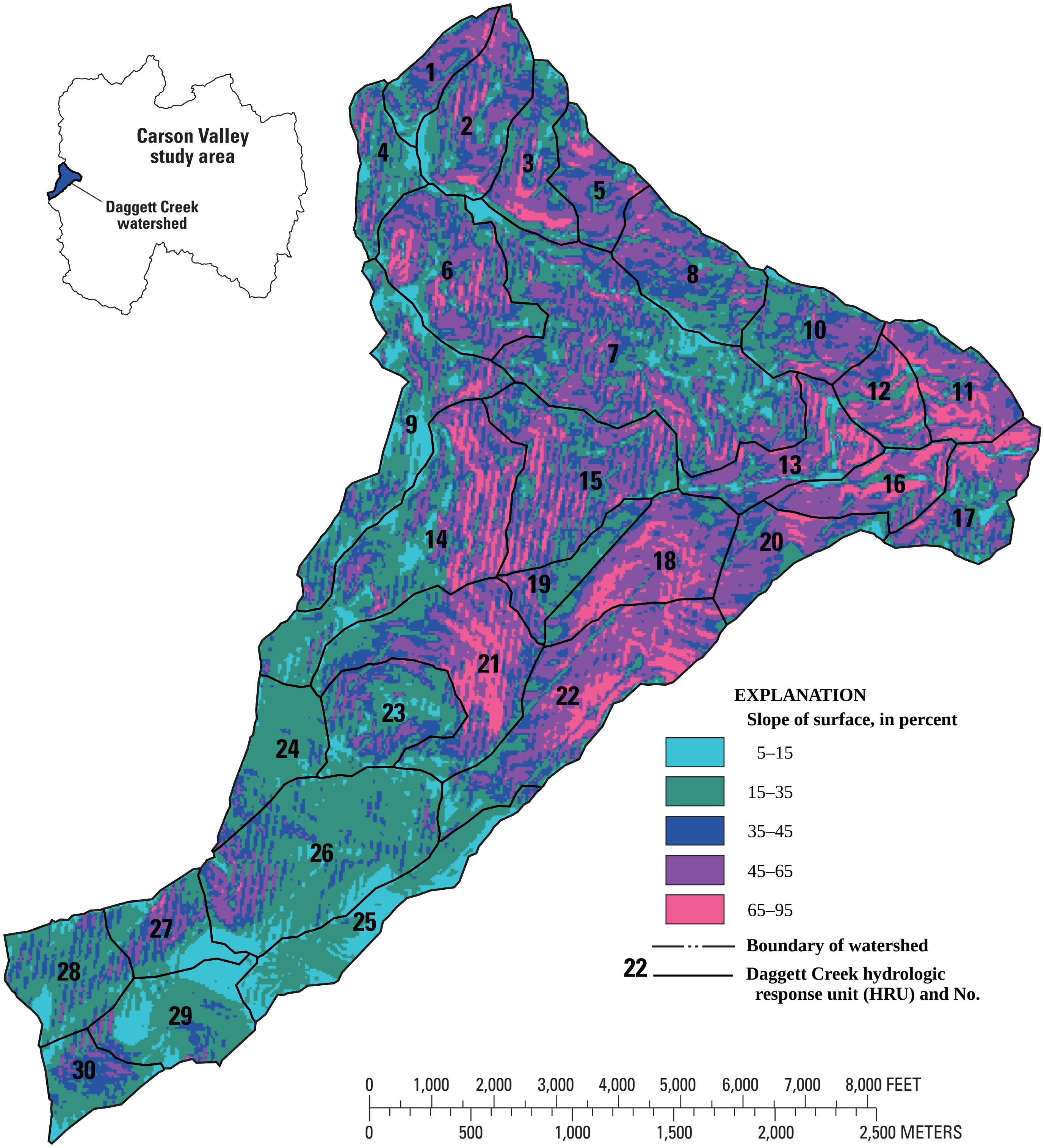
Digital land-cover data for the Carson Range was obtained from the U.S. Forest Service (Kathy Braton, U.S. Forest Service, Carson City, Nevada, written commun., 2006). These data are a modified version of the 1:24,000 Toiyabe National Forest vegetation layer (http://www.fs.fed.us/r5/rsl/clearinghouse/sec-gbasin.shtml), which was mapped using imagery from 2000 (Ralph Warbington, U.S. Forest Service, Remote Sensing Laboratory, oral commun., 2006). For the Pine Nut Mountains, land cover was derived from the 30-meter resolution Southwest Regional Gap Analysis Program (GAP) data (Kepler and others, 2005) for vegetation type and density as mapped between 1998 and 2000. Canopy densities from the Southwest Regional GAP data appeared to be too high based on visual inspection, and arbitrary adjustments were made to lower the density for shrub and pinion-juniper woodlands. HRU vegetation densities primarily affect simulated snowmelt and runoff timing rather than overall runoff volume. Accurate simulation of runoff timing was less of a concern in the present study, however, because the water-budget components were aggregated to annual and mean annual values for comparison with estimates of Maurer and Berger (2007).

Runoff and Climate Data

Daily mean runoff is available for model calibration for 4 gaged perennial watersheds (watersheds 5g and 12g–14g; fig. 3 and table 2) and 10 ungaged perennial watersheds (watersheds 1u–4u and 6u–11u; fig. 3) in the Carson Range. Daily mean runoff for the ungaged watersheds was estimated by Maurer and others (2004, p. 8) using multivariate regressions of more than 400 individual discharge measurements against selected continuously gaged streams in and near Carson Valley. In the remainder of this report, the term "reconstructed" runoff is used for the runoff statistically generated to distinguish the estimates from other estimated runoff values. The term "measured" runoff is used for measured or continuously gaged runoff, and "simulated" runoff is defined as runoff simulated by the watershed models. The reconstructed daily mean runoff was estimated by Maurer and others (2004, p. 17) to have an uncertainty of about 30 percent, and measured daily mean runoff of the gaged watersheds was estimated to have an uncertainty of about 15 percent.

Climate input-data requirements for PRMS are daily total precipitation and daily maximum and minimum air temperature. Daily precipitation from six stations in and near Carson Valley (stations 1p–6p; table 2, fig. 3) was used to determine daily precipitation for each HRU in each watershed model. The stations used for each watershed model initially were selected by their proximity to the watershed and the altitude distribution within the watershed. For the Carson Range, high-altitude climate data were limited to climate stations at Daggett Pass (station 2p at 7,330 ft) and Heavenly Valley (station 3p at 8,582 ft). PRMS simulations using the Minden climate station (station 5p at 4,709 ft), located on the valley floor east of the Carson Range, tended to underestimate precipitation, underscoring the rainshadow effect of the Carson Range. Simulations using Sheridan Acres climate station (station 4p at 4,774 ft), located near the base of the Carson Range, appeared more suitable for estimating precipitation for HRUs with altitudes lower than 7,000 ft.

For the eastern side of Carson Valley, daily precipitation data were limited to Fish Springs, at an altitude of 5,120 ft (station 6p, table 2, fig. 3). Mean annual precipitation for Fish Springs averaged 7.7 in. during 1991–2002. Two storage gaging stations, Lower and Upper Pine Nut Mountains at altitudes of 6,440 ft and 7,201 ft in the Pine Nut Creek watershed, recorded annual precipitation of 13.6 and 15.2 in., respectively, for 1984–2002 (Maurer and Halford, 2004, p. 26). Annual averages for the storage gaging stations were used to compare simulated precipitation estimates for the 1981–97 modeling period.



***A.* Slope**

Figure 7. HRU delineation and distribution of slope, aspect, land cover, and land-surface altitude zones in the Daggett Creek watershed, Carson Valley, Nevada.

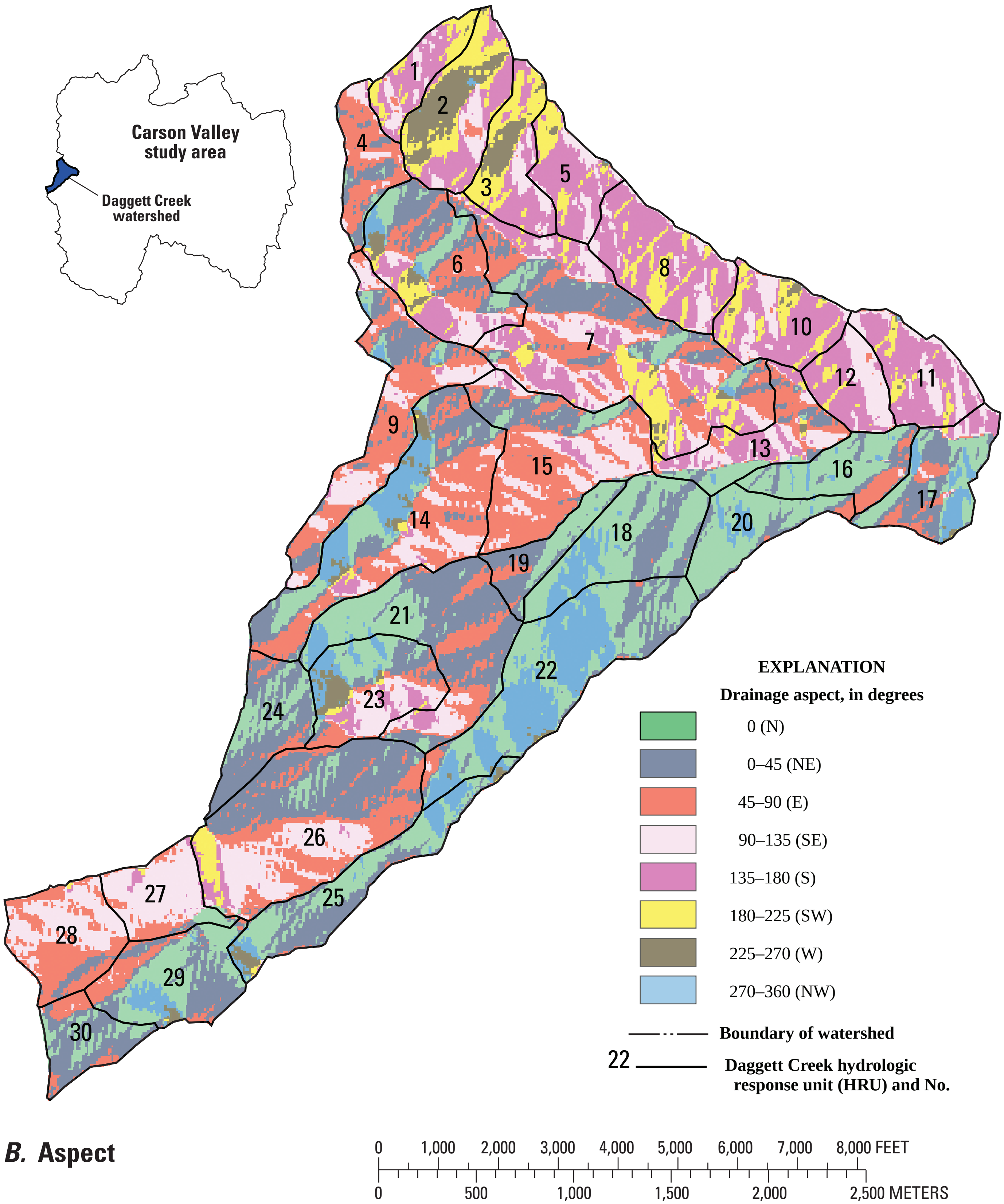
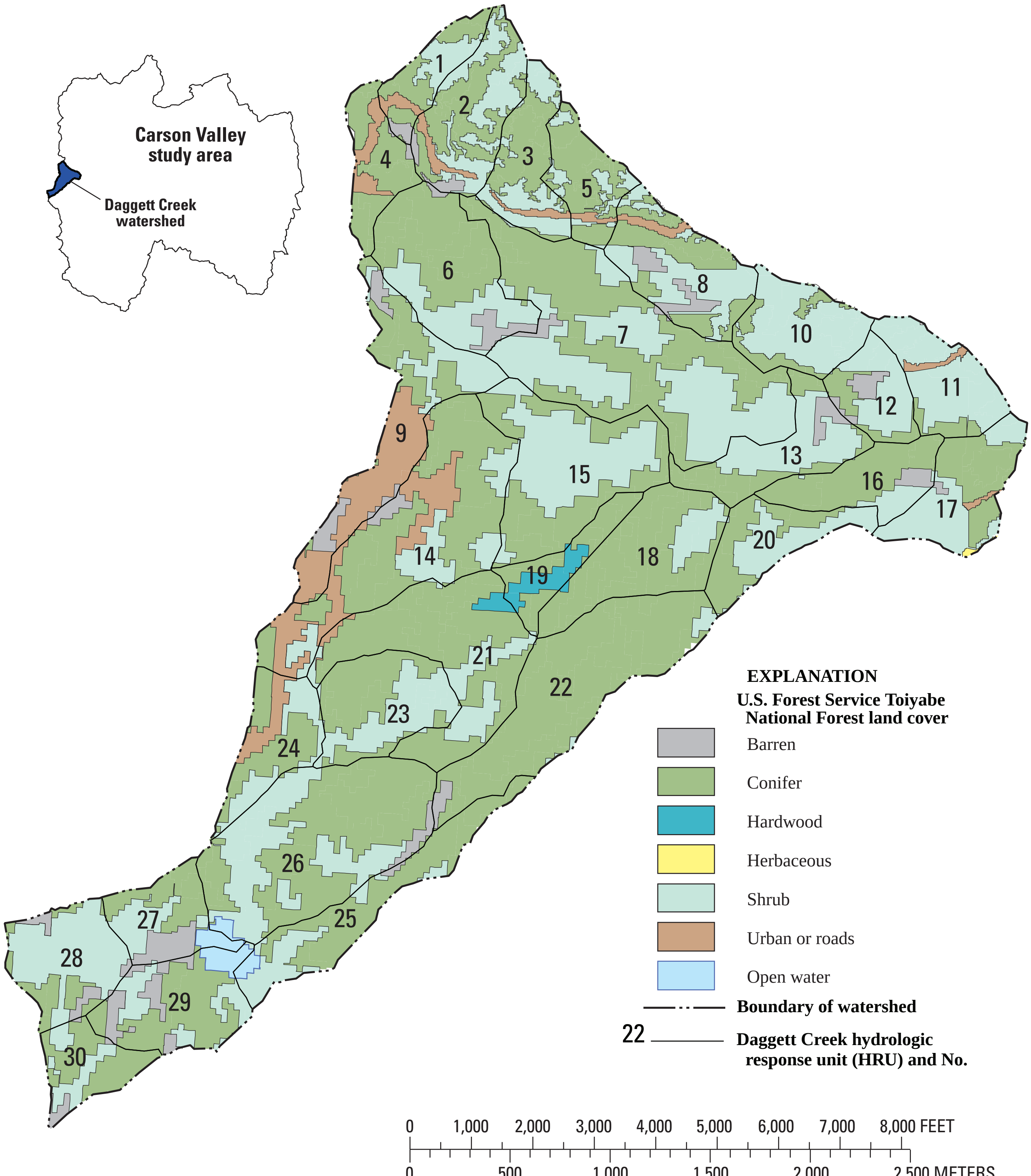
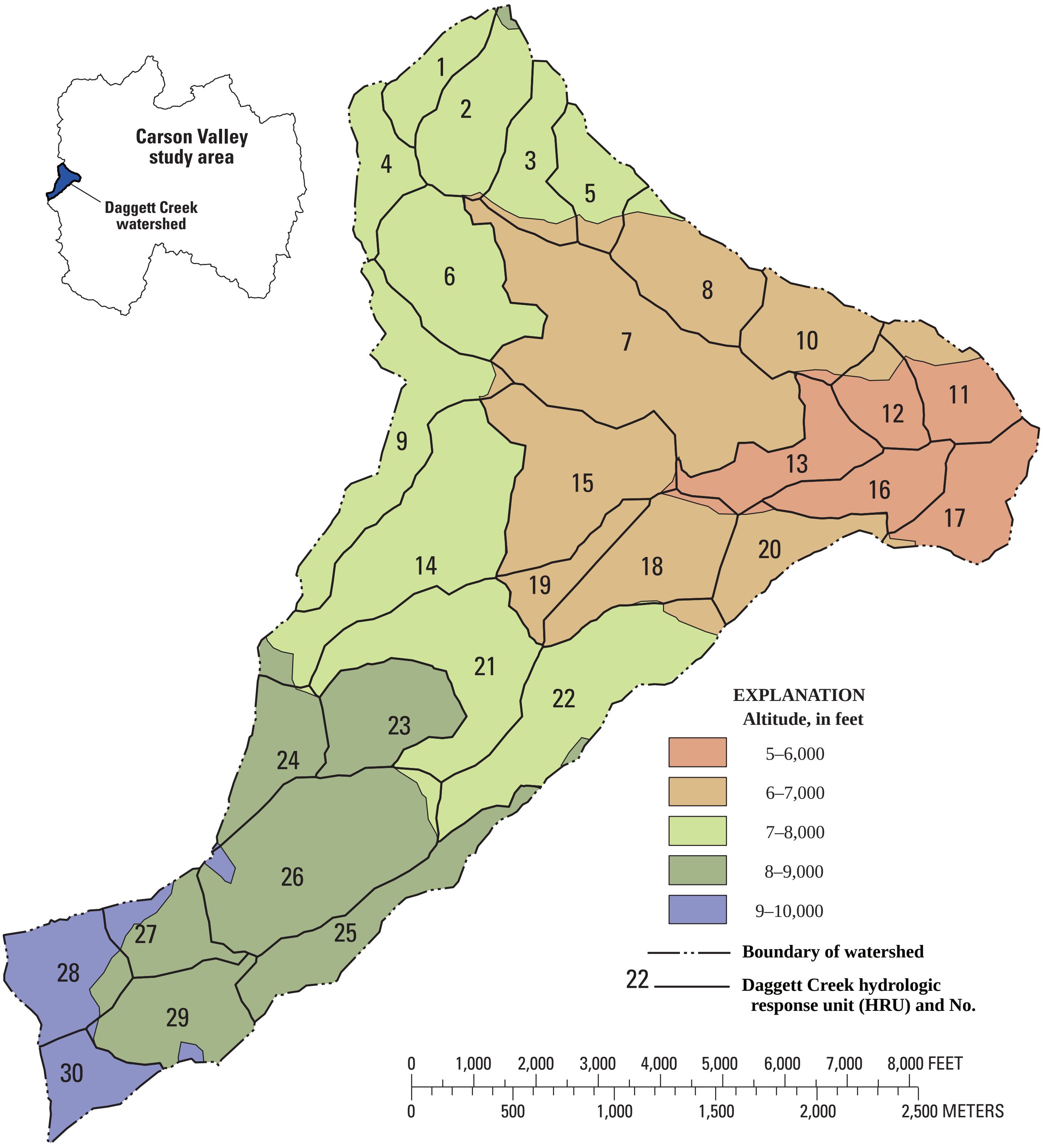


Figure 7.—Continued.



