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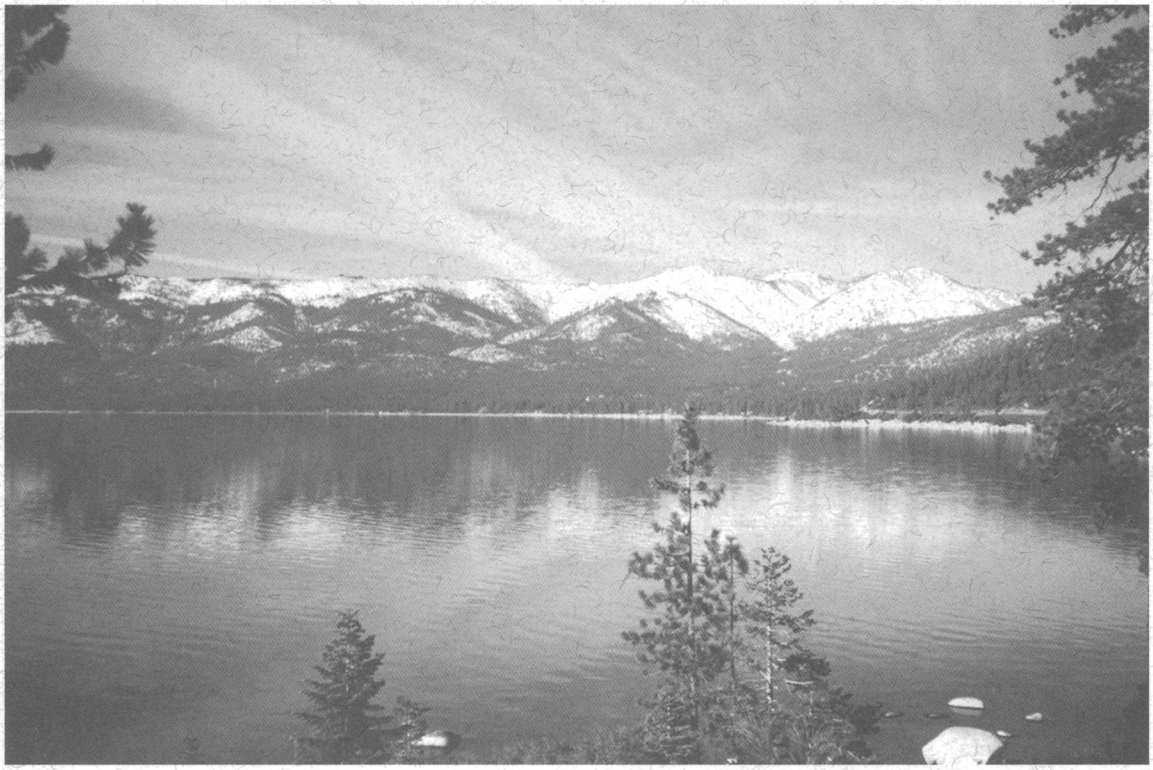
Precipitation-Runoff Simulations for the Lake Tahoe Basin, California and Nevada

Water-Resources Investigations Report 99-4110



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COVER PHOTOGRAPH: Lake Tahoe, March 1995; northward view of Incline Village area, from near Sand Harbor, Nevada. Photograph by Timothy G. Rowe, U.S. Geological Survey.

Precipitation-Runoff Simulations for the Lake Tahoe Basin, California and Nevada

By Anne E. Jeton

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 99–4110

A product of the
TRUCKEE-CARSON PROGRAM

Carson City, Nevada
1999

U.S. DEPARTMENT OF THE INTERIOR
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CONTENTS

Abstract 1
Introduction 2
Purpose and Scope 3
Previous Studies 4
Description of Study Area 4
Acknowledgments 9
Methods of Study 9
Model Description 9
Model Application 11
Description of Gaged Subbasins 12
Ward Creek and Blackwood Creek 12
Third Creek and Incline Creek 12
Glenbrook Creek and Logan House Creek 13
Upper Truckee River and Trout Creek 13
General Creek 13
Streamflow Data 13
Description and Analysis of Climate Data 14
Precipitation Data 15
Temperature Data 16
Basin Characterization, and Delineation of Hydrologic Response Units 17
Model Calibration and Verification for Gaged Subbasins 23
Model Parameterization 24
Error Analysis 25
Ward Creek and Blackwood Creek Subbasins 29
Third Creek and Incline Creek Subbasins 33
Glenbrook Creek and Logan House Creek Subbasins 33
Upper Truckee River and Trout Creek Subbasins 36
General Creek Subbasin 39
Modeling Ungaged Areas 41
Approach 41
Estimating Uncertainty in Ungaged Runoff 50
Limitations of the Model and of its Application to a Lake Tahoe Water Budget 51
Modeling Uncertainties 51
Model Limitations Associated with Application to a Lake Water Budget 52
Summary and Conclusions 55
References Cited 57
Appendix 59

FIGURES

1. Maps showing meteorological sites, gaged and ungaged areas, streamflow data sites used for watershed models, and selected hydrologic features, Lake Tahoe Basin, California and Nevada 6
2. Map showing classification of soils in the Lake Tahoe Basin 8
3. Diagram showing Precipitation-Runoff Modeling System 10
4. Diagram showing steps in basin characterization and hydrologic-response-unit delineation. 18

5–8. Maps showing classification of features in the Lake Tahoe Basin:
- 5. Altitude 19
- 6. Slope 20
- 7. Aspect 21
- 8. Land cover 22

9–10. Hydrographs showing simulated and observed monthly mean streamflow for subbasins in the Lake Tahoe Basin:
- 9. Ward Creek, water years 1981–96 31
- 10. Blackwood Creek, water years 1981–96 31

11–12. Hydrographs showing simulated and observed daily mean streamflow for subbasins in the Lake Tahoe Basin:
- 11. Ward Creek, water years 1996–97 32
- 12. Blackwood Creek, water years 1996–97 32

13–18. Hydrographs showing simulated and observed monthly mean streamflow for subbasins in the Lake Tahoe Basin:
- 13. Third Creek, water years 1981–96 34
- 14. Incline Creek, water years 1989–96 34
- 15. Glenbrook Creek, water years 1990–96. 35
- 16. Logan House Creek, water years 1985–96 35
- 17. Upper Truckee River, water years 1981–96 37
- 18. Trout Creek, water years 1981–96 37

19–20. Hydrographs showing simulated and observed daily mean streamflow for subbasins in the Lake Tahoe Basin:
- 19. Upper Truckee River, water years 1996–97 38
- 20. Trout Creek, water years 1996–97 39

21. Hydrograph showing simulated and observed monthly mean streamflow for General Creek, water years 1981–96 40
22. Hydrograph showing simulated and observed daily mean streamflow for General Creek, water years 1996–97 40

23–25. Maps showing digital classification of hydrologic response units in the Lake Tahoe Basin for:
- 23. Ward Creek and Blackwood Creek Subbasins 44
- 24. Third Creek and Incline Creek Subbasins 46
- 25. Ungaged area 11 and associated index subbasins 49

26. Graph showing simulated and observed daily mean lake-storage volumes, Lake Tahoe for the period 1980–96 54

TABLES

1. Streamflow gaging stations and subbasins used in watershed models for Lake Tahoe Basin, California and Nevada. 14
2. Information for meteorological sites used in watershed models and in regional analysis of precipitation data for Lake Tahoe Basin, California and Nevada 15
3. Source of parameter values for distributed and (selected) nondistributed PRMS parameters for the Lake Tahoe Basin, California and Nevada 26

4-6. Statistical analyses for gaged subbasins in the Lake Tahoe Basin, California and Nevada:
   4. Simulated daily mean streamflow 28
   5. Simulated monthly mean streamflow 29
   6. Simulated annual mean streamflow 29

7. Simulated and observed monthly percentage of annual streamflow for gaged subbasins and simulated monthly percentage of runoff for the ungaged areas in the Lake Tahoe Basin 30
8. Simulated inflow to Lake Tahoe by gaged subbasins and ungaged areas, California and Nevada 51

CONVERSION FACTORS, VERTICAL DATUM, AND ACRONYMS

Multiply	By	To obtain
acre-foot (acre-ft)	0.001233	cubic hectometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer
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: Refers to the 12-month period October 1 through September 30. The water year is designated by the calendar year in which it end. Thus, the year beginning October 1, 1980, and ending September 30, 1981, is called the "1981 water year."

Acronyms:

AET — actual evapotranspiration
AML — arc macro language
EOF — empirical-orthogonal function
GIS — geographic information system
HRU — hydrologic response unit
HSPF — Hydrological Simulation Program-FORTRAN
NRCS — Natural Resources Conservation Service
NWSRFC — National Weather Service River Forecasting System
PCA — principal-component analysis
PET — potential evapotranspiration
PIN — Pattern Identification Number
PRMS — Precipitation-Runoff Modeling System
SNOTEL — Snowpack Telemetry
SWE — snowpack water equivalence
TCP — Truckee-Carson Program
TRPA — Tahoe Regional Planning Agency
USGS — U.S. Geological Survey
USFS — U.S. Forest Service

Precipitation-Runoff Simulations for the Lake Tahoe Basin, California and Nevada

by Anne E. Jeton

ABSTRACT

Precipitation-runoff models for 15 gaged and ungaged watersheds in the Lake Tahoe Basin were developed by the U.S. Geological Survey (USGS) in support of the U.S. Department of Interior implementation of the Truckee-Carson-Pyramid Lake Water Rights Settlement Act of 1990 (Public Law 101-618). Precipitation-runoff simulations were made using the USGS Precipitation-Runoff Modeling System, a physically-based watershed model designed for simulating alpine-snowmelt runoff. Nine gaged tributaries in the Lake Tahoe Basin were modeled using an approach similar to a paired-basin analysis. Procedures were then developed for regionalizing model parameters to simulate runoff from the six ungaged areas. Lastly, lake-storage volumes for Lake Tahoe were simulated using the reservoir-routing module of Hydrological Simulation Program-FORTRAN and the total tributary inflow from the gaged and ungaged tributaries.

Physiographic watershed characteristics were defined with hydrologic-response units using a spatial data base of natural-resources information designed specifically for the Lake Tahoe Basin. Calibrated model parameters were regionalized with the aid of a geographic information system and software for relational data-base management. Hydrologic-response units in the ungaged areas were matched to similar units in the gaged subbasins and calibrated parameters from the gaged subbasins were transferred to the ungaged subbasins.

To assist in indexing the subbasins to the appropriate climate sites and to determine the precipitation and temperature lapse rates, a climate analysis was made using 19 climate sites in the Lake Tahoe and Truckee River Basins. The analysis defined, first, the monthly relations between the altitude of climate sites and the mean precipitation and mean temperature rates, and second, the short-term spatial variability, using principal-component analysis to identify those climate sites that vary together at monthly levels. Results from this analysis show no strong, regional precipitation-altitude relation, especially during the winter months when most of the annual precipitation occurs. This suggests that the rain-shadow effect of the Sierra Nevada influences precipitation at the sites as much as altitude. The principal-component analysis indicated that about 93 percent of the monthly precipitation variability is shared among all of the sites, once seasonality is removed. These results appear to refute an assumption that, on a regional scale, natural clusters of synchronized precipitation variation exist in the Lake Tahoe and Truckee River Basins.

Differences between streamflow measured at gaging stations and simulated by the model were evaluated for the entire simulation period, which for most subbasins was from October 1980 through September 1996. Though not included in the statistical analysis, the historic January 1997 flood was modeled for each of the gaged subbasins. Simulation bias for daily mean streamflow ranged from -9 to 0 percent for the calibration period and from -5 to +8 percent for the verification and validation periods; relative error ranged from +1 to +38 percent and from -5 to +74 percent for the calibration and verification periods, respectively. Simulation bias for annual mean streamflow ranged from -5 to +4 percent and relative error ranged from -1 to +18 percent. Some of the

difficulties in modeling the Lake Tahoe Basin can be attributed to the following: (1) the frequency of winter rain and rain-on-snow storms affecting much of the Lake Tahoe Basin area, thereby affecting snow accumulation and melt rates; (2) increasing urban development; and (3) a significant subsurface and ground-water storage component in some of the modeled subbasins. Thus, parameters most sensitive to simulating runoff were determined to be the nondistributed parameters. In particular these parameters are the subsurface and ground-water routing coefficients, which mainly affect runoff timing and distribution, and the monthly temperature-dependent parameters, which affect snowmelt rates and precipitation form.

About 50 percent of the total Lake Tahoe inflow, as determined in this study, is from the ungaged areas. Comparison of runoff indices for the ungaged basins to the associated gaged basins indicates that the ungaged areas have similar runoff proportions and seasonal distributions. The estimated relative error for daily mean streamflow from the aggregated ungaged areas ranged from +12 to +36 percent. Simulated total tributary inflow to Lake Tahoe averaged 409,000 acre-feet annually for water years 1981-96, which is within the ranged estimated in previous studies.

To determine the sensitivity of the Lake Tahoe water-budget components, a reservoir-routing module of Hydrological Simulation Program–FORTRAN was constructed to simulate daily lake-storage volumes for Lake Tahoe. Tributary inflow simulated in this study, estimated lake-surface precipitation and evaporation, and outflow measured at Tahoe City were used as inputs to the model. In simulating lake storage, deviations from observed storage levels result when bias in one or more of the lake water-budget components is over an extended period. Differences between the observed and simulated storage traces, which were significant for most years, were not caused by errors (bias) in inflow alone, but were exacerbated by errors associated with the precipitation and evaporation components of the water budget.

INTRODUCTION

In the Truckee River system, which originates in the Lake Tahoe Basin in the north-central Sierra Nevada, water use and allocation 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 in the system exceeds the supply—the timing of demands and inadequate storage often result in an apparent water shortage. Rapid growth since the 1980's in the region's urban centers of Reno and Sparks has increased municipal and industrial water demand. This demand is often met by the purchase and conversion of water rights previously used for irrigation. Decades of litigation culminated in the enactment of the Truckee-Carson-Pyramid Lake Water Rights Settlement Act of 1990 (Title II of Public Law 101-618; U.S. Congress, 1990). The law provides a foundation for developing operating criteria for interstate allocation of water and to meet water-quality standards in the approximately 7,000 mi^2 of the Truckee River and Carson River Basins of eastern California and western Nevada. Efficient implementation of the planning, management, and environmental-assessment requirements is aided by detailed water-resources data coupled with numerical models. These models in turn can be used to 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 of the U.S. Geological Survey (USGS) was established by the U.S. Department of the Interior to support implementation of Public Law 101-618. The program has the following objectives:

- Consolidate streamflow and water-quality data from several agencies into a single data base.
- Establish new streamflow and water-quality gaging stations for more complete water-resources information.
- Construct interbasin hydrologic computer models for use by water-resource managers.
- Develop a modular-framework modeling system that includes models for the following processes: precipitation runoff, river-flow routing, water temperature, water quality for selected constituents, and river operations and allocations.

Existing management models for the Truckee River are based on monthly time intervals. The USGS modeling system developed for this study 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, river operations, and allocations; and it can simulate certain water-quality processes. The Truckee River is regulated by several reservoirs upstream from the USGS gaging station at the Farad Powerhouse, Calif. In addition, much of the tributary inflow to the Lake Tahoe Basin, the headwaters of the Truckee River Basin, is ungaged. The need for (1) data on unregulated daily streamflow for the USGS Truckee River flow-routing model (Berris, 1996) and allocations and operations model (S.N. Berris, U.S. Geological Survey, oral commun., 1998) and (2) longer discharge record on currently gaged watersheds, prompted the development of precipitation-runoff models for subbasins in the Lake Tahoe and Truckee River Basins. 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 Precipitation-Runoff Modeling System (PRMS; Leavesley and others, 1983) was selected as the watershed model.

Statistical forecast models developed by the Natural Resources Conservation Service (NRCS) and the National Weather Service River Forecasting Centers (NWSRFC) have been the forecast tools for both streamflow volume and peak flow (flood) for the Carson River and Truckee River Basins. These approaches 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 monthly and annual water budgets developed for Lake Tahoe Basin (McGauhey, and others, 1963, p. 17; Lind and Goodridge, 1978, p. 26; and Myrup and others, 1979, p. 1506–1507) are too simplified and spatially lumped for the requirements of the Truckee River Operating Agreement. Some of the processes that are potentially misrepresented by such simplifications inherent in the statistical and regional water-budget models are canopy interception, sublimation, snowpack accumulation and melt, multizoned soil-moisture storage, evapotranspiration, and subsurface flow routing. In addition, river-basin operations require input of real-time meteorologic and streamflow forecasts (short term or seasonal) and the ability to analyze the effects of projected changes in land use, climate, and water allocations. Thus, a more physically based hydrologic model is needed to simulate interrelated hydrologic processes in greater spatial-temporal detail. Physically based models have the advantage because they are specifically designed to represent hydrologic responses to wide ranges of climatic and watershed conditions.

Finally, the uncertainty as to whether parameters[1] developed at the subbasin scale can be successfully transferred to ungaged basins requires innovative modeling approaches. The hypothesis of this study is that, using a physically based watershed model and digital data from a geographic information system (GIS; including remotely sensed data), large basins composed of gaged and ungaged subbasins can be objectively characterized, calibrated, and their hydrologic processes quantified, thus satisfying the need for more refined water-resource information.

Purpose and Scope

The purpose of this study is to estimate the total basin inflow to Lake Tahoe, on the basis of measured and modeled input values. In conjunction with the Truckee-Carson Program of the USGS, physically based watershed models were constructed for the gaged tributaries and methods developed for transferring calibrated model parameters to simulate runoff from the ungaged areas. This report describes (1) the data and methods used to construct, calibrate, and verify precipitation-runoff models for gaged subbasins in the Lake Tahoe Basin, (2) the procedures developed for transferring (regionalizing) model parameters from gaged to ungaged subbasins, (3) the calibration and verification results from the gaged subbasins as compared to simulation results from similar, adjacent

[1]The term "parameter" as used herein refers to a numeric constant in an equation within the numerical model used to describe a hydrologic process.

subbasins (also gaged but uncalibrated) for evaluation of the parameter-transfer process, and (4) the overall results for modeling inflow to Lake Tahoe using the reservoir flow-routing module of HSPF.

The spatial variability of land characteristics that affect runoff within watersheds is accounted for by conceptual disaggregation of the modeled area into parcels known as Hydrologic Response Units (HRU's). A GIS was used to delineate HRU's and to compute associated watershed model parameters. Daily meteorologic data used to provide input to the models and daily streamflow data used to evaluate the models were obtained for water years 1981–96, where available. Comparisons of simulated and observed runoff for the gaged subbasins for water year 1997 were made to evaluate the models during the major rain-on-snow storm in January 1997.

Previous Studies

A thorough discussion of prior Lake Tahoe Basin geological, hydrological, and water-quality studies is presented by Thodal (1997). In general, the interest in the Lake Tahoe Basin has focused more on the water quality of Lake Tahoe (particularly on causes for reported declines in lake clarity) than on determining basinwide water budgets. Water-budget analyses are often ancillary to the more pertinent question of land-use practices and potential deterioration of water quality. One of the earliest studies (Taylor, 1902) reported on the general hydrology of the Lake Tahoe Basin with an emphasis on supporting irrigation practices in the lower Truckee River Basin. Later studies by McGauhey and others (1963) and the Technical Committee on Hydrology (1971) of the Tahoe Regional Planning Agency (TRPA) were commissioned by various governing agencies in the Lake Tahoe Basin, wherein, general hydrological assessments were made to support discussions on waste disposal and limiting eutrophication. The following studies include annual water-budget estimations: Dugan and McGauhey (1974) include a water budget to support a nutrient budget; Crippen and Pavelka (1970) provide a general geological and hydroclimatic overview of the basin; Lind and Goodridge (1978) provide a precipitation-runoff relation for estimating runoff from ungaged areas. Myrup and others (1979) estimate monthly energy and water budgets as determined from available meteorological, hydrological, and limnological data.

Description of Study Area

The Lake Tahoe Basin is in the north-central Sierra Nevada at approximately 39° latitude and 120° longitude and is transected by the California-Nevada State boundary (fig. 1*A*). Structurally, the Lake Tahoe Basin is a depression, or fault-bounded graben, with the north-northwest trending Sierra Nevada to the west and the Carson Range to the east. The Carson Range is the western boundary of the Basin and Range physiographic province and, as such, represents a transition zone between the Basin and Range and the Sierra Nevada physiographic provinces. Both ranges consist of a granitic rock core of Cretaceous age, capped in many places by Tertiary and Quaternary volcanic and metavolcanic rock and fractured by numerous faults. Tertiary and Quaternary glacio-fluvial and lacustrine sedimentary deposits are common throughout the basin (Burnett, 1971). Within the graben lies Lake Tahoe, a 192-mi^2 water body with approximately 71 mi of shoreline. 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 for about 116 mi to its terminus at Pyramid Lake in 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 6,229.1 and 6,223.0 ft (Bonner and others, 1998, p. 332).

The drainage area of the Lake Tahoe Basin, including the lake, is about 506 mi^2. The contributing land area alone is 314 mi^2. The mountainous topography creates a steeply sloping, bowl-shaped basin with altitudes ranging from about 6,200 ft above sea level at the shoreline to more than 10,000 ft at places along the basin boundary. More than 60 percent of the basin is 7,000 ft above sea level and 3 percent of the basin is 9,000 ft above sea level. Fifty-five tributaries discharge directly into Lake Tahoe, draining about 276 mi^2 of contributing land area. Intervening areas (defined as having no defined stream channel but contributing runoff to the lake as both subsurface and overland flow) constitute about 12 percent of the land area of the basin (39 mi^2; Jorgensen and others, 1978). Sixty-two percent of the slopes are northwest to northeast trending, whereas, 20 percent are south facing. In general, slopes in the basin are gently to moderately sloping (defined here as less than 31 degrees), and only 4 percent of the slopes are steeper than 31 degrees. Soils are granitic, glacial, or volcanic in origin and vary from sand to

loam to bedrock (fig. 2). Deeper granitic soil profiles and the presence of metavolcanic soils on the east side reflect less glaciation, whereas the west side of the basin is characterized by fractured rock outcrops and shallow granitic soils in the highlands and thick glacial colluvium and alluvium in the drainages. Permeabilities range from slow for the metavolcanic soils (represented as volcanic in fig. 2) to rapid for the sandy loams.

Vegetation is dominantly conifer pine with lesser amounts of shrub (chaparral and montane) and grasses in the understory and on exposed slopes. Urban development is concentrated along the lake shore, mostly at the southern and northern ends, with the exception of current timber harvesting of dead and diseased timber and clearing due to expansion of residential and recreational facilities. The Lake Tahoe Basin has not been logged since the late 1800's when the discovery of gold and silver deposits associated with the Comstock Lode, about 15 mi east of Lake Tahoe, lead to extensive deforestation particularly on the east side of the basin.

