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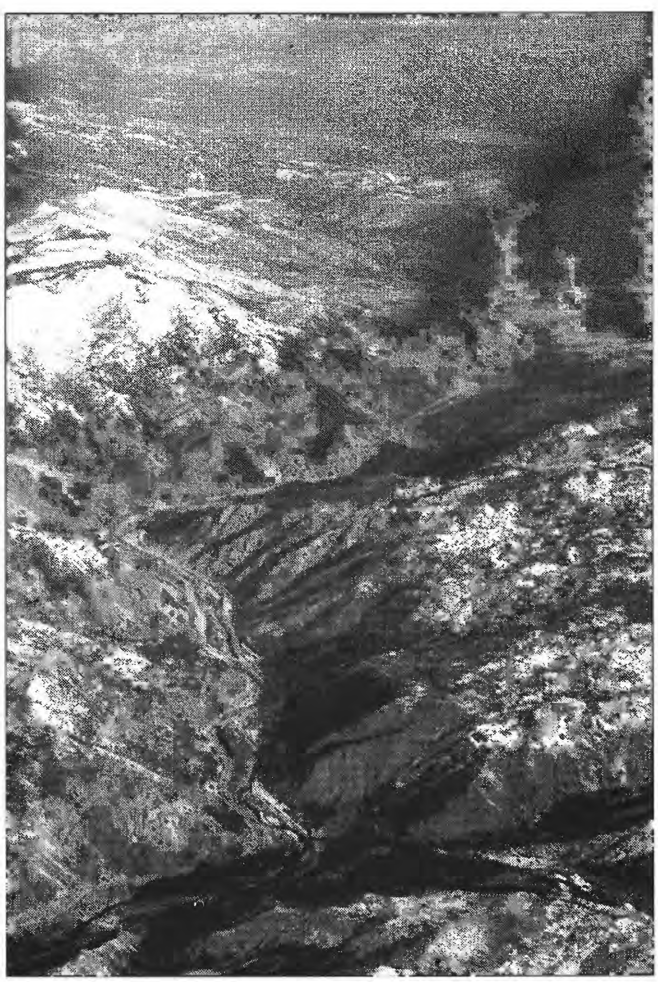
Truckee-Carson Program

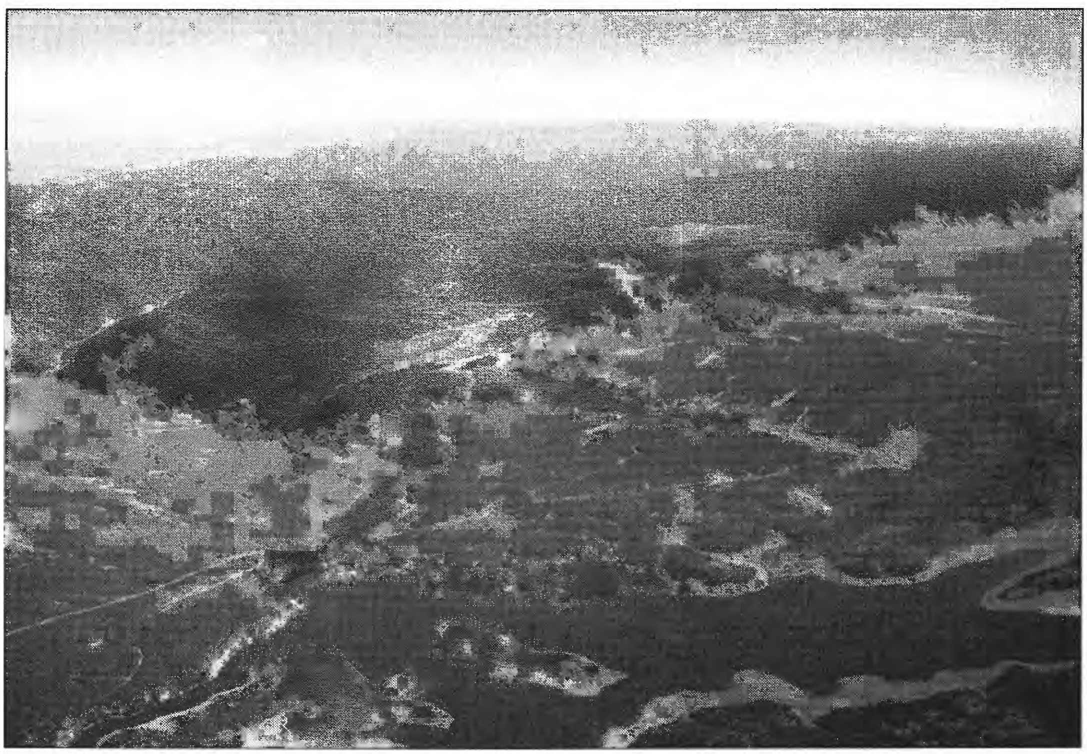
Precipitation-Runoff Simulations for the Upper Part of the Truckee River Basin, California and Nevada

Water-Resources Investigations Report 99-4282



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

PHOTOGRAPH ON FRONT COVER: Northward aerial view of steep-sided Truckee River canyon near California-Nevada state line, December 20, 1997. River flows eastward (from left to right at bottom of view), then northward, then eastward toward Reno (near top of view). Steep-gradient Gray and Bronco Creeks feed into river near lower left and lower right corners of photograph. Farad streamflow gage (station 20 in fig. 1 and table 1) is near northeastward bend of river at left center of view; streamflow was 406 cubic feet per second on December 20. Photograph by A.S. VanDenburgh, U.S. Geological Survey.



A.S. Van Denburgh, U.S. Geological Survey

PHOTOGRAPH ABOVE: Southward aerial view of principal reservoirs north-northeast of Truckee, Calif. Stampede Reservoir, in foreground, and Boca Reservoir, farther south near center of view, are on Little Truckee River, which is a principal tributary to mainstem Truckee River. Prosser Creek Reservoir, west (to right) of Boca Reservoir, also is tributary to mainstem. Northward reach of river in Truckee River canyon near California-Nevada state line (see cover photograph) is at far-left center of this view. Photograph was taken on August 14, 1994, several months before end of prolonged drought. As result, late-summer reservoir levels were lower than usual, exposing large areas of lake bottom. For example, contents of Stampede Reservoir on August 14, at about 71,000 acre-feet, were only 34 percent of comparable volume on same date in wetter-than-average 1995.

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By Anne E. Jeton

U.S. GEOLOGICAL SURVEY

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Truckee-Carson Program

Carson City, Nevada
2000

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
CHARLES G. GROAT, Director

For additional information contact:

District Chief
U.S. Geological Survey
333 West Nye Lane, Room 203
Carson City, NV 89706–0866

email: GS-W-NVpublic-info@usgs.gov

http://nevada.usgs.gov

Copies of this report can be purchased from:

U.S. Geological Survey
Information Services
Building 810
Box 25286, Federal Center
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CONVERSION FACTORS, VERTICAL DATUM, AND ACRONYMS

Multiply	By	To obtain
acre	4,047	square meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Temperature: Degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the formula °F = [1.8(°C)]+32. Degrees Fahrenheit can be converted to degrees Celsius by using the formula °C = 0.556(°F-32).

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

Water Year: Constitutes a 12-month period from October 1 through September 30, and is designated by the year in which the period ends (for example, water year 1995 began October 1, 1994, and ended September 30, 1995).

Acronyms:

AET — actual evapotranspiration
BOR — Bureau of Reclamation
DEM — Digital Elevation Model
DLG — Digital Line Graph
DRI — Desert Research Institute
ESP — Extended Streamflow Prediction
GIS — geographic information system
HRU — hydrologic response unit
HSPF — Hydrological Simulation Program-FORTRAN
MMS — Modular Modeling System
NRCS — Natural Resources Conservation Service
NWS — National Weather Service
PET — potential evapotranspiration
PIN — Pattern Identification Number
PRMS — Precipitation-Runoff Modeling System
RDB — Relational Data Base
RDBMS — Relational Data-Base Management System
SNOTEL — Snowpack Telemetry
TCP — Truckee-Carson Program
USGS — U.S. Geological Survey
USFS — U.S. Forest Service

Precipitation-Runoff Simulations for the Upper Part of the Truckee River Basin, California and Nevada

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ABSTRACT

The Truckee-Carson-Pyramid Lake Water Rights Settlement Act of 1990 provides a foundation for developing operating criteria for interstate allocation of water in the Truckee River and Carson River Basins of western Nevada and eastern California. The Truckee-Carson Program of the U.S. Geological Survey is assisting the U.S. Department of the Interior in implementing the Settlement Act by developing a modeling system to support water-resource planning and management. The U.S. Geological Survey's Precipitation-Runoff Modeling System (PRMS) was used to simulate streamflow from seven gaged subbasins, six reservoir catchments, and three ungaged areas in the upper Truckee River Basin. PRMS is a physically based, distributed-parameter watershed model designed to analyze the effects of precipitation, temperature, and land use on streamflow and general basin hydrology. Each subbasin was partitioned into hydrologically homogeneous subareas called hydrologic response units, or HRU's, whereby the physical properties affecting streamflow are quantified at the HRU level. A geographic information system, relational data-base software, and other computer programs were used to delineate HRU's, to assist in regionalizing model parameters, and to facilitate the construction of the 16 watershed models.

Results of modeling the gaged subbasins in general suggest satisfactory simulation at daily, monthly, and annual intervals, though there exists a bias in simulating runoff during the 1995-97 period. Bias in simulating daily mean runoff ranged from -6 to +4 percent for the calibration period and from -7 to +18 percent for the verification period; relative error ranged from -20 to +47 percent and from -6 to +41 percent for the calibration and verification periods, respectively. For the full modeling period, monthly mean runoff bias ranged from -4 to +5 percent, and relative error ranged from -21 to +17 percent. For the full modeling period, annual mean runoff bias ranged from -7 to +7 percent, and relative error ranged from -9 to +11 percent. Observed winter runoff (November through February) contributes, on average, from 15 to 30 percent of the annual runoff and is expressed as sharp, short duration runoff peaks. Most of these peaks were fairly well modeled, though runoff during years of below-average precipitation was often oversimulated. Spring runoff (April through June) typically ranges from 50 to 65 percent of the annual streamflow.

The ungaged areas and reservoir catchments were indexed to the gaged subbasins of closest geographic and hydroclimatic similarity for the purpose of transferring distributed and nondistributed parameters. HRU-distributed parameter values were generally transferable when physiographic conditions were similar. Nondistributed parameter values were transferable from the template subbasin when hydrogeologic conditions were assumed similar; otherwise, regionalized estimates were used. Modeling results indicated runoff simulations were sensitive to adjustments made to nondistributed, temperature-dependent parameters and the subsurface and ground-water flow-routing coefficients. These parameters in particular affect runoff timing for individual rain or snowmelt events, the shape of the baseflow recession part of the hydrograph, and overall seasonal distribution of runoff.

Streamflows for two of the ungaged areas along the main-stem of the Truckee River were also reconstructed using differences in flow from upstream and downstream gages. These reconstructed flows were unsatisfactory for comparative purposes due to the cumulative error associated with using several gaging station records. However, most of the ungaged areas are at low altitudes that are assumed to contribute little to snowmelt runoff.

No reliable daily inflow data were available to calibrate models for the reservoir catchment. Therefore, the models for these subbasins were constructed in a manner similar to the ungaged areas. Reservoir inflows were reconstructed using a water-balance approach. No statistical analyses were used in

comparing the reconstructed inflows to the PRMS simulated inflows due to the uncertainty in the reservoir-surface precipitation and evaporation components of the water balance. Graphical analyses of monthly reconstructed reservoir inflows and simulated inflows indicate satisfactory correspondence between the two data sets.

INTRODUCTION

Water use and allocation in the Truckee River Basin have been the source of conflict for several decades among the various municipal, industrial, agricultural, and environmental interests in the region. In general, the demand for water commonly is greater than can be supplied—the timing of demands and inadequate storage often result in an apparent water shortage. Truckee River water is used for generating power upstream from the Reno-Sparks vicinity, irrigating in both the Truckee River and the Carson River Basins, maintaining Pyramid Lake levels (the terminus of the Truckee River), and providing spawning flows for the endangered Cui-ui lakesucker and the threatened Lahontan cutthroat trout.

Rapid growth since the 1980's in the urban centers of Reno and Sparks has increased municipal and industrial water demand, which often is met by the acquisition and conversion of water rights previously used for irrigation. Insufficient storage combined with droughts lasting more than 2 years can result in significant shortages of water for irrigation and municipal use and may stress fish and wildlife ecosystems.

Decades of litigation culminated in the enactment of the Truckee-Carson-Pyramid Lake Water Rights Settlement Act of 1990 (Title II of Public Law (P.L.) 101-618). The law provides a foundation for developing an operating criteria for interstate allocation of water in the 7,000-mi^2 Truckee River and Carson River Basins of western Nevada and eastern California. The interdependence of many of the water-management issues of the Truckee River Basin, such as allocation of streamflow and maintenance of instream water-quality standards, suggests a strong need for an overall data-management and modeling system within which individual issues can be addressed in an efficient and coordinated manner. Such a system needs to be interbasin in scope, addressing the interrelated water-management issues of the Truckee and Carson River systems. Efficient implementation of the planning, management, and environmental requirements of the law requires detailed water-resources data and analytical computer models. These models can help assess effects of alternative management and operational scenarios related to Truckee River operations, water-rights transfers, and changes in irrigation practices. The Truckee-Carson Program (TCP) of the U.S. Geological Survey (USGS) is assisting the U.S. Department of the Interior in implementing the Truckee River Operations Agreement, a major component of the Settlement Act. The program has the following objectives:

- Consolidate streamflow and water-quality data from several agencies into a single database. Establish new streamflow and water-quality gaging stations for more complete water-resources information.
- Construct interbasin hydrologic computer models to support water-resources planning, management, and allocation. Develop a modeling system that includes simulations of precipitation-runoff, river flow-routing, water temperature, water-quality for selected constituents, and river-management operations.

Existing management models for the Truckee River are accounting-type models which have a monthly computation interval. The USGS modeling system developed for TCP has a daily time-step, thus allowing for finer resolution of hydrologic processes and river-management practices. The program chosen for the mainstem flow-routing model and the operations/allocation model of the Truckee River is the Hydrological Simulation Program-FORTRAN (HSPF) developed by Bicknell and others (1993). HSPF was selected primarily because it can simulate the hydraulics of complex natural and man-made drainage networks, it can account for channel inflows and diversions and reservoir operations, and it can simulate certain water-quality processes. The Truckee River is regulated by several reservoirs on tributaries upstream from the USGS gaging station at Farad, Calif. (fig. 1). The remaining perennial tributaries that are unregulated are also ungaged. The requirements of the river/reservoir operations model for (1) streamflow at ungaged sites, (2) extended streamflow records at gaged sites, and (3) forecasted inflows at many locations, prompted the development of precipitation-runoff models for designated subbasins in the Truckee River Basin.

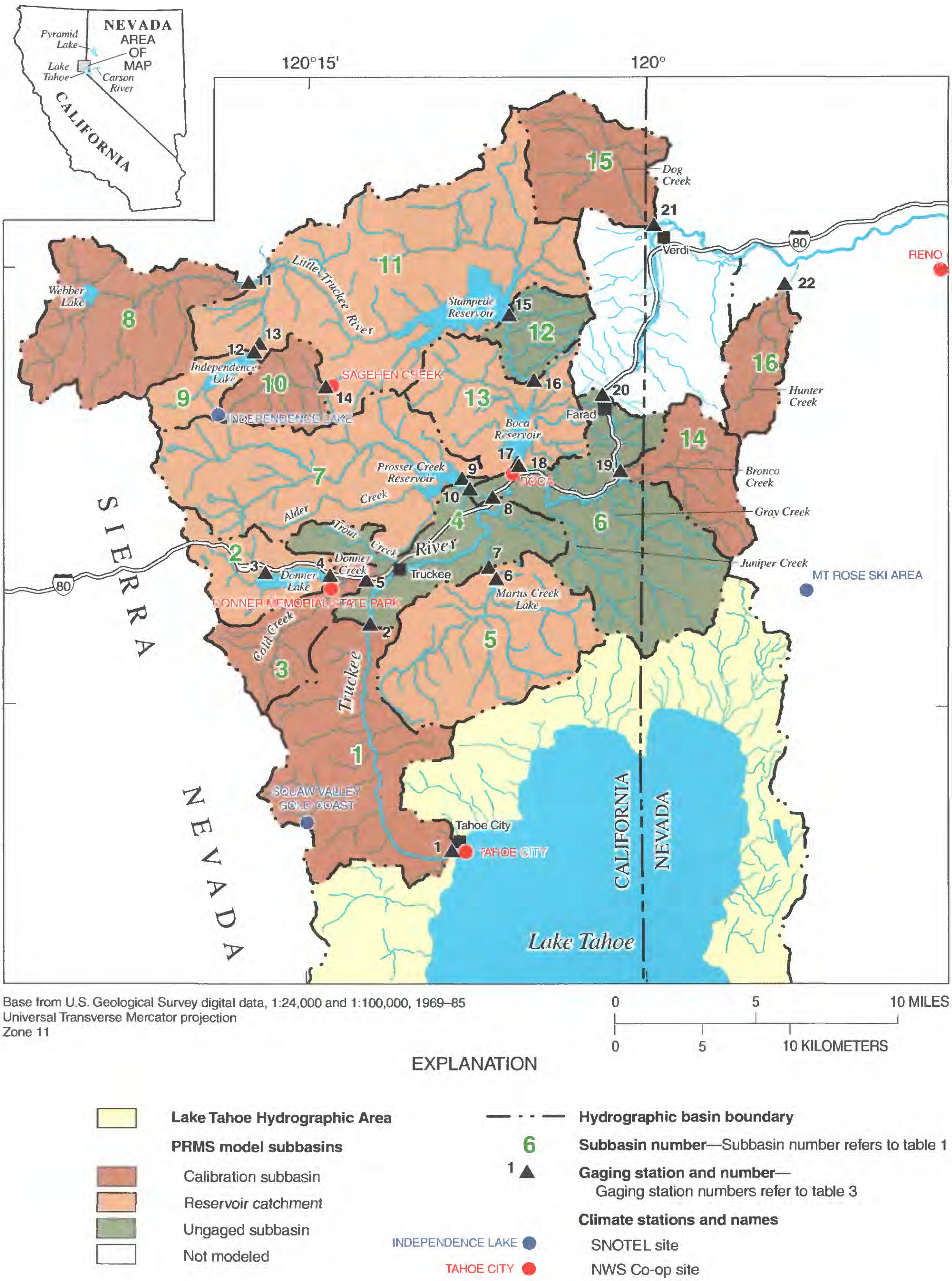

Figure 1. Meteorological sites, gaged and ungaged subbasins, and streamflow data collection sites used for watershed models, and selected hydrologic features, upper Truckee River Basin, California and Nevada.

Statistical forecast models do not explicitly incorporate the physical mechanisms and spatial-temporal detail of watershed processes and thus may not adequately describe hydrologic responses to wide ranges of climate conditions and watershed modifications. Hydrologic components of lumped-parameter watershed models generate monthly and annual water budgets that may be too simplified to model all aspects required in the Truckee River Operating Agreement. Thus, a more physically-based hydrologic model is needed to simulate interrelated hydrologic processes in greater spatial-temporal detail. HSPF has its own precipitation-runoff module for simulating runoff from catchment areas; however, to be compatible with earlier work on the Carson River Basin (Jeton and others, 1996) the USGS PRMS (Leavesley and others, 1983) was selected as the watershed model. Total tributary inflow to Lake Tahoe was simulated using PRMS models developed for gaged and ungaged tributaries (Jeton, 1999). The approach developed in this earlier study utilized a geographic information system of digital physiographic data to define watershed characteristics, and relational data-base programs to facilitate the development of PRMS models for ungaged areas and reservoir catchments in the upper Truckee River Basin. This methodology served as the template for modeling subbasins discussed in this report. Both HSPF and PRMS are well documented, technically supported, and available within the public domain.

Previous Studies

The physical and chemical characteristics of the Truckee River have been modeled by numerous investigators, though few studies have modeled precipitation-runoff relations in the tributaries and reservoir catchment areas. A review of water quality studies is provided by Taylor (1998, p. 4). The Desert Research Institute (DRI) at the University of Nevada, Reno, developed a model that simulates Truckee River flows using historical and reconstructed monthly streamflow data (Butcher and others, 1969); Gupta and Afaq (1974) also from DRI, constructed a flow model of the Truckee River from Tahoe City, Calif., to Nixon, Nev., (near the terminus at Pyramid Lake) requiring hourly data to simulate individual runoff peaks and floods. Matthai (1974) evaluated the reliability of streamflow records in the Truckee River Basin and determined a long-term annual runoff volume based on data from 1900 to 1973. Blodgett and others (1984) estimated daily mean discharge for water years 1944-80 using regression analysis for discontinuous-record tributaries and water-budget methods for reservoirs outflow and regulated tributaries.

The Bureau of Reclamation (BOR) constructed a mass-balance model to analyze both the operation of reservoirs and the allocation of water within the Truckee and Carson River Basins (Cobb and others, 1990). The BOR model was later modified by consultants for Sierra Pacific Power Company to include water-management alternatives. The current database for the BOR model consists of monthly data from 1901 to 1997. Both models are monthly accounting-type models in contrast to the more physically based model developed by Berris (1996) as part of the Truckee-Carson Program suite of hydrologic models.

Berris' flow-routing model for the Truckee River required continuous, daily streamflow time series data as input to the numerous drainage network segments, known as "reaches." Records for discontinuous or intermittent streamflow data were estimated by hydrographic comparison (comparing the shapes of hydrographs between stations) or by water-balance computations. Ungaged tributary inflows to the Truckee River were estimated using regression equations developed for each month and apportioned to each model reach according to intervening ungaged drainage areas.