***C.* Land cover**

Figure 7.—Continued.



D. **Land-surface altitude zones**

Figure 7.—Continued.

Table 2. Precipitation and streamflow-gaging stations, period of record, and altitude, Carson Valley, Nevada and California.

[**Watershed No.:** "g" is gaged station; "p" is precipitation station. Station locations are shown in figure 3. **Altitude**: Datum is North American Vertical Datum of 1988. **Abbreviations:** USGS, U.S. Geological Survey]

Watershed No.	Station name (site identifier)	Period of record (water years)	Altitude (feet)
Precipitation stations[1]			
1p	Carson City	1893–2006	4,750
2p	Daggett Pass	1971–2006	7,330
3p	Heavenly Valley	1970–2006	8,582
4p	Sheridan Acres	1992–2006	4,774
5p	Minden	1928–2006	4,709
6p	Fish Springs	1991–2002	5,120
USGS streamflow-gaging stations[2]			
5g	Daggett Creek near Genoa, NV (10310400)	1965–83 1988–2006	5,100
12g	Fredericksburg Canyon Creek near Fredericksburg, CA (10310300)	1989–2001	5,520
13g	Pine Nut Creek near Gardnerville, NV (10309050)	1981–97	6,340
14g	Buckeye Creek near Minden, NV (19309070)	1981–97	5,640

[1] For location details, see Maurer and Halford (2004, p. 26).

[2] For location details, see Maurer and others (2004, p. 7).

Initial PRMS model simulations in this study used an HRU precipitation correction factor that increased precipitation 15–20 percent for each 1,000 ft of altitude gain above the valley floor. This initial correction factor was derived from local lapse rates calculated using low- and high-altitude precipitation stations and differences in mean HRU altitude. Maximum and minimum daily temperatures were adjusted in the PRMS model with an altitude correction factor of 3.5°F of cooling for every 1,000 ft of altitude gain, which corresponds to regional temperature lapse rates used in similar watershed modeling studies.

Additional adjustments of simulated precipitation were made during model calibration, so that simulated mean annual precipitation was similar to previous mean annual precipitation estimated by Maurer and Berger (2007, p. 29) for the watersheds using the linear relations of Maurer and Halford (2004) for 1971–2000. This was done to assure that the precipitation input to watershed models was consistent with that used previously for estimating ground-water inflow to Carson Valley. Maurer and others (2004, p. 15) reported that mean annual precipitation for 1990–2002 was similar to that for 1971–2000 at Minden, 8.45 and 8.38 in/yr, respectively, and at Heavenly Valley, near the crest of the Carson Range, 33.3 and 32.9 in/yr, respectively.

Precipitation was estimated by Maurer and Halford (2004) using two linear relations between precipitation and altitude, one for the western side and one for the eastern side of Carson Valley, based on data from 14 stations in and near Carson Valley. An areal distribution of precipitation was estimated by applying these relations to a DEM of the study area (Maurer and Halford, 2004, p. 28). In this study, the resulting gridded data set was combined with HRU areas for each modeled watershed and the precipitation estimates of Maurer and Halford (2004) were used to adjust the HRU precipitation correction.

Model Sensitivity

Sensitivity analyses during model calibration typically help to determine the extent to which parameter-value uncertainties result in acceptable runoff predictions. Although this modeling study was focused on estimating ground-water inflow, the hydrologic data to which the watershed model is calibrated is runoff, with ground-water inflow simulated as water in the ground-water reservoir in excess of what reaches the stream channel as baseflow.

The model sensitivities to PRMS parameter values for the present study can be understood from previous watershed modeling studies in the East Fork Carson River basin (Jeton and others, 1996), the Lake Tahoe basin (Jeton, 1999a), and the catchment area of the Truckee River (Jeton, 1999b). The hydroclimatic setting of these earlier studies is similar to that of the watersheds in the present study area with appropriate adjustments made for precipitation distribution. Previous studies of similar watersheds list the parameters modified during calibration (for example, Jeton, 1999b, p. 17).

Sensitivity analyses show that runoff simulations are most sensitive to the (1) snow threshold temperature that determines precipitation form, (2) precipitation-correction factor for snow and rain (similar to a precipitation lapse rate where the measured precipitation is adjusted for differences in altitude between the climate station and the HRU), (3) monthly temperature lapse rates (typically between 3.5 and 4.5°F for every 1,000 ft), (4) monthly evapotranspiration coefficients for the Jensen-Haise potential-evapotranspiration computation (Jensen and Haise, 1963), and (5) coefficient for transmission of solar radiation through winter plant canopies to snow surface, which affects snowmelt timing.

The watershed models also were sensitive to soil moisture storage, and the flow-routing coefficients for interflow and ground-water reservoirs used to simulate ground-water inflow. Parameters that determine flows to and from the ground-water reservoirs were adjusted to fit the observed shapes of the seasonal recession of runoff. Interflow influences the quicker response seen as spikes in the hydrograph in response to snowmelt or rain events and exhibits a short lag in timing. Overland runoff from the rock outcrop or otherwise barren, more impervious areas, reflects a near instantaneous runoff response.

Model Calibration

Calibration of PRMS models is an iterative process where, after each adjustment of model parameters, simulated runoff is visually and statistically compared with measured or reconstructed runoff, with special attention paid to matching flow volumes for seasonal and annual time periods, and runoff timing for large events. Ground-water inflow is a component that is not measured but modeled as a residual component of the water budget. If the dominant gains to the system (precipitation) and losses (evapotranspiration) are adequately modeled, and the simulated hydrograph matches the measured hydrograph overall, water in excess of that which reaches the stream channel can be considered as an adequate representation of ground-water inflow. The simulations are run on a daily time step; however, ground-water inflow is evaluated on a mean annual basis to allow for comparison to previously derived estimates. Seasonal and annual water-budget components derived from the models were of most interest and the detailed timing of runoff and ground-water inflow was not crucial.

Effort was made during calibration to provide the best fit to measured or reconstructed runoff during wet years from 1993 to 1998 for watersheds in the Carson Range, and 1982–83 and 1986 for Pine Nut and Buckeye Creeks (fig. 4). This was done because initial watershed modeling showed that ground-water inflow was greatest or occurred primarily during wet years.

For comparison with previous water-budget estimates, and because reconstructed runoff was available for ungaged watersheds for the same time period, a calibration period of water years 1990–2002 was selected for watershed models of the Carson Range. For Pine Nut Creek and Buckeye Creek watershed models, a calibration period of water years 1981–97 was selected, because it coincides with the period of record of measured runoff for the streams (table 2). Simulations of the Pine Nut Creek and Buckeye Creek watersheds were extended to include water years 1998–2002 using the models developed for the 1981–97 calibration period. To provide simulation results for the same period as the Carson Range models, Pine Nut and Buckeye Creek models were run for the 1990–2002 period.

Error Analysis

No single calibration of a PRMS model will simulate all runoff regimes with equal accuracy. The goal in modeling is threefold: (1) little to no bias, (2) small simulation error, and (3) realistic parameter values reflecting the conditions being modeled. The goals for calibration are to maintain a good visual fit between the simulated and measured hydrographs, to keep mean annual biases to within 5 percent, and to keep relative error to within 10 percent. In watershed modeling, common measures of simulation error include the sum of errors and bias. Bias is computed to determine the presence of systematic error or an indication of central tendency (that is, whether the simulations show a tendency towards under- or overestimating with respect to the measured runoff). Absolute errors (defined as the difference between simulated and measured runoff) tend to be dominated by a few large events (Haan and others, 1982), unless normalized by the measured values to form “relative error,” as used in this report. The un-normalized root mean square error (RMSE) provides a common measure of the magnitude of simulation errors that complements the relative measures provided by the bias and relative errors.

Normalizing runoff error by dividing it by the measured value presents a problem when the extremely low flows result in very large relative errors even though the absolute error may be small (Haan and others, 1982). Though much of the measured runoff of Carson Range watersheds represents low flows, no runoff data for these watersheds were omitted in the error analysis primarily to allow for comparisons between reconstructed and measured runoff. For the east side watersheds, the Buckeye Creek gaging record indicates numerous days with zero flows, possibly due to poor site location of the gaging station downstream of a losing reach, and the Pine Nut Creek simulations resulted in months with zero flow. For this reason, only months with non-zero flows were included in the error analysis.

Model calibration biases, relative errors, and RMSEs for the four watershed models of gaged watersheds are given in table 3. Error statistics were not calculated for models calibrated using reconstructed runoff because of the considerable uncertainty associated with the reconstructed daily mean runoff. The error statistics are presented as seasonal, mean monthly, and mean annual summaries for the simulation period, with the exception of Buckeye Creek watershed model. For Buckeye Creek, error statistics are presented only for February–April due to the prevalence of zero runoff in the measured record during other times of the year. For the remaining watershed models, monthly error statistics were computed for four seasons; October–December, January–March, April–June, and July–September. Each of these seasons represents a particular hydroclimatic regime with October–December characterized by early winter rain, snow, and mixed rain and snow events, and July–September characterized by low-flow conditions and occasional summer convective storms. January–March are characterized by winter snow and occasional rain-on-snow events, and the spring runoff season; April–June tends to produce the most water available for ground-water inflow to basin-fill deposits of Carson Valley. Lastly, the term "runoff efficiency" is used to compare the percentage of precipitation that becomes runoff, which indirectly is a measure of losses to evapotranspiration and infiltration. Runoff efficiencies were simulated for the 1990–2002 period of record and compared to previous estimates.

Carson Range Perennial Watersheds

Daily mean runoff simulated by the models and measured for the Daggett Creek and Fredericksburg Canyon watersheds provides the best fit for wet years (fig. 8). The hydrographs show a distinct increase in baseflow in 1995 and 1996 with another, smaller increase in 1997. The increase in 1997 is the result of a very heavy snow accumulation and melt period in early 1997. Wet conditions continue into 1998 before returning to dry conditions for the remaining years of the modeling period.

Daggett Creek Watershed

With the exception of April–June, calibration statistics for the Daggett Creek model are satisfactory for seasonal, monthly, and annual time scales (table 3). Simulated mean monthly and mean annual runoff show a tendency to slightly underestimate runoff with low associated errors, and a mean annual RMSE of 1.1 in. Based on visual inspection, a satisfactory overall fit was obtained between simulated and measured daily mean runoff for Daggett Creek for the 1993–98 period of high runoff (fig. 8).

The pattern of simulating, on average, an earlier than recorded spring runoff (fig. 8), particularly evident for water years 1995–2000 results in an overestimation of runoff for January–March and a subsequent underestimation of runoff for April–June (table 3). This may be due to cooler temperatures than were modeled resulting in a later measured spring runoff. Comparisons of measured and simulated annual mean runoff and ground-water inflow are illustrated in figure 9. Overall, the Daggett Creek model under-estimates annual runoff for dry (or below normal) years and overestimates runoff for wet years. The mean annual runoff efficiency using the simulated runoff was 20 percent, comparable to the efficiency calculated with the measured flow (table 1).

Table 3. Calibration statistics for PRMS watershed models of gaged watersheds of the Carson Range and Pine Nut Mountains, Carson Valley, Nevada and California.

[**Bias** = ∑(simulated–measured)/∑(measured)*100. **Relative error** = ∑((simulated–measured)/measured)*100/number of measurements. **RMSE** is root mean square error–SQRT(∑(simulated–measured)^2/number of measurements. –, not calculated because of zero flow for many days]

Season	Bias (percent)	Relative error (percent)	RMSE (inches)	Season	Bias (percent)	Relative error (percent)	RMSE (inches)
	Daggett Creek (water years 1990–2002)				Fredericksburg Canyon (water years 1990–2001)		
October–December	-5.4	-8.7	0.1	October–December	6.7	4.8	0.2
January–March	7.6	2.9	0.2	January–March	2.4	7.8	0.3
April–June	-14.0	-7.8	0.2	April–June	18.6	27.0	0.4
July–September	-1.5	1.4	0.1	July–September	-2.3	13.1	0.3
Period of record mean monthly	-3.7	-2.7	0.2	Period of record mean monthly	3.7	14.6	0.4
Period of record mean annual	-3.7	5.6	1.1	Period of record mean annual	3.7	12.0	6.0
	Pine Nut Creek (water years 1981–97)[1]				Buckeye Creek (water years 1981–97)		
October–December	-72.0	-70.0	0.1	February–April	-12.3	5.0	0.1
January–March	16.9	3.8	0.2	–	–	–	–
April–June	6.0	21.8	0.1	–	–	–	–
July–September	40.0	8.5	0.0	–	–	–	–
Period of record mean monthly	-5.4	-9.7	0.2	–	–	–	–
Period of record mean annual	-15.0	-11.0	1.0	Period of record mean annual[2]	7.7	-5.4	0.0

[1] Calculated for months with non-zero simulation results.

[2] Calculated with water year 1994 removed.

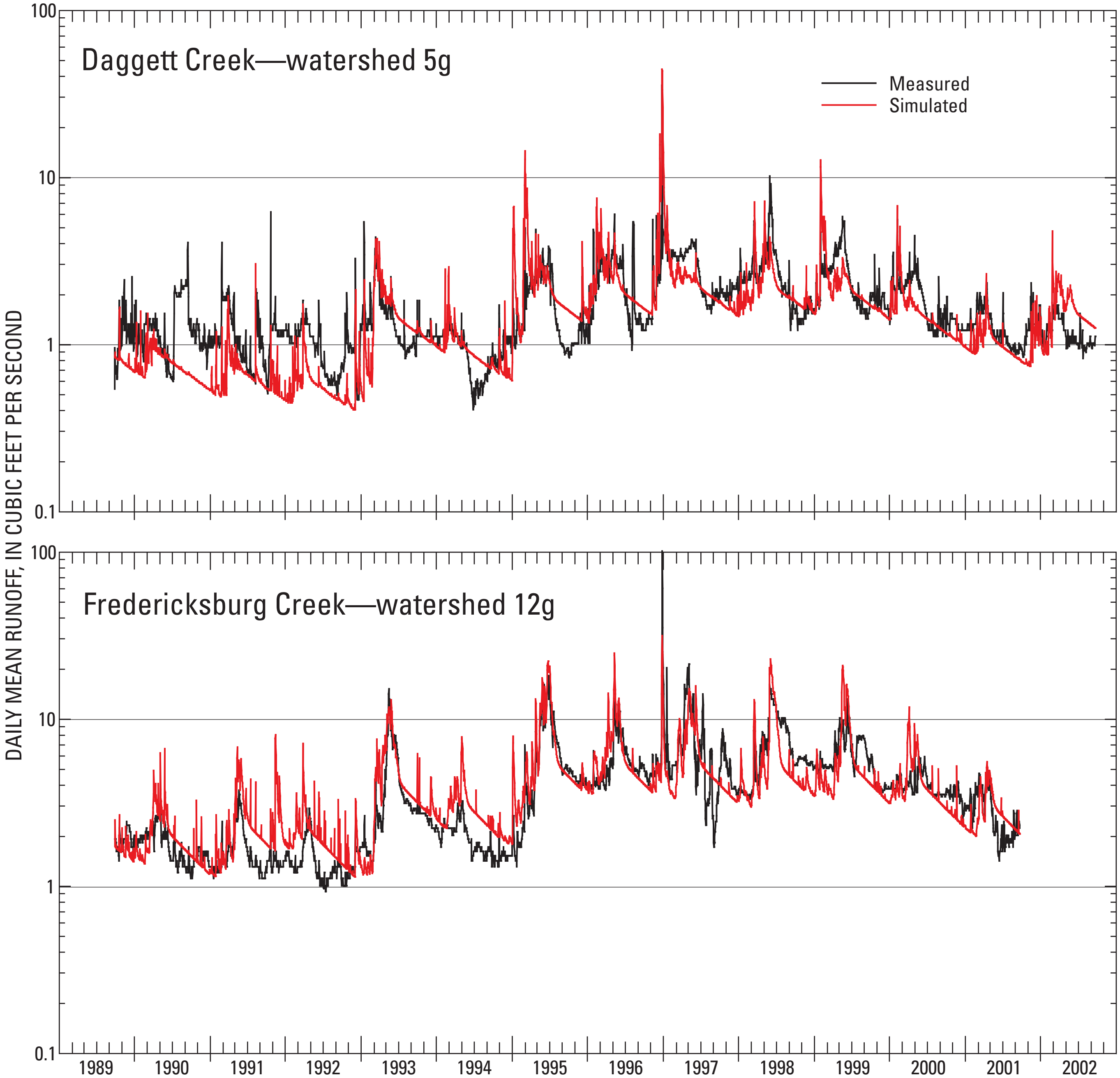


Figure 8. Simulated and measured daily mean runoff for Daggett Creek and Fredericksburg Canyon watersheds, Carson Valley, Nevada and California, water years 1990–2002.