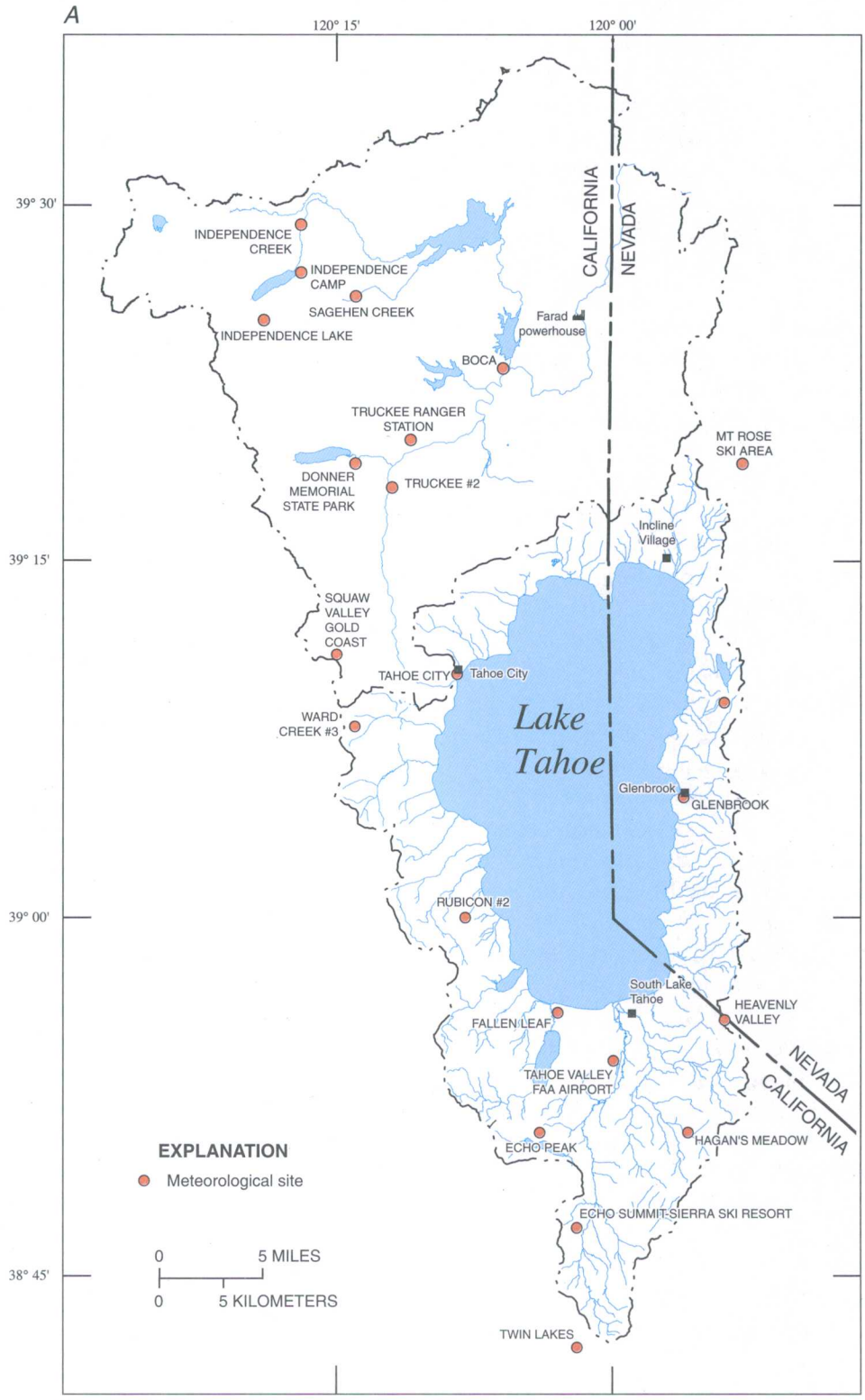
The climate of the Lake Tahoe Basin is strongly influenced locally by the topography of the surrounding mountains and regionally by moist maritime air masses from the Pacific Ocean. Summers are cool compared to the valleys on either side of the mountains, and winters are cold. Mean temperatures at Tahoe City (altitude 6,230 ft) recorded by the National Weather Service (NWS) range from a minimum of 17°F for January to a maximum of 77°F for July. Precipitation amounts vary from 15 in. to 80 in., most of which falls as snow or mixed rain and snow from November through March. "Wet" years, for purposes of this report, are defined as having above-average precipitation and runoff, for example water years 1982, 1983, 1986, 1993, and 1995–97. The "dry" period referenced is from water years 1987–92. Water years 1981 and 1994 were considered slightly below-average runoff years, while water years 1984–85 were average runoff years.

The Lake Tahoe Basin is a snow-dominated basin in which snowmelt runoff generates, on average, more than 80 percent of the annual runoff. In alpine watersheds movement of rain or snowmelt to the stream channel is predominantly as shallow subsurface flow with little overland flow except in those areas of exposed rock outcrop. Some moisture may be lost due to infiltration through fractures, less so in glaciated granitic rock than in highly fractured and porous volcanic and metavolcanic rock (Black, 1996). Subsurface flow in these watersheds occurs typically where the soil horizons are underlain by a horizon of lower permeability (in this case bedrock). Percolation is impeded by this horizon and water accumulates above it and flows downhill through the soil.

Granitic rock on the east side of the basin is not glaciated (Burnett, 1971) and is mantled with decomposed granite that may be as thick as 100 ft, although thicknesses are commonly much less (Harrill, 1977), providing substantial subsurface storage potential. Decomposed granite covers about 32 percent of the Lake Tahoe Basin (Cartier and others, 1994, table 10). Streamflow from tributaries along the western shore discharges a greater part of precipitation to the lake compared to the eastern shore because glaciation removed much of the more permeable soil cover. Runoff computed as a percentage of precipitation is referred to herein as runoff efficiency and is used as an index of ground-water storage and evapotranspiration loss. Runoff efficiencies computed for gaged tributaries on the east side of the basin average 10–20 percent, whereas similar indices computed for gaged tributaries on the glaciated west side average 60–70 percent of precipitation in discharge.

Unconsolidated basin fill comprised of glacial outwash, fluvial material, and lake sediments occupies 29 percent of the basin along drainage channels, shorelines, and elsewhere as thick sedimentary deposits. Estimates of the thickness of basin fill vary throughout the Lake Tahoe Basin: from 20–200 ft on the eastern shore to 1,000 ft near Incline Village and, as glacial outwash deposits, as thick as 1,600–1,900 ft in the South Lake Tahoe area (Thodal, 1997). Permeability is moderate to high and constitutes significant ground-water storage in the basin's two major aquifers at South Lake Tahoe and Incline Village. Alluvial deposits are typically in canyons and along valleys draining into Lake Tahoe. These deposits are local in extent and have less subsurface storage capacity than the glacial deposits described above.

Ground water discharges from aquifers in the Lake Tahoe Basin by pumpage, evaporation, and seepage to springs, streams, smaller lakes, and directly to Lake Tahoe. Ground water probably seeps into the lake where basin-fill deposits intersect the shoreline, commonly along the south and north shores of the lake.



Base modified from U.S. Geological Survey digital data, 1:100,000, 1979-80 and NRCS and USFS data, 1:24,000, 1974
Universal Transverse Mercator projection, Zone 11

Figure 1. Maps showing (A) meteorological sites; (B) gaged and ungaged areas, streamflow data sites used for watershed models, and selected hydrologic features, Lake Tahoe Basin, California and Nevada.

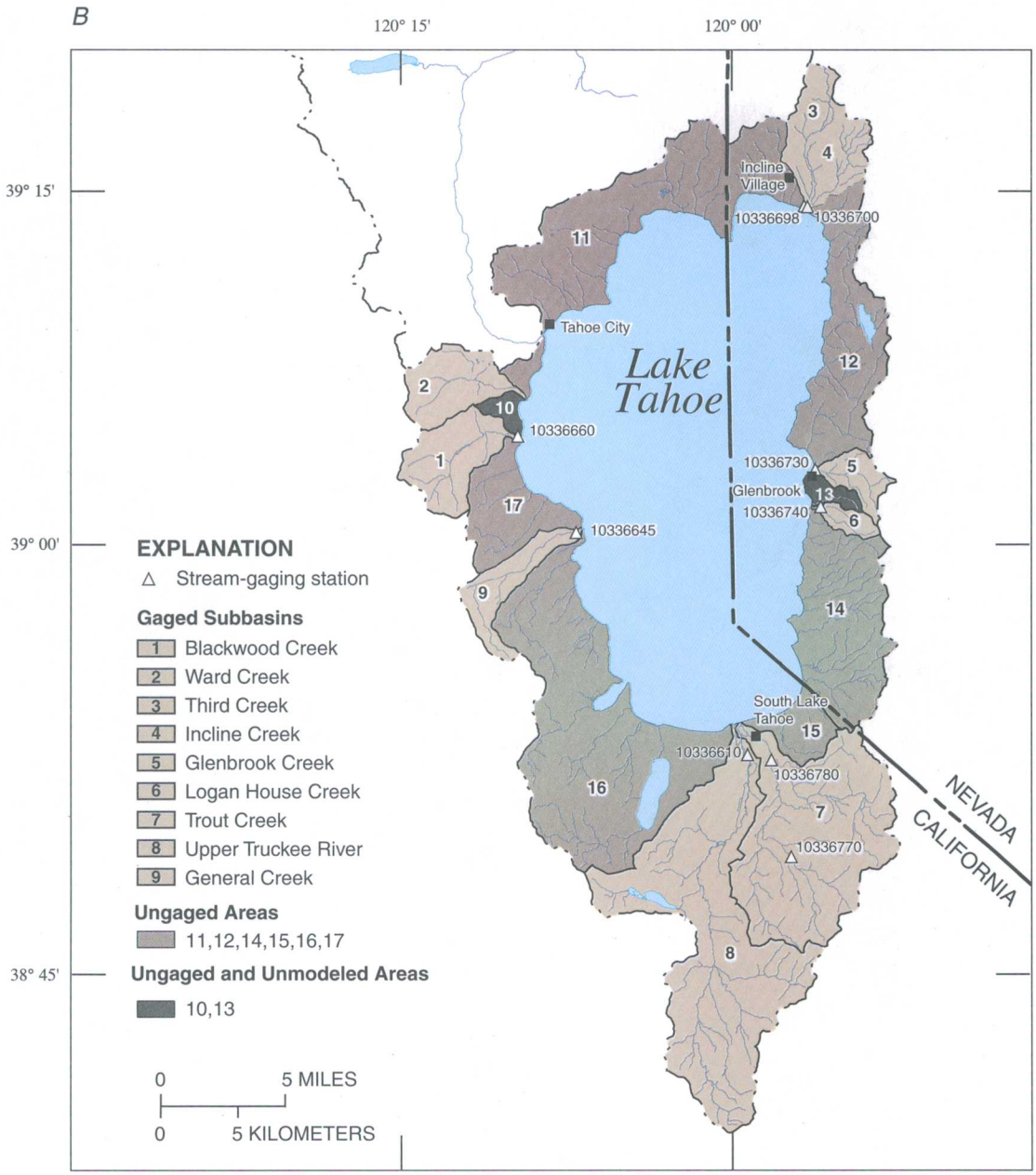


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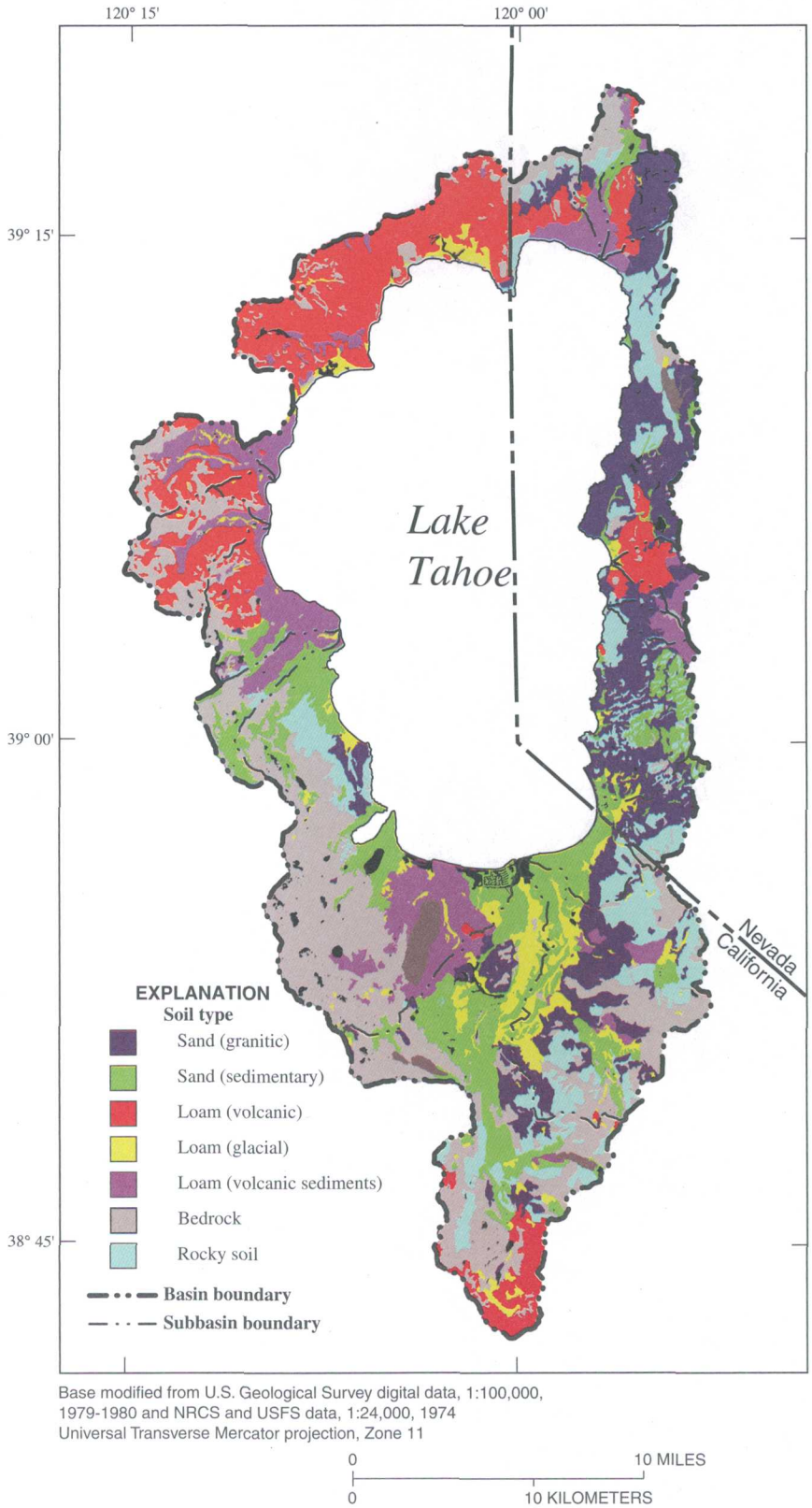
Figure 1. Continued.



Base modified from U.S. Geological Survey digital data, 1:100,000, 1979-1980 and NRCS and USFS data, 1:24,000, 1974
Universal Transverse Mercator projection, Zone 11

Figure 2. Classification of soils in the Lake Tahoe Basin.

Urbanization of the Lake Tahoe Basin implies semi-impervious to impervious land areas whereby runoff is usually routed as storm flow. Urban areas in South Lake Tahoe and Incline Village on the north shore route some of the storm runoff into infiltration basins, thereby detouring conventional flow paths to stream channels.

Acknowledgments

Thanks go to the following people for their contributions: U.S. Forest Service (USFS) soil scientists in the Lake Tahoe Basin Management Unit for their assistance in identifying the soil and vegetation characteristics in the Lake Tahoe Basin; the NRCS of the U.S. Department of Agriculture for their assistance in providing quality meteorologic data and technical support; Steve Markstrom of the USGS for assistance in upgrading the watershed model to meet project objectives; and LaRue Smith and Brian Reece of the USGS for their assistance in the GIS component of the study.

METHODS OF STUDY

The approach developed to model runoff from the Lake Tahoe Basin is discussed in this section. The procedures listed below and the terminology used are explained in following sections.

1. GIS and associated relational data-base programs were used to characterize and delineate hydrologic response units.
2. Gaged "paired" subbasins were identified and PRMS models constructed for one of the two paired, gaged subbasins.
3. Calibrated model parameters were transferred to the validation subbasin using GIS techniques, and the uncalibrated results were evaluated to establish a likely range of errors associated with this method of regionalization.
4. The validation subbasin models were then adjusted, where necessary, against the observed streamflow record for a better calibration.
5. A GIS and a relational data base were used to match HRU's in the ungaged areas to HRU's in selected, gaged "index" subbasins.
6. PRMS models for the ungaged areas were constructed from "master" files of HRU-distributed and nondistributed parameters.
7. Runoff from the ungaged areas was compared to the runoff from their respective gaged subbasins using simple index measures.
8. Lake-storage volume for Lake Tahoe was simulated using the HSPF reservoir module.

Model Description

PRMS is a physically based, deterministic, distributed-parameter model designed to simulate precipitation and snowmelt runoff as well as alpine snowpack accumulation and snowmelt processes. PRMS requires estimates of approximately 50 global parameters and 35 HRU-specific parameters. Daily total precipitation, maximum and minimum air temperature, and solar radiation are used to drive the models. 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 from daily air temperatures using a modified degree-day method and is adjusted for slope and aspect (Frank and Lee, 1966; Swift, 1976).

The spatial variability of land characteristics that affect runoff within watersheds is accounted for by conceptual disaggregation of the modeled area into parcels known as 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 their hydrologic responses: altitude, slope, aspect, vegetation, soil, geology, and climate. An HRU can be composed of many spatially noncontiguous land units. PRMS is an accounting model that computes a daily water-energy balance for each HRU. The area-weighted sum of daily hydrologic fluxes from all HRU's is the simulated basin response. Changes in moisture within the HRU's are conceptualized as fluxes through and from a series of reservoirs (fig. 3). The term "reservoir" used throughout this report refers to the conceptualization of a

watershed system as a series of containments where water is collected and stored. Typically, each HRU is indexed to a climate site but not necessarily in the HRU. Monthly temperature lapse rates and precipitation-correction factors extrapolate measured daily air temperature and precipitation to individual HRU's, thereby accounting for spatial and altitude differences. Precipitation form (rain, snow, or mixed) is dependent on relations between a specified snow-rain threshold temperature and minimum and maximum temperatures for each HRU.

Snowmelt is a significant component of the hydrologic cycle for alpine watersheds in the Lake Tahoe Basin. Simulating snowmelt-generated runoff requires transforming snowpack melt and accumulation processes into numerical algorithms that represent the snow-energy budget. The energy-balance approach uses a form of the energy-balance equation for a snowpack (U.S. Army Corps of Engineers, 1956) that can be written as:

$$Hm = Hsn + Hln + Hc + He + Hg + Hp + Hq, \quad (1)$$

where Hm is energy available for snowmelt,

Hsn is net shortwave radiation,

Hln is net longwave radiation,

Hc is convective heat flux,

He is latent heat flux,

Hg is conduction of heat from the ground,

Hp is the flux of heat from rain, and

Hq is change in energy content of the snowpack.

Limits on the availability of data and application to point locations initiated a modified version of equation 1 whereby Hsn, Hln, Hp, and Hq are measured and the remaining components are either parameterized or considered negligible (Leavesley, 1989). In this way, mean areal values of snow accumulation and melt can be obtained on a watershed scale.

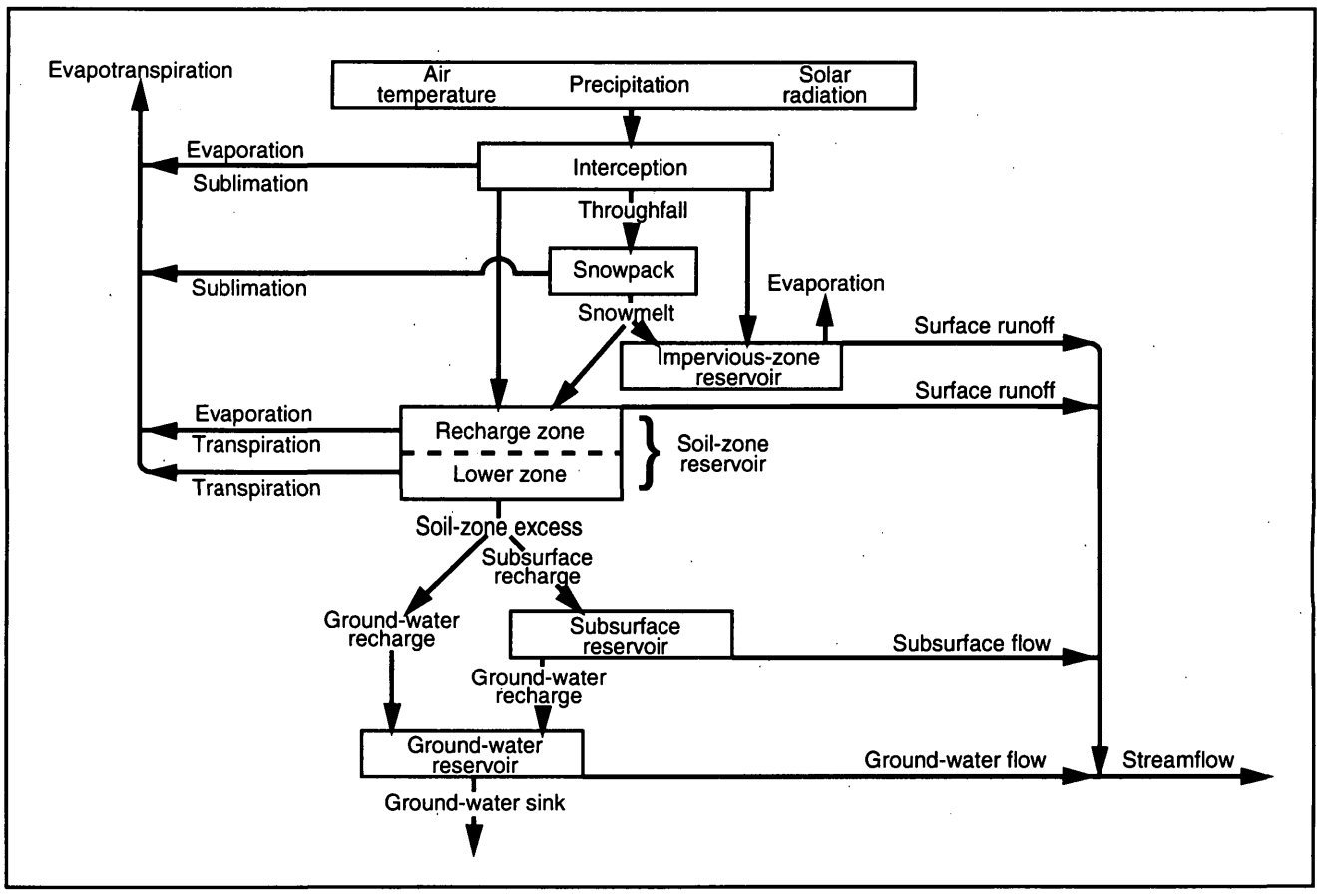


Figure 3. Precipitation-Runoff Modeling System (Leavesley and others, 1983).

The conceptual model for snowmelt in PRMS follows the design of Obled and Rosse (1977). The snowpack is represented as two layers: an upper boundary layer (1.2–2.0 in. thick) and the underlying part of the pack. The snowpack in each HRU is always in either an accumulation phase or a melt phase, depending on the snowpack temperature. The snowpack-heat balance is in a state where either (1) radiant energy acquired during daylight hours can be discharged to the atmosphere by sensible and latent-heat fluxes over the course of the day and night or (2) these fluxes cannot transfer heat from the snowpack to the atmosphere. Near-surface instability and upward temperature/humidity gradients are maintained so that turbulent fluxes carry thermal energy and moisture from the snowpack to the atmosphere when the air temperature is cooler than the snowpack surface, which is near 32°F. In contrast, if air temperature is above freezing, the near-surface atmosphere will tend to be stable (leaving only roughness-induced turbulent fluxes), and temperature/humidity gradients will favor sensible- and latent-heat transport from the air into, not out of, the snowpack. Under this latter condition, daily inputs of radiant energy are trapped in the snowpack, and snowmelt proceeds (Jeton and others, 1996).