Earlier modeling studies by Jeton and Smith (1993) and Jeton and others (1996) provided the techniques used in this study. Jeton's more recent study (1999) enhanced these techniques further to model multiple subbasins. Tributary inflow to Lake Tahoe was modeled using PRMS for nine gaged tributaries and aggregating the remaining ungaged drainage areas into five subbasins. Physiographic watershed characteristics were defined with HRU's using a geographic information system (GIS) of natural resources spatial data. Calibrated model parameters were regionalized where appropriate, by transferring them to the ungaged subbasins. Modeling results for the gaged subbasins indicated satisfactory results for daily, monthly, and annual simulations; however, roughly 50 percent of the Lake Tahoe Basin inflow is estimated to be from the ungaged areas. Error for the ungaged areas was estimated from the error associated with the index (calibrated) subbasins from which the parameter values were obtained. In simulating lake storage, deviations from observed storage levels result when there is bias in one or more of the lake water-budget components over extended periods. Differences between the observed and simulated storage traces shown were not caused by errors (bias) in inflow alone, but may have been exacerbated or compensated by errors associated with the evaporation and precipitation components of the water budgets.

Ryan (1996) also used PRMS and a GIS for modeling the Upper Gunnison River Basin in western Colorado. Outflow from the calibrated subbasins were routed using a flow-routing module developed by Ryan. This allowed for multiple subbasins to be calibrated during one model run as outflow from the upper subbasins were systematically included as inflow to the downstream subbasins. The calibrated Gunnison River Basin model was then used in a climate change analysis and as a forecast tool for a real-time operations model using the extended streamflow prediction (ESP) and real-time meteorologic data.

Purpose and Scope

The purposes of this report are (1) to describe the data and methods used in the construction of daily precipitation-runoff simulation models for the gaged and ungaged subbasins, (2) to describe the calibration and verification of the model and provide an error analysis, (3) to discuss the differences in observed and simulated streamflow for gaged subbasins and for the reconstructed reservoir inflows and simulated inflows, and (4) to discuss the limitations of these models. The scope of this report includes analysis of the Truckee River mainstem and tributaries from near the USGS gaging station at Tahoe City, just downstream from the Lake Tahoe Dam to the USGS gaging station at Farad, Calif. (hereafter referred to as the Farad gaging station), located upstream from the California-Nevada State line (fig. 1). Two other tributaries to the Truckee River, Dog Creek and Hunter Creek, located downstream from the Farad station, are included (fig. 1). The period of streamflow and climatic data used to provide input to the models and for comparison of simulated to observed flow values varied depending on when data were available. The longest period of record was from October 1980 to September 1997, and the shortest record was from April 1993 to September 1997. Where possible, the periods of record selected for calibration best represented the range of dry to wet years. Typically, the verification years represent a similar range of climate conditions; however, for most of the subbasins the availability of observed streamflow data limited the verification period to 1995-97, an abnormally wet period. The reservoir catchments were modeled for the period from October 1980 to September 1996, with the exception of Stampede Reservoir, which has a shorter period (October 1993 to September 1996) due to a limited period of record for tributary inflow.

Description of Study Area

The Truckee River headwaters are in the Sierra Nevada in California, at altitudes ranging from 4,500 ft to above 10,000 ft above sea level. The headwaters of the Truckee River flow into Lake Tahoe, a 192-mi^2 water body surrounded by mountainous topography that creates a steeply sloping, bowl-shaped basin. The only outlet (other than lake-surface evaporation) from the lake is the Truckee River, which begins near Tahoe City, Calif., and flows generally to the northeast approximately 120 mi to its terminus at Pyramid Lake, a topographically-closed desert lake in the Basin and Range physiographic province of western Nevada. Outflow is regulated by a dam at Tahoe City, operational since 1874, which controls about 744,600 acre-ft of lake water by regulating the lake surface altitude between 6,223.0 and 6,229.1 ft, Bureau of Reclamation datum. Drainage area for the entire Truckee River Basin is about 3,120 mi^2, but only about 1,430 mi^2 contribute flow to the 117-mi length of the Truckee River between the outlet of Lake Tahoe and its mouth at Pyramid Lake. Most of the runoff and perennial flow to the Truckee River originates from tributaries and regulated reservoir outflow upstream from the Farad gaging station.

For the flow-routing study (Berris, 1996), the Truckee River Basin was divided into three hydrologic subunits, the upper, middle, and lower Truckee River. These subunits were delineated on the basis of similarity in streamflow characteristics, physiography, human activities, and water quality. The upper Truckee River subunit described in the flow-routing study encompasses most of the study area described in this report (hereafter referred to as the upper Truckee River Basin). In addition to the Dog and Hunter Creek drainage areas that drain into the Truckee River near Verdi and Reno, respectively, the upper Truckee River Basin includes the 426-mi^2 drainage area of the Truckee River between the outlet of Lake Tahoe at Tahoe City dam and the USGS gaging station at Farad. The length of the Truckee River within this subunit is 34 mi.

Streamflow is regulated by six impoundments—Donner Lake, Martis Creek Lake, Prosser Creek Reservoir, Independence Lake, Stampede Reservoir and Boca Reservoir—on tributary streams and a dam on Lake Tahoe at its spillway to the Truckee River, with a capacity to regulate 6.1 ft of lake elevation change on the lake. These lakes and reservoirs were impounded for irrigation, public supply, flood control, enhancement of fish habitat, hydropower, and recreational purposes.

Truckee River flows depend heavily on the yearly snowpack of the Sierra Nevada, which, in addition to Lake Tahoe outflows, supplies most of the water to the Truckee River system. High flows in the Truckee River result either as a response from snowmelt when temperatures increase in late spring or early summer or as a direct response to large, warm rainfalls on large winter snowpacks. In contrast, during late summer and fall after the snowpack has melted, tributary inflows are small, and extremely low flows on the Truckee River commonly result. In general, the hydrographs for the gaged tributaries, whether partly urbanized or not, are similar in seasonal distribution. Average runoff amounts for the upper Truckee River Basin for the spring snowmelt period (April through June) typically range from 50 to 65 percent of annual runoff while the winter runoff (November through February) is typically 15 to 30 percent. In contrast, the baseflow, or low-flow, period from August to October ranges from 2 to 14 percent of the annual runoff.

The study area for this report (fig.1) was partitioned into 16 subbasins as shown in table 1. Roughly two-thirds of the study area lies below 8,000 ft, characterizing most of the subbasins as moderate-altitude. Vegetation ranges from dense coniferous forests in the highlands to drier, open forests mixed with grasses, sagebrush, and rabbitbrush in the lowland areas in the eastern part of the study area. Urban areas are concentrated around Squaw Valley Ski resort, along the Interstate 80 corridor from Donner Lake to east of Truckee and along Alder and Trout Creek drainages north of Truckee. The upper Truckee River Basin has undergone vegetation cover changes attributed to timber cutting and frequent and widespread wildfires, the latter replacing conifer forests with shrubs and grasses.

Table 1. Modeled subbasins in the upper Truckee River Basin, California and Nevada

[Abbreviation: HRU, hydrologic response unit]

Subbasin number (fig. 1)	Subbasin name	Drainage area (square miles) [1]	Mean HRU altitude range (feet above sea level)
1	Tahoe City-to-Truckee Reach	47.0	5,882-8,609
2	Donner Lake	13.2	5,932-8,612
3	Cold Creek	14.7	5,879-8,356
4	Ungaged area 1 (Truckee to below Prosser Creek Reservoir)	25.7	5,610-7,224
5	Martis Creek Lake	39.6	5,794-8,320
6	Ungaged area 2 (Juniper and Gray Creeks)	46.6	5,200-10,184
7	Prosser Creek Reservoir	49.0	5,777-8,487
8	Webber Lake	35.4	6,470-9,062
9	Independence Lake	6.5	6,955-8,806
10	Sagehen Creek	10.7	6,430-8,320
11	Stampede Reservoir	76.7	5,948-8,419
12	Ungaged area 3 (between Stampede and Boca Reservoirs)	9.8	5,669-8,215
13	Boca Reservoir	24.9	5,630-7,254
14	Bronco Creek	15.4	5,731-10,358
15	Dog Creek	21.7	4,908-8,323
16	Hunter Creek	11.3	5,292-9,528

[1] The drainage area for the study area does not include the drainage area for the Little Truckee Ditch, upstream from the USGS gage no. 10341950.

The western Truckee River Basin boundary along the Sierra Nevada crestline typically is granitic rock outcrop while the dominant soil types elsewhere typically are loam or clay loams of volcanic origin with lesser amounts of soils from re-worked glacial sediments or unconsolidated alluvium. In addition, wetlands adjacent to several of the lowland tributaries contain nearly saturated alluvium-derived soils reflecting high water table conditions and characterized by riparian vegetation.

On most of the hillslopes, rain or snowmelt moves to the stream channel mostly as shallow subsurface flow, with little overland flow except in areas of exposed rock and wetlands. Some moisture may be lost to infiltration through fractures, less so in glaciated granitic rock than in highly fractured and porous volcanic and metavolcanic rock. Subsurface flow in alpine, forested watersheds typically flows at the bottom of permeable soil horizons that are underlain by a horizon of lower permeability or bedrock. This horizon impedes percolation, and water accumulates above it and flows downhill through the soil.

The climate of the upper Truckee River Basin is strongly influenced locally by the topography of the surrounding mountains and regionally by moist maritime air masses from the Pacific Ocean. Summers are cool relative to the valleys on either side of the mountains, and winters are cold, with mean temperatures at Donner Memorial State Park (5,940 ft, National Weather Service) ranging from an average minimum of 13°F for January to an average maximum of 80°F for August. Between 30 and 60 in/yr of precipitation falls in the higher elevations—mostly as snow or mixed precipitation (rain and snow) during the winter and early spring months from November to April. The Sierra Nevada cause a distinct rain shadow to the east resulting in only about 12-16 in/yr of precipitation in the drier parts of the Truckee River Basin at the lower elevations near the Nevada State line.

Acknowledgments

The author gratefully acknowledges the following USGS staff: LaRue Smith and Brian Reece for their creative assistance in streamlining the GIS computations, Steven Markstrom for assistance in upgrading the watershed model to meet project objectives, and Michael Dettinger for assistance in a regional climate analysis. In addition, the author would like to thank the U.S. Forest Service Region 5 personnel for their assistance in compiling the digital soils and vegetation data.

METHODS OF STUDY

The approach taken to simulate runoff from the upper Truckee River Basin is discussed in the following section. The general procedure listed below and the terminology used are explained in the following sections. Descriptions of the PRMS watershed model, input data used to run the models, use of a GIS to characterize the watershed land units, and methodology used for modeling ungaged and regulated subbasins are discussed in the following subsections.

1. Subbasin boundaries were delineated according to streamflow data requirements for the TCP operations model. GIS and associated relational data-base programs were used to characterize and delineate HRU's.
2. PRMS models were initially constructed for the gaged subbasins including those subbasins where streamflow was reconstructed from an upstream and downstream gaging station. Resultant streamflow time series for the gaged subbasins were analyzed statistically and graphically.
3. Distributed, HRU-dependent parameter values from the gaged subbasins were used in constructing PRMS models for the ungaged reservoir catchments and the three ungaged areas. Lack of subsurface flow data on reservoir catchments and ungaged areas precluded a direct transfer of non-distributed parameter values to the uncalibrated areas. Rather, regionalized non-distributed parameter values from the Lake Tahoe Basin study (Jeton, 1999) were used. Inflows to the reservoir catchments were reconstructed with a water balance approach for comparative purposes only using estimated reservoir-surface precipitation and surface evaporation.

Model Description

PRMS (Leavesley and others, 1983) is a physically based, distributed-parameter model designed to simulate precipitation and snowmelt runoff as well as alpine snowpack accumulation and snowmelt processes. "Physically based" refers to the use of mathematical equations to simulate water budget components. "Distributed-parameter" refers to the representation of the watershed as a collection of hydrologic unit types, each unit type having a unique set of physical parameter values. The PRMS computer program is part of a larger modeling system, the Modular Modeling System (MMS; Leavesley and others, 1996). MMS uses a module library that contains algorithms for simulating a variety of water, energy, and biogeochemical processes. Where an existing PRMS module does not provide appropriate algorithms, new modules can be developed and incorporated into MMS.

The spatial variability of land characteristics that affect runoff within watersheds is accounted for by disaggregation of the modeled area into land units known as Hydrologic Response Units (HRU's). A critical assumption is that the hydrologic response to uniformly distributed precipitation and simulated snowmelt is homogeneous within each HRU. HRU's are characterized by those physiographic properties that determine hydrologic response: altitude, slope, aspect, vegetation, soil, geology, and climate. An HRU can be composed of many hydrologically similar, but spatially noncontiguous land units.

PRMS computes a daily water-energy balance for each HRU (fig. 2). The area-weighted sum of daily hydrologic fluxes from all HRU's is the simulated basin response. The term "reservoir," illustrated in figure 2 as a rectangle around a water-budget term, denotes the conceptual collection and storage of water. Movement of water into and out of the reservoirs is initiated by user-defined coefficients representing fluxes. Typically, each HRU is indexed to a climate station not necessarily in the HRU. Monthly temperature lapse rates and precipitation-correction factors extrapolate measured daily air temperature and precipitation from nearby climate stations to individual HRU's, 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 estimated for each HRU.

PRMS requires estimates of approximately 50 basin-wide parameters and 35 HRU-specific parameters. Daily total precipitation and daily maximum and minimum air temperature are used to drive the model. A lapse rate computation is applied to air temperature to account for the difference in temperature due to altitude between the point of measurement and the area of application. In this study, solar radiation is estimated

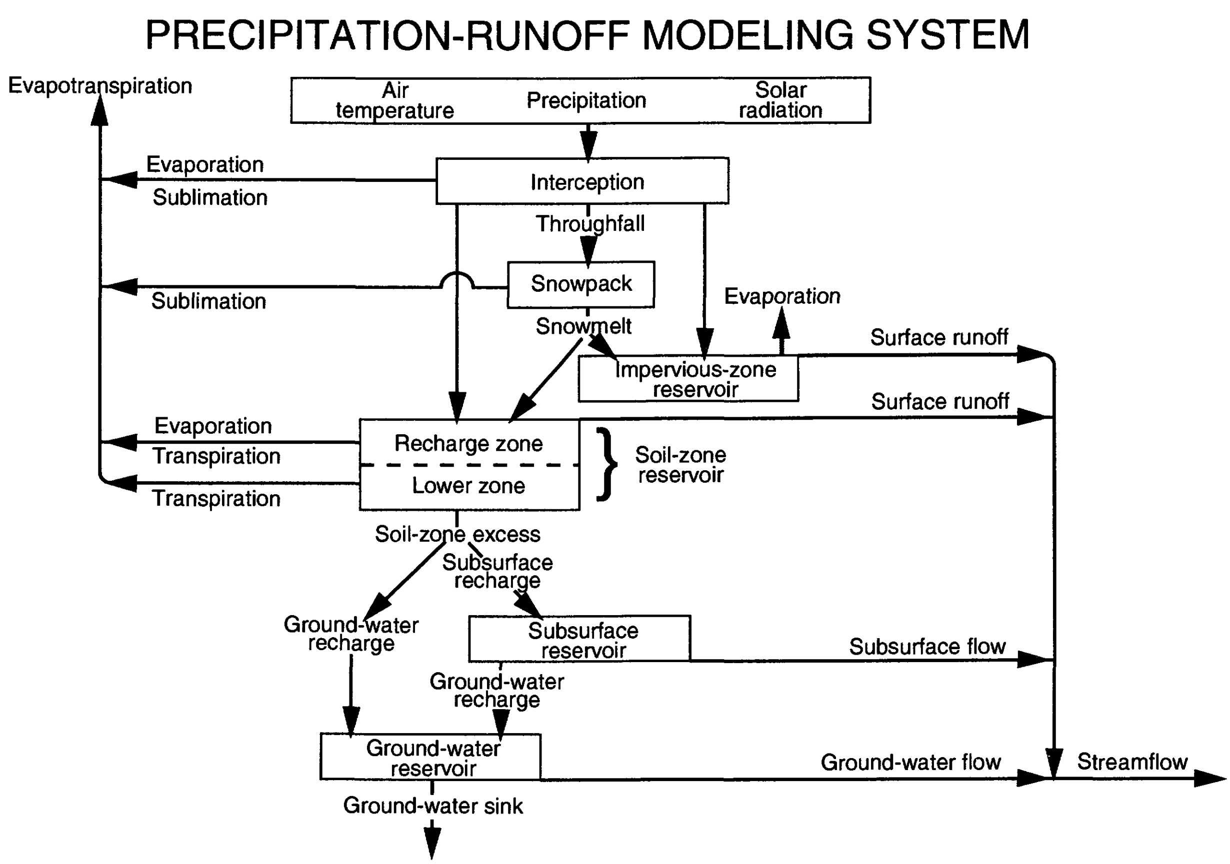

Figure 2. Schematic diagram for Precipitation-Runoff Modeling System (Leavesley and others, 1983).

from daily air temperatures using a modified degree-day method and is adjusted for slope and aspect (Frank and Lee, 1966; Swift, 1976).

Snowmelt is a significant component of the water budget for alpine watersheds in the upper Truckee River Basin. Simulating snowmelt-generated runoff requires transforming snowpack accumulation and melt processes into algorithms that represent the snow-energy budget. Because data and application to point locations were limited for this study, a modified version of the snow-energy budget used some measured components (longwave and shortwave radiation, flux of heat from rain, and the change in energy content of the snowpack) and either parameterized the remaining components or considered them negligible (Leavesley, 1989). In this way, mean areal values of snow accumulation and melt can be obtained at a watershed scale. For the Sierra Nevada, the U.S. Army Corps of Engineers (1956) and Aguado (1985) note that radiation fluxes, rather than turbulent transfers from the atmosphere, are the dominant energy contributors to snowmelt. For moderate-altitude, snow-dominated subbasins of the upper Truckee River Basin, the importance of climatological influences, particularly seasonal anomalies of temperature and precipitation, is reflected in snowpack accumulation and melt rates, and, ultimately, in the timing of runoff. Storms of mixed rain and snow are common in the Sierra Nevada and present a challenge to models like PRMS, which are designed for simulating colder, higher alpine snowpacks. In the PRMS model, snowmelt is simulated when the snowpack contains enough heat to fuel melting, and, thus, its timing is indirectly linked to the annual temperature cycle.

In this study, potential evapotranspiration (PET) is computed with a version of the Jensen and Haise method (Jensen and Haise, 1963; Jensen and others, 1969) modified to account for forest canopies and changes in altitude and humidity. PET is first satisfied from canopy-interception storage, then from sublimation and impervious-surface evaporation. When snow is present and there is no transpiration (PRMS assumes no sublimation when plants are transpiring), sublimation is computed as a percentage of the total PET. 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. During each year of simulation, a cumulative degree-day index is used to determine the start of transpiration, allowing for earlier and later initiation of the transpiration period during warmer and cooler springs.

PRMS models the soil zone as a two-layer system: a shallow, upper zone where losses are from soil evaporation and transpiration and a deeper, lower zone where the soil-moisture depletion is by transpiration and ground-water recharge only. The total soil profile depth for an HRU is defined as the average rooting depth of the dominant vegetation. Actual evapotranspiration (AET) losses from the soil zone are proportional to the remaining PET demand and the ratio of currently available soil moisture to the maximum water-holding capacity of the soil profile, and are limited by PET. Soil-moisture losses are computed separately for each soil layer. Infiltration is computed for rain and for snowmelt differently. For rain falling on ground with no snow cover, infiltration is computed as a function of soil characteristics (field capacity) and antecedent soil-conditions. Surface runoff is computed using the contributing or variable source area approach (Dickinson and Whiteley, 1970) described as a nonlinear function of antecedent soil moisture and rainfall amount. For snowmelt, infiltration is a user-defined rate until field capacity is reached.

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. Excess infiltration into the soil zone, after the daily ground-water recharge has been met, will recharge the subsurface reservoir. The rate of subsurface flow from the subsurface reservoir (to either the ground-water reservoir or directly to the stream channel as interflow) is nonlinear and is computed using the storage volume of the reservoir and two user-defined routing coefficients. Flow to the ground-water reservoir is linear and is the source of baseflow. Movement of ground water outside the basin is simulated by decreasing ground-water storage and labeling this portion of the water budget as a ground-water sink.

Streamflow, as simulated by PRMS, is a summation of three flow components: (1) surface flow (commonly referred to as overland flow) from saturated soils or runoff from impervious surfaces, (2) subsurface flow (or interflow) defined as shallow subsurface flow that receives a percentage of soil water in excess of the available water-holding capacity of the soil, and (3) ground-water flow (baseflow) that receives water from both the soil zone and the subsurface reservoir.

Model Development

The development of the PRMS model required delineating subbasins, compiling daily time series of observed streamflow and climate data, delineating HRU's by objective methods, and using a GIS-to-hydrologic model interface for computing model parameters. These data and tools along with methods for modeling ungaged areas and reservoir catchments are discussed in this section.

Subbasin Delineation

The hydrographic boundaries for the PRMS subbasins were governed by the streamflow data needed for the HSPF river/reservoir operations model. The flow-routing module within HSPF requires that the linked network of river channels, lakes, reservoirs, wetlands, or drainage pipes be divided into segments called reaches. A reach must have relatively uniform hydraulic properties. In Berris' (1996) study, reach segmentation for the Truckee River Basin was generalized to simulate only the essential properties that affect main-stem streamflow. The HSPF flow-routing model for the upper Truckee River subunit is composed of 22 main-stem and tributary reaches and 5 lake or reservoir reaches (Berris, 1996, pl. 1). For precipitation-runoff modeling, the flow-routing reaches were aggregated into 16 hydrographic subbasins (fig. 1 and table 1). Subbasins with observed streamflow data constitute 35 percent of the total study area, with drainage areas ranging from 11.3 mi^2 (Hunter Creek) on the east side of the Sierra Nevada to 47 mi^2 (Tahoe City-to-Truckee) on the Little Truckee River. Thus, the bulk of the study area (65 percent) is either a reservoir catchment or an ungaged area.

Climate Data

Climate data requirements for PRMS are daily total precipitation, and maximum and minimum air temperature. These are particularly important for energy-balance models such as PRMS. Some of the most significant problems in modeling snowmelt runoff are attributable to limitations of climate data availability and extrapolation from point measurements to areal values. Orographic effects (increases in precipitation with altitude) can cause significant spatial variations of precipitation and usually are accounted for by specification of long-term mean precipitation lapse rates; however, spatial variations in the lapse rates may be large (Leavesley, 1989).