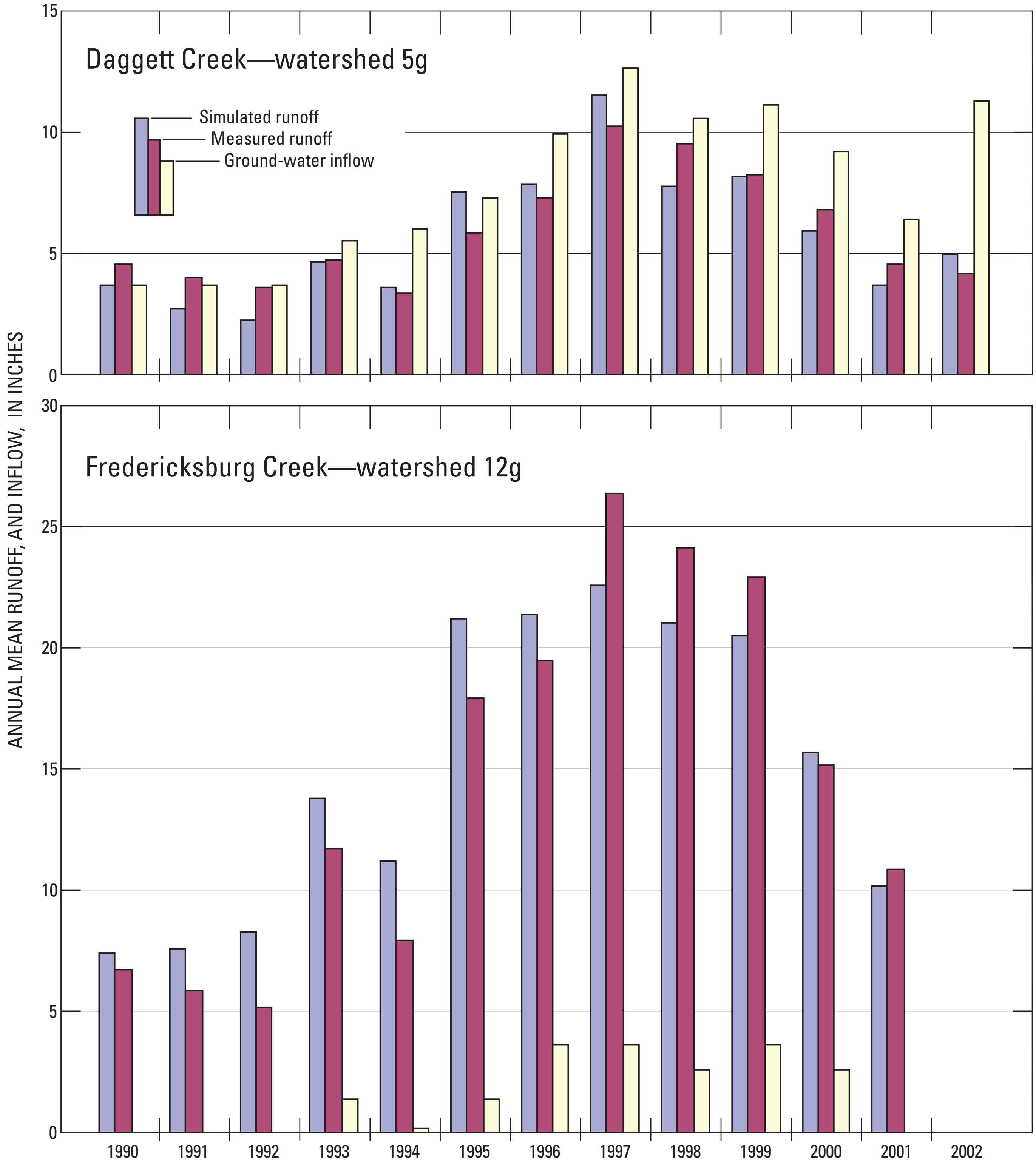


Figure 9. Simulated and measured annual mean runoff and ground-water inflow for Daggett Creek, water years 1990–2002, Fredericksburg Canyon, water years 1990–2001, and Pine Nut Creek and Buckeye Creek watersheds, water years 1981–97, Carson Valley, Nevada and California.

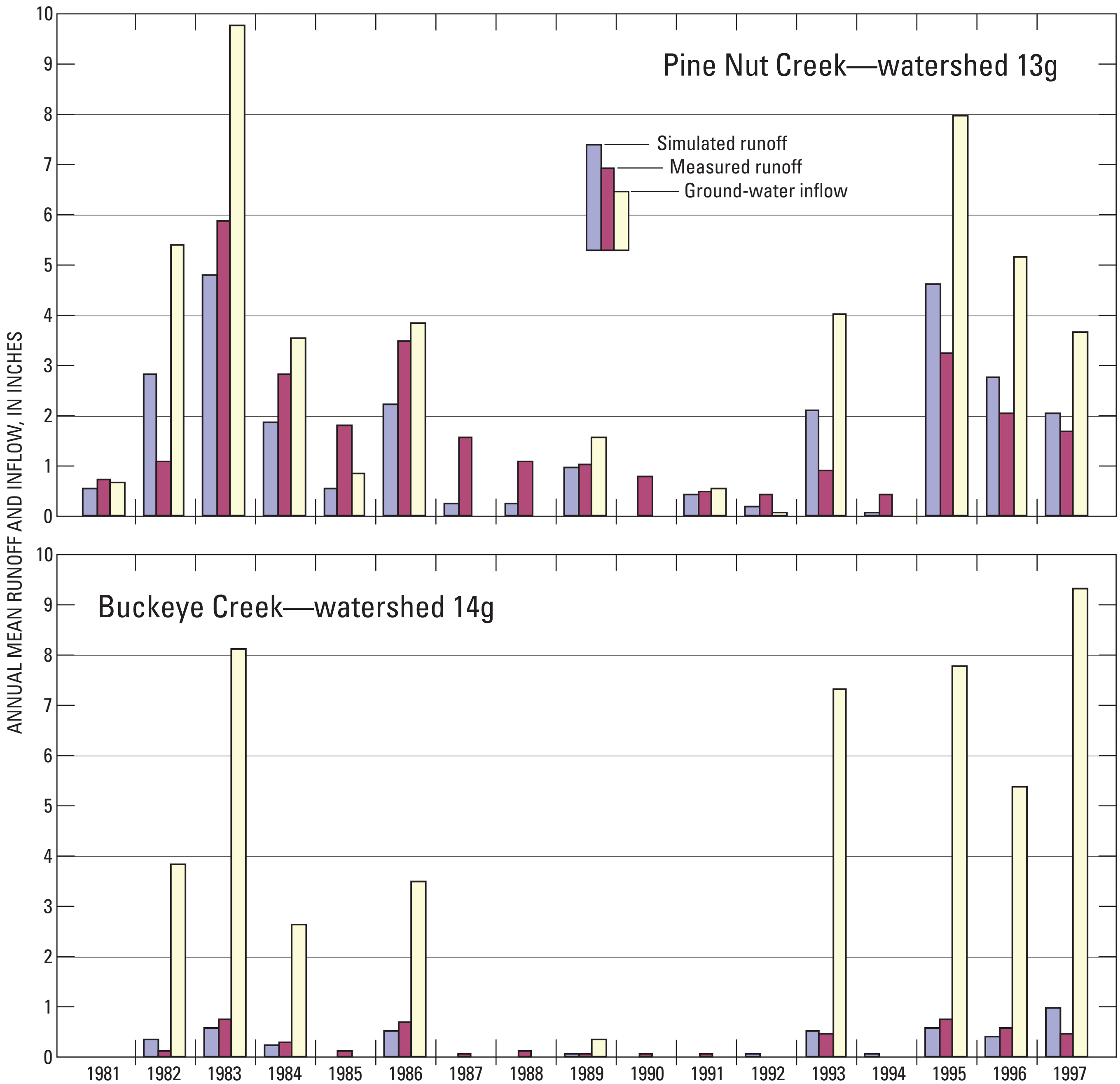


Figure 9.—Continued.

Fredericksburg Canyon Watershed

Mean monthly and mean annual statistics for the Fredericks Canyon model (table 3) indicate a slight bias to overestimate runoff. Mean monthly and mean annual relative errors were about 15 and 12 percent, respectively, and mean annual RMSE was 6 in. For April–June, the bias and relative error are large and indicate a tendency to overestimate runoff during this period. Statistics for the other seasonal aggregates (table 3) indicate an adequate fit between simulated and measured values.

The simulated and measured runoff indicate that spring runoff in general and the baseflow recession for 1993 and 1995–97 match well (fig. 8), but annual runoff for 1998–99 is overestimated. For the drier years (water years 1990–92 and 1994), baseflow and annual runoff are overestimated. Beginning in 1993, precipitation appears to have recharged subsurface storage sufficiently to increase baseflow for subsequent years, only returning to baseflow conditions similar to 1990 by water year 2001 (fig. 8). For 1997, the measured snowmelt recession curve shows an erratic response (fig. 8), possibly attributed to poor data. Runoff for most days of the year is less than 2 ft^3/s for dry years and increases to more than 10 ft^3/s only during spring runoff for wet years (fig. 8).

The recorded January 1997 flood peak for Fredericksburg Canyon of 5,000 ft^3/s (Bonner and others, 1998, p. 152) is considered to be highly unlikely when compared to the same flood peaks in other Carson Range watersheds (Mike Nolan, U.S. Geological Survey, oral commun., 2006). For this study, the January 1997 peak was therefore arbitrarily adjusted to 100 ft^3/s (rather than omitted), to not unduly skew the statistical analyses. Measured runoff for January–May 1997 has numerous days when the runoff had been estimated (Bonner and others, 1998, p. 152) and overall the record for this water year is rated as poor. The runoff efficiency calculated for the 1990–2001 period is 45 percent, comparable to that calculated using measured runoff (table 1).

Pine Nut Mountains Perennial Watersheds

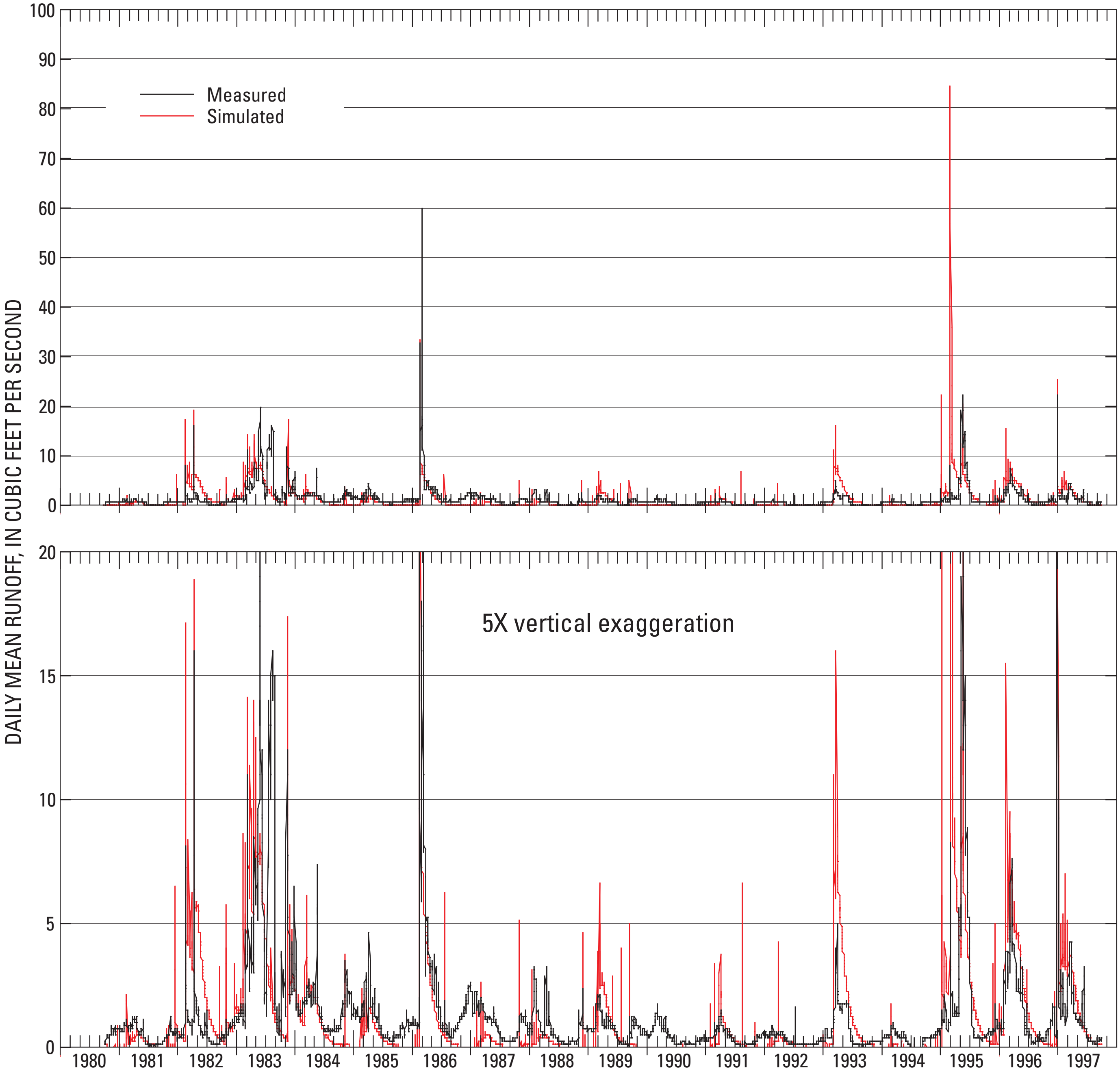
The period of record of the runoff used for calibration of the Pine Nut Creek and Buckeye Creek watersheds differs from the Carson Range watersheds, and represents an earlier period from water years 1981–97. Both the Buckeye Creek and Pine Nut Creek watershed models used a combination of precipitation data from the Minden station for 1981–91, and the Fish Springs station for 1992–2002 as input data.

There is considerably more uncertainty associated with the watershed models on the eastern side than with those on the western side for the following reasons: (1) the Pine Nut Mountains are subjected to more convective storm activity and without local precipitation data (Minden and Fish Springs stations may be too far from the modeled drainages to accurately estimate their precipitation), and lacking high-altitude data, the models may not adequately simulate the spatial and temporal distribution of precipitation; (2) the model-input precipitation time series is based on a combination of two stations (Minden and Fish Spring climate stations) that have different periods of record and slightly different altitudes but the model applies the same precipitation adjustments to each station record; (3) the Buckeye Creek watershed may be too large to fit the assumption that runoff and subsurface flow reach the stream channel within a daily time step; and (4) there is uncertainty about the soil-water holding capacity, which affects simulated evapotranspiration, runoff, and ground-water inflow to basin-fill aquifers of Carson Valley.

Pine Nut Creek Watershed

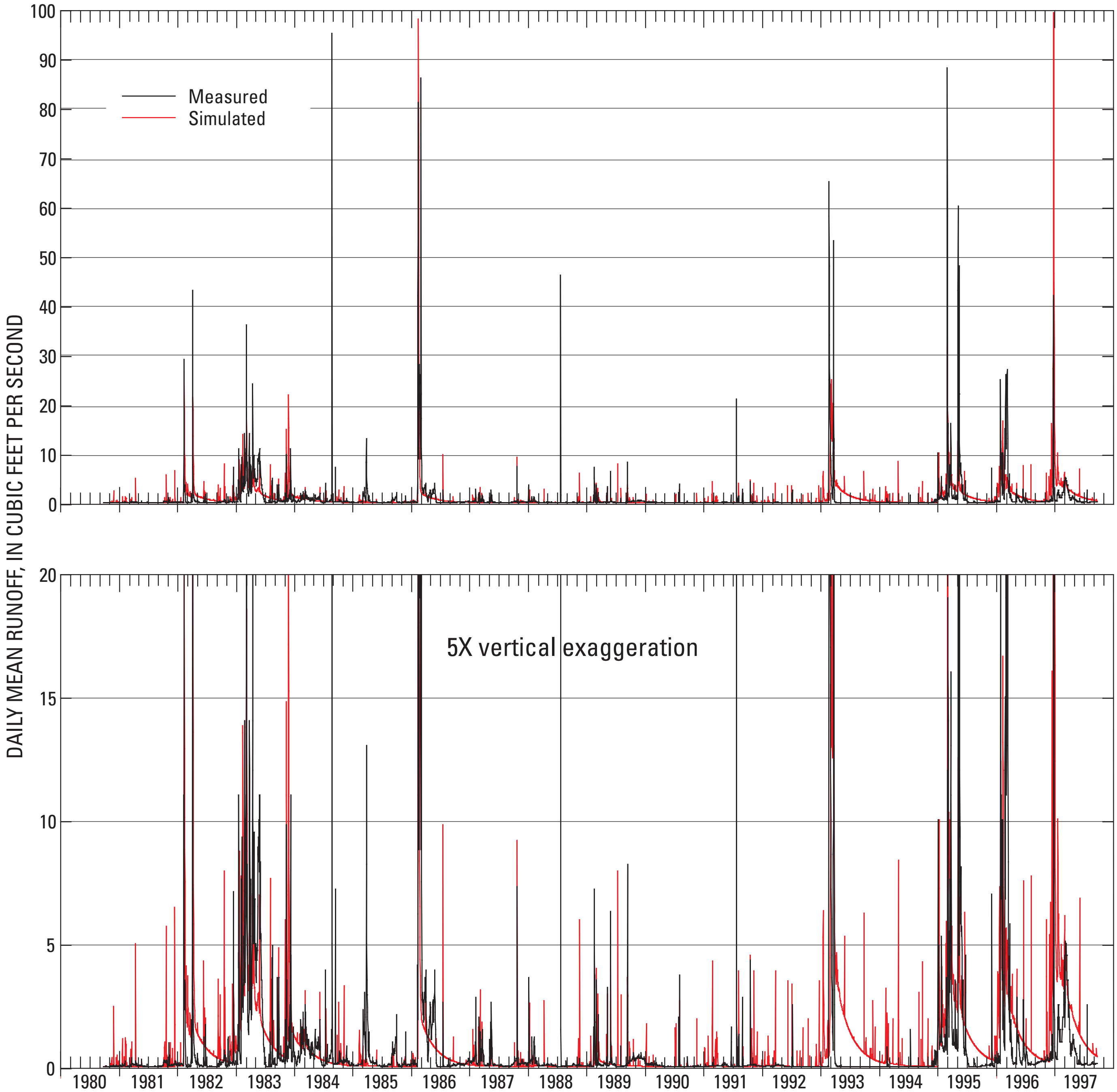
Mean monthly and mean annual bias and relative error are large in the Pine Nut Creek watershed model, and indicate systematic underestimations for mean annual and mean monthly runoff, though less so for the latter. As illustrated in figure 10, the model underestimates annual runoff for all years with the exception of 1982 and 1993 and wet years from 1995 to 1997.

Precipitation volumes for the Pine Nut Creek model were not adjusted to exactly match the 1971–2000 mean annual precipitation volumes determined by Maurer and Berger (2007, p. 29; table 4), which estimated a mean annual rate of 16 in., resulting in excessive simulated runoff. Precipitation amounts were decreased to better match the mean annual precipitation of about 14 in. at the Lower Pine Nut storage gage (Maurer and Halford, 2004, p. 26). Simulating runoff using the adjusted precipitation amounts improved runoff comparisons for the currently underestimated dry years, yet for the wet years particularly 1993, and 1995–97, the model-overestimated runoff resulted in a relative error ranging from 19 percent in 1997 to more than 100 percent in 1993 (fig. 10). Overall, the model underestimates runoff for the dry years when runoff typically was less than 2 ft^3/s. The runoff efficiency for the model estimates is about 2 percent as compared to the 8 percent computed by Maurer and Berger (2007, p. 29).



***A.* Pine Nut Creek—watershed 13g**

Figure 10. Simulated and measured daily mean runoff for Pine Nut Creek and Buckeye Creek watersheds, Carson Valley, Nevada, water years 1981–97.



B. Buckeye Creek—watershed 14g

Figure 10.—Continued.

Table 4. Summary of model results for 14 perennial watersheds in Carson Valley, water years 1990–2002, and comparison with estimates from Maurer and Berger (2007).