In this study, potential evapotranspiration (PET) is computed using 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 transpiration is not occurring (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 community 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 phenology during cooler and warmer springs or in response to long-term climate changes.

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. Surface runoff from a snow-free surface is estimated by a nonlinear function of antecedent soil-moisture conditions, daily precipitation amounts, and soil-moisture storage (Dickinson and Whiteley, 1970). For snowmelt, infiltration is a user-defined rate.

Streamflow, as simulated by PRMS, is a summation of three flow components: surface flow (commonly referred to as overland flow) from saturated soils or runoff from impervious surfaces; subsurface flow (or interflow) defined as a shallow subsurface zone between the soil zone and the ground-water reservoir receiving a percentage of excess soil water, and ground-water flow from both the soil zone and the subsurface reservoir. Ground-water losses, referred to as the ground-water sink, are used to account for ground-water discharge to Lake Tahoe.

Model Application

Precipitation-runoff models simulate the hydrologic cycle in some manner, most attempting to describe hydrologic processes such as canopy interception, evapotranspiration, sublimation from snow, movement of water through the soil profile and the subsurface zone, ground-water movement, and possibly surface-water/ground-water interactions. In this study, simulations of the spatial and temporal variability of hydrologic processes required (1) observed streamflow data for comparison; (2) characterization of historical climatic variations affecting the subbasins; and (3) development of objective methods for subbasin characterization, HRU delineation, and computation of GIS-based model parameters. For this study, a paired-basin analysis was used to develop regional PRMS parameters for modeling ungaged areas.

Description of Gaged Subbasins

Paired basins are most commonly used to determine changes in streamflow in response to changes in land use or land cover. Paired basins are typically defined as two watersheds having comparable drainage areas, physiographic and hydrologic characteristics, and thus, similar climatic inputs. One of the pair is considered the "control" watershed, whereas the other typically undergoes some land-use or land-cover modification.

Tributaries with streamflow gaging records are referred to in this report as the "gaged subbasins." In this study, four "pairs" of gaged subbasins were identified wherein PRMS parameters from the calibration basin (or "control" basin) were transferred to the validation ("test") basin. No modifications in land use or land cover were made on the validation basin. The four sets of paired subbasins are (fig. 1*B*): Ward Creek and Blackwood Creek, Third Creek and Incline Creek, Glenbrook Creek and Logan House Creek, and Upper Truckee River and Trout Creek. The General Creek subbasin is unpaired but is included as a calibration subbasin.

The nine gaged subbasins, while constituting only 47 percent of the total basin area, adequately represent a wide range of typical geologic conditions as well as hydroclimatic characteristics. In general, the hydrographs for the gaged Lake Tahoe Basin tributaries, whether partly urbanized or not, are similar in seasonal distribution. While monthly runoff amounts differ for the individual subbasins, Lake Tahoe Basin runoff reflects moderate-altitude snowmelt patterns. Runoff during the April–June snowmelt period typically ranges from 50 to 65 percent of annual runoff for the gaged tributaries used in this study and is probably reflective of runoff patterns for the Lake Tahoe Basin as a whole. In contrast, the baseflow, or low-flow period, from August to October ranges from 2 to 14 percent of the annual runoff. The higher percentages are for those basins with greater amounts of groundwater storage. Sudden runoff is common during late fall and early winter months, usually resulting from rapid snowpack melt caused by warm, maritime storms which bring precipitation in the form of rain to altitudes up to 8,000 ft or higher. This happened during the February 1982 and January 1997 floods when snow levels were above 9,000 ft in the Lake Tahoe and Truckee River Basins (hereafter referred to as the Tahoe–Truckee Basins). Runoff patterns differ during dry years (water years 1987–92) with fewer fall and winter runoff peaks.

Ward Creek and Blackwood Creek

Ward and Blackwood Creeks are on the west side of the Lake Tahoe Basin and constitute the only "true" paired-basin set, as defined by similar altitude-area distribution, land cover, and soil type. These subbasins are predominantly volcanic and alluvial, and climatically represent the precipitation patterns of the western shore. The only dissimilarity is that the Blackwood Creek subbasin has slightly more exposed rock and less loamy soil of volcanic-rock origin than the Ward Creek subbasin. However, this difference appears to be negligible when comparing observed runoff, which differs only slightly in magnitude during certain runoff events.

Third Creek and Incline Creek

Third and Incline Creeks drain two subbasins on the north shore of the Lake Tahoe Basin. Unlike the Ward Creek and Blackwood Creek pair of subbasins, Third Creek and Incline Creek differ primarily in distribution of altitude, rock outcrop, and soil type. Incline Creek and Third Creek represent weathered granitic rock in the uplands and lacustrine and glacial sediments below an altitude of 7,000 ft. Although Third Creek and Incline Creek have nearly identical drainage areas, Third Creek is a higher altitude watershed with about a third of the drainage area at altitudes of 9,000 ft and above, and about a third of the area in each of the lower altitude zones (6,000–8,000 ft and 8,000–9,000 ft). In contrast, all of Incline Creek is below 9,000 ft with two-thirds of the drainage area in the 6,000–7,000-ft zone. This difference in altitude-area relation results in significantly different seasonal runoff characteristics. Third Creek has an average of 7 percent more of its annual flow during the May–July period than does Incline Creek, mostly due to snowmelt from the area above 9,000 ft. The snowline for the Lake Tahoe Basin (lowest altitude at which precipitation falls as snow) is approximately 6,500 ft. This suggests that the Incline Creek subbasin receives more rain and mixed rain and snow than Third Creek, which receives more of its precipitation as snow. Third Creek maintains more of a snowpack throughout the winter season, due to its higher altitudes and cooler temperatures. Other physiographic differences include 32 percent more rock out-

crop in the Third Creek subbasin, mainly above 8,000 ft. The Incline Creek subbasin has about 50 percent more granitic sandy soil than the Third Creek drainage area. Both subbasins have a thick sedimentary basin in the lower altitudes with a large ground-water component, although there appears to be a higher storage capacity in the Incline Creek subbasin.

Glenbrook Creek and Logan House Creek

Glenbrook Creek and Logan House Creek subbasins are on the east side of the Lake Tahoe Basin and represent the climate and hydrogeology typical of the eastern shore. The subbasins are characterized by deeply weathered granitic bedrock, in places capped by younger volcanics; by less urban development; and on average by 40 percent less precipitation than the western side of the basin. Runoff efficiencies for the eastern shore typically are 10 to 20 percent (Thodal, 1997), reflecting more subsurface storage, presumably in the weathered granitic rock. Calibrating these subbasin models to observed streamflow, however, is problematic due to diversions upstream from the Logan House Creek streamgage, ground-water withdrawals in the Glenbrook area, and the frequency of low flows less than 3 ft^3/s (which is the filter applied prior to statistical analysis for the other modeled subbasins). Lack of data prevented adjusting the observed record for these diversions and withdrawals. The combined contributions from these two subbasins to Lake Tahoe amount to less than 0.5 percent of the total estimated inflow to the lake.

Upper Truckee River and Trout Creek

The Upper Truckee River and Trout Creek subbasins drain the southern end of the Lake Tahoe Basin. Precipitation at the south end of the lake reflects a combination of west and east shore patterns, depending on location. Together their subbasins include about 32 percent of the total study area, represent all geologic and soil types found in the Lake Tahoe Basin, and contain the highest concentration of urban development in the study area. The geology is mixed in these tributaries, with predominantly granitic rock exposed in the highlands and thick glacial and lacustrine sediments in the lowlands. The 6,000–8,000-ft altitude zone have similar distributions for both subbasins, although Trout Creek has a greater percentage in the 9,000–10,000-ft altitude zone (18 percent compared to 6 percent for Upper Truckee River). Soil-type distributions in the two subbasins usually are within 5 percent of one another. Land-cover distributions are similar with more grass and shrub in the Upper Truckee River than in Trout Creek watersheds. These drainage areas contain the largest urban centers in the Lake Tahoe Basin: Stateline, Nev., and South Lake Tahoe, Calif. Diversions out of the Lake Tahoe Basin from Echo Lake (in the Upper Truckee River catchment area) generally occur from September through December. Regulated releases from Echo Lake to Echo Creek, a tributary to the Upper Truckee River, also occur. However, the streamflow record for the Upper Truckee River was not adjusted to account for either the releases to Echo Creek or the diversions out of the Upper Truckee River subbasin. Water-use practices such as ground-water pumping, surface-water diversions, and urban stormflow routing substantially affect runoff.

General Creek

General Creek subbasin, on the western side of the Lake Tahoe Basin, is at a moderate altitude of 7,157 ft above sea level. The lower part of the drainage area consists of glacial sediments derived from volcanic and granitic rock, whereas the upper part is mainly unglaciated granitic rock outcrop with or without incipient soil and sandy granitic soils. The vegetation is predominantly conifer forests with lesser amounts of grass and shrub. No upstream diversions are known, and development is minor in the drainage area. Runoff efficiencies for the western shore typically are 60 to 80 percent (Thodal, 1997, p. 27) reflecting much less subsurface storage than in the weathered granitic rock on the eastern shore.

Streamflow Data

Streamflow data computed from gage-height records collected at gaging stations are referred to as "observed" data throughout this report. USGS gaging stations used for observed streamflow data during model calibration and verification are listed in table 1. Streamflow into Lake Tahoe from most of the 55 tributaries has either never been measured or not measured continuously. Nine of these tributaries were modeled with PRMS (Taylor Creek gage, downstream from Fallen Leaf Lake on the south shore of Lake Tahoe, was omitted due to dam regulation). The USGS rates the accuracy of its streamflow records primarily on the

basis of (1) the stability of the stage-discharge relation, (2) the accuracy of measurements of stage and discharge, and (3) interpretation of records (Bonner and others, 1998). Accuracy levels of "good" indicates that about 95 percent of the daily discharges are within 10 percent of their true values and "fair" indicates that daily discharges are within 15 percent (Bostic and others, 1997). Six of the nine gaging stations used in this study are rated as "fair" and the remaining three are rated as "good." The water year 1981–96 period of record was used for modeling most of the gaged tributaries. This period coincided with the availability of high altitude snowpack-telemetry (SNOTEL) climate data and is a subset of the period used in the HSPF flow-routing model for the Truckee River Basin (Berris, 1996).

Table 1. Streamflow gaging stations and subbasins used in watershed models for Lake Tahoe Basin, California and Nevada

[Abbreviation: mi^2, square miles]

Subbasin name [1]	Station number [2]	Drainage area of subbasin (mi^2)	Period of record used in study (water years)
Blackwood Creek	10336660	11.1	1981-96
Ward Creek	10336676	9.7	1981-96
Third Creek	10336698	6.1	1981-96
Incline Creek	10336700	6.7	1989-96
Glenbrook Creek	10336730	4.1	1990-96
Logan House Creek	10336740	2.1	1985-96
Trout Creek	10336780	41.0	1981-96
Upper Truckee River	10336610	56.4	1981-96
General Creek	10336645	7.6	1981-96

[1] Paired subbasins are grouped.
[2] Bonner and others, 1998.

Description and Analysis of Climate Data

Climate data requirements for PRMS are daily total precipitation, and daily maximum and minimum temperatures. These requirements are particularly important for energy-balance models such as PRMS. Some of the most significant problems in modeling snowmelt runoff are attributed to limitations of climate-data availability and extrapolation from point measurements to areal values. During the World Meteorological Organization (1986) conference, comparisons of snowmelt-runoff simulation models were made and concluded that the distribution and form of precipitation were the most important factors in producing accurate estimates of runoff volume. Orographic effects (increases in precipitation with increasing 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 broadly temperature dependent and usually is simulated by setting a snow-threshold temperature. Precipitation is assumed to be snow when the maximum daily temperature is below this threshold value, and rain when above. Temperature generally decreases with increasing altitude except where and when temperature inversions develop. Temperature measurements usually are extrapolated over a basin by assuming some fixed lapse rate. In PRMS, monthly constant maximum and minimum temperatures are specified; however, these constants generally do not reflect the actual variability observed in daily lapse rates (Leavesley, 1989).

Two kinds of variability must be considered when constructing watershed models: (1) spatial variation of the mean for precipitation and temperature, and (2) spatial variation of deviations of precipitation and temperature around their means. The means typically are represented in PRMS through the precipitation and temperature correction factors, which usually are specified as lapse rate to account for altitude differences. Deviations about the mean are represented by indexing each HRU with the daily weather series from a particular observation site. The initial climate analysis for this study was two-fold: first, define the monthly relations between the altitude of climate sites and the mean precipitation and mean temperature rates, and second, map short-term spatial variability to identify those climate sites that vary together at monthly levels. While precipitation and temperature locally are functions of altitude, they also vary depending on location in the Lake Tahoe Basin and the rain-shadow effect of the Sierra Nevada.

The meteorological data network for the Lake Tahoe Basin is well-distributed over the basin (fig. 1*A*) and is notable for providing many high-altitude/low-altitude pairs of meteorological sites. Several of the NWS climate sites are at or near lake level; whereas, the SNOTEL sites of the NRCS measure and record ambient air temperature, precipitation, and snowpack-water equivalence are near the ridgelines, typically

above 7,500 ft. Precipitation and temperature data and the associated climate sites used in the PRMS models for both the gaged subbasins and the ungaged areas are listed in table 2. In addition, precipitation data used in the regional precipitation analysis is listed. Prior to constructing the watershed models, these data and other climate data for sites near the Tahoe-Truckee Basins were analyzed to identify climate variability in the basins and to assist in indexing the gaged and ungaged areas to "appropriate" climate sites.

Precipitation Data

Mean monthly precipitation series from 19 climate sites (table 2) in the Tahoe and Truckee River Basins were plotted against altitude to estimate mean regional precipitation lapse rates. The site locations are shown in figure 1*A*. No strong, consistent precipitation-altitude relations were evident on a regional scale amidst the scatter of points, especially during the winter months when most of the annual precipitation falls. Influences of east-west rain shadow appear to affect the sites about the same as the altitude relations. For example, Boca (5,580 ft; fig. 1*A*), receives on average 50 percent less precipitation than Donner Memorial State Park (5,940 ft) during January and February. The Boca site is sufficiently east of the Sierra Nevada crestline to be influenced by the rain-shadow effect that results in decreased precipitation. From a regional perspective, most of the high-altitude SNOTEL sites are located on or near ridgelines, not on leeward or windward sides. A weak, north-south gradient is apparent within similar altitude zones, with a trend towards decreasing precipitation to the south. However, on a local subbasin scale, orographic effects are assumed present, requiring that the observed precipitation data be adjusted accordingly.

Table 2. Information for meteorological sites used in watershed models and in regional analysis of precipitation data for Lake Tahoe Basin, California and Nevada

[Abbreviations: FAA, Federal Aviation Administration; NRCS, Natural Resources Conservation Service; NWS, National Weather Service; ppt, precipitation; temp, temperature; RA, regional precipitation analysis; U-11, ungaged area 11 (for example)]

Meteorological site name [1] (see fig. 1*A*)	Altitude (feet above sea level)	Operating agency	Data used in model	Subbasin model	Data used in regional analysis or ungaged model
Boca, Calif.	5,580	NWS	ppt, temp		RA
Donner Memorial State Park, Calif.	5,940	NWS	ppt, temp		RA
Truckee Ranger Station, Calif.	6,020	NWS	ppt, temp		RA
Tahoe City, Calif.	6,230	NWS	ppt, temp	Blackwood, General, Ward	RA; U-11; U-17
Tahoe Valley FAA Airport, Calif	6,250	NWS	temp	Trout, Upper Truckee River	RA; U-15; U-16
Fallen Leaf, Calif.	6,300	NRCS	ppt	Trout, Upper Truckee River	U-15; U-16
Sagehen Creek, Calif.	6,340	NWS	ppt, temp		RA
Glenbrook, Nev.	6,360	NWS	ppt, temp	Glenbrook, Logan House, Third, Incline	U-12; U-14
Truckee #2, Calif.	6,400	NRCS	ppt		RA
Independence Creek, Calif.	6,500	NRCS	ppt		RA
Ward Creek #3, Calif.	6,750	NRCS	ppt		RA
Independence Camp, Calif.	7,000	NRCS	ppt		RA
Echo Summit-Sierra Ski Resort, Calif.	7,350	NWS	ppt, temp		RA
Rubicon #2, Calif.	7,500	NRCS	ppt	Upper Truckee River	RA
Echo Peak, Calif.	7,800	NRCS	ppt		RA; U-16
Hagan's Meadow, Calif.	8,000	NRCS	ppt	Trout	RA; U-14; U-15
Marlette Lake, Calif.	8,000	NRCS	ppt	Glenbrook, Logan House	RA; U-12; U-14
Twin Lakes, Calif.	8,000	NWS	ppt, temp		RA
Squaw Valley Gold Coast, Calif.	8,200	NRCS	ppt	Blackwood, General, Ward	RA; U-11; U-17
Independence Lake, Calif.	8,450	NRCS	ppt		RA
Heavenly Valley, Calif.	8,850	NRCS	ppt		RA
Mt. Rose Ski Area, Nev.	8,850	NRCS	ppt	Incline, Third	RA

[1] sites are listed in order of increasing altitude.

The second part of the precipitation-data analysis looked at the spatial variability to determine whether variations about the local means formed predictable patterns. This was accomplished using a cluster analysis based on a rotated empirical-orthogonal-function (EOF) analysis (Richman, 1986). EOF analysis is a form of principal-component analysis (PCA) that decomposes data sets in terms of coherent spatial variability around long-term mean values. Rotated EOF analysis separates spatially distributed data sites into distinct subsets that vary together and without much correlation to sites outside the subset (Richman, 1986; Aguado, 1990; Cayan, 1996). For this study, monthly precipitation totals for November through March for 19 sites were computed for the period 1980-92. The mean-monthly values for each site were subtracted, and each monthly value was normalized (divided) by the standard deviation for that month and site. The result is a uniformly weighted series of deviations at 19 sites for 65 months. A covariance matrix among all the sites was computed and from that matrix, a time series (called the principal component) was calculated. This time series represents the single largest component of variation in the 65 months and 19 sites.

Theoretically, the resultant EOF clusters can be used to develop a rational scheme for indexing HRU's to particular climate sites with special attention to the broad, ungaged areas in the Lake Tahoe Basin. The resulting principal component indicates that the normalized precipitation variations are largely identical. The correlations of the individual precipitation series to this shared-component series (of shared precipitation variability) were within a few percent of each other with two minor exceptions: Donner Memorial State Park and Independence Creek sites (fig. 1*A*). Some 93 percent of the monthly precipitation variability is shared among all the sites, once seasonality is removed. The remaining 7 percent was examined with a second PCA, once the shared component was removed; the resultant analysis indicated that the remaining variability was indistinguishable from random chance. The EOF analysis indicates that, on a regional scale, no natural clusters of synchronized precipitation variation exist in the Tahoe–Truckee Basins. These basins are evidently small enough so that precipitation variations are either shared or effectively random, at monthly time scales. As a result, the gaged and ungaged subbasins were indexed to climate sites in closest geographic proximity to the subbasins.

PRMS typically adjusts precipitation amounts to individual HRU's by multiplying observed daily precipitation amounts by specified monthly lapse-rate correction factors. In this study, time series of observed precipitation were 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 sites: a low-altitude site typically at lake level (around 6,200 ft) and a higher altitude site at or above 7,500 ft (table 2). Daily precipitation values for each HRU (P_i), were generated using the following linear interpolation equation:

$$P_i = \left\{\frac{E_{hru} - E_{low}}{E_{high} - E_{low}}\right\}(P_{i,\,high} - P_{i,\,low}) + P_{i,\,low}\,. \qquad (2)$$

Where E_{hru} is mean altitude of the HRU, in feet;
E_{low} is the low-climate site altitude, in feet;
E_{high} is the high-altitude high-climate site, in feet;
$P_{i,\,high}$ is precipitation at day$_i$ at the high-altitude site, in inches; and
$P_{i,\,low}$ is precipitation at day$_i$ at the low-altitude site, in inches.

Temperature Data

Mean monthly air-temperature data for 22 long-term (30-year) sites in and around the north-central Sierra Nevada were examined to estimate mean monthly regional lapse rates. Five of the sites are in the Tahoe–Truckee Basins at or near an altitude of 6,000 ft and one site (outside the Tahoe-Truckee Basins), Twin Lakes, is at 8,000 ft, reflecting a narrow altitude range of long-term temperature sites. This limits the ability to project temperatures to higher altitude HRU's. Plots of temperature compared to altitude indicate that the regional lapse rates vary little from month to month, averaging 3.3°F per 1,000-ft altitude change. The standard regional-temperature lapse rate is 3.6°F per 1,000-ft altitude change (Ahrens, 1985, p. 25). More importantly the plots indicate that during the cool-

season, simple linear relations between altitude and temperature are less apparent. For example from November through February, the linear relations do not apply at the highest and lowest altitude sites. The highest site (Twin Lakes) averages about the same temperatures as the Tahoe–Truckee Basins sites, which are about 2,000 ft lower. Twin Lakes site data was compared to a second high-altitude site, Echo Summit (7,350 ft) north of Twin Lakes near the Lake Tahoe Basin divide, for a shorter period of record. Both data sets were compared to the Tahoe City site (6,250 ft) on the northwest shore. During the winter months, Twin Lakes on average is warmer than Tahoe City, while Echo Summit is within one degree of Tahoe City for the same months.

While additional higher altitude sites are needed to remove some of the uncertainty, these regional comparisons suggest that, during the coldest months for the Lake Tahoe Basin no strong temperature lapse rate is evident, between the ridgeline and the lake level. This weak lapse rate may be due to (1) seasonal inversion effects which may frequently nullify or reverse the typical lapse rate of 3°F per 1,000-ft altitude change, (2) local conditions like gravity drainage effects that might pool cooler-than-expected air near the lake, or (3) unrepresentative conditions at Twin Lakes, which lies beyond the Lake Tahoe Basin (M.D. Dettinger, U.S. Geological Survey, written commun., 1995). However, model runs made without a temperature lapse rate typically resulted in an undersimulation of spring snowmelt, and excessive rain-based runoff. This suggests that on a subbasin scale, as represented in this study, temperature adjustments to account for altitude differences are necessary to adequately simulate runoff. For this study, temperature sites closest to the modeled subbasins were selected and the observed air temperatures were adjusted with monthly lapse rates estimated from the regional-temperature data set. The lapse rates used in this study are within 0.5°F of the regional lapse rates.

Basin Characterization, and Delineation of Hydrologic Response Units

A GIS can be used to assist in land characterization and parameter estimation for various hydrologic modeling systems. A GIS was developed for this study so that spatial variation of important basin characteristics could be analyzed objectively and automatically. Procedures used were similar to those described in a previous modeling study (Jeton and Smith, 1993; Jeton and others, 1996).

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-feature characteristics). Source data layers used in basin characterization were obtained from the Tahoe Environmental Geographic Information System (Cartier and others, 1994), a set of spatial data bases of natural-resources information for the Lake Tahoe Basin developed by the USGS in joint cooperation with the TRPA, the USFS, and the NRCS. The source data layers include altitude, slope, aspect, soil, land cover, geology, and hydrography. In addition, a digital coverage of impervious areas used to delineate development in the Lake Tahoe Basin was provided by the USFS, Lake Tahoe Basin Management Unit. Using 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 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. A method was developed to delineate hydrologically homogeneous and spatially noncontiguous 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 limited by contiguity, (3) the technique was flexible to accommodate different classification criteria, and (4) the technique was objective and reproducible.