In PRMS, the form of precipitation (rain or snow) is temperature dependent and usually simulated by setting a snow-threshold temperature (the temperature at which precipitation is snow). Temperature measurements usually are extrapolated over a basin by assuming a fixed lapse rate. In PRMS, constant monthly lapse rates for maximum and minimum temperatures are user-specified; however, these constant rates generally do not reflect the actual variability observed in daily lapse rates (Leavesley, 1989).

Two kinds of variability are considered when watershed models are constructed: (1) spatial variation of the mean for both precipitation and temperature and (2) spatial variation of deviations of precipitation and temperature around their means. The means are typically represented in PRMS through the precipitation and temperature correction factors, which usually are specified as a lapse rate to account for altitude differences. Deviations about the mean are represented by indexing each HRU to the daily weather series from a particular observation site. Results from a regional climate analysis (Jeton, 1999) of monthly relations between the altitude of climate stations and the mean precipitation or mean temperature rates showed no strong consistent precipitation-altitude relations, especially during the winter months when most of the annual precipitation falls. This suggests that the rainshadow effect of the Sierra Nevada influences precipitation at the sites as much as altitude. For example, mean annual precipitation ranges from 40 in. for the Donner Memorial State Park climate station at the base of the Sierra Nevada crestline (5,940 ft) to 23 in. for the Boca station (5,580 ft), a distance of roughly 9.5 mi (table 2). A principal component analysis on 19 sites in the Tahoe and upper Truckee River Basin (Jeton, 1999) indicated that once seasonality is removed, about 93 percent of the monthly precipitation variability is shared among all of the sites, suggesting the absence of clusters of synchronized precipitation variation. However, on a local subbasin scale, orographic effects are assumed present, requiring that the observed precipitation data be adjusted accordingly.

The meteorological data network for the upper Truckee River Basin (fig. 1 and table 2) is composed of low-altitude National Weather Service (NWS) cooperative sites, usually below 7,000 ft and high-altitude (8,200 to 8,850 ft) snowpack telemetry (SNOTEL) data-collection sites of the Natural Resources Conservation Service (NRCS). These latter sites measure and record ambient air temperature, precipitation, and snowpack-water equivalence at

Table 2. Meteorological stations used in watershed models for the upper Truckee River Basin, California and Nevada

[NRCS, Natural Resources Conservation Service; NWS, National Weather Service. Abbreviations: Ck, Creek; ppt, precipitation; Res, Reservoir; temp, minimum and maximum temperature.]

Meteorological station name	Altitude (feet above sea level)	Operating agency	Daily data used in model	Subbasin models	Mean annual precipitation (inches) [1]
Reno	4,400	NWS	ppt, temp	Dog Ck; Hunter Ck	8
Boca	5,580	NWS	ppt, temp	Dog Ck; Bronco Ck; Boca Res; ungaged areas 1-3	23
Donner Memorial State Park	5,940	NWS	ppt, temp	Cold Ck; Martis Res.; Donner Res; Ungaged area 4	40
Tahoe City	6,230	NWS	ppt, temp	Tahoe-to-Truckee Reach	36
Sagehen Creek	6,340	NWS	ppt, temp	Sagehen Ck; Stampede Res; Webber Lake; Independence Lake; Prosser Res	35
Squaw Valley Gold Coast	8,200	NRCS	ppt	Tahoe-to-Truckee Reach; Cold Ck; Martis Res; Donner Res	67
Independence Lake	8,450	NRCS	ppt	Sagehen Ck; Stampede Res; Webber Lake; Independence Lake; Boca Res; Ungaged area 3; Prosser Res	48
Mt. Rose Ski Area	8,850	NRCS	ppt	Hunter Ck; Bronco Ck; Ungaged area 2	58

[1] Computed for water years 1981-97.

locations nearer the ridge lines. Snow-water equivalence (the snowpack water content) obtained from a snow pillow is a function of snow depth, snow density, depositional area, and the snowcatch deficiency. When plotted against precipitation, periods of undercatch can be detected, as was noted for several years for both the Squaw Valley and Independence Lake SNOTEL data.

PRMS adjusts precipitation amounts to individual HRU's by multiplying observed daily precipitation by specified monthly lapse rates. In this study, observed precipitation was adjusted daily for each individual HRU to account for local, day-to-day variations in precipitation rates on the scale of the individual subbasins. Each modeled subbasin was indexed to two climate stations: a low-altitude station typically around 6,000 ft, and a higher altitude station at or above 8,000 ft. Daily precipitation values for each HRU, (P_i), were generated using the following linear equation:

$$P_i = \left\{\frac{E_{hru} - E_{low}}{E_{high} - E_{low}}\right\}(P_{i,high} - P_{i,low}) + P_{i,low}, \quad (1)$$

Where E_{hru} is mean altitude of the HRU, in feet;
E_{low} is the low climate station altitude, in feet;
E_{high} is the high altitude high climate station, in feet;
$P_{i,high}$ is precipitation at day_i at the high altitude station; and
$P_{i,low}$ is precipitation at day_i at the low altitude station.

Data for 22 long-term (30-yr) sites representing mean monthly air temperature in and around the Tahoe and upper Truckee River Basins were examined to estimate mean monthly regional lapse rates (Jeton, 1999). A narrow altitude range of long-term temperature sites within the basin limits the ability to project temperatures to higher altitude HRU's. Plots of temperature/altitude relations indicate that the regional lapse rates vary little from month to month, averaging 3.3°F per 1,000 ft (the average regional temperature lapse rate cited from the literature is 3.6°F per 1,000 ft; Ahrens, 1985, p. 25). For this study, the five temperature stations at the closest proximity to modeled subbasins were selected, and the observed air temperatures were adjusted with monthly lapse rates estimated from the 22-station regional temperature data set. The lapse rates used in this study are within 0.5°F of the regional lapse rates.

Observed Streamflow Data

Construction of the PRMS models described in this report required streamflow and climatic data. Streamflow data computed from gage-height records collected at gaging stations are referred to as "observed" throughout this report. Streamflow data used in the PRMS models are listed in table 3. Observed flow or reservoir storage data were used for three purposes: (1) PRMS calibration and evaluation,

Table 3. Streamflow gaging stations and reservoir stage-recording stations used in watershed modeling and lake water-balance computations for the upper Truckee River Basin, California and Nevada

[**Data type:** Flow in cubic feet per second and lake storage in acre feet.]

Site number (fig. 1)	Station number [1]	Data type	Period of record used in study	Subbasin name where data is used	Station Name
1	10337500[a]	flow	10/1/80-9/30/82; 10/1/92-9/30/95; 10/1/96-9/30/97	Tahoe City-to-Truckee reach	Truckee River at Tahoe City, Calif.
2	10338000[b]	flow	10/1/80-9/30/82; 10/1/92-9/30/95; 10/1/96-9/30/97	Tahoe City-to-Truckee reach; Ungaged area 1	Truckee River near Truckee, Calif.
3	10338400	lake storage	10/1/80-9/30/96	Donner Lake	Donner Lake near Truckee, Calif.
4	10338500[a]	flow	4/1/93-9/30/97	Cold Creek	Donner Creek at Donner Lake near Truckee, Calif.
5	10338700[b]	flow	4/1/93-9/30/97	Cold Creek; Ungaged area 1	Donner Creek at Highway 89 near Truckee, Calif.
6	Army Corps of Engineers gage	lake storage	10/1/80-9/30/96	Martis Creek Lake	Army Corps of Engineers gage
7	10339400	flow	10/1/80-9/30/96	Martis Creek Lake; Ungaged area 1	Martis Creek near Truckee, Calif.
8	10339419	flow	10/1/93-9/30/96	Ungaged areas 1-2	Truckee River above Prosser Creek near Truckee, Calif.
9	10340300	lake storage	10/1/80-9/30/96	Prosser Reservoir	Prosser Creek Reservoir near Truckee, Calif.
10	10340500	flow	10/1/80-9/30/96	Prosser Reservoir	Prosser Creek below Prosser Creek Dam near Truckee, Calif.
11	10341950	flow	7/1/93-9/30/97	Webber Lake	Little Truckee River below Diversion Dam near Sierraville, Calif.
12	10342900	lake storage	10/1/80-9/30/96	Independence Lake	Independence Lake near Truckee, Calif.
13	10343000[2]	flow	10/1/80-9/30/96	Independence Lake	Independence Creek near Truckee, Calif.
14	10343500	flow	10/1/80-9/30/97	Sagehen Creek	Sagehen Creek near Truckee, Calif.
15	10344300	lake storage	10/1/93-9/30/96	Stampede Reservoir	Stampede Reservoir near Truckee, Calif.
16	10344400[2]	flow	10/1/80-9/30/96	Ungaged area 3	Little Truckee River above Boca Reservoir near Truckee, Calif.
17	10344500[2]	flow	10/1/80-9/30/96	Boca Reservoir	Little Truckee River below Boca Dam near Truckee, Calif.
18	10344490[2]	lake storage	10/1/80-9/30/96	Boca Reservoir	Boca Reservoir near Truckee, Calif.
19	10345700	flow	4/23/93-9/30/97	Bronco Creek; Ungaged area 2	Bronco Creek at Floriston, Calif.
20	10346000[2]	flow	10/1/93-9/30/97	Ungaged area 2	Truckee River at Farad, Calif.
21	10347310	flow	11/5/92-9/30/97	Dog Creek	Dog Creek at Verdi, Nev.
22	10347600	flow	10/1/80-9/30/92	Hunter Creek	Sierra Pacific Power Co. station

[1] Reconstructed streamflow where the upstream gage (a) is subtracted from the downstream gage (b).

[2] Streamflow data used in reconstructing reservoir inflows or estimates to ungaged areas.

limited by contiguity, (3) the technique was flexible to accommodate different classification criteria, and (4) the technique was objective and reproducible.

HRU's were delineated for the study basins using raster and vector-based data interpolated on 30-meter (98-ft) grids where the minimum mapping unit was 10 acres. Using pattern-recognition techniques, land areas in the grid were partitioned into noncontiguous, hydrologically similar land units based on groupings of the source data and nominal filtering to merge isolated cells into broader homogenous land units (fig. 3). HRU's ranged from 10 acres to 11,590 acres, with an average size of 232 acres. The source data layers were regrouped into the following broader categories: elevation into seven 1,000-ft intervals; aspect into 4 cardinal directions (NW-N-NE, E, SE-S-SW, and W); slope into 3 classes (0-7, 8-30 and 31-90 degrees); land-use/land-cover into 9 classes (conifer forests, deciduous forests, herbaceous rangeland, shrub rangeland, rock, urban, water bodies, bare soils, and wetlands); and soils into 11 classes according to whether the parent material was granitic, volcanic, or sedimentary and the soil texture clay, sand, or loam. This methodology is detailed in Jeton (1999).

Maintaining a digital data base for modeling current watershed conditions where land cover and land-use type and density are in flux or for including more recent digital coverages would require the modeler to redefine the HRU coverage for each new entry and rerun the GIS-to-modeling component.

Computer programs were developed to aid users in reconstructing the HRU digital data layer as well as for computing certain PRMS model parameters to allow for incorporating updates and corrections into the

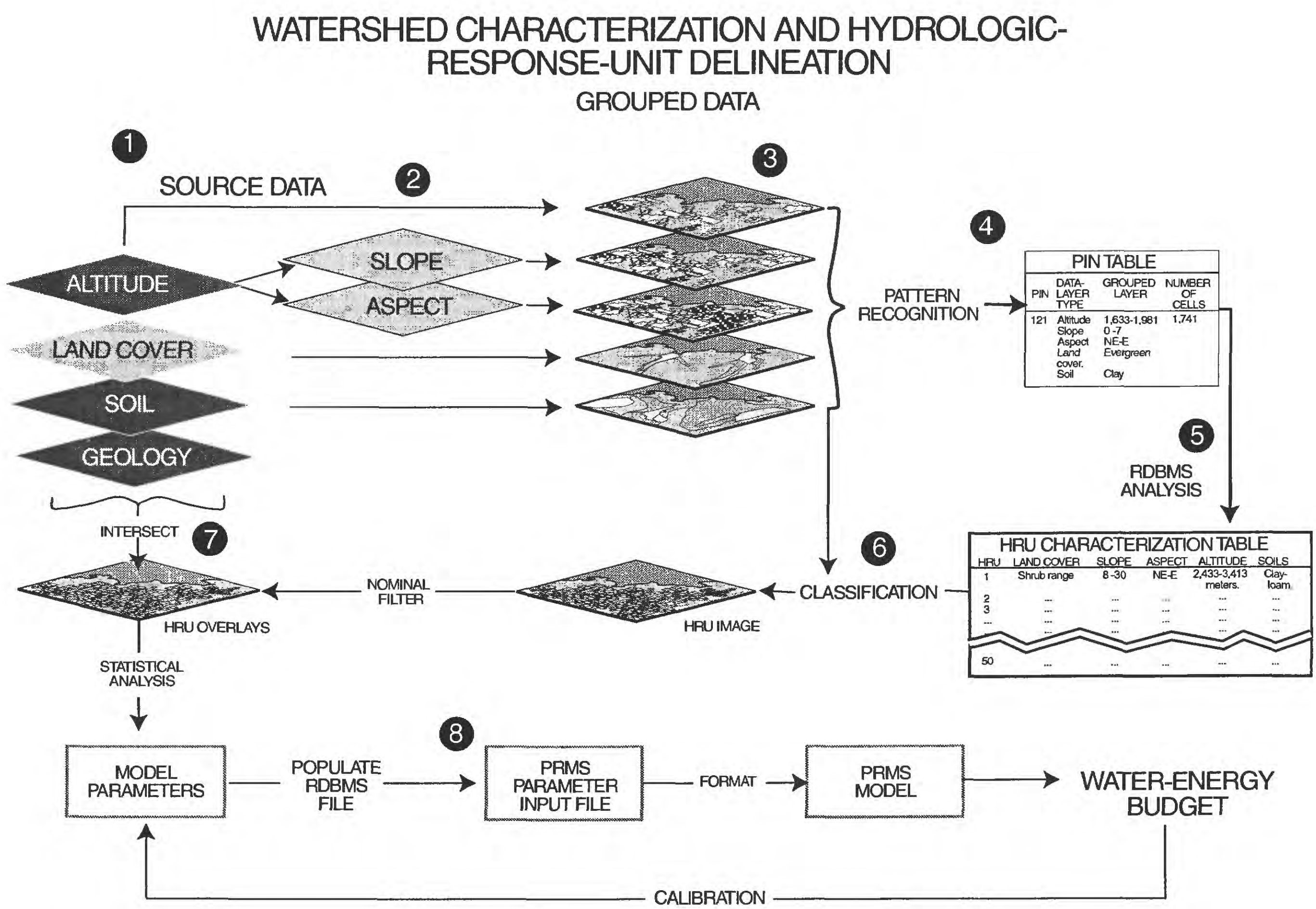

Figure 3. Steps in basin characterization and hydrologic-response-unit (HRU) delineation. (Abbreviations: PIN, Pattern Identification Number; PRMS, Precipitation-Runoff Modeling System; RDBMS, Relational Data-Base Management System.)

(2) streamflow reconstruction whereby downstream flow data were corrected to account for upstream diversions and used for calibration, and (3) river or reservoir water-balance computations. Flow data for the following subbasins (fig. 1) were modified for calibrating the models: Tahoe City-to-Truckee reach (subbasin 1) of the Truckee River where the downstream record at the gage site near the town of Truckee (10338000) was adjusted to account for releases from Lake Tahoe at the Tahoe City dam (10337500); Cold Creek (subbasin 3) where Donner Lake releases (10338500) were subtracted from the Donner Creek gage below the confluence with Cold Creek (10338700); and Webber Lake (subbasin 8) where diversions to the Little Truckee Ditch were added to the Little Truckee River gaging site (10341950). The remaining gaging stations listed in table 3 were used either directly with no adjustments (for example, Dog Creek, Hunter Creek, and Sagehen Creek subbasins) or as outflow or lake storage to compute a water-balance for each of the 5 reservoirs in the study area.

The USGS specifies the accuracy of its streamflow records primarily on the stability of the stage-discharge relation, the accuracy of measurements of stage and discharge, and the interpretation of records. An accuracy level of "good" indicates that about 95 percent of the daily discharges are within 10 percent of their true values; "fair" indicates daily discharges are within 15 percent; and records that do not meet the criteria mentioned are specified as "poor" (Bonner and others, 1998, p. 24). Most of the gaging stations used for calibration in this study are specified as either "good" or "fair," with individual years on some of the gages specified as "poor."

The observed daily streamflow for the January 1997 flood was either estimated from either water-budget computations using upstream and downstream flow data or determined from measurements used to modify water-surface elevation and discharge ratings computed for several tributaries in the study area. Uncertainties associated with both of these methods precluded assigning a definitive error value to the observed January 1997 flood estimates.

Basin Characterization and Delineation of Hydrologic Response Units

A GIS assisted in characterizing the watersheds and estimating the parameters so that spatial variation of important basin characteristics could be analyzed objectively and automatically. Each modeled subbasin was partitioned into hydrologically homogeneous subareas—HRU's. The procedures were similar to those described in previous modeling studies (Jeton and Smith, 1993; Jeton and others, 1996; Jeton, 1999). Data were acquired for the GIS in the forms of digitized paper maps, digital raster data (a cellular data structure composed of rows and columns), vector data (points or lines defined by a cartesian coordinate system), and attribute tables (descriptions of digital map features). The digital data layers included altitude, slope, aspect, soil, land cover, and hydrography. The sources included 1:24,000-scale USGS Digital Elevation Model (DEM) data for altitude (U.S. Geological Survey, 1987) from which slope and aspect data layers also were derived; 1:24,000-scale USFS soil and vegetation-type data from the Tahoe National Forest Area (U.S. Forest Service, 1994) and the Toiyabe National Forest Area; soil data from the National Resources Conservation Service (1980); land-cover and land-use digital data from 1:250,000-scale maps reflecting land cover in 1979 (U.S. Geological Survey, 1986a); and a composite of 1:100,000-scale and 1:24,000 digital line graph (DLG) hydrographic data (U.S. Geological Survey, 1985, 1986b). Slope and aspect data layers were generated from the DEM altitude data layer using the GIS software ARC/INFO (Environmental Systems Research Institute, 1994).

With these data, HRU's were delineated by assuming that basin properties can be grouped according to hydrologically significant characteristics even when the corresponding areas are not contiguous. This approach allows for a high-resolution model that captures the physiographic variability in mountainous basins without requiring hundreds of distinct HRU's. Because PRMS assumes that instream travel times (from the headwaters to the outlet) are less than the daily time step, time lags between noncontiguous parts of an HRU were not modeled, and therefore contiguity was not necessary. In PRMS, hydrologic fluxes are assumed to be uniform over all parts of an HRU and are scaled by its total area. To delineate these noncontiguous HRU's, a method was developed to delineate hydrologically homogeneous and spatially noncontiguous land units for use as HRU's according to the following criteria: (1) source data layers and groupings of classed data that had resolutions appropriate to the basin's natural spatial variability were selected for their hydrologic significance, (2) definitions were not digital data base as new data becomes available. To streamline this multistep procedure for building parameter files for the ungaged areas and reservoir catchments, a method was developed (Jeton, 1999) to enhance the GIS-to-hydrologic model interface by using numerous UNIX-based computer programs for processing the digital data as well as for computing certain PRMS model parameters. The UNIX-based programs for delineating HRU's contain links to the ARC GRID (Environmental Systems Research Institute, 1994) software program, in which the complex, multistep grid-based process is automated. A UNIX-based relational data base program outside of ARC/INFO computes an analysis of tabular data in a manner easily modified by the user. The GIS-to-model interface allows for changes to be made in the watershed characterization and modeling procedure at any point in the process. This is particularly applicable where updated or improved digital coverages become available and the modeler chooses to redefine HRU boundaries and later re-run the hydrologic model. In addition, the set of programs facilitate use of the watershed model for comparison of land-use change "scenarios" that may affect runoff volume and timing.

Modeling Ungaged Areas and Reservoir Catchments

One method frequently used for estimating water yield from ungaged areas is regression analysis in which statistical relations are developed between streamflow and climatic or physiographic characteristics of the gaged watersheds (Hess and Bohman, 1996; Parrett and Cartier, 1990). Another approach is to regionalize hydrologic model parameter values from calibrated watersheds that are ungaged (Dinicola, 1990; Laenen and Risley, 1997; Risley, 1994; and Kuhn and Parker, 1992). A detailed discussion of these studies is presented in Jeton (1999). Areas termed "ungaged" herein, which are illustrated in figure 1 as subbasin 4, 6 and 12, and correspond to ungaged areas 1-3, respectively (fig. 1), are aggregated areas composed of numerous tributaries that are ungaged or contain upstream diversions that preclude accurate runoff estimates. The ungaged areas were modeled with PRMS on the assumption that they could be modeled as hydrologically continuous areas. The reservoir catchments are hydrologically-defined watersheds (included in reservoirs are lakes since Donner and Independence Lakes have regulated outflow). The reservoir subbasins have no measured total inflow. The uncertainty in particularly lake-surface evaporation (and lake-surface precipitation for those reservoirs without lakeside climate stations) and the tendency of reservoir simulations to accumulate error and bias with time resulted in classifying the reservoir catchments as ungaged areas.

The approach for modeling the ungaged areas was developed in an earlier, companion study for the Lake Tahoe Basin (Jeton, 1999). That study was centered around a GIS developed for the Lake Tahoe Basin and an associated relational data-base system (RDB). In the Lake Tahoe precipitation-runoff study, a loosely-defined "paired-basin" analysis was used in which pairs of subbasins with similar hydroclimatic characteristics were identified. One of the subbasins was designated the "control" or calibration subbasin and the other the verification subbasin. The method developed for transferring model parameters from gaged or calibrated tributaries to large, aggregated ungaged areas was facilitated through a number of computer programs that have several functions. In summary, (1) the RDB software populated, or created, the gaged subbasin parameter file; (2) a master HRU data file of HRU data combinations and their associated parameter values was created once the gaged tributaries were modeled; (3) the GIS data base was queried to match similar HRU's from gaged to ungaged areas; and lastly, (4) modeled HRU parameter values were transferred to corresponding HRU's in ungaged areas in a PRMS format. This facilitated modifications to the parameter tables and, thus, supported iterative PRMS model runs. The ungaged areas were indexed to template or gaged subbasins once parameter transferrability had been tested on the paired, gaged subbasins.