[Values in inches are volumes in acre-feet, divided by watershed area, in acres, multiplied by 12. **Watershed No.** ending in “u” is ungaged; watershed No. ending in “g’ is gaged watershed. Locations of watersheds are shown in figure 3. **Measured or reconstructed mean annual runoff**: From Maurer and others (2004, p. 14); measured for gaged watersheds; reconstructed for ungaged watersheds. **Relative difference in runoff**: Computed from values in acre-feet as (simulated−estimated/estimated)*100. **Estimated mean annual precipitation**: From Maurer and Berger (2007, p. 29). **Estimated mean annual ET:** Multiply reported ET rate, in feet, by watershed area to obtain ET volume in acre-feet. **Estimated mean annual ground-water inflow**: From Maurer and Berger (2007, p. 32). **Ground-water inflow**: Defined as ground-water inflow to basin-fill aquifers of Carson Valley. **Abbreviations:** acre-ft, acre-feet; ET, evapotranspiration]

Watershed No.	Watershed name	Drainage area, (acres, rounded)	Mean annual precipitation: Estimated by Maurer and Berger, 2007 1971–2000 acre-ft (in.)	Mean annual precipitation: Simulated by watershed models 1990–2002 acre-ft (in.)	Relative difference in precipitation estimates (percent)	Mean annual runoff: Measured or reconstructed by Maurer and others, 2004 1990–2002 acre-ft (in.)	Mean annual runoff: Simulated by watershed models, 1990–2002 acre-ft (in.)	Relative difference in runoff (percent)	Mean annual ET: Estimated by Maurer and Berger, 2007 acre-ft (in.)	Mean annual ET: Simulated by watershed models, 1990–2002 acre-ft (in.)	Mean annual ground-water inflow: Estimated by Maurer and Berger, 2007 acre-ft (in.)	Mean annual ground-water inflow: Simulated by watershed models, 1990–2002 acre-ft (in.)
1u	Water Canyon	1,700	4,200 (30)	4,200 (30)	0	1,900 (13)	2,100 (15)	11	2,400 (17)	1,900 (14)	0 (9)	100 (0.9)
2u	James Canyon	1,300	3,400 (31)	3,300 (30)	-3	1,300 (12)	1,300 (12)	0	2,100 (19)	1,700 (16)	60 (0.6)	200 (2.2)
3u	Sierra Canyon	2,000	4,900 (29)	4,900 (29)	0	1,500 (9.0)	1,400 (8.4)	-7	3,200 (19)	2,800 (17)	200 (1.2)	600 (3.5)
4u	Genoa Canyon	1,400	3,200 (27)	3,000 (26)	-6	960 (8.2)	1,000 (8.6)	4	2,100 (18)	1,700 (15)	80 (3.5)	400 (3.1)
5g	Daggett Creek	2,400	5,600 (28)	5,700 (29)	2	1,200 (6.0)	1,100 (5.5)	-8	3,600 (18)	3,000 (15)	700 (3.5)	1,600 (7.9)
6u	Mott Canyon	1,300	3,300 (30)	3,400 (31)	3	1,700 (15)	1,600 (15)	-6	1,600 (14)	1,600 (14)	0 (0)	0 (0)
7u	Monument Creek	1,500	3,500 (28)	3,600 (29)	3	2,600 (21)	1,800 (14)	-31	900 (7)	1,800 (14)	0 (0)	0 (0)
8u	Stutler Canyon	1,600	4,000 (30)	4,000 (30)	0	450 (3.4)	450 (3.4)	0	[2]3,500 (19)	1,900 (14)	[2]100 (0.5)	[1]1,600/1,000 (12.3)
9u	Sheridan Creek	640	1,400 (26)	1,400 (26)	0	1,300 (24)	700 (13)	-46		660 (12)		0 (0)
10u	Jobs Canyon	2,000	5,500 (33)	5,500 (33)	0	1,700 (10)	2,000 (12)	18	3,200 (19)	2,800 (17)	700 (1.3)	800 (4.7)
11u	Luther Creek	2,800	7,200 (31)	7,200 (31)	0	2,200 (9.4)	2,100 (9)	-5	4,500 (19)	4,100 (18)	500 (2.1)	1,200 (5.3)
12g	Fredericksburg Canyon	2,400	6,400 (32)	6,700 (34)	5	2,900 (14)	3,000 (15)	3	3,800 (19)	3,300 (17)	0 (0)	300 (1.6)
Subtotal, Carson Range[3]		21,000	52,600 (30)	52,900 (30)	0	19,700 (11)	18,600 (11)	-6	30,200 (19)	27,300 (16)	2,300 (1.3)	[4]6,200 (3.5)

Table 4. Summary of model results for 14 perennial watersheds in Carson Valley, water years 1990–2002, and comparison with estimates from Maurer and Berger (2007)—Continued.

[Values in inches are volumes in acre-feet, divided by watershed area, in acres, multiplied by 12. **Watershed No.** ending in “u” is ungaged; watershed No. ending in “g’ is gaged watershed. Locations of watersheds are shown in figure 3. **Measured or reconstructed mean annual runoff**: From Maurer and others (2004, p. 14); measured for gaged watersheds; reconstructed for ungaged watersheds. **Relative difference in runoff**: Computed from values in acre-feet as (simulated−estimated/estimated)*100. **Estimated mean annual precipitation**: From Maurer and Berger (2007, p. 29). **Estimated mean annual ET:** Multiply reported ET rate, in feet, by watershed area to obtain ET volume in acre-feet. **Estimated mean annual ground-water inflow**: From Maurer and Berger (2007, p. 32). **Ground-water inflow**: Defined as ground-water inflow to basin-fill aquifers of Carson Valley. **Abbreviations:** acre-ft, acre-feet; ET, evapotranspiration]

Watershed No.	Watershed name	Drainage area, (acres, rounded)	Mean annual precipitation		Relative difference in precipitation estimates (percent)	Mean annual runoff		Relative difference in runoff (percent)	Mean annual ET		Mean annual ground-water inflow	
			Estimated by Maurer and Berger, 2007 1971–2000	Simulated by watershed models 1990–2002		Measured or reconstructed by Maurer and others, 2004 1990–2002	Simulated by watershed models, 1990–2002		Estimated by Maurer and Berger, 2007	Simulated by watershed models, 1990–2002	Estimated by Maurer and Berger, 2007	Simulated by watershed models, 1990–2002
			acre-ft (in.)	acre-ft (in.)		acre-ft (in.)	acre-ft (in.)		acre-ft (in.)	acre-ft (in.)	acre-ft (in.)	acre-ft (in.)
13g	Pine Nut Creek	6,400	8,500 (16)	7,200 (14)	-15	670 (1.3)	690 (1.3)	3	7,000 (13)	5,200 (10)	700 (1.3)	1,200 (2.3)
14g	Buckeye Creek	28,900	34,000 (14)	33,000 (14)	-3	690 (0.2)	700 (0.3)	1	29,000 (12)	25,000 (10)	3,600 (1.5)	7,000 (2.9)
Subtotal, Pine Nut Mountains[3]		35,300	42,500 (14)	40,200 (14)	-5	1,360 (0.5)	1,390 (0.5)	2	36,700 (12)	30,100 (10)	4,300 (1.5)	8,200 (2.8)
Total (rounded)		56,300	95,100 (20)	93,100 (20)	[3]-2	21,000 (4.5)	20,000 (4.3)	[3]-5	66,900 (14)	57,400 (12)	6,600 (1.4)	14,400 (3.2)

[1] About 600 acre-ft from Stutler Canyon is assumed to supply streamflow to Sheridan Creek, and is not available as ground-water inflow to basin-fill aquifers of Carson Valley. Remaining 1,000 acre-ft assumed to supply ground-water inflow to basin-fill aquifers of Carson Valley.

[2] Estimates from Maurer and Berger (2007) are for the combined watersheds of Stutler Canyon and Sheridan Creeks.

[3] Values of relative difference for subtotal and total are actually average values, rather than subtotals.

[4] Includes 1,000 acre-ft from Stutler Canyon.

As with all other watershed models presented in this study, the PRMS method for computing ground-water inflow affects the baseflow period for the dry years in a more pronounced manner when adjusting ground-water inflow to minimize overestimation of runoff during the wet years. This resulted in days with zero simulated runoff for the Pine Nut Creek model. Due to the use of a normalized error, only months with non-zero simulated runoff were included in the seasonal error analyses. The only seasonal aggregate with a reasonable bias is April–June. The tendency however, is to overestimate spring runoff during the wet years from water years 1995–97, resulting in an overall relative error of about 22 percent for April–June.

Buckeye Creek Watershed

Although the Buckeye Creek watershed is considered to be a perennial watershed, records indicate periods of very low to zero runoff for much of the year, thus characterizing this watershed as more of an ephemeral- than perennial-stream watershed. The Buckeye Creek gaging station is downstream of a losing reach and has many days with zero flows except during the early spring snowmelt. For that reason, error statistics were computed for mean annual runoff, and the February–April aggregate, the latter for years with measured flow (table 3).

Overall, the simulated hydrograph indicates that the model simulates a much quicker response to precipitation than what is measured at the gage and it tends to overestimate mean annual runoff by as much as 12 percent relative to the measured runoff (fig. 10: table 3) However, for the February–April period, the only season with consistently measured runoff greater than zero, seasonal simulations underestimate runoff. For water years 1981–97, mean annual relative error is 102 percent. However, removing water year 1994 from the analysis, when the annual difference in simulated and measured runoff exceeds 1,000 percent (0.046 in. simulated versus 0.003 in. measured), reduces the relative error to about -5 percent (table 3).

The ground-water inflow component of the water budget is greater than zero for those years with above normal precipitation (fig. 9). For wet years (1982–83, 1986, 1993, 1995–97), ground-water inflow ranges from 20 percent of the precipitation in 1982 to more than 40 percent in 1997. The runoff efficiency for Buckeye Creek watershed is estimated to be 2 percent (table 1) indicating most of the precipitation is lost to evapotranspiration and infiltration.

Whether computed ground-water inflow from the Buckeye Creek watershed is reasonable depends primarily on the accuracy of the precipitation inputs. Simulated daily hydrographs for individual years with above normal precipitation (fig. 10) reasonably fit measured hydrographs for most of the winter to early spring runoff peaks, although there is a tendency for the model to underestimate March–April runoff. Conversely, during dry or below average precipitation years, not only is the runoff well below 1 ft^3/s for every day during the year, but there are a larger number of measured summer runoff peaks that the model did not simulate.

Model and Data Limitations

The precipitation-runoff model is a mathematical representation of the physical processes that occur in the watershed. The quality of the model results depends on the accuracy of the representation of the physical processes (model error), the quality and accuracy of the precipitation and air-temperature input time series and runoff calibration time series (data error), and the accuracy of the calibrated model parameters (parameter error: van Heeswijk, 2006).

Those error sources most affecting the watershed models for Carson Valley include: the assumption that the ungaged perennial and ephemeral watersheds are hydrologically similar to the index watersheds, the scale of available soil data, the adequacy of available climate data and accuracy of precipitation estimates using the precipitation distribution of Maurer and Halford (2004), the accuracy of the reconstructed daily mean runoff used for calibration of the ungaged perennial watersheds, and the sensitivity of the model in simulating baseflow during years of below normal precipitation. Watersheds are dynamic systems. Land-cover type, density, and the percentage of impervious or barren areas are static parameters in PRMS, and therefore reflect land cover conditions for 1998–2000, when the digital maps were compiled.

The hydrologic similarity of ungaged watersheds to index watersheds cannot be further addressed without additional, definitive measurements of runoff from the ungaged watersheds. The effect of index model selection for ephemeral watersheds of the Carson Range is evaluated in the section, “Uncertainty in Estimates of Simulated Ground-Water Inflow.”

The scale of available soil data limits the extent to which the watershed models can represent the actual hydrologic system. The STATSGO soils data are mapped at a scale of 1:250,000, resulting in a 1,000-m grid resolution and a minimum mapping unit of 1,544 acres, an area larger than many of the modeled watersheds. Most of the Carson Range watersheds are characterized as having either one or two soil types, reflecting the dominance of granitic or metamorphic bedrock. Watersheds on the eastern side of Carson Valley have from four to five different soil types reflecting a more varied geologic landscape that includes crystalline volcanic rocks, Tertiary sediments, and alluvial-fan deposits.

The soil-water holding capacity was adjusted upward for most of the HRUs, reflecting an increase from 30 to more than 100 percent of the initial value computed from the STATSGO data to better match the reconstructed or measured runoff. The soil parameters influence the distribution of water between the surface and subsurface reservoirs and ultimately affect the distribution of interflow or shallow subsurface flow, baseflow, and ground-water inflow. In addition, the amount of actual evapotranspiration (AET) is influenced by the generalized PRMS soil designation of sand, loam or clay (derived from STATSGO), and the ratio of available water to the maximum soil-water storage at a given simulation time step.

The dominance of one flow coefficient over the other influences the shape of the simulated hydrograph. The simulated ground-water inflow is set at a constant rate in the model for the selected modeling period. The constant rate affects low-runoff years more visibly than the above-average precipitation years. In low runoff years, less water is routed to the subsurface reservoirs and thus, less water is available for baseflow. This results in a tendency to underestimate baseflow for the drier years, when adjusting the model to better fit wet years. Though there can be remaining soil-moisture storage at the end of a simulated water year, this may be underestimated compared to the actual year-to-year subsurface storage. Propogated over several consecutively low precipitation years, the tendency to underestimate baseflow can potentially increase the modeling error for the period of record.

The rainshadow effect of the Carson Range influences precipitation in Carson Valley as much as altitude. The Sheridan Acres, Daggett Pass, and Heavenly Valley climate stations (stations 4p, 2p, and 3p in fig. 3, respectively) adequately represent the range in precipitation distribution for the Carson Range while the Minden station (station 5p) appears to be influenced by the Carson Range rainshadow effect. The Fish Spring station (station 6p) in the Pine Nut Creek drainage recorded data from 1991 to 2002. The Minden data were used to complete the earlier part of the record and used to model both Buckeye Creek and Pine Nut Creek watersheds. The Pine Nut Mountains are more influenced by localized, convective storm activity, which may not be adequately represented by the Minden or Fish Springs climate stations. There may be some error introduced at the scale of daily runoff simulations in the use of one low-altitude climate station in simulating air temperatures for the higher altitude HRUs, and the use of regional monthly temperature lapse rates to adjust for differences in HRU altitude.

Precipitation inputs were corrected to closely match the long-term precipitation estimates for each watershed determined by Maurer and Berger (2007, p. 29) using the linear relations developed by Maurer and Halford (2004) for 1971–2000. Although the simulated mean annual volume of precipitation may correlate well with the previous estimates of Maurer and Berger (2007; table 4), there is uncertainty as to the interannual variability introduced by the model in using the same monthly HRU precipitation correction factor from year to year. Maurer and Halford (2004) report an uncertainty estimate of 15 percent of the total precipitation estimated for Carson Valley, however, the uncertainty associated with precipitation estimates for high-altitude areas is unknown.

Lastly, the reconstructed runoff time series to which the simulated runoff for ungaged perennial watersheds in the Carson Range was compared during model calibration, have an estimated uncertainty of about 30 percent. Sparse measurements accompany this data set and thus comparison of reconstructed and simulated daily mean runoff is most reliably done on an annual basis. The PRMS models generally exhibit a quicker runoff response to precipitation than most of the reconstructed time series, which use a composite of Carson River flows and gaged records from nearby watersheds. The overall effect is to minimize the daily variations typically present in the measured runoff. This is particularly evident for those watersheds with barren or rock exposure where runoff tends to be more immediate, reflecting the low infiltration during periods of rapid snowmelt or heavy rain.

Results of Watershed Modeling and Comparison with Previous Estimates

The watershed models provide estimates of annual mean unit-area rates of precipitation, runoff, evapotranspiration (ET), and ground-water inflow, in inches per acre for water years 1990–2002. In this report, the annual mean rates are reported as water-equivalent heights, in inches. Mean annual volumes, in acre-feet, were computed for water years 1990–2002 by averaging the annual mean rates and multiplying by the drainage area of the watersheds, for comparison with the volumes estimated by Maurer and Berger (2007).

Perennial Watersheds

Simulated daily mean and annual mean runoff matches measured and reconstructed runoff reasonably well for most perennial watersheds, with the exceptions of Monument Creek, Sheridan Creek, and Jobs Canyon (table 4; figs. 11 and 12). The difference between simulated and measured or reconstructed mean annual runoff was 11 percent or less, also with the exceptions of Monument Creek, Sheridan Creek, and Jobs Canyon (table 4). The simulated mean annual runoff was 31 percent less than the reconstructed runoff for Monument Creek watershed (table 4). High amounts of runoff as a percentage of precipitation for Mott Canyon and Monument Creek watersheds were noted by Maurer and Berger (2007, p. 32; table 1) along with the observation that they are not incised as greatly into the mountain blocks as other watersheds. Both observations indicate that these watersheds may be underlain by less permeable and less fractured bedrock, which is consistent with no ground-water inflow simulated from the two watersheds (table 4, fig. 12).