Figure 4 illustrates the resulting methodology. In step 1, source data were reformatted to provide consistent GIS coverages as raster cells on a 30-m (meter; 98-ft) grid. Slope and aspect layers were derived from the altitude layer (fig. 4, step 2). Data in the source layers were lumped into discrete categories according to hydrologic and climatic considerations (fig. 4, step 3). Grouped digital-data layers are illustrated in figures 2 and 5–8. Slope categories were selected to distinguish geomorphic landforms, and aspect categories were selected to span solar-radiation estimates from Liebermann (1991). Land-cover categories describe generalized vegetation classes within the basins. Soils were regrouped according to generalized soil textures and parent material. The sixth data layer, geology, was not used in the HRU delineation process, but was used later in step 7 to assign each HRU to one of two subsurface reservoirs in the Lake Tahoe Basin.

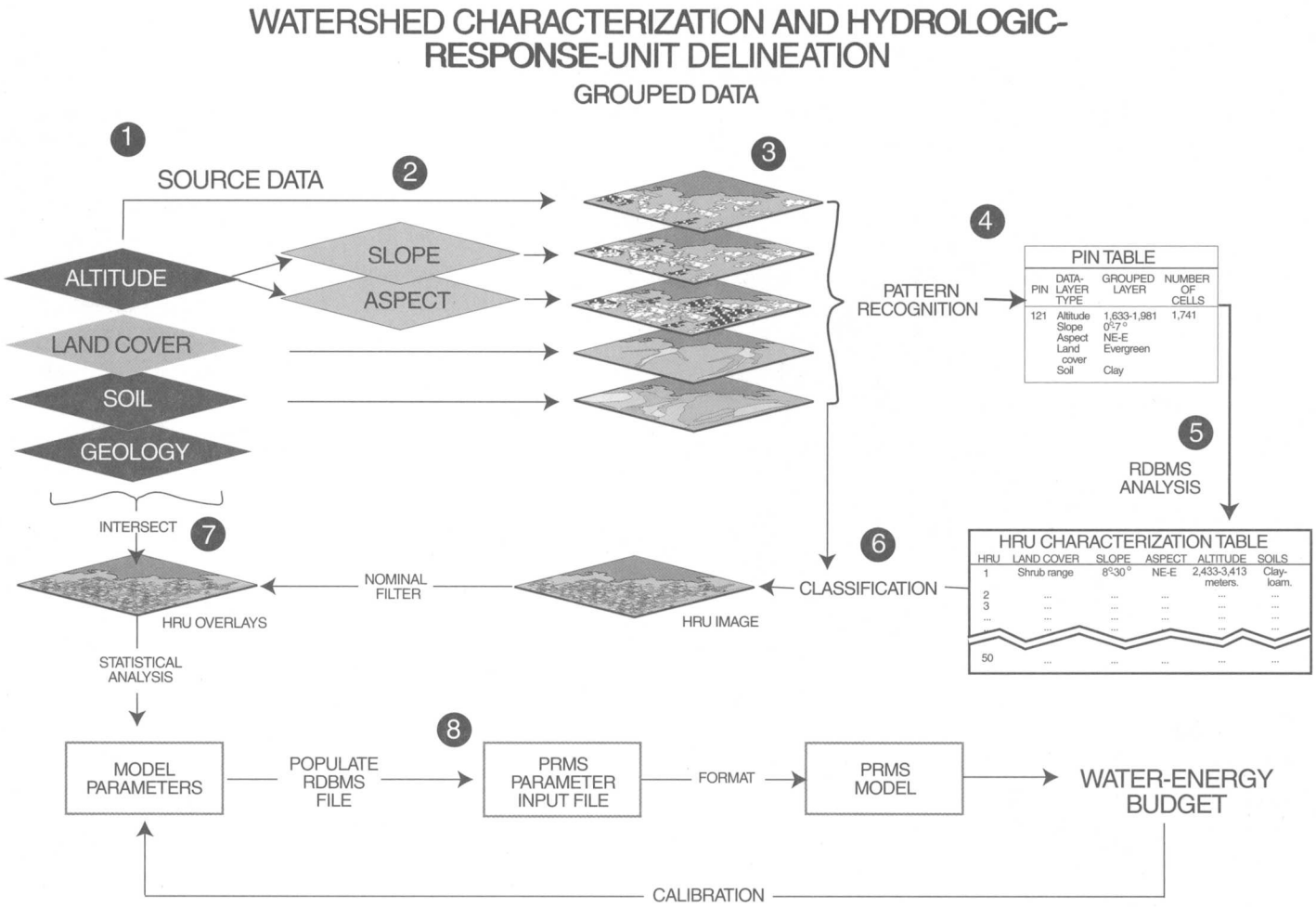


Figure 4. Steps in basin characterization and hydrologic-response-unit (HRU) delineation. PIN, Pattern Identification Number, PRMS, Precipitation-Runoff Modeling System; RDBMS, Relational Data-Base Management System.

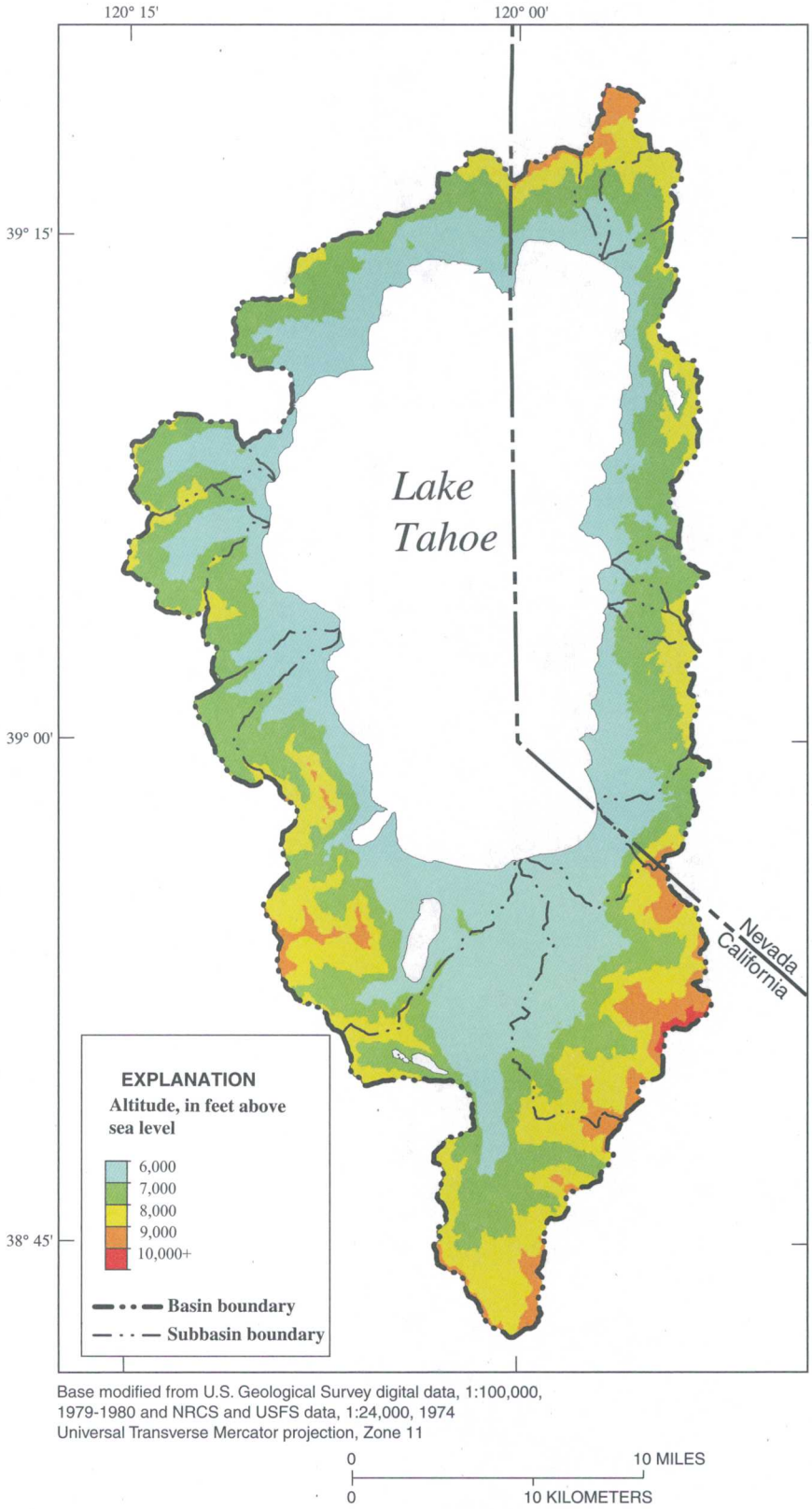
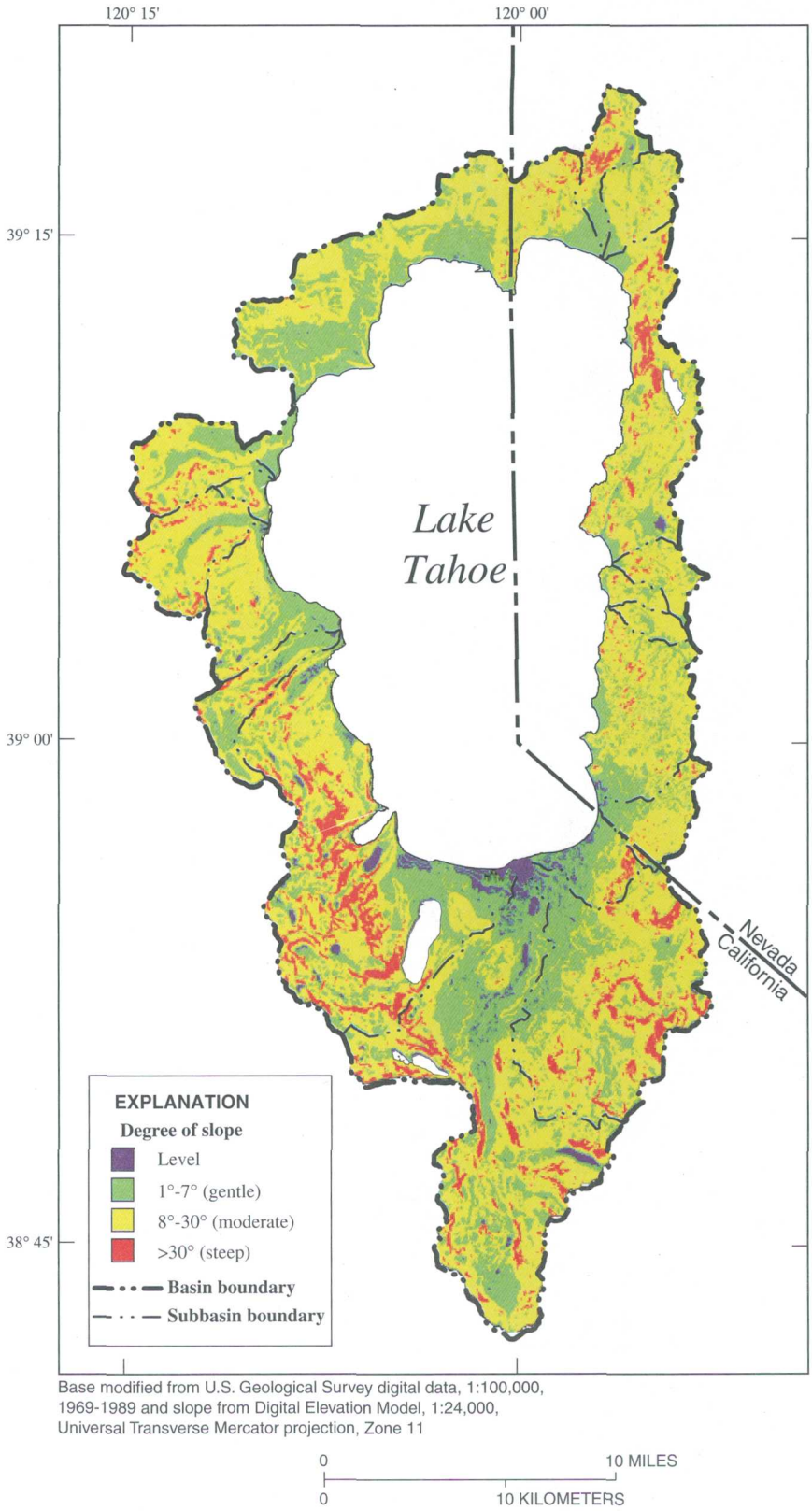


Figure 5. Classification of altitude in the Lake Tahoe Basin.



Base modified from U.S. Geological Survey digital data, 1:100,000, 1969-1989 and slope from Digital Elevation Model, 1:24,000, Universal Transverse Mercator projection, Zone 11

Figure 6. Classification of slope in the Lake Tahoe Basin.

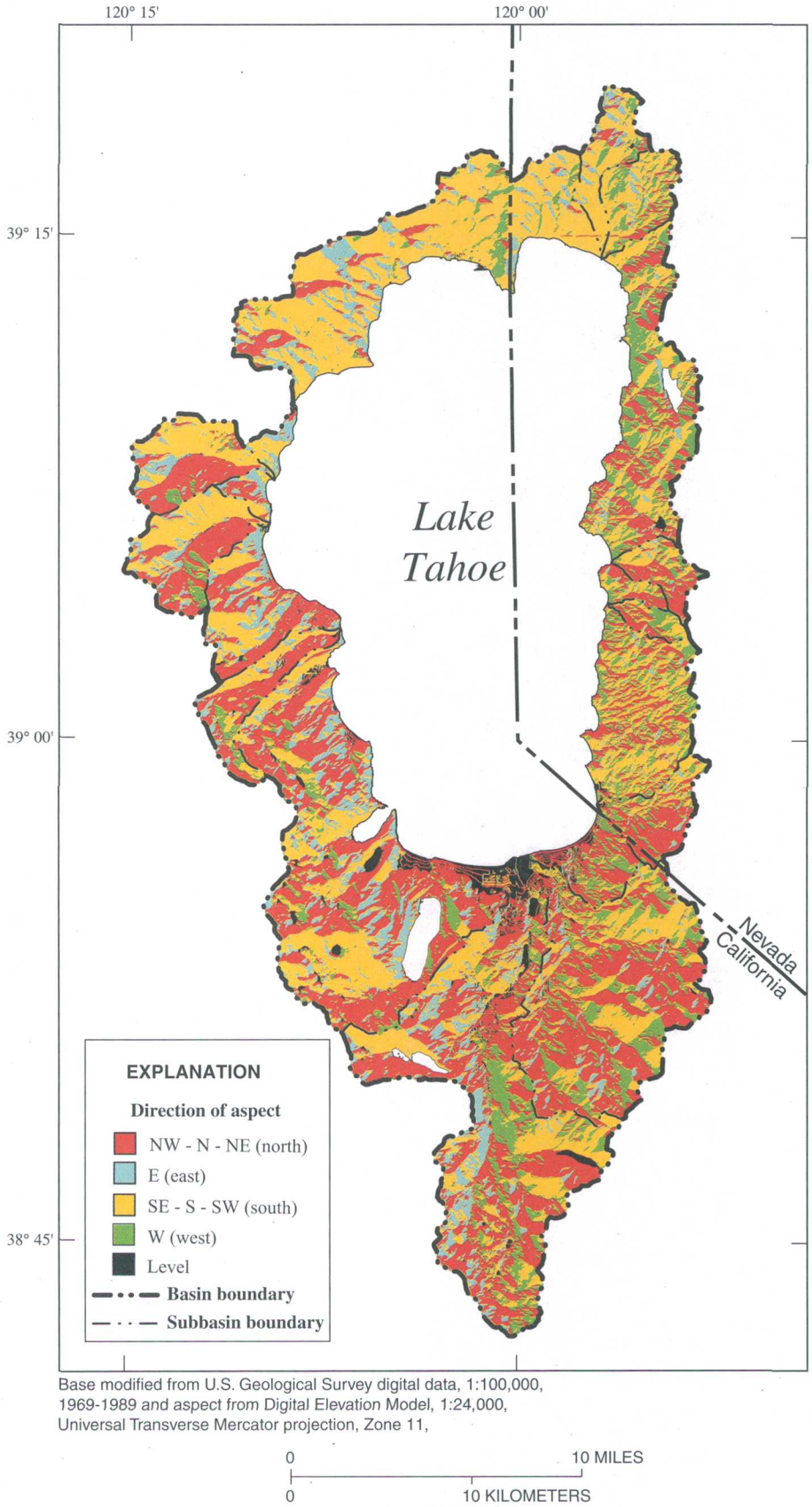


Figure 7. Classification of aspect in the Lake Tahoe Basin.

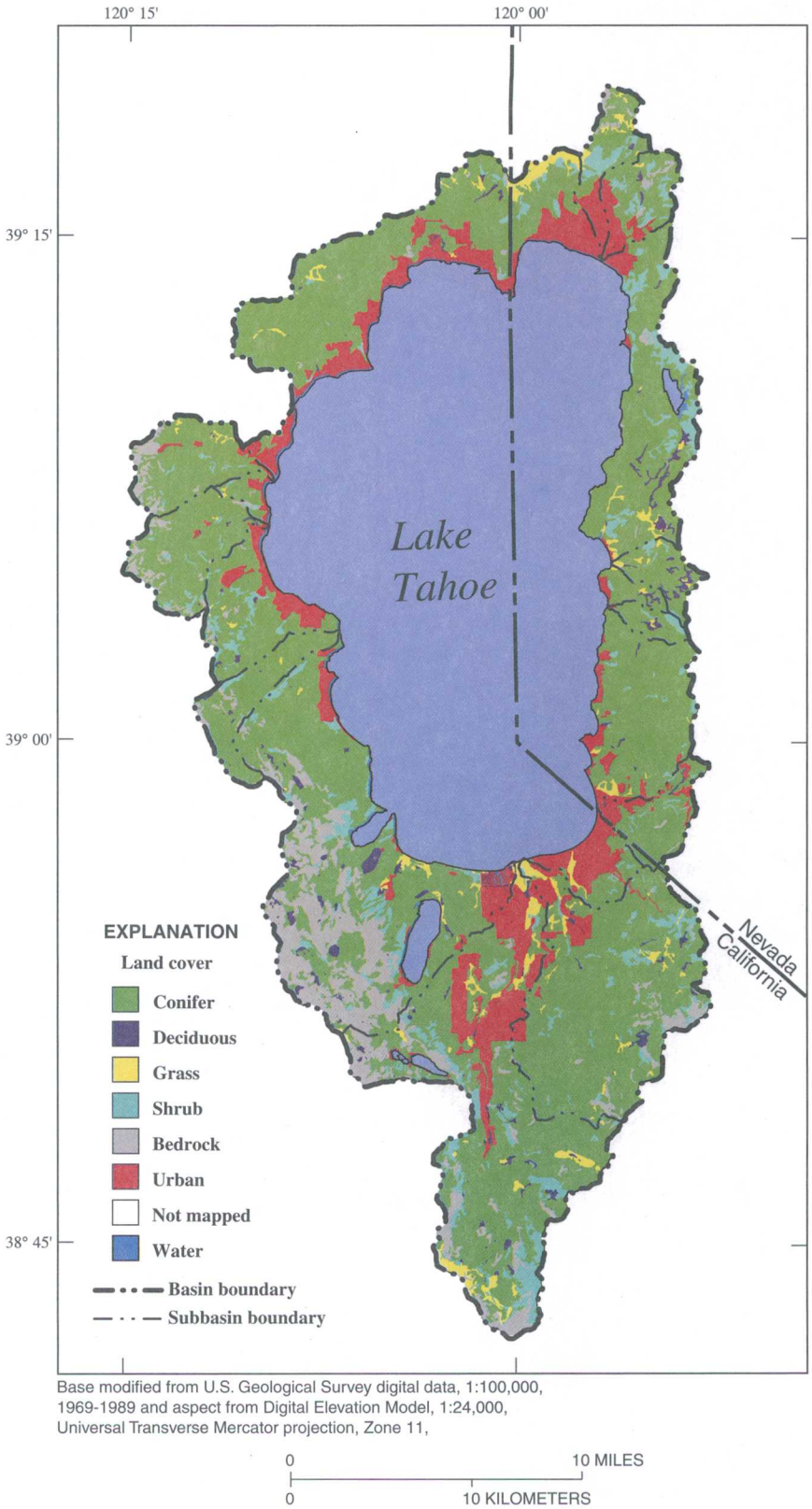


Figure 8. Classification of land cover in the Lake Tahoe Basin.

A spatial pattern-recognition technique similar to standard-image classification (Lillesand and Kiefer, 1987) was then applied to the five grouped data layers (fig. 4, step 4). Each 30-m by 30-m area in the basin was characterized by its own combination of the five data layers, and each pattern realized was given a pattern-identification number (PIN). A relational data-base management system (RDBMS; fig. 4, step 5) was used to analyze the distribution and frequency of PIN's and to reassign hydrologically similar PIN's to common subsets. For example, two PIN's, both characterized by steep slopes, similar aspect, and similar vegetation cover, but differing in soil type, would be regrouped into a single, slightly more general subset. Such regrouping would be justified because soils on steep slopes commonly are shallow and poorly formed, and thus the role and importance of the soil-zone reservoir is reduced. Then, cells were assigned to HRU's on the basis of the PIN subsets (fig. 4, step 6). The resulting HRU layer was nominally filtered—a raster-processing technique that removes isolated cells or small clusters that are different from their surroundings.

For each HRU, the frequency distributions of characteristics (from the original data sources) of all cells within the HRU were determined (fig. 4, step 7). These distributions were used as a basis for estimating HRU-dependent parameters to reduce errors attributable to the spatial lumping of parameters and to use the "distributed" nature of PRMS to its fullest extent. To illustrate, in a particular HRU, soil texture might be classed as clay among the grouped categories, when in reality the soil was more varied. The soil-data layer containing the original 32 soil classes would be intersected with the HRU layer. Then, the actual range of soil classes within the HRU would provide a basis for selecting infiltration rates and water-holding capacities. Finally in step 8, the RDBMS was used to build the HRU parameter file.

Maintaining a digital data base for modeling current watershed conditions where land cover and land-use type and density are in flux, or for inclusion of more recent digital coverages, would require the modeler to redefine the HRU coverage for each new entry and rerun the GIS-to-modeling component, as illustrated in figure 4. Recognizing the need to streamline this objective, multistep procedure for building parameter files for the ungaged areas, a method was developed to enhance the GIS-to-hydrologic model interface developed earlier using numerous UNIX-based computer programs for processing the digital data as well as for computing certain PRMS model parameters. For example, steps 1 through 6 in figure 4 constitute what will be referred to here as "watershed characterization."

The computer program for delineating HRU's contains links to the ARC GRID software program (Environmental Systems Research Institute, Inc., 1994) in which the complex, multistep grid-based process is automated. A UNIX-based relational data-base (RDB) program outside of ARC/INFO computes an analysis of tabular data in a manner easily modified by the user. The process defining the GIS-to-hydrologic model interface, illustrated as steps 6 through 8 in figure 4, is currently embedded in a single program. Within the program, ARC macro language (AML) programs compute GIS-based model parameters. Many of the distributed (HRU-dependent) parameters were assigned values from relational data-base tables because field and laboratory values were related to mapped basin features. The program finally outputs the computed model parameters in a format compatible with PRMS input requirements.

The GIS-to-model interface as developed in this study 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 rerun the hydrologic model. In addition, the set of programs facilitates use of the watershed model for comparison of land-use change "scenarios" which may affect runoff volume and timing.