The absence of physiographically similar pairs of gaged watersheds in the upper Truckee River Basin precluded a paired-basins analysis similar to the Lake Tahoe Basin study (Jeton, 1999). Each ungaged area and reservoir catchment was indexed to the gaged subbasins of closest hydro-physiographic similarity for the purpose of transferring distributed and, where applicable, nondistributed parameters. Results from modeling the Lake Tahoe Basin indicated that few of the distributed (HRU) parameters needed adjustment during calibration, implying that HRU parameter values could be obtained from RDB tables where the HRU parameters are assigned numeric values according to physiographic attributes.

Many assumptions were inherent in modeling the reservoir catchments and the ungaged areas. The most important assumptions were (1) the HRU characterization and delineations were realistic; (2) the temporal and spatial distributions of precipitation and temperature were appropriate; and (3) the ungaged areas behaved hydrologically in a manner similar to the gaged subbasins selected as the template. No field verification of HRU's was made, nor were any measured hydrologic data used except for the streamflow data collected by the USGS. Understanding the hydrologic processes was limited to inferences made on general hydrogeologic characteristics.

MODEL CALIBRATION AND VERIFICATION FOR GAGED SUBBASINS

In distributed-parameter precipitation-runoff models, hydrologic processes are parameterized to account for the spatial and temporal variability of basin characteristics. The term "parameter" used throughout this report refers to a numeric constant in equations used to describe hydrologic processes. Although partitioning methods differ (see Leavesley, 1973, p. 18-26), 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 following section describes the major distributed (HRU-dependent) and nondistributed parameters modified during the calibration process, the source for their initial values as listed in table 4, and a summary of a sensitivity analysis. The last section presents the model results in the form of an error analysis for the seven gaged subbasins.

Model Parameterization

Distributed parameters in PRMS are those parameters that either describe physiographic characteristics of an HRU—for example drainage area, slope, aspect, and vegetation type and density—or describe components and processes of the hydrologic cycle on or within the HRU. Examples of such HRU-dependent processes are soil-moisture infiltration, evapotranspiration losses, seepage to the subsurface and ground-water reservoirs, potential evapotranspiration, precipitation-correction adjustments and precipitation form (rain or snow), vegetation-canopy interception, runoff from impervious areas, and overland flow from saturated soils. In contrast, non-distributed or lumped parameters (also referred to as "basin-wide" or "global" parameters) are those whose values apply over the entire basin. Non-distributed parameters are used to describe watershed processes that are independent of HRU characteristics. In PRMS, non-distributed parameters are either (1) monthly in scale, such as the temperature lapse rates where, for example, the January minimum temperature lapse rate is the January lapse-rate for all HRU's within the subbasin, or (2) scalar, defined as having magnitude but no direction in space (or time). Examples of scalar parameters are those used in the initiation, accumulation, and depletion of a snowpack; subsurface and ground-water routing; and in solar-radiation computations.

Table 4 lists the distributed (HRU-dependent) parameters and the nondistributed (basin-wide) parameters modified during calibration. For a complete listing of PRMS parameters, refer to the PRMS manual (Leavesley and others, 1983). The basin-wide parameters have been grouped into three types: (1) temperature-precipitation dependent, (2) ground-water routing, and (3) subsurface-routing coefficients. The designation "calibration parameter" refers to a parameter that could not be determined from available data, rather a generalized estimate was used as the initial value and later finalized as the result of iterative model runs.

Sensitivity analyses during model calibration typically help to determine the extent to which parameter value uncertainties may result in unacceptable streamflow predictions. Parameters are selected according to whether they affected long-term volume (monthly and annual) response, short-term runoff (with particular attention to timing), or storage volumes for the model reservoirs (canopy interception, snowpack, soil, and subsurface zones). Sensitivity analyses were not made for the models developed for the upper Truckee River Basin because such analyses had already been made in a previous PRMS modeling study for the headwaters of the East Fork Carson River Basin (Jeton and others, 1996) and applied to watershed models developed for the Lake Tahoe Basin (Jeton, 1999).

Sensitivity analyses from the East Fork Carson River study indicated that streamflow predictions were most sensitive to the snow-threshold temperature that determines precipitation form; the precipitation-correction factor (similar to a precipitation lapse rate) for snow; the monthly evapotranspiration coefficients for the Jensen-Haise PET computation; the winter canopy-transmission coefficient; and the monthly temperature lapse rates. Lapse rates for maximum and minimum temperatures were equally sensitive. Assuming that precipitation is correctly distributed over the watershed, uncertainties in the nondistributed parameters listed in table 4 (primarily the temperature-

Table 4. Source of parameter values for distributed and (selected) nondistributed Precipitation-Runoff Modeling System parameters for the upper Truckee River Basin, California and Nevada

[Abbreviation: HRU, Hydrologic response unit]

Model parameter	Description of parameter	Source of parameter value				
		GIS derived [1]	Computed [2]	Literature [3]	Default value [4]	Calibration [5]
	Distributed (HRU-dependent) parameters					
CAREA_MAX	Maximum area contributing to surface runoff					X
COV_TYPE	Vegetation cover type (tree, shrub, grass, or bare)	X				
COVDEN-SUM	Vegetation cover density (in percent) for summer	X				
COVDEN_WIN	Vegetation cover density (in percent) for winter	X				
HRU_AREA	HRU area (in acres)	X				
HRU_DEPLCRV	Index number for snowpack depletion curve		X			
HRU_ELEV	Mean HRU altitude (in feet)	X				
HRU_GWRES	Index number for ground-water reservoir		X			
HRU-PERCENT_IMPERV	HRU impervious area as a decimal percent of the total HRU area	X				
HRU_PSTA	Index number of the precipitation station used to compute rain and snow on HRU		X			
HRU_RADPL	Index number of the solar radiation plane		X			
HRU_SLOPE	HRU slope in decimal percent (vertical feet/horizontal feet)	X				
HRU_SSRES	Index number of the subsurface reservoir receiving excess water from the HRU soil zone		X			
HRU_TSTA	Index number of the temperature station used to compute HRU temperatures		X			
IMPERV_STOR_MAX	Maximum impervious retention storage for the HRU (in inches)			X		
JH_COEF-HRU	Air temperature coefficient used in the Jensen-Haise potential-evapotranspiration computations for each HRU		X			
RAD_TRNCF	Transmission coefficient for short-wave radiation through the winter canopy		X			
SMIDX-COEF	Coefficient in non-linear contributing area algorithm (computing surface runoff)				X	
SMIDX_EXP	Exponent in non-linear contributing area algorithm (computing surface runoff)				X	
SNAREA_THRESH	Maximum snow water equivalent below which the snow-covered area depletion curve is applied			X		

Table 4. Source of parameter values for distributed and (selected) nondistributed Precipitation-Runoff Modeling System parameters for the upper Truckee River Basin, California and Nevada—Continued

Model parameter	Description of parameter	Source of parameter value				
		GIS derived [1]	Com-puted [2]	Litera-ture [3]	Default value [4]	Calibra-tion [5]
SNOW_INTCP	Snow interception storage capacity for the major vegetation type on an HRU			X		
SNOWINFIL_MAX	Maximum infiltration rate for snowmelt (in inches per day)					X
SOIL2GW_MAX	Amount of soil water excess for an HRU that is routed directly to the associated groundwater reservoir each day (in inches)					X
SOIL_MOIST_INIT	Initial value of available water in soil profile (in inches)			X		
SOIL_MOIST_MAX	Maximum available water holding capacity of soil profile (in inches)			X		
SOIL_RECHR_INIT	Initial value for available water in the soil recharge zone, in inches (upper soil zone)			X		
SOIL_RECHR_MAX	Maximum value for available water in the soil recharge zone (in inches)			X		
SOIL_TYPE	HRU soil type (sand, loam or clay)	X				
SRAIN_INTCP	Summer interception storage capacity for the major vegetation type on an HRU (in inches)			X		
TMAX_ADJ	HRU maximum temperature adjustment to HRU temperature based on slope and aspect of HRU				X	
TMIN_ADJ	HRU minimum temperature adjustment to HRU temperature based on slope and aspect of HRU				X	
TRANSP_BEG	Month to begin summing maximum temperature for each HRU; when sum is greater than or equal to TRANSP_TMAX transpiration begins			X		
TRANSP_END	Last month for transpiration computations			X		
TRANSP_TMAX	Temperature index to determine the specific date of the start of the transpiration period				X	
WRAIN_INTCP	Winter rain interception storage capacity for the major vegetation type on an HRU (in inches)			X		
	Selected nondistributed (basin-wide) parameters					
	Temperature/precipitation dependent					
ADJMIX_RAIN	Monthly factor to adjust rain proportion in a mixed rain/snow event					X
JH_COEF	Monthly air temperature coefficient used in the Jensen-Haise potential evapotranspiration computations		X			
RAIN_ADJ	Monthly factor to adjust measured precipitation (rain) to each HRU					X
SNOW_ADJ	Monthly factor to adjust measured precipitation (snow) to each HRU					X
TMAX_ALLSNOW	Maximum temperature below which all precipitation is simulated as snow					X

Table 4. Source of parameter values for distributed and (selected) nondistributed Precipitation-Runoff Modeling System parameters for the upper Truckee River Basin, California and Nevada—Continued

Model parameter	Description of parameter	Source of parameter value				
		GIS derived [1]	Computed [2]	Literature [3]	Default value [4]	Calibration [5]
TMAX_ALLRAIN	Maximum temperature above which all precipitation is simulated as rain					X
MELT_LOOK	Julian date to start looking for spring snowmelt					X
MELT_FORCE	Julian date to force snowpack to spring snowmelt					X
TMAX_LAPSE	Monthly maximum temperature lapse rate representing the change in maximum temperature per 1,000 feet of elevation change for each month		X			
TMIN_LAPSE	Monthly minimum temperature lapse rate representing the change in minimum temperature per 1,000 feet of elevation change for each month		X			
	Ground-water routing					
GWFLOW_COEF	Ground-water routing coefficient to obtain ground-water flow contribution to streamflow					X
GWSINK_COEF	Ground-water sink coefficient to compute the seepage from each reservoir to a ground-water sink					X
GWSTOR_INIT	Storage in each ground-water reservoir at the beginning of the simulation (in inches)					X
	Subsurface routing					
SSR2GW_RATE	Coefficient to route water from the subsurface to ground-water reservoir					X
SSRCOEF_LIN	Linear subsurface routing coefficient to route subsurface storage to streamflow					X
SSRCOEF_SQ	Non-linear subsurface routing coefficient to route subsurface storage to streamflow					X

[1] Computed in geographic information system from digital data.

[2] Computed from climatological data or other measured data.

[3] Obtained from the literature as estimated or empirical data.

[4] Parameters whose values are considered constants as provided by Leavesley and others (1983).

[5] Parameters that cannot be estimated from available data and are adjusted during calibration or that have an initial value estimated from observed or published data and later adjusted during calibration.

dependent and subsurface and ground-water flow-routing parameters) contributed to simulation error. Excess soil water is routed first to the ground-water reservoir, then to the subsurface reservoir. The dominance of one coefficient over the other influences the distribution of runoff. Subsurface flow-routing coefficients determine the rate of flow from the subsurface reservoir to the stream channel, and thus affect the timing of runoff. The shape of the baseflow recession is governed by the relative proportion of ground-water inflow from the subsurface reservoir and discharge from the ground-water reservoir.

Error Analysis

Measures of prediction error are most commonly the sum of the difference in error (residual), the sum of the absolute values of the residual, and the square of the residuals (Leavesley and others, 1983). Though correlation-based measures are commonly used in hydrologic modeling studies, such measures are more sensitive to outliers than to observations near the mean. This leads to a skewed characterization of the real error because large, individual errors unduly influence the overall error values. The absolute error and the error squared tend to be dominated by a few large errors (Troutman, 1985; Haan and others, 1982), particularly given the tendency for larger events to have larger prediction errors. Normalizing the sum of the residuals by the observed flow, hereafter referred to as relative error, reduces the influence of larger events statistically represented as outliers.

The goal in modeling is threefold: little to no bias; realistic parameter values reflecting the watershed condition being modeled; and satisfactory runoff predictions, both in volume and timing. No single calibration of the PRMS model will simulate all flow regimes with the same level of error. In this study, the focus of calibration was mostly on average to wet years. Rainfall-runoff simulations typically split the observed period of record for streamflow into two periods, the calibration and verification periods. The calibration period, generally reflecting the range of climate conditions in the watershed being modeled, is used to make adjustments to the model parameter values in order to best fit the simulated hydrograph to the observed hydrographs; the verification period is used to evaluate the model when run on a new set of climate data.

Error analyses listed in tables 5-7 include computations of bias to determine the presence of systematic error or an indication of central tendency, and error, to determine the degree of variability or statistical spread in the residuals. Relative error was selected as the measure of prediction error. Statistics computed for daily mean, monthly mean, and annual mean streamflow for the gaged subbasins are listed in tables 5-7. Simulated and observed monthly runoff for the full period of record are evaluated as a percent of annual runoff and are listed in table 8.

The analysis focused on whether the spring snowmelt period was adequately modeled, given the importance of spring snowmelt runoff to total annual runoff. In the following sections, data from table 8 are referred to in the text as seasonal aggregates. Specifically, spring snowmelt refers to accumulated runoff during April through June, baseflow refers to accumulated runoff during August through October, and winter runoff refers to accumulated runoff during November through February. The months March and July were excluded from these seasonal aggregates. Depending on whether the subbasin is a high- or low-altitude subbasin, March might be considered either a spring runoff month (for a high-altitude watershed) or a winter runoff month (for a low-altitude watershed). Likewise, July might be either a spring runoff month (for a high-altitude watershed) or a baseflow month (for a low-altitude watershed). For statistical analyses, simulated streamflow data sets were filtered to exclude values less than or equal to 3 ft^3/s. For several of the subbasins, the observed streamflow record began after the start of the water year usually during spring runoff. In these instances, the PRMS model was run from the prior October, and the simulation results are displayed when concurrent observed data are available.

Tahoe City-to-Truckee Reach

The Tahoe City-to-Truckee reach is the most upstream subbasin in the study area, draining 47 mi^2 of forested, mountainous terrain adjacent to the Truckee River, with development mainly limited to ski resorts. Flow in the upper Truckee River is regulated by releases from Lake Tahoe. Simulated streamflow was compared to an adjusted streamflow data set whereby the outflow from Lake Tahoe at the Tahoe City dam (10337500) was subtracted from the downstream gage near the town of Truckee (10338000). The period of record coincident for these two stations was interrupted by a 10-yr hiatus. The 1980-82 period was designated as the calibration period, the latter period from 1992 to 1995 and again from 1996 to 1997 as the verification period (the downstream gage was not in operation

Table 5. Statistical analyses of simulated daily mean streamflow for gaged subbasins in the upper Truckee River Basin, California and Nevada

Subbasin	Period of record simulated		Relative error [1] (percent)			Bias [2] (percent)		
	Calibration period	Verification period (water years)	Calibration period	Verification period	Entire period of record	Calibration period	Verification period	Entire period of record
Tahoe City-to-Truckee Reach	10/1/80-9/30/82	10/1/92-9/30/97	47	13	23	4	-7	-3
Cold Creek	4/1/93-9/30/95	10/1/95-9/30/97	2	41	20	-6	18	4
Webber Lake	7/1/93-9/30/95	10/1/95-9/30/97	10	-6	-2	-3	-5	-6
Sagehen Creek	10/1/80-9/30/86	10/1/86-9/30/97	-19	4	-7	-5	13	3
Bronco Creek	4/23/93-9/30/95	10/1/95-9/30/97	-20	4	-9	1	13	7
Dog Creek [3]	11/5/92-9/30/95	10/1/95-9/30/97	1	19	26	-3	12	9
Hunter Creek	10/1/81-9/30/85	10/1/85-9/30/92	-1	10	6	-5	7	0

[1] Equation used for calculating relative error: $\Sigma[(s-o)/o]/N \times 100$.

[2] Equation for bias calculation: $\Sigma(s-o)/\Sigma o \times 100$.

For both equations:

where s is simulated daily mean streamflow, in cubic feet per second;
o is observed daily mean streamflow, in cubic feet per second; and
N is number of observed values greater than 3 cubic feet per second.

[3] Daily values for the period from January to March of 1997 were removed from the analysis due to malfunctioning of the Dog Creek gage during this period.

Table 6. Statistical analyses of simulated monthly mean streamflow for the combined calibration and verification period for gaged subbasins in the upper Truckee River Basin, California and Nevada

Subbasin	Period of record simulated (water years)	Relative error (percent) [1]	Bias (percent) [2]
Tahoe City-to-Truckee Reach	1981-82; 1993-95; 1997	17	-3
Cold Creek	1993-97	14	5
Webber lake	1993-97	0	-4
Sagehen Creek	1981-97	-10	4
Bronco Creek	1993-97	-21	3
Dog Creek [3]	1993-97	12	2
Hunter Creek	1981-92	-21	3

[1] Equation used for calculating relative error: $\Sigma[(s-o)/o]/N \times 100$.

[2] Equation for bias calculation: $\Sigma(s-o)/\Sigma o \times 100$.

For both equations:
where s is simulated daily mean streamflow, in cubic feet per second
o is observed daily mean streamflow, in cubic feet per second, and
N is number of observed values greater than 3 cubic feet per second.
Some have incomplete water years due to lack of observed data.

[3] Months of January to March of 1997 were removed from the analysis due to malfunctioning of the Dog Creek gage during this period.

Table 7. Statistical analyses of simulated annual mean streamflow for the combined calibration and verification period for gaged subbasins in the upper Truckee River Basin, California and Nevada

Subbasin	Period of record simulated (water year) [1]	Relative error (percent) [2]	Bias (percent)[3]
Tahoe City-to-Truckee Reach	1981-82; 1992-95; 1997	-3	-3
Cold Creek	1994-97	11	7
Webber lake	1994-97	-4	-7
Sagehen Creek	1981-97	-4	-1
Bronco Creek	1994-97	-9	-2
Dog Creek [4]	1994-97	0	-2
Hunter Creek	1981-92	2	-1

[1] Includes only data with complete water years.

[2] Equation used for calculating relative error: $\Sigma[(s-o)/o]/N \times 100$.

[3] Equation for bias calculation: $\Sigma(s-o)/\Sigma o \times 100$.

For both equations:
where s is simulated daily mean streamflow, in cubic feet per second;
o is observed daily mean streamflow, in cubic feet per second; and
N is number of observed values greater than 3 cubic feet per second.

[4] Months of January to March of 1997 were removed from the analysis due to malfunctioning of the Dog Creek gage during this period.

Table 8. Simulated and observed monthly distribution of runoff, in percent of annual streamflow, for gaged subbasins in the upper Truckee River Basin, California and Nevada

First row: Simulated monthly percentage calculated using (simulated mean monthly for a given month divided by the simulated total of mean monthly values) × 100
Second row: Observed monthly percentage calculated using (simulated mean monthly for a given month divided by the simulated total of mean monthly values) × 100, listed in italics.

Subbasin	Period (water year)	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
Tahoe City-to- Truckee Reach	1981-82; 1993-95; 1997	0.7	6.9	7.9	9.7	6.1	11.5	12.2	20.4	14.7	6.2	2.2	1.5
		.7	*4.4*	*6.9*	*9.4*	*7.5*	*10.1*	*14.6*	*23.6*	*14.7*	*6.0*	*1.3*	*.8*
Cold Creek	1993-97	.3	4.0	7.1	10.7	6.3	10.1	13.9	23.9	15.0	6.5	1.8	.4
		.4	*1.0*	*5.6*	*9.7*	*6.7*	*9.4*	*13.5*	*26.8*	*17.9*	*7.2*	*1.2*	*.6*
Webber Lake	1993-97	.3	1.1	8.4	7.8	5.8	10.3	11.0	25.3	17.5	9.8	2.2	.5
		.4	*1.0*	*3.2*	*8.0*	*5.4*	*7.5*	*14.0*	*29.2*	*21.9*	*7.5*	*1.4*	*.5*
Sagehen Creek	1981-97	.5	2.7	3.4	3.5	7.1	12.8	17.7	25.8	17.9	5.9	1.9	.8
		2.2	*4.0*	*4.8*	*6.4*	*6.1*	*9.1*	*16.8*	*25.5*	*16.2*	*5.0*	*2.1*	*1.8*
Bronco Creek	1993-97	2.5	2.0	2.1	5.8	3.6	6.8	8.5	26.1	23.6	11.1	4.7	3.2
		3.8	*3.6*	*4.0*	*5.9*	*4.3*	*5.7*	*10.3*	*19.7*	*18.2*	*14.5*	*6.0*	*4.0*
Dog Creek	1993-97	.0	.1	7.4	24.3	16.7	27.0	13.8	8.0	2.2	.4	.1	.0
		.7	*.8*	*5.1*	*13.9*	*12.6*	*32.1*	*20.7*	*9.4*	*2.9*	*.9*	*.4*	*.5*
Hunter Creek	1981-92	3.9	4.5	4.8	3.5	9.2	8.8	15.4	15.5	16.2	8.3	5.3	4.5
		4.7	*5.2*	*5.3*	*4.7*	*7.4*	*7.2*	*8.3*	*16.1*	*20.5*	*10.2*	*5.7*	*4.7*

during water year 1996). The USGS streamflow accuracy records for these two stations vary from "poor" to "fair" for the Tahoe City gage (except for the records for water years 1981-82, which are rated as "excellent" to "good" for the downstream gage records). No analysis was made to determine the error associated with the adjusted streamflow data set.