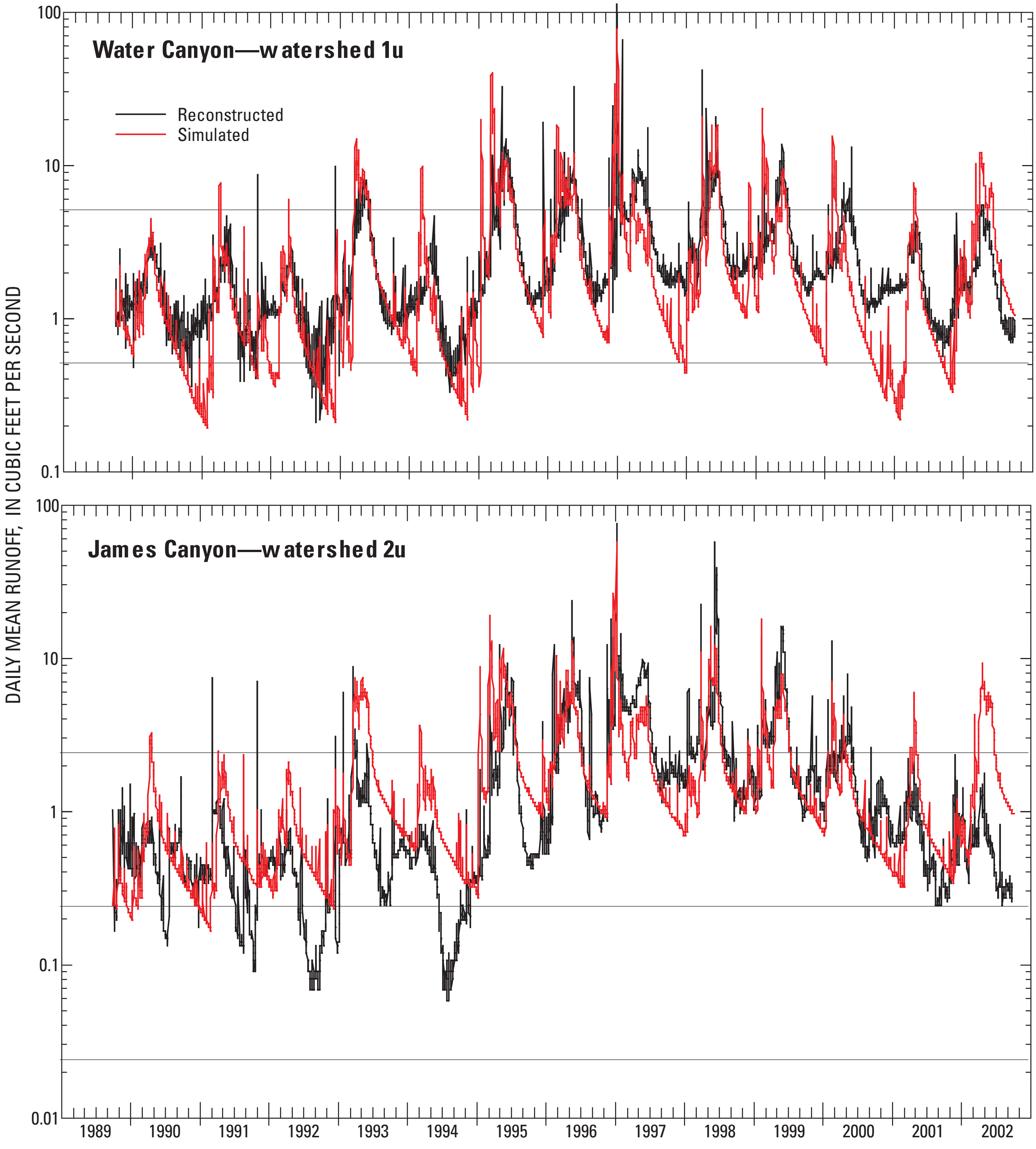


Figure 11. Simulated and reconstructed daily mean runoff for 10 ungaged perennial watersheds in Carson Valley, Nevada and California, water years 1990–2002.

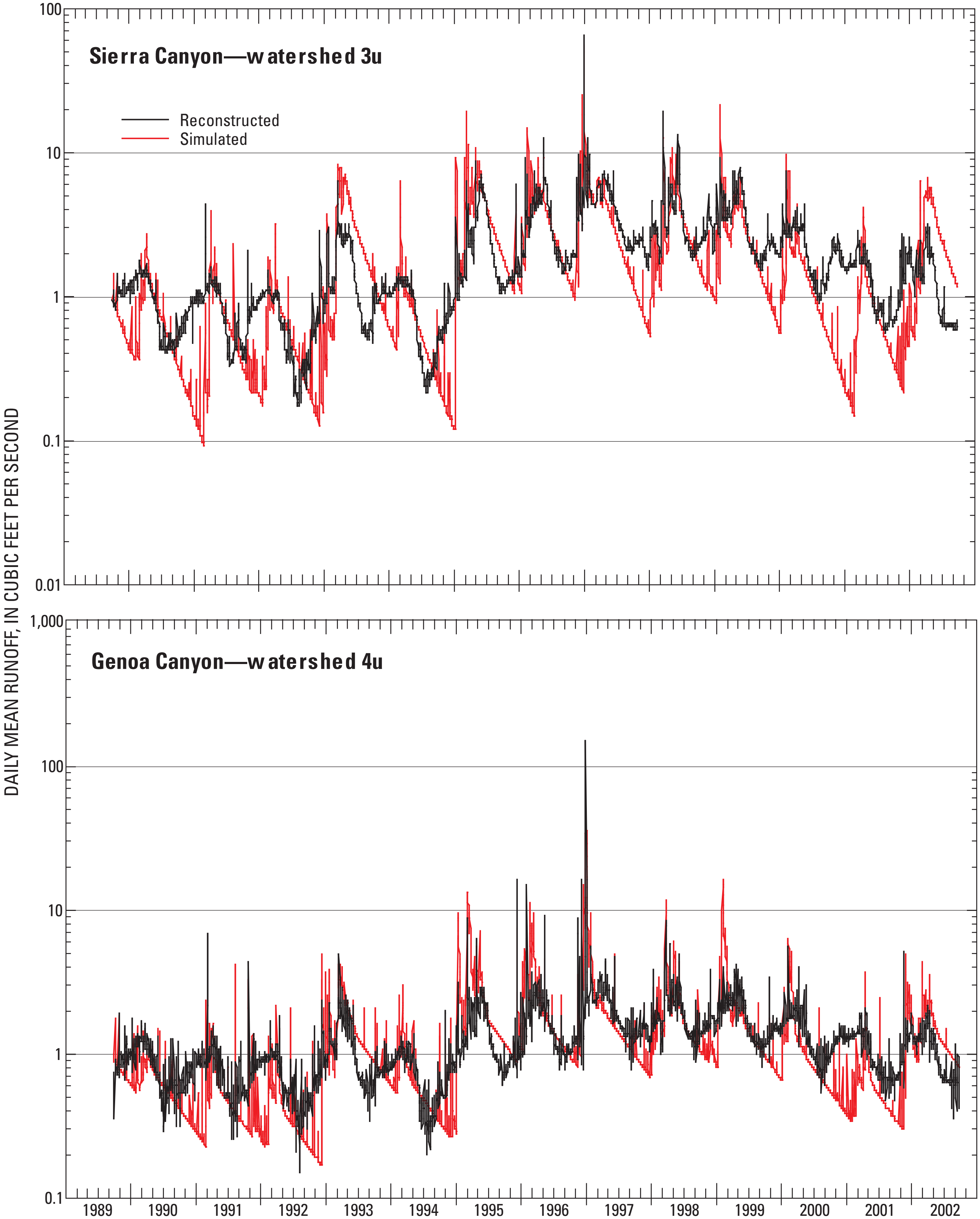


Figure 11.—Continued.

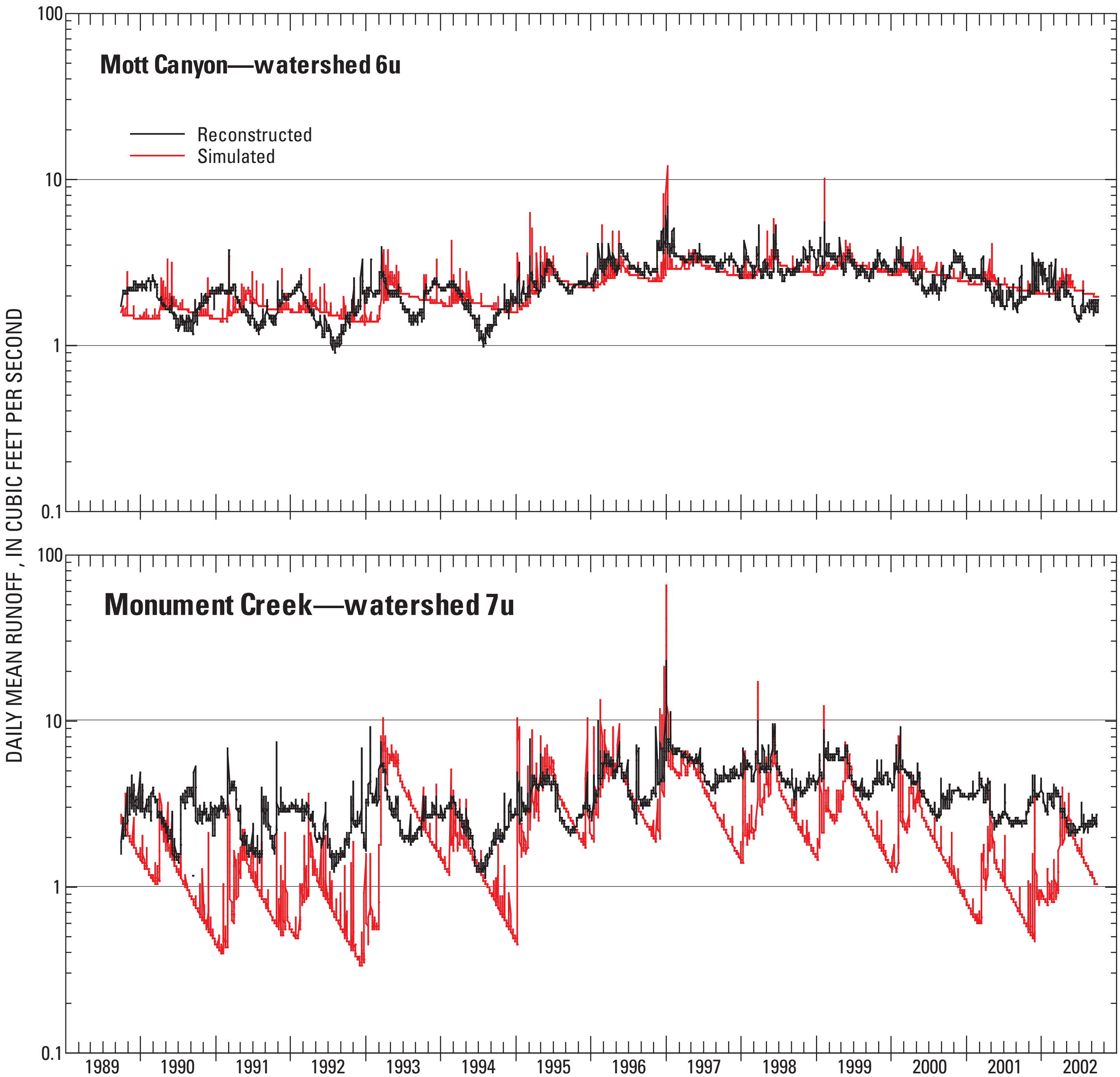
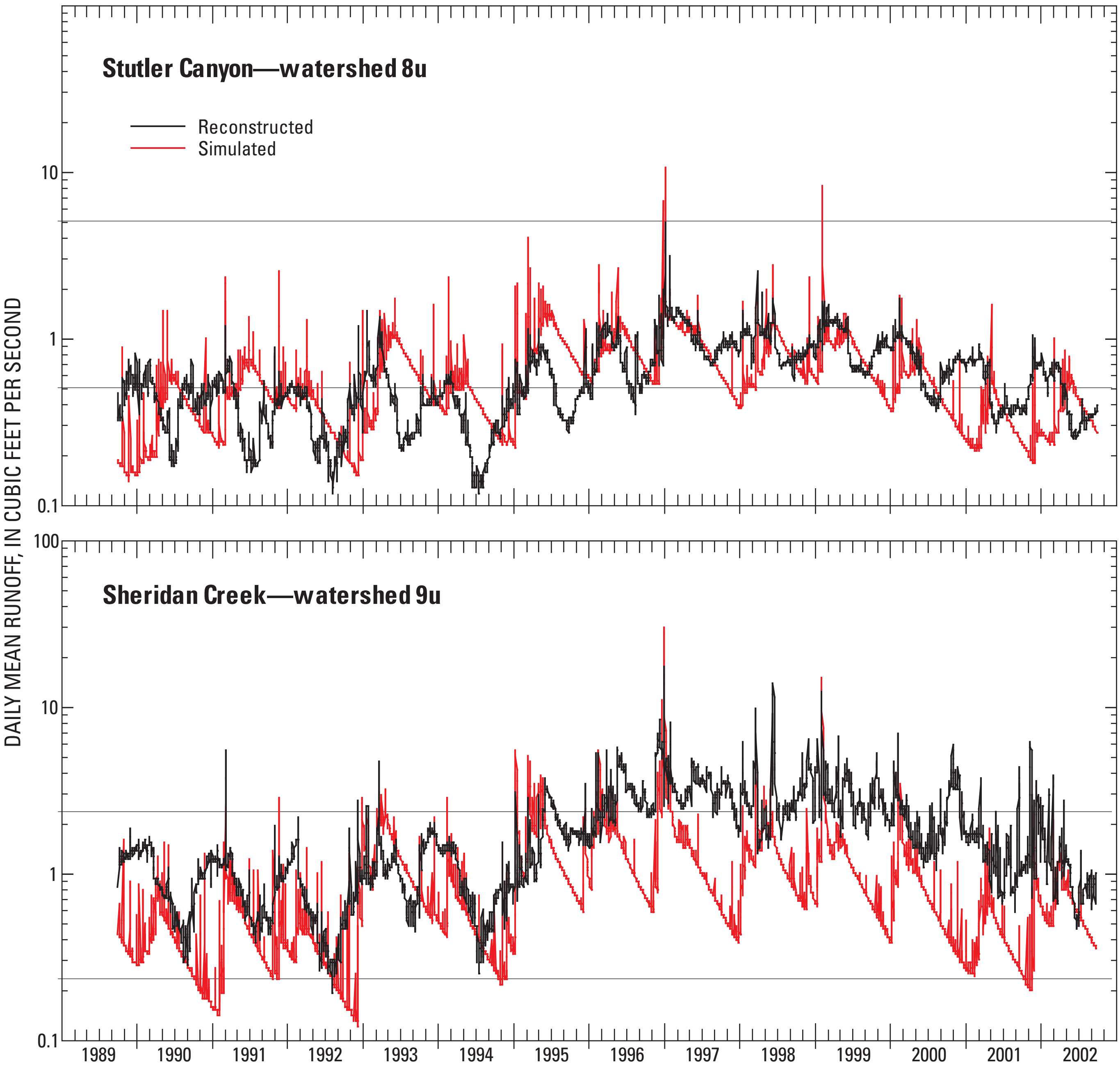


Figure 11.—Continued.



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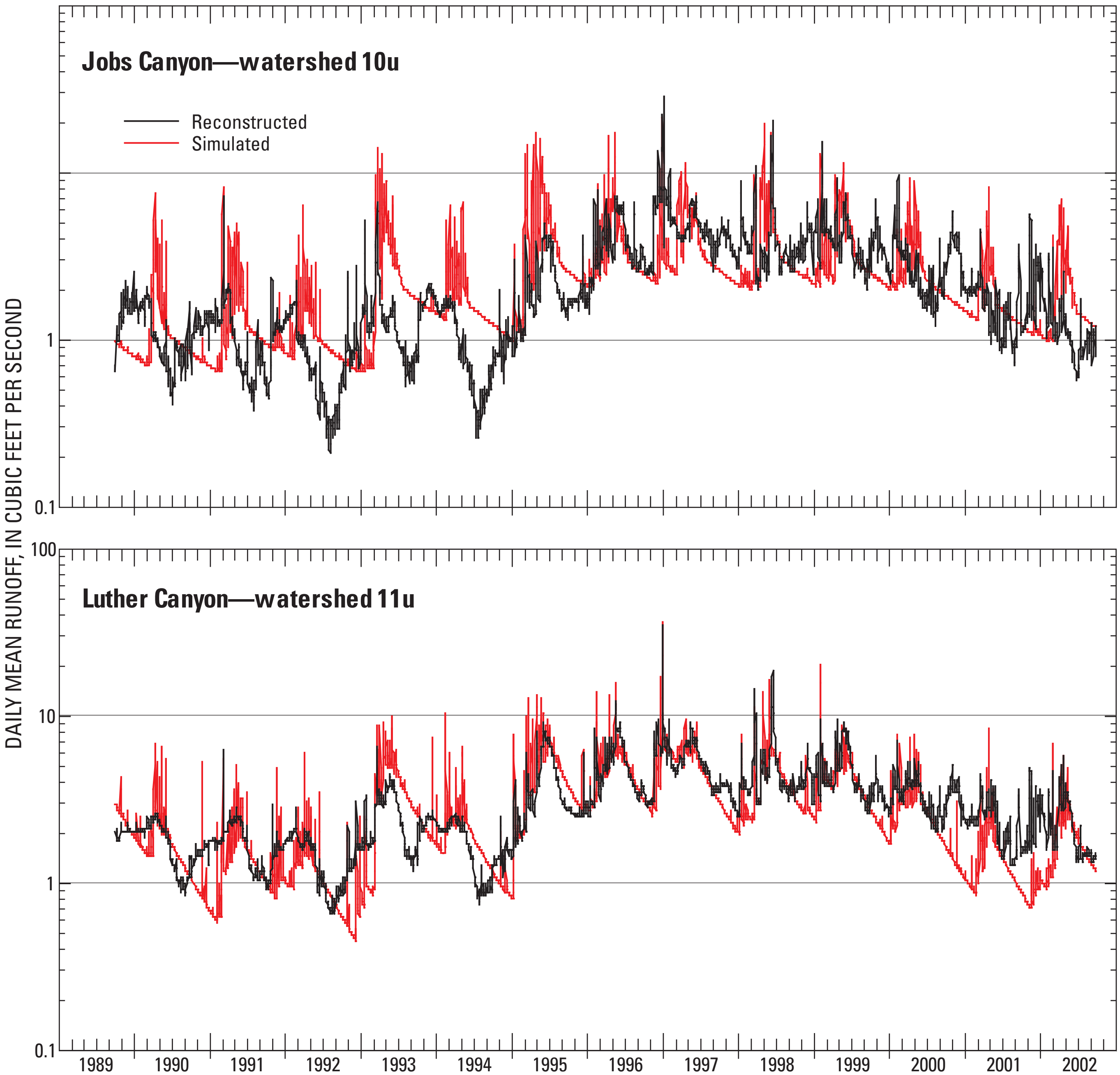