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. 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. Lumped-parameter models depend inherently on assumptions that the modeled systems are sufficiently linear to permit the modeling of large-scale average descriptions of vegetation cover,

altitude, and climate to yield an "average" streamflow. In reality, runoff generation can be described more accurately in terms of climate-terrain interactions, which require the inclusion of spatial variability. The following section describes the PRMS HRU-dependent or distributed parameters and the nondistributed parameters modified during the calibration process, the source for their initial values as listed in table 3, and a summary of a sensitivity analysis. The subsequent section presents the model results in the form of an error analysis for the "paired subbasins" and for the unpaired General Creek subbasin model.

Model Parameterization

Distributed parameters attributed to individual HRU's are those parameters (1) that describe physiographic characteristics, for example drainage area, slope, aspect, and vegetation type and density, or (2) that have hydrologic processes on or within the HRU, or (3) that modify the meteorologic inputs to the model. Examples of the latter two are: soil-moisture infiltration; evapotranspiration losses; seepage to the subsurface and ground-water reservoirs; potential evapotranspiration; precipitation-correction adjustments; precipitation form (rain or snow); vegetation-canopy interception; runoff from impervious areas; and overland flow from saturated soils. In contrast, nondistributed or lumped parameters (also referred to as "basinwide" or "global" parameters) are those whose values apply over the entire basin. Nondistributed parameters are used to describe watershed processes that are independent of HRU characteristics. In PRMS, nondistributed 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; in subsurface and groundwater routing; and in solar-radiation computations.

Table 3 lists the distributed (HRU-dependent) parameters and the nondistributed (basinwide) parameters modified during calibration. For a complete listing of PRMS parameters, refer to the PRMS manual (Leavesley and others, 1983). Sources for initial parameter values are indicated in table 3. The designation of "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 latter finalized as the result of iterative model runs.

Sensitivity analyses during calibration typically help to determine the extent to which parameter-value uncertainties may result in unacceptable streamflow predictions. Parameters were selected for calibration 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 Lake Tahoe Basin because such analyses were made in a previous PRMS modeling study for the headwaters of the East Fork River Basin (Jeton and others, 1996), an area which has hydroclimatic and physiographic characteristics similar to those of the Lake Tahoe Basin. Sensitivity analyses from the East Fork Carson River study indicated that the following parameters were the most sensitive: the snow-threshold temperature that determines precipitation form; the precipitation-correction factor 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.

The importance of climatological influences, particularly seasonal anomalies of temperature and precipitation for moderate-altitude snow-dominated subbasins of the Lake Tahoe Basin, 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 colder, higher alpine snowpack. Simulated snowmelt occurs when the snowpack contains enough heat to fuel melting and, thus, its timing is indirectly linked to the annual temperature cycle. For the Sierra Nevada, the U.S. Army Corps of Engineers (1956) and Aguado (1985) note that radiation balances, rather than turbulent transfers from the atmosphere, are the dominant energy contributors. Assuming that precipitation is correctly distributed over the watershed, uncertainties in the nondistributed parameters listed in table 3

(primarily the temperature-dependent and subsurface and ground-water flow-routing parameters) contributed to simulation error. Runoff timing also was affected by the subsurface and ground-water routing coefficients. Subsurface flow-routing coefficients determine the rate of flow from the subsurface reservoir to the stream channel, and thus affect timing of runoff. The shape of the baseflow recession curve is influenced by the relative proportion of ground-water recharge from the soil zone and from the subsurface reservoir (fig. 3).

For each set of paired subbasins, one was selected as the calibration basin, the second as the validation basin. The calibration basin was selected as the basin most "representative" of the pair to avoid validating the model using physiographic conditions not present in the calibration basin. For example, if there were several unique HRU's in one subbasin and not in the other, the former was selected as the calibration subbasin. Within the calibration basin, the period of record was partitioned into a calibration period and a verification period. The HRU-scale parameter values from the calibration basin were transferred to the validation basin model. Initially, all nondistributed parameter values from the calibration subbasin model were used in the validation basin model and later adjusted, if warranted.

Computed simulation errors are presented in the following section. Differences in physiographic and hydroclimatic characteristics between the calibration basin and the validation basin for all sets of paired basins, excluding Ward and Blackwood Creeks, required some adjustments to the validation models.

Error Analysis

Calibration results were analyzed in a manner similar to regression analysis (Troutman, 1985). Although precipitation-runoff models are nonlinear, model simulations—such as streamflow—are analyzed in a linear manner. The goal in modeling is threefold: little to no bias, realistic parameter values reflecting the watershed condition being modeled, and satisfactory runoff predictions for 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. Measures of prediction error commonly are 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 commonly are 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.

Error analyses presented in tables 4–6 include computations of bias to determine the presence of systematic error or an indication of central tendency, and relative error to determine the degree of variability or statistical spread in the residuals. Errors listed in tables 4–6 are statistics computed on daily, monthly, or annual mean streamflow simulations for the calibration subbasins and for the simulation results from adjustments made to the validation subbasins. Initial model results for the validation subbasins are presented in the discussions for each subbasin pair. In table 7, simulated and observed monthly runoff are evaluated as a percentage of annual runoff. Simulated and observed runoff are discussed relative to the contribution to annual runoff from either a particular month or a seasonal aggregate. Attention is focused on whether the spring snowmelt period is adequately modeled, given the importance of spring snowmelt runoff to total annual runoff. In the following sections, data from table 7 are referred to in the text as seasonal aggregates. Specifically, spring snowmelt refers to April through June; baseflow refers to August through October, and the late fall to early winter refers to November through February. March and July were excluded from the seasonal aggregates due to their "transitional" nature. For example, depending on whether the subbasin is a high- or low-altitude watershed, March might be considered a winter or spring snowmelt month, respectively. Likewise, July might be either a spring runoff month (for a high-altitude watershed) or a baseflow month (for a low-altitude watershed).

Table 3. Source of parameter values for distributed and (selected) nondistributed PRMS parameters for the Lake Tahoe Basin, California and Nevada

[Abbreviation: HRU, Hydrologic Response Unit]

Model parameter	Description of parameter	Source of parameter value				
		GIS derived[1]	Com-puted[2]	Litera-ture[3]	Default value[4]	Calibra-tion[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 for summer, in percent	X				
COVDEN_WIN	Vegetation cover density for winter, in percent	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 site 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 sites used to compute HRU temperatures, in degrees Fahrenheit		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, in degrees Fahrenheit		X			
RAD_TRNCF	Transmission coefficient for short-wave radiation through the winter canopy		X			
SMIDX-COEF	Coefficient in nonlinear contributing area algorithm (computing surface runoff)				X	
SMIDX_EXP	Exponent in nonlinear contributing area algorithm (computing surface runoff)				X	
SNAREA_THRESH	Maximum snow water equivalent below which the snow-covered area depletion curve is applied			X		
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 ground-water reservoir, in inches per day					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 (upper soil zone), in inches			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, in degrees Fahrenheit				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 (basinwide) 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			
RAINJH_COEF_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
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 altitude change for each month	X			
TMIN_LAPSE	Monthly minimum temperature lapse rate representing the change in minimum temperature per 1,000 feet of altitude change for each month	X			
	Ground-water flow 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 flow routing				
SSR2GW_RATE	Coefficient to route water to from the subsurface to ground-water reservoir				X
SSRCOEF_LIN	Linear subsurface routing coefficient to route subsurface storage to streamflow				X
SSRCOEF_SQ	Nonlinear 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 either cannot be estimated from available data and are adjusted during calibration, or parameters that have an initial value estimated from observed or published data and later adjusted during calibration.

Table 4. Statistical analyses for simulated daily mean streamflow for gaged subbasins in the Lake Tahoe Basin, California and Nevada

[Symbol: --, statistics not computed. Paired subbasins are grouped]

Subbasin [1]	Period of record (water year)	Relative error [2] (percent)			Bias [3] (percent)		
		Calibration period	Verification period	Entire period of record	Calibration period	Verification period	Entire period of record
Blackwood Creek*	1981-96	--	--	+19.8	--	--	-5.4
Ward Creek	1981-96	+15.6	+16.7	+16.0	-9.0	+1.4	-3.0
Third Creek	1981-96	+1.0	-4.9	-2.6	-1.7	-3.1	-2.5
Incline Creek*	1989-96	--	--	+15.0	--	--	+6.0
Glenbrook Creek	1990-96	--	--	+12.1	--	--	+1.2
Logan House Creek*	1985-96	--	--	+73.7	--	--	-4.7
Trout Creek*	1981-96	--	--	+4.6	--	--	-2.9
Upper Truckee River	1981-96	+38.0	+65.0	+56.6	-.5	+7.6	+7.6
General Creek	1981-96	+32.0	+8.7	+18.6	-4.1	-1.4	-2.5

[1] Validation subbasin indicated by asterisk. Results presented in this table for validation subbasins reflect final model adjustments. With the exception of Blackwood Creek, all the validation models had one or more parameter values modified from calibration model value(s) to better fit observed hydrograph.

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

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

For both equations:

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 (except for Logan House Creek where all observations were used).

Included in the discussions for Ward Creek, Blackwood Creek, Upper Truckee River, Trout Creek, and General Creek are comparisons of observed and simulated hydrographs for water years 1996–97. In late December 1996, snowstorms built up a large snowpack (more than 180 percent of normal) in the higher elevations of the Sierra Nevada. A subtropical storm in early January 1997 subsequently brought in heavy, unseasonably warm rains to altitudes near 9,000 ft, which caused snowmelt and major flooding of the Truckee River and Carson River Basins. The 1997 water year was not included in the statistical analysis; however, selected hydrographs are included in the following discussions to provide an indication of model simulation during this major rain-on-snow storm. The observed flows for the January 1997 flood were estimated from "indirect" measurements, which are based on hydraulic equations that relate the discharge to the water-surface profile and the geometry of the stream channel.

With the exception of Incline, Glenbrook, and Logan House Creeks, which have shorter periods of record, all the tributaries in the Lake Tahoe Basin were modeled for a 16-year period of record from October 1, 1980, through September 30, 1996 (water years 1981–96). The calibration period was from October 1980 through September 1985. The verification period was from October 1985 through September 1996. For statistical analyses, simulated streamflow data sets were filtered to remove values less than or equal to 3 ft^3/s. Model simulations were evaluated on daily, monthly, seasonal, and annual time intervals as well as for wet and dry periods.

Table 5. Statistical analyses for simulated monthly mean streamflow for gaged subbasins in the Lake Tahoe Basin, California and Nevada

[Paired subbasins are grouped]

Subbasin [1]	Period of record (water year)	Relative error (percent) [2]	Bias (percent) [3]
Blackwood Creek*	1981-96	+17.6	-5.6
Ward Creek	1981-96	+15.6	-3.1
Third Creek	1981-96	-5.8	-3.3
Incline Creek*	1989-96	+13.0	+5.8
Glenbrook Creek	1990-96	+9.1	+.6
Logan House Creek*	1985-96	+70.5	-4.8
Trout Creek*	1981-96	+4.1	-2.8
Upper Truckee River	1981-96	+56.7	+4.3
General Creek	1981-96	+12.4	-2.2

[1] Validation subbasin indicated by asterisk. Results presented in this table for validation subbasins reflect final model adjustments. With the exception of Blackwood Creek, all the validation models had one or more parameter values modified from calibration model value(s) to better fit observed hydrograph.

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

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

For both equations:
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 (except for Logan House Creek where all observations were used).

Table 6. Statistical analyses for simulated annual mean streamflow for gaged subbasins in the Lake Tahoe Basin, California and Nevada

[Paired subbasins are grouped]

Subbasin [1]	Period of record (water year)	Relative error (percent) [2]	Bias (percent) [3]
Blackwood Creek*	1981-96	-0.8	-4.7
Ward Creek	1981-96	+6.0	-1.3
Third Creek	1981-96	-.9	-1.9
Incline Creek*	1989-96	+3.1	+3.2
Glenbrook Creek	1990-96	+13.1	+4.1
Logan House Creek*	1985-96	+18.0	-5.1
Trout Creek*	1981-96	+4.5	-2.9
Upper Truckee River	1981-96	+16.0	+4.2
General Creek	1981-96	+8.4	+2.7

[1] Validation subbasin indicated by asterisk. Results presented in this table for validation subbasins reflect final model adjustments. With the exception of Blackwood Creek, all the validation models had one or more parameter values modified from calibration model value(s) to better fit observed hydrograph.

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

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

For both equations:
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 (except for Logan House Creek where all observations were used).

Ward Creek and Blackwood Creek Subbasins

Ward Creek was selected as the calibration subbasin and Blackwood Creek as the validation subbasin. The Blackwood Creek model was constructed using both HRU-distributed and nondistributed parameter values from the calibrated Ward Creek model. No further adjustments to the parameters were made to the Blackwood Creek model. Modeling results tabulated for Ward and Blackwood Creeks are listed in tables 4–6.

Daily mean streamflow simulation for the Ward Creek (table 4) model indicated a bias towards undersimulation by -9.0 percent during the calibration period and a bias of +1.4 percent during the validation period. Relative error was +16.0 percent for the entire period of record. Plots of observed and simulated monthly mean streamflow for Ward and Blackwood Creeks are given in figures 9 and 10, respectively. Simulated monthly mean streamflow (table 5) for Ward Creek shows a bias of -3.1 percent and a relative error of +15.6 percent. Simulated annual mean streamflow (table 6) for Ward Creek has a bias of -1.3 percent and +6.0 percent relative error. Blackwood Creek bias was about -5 percent for daily, monthly, and annual runoff, whereas the relative error ranged from +19.8 for daily runoff to -0.8 percent for annual mean runoff. The USGS streamflow rating for the Ward Creek gage is "fair" and the rating for the Blackwood Creek gage is "good."

Observed runoff for Ward and Blackwood Creeks during the snowmelt period is about 64 percent of the total annual runoff (table 7). Simulated runoff (57 percent) was less during this period for both subbasins. Figures 11 and 12 illustrate streamflow simulation for water years 1996–97 for Ward and Blackwood Creeks, respectively.

Table 7. Simulated and observed monthly percentage of annual streamflow for gaged subbasins and simulated monthly percentage of annual runoff for the ungaged areas in the Lake Tahoe Basin

[For each subbasin or area: first line (non-italic) is simulated monthly percentage; second line (italic) is observed monthly percentage. Both sets of values are calculated using (monthly mean for month i/mean annual total) × 100]

Subbasin or area (fig. 1*B*)	Period of record (water year)	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
Blackwood Creek	1981–96	1.7	7.6	5.7	2.9	5.4	9.4	15.5	24.3	17.1	6.9	2.2	1.3
		1.1	*3.7*	*4.3*	*3.1*	*6.1*	*8.6*	*15.1*	*27.2*	*21.2*	*7.2*	*1.6*	*.8*
Ward Creek	1981–96	1.7	7.5	5.3	2.5	4.9	8.9	14.5	23.9	18.4	7.9	3.0	1.5
		1.1	*4.0*	*4.3*	*3.2*	*5.9*	*8.0*	*14.7*	*27.3*	*22.1*	*7.4*	*1.4*	*.6*
Ungaged area 11	1981–96	1.9	7.5	6.5	4.1	7.5	11.4	14.3	20.0	14.7	6.9	3.3	1.8
Third Creek	1981–96	4.3	4.7	3.5	2.7	3.4	3.7	7.5	19.4	24.0	15.6	6.9	4.3
		3.8	*4.8*	*4.6*	*4.0*	*4.7*	*6.7*	*10.6*	*18.4*	*21.9*	*12.4*	*4.7*	*3.4*
Incline Creek	1989–96	2.7	3.0	3.4	3.3	5.9	12.3	14.2	19.1	16.0	10.3	5.9	3.9
		3.6	*3.8*	*4.1*	*4.2*	*6.1*	*9.8*	*12.9*	*18.2*	*17.2*	*10.3*	*5.5*	*4.3*
Ungaged area 12	1981–96	3.1	6.1	7.8	6.8	10.5	15.8	12.4	13.5	9.4	6.5	4.6	3.5
Glenbrook Creek	1990–96	2.7	2.3	3.3	2.5	5.5	17.2	19.1	21.0	13.8	6.4	3.6	2.6
		2.5	*3.7*	*4.4*	*4.4*	*6.9*	*13.7*	*16.9*	*25.0*	*13.1*	*5.0*	*2.5*	*1.9*
Logan House Creek	1985–96	1.8	1.8	3.6	2.5	6.7	20.7	20.3	16.8	13.3	6.5	3.6	2.4
		4.4	*4.8*	*5.2*	*5.0*	*5.4*	*9.0*	*20.0*	*24.8*	*10.9*	*4.7*	*2.8*	*3.0*
Ungaged area 14	1981–96	3.9	8.3	9.5	7.7	14.5	19.2	13.2	10.7	4.9	2.5	2.5	3.1
Ungaged area 15	1981–96	3.5	6.4	8.4	9.6	12.4	14.8	11.2	14.2	10.2	4.3	2.6	2.4
Trout Creek	1981–96	2.5	3.3	4.5	6.2	6.8	9.1	8.9	18.9	22.2	10.4	4.7	2.5
		3.9	*4.5*	*4.7*	*4.6*	*5.8*	*7.4*	*10.4*	*17.0*	*20.5*	*11.6*	*5.7*	*3.9*
Upper Truckee River	1981–96	3.7	4.5	3.3	4.7	6.6	9.5	12.5	19.4	20.6	8.8	3.7	2.7
		1.4	*3.4*	*4.0*	*3.9*	*6.7*	*9.4*	*14.4*	*25.0*	*21.2*	*7.6*	*1.8*	*1.2*
Ungaged area 16	1981–96	4.0	7.5	7.2	5.8	5.9	7.8	12.5	19.5	16.2	7.0	3.5	3.1
Ungaged area 17	1981–96	1.9	6.9	6.2	5.4	10.6	13.0	14.7	18.2	12.7	6.2	2.7	1.5
General Creek	1981–96	2.8	5.1	4.1	1.7	4.8	7.6	20.5	24.4	17.2	7.3	2.7	1.8
		1.1	*3.8*	*4.4*	*3.4*	*6.7*	*9.2*	*18.9*	*30.7*	*16.9*	*3.5*	*.7*	*.7*

Ward Creek peak daily mean for the January 1997 flood was undersimulated by -6 percent (1,310 ft^3/s simulated compared to 1,390 ft^3/s observed). Blackwood Creek peak daily mean discharge was -22 percent of the observed peak (1,566 ft^3/s simulated compared to 2,000 ft^3/s observed). Within 6 days, simulated and observed runoff for both models had returned to preflood discharge rates.

In general, the models perform better during wet years (mean annual streamflow error averaged 5 percent of the observed for Ward and Blackwood Creeks) than during dry years (mean annual error averaged 16 percent for Ward Creek and 8 percent for Blackwood Creek). For Ward Creek, the simulated runoff efficiency for the 6-year dry period 1987–92 averaged 50 percent (compared to a 44 percent runoff efficiency when using observed runoff) and for wet years it averaged 65 percent (compared to a 69 percent runoff efficiency when using observed runoff). For Blackwood Creek, the simulated runoff efficiency for this same dry period averaged 57 percent (compared to a 55 percent runoff efficiency when using observed runoff) and for the wet years it was 72 percent (compared to 78 percent runoff efficiency when using observed runoff). Ground water makes up about 13 percent of the total water yield for Ward Creek and 8 percent for Blackwood Creek, which suggests that about 40 percent of the total precipitation received on the subbasins returns to the atmosphere in the form of sublimation and evapotranspiration, and that minor amounts of ground water are assumed to seep into the lake.

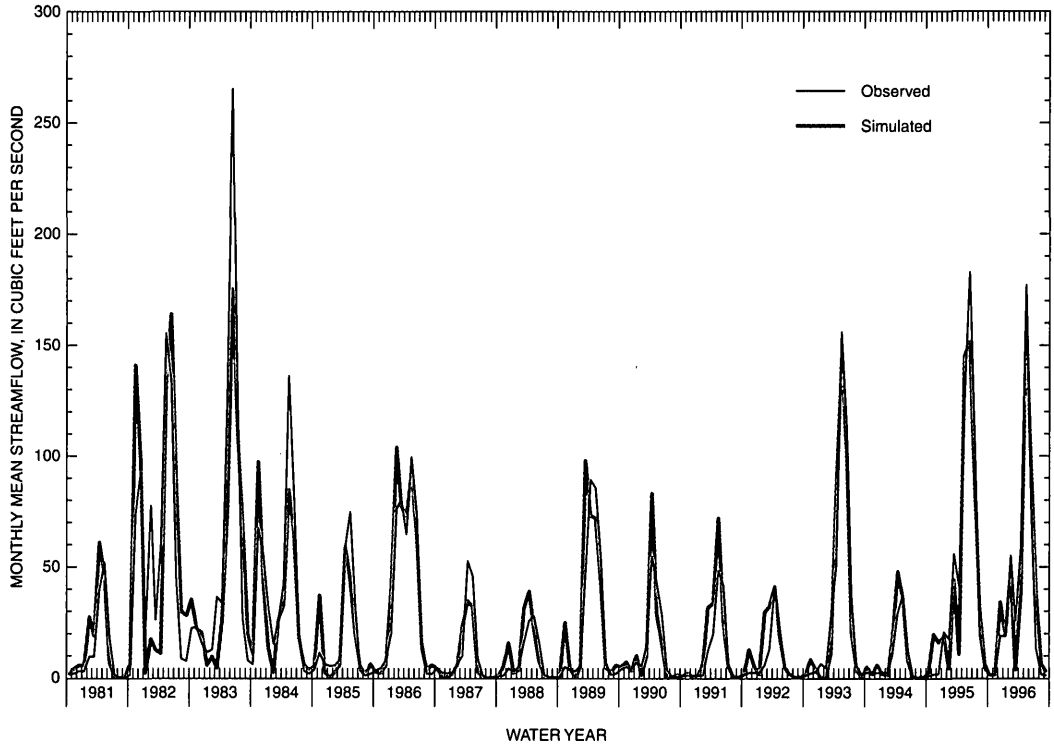


Figure 9. Simulated and observed monthly mean streamflow for Ward Creek, Lake Tahoe Basin, water years 1981–96.

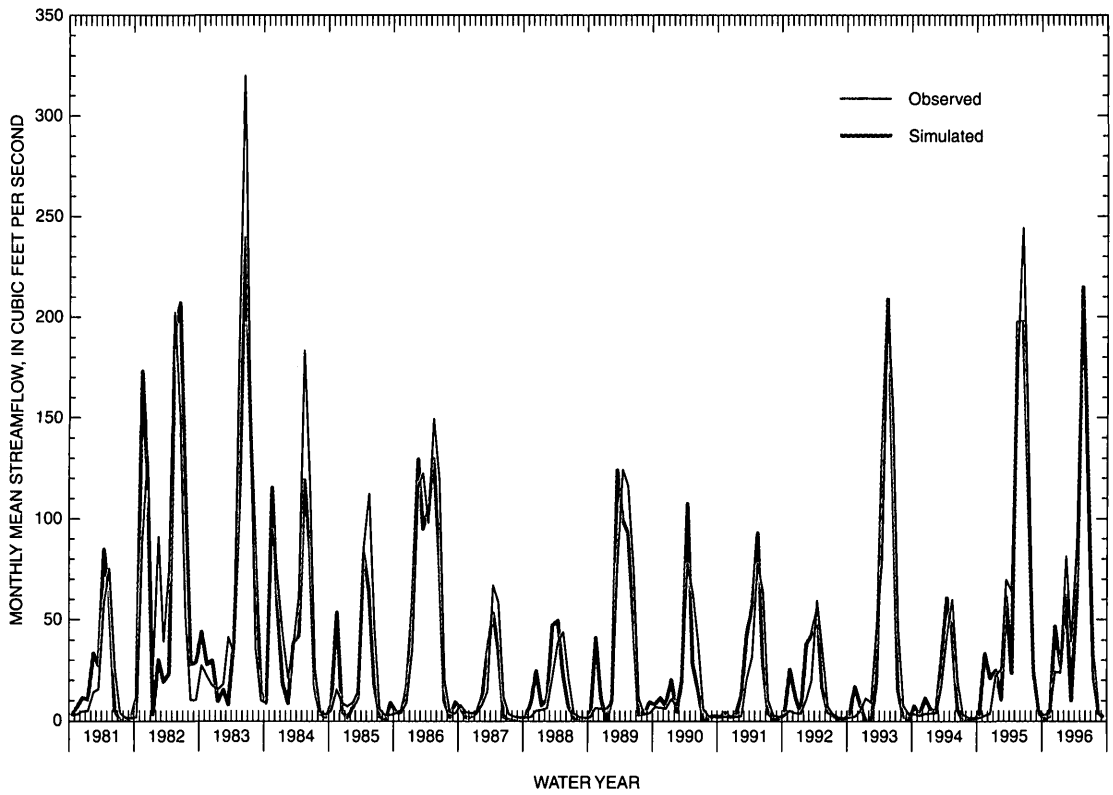


Figure 10. Simulated and observed monthly mean streamflow for Blackwood Creek, Lake Tahoe Basin, water years 1981–96.