Daily mean simulation bias ranged from +4 percent for the calibration period to -7 percent for the verification period; relative error ranged from +47 percent to +13 percent, respectively. Annual mean streamflow bias and relative error were each -3 percent, respectively. Monthly mean streamflow had a -3 percent bias and a +17 percent relative error. The hydrographs (figs. 4-5) indicate oversimulation for a lower flow period for the 1981 winter period, though timing and volume are improved during the second year of calibration. The verification period (1992-95; 1997) includes an above-average precipitation period (with the exception of water year 1994) and the January flood of 1997. Late fall to early winter streamflow, expressed as sudden runoff generated by rain-on-snow (figs. 4-5), is typical for this and all subbasins modeled in this study. In this subbasin, these sharp runoff events are adequately simulated while maintaining a spring snowpack. As a percentage of total runoff (table 8), simulated spring snowmelt (47 percent) was less than observed spring snowmelt (53 percent), and simulated winter runoff (31 percent) was more than observed winter runoff (28 percent). Observed daily mean flows during the January 1997 flood were determined from stage-discharge relations or ratings. The peak daily mean for the January 1997 flood was 4,941 ft^3/s, 25 percent less than the 6,570 ft^3/s estimated by the rating analysis.

Cold Creek

Cold Creek is a 14.7-mi^2 subbasin draining into Donner Creek, where streamflow is affected by releases from Donner Lake. Streamflow was adjusted for the period April 1993 to September 1997 by subtracting the outflow from the gaging station Donner Creek at Donner Lake, near Truckee, Calif. (station no. 10338500, located upstream of Cold Creek) from the streamflow at the gaging station Donner Creek Highway 89 near Truckee, Calif. (station no. 10338700, located just below the mouth of Cold Creek). The USGS streamflow record accuracy for these two gaging stations varies by year between "good" and "fair." Daily mean streamflow bias (table 5) ranged from -6 percent for the calibration period (April 1993 to September 1995) to +18 percent for the verification period (October 1995 to September 1997); relative error ranged from +2 to +41 percent, respectively. With the exception of 1994 (fig. 6), runoff timing during the calibration period is fairly well represented, particularly during 1996. Oversimulation of water year 1997 accounts for the high bias during the verification period (fig. 7). The accuracy of the observed daily peak flow for the January 1997 flood is questionable because it is based on the mainstem Truckee River gaging stations during the period when the Donner Creek gaging record was unusable. Based on this estimate of observed flow, the simulated daily peak flow on January 2, 1997, was oversimulated by + 42 percent. As a percentage of total runoff (table 8), spring snowmelt was slightly undersimulated (53 percent) when compared to observed spring snowmelt (58 percent). There was no difference for the baseflow period.

Webber Lake

The Webber Lake area is a 35.4-mi^2 subbasin draining into the Little Truckee River, a principal tributary to Stampede Reservoir. An agricultural diversion, the Little Truckee ditch, is located 0.7 mi. upstream from the Little Truckee River gage. The data representing withdrawals out of the Little Truckee River to the ditch were added back to the discharge record at the outlet gage for modeling purposes. The USGS streamflow accuracy for the observed record is "fair." Daily mean streamflow bias ranged from -3 percent for the calibration period (July 1993 to September 1995) to -5 percent for the verification period (October 1995 to September 1997); relative error ranged from +10 to -6 percent, respectively. The daily mean hydrographs are illustrated in figures 8 and 9. The timing and volume are best simulated for water year 1996, while the annual volume in 1997 was undersimulated by -24 percent in part due to undersimulation during the spring runoff months (fig. 9). In contrast, the flood period in January 1997 was oversimulated by 11 percent of the estimated observed daily peak. As a percentage of total runoff (table 8), simulated spring snowmelt (54 percent) was less than observed (65 percent), baseflow was essentially the same, and simulated winter runoff was more (23 percent) than observed (18 percent).

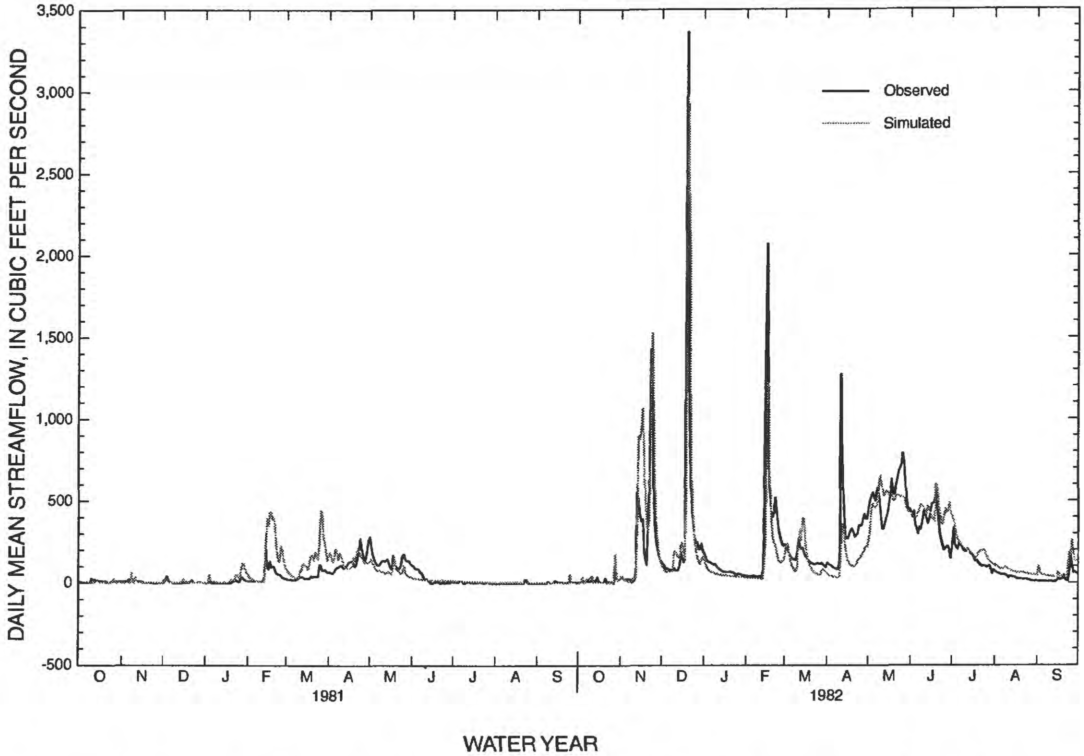

Figure 4. Simulated and observed daily mean streamflow for the calibration period, Tahoe City-to-Truckee Reach, water years 1981-82.

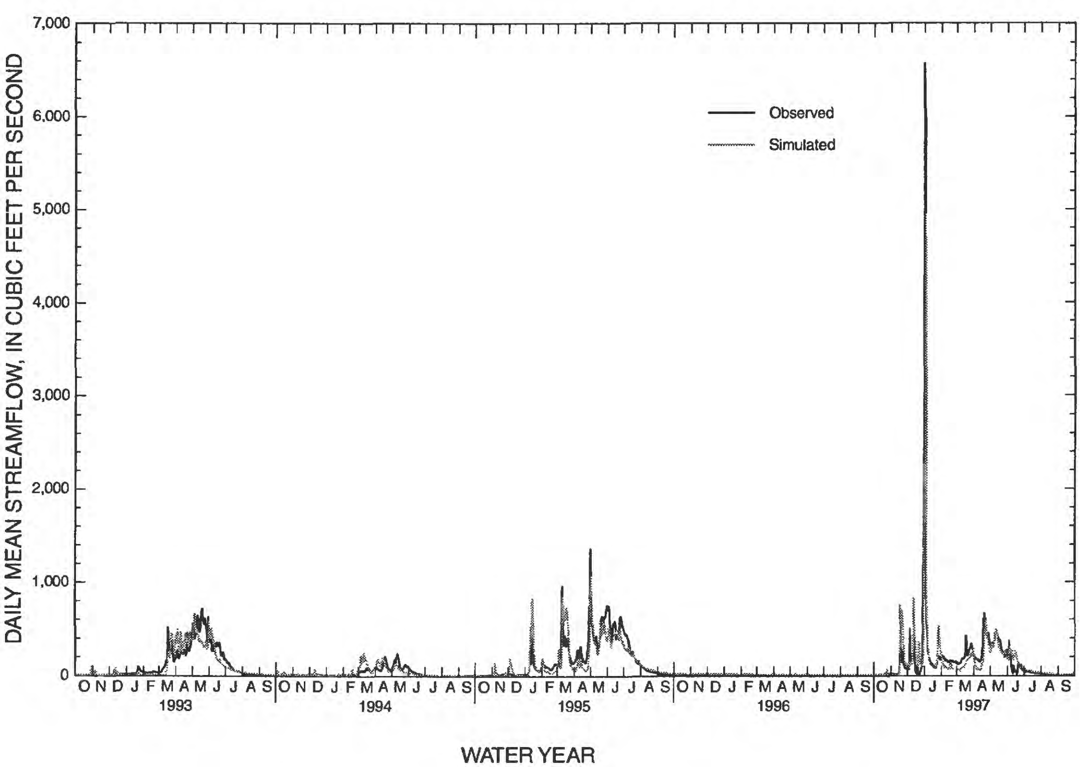

Figure 5. Simulated and observed daily mean streamflow for the verification period, Tahoe City-to-Truckee Reach, water years 1993-97.

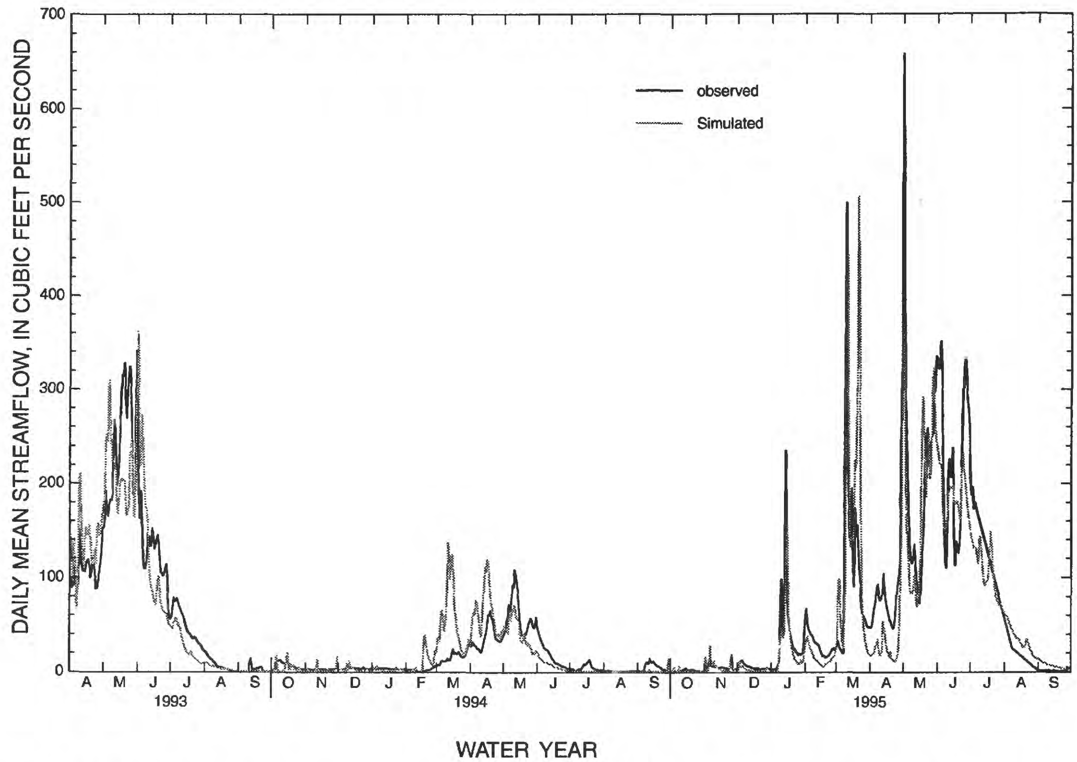

Figure 6. Simulated and observed daily mean streamflow for the calibration period, Cold Creek, water years 1993-95.

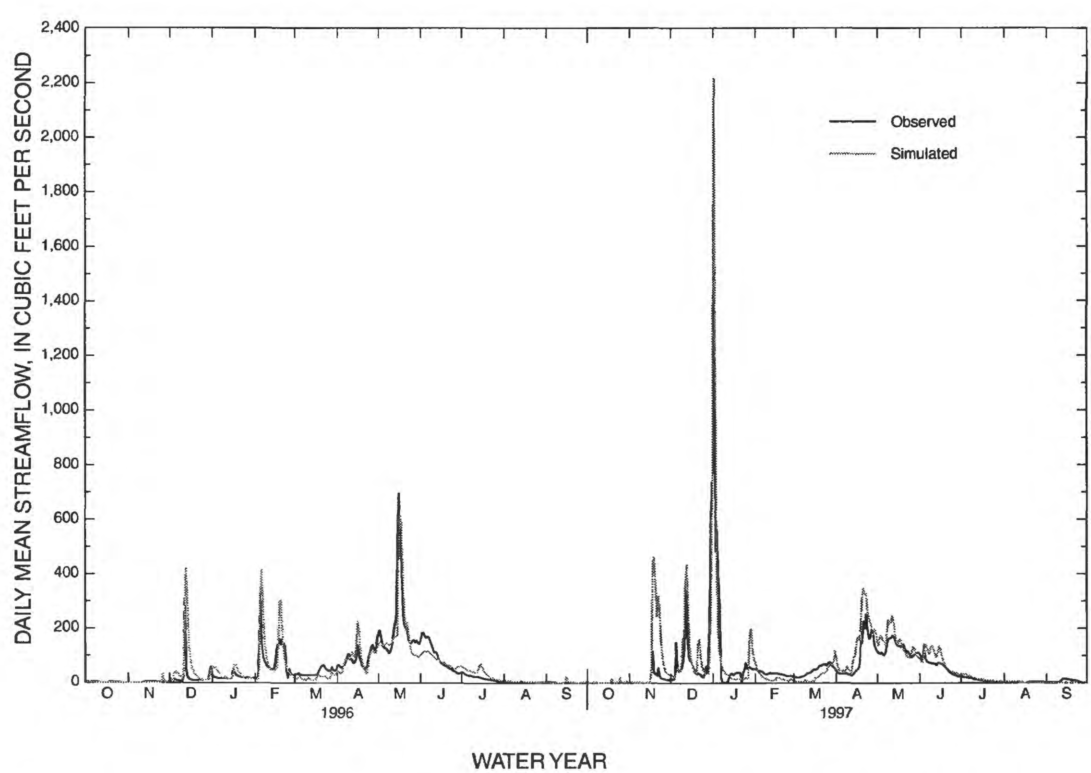

Figure 7. Simulated and observed daily mean streamflow for the verification period, Cold Creek, water years 1996-97.

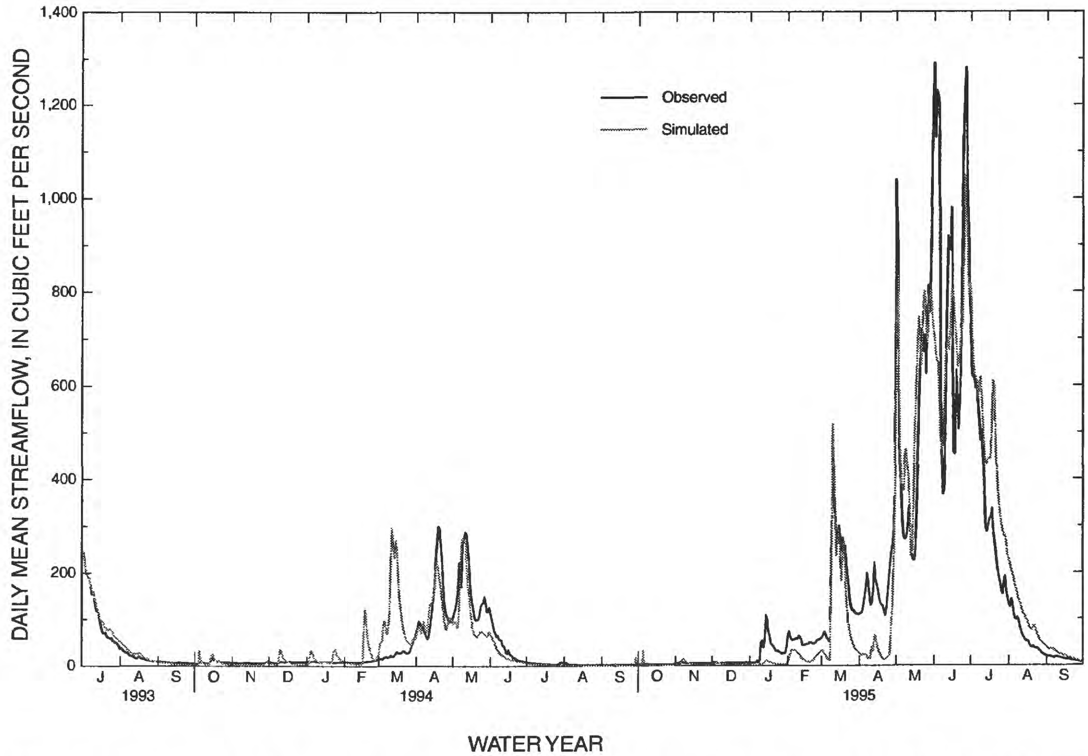

Figure 8. Simulated and observed daily mean streamflow for the calibration period, Webber Lake, water years 1993-95.

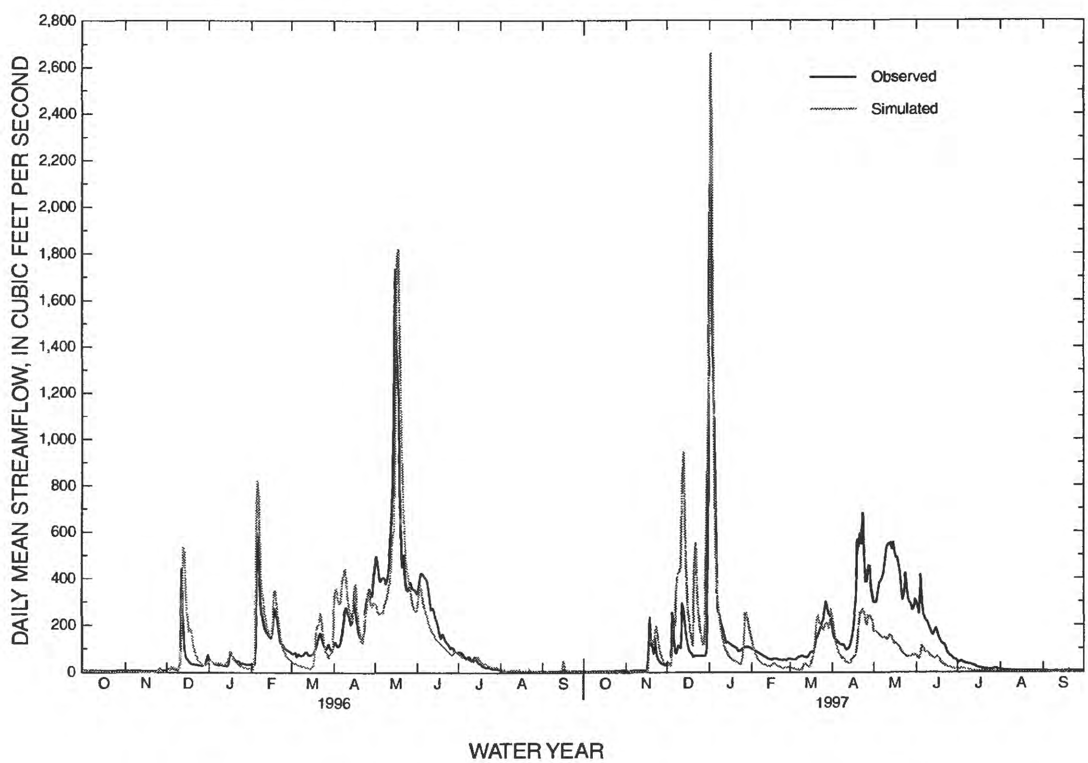

Figure 9. Simulated and observed daily mean streamflow for the verification period, Webber Lake, water years 1996-97.

Sagehen Creek

Sagehen Creek subbasin is a 10.7-mi ^{2} drainage area with no regulation of streamflow or urban development. The gaging station (10343500) record length is 17 years, the longest in the study area. USGS streamflow records accuracy for this gaging station is "good." Daily mean streamflow bias ranged from -5 percent for the calibration period (October 1980 to September 1986) to +13 percent for the verification period (October 1986 to September 1997); relative error ranged from -19 to +4 percent, respectively (table 5). Bias for annual mean streamflow for the 17-year period of record was -1 percent and relative error was -4 percent (table 7). Observed and simulated hydrographs are illustrated in figures 10 and 11. The verification period (fig. 11) shows a trend to oversimulating most of the dry years (1987-92), while the daily peak flow for January 1997 was undersimulated by 75 percent. Observed flow for the January flood was determined from ratings. Simulated spring snowmelt (61 percent) was more than observed (58 percent) and simulated baseflow (3 percent) was less than observed (6 percent) (table 8).

Bronco Creek

Bronco Creek subbasin is a 15.4-mi^2 area draining into the mainstem of the Truckee River 3.5 mi upstream from the Farad gaging station. The Bronco Creek subbasin is one of the higher altitude subbasins in the study area with roughly 67 percent of area above 8,000 ft; however, Bronco Creek receives less precipitation than similar subbasins along the Sierra Nevada crest due to the rain-shadow effect. The USGS records accuracy for the Bronco Creek gage (10345700) varies from "fair" to "poor," depending on the year. Daily mean streamflow bias ranged from +1 percent for the calibration period (April 1993 to September 1995) to +13 percent for the verification period (October 1995 to September 1997); relative error ranged from -20 to +4 percent, respectively (table 5). Bias for annual mean streamflow was -2 percent and relative error was -9 percent (table 7).