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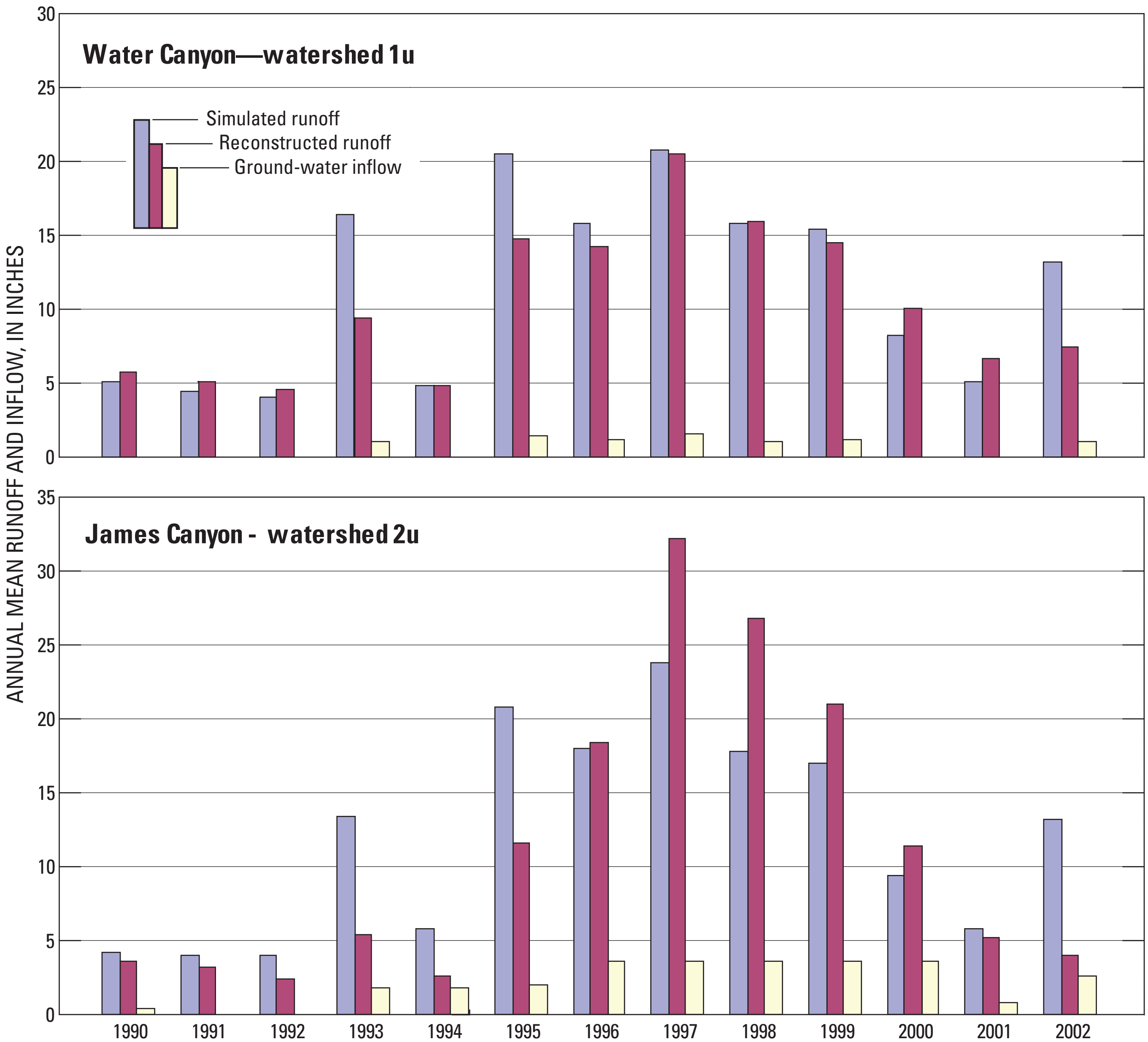
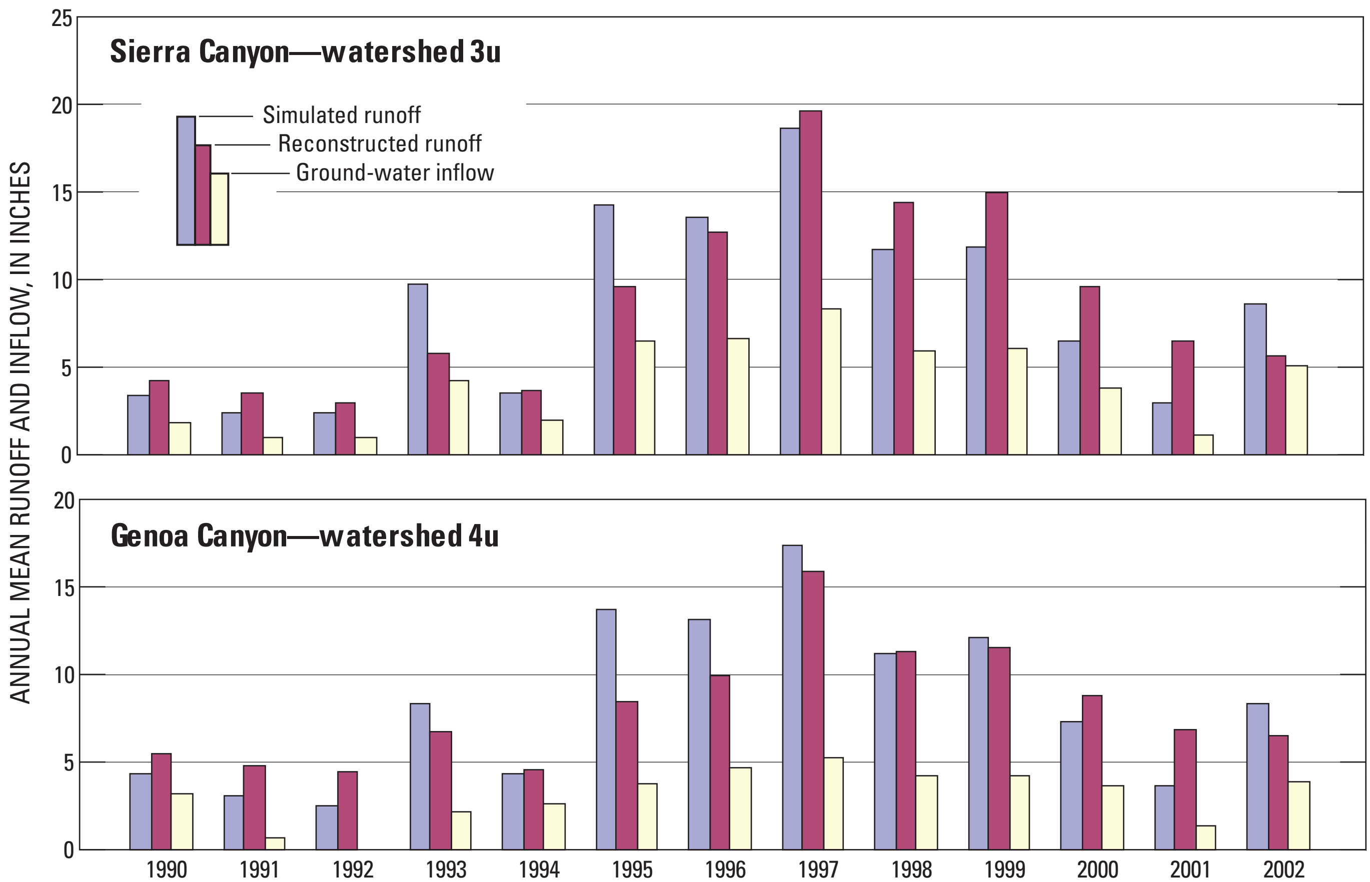


Figure 12. Simulated and reconstructed annual mean runoff and ground-water inflow for 10 ungaged perennial watersheds in Carson Valley, Nevada and California, water years 1990–2002.



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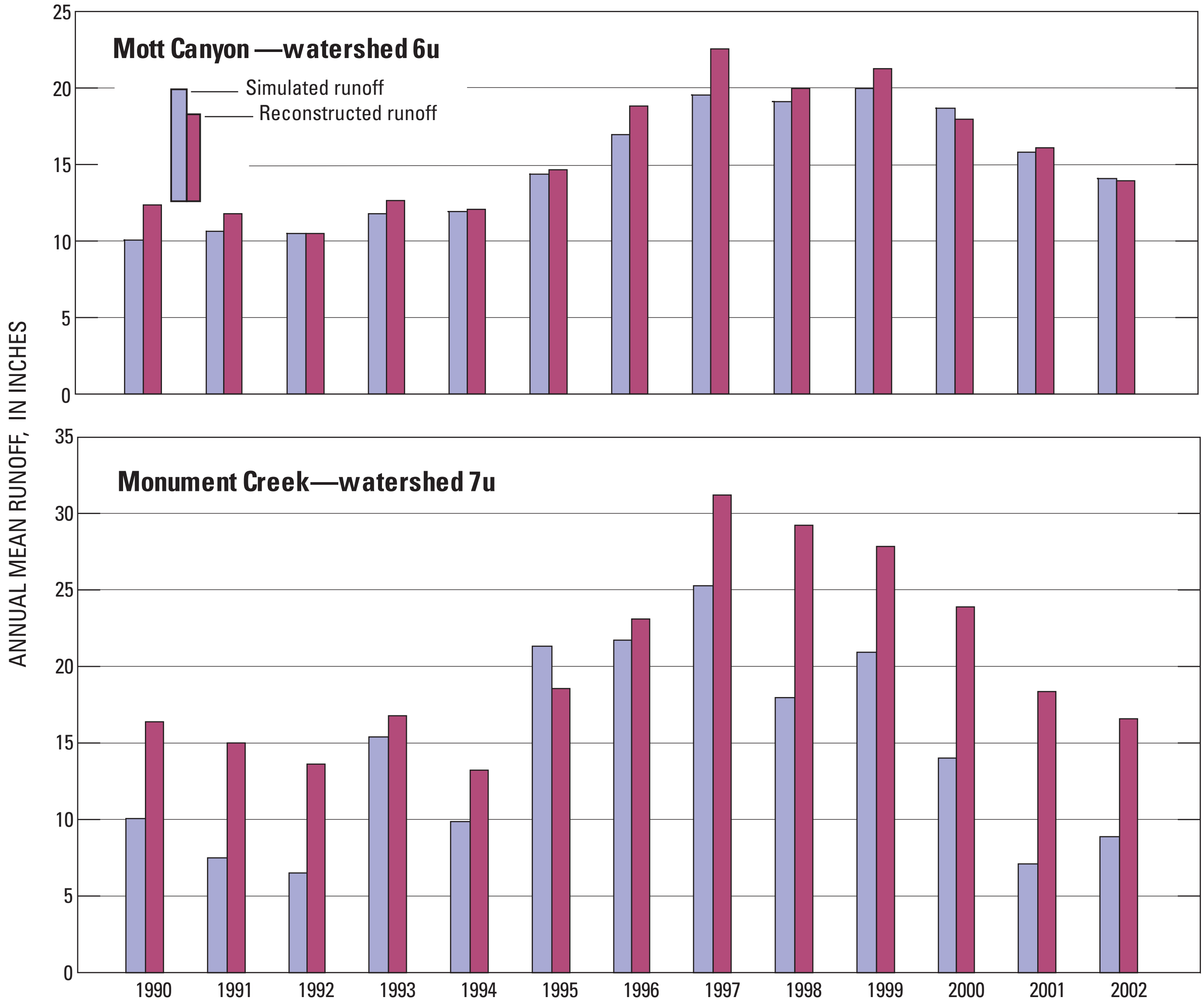

Figure 12.—Continued.

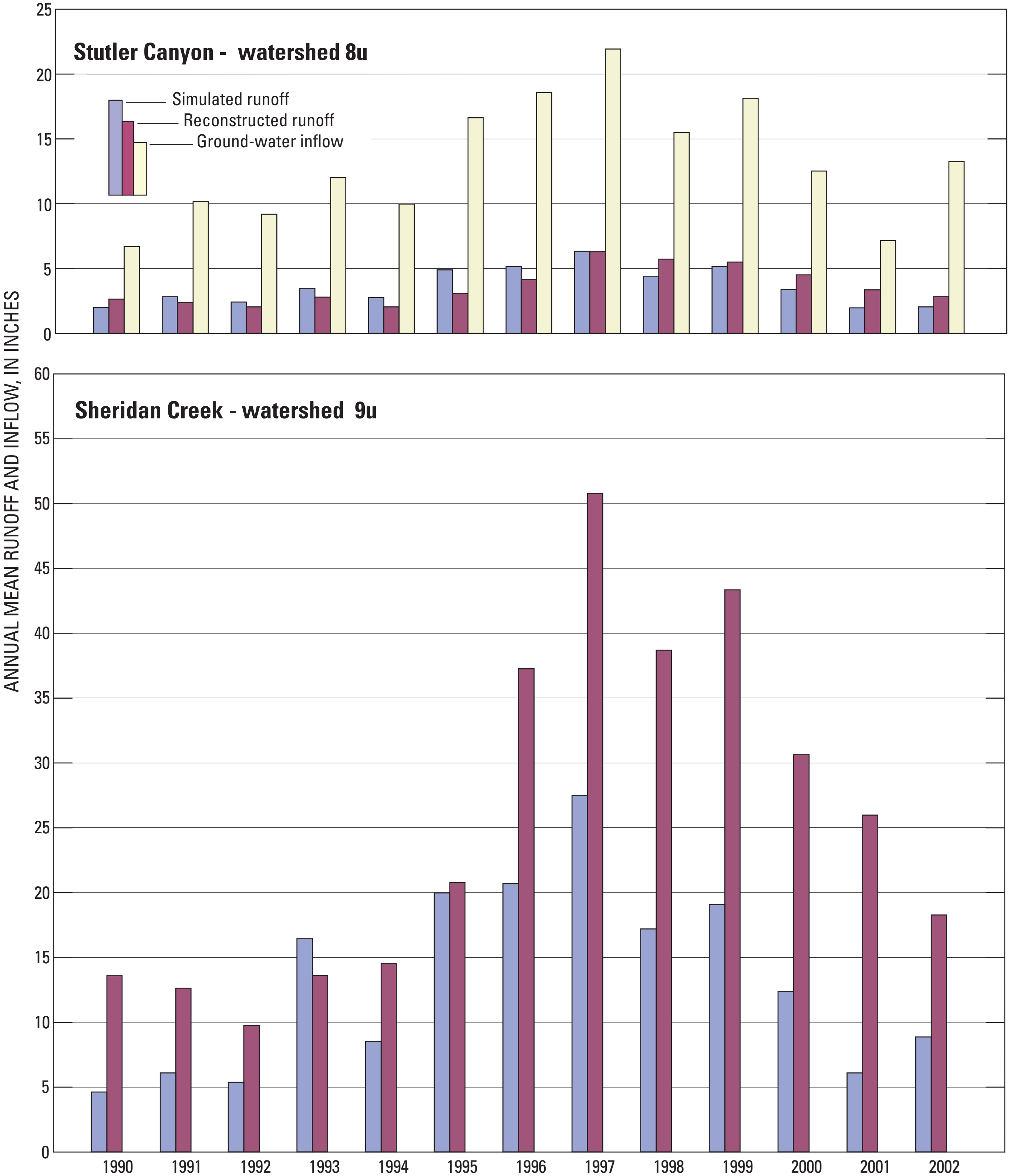

Figure 12.—Continued.

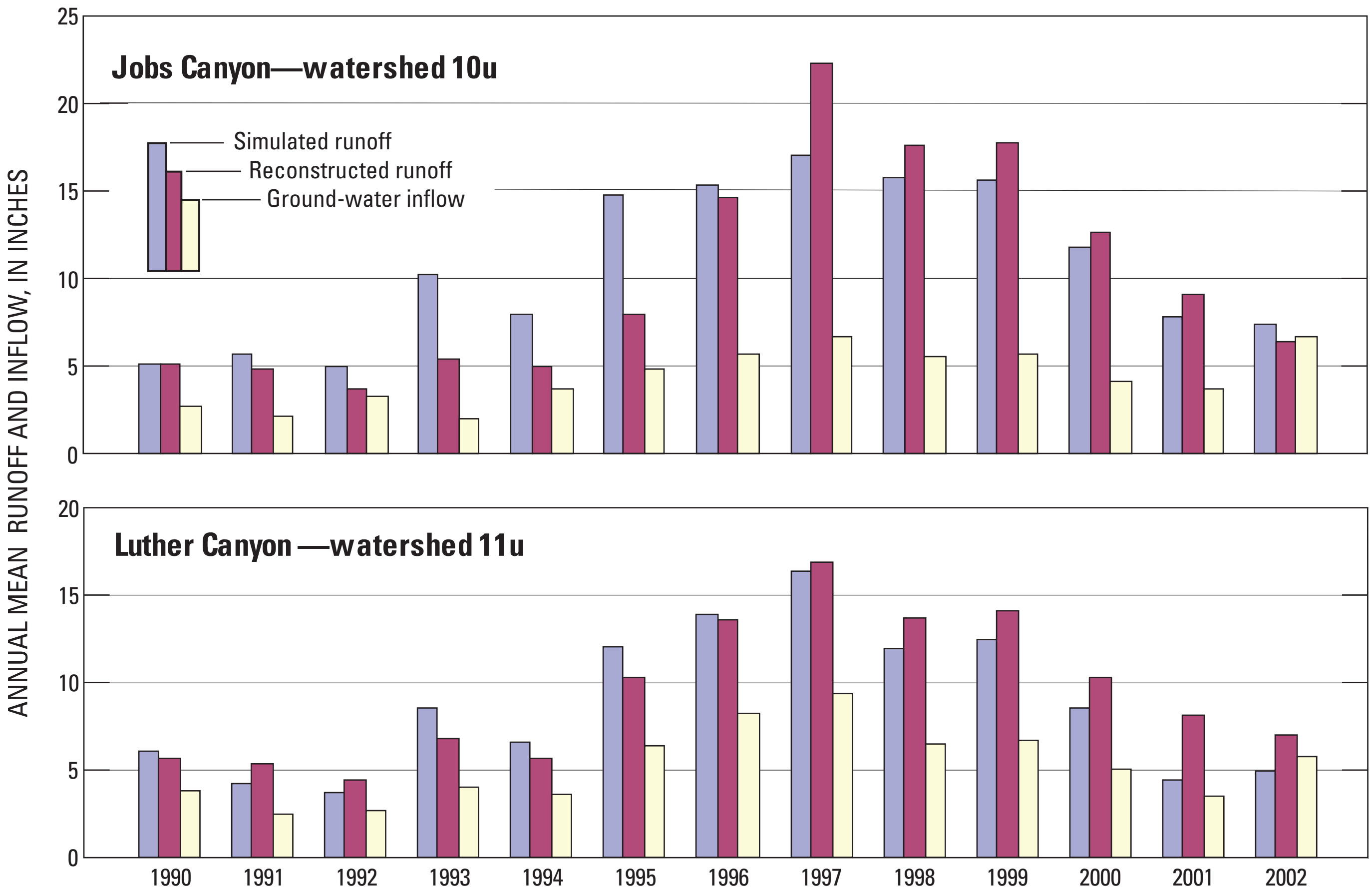

Figure 12.—Continued.

Mean annual runoff was underestimated for Sheridan Creek watershed by 46 percent, no ground-water inflow from the watershed was simulated, and the rates of ground-water inflow simulated for Stutler Canyon watershed were considerably greater than any other watershed (table 4; fig. 12). These results are consistent with the observations of Maurer and Berger (2007, p. 30), who noted large differences in runoff as a percentage of precipitation from the two watersheds (table 1), and suggested that subsurface flow may be taking place from the Stutler Canyon watershed to the Sheridan Creek watershed.