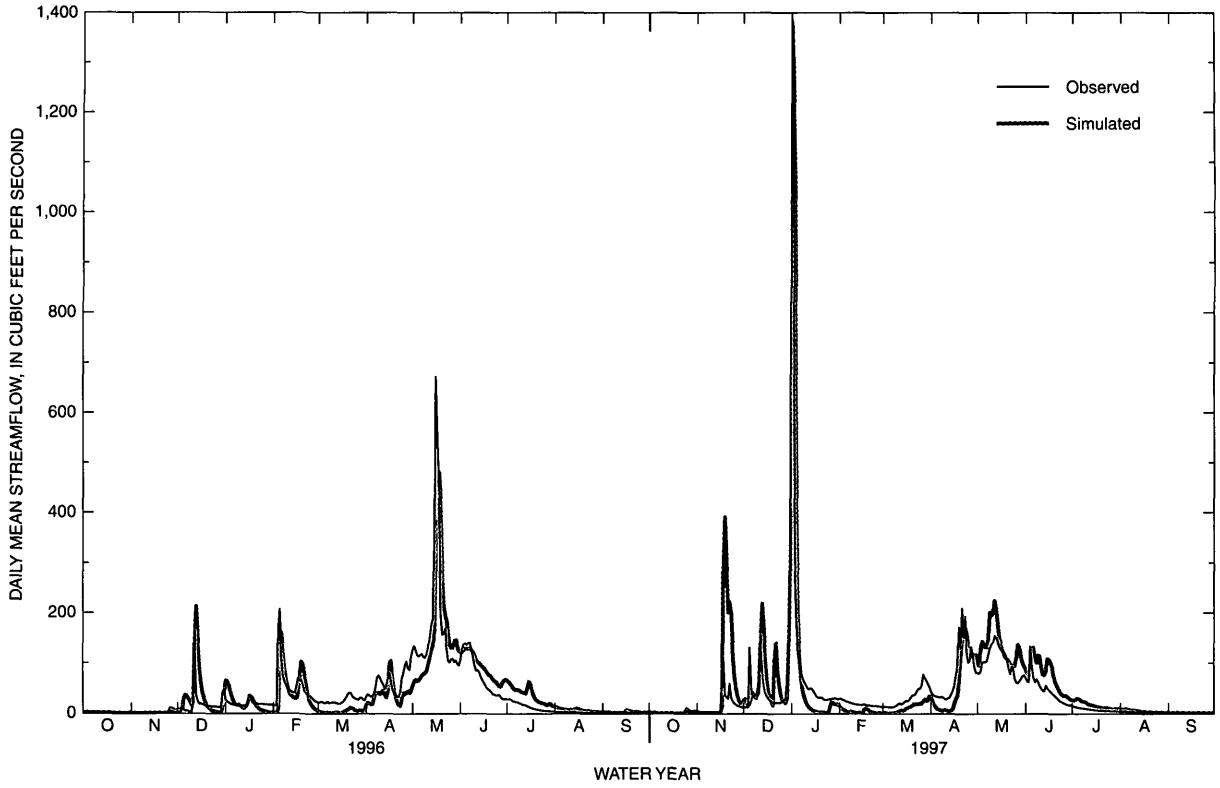


Figure 11. Simulated and observed daily mean streamflow for Ward Creek, Lake Tahoe Basin, water years 1996–97.

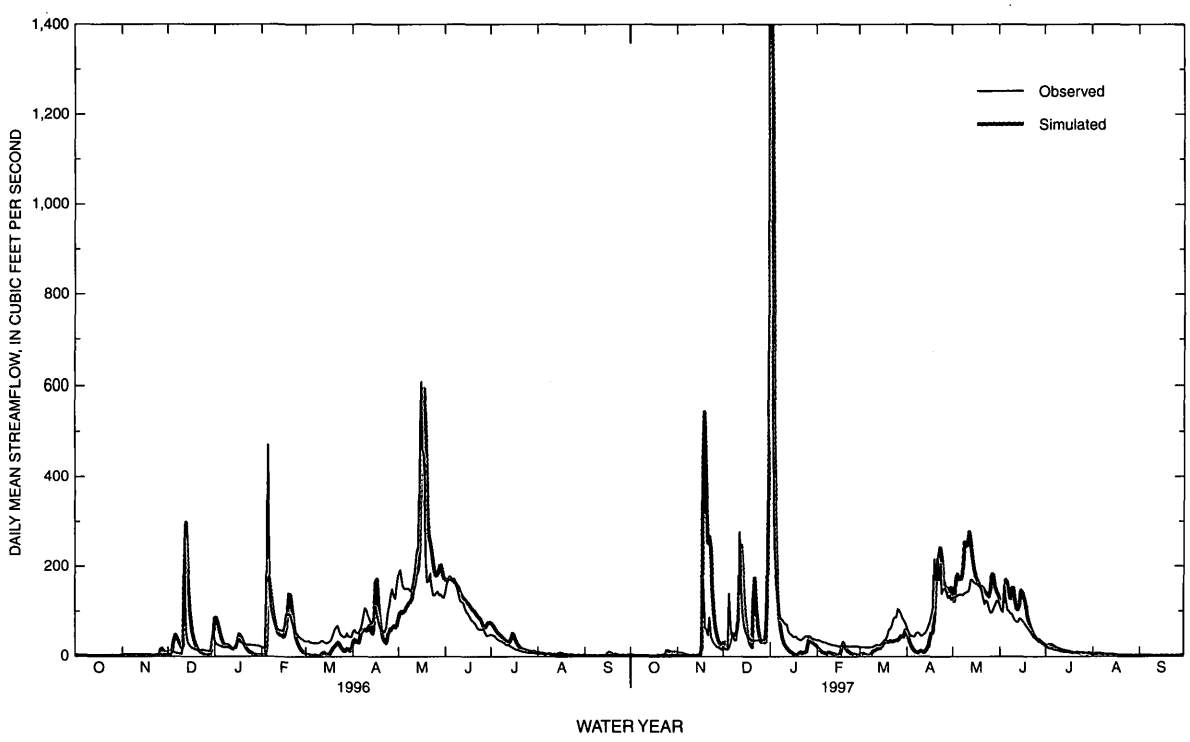


Figure 12. Simulated and observed daily mean streamflow for Blackwood Creek, Lake Tahoe Basin, water years 1996–97.

Third Creek and Incline Creek Subbasins

Third Creek was selected as the calibration subbasin and Incline Creek as the validation subbasin. The USGS streamflow record for the Third Creek gage is rated as "fair" and Incline Creek record is rated as "good." Daily mean streamflow bias for Third Creek averaged about -2.0 percent for the calibration and verification period. Relative error ranged from +1.0 percent for the calibration period to -4.9 percent for the verification period. Plots of observed and simulated monthly mean streamflow for Third Creek and Incline Creek, respectively, are given in figures 13 and 14. Monthly mean streamflow for the full period shows a bias of -3.3 percent and relative error of -5.8 percent. Annual mean streamflow bias was -1.9 percent and relative error -0.9 percent. Streamflow is affected by diversions made in the upper reach of Third Creek across the Lake Tahoe Basin boundary to Washoe Valley, east of the Sierra Nevada. Diversion amounts are about 2 ft^3/s per day during the period from June through October and 4 ft^3/s during the period from December through May. Depending on the month, this can be as much as 50 percent of the streamflow. Inadequate records of diverted water prevented modifying the observed Third Creek record for modeling purposes. Simulated spring snowmelt and winter runoff (table 7) are comparable to the observed seasonal aggregates, suggesting that runoff volumes are being appropriately modeled.

Only 30 percent of the HRU's in the Third Creek subbasin correlated to those mapped for the Incline Creek subbasin. The differences were attributed mainly to Third Creek subbasin HRU's in unique altitude zones and to the number of HRU's classed as rock outcrop. The proportion of urban area in the two subbasins was within 4 percent of one another. The streamflow-gaging record for Incline Creek is intermittent during the earlier part of the record; therefore, only the continuous record from water years 1990–96 was used for this study. Initial model runs using the global parameters from the Third Creek model resulted in a daily mean bias and relative error of -30 percent. Increasing the ground-water flow coefficient, reducing the subsurface flow rate (which in turn increases the ground-water contribution), and decreasing the seepage rate from the soil profile to the ground-water reservoir improved timing and volume of runoff. In addition, timing in the Incline Creek model was improved by adjusting the melt dates to April 1 (from June 1 for the Third Creek model) and increasing the proportion of rain in a rain-on-snow storm for the winter months. The resultant improvement in timing of snowmelt and simulation of rain-on-snow storms for the Incline Creek model reflects the sensitivity of runoff to temperature. Bias for the Incline Creek model after these adjustments ranged from +6.0 percent for daily mean flow to +3.1 percent for annual mean flow; relative error for Incline Creek ranged from +15.0 percent for the daily mean flow to +3.1 percent for annual mean streamflow.

For most years, the snowmelt baseflow recession is fairly well simulated, though streamflow during the late fall to early winter months is undersimulated for individual years by as much as 14 percent. Observed streamflow data indicate about 16 percent of annual streamflow during the October-January period. This may be attributed to more rain than the model is simulating, or recharge near the gaging station, or a rise in baseflow associated with ground-water storage in the aquifer underlying the lower part of the Third Creek and Incline Creek subbasins. Thodal (1997) suggests that ground-water seepage from the aquifer to the lake accounts for some of the ground-water storage loss. To simulate this loss, a ground-water "sink" function in PRMS subtracts a user-defined percentage of ground-water storage and writes these data to an external time series. These data are later added to the total tributary inflow computed for Lake Tahoe. The ground-water component comprises 30 percent of total simulated water yield for Third Creek and 48 percent for Incline Creek. Runoff efficiencies for both subbasins in dry years averaged 30 percent using simulated and observed runoffs. For wet years, simulated and observed runoff efficiencies averaged 39 percent for Third Creek and 47 percent for Incline Creek (compared to 49 percent using observed runoff).

Glenbrook Creek and Logan House Creek Subbasins

Glenbrook Creek was selected as the calibration subbasin and Logan House Creek as the validation subbasin. Given the short period of record, the data set was not split into calibration and verification periods; instead the model was calibrated for water years 1990–93 and the later years added as data became available. Simulation results are listed in tables 4–6 for water years 1990–96. Daily mean and monthly mean streamflow biases for Glenbrook Creek were +1.2 and +0.6 percent, respectively, whereas annual mean bias was +4.1 percent. Relative error was +12.1 percent for daily mean streamflow, +9.1 percent for monthly mean streamflow, and +13.1 percent for annual mean streamflow. Plots of observed and simulated monthly mean streamflow are shown in figures 15 and 16 for Glenbrook Creek and Logan House Creek, respectively. The USGS streamflow rating for Glenbrook and Logan House Creeks is "fair."

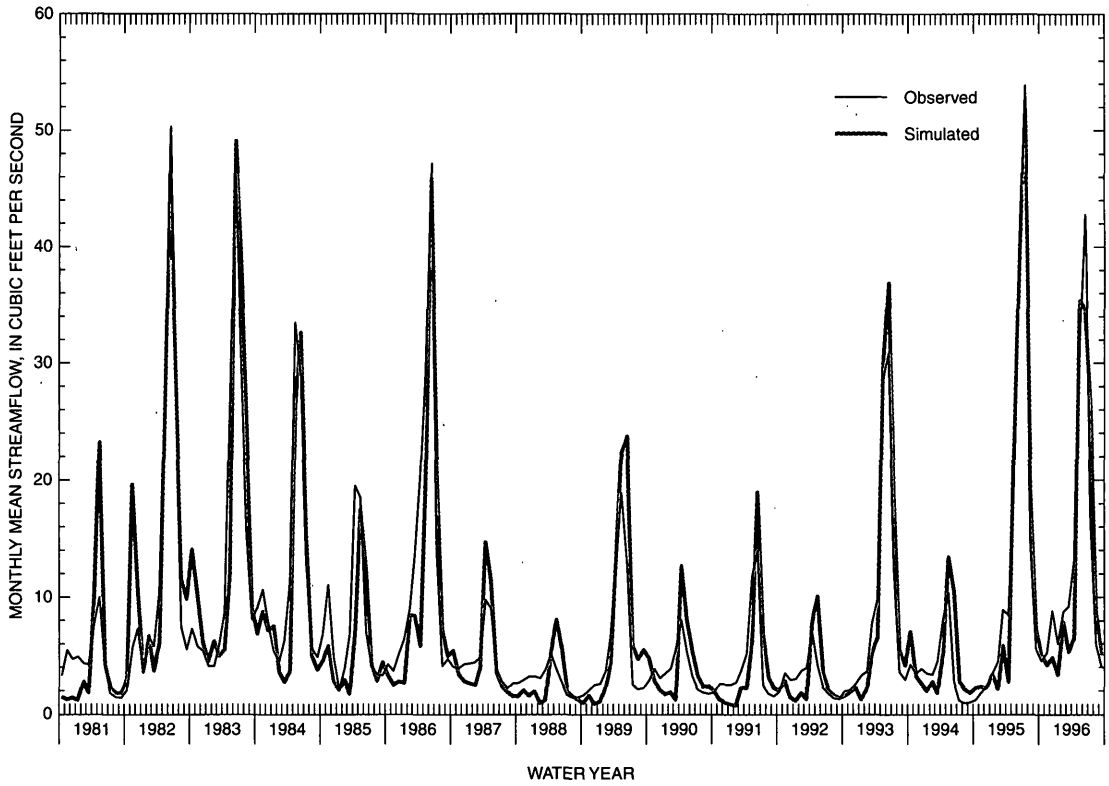


Figure 13. Simulated and observed monthly mean streamflow for Third Creek, Lake Tahoe Basin, water years 1981–96.

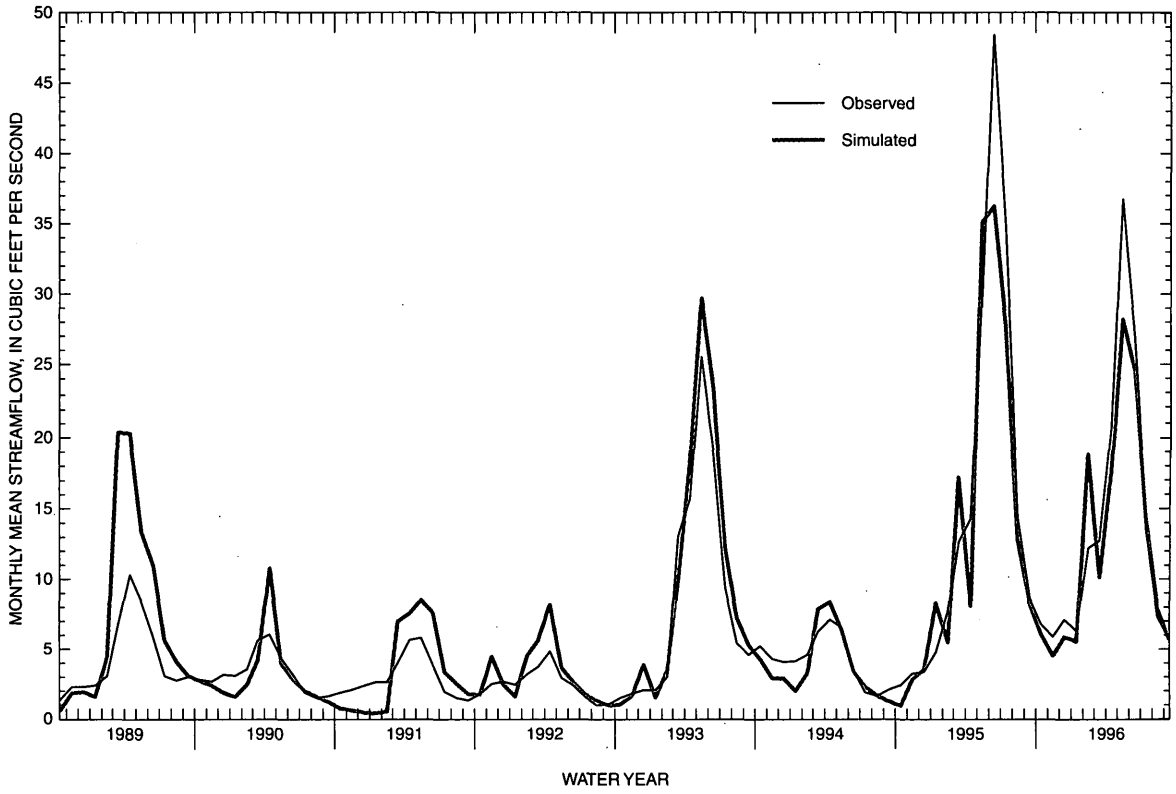


Figure 14. Simulated and observed monthly mean streamflow for Incline Creek, Lake Tahoe Basin, water years 1989–96.

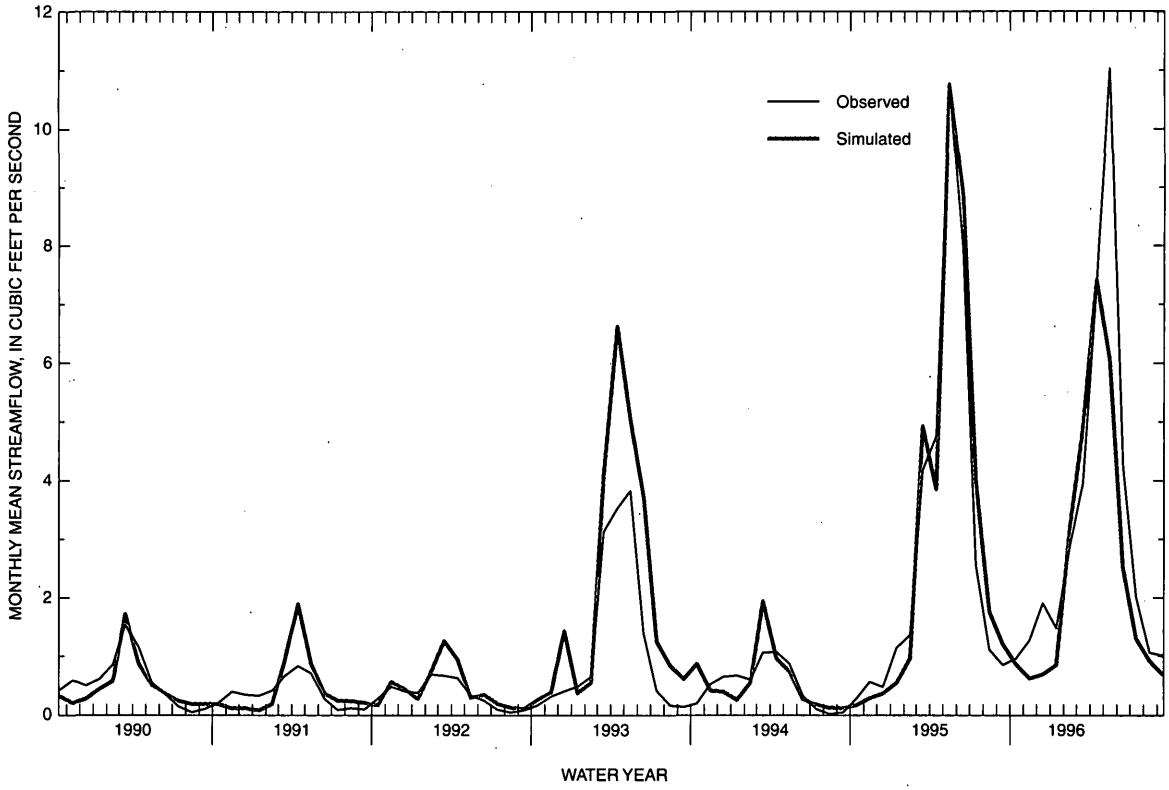


Figure 15. Simulated and observed monthly mean streamflow for Glenbrook Creek, Lake Tahoe Basin, water years 1990–96.

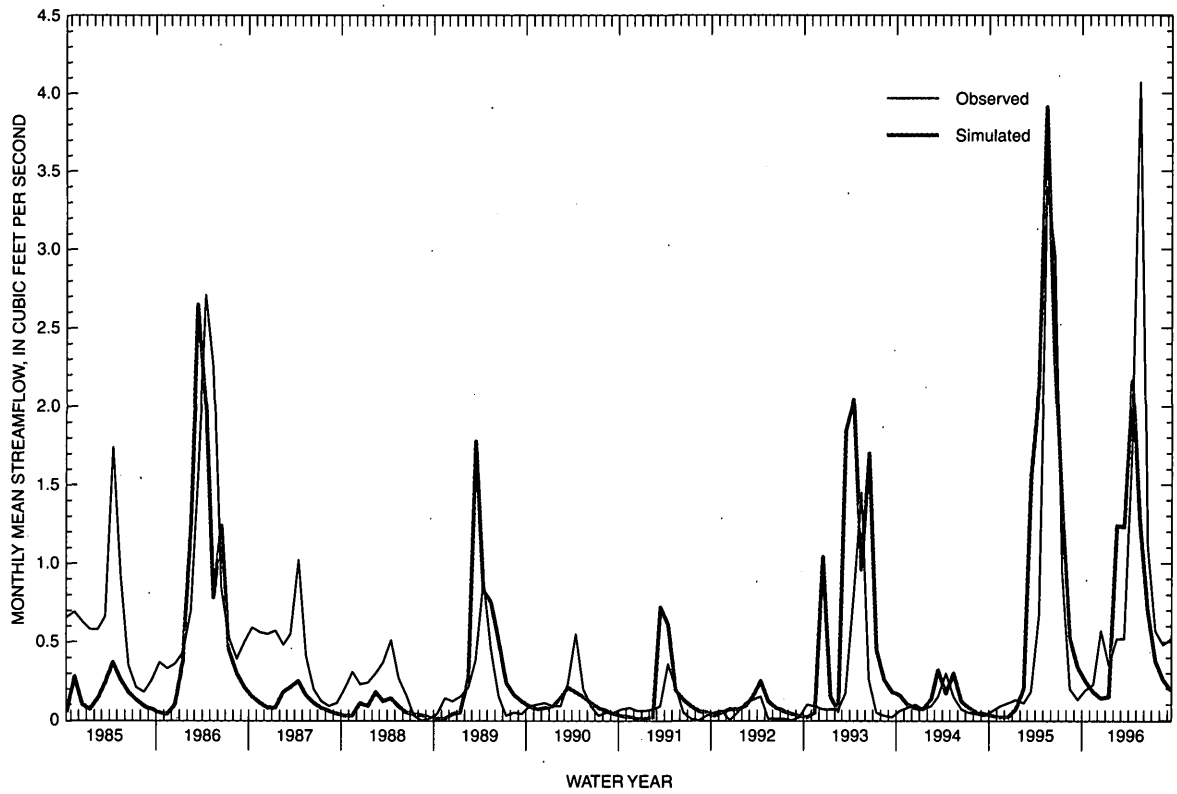


Figure 16. Simulated and observed monthly mean streamflow for Logan House Creek, Lake Tahoe Basin, water years 1985–96.