The difficulties in modeling this subbasin are attributable to precipitation inputs, vegetation classification and canopy density, and inaccuracies in the measured streamflow. Timing of simulated runoff is less accurate for this subbasin than for modeled subbasins previously discussed, particularly for the calibration period (fig. 12). The spring runoff timing for 1995 may be mismatched due to simulated temperatures warmer than actual temperatures, thus initiating earlier-than-observed snowpack melt. Although the daily mean streamflow bias for the verification period is higher, streamflow timing is better simulated for this period (fig. 13). The simulated daily peak flow for January 1997 lagged one day behind the observed daily peak flow, resulting in a -47 percent difference for the peak and a -9 percent difference the following day.

As a percentage of total runoff (table 8), more spring runoff (58 percent) was simulated than observed (48 percent), less winter runoff (13 percent) was simulated than observed (18 percent), and less baseflow (10 percent) was simulated than observed (14 percent). With the exception of Hunter Creek, observed baseflow for Bronco Creek was greater than for the other subbasins, suggesting more subsurface storage.

Dog Creek

Dog Creek is a 21.7-mi ^{2} subbasin draining into the Truckee River 8.4 mi downstream of the Farad gaging station. USGS streamflow accuracy varied from "fair" to "good," depending on the year. Because the USGS gaging station Dog Creek was not recording streamflow from January to mid-March 1997 due to instrument failure, the streamflow data were not included in the error analysis. Daily mean streamflow bias ranged from -3 percent for the calibration period (November 1992 to September 1995) to +12 percent for the verification period (October 1995 to September 1997); relative error ranged from +1 percent to +19 percent, respectively (table 5). Monthly mean bias was +2 percent and relative error +12 percent (table 6). Runoff timing was well simulated as illustrated in daily mean hydrographs (figs. 14-15). The greatest daily mean flow for the January 1997 flood was within 19 percent of the estimated observed flow. Simulated spring snowmelt (24 percent) was less than observed (33 percent) as determined from table 8, and simulated winter runoff (22 percent) was less than observed winter runoff (32 percent). Observed and simulated baseflow were less than 2 percent of the annual runoff.

Hunter Creek

Hunter Creek is 11.3-mi ^{2} drainage area representing a Sierra Nevada eastern slope subbasin where land cover and precipitation amounts reflect the rainshadow effect of the Sierra Nevada. The Hunter Creek streamflow gage is currently operated by Sierra

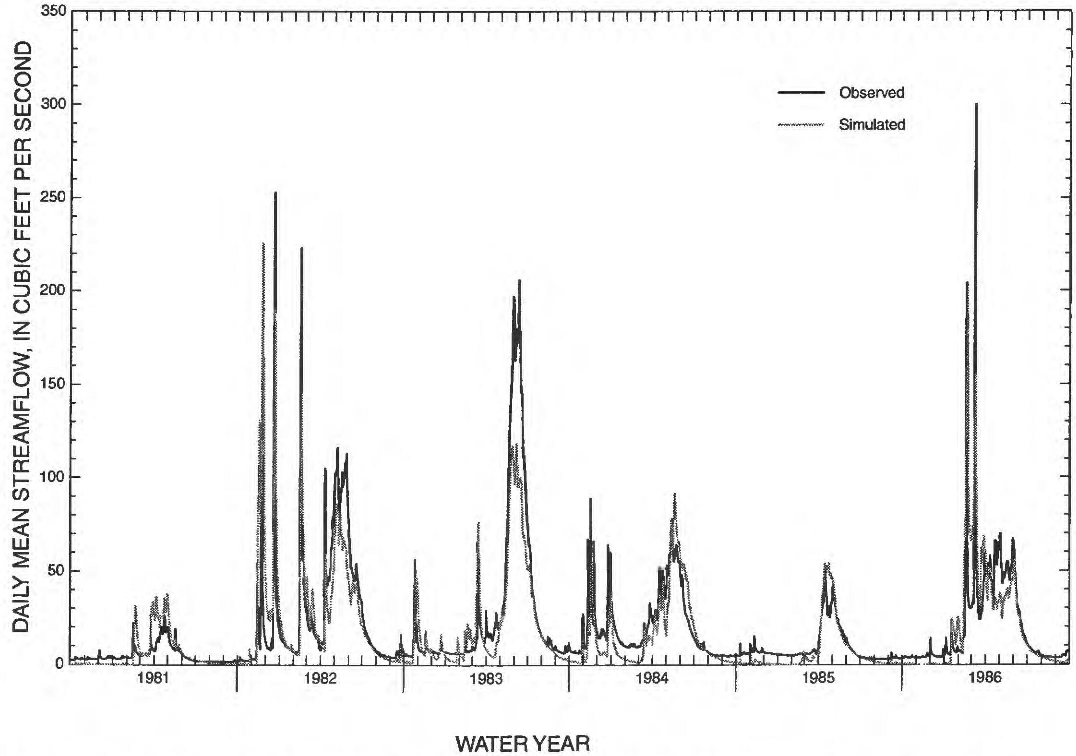

Figure 10. Simulated and observed daily mean streamflow for the calibration period, Sagehen Creek, water years 1981-86.

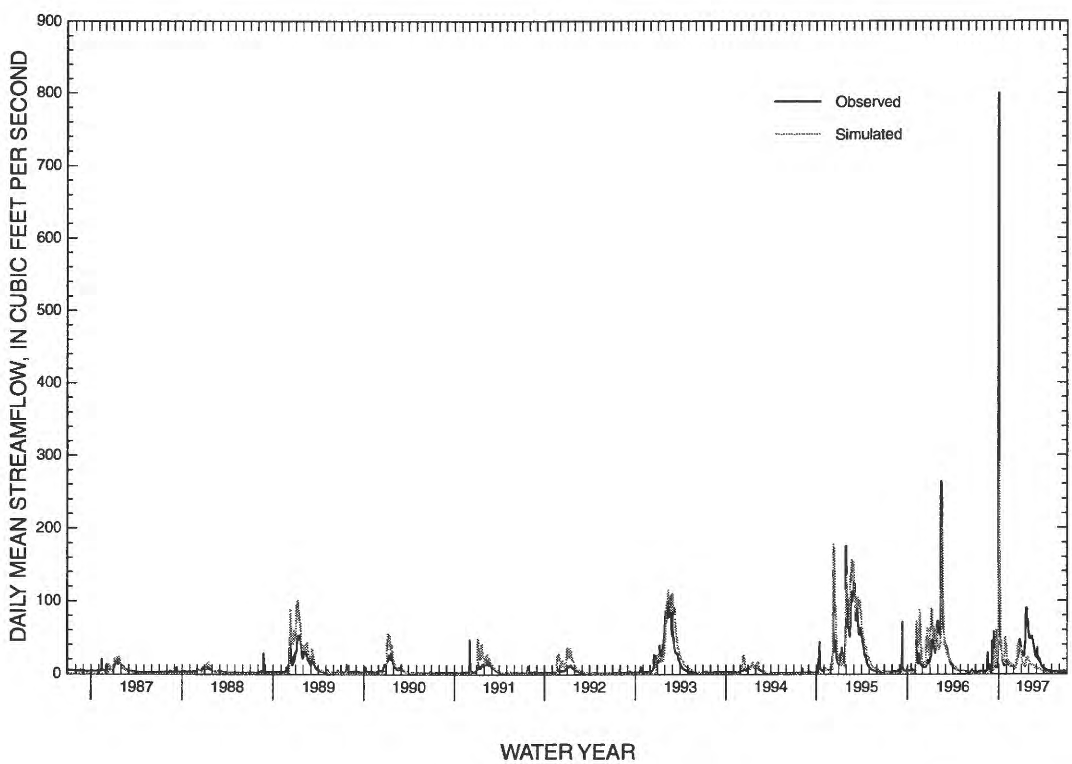

Figure 11. Simulated and observed daily mean streamflow for the verification period, Sagehen Creek, water years 1987-97.

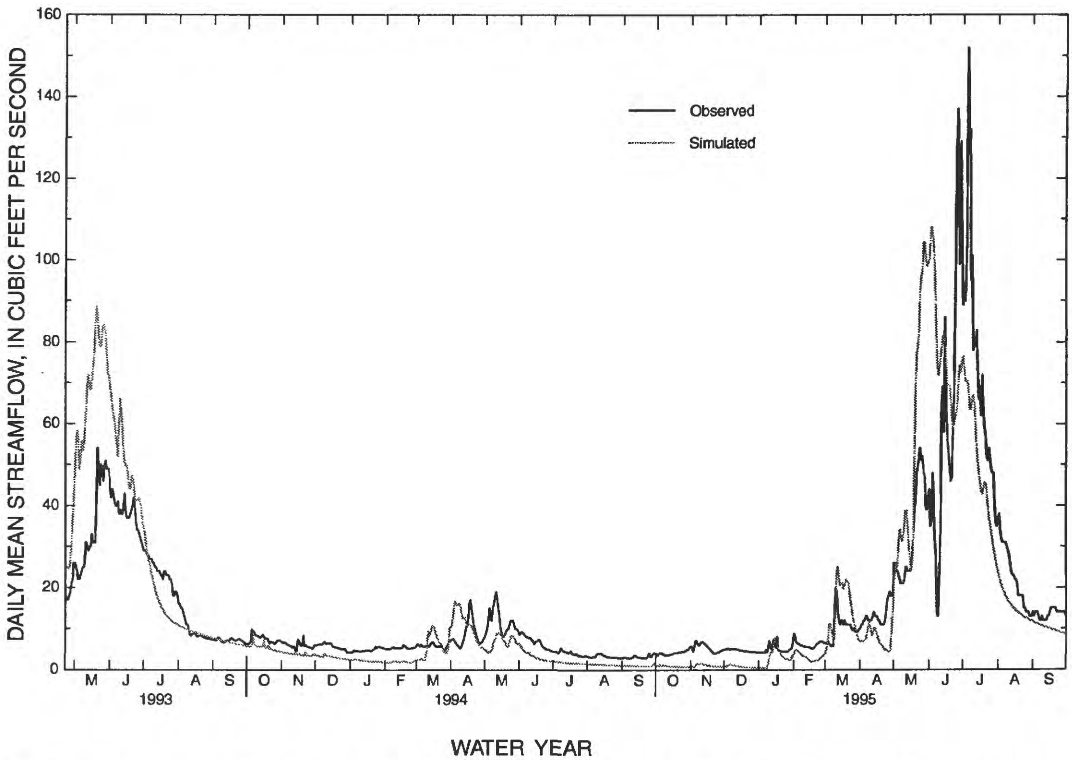

Figure 12. Simulated and observed daily mean streamflow for the calibration period, Bronco Creek, water years 1993-95.

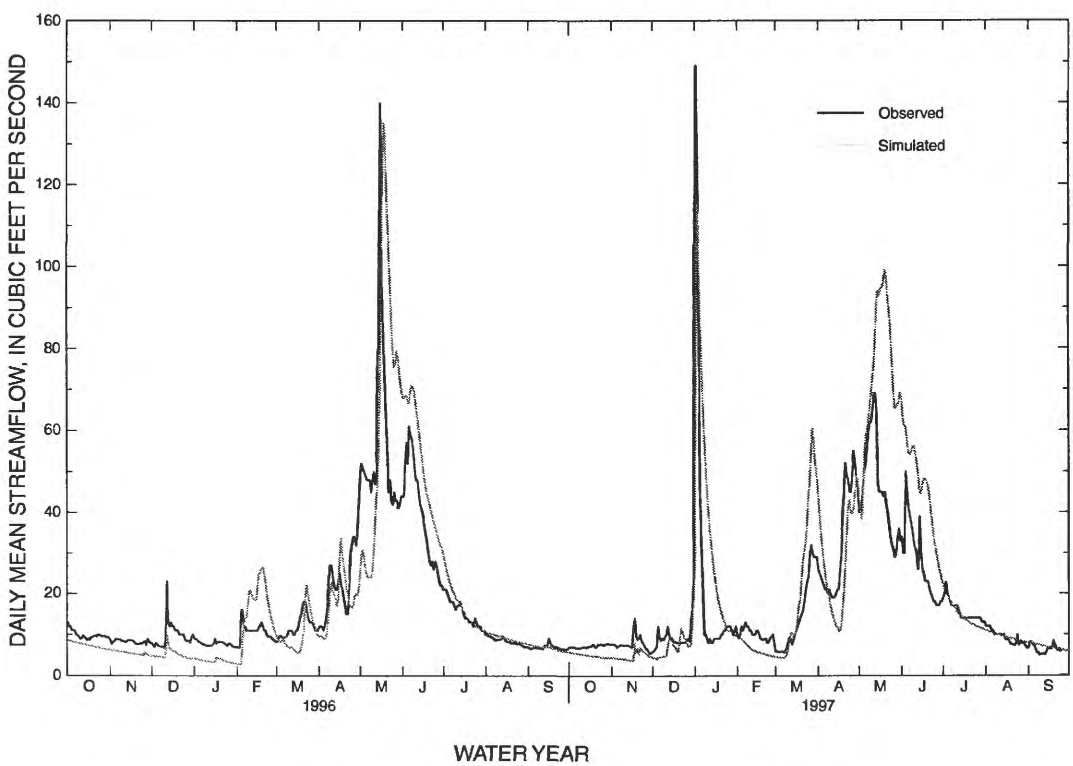

Figure 13. Simulated and observed daily mean streamflow for the verification period, Bronco Creek, water years 1996-97.

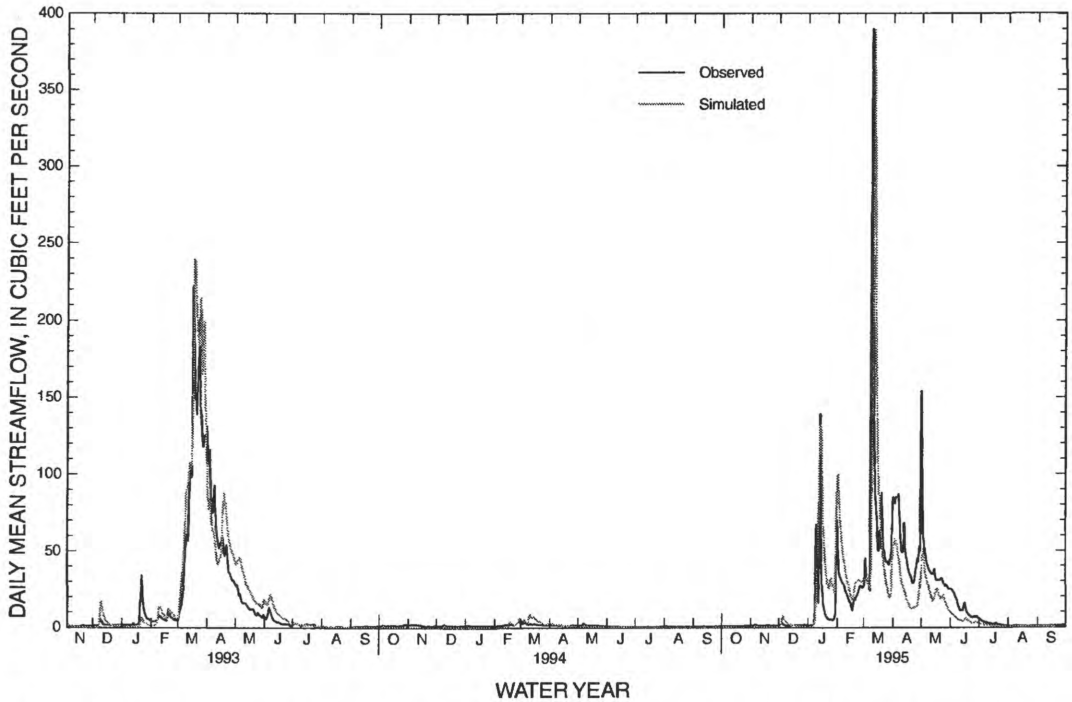

Figure 14. Simulated and observed daily mean streamflow for the calibration period, Dog Creek, water years 1993-95.

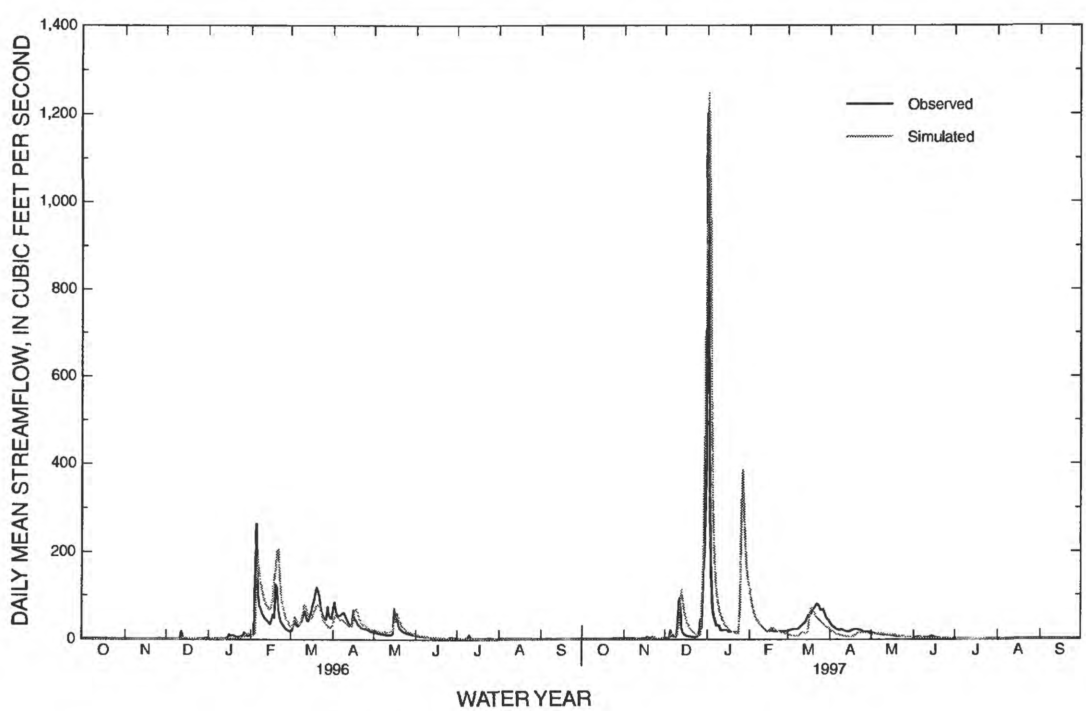

Figure 15. Simulated and observed daily mean streamflow for the verification period, Dog Creek, water years 1996-97.

Pacific Power Company and as such does not have a USGS records rating. Complete flow records were only available from water years 1981 to 1992 due to frequent equipment malfunctions during 1993-97. Water year 1981 was omitted due to questionable data. Runoff was reasonably well simulated during the 1981-85 calibration period (fig. 16) though oversimulated during spring runoff for the 1986-92 verification period (fig. 17), the latter considered a drought period. Daily mean streamflow bias ranged from -5 percent for the calibration period (October 1981 to September 1985) to +7 percent for the verification period (October 1985 to September 1992); relative error ranged from -1 percent to +10 percent, respectively (table 5). Bias for annual mean streamflow was -1 percent, and relative error averaged +2 percent (table 7). Seasonal percentages of annual runoff were similar for both simulated and observed aggregates (table 8).

RESERVOIR INFLOW AND SIMULATED INFLOWS FROM UNGAGED AREAS

Reservoir catchment inflows from the six reservoirs and runoff from the three ungaged areas (fig. 1) were simulated with PRMS and simulation results discussed below. Water balances were simulated for each reservoir and lake (hereafter Donner, Independence, and Martis Creek lakes are referred to as "reservoirs" in the water balance discussions) to compute reservoir inflows. The water balances used observed records of reservoir outflow and tributary inflow, surface precipitation computed from observed data from nearby meteorological stations, and surface evaporation generated from previously published monthly evaporation tables (McGauhey and others, 1963, p. 9; Rod Hall, Sierra Hydrotech, written commun., 1994), as determined from evaporation data at Tahoe City and Boca Reservoir. Seepage losses from the reservoir were not considered.

Evaporation from reservoir surfaces is the most sensitive of all components (and the most difficult to quantify; Winter, 1981, p. 92; Myrup and others, 1979, p. 1501) and thus has the highest uncertainty of any component in the water balance. Due to the absence of total observed inflows and the uncertainty associated with surface precipitation and evaporation, no statistical analyses were computed for the reservoir simulations. Instead, monthly results are presented graphically in figures 18-21. The period of record simulated was determined by the availability of measured tributary inflow and outflow. All the reservoirs were modeled for the 1980-96 period, with the exception of Stampede Reservoir, where inflow from the Little Truckee River above Stampede Reservoir was limited to the 1993-96 period. The "reconstructed" inflow time series ($Q_{\text{unregulated}}$) presented in these figures was computed using the following reservoir water balance equation:

$$Q_{\text{unregulated}} = Q_{\text{outflow}} + E - P - Q_{\text{gaged tributaries}} + \Delta S, \quad (2)$$

where ΔS is a change in reservoir storage,

Q is streamflow,

E is evaporation from the reservoir surface, and

P is precipitation on the reservoir surface.

The data used to reconstruct the reservoir inflows are presented in table 9. The volume and timing of PRMS simulated inflows are well represented for Donner Lake, Prosser Creek Reservoir, Martis Creek Lake, and Boca Reservoir (fig. 18-21). The reconstructed data for the Independence Lake and Stampede model were unsatisfactory even for graphical comparison due to either inadequate or insufficient tributary and lake-stage data. Analysis of Martis Creek Lake model results suggested a significant part of the runoff is lost to the subsurface zone before it reaches the impoundment at Martis Creek Lake. The Martis Creek Lake subbasin is a low-altitude drainage basin where only 2 percent of the drainage area is above the 8,000-ft elevation zone, thus contributing less snowmelt runoff than some of the other modeled subbasins. Simulated inflow approximated the reconstructed time series (fig. 20) only after a shallow ground-water sink term was applied to reduce excessive simulated inflow. Upstream from the reservoir, thick sediments may have a greater storage potential than is accounted for by the model. Actual ground water may be routed directly to the Truckee River, bypassing Martis Creek.

Three ungaged areas were modeled (fig. 1). Essentially the ungaged areas are either aggregated areas of ungaged tributary inflow to the Truckee River (for example ungaged areas 1 and 2) or an intervening area between two reservoir catchments (ungaged area 3). The ungaged areas total 18 percent of the study area. With the exception of Gray and Juniper Creeks in ungaged area 2 whose headwaters are above 8,000 ft, most of the ungaged-areas are well below 7,500 ft and thus are not significant contributors of snowmelt runoff to the Truckee River.