The source of runoff in the Sheridan Creek watershed is a series of springs that issue from the base of a ridge separating the two watersheds, and the Stutler Canyon watershed lies at a higher altitude, to the west of the Sheridan Creek watershed (watersheds 8u and 9u, respectively, in fig. 3). For these reasons, estimates of ground-water inflow to Carson Valley were made from the combined areas of the Stutler Canyon and Sheridan Creek watersheds by Maurer and Berger (2007). Results of the watershed modeling suggest that the deficiency of simulated runoff from Sheridan Creek watershed, 600 acre-ft/yr, may be supplied from the 1,600 acre-ft/yr of subsurface flow simulated from Stutler Canyon watershed (table 4). The remaining 1,000 acre-ft/yr from Stutler Canyon watershed likely becomes ground-water inflow to basin-fill aquifers of Carson Valley.

Simulated daily mean runoff from Jobs Canyon watershed generally was overestimated from 1990 to 1995, but matches reconstructed runoff more closely from 1996 to 2002 (fig. 10). Annual mean runoff appears to match reconstructed runoff more closely than daily mean runoff from 1990 to 1995 (fig. 12), likely because of compensating differences from periods of under- and overestimation during the year. Mean annual runoff was overestimated by 18 percent for water years 1990–2002 (table 4). The difference between the simulated and estimated runoff volumes may not be meaningful because, as stated previously, the reconstructed daily mean flows have an uncertainty of as much as 30 percent. However, the reconstructed runoff represents the best available estimate of daily flows from the ungaged watersheds.

For all perennial watersheds, simulated precipitation was within 15 percent of that estimated by Maurer and Berger (2007), largely because effort was made during calibration to match the previous estimate of precipitation, as previously discussed. Simulated ET from the models generally was less than ET estimated by Maurer and Berger (2007) largely because of the greater volumes of simulated ground-water inflow, and also in part, because of differences between simulated and reconstructed runoff. The ET estimates made by Maurer and Berger (2007) were calculated as the difference between precipitation and the combined volumes of runoff and estimates of ground-water inflow. Their ET estimates therefore include the combined errors associated with ground-water inflow estimates and the reconstructed runoff estimates. ET estimates in the PRMS model are a summation of sublimation, soil water loss, canopy interception loss, and evaporation from impervious surfaces.

Simulated annual rates of ground-water inflow from the watersheds to the basin-fill deposits of Carson Valley generally are less than 5 in. for most watersheds, but are as great as 22 in. for Stutler Canyon, about 12 in. for Daggett Creek, and about 10 in. for Pine Nut and Buckeye Creeks (figs. 9 and 12). The high annual rates for Stutler Canyon watershed are explained by the likelihood of subsurface flow to Sheridan Creek (not simulated), which would reduce ground-water inflow contributions from Stutler Canyon watershed to the basin-fill deposits of Carson Valley. The high rates for Daggett Creek watershed are consistent with its low amount of runoff as a percentage of precipitation, 21 percent (table 1). The relatively low amount of runoff indicates that bedrock underlying the Daggett Creek watershed likely is more fractured and permeable than other watersheds, allowing greater rates of infiltration and ground-water inflow. The Daggett Creek watershed lies at the topographically lowest point along the crest of the Carson Range; further indication that bedrock underlying the watershed is more fractured, erodible, and permeable than other watersheds of the Carson Range. Bedrock underlying the Pine Nut and Buckeye Creek watersheds (watersheds 13g and 14g, respectively, in fig. 3) also may be more fractured than those of the Carson Range, as indicated by the number of mapped faults. Moore (1969, p. 18) describes the Pine Nut Mountains as being composed of several orographic blocks which have been tilted individually, in contrast to the Carson Range, which generally was uplifted along a single fault zone with a large displacement (fig. 3).

The simulated mean annual volume of ground-water inflow to the basin-fill aquifers of Carson Valley from the 14 perennial watersheds for 1990–2002 totaled 14,400 acre-ft, more than twice the 6,600 acre-ft estimated by Maurer and Berger (2007; table 4) using the water-yield method. In most cases, greater volumes of simulated ground-water inflow coincided with greater volumes estimated by Maurer and Berger (2007). The watershed models simulated ground-water inflow from Water Canyon and Fredericksburg Canyon watersheds, whereas Maurer and Berger (2007) estimated no ground-water inflow using the water-yield method.

Ephemeral Watersheds

Lacking measured streamflow data, calibration of the ephemeral watershed models was limited to the adjustment of precipitation volumes to match that estimated by Maurer and Halford (2004) because the amount of ephemeral runoff is uncertain. Simulated precipitation rates generally were less than those simulated for the perennial watersheds (tables 4 and 5), as would be expected because of the lower altitude of most of the ephemeral watersheds. Similarly, simulated ET rates generally were less than those for the perennial watersheds, primarily because of the lower rates of precipitation.

Simulated runoff and ground-water inflow for the ephemeral watersheds of the Carson Range depend greatly on the selected index model and precipitation inputs (table 5). For those watersheds that used the Daggett Creek index model, simulated runoff rates and volumes were similar in magnitude to simulated ground-water inflow rates and volumes. For those watersheds that used the Fredericksburg Canyon index model, simulated runoff rates and volumes were considerably greater than simulated ground-water inflow rates and volumes. The two ephemeral watersheds that have large volumes of runoff (watersheds 5e and 10e, table 5 and fig. 3) are large in area and, more importantly, have HRUs at altitudes greater than 8,000 ft, thus receiving proportionately more precipitation.

Simulated mean annual runoff rates ranged from about 5 to 7 in. for ephemeral watersheds using Daggett Creek watershed model as an index model, and from 9 to 13 in. for ephemeral watersheds using Fredericksburg Canyon as an index model (table 5). Mean annual ephemeral runoff from the Carson Range simulated from the models totaled 9,900 acre-ft with an overall runoff rate of 8.4 in., similar to the volume of 8,000 acre-ft and rate of 7 in. estimated by Maurer and others (2004, p. 14).

The large area of ephemeral runoff modeled near the Pine Nut Mountains (watershed 11e, fig. 3) had a mean annual simulated runoff volume of 800 acre-ft, for the area of 78,200 acres, or a rate of 0.1 in. The area of the watershed model near the Pine Nut Mountains was selected to include the general area of exposed semiconsolidated sediments (fig. 3). In this study, runoff from the eastern side of the valley floor underlain by alluvial fans was assumed to be negligible.

Mean annual ground-water inflow rates simulated for ephemeral watersheds of the Carson Range ranged from 0.07 to 0.7 in. for watersheds using the Fredericksburg Canyon index model, and from about 5 to 7 in. for watersheds using the Daggett Creek index model (table 5). The mean annual ground-water inflow simulated from ephemeral watersheds of the Carson Range totaled 3,500 acre-ft. Simulated mean annual ground-water inflow from the ephemeral watershed on the eastern side of the valley (watershed 11e) totaled 5,700 acre-ft, for an annual rate of 0.9 in. (table 5).

Table 5. Summary of model results for selected ephemeral watersheds in Carson Valley, Nevada and California, water years 1990–2002.

[Values in inches are volumes in acre-feet, divided by watershed area, in acres, multiplied by 12. **Watershed No.:** "e" indicates ephemeral watershed. Locations are shown in figure 3. **Index model**: Watershed model of gaged watershed (see table 1) used as index model for watershed model of ephemeral watershed. **Simulated runoff efficiency**: Runoff as a percentage of precipitation. **Simulated mean annual ground-water inflow**: Ground-water inflow is defined as ground-water inflow to basin-fill aquifers of Carson Valley. **Abbreviations:** acre-ft, acre-feet; in., inch]

Watershed No.	Drainage area (acres, rounded)	Index model	Simulated: Mean annual precipitation, acre-ft (in.)	Simulated: Mean annual evapotranspiration, acre-ft (in.)	Simulated: Mean annual runoff, acre-ft (in.)	Simulated: Runoff efficiency (percent)	Simulated: Mean annual ground-water inflow, acre-ft (in.)
1e	2,120	Daggett Creek	3,980 (23)	2,090 (12)	930 (5.3)	23	960 (5.4)
2e	600	Fredericksburg Canyon[1]	1,150 (23)	590 (12)	530 (11)	46	4 (0.08)
3e	1,320	Fredericksburg Canyon	2,430 (22)	1,320 (12)	1,020 (9.3)	42	8 (0.07)
4e	500	Fredericksburg Canyon	830 (20)	410 (9.8)	370 (9)	45	4 (0.1)
5e	2,270	Fredericksburg Canyon	4,330 (23)	2,350 (12)	1,760 (9.3)	41	30 (0.2)
6e	2,190	Daggett Creek	3,930 (22)	1,660 (9.1)	980 (5.4)	25	1,230 (6.7)
7e	340	Daggett Creek	750 (27)	350 (12)	200 (7.3)	27	210 (7.4)
8e	1,700	Daggett Creek	3,460 (24)	1,670 (12)	950 (6.7)	27	910 (6.4)
9e	720	Fredericksburg Canyon	1,290 (22)	640 (11)	590 (9.8)	46	8 (0.1)
10e	2,500	Fredericksburg Canyon	5,790 (28)	2,890 (14)	2,610 (13)	43	150 (0.7)
Subtotal, Carson Range (rounded)							
	14,300		27,900 (23)	14,000 (12)	9,900 (8.3)	36	3,500 (2.9)
Subtotal Pine Nut Mountains 11e							
	78,200	Buckeye Creek	58,300 (8.9)	51,500 (7.9)	800 (0.1)	1	5,700 (0.9)
Total (rounded)							
	92,500		86,200 (11)	65,500 (8.5)	10,700 (1.4)	12	9,200 (1.2)

[1]Simulated using Fredricksburg Canyon index model because of small outcrop of metamorphic rocks near top of watershed.

Ground-Water Inflow Simulated from Watershed Models and Variation from Dry to Wet Conditions.

The simulated ground-water inflow from the perennial and ephemeral watersheds was combined with estimates of the infiltration of simulated ephemeral runoff to provide the total volumes of ground-water inflow to the basin-fill aquifers of Carson Valley from the Carson Range and Pine Nut Mountains (table 6). Application of the watershed models provides insight into the effect of climate variability on the water resources of Carson Valley. For this reason, ground-water inflow simulated from the watershed models was summarized for water years 1990–2002, for dry conditions during water years 1990–92, and for wet conditions during water years 1995–97 to show the variability in ground-water inflow.

Maurer and Berger (2007, p. 36) assumed all ephemeral runoff infiltrates the western alluvial fans and becomes ground-water inflow, supported by evidence that little ephemeral runoff from the Carson Range reaches the valley floor. Studies by Constantz and others (1994, p. 3261) in New Mexico, and Ronan and others (1998, p. 2142) in Eagle Valley, Nev., show that 4 to 6 percent of runoff from similar ephemeral streams is lost to evaporation and near-channel evapotranspiration. For this reason, the volumes of simulated ephemeral runoff that were assumed to infiltrate and become ground-water inflow were decreased by 5 percent. During extreme runoff events, some runoff likely reaches the valley floor. However, such events are rare and runoff reaching the valley floor is assumed to be a small percentage of mean annual runoff, and can be neglected.

Table 6. Mean annual ground-water inflow to basin-fill deposits of Carson Valley simulated with watershed models, water years 1990–2002, and compared with mean annual inflow simulated during dry conditions, water years 1990–92, and wet conditions, water years 1995–97, Nevada and California.

{Values are rounded to two significant figures. **Mean annual ground-water inflow, dry conditions**: If MAG is mean annual ground-water inflow, percent difference calculated as 100*(MAG$_{\text{dry conditions}}$–MAG$_{1990–2002}$/MAG$_{1990–2002}$; **wet conditons:** If MAG is mean annual ground-water inflow, percent difference calculated as 100*(MAG$_{\text{wet conditions}}$–MAG$_{1990–2002}$/MAG$_{1990–2002}$. **Abbreviations**: acre-ft, acre-feet]

Ground-water inflow source	Simulated mean annual ground-water inflow: Water years 1990–2002 (acre-feet)	Dry conditions, water years 1990–92 (acre-ft)	Dry conditions, water years 1990–92 (Percent difference)	Wet conditions, water years 1995–97 (acre-ft)	Wet conditions, water years 1995–97 (Percent difference)
Carson Range					
Ground-water inflow from watersheds					
Perennial	[1]6,200	3,400	-45	9,900	60
Ephemeral	[2]3,500	1,200	-66	5,200	49
Infiltration of ephemeral runoff	[3]9,400	2,600	-72	17,000	81
Subtotal (rounded)	19,000	7,200	-62	32,000	68
Pine Nut Mountains					
Ground-water inflow from watersheds					
Perennial	[1]8,200	100	-99	21,000	156
Ephemeral	[2]5,700	0	-100	18,000	216
Infiltration of ephemeral runoff	[4]2,100	470	-78	4,800	128
Subtotal (rounded)	16,000	570	-96	44,000	175
Total for Carson Range and Pine Nut Mountains					
Total (rounded)	35,000	7,800	-78	76,000	117

[1] From table 4.

[2] From table 5.

[3] From table 5, simulated mean annual ephemeral runoff, 9,900 acre-ft, less 5 percent loss to evapotranspiration, 500 acre-ft.

[4] From table 5, plus runoff of Pine Nut and Buckeye Creeks, less 5 percent loss to evapotranspiration.

Variability in ground-water recharge to basin-fill aquifers of Carson Valley reflects the year-to-year differences in climatic conditions. Quantifying potential changes in ground-water recharge during wet and dry hydrologic conditions is useful for estimating the ground-water and surface-water response to changing conditions, as well as for evaluating the hypothetical effects of long-term climate change on ground-water inflow to Carson Valley if annual precipitation is reduced. The mean annual ground-water inflow to basin-fill aquifers of Carson Valley simulated by the watersheds models for water years 1990–2002 was 35,000 acre-ft, with 19,000 acre-ft from the Carson Range and 16,000 acre-ft from the Pine Nut Mountains (table 6). Simulated mean annual ground-water inflow varied an order of magnitude, from 7,800 acre-ft during dry conditions (water years 1990–92), to 76,000 acre-ft during wet conditions (1995–97). The variation in ground-water inflow from dry to wet conditions is less in the Carson Range than the Pine Nut Mountains.

The large variability in ground-water inflow indicates that the annual volume of this source of recharge to basin-fill aquifers of Carson Valley depends greatly on climate. Knowledge of the potential range in ground-water inflow from wet to dry conditions is useful in developing drought-mitigation plans by water managers. Long-term climate changes that reduce the amount of annual precipitation have the potential to greatly affect ground-water inflow to the basin-fill aquifers of Carson Valley.

Uncertainty in Estimates of Simulated Ground-Water Inflow

A major source of uncertainty in the estimates of ground-water inflow simulated by the watershed models was the selection of index models for the ephemeral watersheds of the Carson Range. For the ephemeral watersheds where runoff has not been measured, bedrock type was the only basis for index model selection. Therefore, simulated runoff could not be verified. The uncertainty in ground-water inflow from ungaged perennial watersheds from index model selection was considered much less because model parameters were adjusted to match the reconstructed runoff from each watershed. The uncertainty in ground-water inflow and runoff from the area of ephemeral runoff on the eastern side of the valley (watershed 11e, fig. 3) also is considered small because the Buckeye Creek index model represents an area with surficial geology similar to that of the area of ephemeral runoff.

The uncertainty involved with selection of the appropriate index model for ephemeral watersheds was evaluated by applying the mean annual unit-area rates obtained for watersheds modeled with each index model type to the entire area of ephemeral runoff from the Carson Range (table 7). The index models developed for the Daggett Creek and Fredericksburg Canyon watersheds may be viewed as end-members for estimates of ground-water inflow and ephemeral runoff from the Carson Range.

The mean annual unit-area values for runoff and ground-water inflow from the combined area of ephemeral watersheds of the Carson Range were 10.5 and 0.3 in., respectively for watersheds using the Fredericksburg Canyon index model, and 5.8 and 6.2 in., respectively for watersheds using the Daggett Creek index model (table 7). Applying these unit-area values to the entire area of all ephemeral watersheds, 14,300 acres, results in volumes of mean annual runoff ranging from 6,900 to 12,500 acre-ft, and volumes of mean annual ground-water inflow ranging from 400 to 7,400 acre-ft.

The potential range of ground-water inflow from the Carson Range can be assessed by substituting the low- and high-range values from the uncertainty analysis for ephemeral watersheds of the Carson Range in table 6. The resulting totals for annual ground-water inflow, after reducing the range in ephemeral runoff by 5 percent for evapotranspiration losses, range from 13,000 to 26,000 acre-ft. This range is considerably less than the range in annual ground-water inflow from dry to wet conditions, 7,200 to 32,000 acre-ft.

Watersheds of the Carson Range underlain by metamorphic rocks had runoff efficiencies of 38 to 45 percent, with the exception of Sierra Canyon (table 1). With the exceptions of the anomalous high-runoff-efficiency watersheds of Mott Canyon, Monument Creek, and Sheridan Creek, and the anomalous low-runoff efficiency watershed of Stutler Canyon, watersheds underlain by granitic rocks had runoff efficiencies of 21 to 31 percent. Thus, bedrock type appears to affect hydrologic processes controlling runoff and ground-water inflow to the basin-fill deposits of Carson Valley. For this reason, the volumes simulated for ephemeral watersheds of the Carson Range using the index model selected on the basis of bedrock type is considered to be the best and most reasonable estimate.

Table 7. Potential range in estimates of runoff and ground-water inflow to basin-fill aquifers of Carson Valley from ephemeral watersheds of the Carson Range, Nevada and California.

[Values in inches are volumes in acre-feet, divided by watershed area, in acres, multiplied by 12. **Simulated mean annual runoff:** Values may not match presented values due to rounding. **Simulated mean annual ground-water inflow:** Ground-water inflow defined as ground-water inflow to basin-fill sediments of Carson Valley. **Abbreviations:** acre-ft, acre-feet; in., inch]

Watershed and index model	Drainage area (acres, rounded)	Simulated mean annual			
		Runoff		Ground-water inflow	
		(acre-ft)	(in.)	(acre-ft)	(in.)
All ephemeral watersheds[1]	14,300	9,900	[2]8.3	3,500	[2]2.9
Ephemeral watersheds using Fredericksburg Canyon index model[1]	7,900	6,900	[2]10.5	200	[2]0.3
Ephemeral watersheds using Daggett Creek index model[1]	6,400	3,100	[2]5.8	3,300	[2]6.2
All ephemeral watersheds using unit-area rates for Fredericksburg Canyon index watersheds	14,300	[3]12,500	10.5	[3]400	0.3
All ephemeral watersheds using unit-area rates for Daggett Creek index watersheds	14,300	[4]6,900	5.8	[4]7,400	6.2

[1]From table 5.

[2] Unit-area runoff and ground-water inflow, calculated by dividing runoff or ground-water inflow, in acre-feet, by drainage area, in acres, and multiplying by 12.

[3] Calculated by dividing unit-area runoff and ground-water inflow for ephemeral watershed models using Fredericksburg canyon index model by 12, and multiplying by drainage area, in acres.