Only 25 percent of the HRU's in the Glenbrook Creek subbasin were matched to the Logan House Creek subbasin. Much of the discrepancy is attributed to differences in altitude-area distribution. Although the Logan House Creek tributary is half the area of the Glenbrook Creek tributary, 34 percent of the Logan House Creek subbasin is at or above the 8,000-ft altitude zone, in contrast to only 12 percent for the Glenbrook Creek subbasin. Observed monthly mean streamflow for Logan House Creek (computed for water years 1985–96) averaged less than 1 ft^3/s. Using the Glenbrook Creek subbasin-model settings, the Logan House Creek subbasin model oversimulated daily mean streamflow by as much as +60 percent and annual mean streamflow by more than +500 percent. Final adjustments to the Logan House Creek model included changing the snowmelt start date (which forces the snowpack to begin melting and affects timing of runoff) from May 1 to June 1 and adding a ground-water "sink" to compensate for streamflow loss due to withdrawals upstream from the gage. Although daily mean streamflow bias was reduced from -58 percent to -5 percent, relative daily mean error still averaged +74 percent. Unlike the other gaged subbasins in this study, the error measurements for Logan House Creek presented in tables 3 and 4 were computed for all observed values. Given the very low flows and the diversions upstream from the gage, the Logan House Creek subbasin model cannot be considered reliable. Runoff efficiencies for Glenbrook Creek averaged 23 percent for wet years (compared to 24 percent using observed runoff) and 10 percent for dry years (compared to 9 percent using observed runoff), suggesting substantial shallow ground-water storage within the thick weathered granite. Runoff efficiencies for Logan House Creek averaged 12 percent for wet years, compared to 10 percent using observed runoff, and 4 percent for dry years, using simulated and observed runoffs.

Upper Truckee River and Trout Creek Subbasins

The Upper Truckee River was selected as the calibration subbasin and Trout Creek as the validation subbasin. Plots of observed and simulated monthly mean streamflow for the Upper Truckee River and Trout Creek are shown in figures 17 and 18, respectively. Simulation results are listed in tables 4–6 for water years 1981–96. Daily mean streamflow bias for the Upper Truckee River model during the calibration period was -0.5 percent, bias during the verification period was +7.6 percent. Relative error during the calibration period was +38 percent; during the verification period it was +65 percent. Monthly and annual mean streamflow bias were about +4 percent, whereas relative errors were +56.7 percent and +16.0 percent, respectively. The USGS gage on lower Upper Truckee River is rated as "fair." As a percentage of total runoff (table 7) there was less simulated spring snowmelt (52 percent) than observed (60 percent) and more simulated baseflow (10 percent) than observed (4 percent). For wet years, simulated runoff efficiencies averaged 59 percent (compared to 64 percent for observed runoff); for dry years, they averaged 47 percent (versus 36 percent for observed runoff). In general, the model tends to oversimulate during the dry years (by an average of +37 percent) and undersimulate during the wet years (by an average of -4 percent).

Eighty-one percent of the HRU's in the Trout Creek subbasin correspond to similar HRU's in the Upper Truckee River subbasin. Initial Trout Creek model runs using the Upper Truckee River climate data and the nondistributed parameter values from the Upper Truckee River resulted in over 100 percent oversimulation of daily mean and mean annual runoff. This oversimulation was attributed to excessive precipitation inputs and a larger ground-water contribution in the Upper Truckee River than probably occurs in Trout Creek. The Hagan's Meadows climate site in the Trout Creek subbasin is at an altitude of 8,000 ft. This site was substituted for Rubicon #2 (fig. 1*A*). Hagan's Meadow receives an average 20 percent less precipitation than Rubicon #2. Initial Trout Creek model runs used the Hagan's Meadow climate site and the nondistributed parameter values from Upper Truckee River subbasin model. This resulted in a daily mean streamflow bias of +9 percent and relative error of +5 percent. Lowering the ground-water contribution in the Trout Creek model lowered the daily mean streamflow bias to -2.9 percent, while the relative error remained at +4.6 percent (table 4). (Monthly and annual mean bias and relative error are similar to the daily mean streamflow values.) The Trout Creek gaging station is rated as "fair." Seasonal aggregates of simulated spring snowmelt, baseflow, and winter runoff (table 7) were comparable to the observed aggregates.Streamflow diversions, ground-water pumpage, and urban runoff were assumed to reduce streamflow, particularly during the baseflow period and during dry years. These "losses" were partly accounted for in PRMS by a ground-water sink term. Simulated runoff efficiencies averaged 51 percent for wet years (versus 54 percent using observed runoff) and averaged 32 percent for dry years (versus 29 percent using observed runoff).

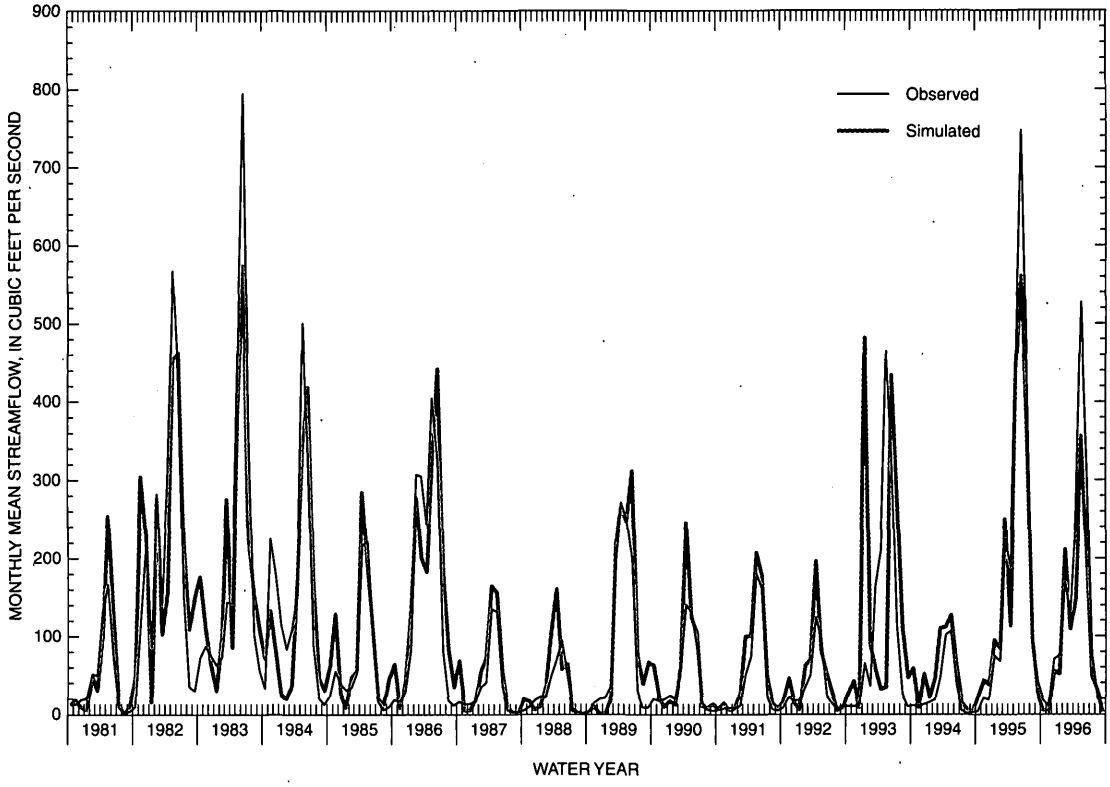


Figure 17. Simulated and observed monthly mean streamflow for Upper Truckee River, Lake Tahoe Basin, water years 1981–96.

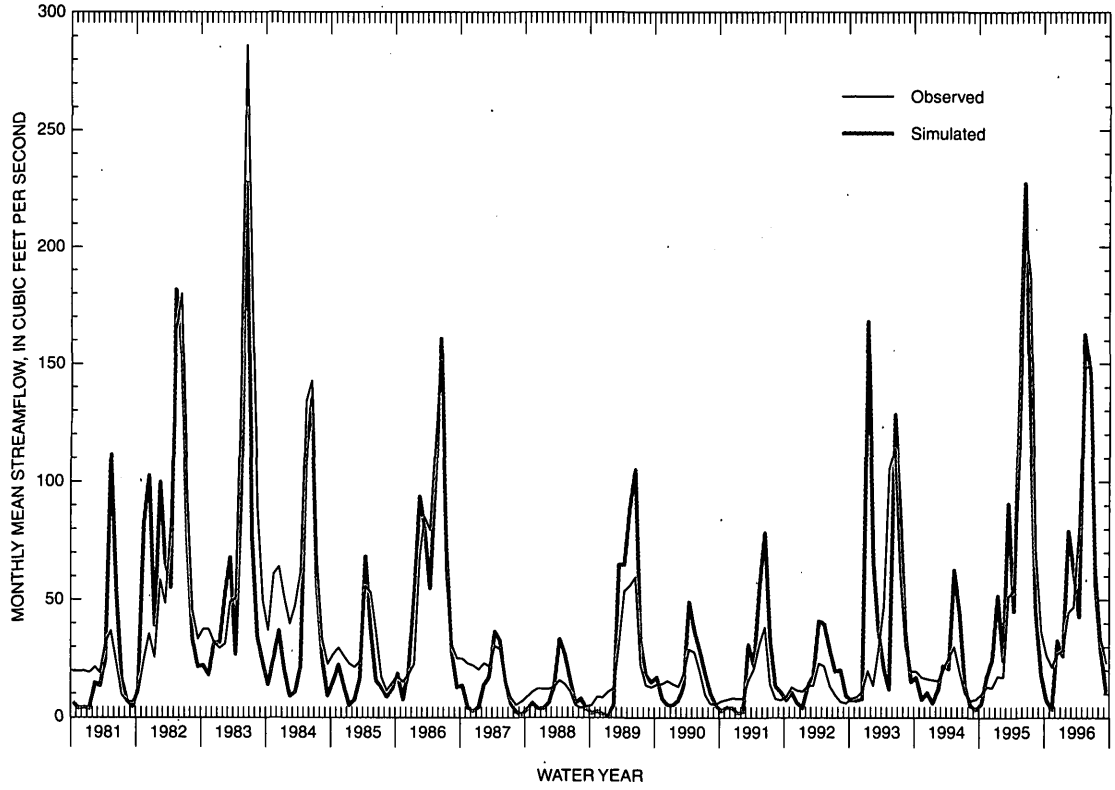


Figure 18. Simulated and observed monthly mean streamflow for Trout Creek, Lake Tahoe Basin, water years 1981–96.

Figures 19 and 20 show streamflow simulation for water years 1996–97 for Upper Truckee River and Trout Creek, respectively. The daily mean discharge peak for the Upper Truckee River for the January 1997 flood was undersimulated by -33 percent (2,098 ft^3/s simulated compared to 3,150 ft^3/s observed). The daily mean discharge peak for Trout Creek was oversimulated by +8 percent (544 ft^3/s simulated compared to 501 ft^3/s observed). Within 14 days, simulated and observed runoff for both models had returned to pre-flood discharge rates.

The simulated daily hydrographs indicate similar patterns for Upper Truckee River and Trout Creek subbasins. The first pattern is a low-flow "flashiness" that is attributed to an overland-flow component from impervious (or urban) areas. In reality, urban storm runoff is routed to Lake Tahoe or local infiltration ponds, or transported out of the Lake Tahoe Basin. Model runs made with the impervious cover set to zero resulted in a smoothing out of the hydrograph, although differences in runoff volumes were minor. The second pattern is the frequency of sudden snowmelt runoff in the late fall and early winter. This sudden melt is attributed to the frequency of unseasonally warm storm events characterized by rain or mixed rain and snow that result in rapid snowmelt. The hydrographs of observed runoff indicate that a winter snowpack is maintained for the spring melting period. In contrast, the model simulates warm snowmelt events, usually at the expense of maintaining a full spring snowpack. In a model sensitivity run with the Upper Truckee River model, temperature lapse rates for November through March were set to 32°F (thereby using the observed temperature without adjustments for altitude differences). The resultant hydrograph showed a near-fit for sudden runoff, particularly for February of 1982 and 1986 when observed flow exceeded 1,600 ft^3/s. This was achieved, however, at the expense of the spring snow pack; as a result, runoff for April–July was undersimulated by an average of more than 50 percent.

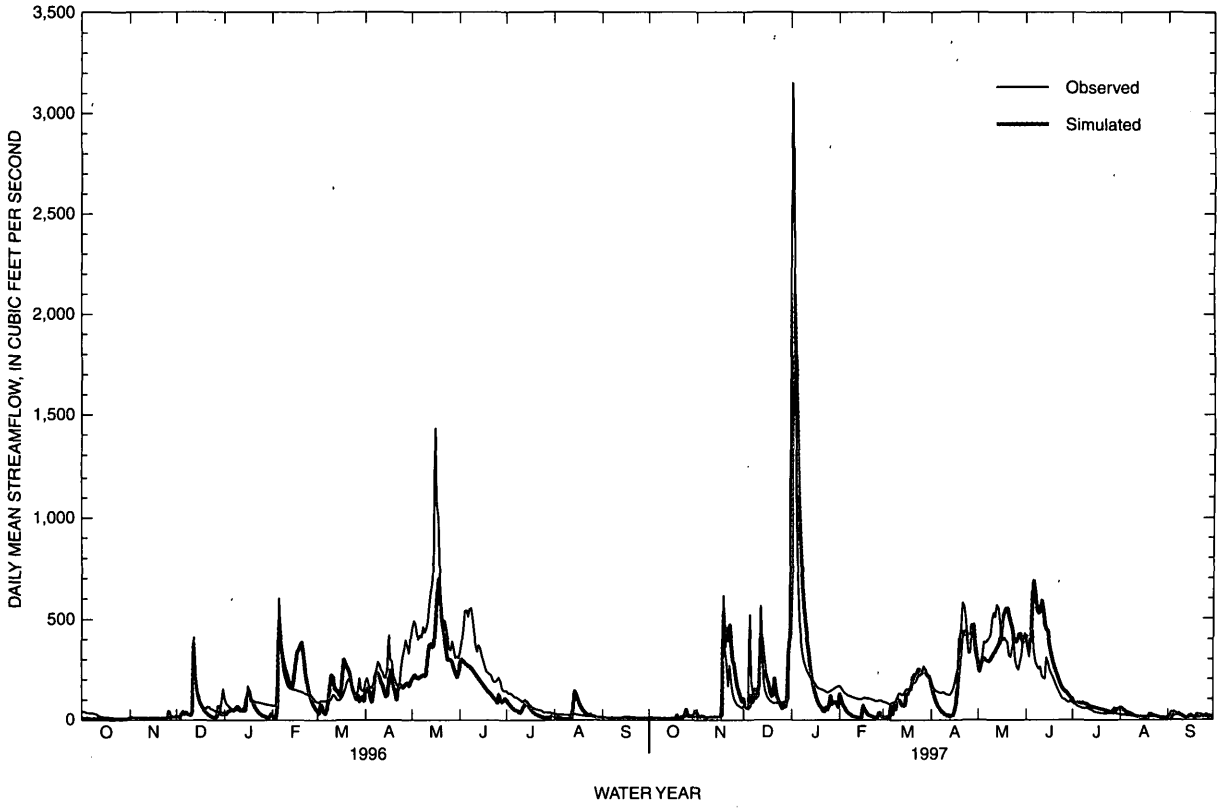


Figure 19. Simulated and observed daily mean streamflow for Upper Truckee River, Lake Tahoe Basin, water years 1996–97.

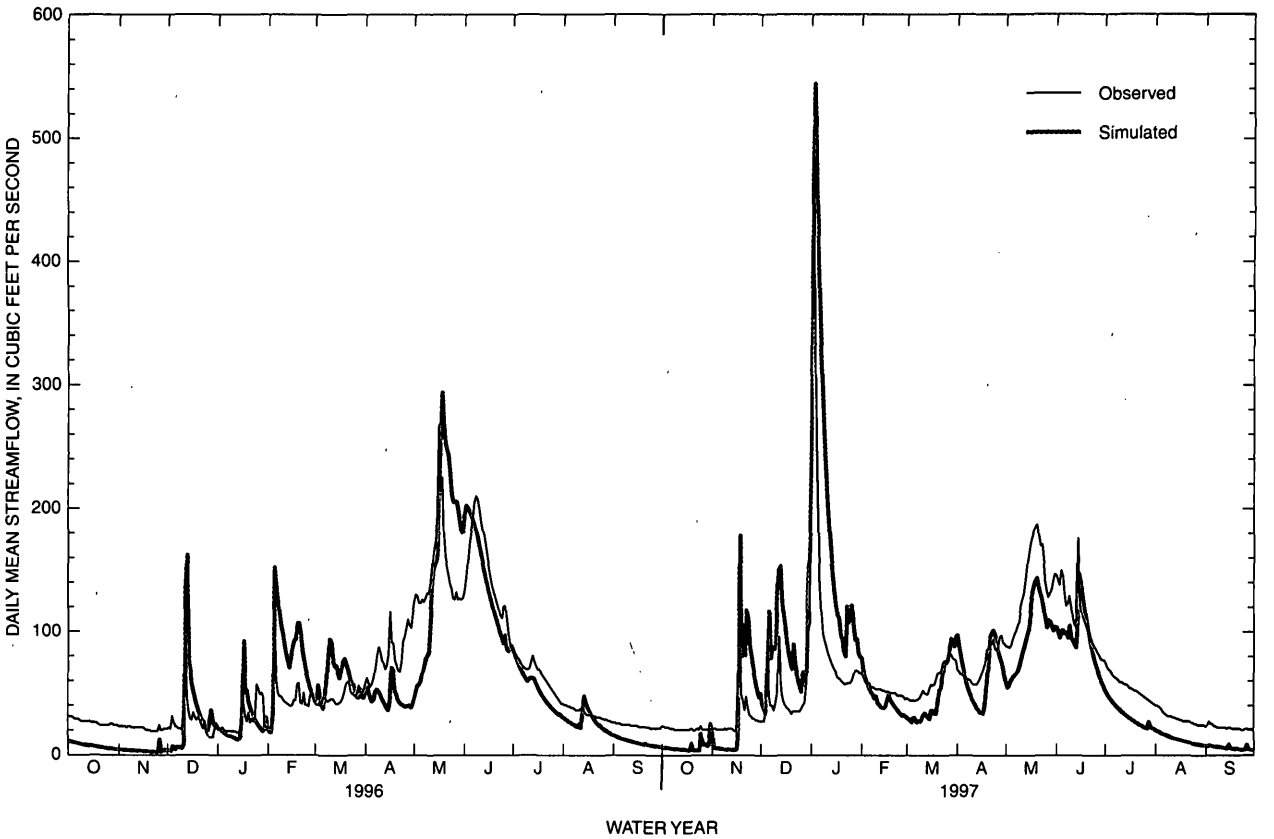


Figure 20. Simulated and observed daily mean streamflow for Trout Creek, Lake Tahoe Basin, water years 1996–97.

General Creek Subbasin

General Creek subbasin is the only "unpaired" subbasin of the gaged subbasins used in this study. The 16-year period of record was split into the same calibration-verification periods as the previously described calibration subbasins. Simulation results are listed in tables 4–6 for water years 1981–96. Daily mean streamflow-simulation bias was -4.1 percent for the calibration period and -1.4 percent for the verification period; relative error was +32 percent and +8.7 percent for the calibration and verification periods, respectively. Plots of observed and simulated monthly mean streamflow are shown in figure 21. Bias for monthly mean streamflow was -2.2 percent, whereas relative error was +12.4 percent. Annual mean bias for the full period of record was +2.7 percent, and relative error was +8.4 percent. The USGS streamflow rating for the General Creek gage is "good." Runoff efficiencies averaged 68 percent for the wet years (compared to 70 percent using observed runoff) and 50 percent for the dry years (compared to 45 percent using observed runoff).

Roughly two-thirds of the observed annual streamflow occurs during the spring snowmelt months and only 2 percent occurs during the baseflow period. Winter runoff accounts for 18 percent of observed annual streamflow. Less spring snowmelt (table 7) was simulated (62 percent) than observed (66 percent), while more baseflow was simulated (7 percent) compared to the observed baseflow (2 percent) aggregate. Figure 21 shows baseflow and winter runoff were oversimulated for most years. Residual snowmelt into the late summer during wet years and excessive early fall subsurface flow during dry years probably account for the oversimulation of streamflow during these periods. Ground-water flow contributions reflect the hydrogeology on the western side of the lake. On average, 15 percent of the annual water yield was simulated as ground water during wet years and it increased to 20 percent during dry years. Successfully simulating the bulk of spring runoff occurs somewhat at the expense of simulating warm, mid-winter rain-on-snow runoff events. Adjusting the temperature-dependent parameter to better simulate these warm events results in an undersimulation of the spring snowpack. In such a simulation, PRMS appears to deplete the upper-altitude snowpack faster than the data indicate.

Peak daily mean discharge for the January 1997 flood (fig. 22) was oversimulated by +62 percent (973 ft^3/s simulated compared to 600 ft^3/s observed). By January 6, 1997, simulated and observed runoff for General Creek had returned to preflood-discharge rates. Simulated runoff for January 1997 averaged +31 percent of the observed.

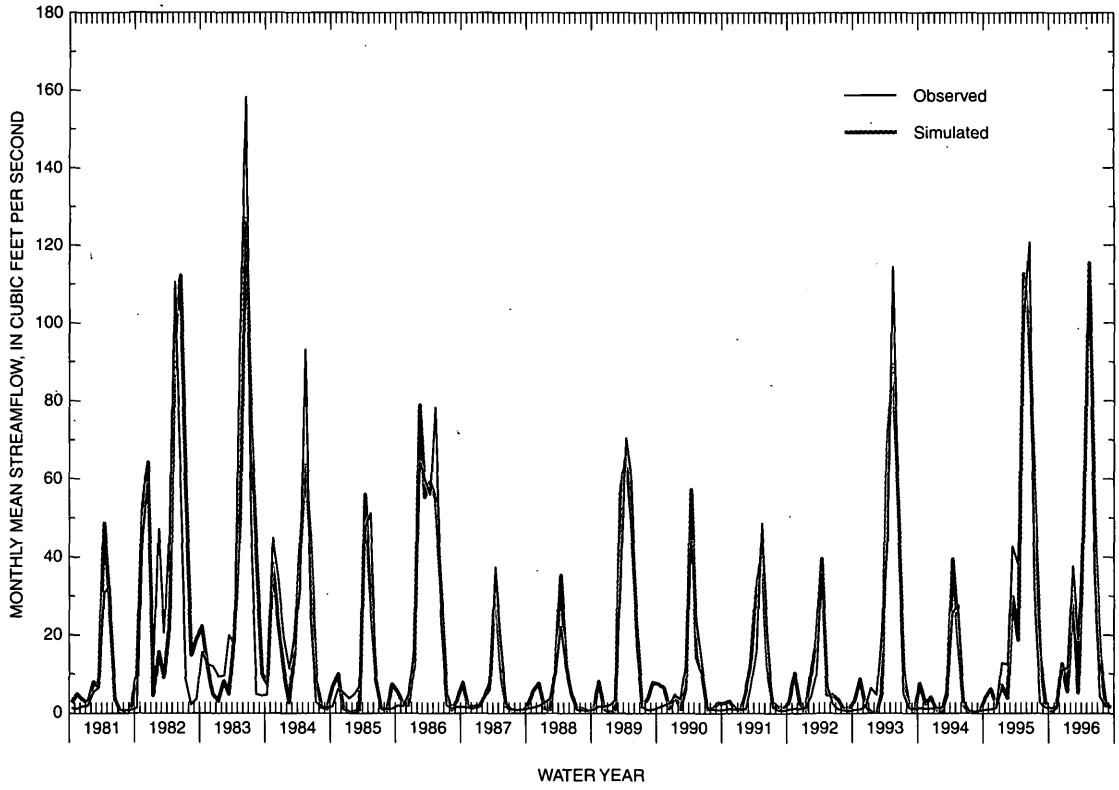


Figure 21. Simulated and observed monthly mean streamflow for General Creek, Lake Tahoe Basin, water years 1981–96.