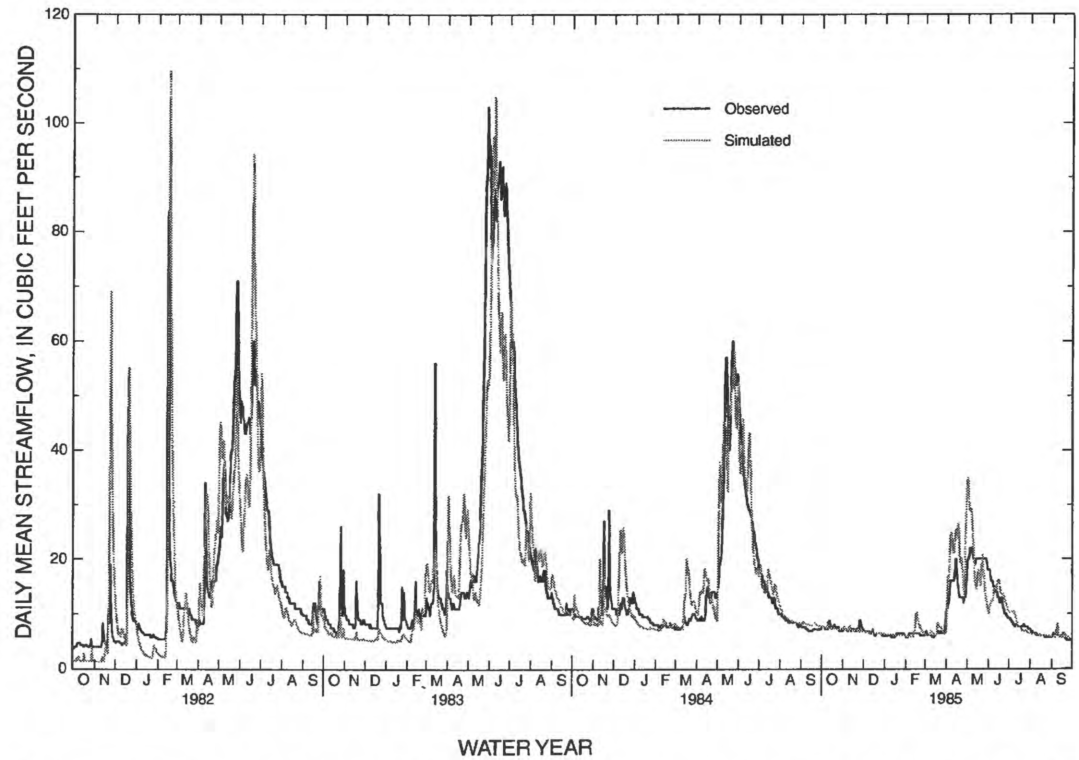

Figure 16. Simulated and observed daily mean streamflow for the calibration period, Hunter Creek, water years 1982-85.

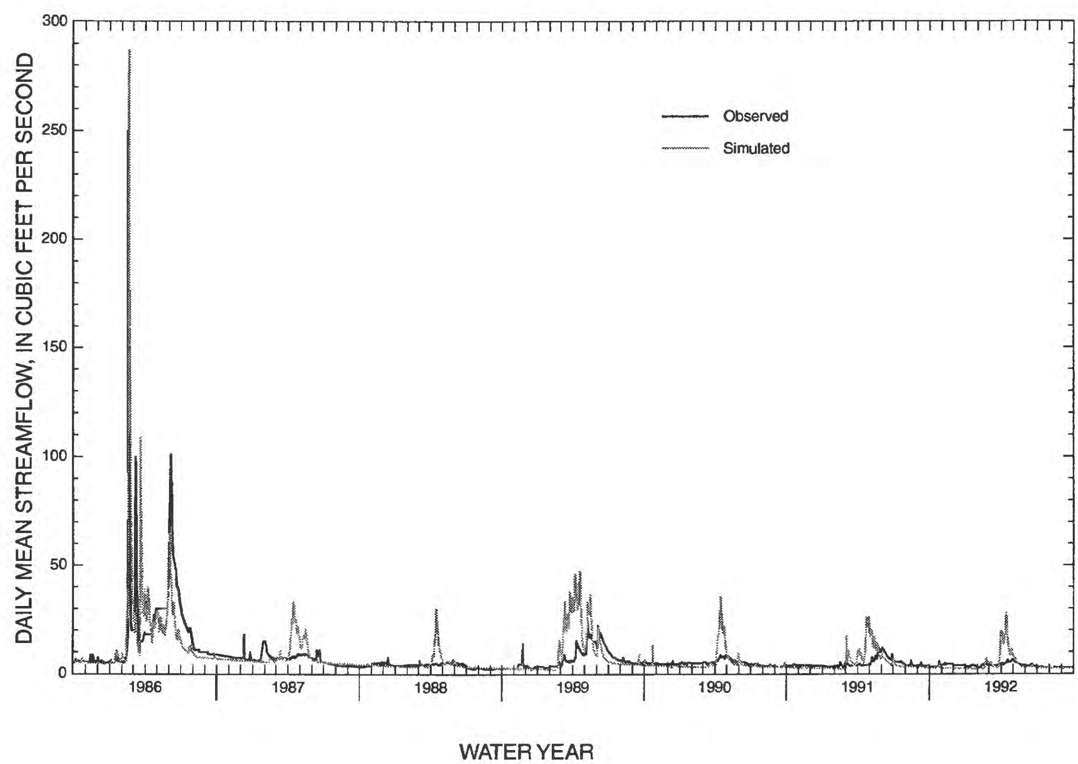

Figure 17. Simulated and observed daily mean streamflow for the verification period, Hunter Creek, water years 1986-92.

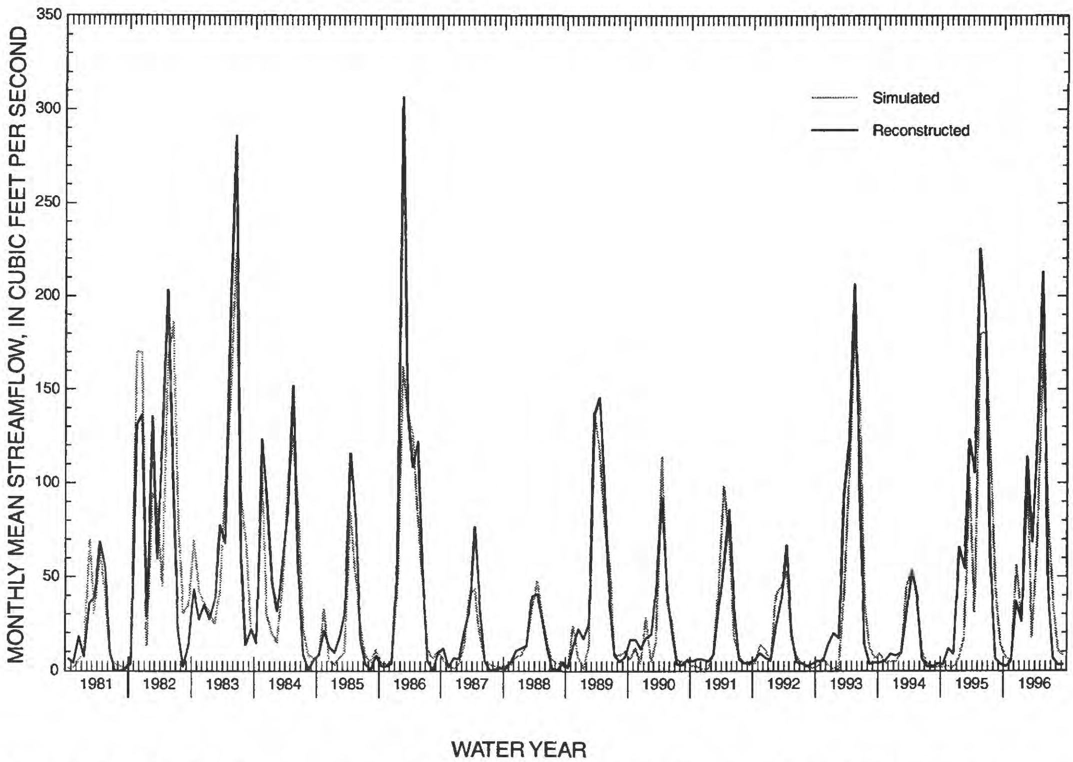

Figure 18. Simulated and reconstructed monthly mean streamflow for Donner Lake, water years 1981-96.

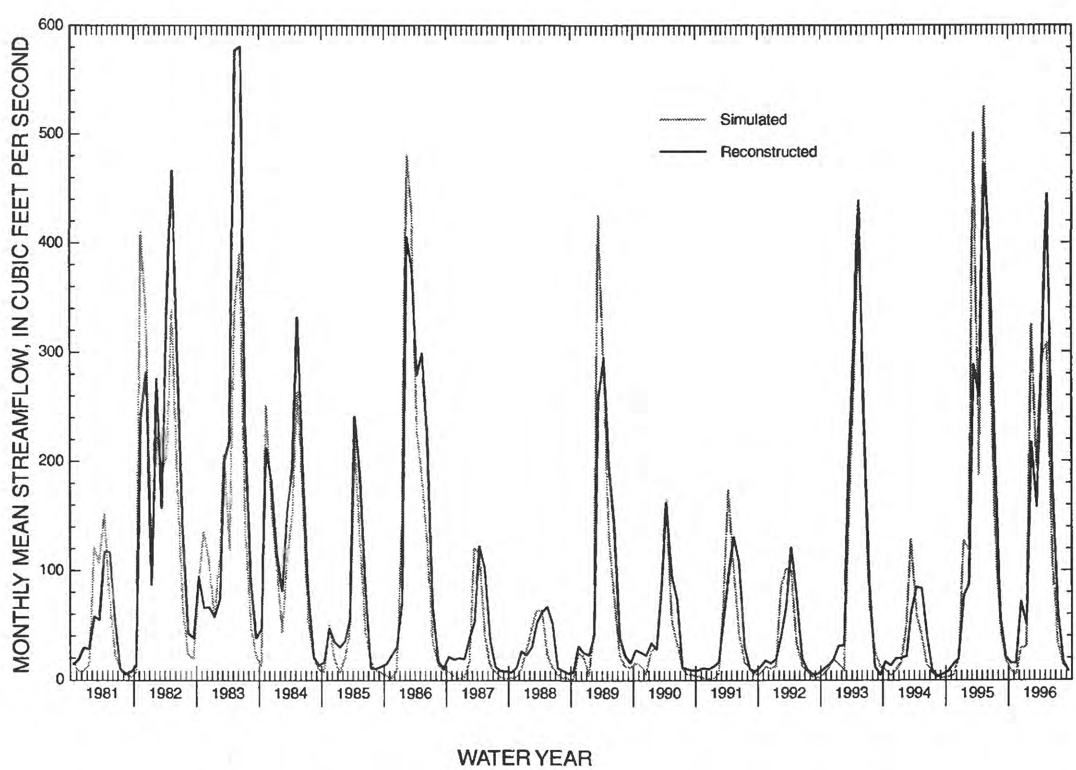

Figure 19. Simulated and reconstructed monthly mean streamflow for Prosser Creek Reservoir, water years 1981-96.

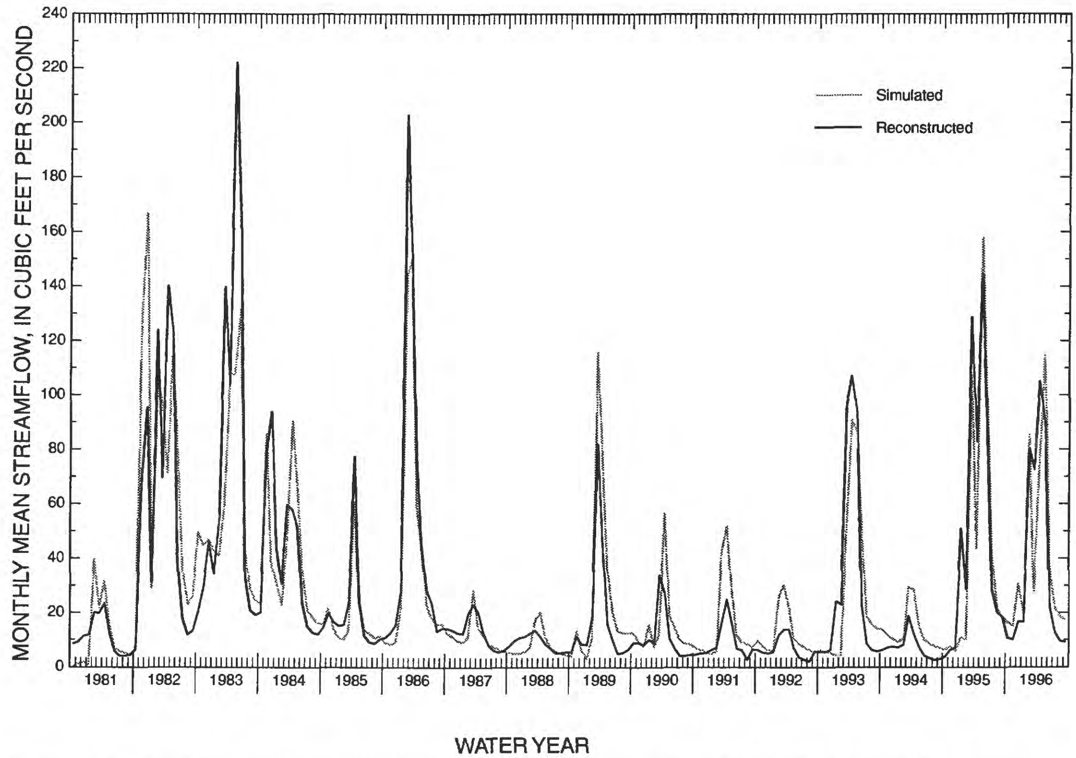

Figure 20. Simulated and reconstructed monthly mean streamflow for Martis Creek Lake, water years 1981-96.

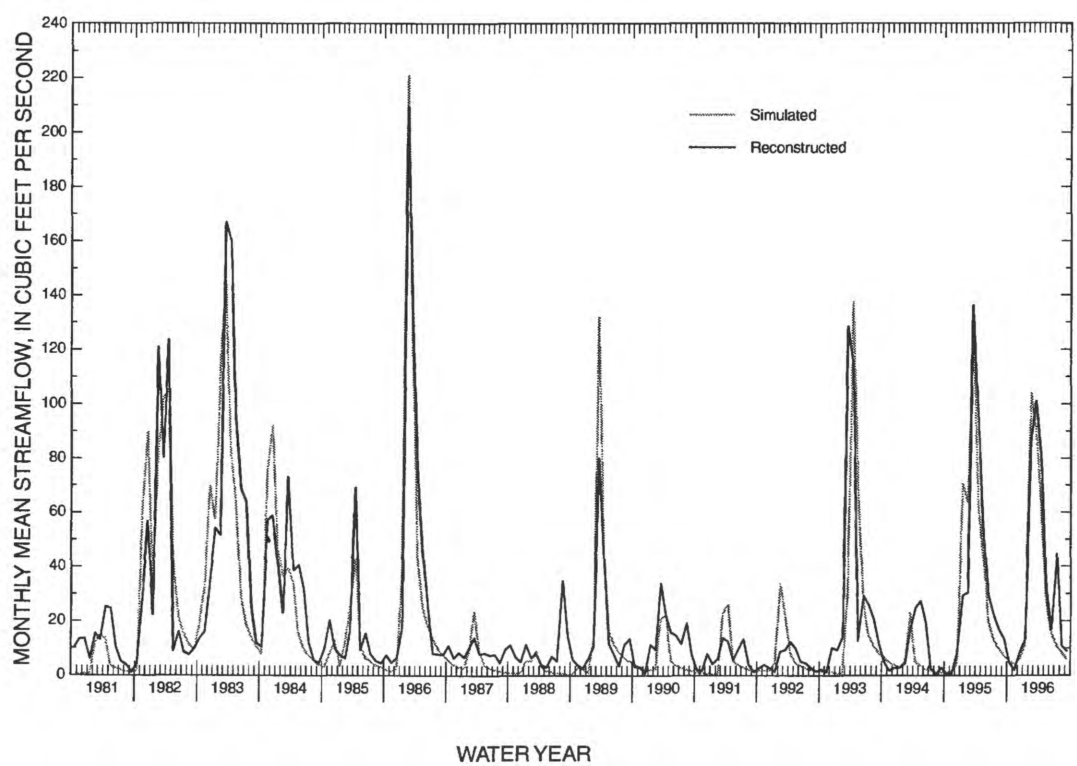

Figure 21. Simulated and reconstructed monthly mean streamflow for Boca Reservoir, water years 1981-96.

Table 9. Data used to compute water balance estimates (see equation 2) for reservoirs and regulated lakes in the upper Truckee River Basin, California and Nevada

[Refer to tables 2 and 3 and figure 1 for gaging and climate station descriptions and locations]

Reservoir or lake	Period of simulation	Reservoir storage (station number)	Outflow (station number)	Surface evaporation	Surface precipitation	Gaged tributaries (station number)
Donner Lake	1980-96	10338400	10338500	Tahoe City [1]	Donner Memorial State Park	none
Martis Creek Lake	1980-96	USACE [2] gage	10339400	Boca [3]	Boca	none
Prosser Creek Reservoir	1980-96	10340300	10340500	Boca	Boca	none
Independence Lake	1980-96	10342900	10343000	Tahoe City	Sagehen	none
Stampede Reservoir	1993-96	10344300	10344400	Boca	Boca	(10343500+ 10341950+ 10343000)
Boca Reservoir	1980-96	10344490	10344500	Boca	Boca	10344400

[1] Monthly evaporation from Tahoe City (McGauhey and others, 1963) gage ajdusted by a pan coefficient of 0.85.

[2] U.S. Army Corps of Engineers stage gage.

[3] Monthly evaporation from the Boca meteorological station (R. Hall, Sierra Hydro Tech, written commun., 1994).

Reconstructed flow ($Q_{subbasin}$) was simulated for the ungaged areas along the Truckee River (ungaged areas 1 and 2) using the general equation:

$$Q_{subbasin} = Q_{downstream} - Q_{upstream} - Q_{tributaries}. \quad (3)$$

Data constraints limited the period of record to water years 1994-96. The reconstructed flows for ungaged areas 1 and 2 were not used to calibrate the PRMS model due to the uncertainty in accumulated error associated with using streamflow data from more than one gaging station. However, most of the ungaged area is situated at low altitudes and probably contributes little to snowmelt runoff. The 9.8-mi^2 area between Stampede and Boca Reservoirs was modeled as the third ungaged area (subbasin 12). No reconstructed flow was computed due to the lack of upstream and downstream flow data.

MODEL LIMITATIONS

Model uncertainties are due to simplifications made in the representations of hydrologic processes and the assumption that the ungaged areas and the reservoir subbasins are hydrologically similar to the gaged subbasins. These various sources of uncertainty are discussed in this section, as well as uncertainties in data input, and suggestions for model improvements. Discrepancies in matching simulated streamflow to observed streamflow appear to be due primarily to difficulties in modeling the temporal and spatial distribution of precipitation and temperature, the form of precipitation, and snowpack melt-rates.

Point precipitation from measured locations (table 2) was adjusted with altitude-dependent lapse rates to correct for daily differences in elevation between the HRU and the index climate station. Monthly regional temperature lapse rates were used to adjust air temperature. Climate data for some of the modeled subbasins were adjusted further in PRMS using a correction factor as applied to the daily values, suggesting some uncertainty in the spatial and temporal distribution of climate input.

Simulating the actual form of precipitation is particularly a problem for middle-altitude zones (6,000-7,500 ft) for most of the upper Truckee River Basin where winter storms produce a mix of rain and snow. In middle-altitude basins, winter temperatures are near the freezing point over large areas. This makes these basins more sensitive to changes in winter temperature. The observed range of surface-air temperatures at which snow may be formed is broad, and calibrated values for the snow-threshold temperature can range over several degrees without violating physical reasonableness. The result is a simulated snow-threshold value suitable for many storms but too warm for others. In turn, simulated snow accumulation or snowmelt rates may be affected, especially during warm storms, which are large precipitation contributors in the Sierra Nevada (Cayan and Riddle, 1992). In addition, model monthly lapse rates for temperature may not reflect the variability in actual daily lapse rates, which can be a source of modeling error.

Problems with the simulated timing of snowmelt may be partly related to how PRMS represents the dynamics of warm snowpacks. PRMS tends to simulate fairly rapid snowmelt for most alpine basins once the snowpack is primed for melt (the temperature at which the snowpack is ready for melt), which usually occurs in the spring. In actuality, though, winter snowmelt in the upper Truckee River Basin is sporadic due to the frequency of rain-on-snow storms and the wide range of springtime daily temperatures and thus, results in less overall spring-melt streamflow. For most simulations, maintaining a spring snowpack while attempting to model the late fall-early winter rain-on-snow storms often results in a longer-than-observed spring snowpack, which results in more snowmelt and streamflow later in the year. Conversely, adjusting the temperature-dependent parameters to better model the rain-on-snow events commonly results in simulation of less-than-observed spring snowmelt runoff.

Losses from the snowpack by sublimation are probably significant, although no observations are available for the study basins. Dozier and Melack (1989) estimated that sublimation accounted for 80 percent of total annual loss to the atmosphere in a study at the Emerald Lake watershed in Sequoia National Forest in the southern Sierra Nevada. These losses may be higher than in the upper Truckee River Basin. The Emerald Lake Basin has virtually no vegetation cover and thus no shading, which would reduce snowpack losses by sublimation. Still, Dozier and Melack's results suggest that sublimation may be quite important in the study basins and that some limitations of PRMS' estimates of sublimation need to be considered. PRMS assumes that no sublimation takes place while plants are transpiring. For moderate-to-high altitude watersheds where transpiration begins in late March to early April (when much of the snowpack is still present, particularly for higher-than-normal precipitation years), sublimation may be underestimated.