[4] Calculated from unit-area runoff and ground-water inflow for ephemeral watershed models using Daggett Creek index model by 12, and multiplying by drainage area, in acres.

Ground-Water Inflow Simulated from Watershed Models Compared with Previous Estimates

Ground-water inflow and ephemeral runoff simulated using the watershed models of the Carson Range and Pine Nut Mountains were combined with previous estimates of ground-water inflow to the northern part of Carson Valley, and ground-water recharge from precipitation on the western alluvial fans and eolian sand and gravel deposits made by Maurer and Berger (2007), for comparison with the previous estimates of ground-water inflow. The estimates for ground-water inflow and runoff from ephemeral watersheds of the Carson Range using index models selected on the basis of bedrock type, as described above, were used in calculating the totals.

Mean annual ground-water inflow to the basin-fill deposits of Carson Valley from the Carson Range simulated from the ephemeral and perennial watersheds totals 20,000 acre-ft. The volume of 20,000 acre-ft is 7,000 acre-ft less than the estimate obtained from the chloride-balance method and almost double the estimate from the water-yield method (table 8). Inflow simulated from the Pine Nut Mountains and the eastern alluvial fans was 16,000 acre-ft, which is almost 50 percent greater than the 11,000 acre-ft estimated from the chloride-balance method. For both the Carson Range and the Pine Nut Mountains, the estimates of ground-water inflow simulated from the watershed models were considerably greater than the estimate obtained using the water-yield method. This is in part because the models simulated greater volumes of ground-water inflow from the perennial watersheds, and in part because the models indicate that ground-water inflow does take place from the ephemeral watersheds, which was assumed to be negligible by Maurer and Berger (2007, p. 31).

Maurer and others (2007, p. 28) used soil-chloride data to determine that ground-water recharge from precipitation was not taking place on the eastern side of Carson Valley. However, the soil-chloride data were collected only near the tops of hills in the area of ephemeral runoff, and not in ephemeral stream channels. The soil-chloride data and watershed modeling results suggest ground-water inflow estimated from watershed 11e likely is derived from infiltration of runoff beneath ephemeral stream channels.

The total mean annual ground-water inflow simulated from the watershed models for Carson Valley was 38,000 acre-ft, similar to the volume obtained from the chloride-balance method, 40,000 acre-ft.

Table 8. Estimates of mean annual ground-water inflow to basin-fill aquifers of Carson Valley using water-yield and chloride-balance methods by Maurer and Berger (2007) and simulated with watershed models of this study, Nevada and California.

[**Mean annual ground-water inflow:** From yield and chloride-balance methods from Maurer and Berger (2007, p. 38); represents values estimated using precipitation estimates for 1971–2000, and runoff estimates for 1990–2002. **Abbreviations:** –, indicates information not available.]

Ground-water inflow source	Mean annual ground-water inflow (acre-feet)		
	Simulated with watershed models, water years 1990–2002	Water-yield method	Chloride-balance method
Northern Carson Valley			
Ground-water inflow from Eagle Valley[1]	1,450	1,450	1,450
Precipitation on eolian sand and gravel deposits	250	250	250
Subtotal (rounded)	1,700	1,700	1,700
Carson Range and western alluvial fans			
Precipitation on alluvial fans	500	500	–
Ground-water inflow from watersheds			
Perennial	[2]6,200	2,400	–
Ephemeral	[3]3,500	0	–
Infiltration of ephemeral runoff	[4]9,400	8,000	–
Subtotal (rounded)	20,000	11,000	27,000
Pine Nut Mountains and eastern alluvial fans			
Ground-water inflow from watersheds			
Perennial	[2]8,200	4,300	–
Ephemeral	[3]5,700	0	–
Infiltration of ephemeral runoff	[5]2,100	5,000	–
Subtotal (rounded)	16,000	9,300	11,000
Total for Carson Valley			
Total (rounded)	38,000	22,000	40,000

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

[2]From table 4.

[3]From table 5.

[4]From table 5, simulated mean annual ephemeral runoff, 9,900 acre-ft, less 5 percent loss to evapotranspiration, 500 acre-ft.

[5]From table 5, plus runoff of Buckeye and Pine Nut Creeks, less 5 percent loss to evapotranspiration.

Updated Ground-Water Budget for Basin-fill Aquifers of Carson Valley

An updated water budget for the basin-fill aquifers of Carson Valley was calculated using estimates of ground-water inflow and ephemeral runoff from the Carson Range and Pine Nut Mountains simulated from the watershed models, combined with estimates of other ground-water budget components made by Maurer and Berger (2007, p. 53). Estimates of mean annual ground-water inflow for water years 1990–2002 were assumed to be representative of water years 1990–2005, the period for which the other water-budget components were derived.

Mean annual ground-water recharge using ground-water inflow simulated from the watershed models ranged from 51,000 to 54,000 acre-ft (table 9). Estimates of mean annual ground-water discharge ranged from 44,000 to 47,000 acre-ft, including an increase of 3,000 acre-ft/yr from the previous estimate of net ground-water pumping by Maurer and Berger (2007, p. 42). Maurer and Berger (2007, p. 43) subtracted estimates of 3,000 acre-ft for return flow from ground water pumped for irrigation and for a U.S. Fish and Wildlife fish hatchery from total pumping for water years 1990–2005 to obtain estimates of net ground-water pumping. The return flow to irrigation ditches, however, is likely to be diverted further downstream in Carson Valley for irrigation. Thus, the return flow may effectively be removed from the hydrologic system prior to leaving Carson Valley and not be available for ground-water recharge. This is especially true during dry years when ground-water pumping for irrigation is greatest. For these reasons, estimates of net ground-water pumping for water years 1990–2005 were increased from the estimate made by Maurer and Berger (2007, p. 43; 15,000–18,000) by 3,000 acre-ft/yr, to range from 18,000 to 21,000 acre-ft.

Estimates of ground-water recharge using results of the watershed models were somewhat greater than estimates of ground-water discharge. The difference is likely because of the uncertainties in both estimates, rather than an actual difference between recharge and discharge. Estimates of ground-water

Table 9. Updated ground-water budget for basin-fill aquifers of Carson Valley using previous estimates by Maurer and Berger (2007), and estimates simulated from watershed models in this study, water years 1990–2005.

Source of ground-water recharge to and discharge from basin-fill aquifers of Carson Valley	Estimated mean annual volume (acre-feet)	
	Maurer and Berger (2007)	Current study
Ground-water recharge		
Ground-water inflow from Carson Range, Pine Nut Mountains, and Eagle Valley, and recharge from precipitation on alluvial fans eolian sand, and gravel deposits	[1]22,000 – 40,000	[2]38,000
Ground-water recharge from runoff of the Carson River	[1]10,000	[1]10,000
Secondary recharge of pumped ground water	[1]3,000 – 6,000	[1]3,000 – 6,000
Total	35,000 – 56,000	51,000 – 54,000
Ground-water discharge		
Ground-water evapotranspiration from phreatophytic and riparian vegetation and non-irrigated pasture grasses	[1]11,000	
Ground-water discharge to streamflow of the Carson River	[1]15,000	
Net ground-water pumping	[3]18,000 – 21,000	
Total	44,000 – 47,000	

[1]From Maurer and Berger (2007, p. 53).

[2]From table 8.

[3]From Maurer and Berger (2007, p. 42) with the addition of 3,000 acre-ft/yr assumed unavailable for ground-water recharge in this study. Includes domestic pumping in California portion of study area.

inflow simulated from the watershed models were in close agreement with those obtained from the chloride-balance method (table 8). This provides more confidence that the relatively independent estimates from the chloride-balance method and simulated values from the watershed models provide a reasonably accurate volume for estimates of ground-water recharge components. The two estimates are not completely independent, however, because they use the same distribution of annual precipitation. The chloride-balance method uses physical data on runoff and the chloride concentration of precipitation, runoff, and ground water; whereas the watershed models use physical data on vegetation, soils, and topography, and daily data on runoff and climate.

The estimate for mean annual ground-water recharge at the low end of the range, 51,000 acre-ft, is similar to the estimate for mean ground-water discharge at the high end of the range, 47,000 acre-ft (table 9). Thus, a mean annual volume of about 50,000 acre-ft is a reasonable estimate for ground-water recharge to and discharge from the basin-fill aquifers of Carson Valley.

Estimates of infiltrated ephemeral runoff and mean annual ground-water inflow from the mountains simulated using the watershed models vary over an order of magnitude from dry to wet conditions from 7,800 to 76,000 acre-ft, respectively (table 6). Ground-water inflow is only one component of recharge for the ground-water budget, although it is the largest in magnitude. Ground-water recharge from runoff of the Carson River would likely be greater in wet years and lesser in dry years, but the magnitude of change is uncertain. Secondary recharge or return flows of pumped ground water from municipal and domestic pumping would likely not change significantly from wet to dry years. During multi-year drought conditions, the watershed simulations indicate that ground-water recharge could be as much as 80 percent less than the mean annual volume of 50,000 acre-ft.

Summary and Conclusions

To address concerns over increased development in Carson Valley, the U.S. Geological Survey (USGS) recently made estimates of ground-water inflow to basin-fill aquifers of Carson Valley from the adjacent Carson Range and Pine Nut Mountains. Ground-water inflow was estimated to range from 22,000 acre-ft/yr using a water-yield method, to 40,000 acre-ft/yr using a chloride-balance method. Because of the relatively large range in these estimates, and uncertainties in each method, watershed models were developed for perennial watersheds of the Carson Range and Pine Nut Mountains to provide an independent estimate of ground-water inflow to Carson Valley

The model used for this study was the Precipitation-Runoff Modeling System (PRMS), a physically based, distributed-parameter model. A Geographic Information System (GIS) program, the Weasel Toolbox was used to manage spatial data and characterize model drainages and to develop HRUs.

Models were developed first for the four perennial watersheds having gaged daily mean runoff; Daggett Creek, Fredericksburg Canyon, Pine Nut Creek, and Buckeye Creek watersheds. Models were then developed for 10 ungaged perennial watersheds in the Carson Range using the models developed for either the Daggett Creek or the Fredericksburg Canyon watersheds as an index model. Selection of the gaged watershed to be used as an index model was based on similarity between the major bedrock type and the percentage of precipitation that becomes runoff in each watershed. Finally, models were developed for 10 ephemeral watersheds in the Carson Range and a large area of ephemeral runoff near the Pine Nut Mountains to estimate the quantity of ephemeral runoff tributary to Carson Valley and the potential for ground-water inflow from ephemeral watersheds. Because the ephemeral runoff is uncertain, selection of the index model was based only on the bedrock type underlying the ephemeral watershed. The Buckeye Creek watershed model was used as an index model for the area of ephemeral runoff near the Pine Nut Mountains because of the similarity of geologic units exposed in the two areas. Model calibration was constrained by daily mean flows for four gaged watersheds in Carson Valley and ten ungaged watersheds in the Carson Range estimated in a previous study. The models were further constrained by annual precipitation volumes estimated in a previous study to provide estimates of ground-water inflow using similar water input.

The calibration periods were water years 1990–2002 for watersheds in the Carson Range, the period for which reconstructed runoff was available for ungaged perennial watersheds, and water years 1981–97 for Pine Nut Creek and Buckeye Creek watersheds. Simulations for water years 1990–2002 were then made using the calibrated models for Pine Nut Creek and Buckeye Creek watersheds to obtain daily mean values for the 1990–2002 period.

The watershed models were affected by the assumption that the ungaged perennial and ephemeral watersheds are hydrologically similar to the index watersheds, the scale of available soil data, the adequacy of available climate data and accuracy of precipitation estimates using the linear-relations, and the accuracy of the reconstructed daily mean runoff used for calibration of the ungaged perennial watersheds.

The error of the resulting models was determined for watersheds having gaged runoff data. Mean annual bias for the period of record for Daggett Creek and Fredericksburg Canyon watersheds was negligible, relative error was about 6 and 12 percent, respectively, and RMSE was about 1 and 6 in., respectively. A satisfactory overall fit was obtained between simulated and measured runoff for Daggett Creek for the 1993–98 period of high runoff (and periods of higher ground-water inflow); however, runoff is underestimated for the drier years (1990–92, 1994).

Overall, mean annual water budget volumes indicate that the Daggett Creek and Fredericksburg Canyon watershed model simulations are in agreement with previous estimates for the 1990–2002 period. The mean annual runoff efficiency using the simulated runoff and simulated precipitation was 20 percent for Daggett Creek watershed and 45 percent for Fredericksburg Canyon watershed, both comparable to the efficiency calculated with the measured flow. With the exception of the April–June season, calibration statistics for the seasonal aggregates are considered satisfactory for both the Daggett Creek and Fredericksburg Canyon watershed simulations.

Error for the period of record for the Pine Nut and Buckeye Creek watersheds was greater, in part due to the sensitivity of the calibration statistic for days with zero and low runoff whereby differences in runoff were assigned a large relative error. In addition, the spatial and temporal distribution of precipitation on the east side of Carson Valley may not be adequately represented due to the more localized nature of storm events, and the lack of high-altitude precipitation data. The mean annual runoff efficiency for the 1990–2002 period using the simulated runoff and simulated precipitation was 2 percent for Pine Nut Creek and 2 percent for Buckeye Creek, both comparable to the efficiency calculated with measured flow.

The Pine Nut Creek watershed model underestimates runoff for all but the wet years in the latter part of the record, while adequately simulating the bulk of spring runoff for most years. The Pine Nut Creek watershed model has a large negative bias, and under-estimates mean annual runoff on average by 11 percent. Overall. the simulated hydrograph for Buckeye Creek indicates a much quicker response to precipitation than measured at the gage and the Buckeye Creek model tends to over-estimate runoff. For water years 1981–97, the mean annual error is about –5 percent when water year 1994 is removed. For the February–April period, the Buckeye Creek model has a large negative bias and 5 percent relative error. The bias and error of the calibrated models are within generally accepted limits for watershed models, indicating the simulated rates and volumes of runoff and ground-water inflow are reasonable.

The daily mean values of precipitation, runoff, ET, and ground-water inflow simulated from the watershed models were summed to provide annual mean rates and volumes for each year of the simulations, and mean annual rates and volumes for water years 1990–2002. Daily mean and annual mean simulated runoff matched measured or reconstructed runoff reasonably well for most watersheds, with the exceptions of Monument Canyon, Sheridan Creek, and Jobs Canyon. The difference between mean annual simulated and measured or reconstructed runoff was 11 percent or less, also with the exceptions of Monument Creek, Sheridan Creek, and Jobs Canyon.

Model results were consistent with a previous study, in that no subsurface flow was simulated from Mott Canyon, Monument Creek, and Sheridan Creek watersheds, and subsurface flow may be taking place from the Stutler Canyon to the Sheridan Creek watershed. However, the watershed models simulated ground-water inflow from the Water Canyon and Fredericksburg Canyon watersheds, and ground-water inflow from ephemeral watersheds in the Carson Range and Pine Nut Mountains. The simulated mean annual volume of ground-water inflow for the 14 perennial watersheds totaled 14,400 acre-ft. The annual ground-water inflow simulated from the 10 ephemeral watersheds of the Carson Range totaled 3,500 acre-ft, whereas a previous study assumed ground-water inflow from ephemeral watersheds of the Carson Range was negligible. Simulated ground-water inflow from the ephemeral watershed near the Pine Nut Mountains was 5,700 acre-ft.

Simulated mean annual runoff rates ranged from about 5 to 7 inches for ephemeral watersheds using Daggett Creek as an index station and from 9 to 13 inches for ephemeral watersheds using Fredericksburg Canyon as an index station. Mean annual ephemeral runoff from the Carson Range simulated from the models totaled 9,900 acre-feet. For the area of ephemeral runoff near the Pine Nut Mountains, the mean annual ephemeral runoff rate simulated from the model was 0.1 inch for a total runoff of 800 acre-feet.

The mean annual ground-water inflow to basin-fill aquifers of Carson Valley from the Carson Range and the Pine Nut Mountains simulated by the watersheds models for water years 1990–2002 was 35,000 acre-feet, with 19,000 acre-feet from the Carson Range and 16,000 acre-feet from the Pine Nut Mountains. The simulated mean annual inflow varied over an order of magnitude, from 7,800 acre-feet during dry conditions (water years 1990–92), to 76,000 acre-feet during wet conditions (1995–97).

The uncertainty in simulated annual runoff and ground-water inflow from ephemeral watersheds of the Carson Range caused by selection of the index model ranged from 13,000 to 26,000 acre-feet, considerably less than the range from dry to wet conditions. Because bedrock type appears to affect the volumes of runoff and ground-water inflow from gaged and ungaged perennial watersheds, volumes simulated for the ephemeral watersheds using the appropriate index model were considered to be the best and most reasonable estimate.

Total mean annual ground-water inflow simulated by the models is 38,000 acre-feet with the addition of ground-water inflow from Eagle Valley and recharge from precipitation on eolian sand and gravel deposits, 1,700 acre-feet, and ground-water recharge from precipitation on the western alluvial fans, 500 acre-feet. The estimate of 38,000 acre-feet for mean annual ground-water inflow simulated from the watershed models, was in close agreement with that obtained from the chloride-balance method, 40,000 acre-feet, but was considerably greater than the estimate obtained from the water-yield method, 22,000 acre-feet from a previous study. The similar estimates obtained from the watershed models and chloride-balance method, two relatively independent methods, provide more confidence that they represent a reasonably accurate volume of mean annual ground-water inflow to

Carson Valley. However, the two estimates are not completely independent because they use the same distribution of annual precipitation.

Annual ground-water recharge of the basin-fill aquifers in Carson Valley ranged from 51,000 to 54,000 acre-feet using estimates of ground-water inflow to Carson Valley simulated from the watershed models combined with estimates of other ground-water budget components from a previous study. Estimates of mean annual ground-water discharge ranged from 44,000 to 47,000 acre-feet, including an increase of 3,000 acre-ft/yr in the amount of net ground-water pumping from the estimate in a previous study.

The low range estimate for ground-water recharge, 51,000 acre-feet per year, is most similar to the high range estimate for ground-water discharge, 47,000 acre-feet per year. Thus, an average annual volume of about 50,000 acre-feet is a reasonable estimate for mean annual ground-water recharge to and discharge from the basin-fill aquifers in Carson Valley. However, the results of watershed models indicate that significant interannual variability in the volumes of ground-water inflow is caused by climate variations. During multi-year drought conditions, the watershed simulations indicate that ground-water recharge could be as much as 80 percent less than the mean annual volume of 50,000 acre-feet per year.

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For more information contact:
Director, Nevada Water Science Center
U.S. Geological Survey
2730 N. Deer Run Road
Carson City, Nevada 89701
http://nevada.usgs.gov

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