The net short- and long-wave components of the snowpack energy budget depend on estimates of winter canopy-cover density. As a result, errors in canopy cover affect simulated snowmelt and streamflow timing. Absorption of incoming short-wave radiation by the snowpack is a function of the snow albedo and the canopy-transmission coefficient. An earlier study on the Carson River Basin (Jeton and others, 1996) indicated that a 20-percent change in canopy results in a change in streamflow timing of several weeks. In the present study, canopy density estimates vary according to the vegetation type. Canopy density for conifers was derived from the USFS 1980 timber-type data source (U.S. Forest Service, 1994). Because no USFS estimates were provided for non-conifer vegetation (grasses, shrubs, and deciduous), a default value was assigned. Real-time watershed runoff simulations would require that the vegetation type and density data be updated to reflect the watershed conditions during the modeling (or forecast) period. Canopy density or vegetation-type values were not modified in this study to account for departures from the initial 1980 values that were attributable to fires, timber cutting, drought-induced die-off, or urban development since then.

River basins are dynamic systems. Land-cover type, density, and the percentage of impervious surface in urban areas are static parameters in PRMS and, therefore, reflect development or land cover existing at the time data were collected or when the digital maps were compiled. Population growth in the upper Truckee River Basin since the late 1970's, when the land-cover data base was compiled, has increased as has the amount of land-surface area that can be classified as urban. Of more significance, hydrologically, is the prevalence of wide-spread forest fires during the 1980-97 period, which changed the vegetation type, density, canopy interception, and, for a period following a fire, the infiltration-capacity of the soil. None of the model parameter values were changed to reflect the modified conditions.

Accurate delineation of bedrock areas is important because PRMS emphasizes routing precipitation or snowmelt on bedrock primarily as surface runoff, with little or no surface-water/ground-water interaction. Several subbasins modeled—Cold Creek, Webber Lake, Sagehen Creek, and particularly Martis Creek Lake —have substantial sedimentary units as indicated by geologic and soils maps for the area. However, because little is known about the ground-water storage capacity of these units, the subsurface flow contribution to water yield is uncertain.

Potential model improvements might include additional tributary inflow data, incorporating changing land-cover and canopy density to reflect changes during the modeling period, ground-water observations, improved reservoir-surface precipitation and evaporation data to allow for calibration of PRMS inflows, and sublimation estimates specific to the north-central Sierra Nevada.

SUMMARY AND CONCLUSIONS

Decades of litigation culminated in the enactment of the Truckee-Carson-Pyramid Lake Water Rights Settlement Act of 1990 (Title II of Public Law (P.L.) 101-618). The law provides a foundation for developing operating criteria for interstate allocation of water as well as to meet water-quality standards in the Truckee River and Carson River Basins of western Nevada and eastern California. The Truckee-Carson Program of the U.S. Geological Survey is assisting the U.S. Department of the Interior in implementing the Truckee-Carson-Pyramid Lake Water Rights Settlement Act of 1990, and particularly the Truckee River Operating Agreement. Some of the program objectives include: consolidate streamflow and water-quality data from several agencies into a single database; establish new streamflow and water-quality gaging stations for more complete water-resources information, and construct interbasin hydrologic computer models to support water-resource planning and management. The Truckee River is regulated by several reservoirs upstream from the USGS gaging station at Farad, California. Most of the remaining perennial tributaries that are unregulated are also ungaged. The need for unregulated daily streamflow time series input to the USGS Truckee River operations model (Steven Berris, oral commun., 1998) prompted the development of precipitation-runoff models for designated flow-routing reaches in the Tahoe and Truckee River Basin.

The USGS Precipitation-Runoff Modeling System was used to simulate streamflow from seven gaged subbasins, six reservoir catchments and three ungaged areas in the upper Truckee River Basin, from Lake Tahoe to the USGS streamflow gaging station at Farad, Calif. The study area also includes two tributaries downstream from Farad, Dog Creek, and Hunter Creek. PRMS is a physically based, distributed-parameter watershed model designed to analyze the effects of precipitation, temperature, and land use on streamflow and general basin hydrology. Each subbasin was partitioned into hydrologically homogeneous subareas called hydrologic response units, or HRU's. HRU's were delineated for the study basins using an integrated geographic information system (GIS) containing raster and vector-based data interpolated on 30-meter (98-ft) grids. Data included altitude, slope, aspect, land cover, soils, and geology. Using pattern-recognition techniques, land areas in the grid were partitioned into noncontiguous but hydrologically similar land units, called HRU's, based on groupings of the source data. The physical properties affecting streamflow are quantified at the HRU level. Computer programs were developed to aid users in reconstructing the HRU digital data layer and allow for incorporating updates and corrections into the digital data base as new data becomes available.

Precipitation amounts to each HRU were adjusted with a lapse rate equation developed to account for daily, rather than monthly, spatial distributions. Daily temperature data were adjusted using regional monthly lapse rates to account for decreases in temperature relative to increasing altitude. No total observed inflow data existed for the reservoir catchments so these subbasins were modeled as ungaged. Reservoir inflows were reconstructed with a water balance approach using measured change in reservoir storage, estimated surface precipitation and evaporation, and measured outflow. No statistical analyses were used in comparing the reconstructed inflows to the PRMS inflows due to the uncertainty in the reservoir-surface precipitation and evaporation components of the water-budget equation. Graphical analyses of monthly reconstructed reservoir inflows and simulated inflows indicate satisfactory correspondence between the two data sets for all but two of the reservoirs.

Bias in simulating daily mean runoff ranged from -6 to +4 percent for the calibration period and from -7 to +18 percent for the verification period; relative error ranged from -20 to +47 percent for the calibration period and from -6 to +41 percent for the verification period. For the full modeling period, monthly mean runoff bias ranged from -4 to +5 percent, and relative error ranged from -21 to +17 percent. For the full modeling period, annual mean runoff bias ranged from -7 to +7 percent, and relative error ranged from -9 to +11 percent. In general, runoff during the 1995-97 verification period was oversimulated for most of the gaged subbasins. Winter runoff (November through February) can contribute, on average, from 15 to 30 percent of the annual runoff, and is expressed as sharp, short duration runoff peaks. Most of these peaks were fairly well modeled, though runoff during years of below-average precipitation was often oversimulated. Spring runoff (April through June) contributes, on average, 55 percent of the annual streamflow, while simulated runoff during this period averages 50 percent. Timing of simulated spring runoff generally matches that of the observed record.

The method developed for transferring model parameters from gaged, calibrated tributaries to large, aggregated ungaged areas was facilitated through the use of a GIS and an associated relational data base. The ungaged areas and reservoir catchment were indexed to the gaged subbasins of closest geographic and (assumed) hydroclimatic similarity for the purpose of transferring distributed and nondistributed parameters, where applicable. Streamflow for two of the ungaged areas along the main stem of the Truckee River were also reconstructed using differences in flow from upstream and downstream gages. These reconstructed flows were unsatisfactory for comparative purposes due to the cumulative error associated with using several gaging station records.

The upper Truckee River Basin is characterized by moderate-altitude drainage subbasins. Modeling results indicated runoff simulations were sensitive to adjustments made to nondistributed, temperature-dependent parameters and the subsurface and ground-water flow routing coefficients. These parameters in particular affect runoff timing for individual rain or snowmelt events, the shape of the baseflow recession part of the hydrograph, and overall seasonal distribution of runoff. When temperature-dependent model parameters are adjusted to simulate late fall and early winter runoff characteristics of these basins, more of the snowpack at the higher altitudes is melted than is indicated by observed runoff. Conversely, when calibration is adjusted so that spring snowpack is maintained, some of the simulated snowpack lingered beyond what the observed snow-water equivalence data indicated, often producing more summer runoff than was observed. Nondistributed parameter values were transferrable from the template subbasin when hydrogeologic conditions were assumed similar, otherwise regionalized estimates were used.

Few of the distributed (HRU) parameters are adjusted during calibration implying that HRU parameter values can be obtained from relational data-base lookup tables where the HRU parameters are assigned numeric values according to physiographic attributes. HRU-distributed parameter values were generally transferable when physiographic conditions were similar. Many assumptions were inherent in modeling the ungaged areas. The most important assumptions were: the HRU characterization and delineations were realistic, the temporal and spatial distributions of precipitation and temperature were appropriate, and the ungaged areas behaved in a hydrologically similar manner to the gaged subbasins selected as the template.

The mapping of HRU's assumes that the digital data base adequately characterizes the dominant physiographic and land cover features. Error attributed to the digital physiographic data was not computed and, for purposes of evaluating runoff, is considered to be insignificant. Because of model and data limitations, the results from the ungaged areas and the reservoir catchments should be considered initial estimates of simulated runoff. The models for the gaged subbasins were calibrated under a specific set of environmental conditions and assumptions (meteorological, physiographic, hydrologic, and land use). Changing conditions, particularly changes in land cover type and density, climate data, or incorporating new subsurface or ground-water use information may require updated model input data sets and, possibly, recalibration to the new set of conditions.

REFERENCES CITED

Ahrens, D.C., 1985, Meteorology today, an introduction to weather, climate, and the environment: St. Paul, Minn., West Publishing Company, 524 p.

Aguado, Edward, 1985, Radiation balances of melting snow covers at an open site in the central Sierra Nevada, California: Water Resources Research, v. 21, p. 1649–1654.

Berris, S.N., 1996, Daily flow-routing simulations for the Truckee River, California and Nevada: U.S. Geological Survey Water-Resources Investigations Report 96-4097, 83 p.

Bicknell, B.R., Imhoff, J.C., Kittle, J.L., Donigan, A.S., and Johanson, R.C., 1993, Hydrological simulation program-FORTRAN–User's manual for release 10: U.S. Environmental Protection Agency, Environmental Research Laboratory, Report EPA/600/R-93/174, 660 p.

Blodgett, J.C., Oltmann, R.N., and Poeschel, K.R., 1984, Estimation of streamflow for selected sites on the Carson and Truckee Rivers in California and Nevada, 1944-80: U.S. Geological Survey Water-Resources Investigations Report 84-4058, 223 p.

Bonner, L.J., Elliott, P.E., Etchemendy, L.P., and Swartwood, J.R., 1998, Water resources data, Nevada, water year 1997: U.S. Geological Survey Water-Data Report NV-97-1, 636 p.

Butcher, W.S., Gupta, V.L., Fordham, J.W., and Miller, R.E., 1969, Simulation theory applied to water resources management: University of Nevada, Desert Research Institute Technical Report H-W 7, 56 p.

Cayan, D.R., and Riddle, L.G., 1992, Atmospheric circulation and precipitation in the Sierra Nevada, *in* Hermann, Raymond, ed., Managing Water Resources during Global Change: 28th Annual Conference American Water Resources Association, Reno, Nev., November 1992, Proceedings, p. 711–720.

Cobb, E.D., Olson, A.F., Mooseburner, Otto, and Pupacko, Alex, 1990, Review of selected water-management models and results of simulations for the Truckee-Carson Rivers system, California and Nevada: U.S. Geological Survey Open-File Report 90-393, 40 p.

Dickinson, W.T., and Whiteley, H.Q., 1970, Watershed areas contributing to runoff: International Association of Hydrologic Sciences Publication 96, p. 1.12–1.28.

Dinicola, R.S., 1990, Characterization and simulation of rainfall-runoff relations for headwater basins in western King and Snohomish Counties, Washington: U.S. Geological Survey Water-Resources Investigations Report 89–4052, 52 p.

Dozier, Jeff, and Melack, J.M., 1989, Snow, snowmelt, rain, runoff, and chemistry in a Sierra Nevada watershed: Santa Barbara, University of California, Center for Remote Sensing and Environmental Optics, Final report to California Air Resources Board, Contract A6-147-32, 268 p.

Environmental Systems Research Institute, Inc., 1994, GRID command references, ARC/INFO Version 7.0: Redlands, Calif., Environmental Systems Research Institute, 357 p.

Frank, E.C., and Lee, R., 1966, Potential solar beam irradiation on slopes: U.S. Department of Agriculture, Forest Service Research Paper RM-18, 116 p.

Gupta, V.L., and Afaq, S.M., 1974, Numerical simulations of unsteady flows in the Truckee River: University of Nevada, Desert Research Institute Technical Report H-W 21, 69 p.

Haan, C.T., Johnson, H.P., and Brakensiek, D.L., 1982, Hydrologic modeling of small watersheds: American Society of Agricultural Engineers, ASAE Monograph no. 5, 533 p.

Hess, G.W., and Bohman, L.R., 1996, Techniques for estimating monthly mean streamflow at gaged sites and monthly streamflow duration characteristics at ungaged sites in central Nevada: U.S. Geological Survey Open-File Report 96–559, 15 p.

Jensen, M.E., and Haise, H.R., 1963, Estimating evapotranspiration from solar radiation: American Society of Civil Engineers, Journal of Irrigation and Drainage, v. 89, no. IR4, p. 15–41.

Jensen, M.E., Rob, D.C., and Franzoy, C.E., 1969, Scheduling irrigations using climate-crop-soil data: American Society of Civil Engineers, National Conference on Water Resources Engineering, Proceedings, 20 p.

Jeton, A.E., 1999, Precipitation-runoff simulations for the Lake Tahoe Basin, California and Nevada: U.S. Geological Survey Water-Resources Investigations Report 99-4110, 61 p.

Jeton, A.E., Dettinger, M.D., and Smith, J.L., 1996, Potential effects of climate change on streamflow, eastern and western slopes of the Sierra Nevada, California and Nevada: U.S. Geological Survey Water-Resources Investigations Report 95–4260, 44 p.

Jeton, A.E., and Smith, J.L., 1993, Development of watershed models for two Sierra Nevada basins using a geographic information system: Water Resources Bulletin, v. 29, no. 6, p. 923–932.

Kuhn, G., and Parker, R.S., 1992, Transfer of watershed-model parameters from calibrated to noncalibrated basins in the Gunnison River Basin, Colorado *in* Hermann, Raymond, ed., Managing Water Resources during Global Change: 28th Annual Conference American Water Resources Association, Reno, Nev., November 1992, Proceedings, p. 741–759.

Laenen, Antonius, and Risley, J.C., 1997, Precipitation-runoff and streamflow-routing models for the Willamette River Basin, Oregon: U.S. Geological Survey Water-Resources Investigations Report 95–4284, 197 p.

Leavesley, G.H., 1973, A mountain watershed simulation model: Fort Collins, Colo., Colorado State University, Ph.D. dissertation, 174 p.

———1989, Problems in snowmelt runoff modeling for a variety of physiographic and climatic conditions: Hydrological Sciences, v. 34, no. 6, p. 617–634.

Leavesley, G.H., Litchy, R.W., Troutman, M.M., and Saindon, L.G., 1983, Precipitation-runoff modeling system—User's manual: U.S. Geological Survey Water-Resources Investigation Report 83–4238, 207 p.

Leavesley, G.H., Restrepo, P.J., Markstrom, S.L., Dixon, M., and Stannard, L.G., 1996, The modular modeling system (MMS)—User's manual: U.S. Geological Survey Open-File Report 96-151, 142 p.

Matthai, H.F., 1974, Long-term flow of the Truckee River in California and Nevada: U.S. Geological Survey Open-File Report 74-213, 24 p.

McGauhey, P.H., Eliassen, R., Gerald, R., Ludwig, H.F., and Pearson, P.A., 1963, Comprehensive study on protection of water resources of Lake Tahoe Basin through controlled waste disposal: Arcadia, Calif., Engineering Science, Inc., 157 p.

Myrup, L.O., Powell, T.M., Godden, D.A., and Goldman, C.R., 1979, Climatological estimate of the average monthly energy and water budgets of Lake Tahoe, California and Nevada: Water Resources Research, v. 15, no. 6, p. 1499-1508.

Natural Resources Conservation Service, 1980, Soil Survey of Washoe County, Nevada, South Part: U.S. Department of Agriculture, 608 p.

Parrett, Charles, and Cartier, K.D., 1990, Methods for estimating monthly streamflow characteristics at ungaged sites in western Montana: U.S. Geological Survey Water-Supply Paper 2365, 30 p.

Risley, J.C., 1994, Use of a precipitation-runoff model for simulating effects of forest management on streamflow in 11 small drainage basins, Oregon Coast Range: U.S. Geological Survey Water-Resources Investigations Report 93–4181, 61 p.

Ryan, Thomas, 1996, Development and application of a physically based distributed parameter rainfall runoff model in the Gunnison River Basin: Bureau of Reclamation, Climate Change Response Program, 64 p.

Swift, L.W., Jr., 1976, Algorithm for solar radiation on mountain slopes: Water Resources Research, v. 12, no. 1, p. 108–112.

Taylor, R.L., 1998, Simulation of hourly stream temperature and daily dissolved solids for the Truckee River, California and Nevada: U. S. Geological Survey Water-Resources Investigations Report 98-4064, 70 p.

Troutman, B.M., 1985, Errors and parameter estimation in precipitation-runoff modeling—1. Theory: Water Resources Research, v. 12 no. 8, p. 1195-1213.

U.S. Army Corps of Engineers, 1956, Snow hydrology—Summary of snow investigations: Portland, Oreg., U.S. Army Corps of Engineers Technical Summary, 437 p.

U.S. Forest Service, 1994, Soil Survey, Tahoe National Forest Area, California: Pacific Southwest Region, U.S. Department of Agriculture.

U.S. Geological Survey, 1985, U.S. Geodata—Digital Line Graphs from 1:100,000 scale maps: National Mapping Program Technical Instructions, Data Users Guide 2, 74 p.

____1986a, U.S. Geodata—Land use and land cover digital data from 1:250,000 scale maps: National Mapping Program Technical Instructions, Data Users Guide 1, 109 p.

____1986b, U.S. Geodata—Digital Line Graphs from 1:24,000 scale maps: National Mapping Program Technical Instructions, Data Users Guide 1, 109 p.

____1987, U.S. Geodata—Digital elevation models: National Mapping Program Technical Instructions, Data Users Guide v. 5, 38 p.

Winter, T.C., 1981, Uncertainties in estimating the water balance of lakes: Water Resources Bulletin, v. 17, no. 1, p. 82-114.

Appendix. Name, size, and description of files used in precipitation-runoff simulations for the upper Truckee River Basin, California and Nevada [1]

[Abbreviations: HRU, hydrologic response unit; PRMS, precipitation-runoff modeling system]

File	Size (bytes)	Description
tahoe-truckee_adj_climateQ.mms	461,227	Daily precipitation and temperature adjusted for each HRU and observed streamflow - Tahoe City-to-Truckee model input.
donner_adj_climateQ.mms	3,021,542	Daily precipitation and temperature adjusted for each HRU and observed streamflow - Donner Reservoir model input.
coldck_adj_climateQ.mms	637,514	Daily precipitation and temperature adjusted for each HRU and observed streamflow - Cold Creek model input.
ungaged1_adj_climateQ.mms	2,741,018	Daily precipitation and temperature adjusted for each HRU and observed streamflow - Ungaged area1 model input.
martis_adj_climateQ.mms	2,460,517	Daily precipitation and temperature adjusted for each HRU and observed streamflow - Martis Creek Lake model input.
ungaged2_adj_climateQ.mms	5,651,327	Daily precipitation and temperature adjusted for each HRU and observed streamflow - Ungaged area 2 model input.
prosser_adj_climateQ.mms	4,739,675	Daily precipitation and temperature adjusted for each HRU and observed streamflow - Prosser Creek Reservoir model input.
webber_adj_climateQ.mms	955,242	Daily precipitation and temperature adjusted for each HRU and observed streamflow - Webber Lake model input.
independence_adj_climateQ.mms	1,829,359	Daily precipitation and temperature adjusted for each HRU, and observed streamflow - Independence Lake model input.
sagehenck_adj_climateQ.mms	1,012,313	Daily precipitation and temperature adjusted for each HRU and observed streamflow - Sagehen Creek model input.
stampede_adj_climateQ.mms	3,477,432	Daily precipitation and temperature adjusted for each HRU and observed streamflow - Stampede Reservoir model input.
ungaged3_adj_climateQ.mms	1,443,644	Daily precipitation and temperature adjusted for each HRU and observed streamflow - Ungaged area 3 model input.
boca_adj_climateQ.mms	2,109,872	Daily precipitation and temperature adjusted for each HRU and observed streamflow - Boca Reservoir model input.
broncock_adj_climateQ.mms	845,676	Daily precipitation and temperature adjusted for each HRU and observed streamflow - Bronco Creek model input.
dogck_adj_climateQ.mms	812,806	Daily precipitation and temperature adjusted for each HRU and observed streamflow - Dog Creek model input.
hunterck_adj_climateQ.mms	1,689,108	Daily precipitation and temperature adjusted for each HRU and observed streamflow - Hunter Creek model input.
tahoe-truckee_final_param.file	143,093	PRMS parameter input file for Tahoe-to-Truckee reach.
donner_final_param.file	92,558	PRMS parameter input file for Donner Reservoir.
coldck_final_param.file	62,649	PRMS parameter input file for Cold Creek.
ungaged1_final_param.file	84,111	PRMS parameter input file for Ungaged area 1.
martis_final_param.file	7,562	PRMS parameter input file for Martis Creek Lake.
ungaged2_final_param.file	17,319	PRMS parameter input file for Ungaged area 2.
prosser_final_param.file	145,239	PRMS parameter input file for Prosser Creek Reservoir.
webber_final_param.file	9,374	PRMS parameter input file for Webber Lake.
independence_final_param.file	56,084	PRMS parameter input file for Independence Lake.
sagehenck_param.file	29,132	PRMS parameter input file for Sagehen Creek.
stampede_param.file	10,663	PRMS parameter input file for Stampede Reservoir.
ungaged3_param.file	44,305	PRMS parameter input file for Ungaged area 3.
boca_param.file	6,465	PRMS parameter input file for Boca Reservoir.
broncock_param.file	82,900	PRMS parameter input file for Bronco Creek.
dogck_param.file	79,683	PRMS parameter input file for Dog Creek.
hunterck_param.file	51,662	PRMS parameter input file for Hunter Creek.

[1] For more information, please contact the USGS, Water Resources Division in Nevada at (702) 887-7649 or email request to <GS-W-NVpublic-info@usgs.gov>.