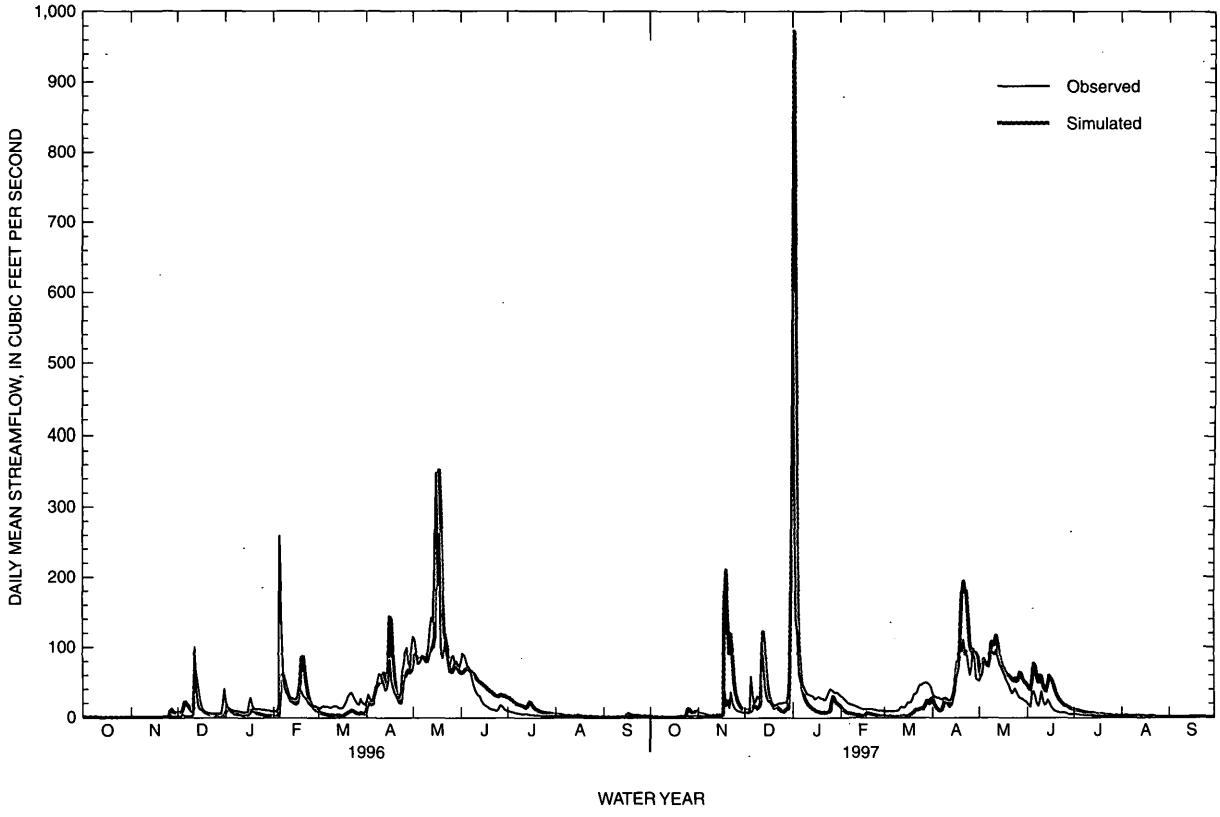


Figure 22. Simulated and observed daily mean streamflow for General Creek, Lake Tahoe Basin, water years 1996–97.

MODELING UNGAGED AREAS

One frequently used method 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 parameters to build similar computer models in watersheds that are ungaged or for which extending the existing streamflow record is desired.

Dinicola (1990) calibrated and validated the HSPF model on five gaged drainage basins in western Washington. The results were 12 sets of HSPF parameter values, each set designed to simulate the distinctive hydrologic response associated with the 12 generalized land-segment types (similar to HRU's). A later study (R.S. Dinicola, U.S. Geological Survey, written commun., 1993) tested the validity of using the precalibrated parameter sets on 11 drainage basins in the same region with similar soil and land cover as the initial calibration basins. Simulation using the earlier calibrated parameter values indicated that errors were related to incorrectly simulated ground-water discharge for 5 of the 11 basins. Modifying the nondistributed ground-water recharge parameter improved simulation. For the remaining six basins, errors were related to the runoff flow paths.

In another northwest study, Laenen and Risley (1997) describe the development of flow-routing and precipitation-runoff models used to drive a water-quality transport model for the Willamette River Basin, Oreg. PRMS was used to simulate runoff from 10 gaged, unregulated subbasins and calibrated model parameters were applied to ungaged subbasins. Initial parameter values were obtained from an earlier study (Risley, 1994). Of the many PRMS parameters required for modeling, only 11 (all nondistributed) had to be specified for the ungaged areas. Four of these parameters were snow related, six were subsurface, and one was ground-water related. Observed discharge and simulated streamflow from the ungaged tributaries were combined as inputs to the network flow-routing model and results evaluated at downstream points where streamflow was measured. The modeling results, which incorporated runoff from larger areas than were simulated with PRMS alone indicated that the accuracy of the network-routing simulation increased when less of the area was simulated with PRMS. Absolute error for the network-routing models ranged from 4 percent, when only 9 percent of the basin was ungaged, to about 21 percent, when 70 percent of the basin was ungaged.

Kuhn and Parker (1992) evaluated the feasibility of transferring PRMS parameters to uncalibrated basins in the Gunnison River Basin of Colorado. The applicability of transferring calibrated model-parameter values largely depends on whether the parameter is distributed or nondistributed. PRMS model parameters were divided by Kuhn and Parker into three general categories: (1) those that can be estimated from regional climatic characteristics, (2) those distributed by HRU that can be estimated from the physical characteristics of the HRU, and (3) those distributed by subsurface or ground-water reservoirs that can be estimated from streamflow records. These are similar categories to those used in the present study. Kuhn and Parker concluded that methods used to estimate the HRU-distributed parameters values can be readily transferred to other basins if HRU's are similar and physically based, whereas subsurface-flow routing parameters may or may not apply to ungaged basins since these parameters depend on streamflow-recession characteristics that are basin specific.

Approach

Simulation of runoff from each of the 43 ungaged tributaries was not the intent of this study. Instead, adjacent ungaged drainage areas were aggregated into larger subbasins termed "ungaged areas" in this report. Ungaged areas, which are shown in figure 1*B*, are aggregated areas composed of numerous tributaries that are ungaged, or that have an insufficient period of gaging record for this study, or that contain upstream diversions which preclude accurate runoff estimates. Ungaged areas constitute 52 percent of the Lake Tahoe Basin (see fig. 1*B*). The approach for modeling these ungaged areas was centered around the Lake Tahoe Basin GIS and an associated relational data-base system. The procedure was as follows: (1) gaged subbasin models were selected to represent the ungaged area; (2) HRU's in the gaged and ungaged areas were compared and ranked according to a defined matching criterion, and matched HRU-dependent parameter values were used to generate the PRMS parameter files; (3) unmatched HRU parameters were computed using the GIS and RDB tables; (4) nondistributed-parameter values were transferred from the designated gaged, index model; and (5) runoff simulations of the ungaged areas were evaluated using various indices.

The ungaged areas were modeled with PRMS on the assumption that they could be simulated as hydrologically continuous areas. All the ungaged areas have been modeled with the exception of two that were considered to be insignificant in size and runoff potential (fig. 1*B*). These lowland areas constitute only 1.2 percent of the total area in the Lake Tahoe Basin.

The method developed for transferring model parameters from gaged or calibrated tributaries to large, aggregated ungaged areas in the Lake Tahoe Basin was facilitated through computer programs that have several functions. The RDB software "populates," or creates, the gaged or index basin parameter file for HRU's, as previously described (fig. 4, step 8). A "master" HRU data file of all possible HRU data combinations and their associated parameter values was created once the gaged tributaries were modeled. The GIS data base was queried to match similar HRU's from gaged to ungaged areas and, lastly, modeled HRU parameter values were transferred to corresponding HRU's in ungaged areas in a PRMS format. Modifications to the parameter tables were facilitated through use of the GIS data base and, thus, supported iterative PRMS model runs.

The regional, digital HRU data layer contains an item referred to as the PIN, as described earlier. An HRU is defined in the source-data layer by different PIN's as a result of unique groupings of selected hydrologic criteria. Several "rules" were defined to provide an objective and consistent basis for grouping PIN's into unique HRU's. For gentle slope areas, aspect was not considered important; therefore, land areas were grouped on the basis of the remaining four characteristics (slope, altitude, soil, and cover). For steep slope areas, soil was considered less important. Therefore, land areas were grouped using only the criteria of similar slope, altitude, aspect, and cover. Discrepancies in the soil and land-cover data bases regarding the occurrence of rock outcrop may be attributed to different mapping scales. The soil-data layer was assumed to be the more precise data layer. Where soil was classed as rock, land cover was considered less important, resulting in a grouping of PIN's on altitude, soil, aspect, and slope. Lastly, where land cover was classed as urban, soil type was considered to be less important and preference was given to the other four attributes. The final unique combination of characteristics for land areas, now classified as an HRU, was given the PIN with the largest area. HRU's in the ungaged areas were initially matched on what is referred to as the first-order criteria (where all five characteristics match). The remaining HRU's were matched using the "rules" described above. These criteria are referred to as second-order criteria.

The gaged subbasins represent nearly the entire spectrum of hydrogeologic and climatic conditions present in the Lake Tahoe Basin. Each ungaged area was indexed to the gaged subbasins of closest hydrogeologic similarity for the purpose of transferring distributed and nondistributed parameters. For example, ungaged area 11 (fig. 1*B*) was indexed to the Ward-Blackwood Creek and Third-Incline Creek pairs; ungaged area 12 was indexed to Third-Incline Creek and Glenbrook-Logan House Creek pairs; ungaged area 14 was indexed to Glenbrook–Logan House Creek and Trout Creek–Upper Truckee River pairs; ungaged area 15 was indexed to the Trout Creek–Upper Truckee River pair; ungaged area 16 was indexed to Trout Creek–Upper Truckee River pair and General Creek, and ungaged area 17 was indexed to General Creek and the Ward-Blackwood Creek pair. Runoff from ungaged area 12 was adjusted to account for diversions from Marlette Lake out of the Lake Tahoe Basin.

To illustrate the technique developed to model ungaged areas, ungaged area 11 and its associated index subbasins (Ward, Blackwood, Third, and Incline Creeks)—in the northwest part of the Lake Tahoe Basin—have been selected for discussion. Figure 23 shows the first-order matching of HRU's for Ward and Blackwood Creeks, and the unmatched HRU's that are unique to each subbasin. Although a unique color has been assigned to each HRU, as illustrated in the associated explanation, not all colors are visually discernible. Sixty-five percent of the Ward Creek subbasin matches directly with HRU's in Blackwood Creek subbasin, representing 70 percent of the Blackwood Creek drainage area. Of the remaining 35 percent unmatched area of Ward Creek, two-thirds of that area is defined by two HRU's which correspond to an unmatched HRU in Blackwood Creek following a second-order criteria. Each remaining HRU individually represents less than one-half percent of the total Ward Creek drainage area.

Figure 24 shows the first-order matching of HRU's for the Third and Incline Creek subbasins and the unmatched HRU's that are unique to each subbasin. HRU's in the Third-Incline Creek pair are less well matched; 30 percent of the drainage area of both subbasins were matched on the first-order criteria. This is attributed to the significant differences in altitude distribution (33 percent more drainage area in Third Creek at or above an altitude of 9,000 ft) and soil types. Most of the unmatched HRU's in Third Creek are in the

9,000-10,000-ft altitude zone and, likewise, most of the unmatched HRU's in Incline Creek are in the 7,000-8,000-ft altitude zone. Distributed parameter values for the unmatched HRU's were obtained from similar HRU's in other gaged basins.

Ungaged area 11 is 40.6 mi^2 and consists of 84 HRU's. Figure 25*A* shows the spatial distribution of the HRU's in ungaged area 11. The area is underlain primarily by volcanic rocks, with small outcrops of granitic rock. Most of the area is forested upslope from the shore, whereas the shoreline area is urbanized. Examples of the spatial distribution of matched and unmatched HRU's in ungaged area 11 are shown in figures 25*B-D*. The color palette is unique for each figure and is intended not for individual HRU identification but to represent general patterns. Using the GIS, the HRU data layer for ungaged area 11 (fig. 25*A*) was matched to the Ward-Blackwood Creek and Third-Incline Creek pairs, as shown in figures 25*B* and *C*, respectively. The result of the data-base query was a 70-percent match to the Ward-Blackwood Creek pair (fig. 25*B*). An additional 15 percent of the ungaged drainage area matched to the Third-Incline Creek pair (fig. 25*C*). Figure 25*D* shows the areas in ungaged area 11 that did not match either set of gaged subbasin HRU's, using the first-order criteria of a match on all five physiographic characteristics. This area represented 15 percent of the total ungaged area.

The unmatched HRU's were subjected to the second-order matching criteria. For example, much of the remaining 15 percent of ungaged area 11 not matched is urban along the shoreline and varies mainly in soil type (colored orange in fig. 25*D*). Densely urbanized areas were assumed to have little exposed soil. Corresponding HRU's in the two gaged pairs (colored gray in fig. 25*D*, at the mouth of Third Creek and Incline Creek) have identical characteristics except for soil type (both are loams with slightly different properties due to different parent material). The unmatched high-altitude HRU, illustrated in dark blue in figure 25*D*, was matched to a corresponding high-altitude HRU in Third Creek, illustrated in gray at the headwaters of the subbasin, when vegetation cover was disregarded. Steep, rock outcrop areas typically have scant vegetation cover. The remaining unmatched HRU area shown in figure 25*D* was less than 7 percent of the total subbasin area and its respective distributed parameters were assigned values from a relational data base. Non-distributed-parameter values were obtained from the Ward Creek PRMS template. The Ward Creek model was selected as the template due to the high percentage of matching HRU's. However, adjustments were made to the ground-water routing coefficients to account for what was assumed to be less ground-water flow in ungaged area 11 (due to very little alluvium) than what was modeled for Ward and Blackwood Creeks. The NWS Tahoe City and the NRCS Squaw Valley Gold Coast climate sites were used to compute the HRU-adjusted time series.

The same methodology was applied to the remaining modeled, ungaged areas (numbers 12 and 14–17). The summary below provides the percentage of area matched using the first-order criteria.

- Ungaged area 12 between Incline Creek and Glenbrook Creek subbasins is 23 mi^2. Much of the area is weathered granitic soil and rock outcrop. Eighteen percent of the area was unmatched by the first-order criteria.

- Ungaged area 14 between Logan House Creek and Trout Creek subbasins is 18.3 mi^2 of granitic soils. Twenty-seven percent of the area was not matched.

- Ungaged area 15 between ungaged area 14 and Trout Creek is 12.4 mi^2. Sixteen percent of the area was unmatched when compared to Trout and Logan House Creeks.

- Ungaged area 16 is similar in area to the Upper Truckee River subbasin occupying 53.3 mi^2 of exposed, heavily glaciated granitic rock between Upper Truckee River and General Creek subbasins. Thirty-nine percent of the area was unmatched; however, most of this area corresponds to HRU's with both soil type and land cover classified as bedrock. Most of these unmatched HRU's were matched to HRU's in the Upper Truckee River on altitude, slope, aspect, and soil. In most of the areas, vegetation is negligible.

- Ungaged area 17 along the west shore is 11.9 mi^2 between Blackwood Creek to the north and General Creek to the south. Thirty percent of this area was unmatched; however, 50 percent of this unmatched area is classified as urban on gentle slopes and matched to similar HRU's in the index subbasins if the second-order criteria omitting aspect are applied, leaving roughly 15 percent of the area unmatched.

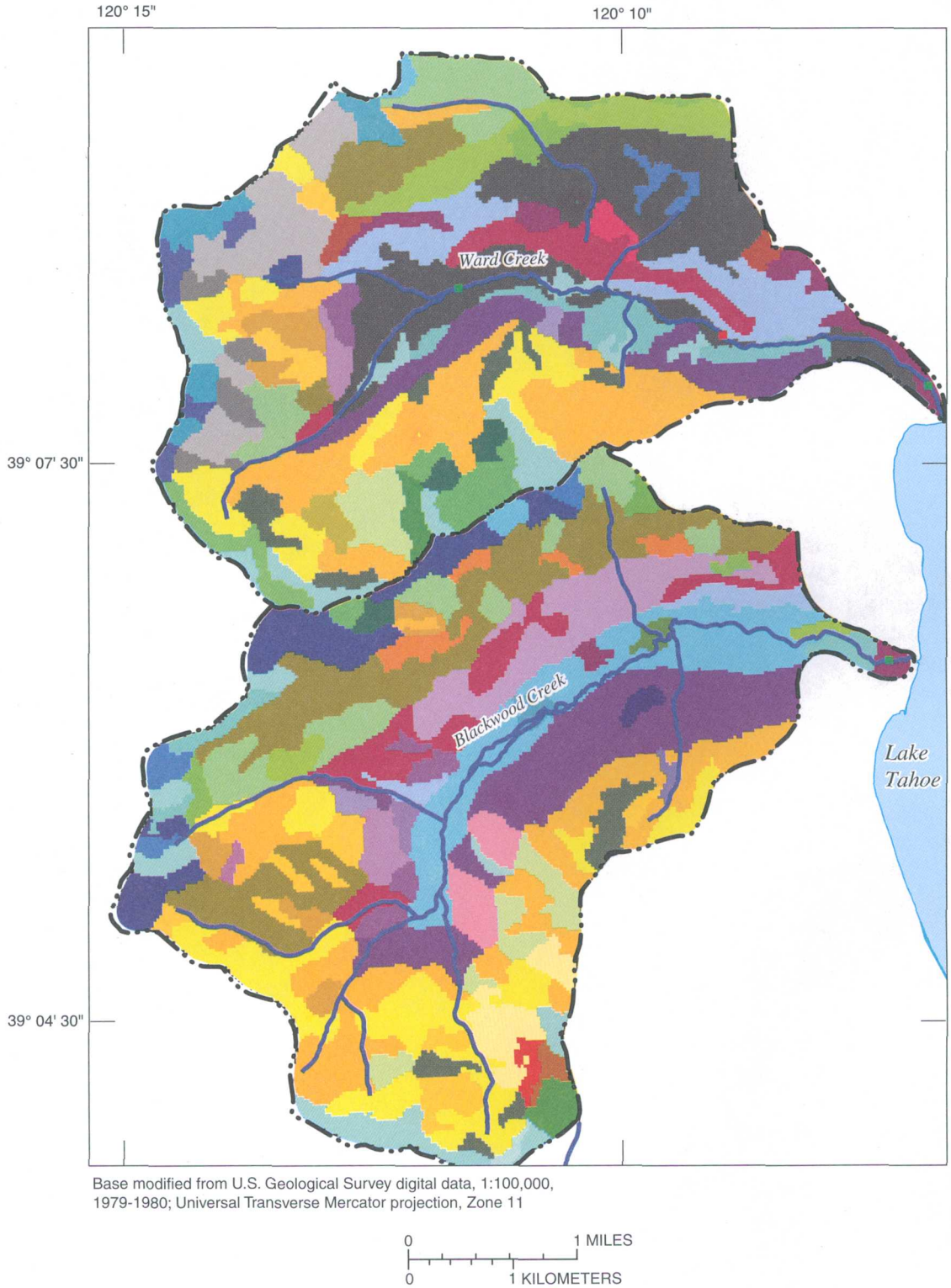


Figure 23. Digital classification of hydrologic response units for Ward Creek and Blackwood Creek subbasins, Lake Tahoe Basin.

EXPLANATION

Hydrologic response units (HRU's) in Ward Creek and Blackwood Creek subbasins

Altitude (feet above sea level)	Slope	Aspect	Land cover	Soil
HRU's common to both subbasins				
8,000	moderate	south	conifer	volcanic loam
8,000	moderate	north	conifer	rock
8,000	moderate	east	conifer	volcanic loam
8,000	moderate	west	conifer	rock
8,000	moderate	north	conifer	volcanic loam
7,000	moderate	south	conifer	volcanic loam
7,000	moderate	south	conifer	glacial-volcanic loam
7,000	moderate	west	conifer	volcanic loam
7,000	moderate	south	conifer	rock
7,000	moderate	north	conifer	rock
7,000	moderate	east	conifer	rock
7,000	moderate	east	conifer	volcanic loam
7,000	moderate	north	conifer	volcanic loam
6,000	gentle	south	urban	glacial-volcanic loam
6,000	moderate	south	conifer	volcanic loam
6,000	moderate	east	conifer	rock
6,000	moderate	east	conifer	volcanic loam
6,000	moderate	north	conifer	volcanic loam
6,000	moderate	north	conifer	rock
6,000	moderate	south	conifer	glacial-volcanic loam
6,000	moderate	north	conifer	glacial-volcanic loam
6,000	moderate	north	shrub	volcanic loam
7,000	steep	north	conifer	rock
HRU's unique to Ward Creek subbasin				
8,000	moderate	east	rock	rock
8,000	moderate	south	rock	rock
7,000	gentle	south	conifer	glacial-volcanic loam
7,000	gentle	north	conifer	volcanic loam
7,000	gentle	south	urban	glacial-volcanic loam
6,000	gentle	south	conifer	volcanic loam
6,000	gentle	south	conifer	glacial-volcanic loam
7,000	moderate	east	rock	rock
7,000	moderate	south	rock	rock
7,000	gentle	south	rock	rock
6,000	gentle	south	grass	glacial-granitic loam
7,000	steep	south	rock	rock
6,000	gentle	north	shrub	glacial-volcanic loam
8,000	steep	north	rock	rock
HRU's unique to Blackwood Creek subbasin				
8,000	moderate	south	conifer	rock
8,000	moderate	east	conifer	rock
8,000	steep	south	rock	rock
8,000	steep	north	conifer	rock
7,000	gentle	south	conifer	volcanic loam
7,000	moderate	west	conifer	rock
8,000	steep	west	conifer	rock
7,000	steep	south	conifer	rock
7,000	steep	west	conifer	rock
6,000	moderate	west	conifer	volcanic loam
6,000	moderate	south	conifer	rock
7,000	moderate	north	rock	volcanic loam
6,000	gentle	north	conifer	volcanic loam
7,000	moderate	north	shrub	volcanic loam
6,000	moderate	east	conifer	glacial-volcanic loam
6,000	gentle	north	urban	rock
6,000	gentle	north	conifer	glacial-volcanic loam
6,000	gentle	south	shrub	glacial-granitic loam
7,000	steep	east	rock	rock
6,000	steep	south	conifer	rock
6,000	gentle	south	deciduous	glacial-volcanic loam

Figure 23. Continued.

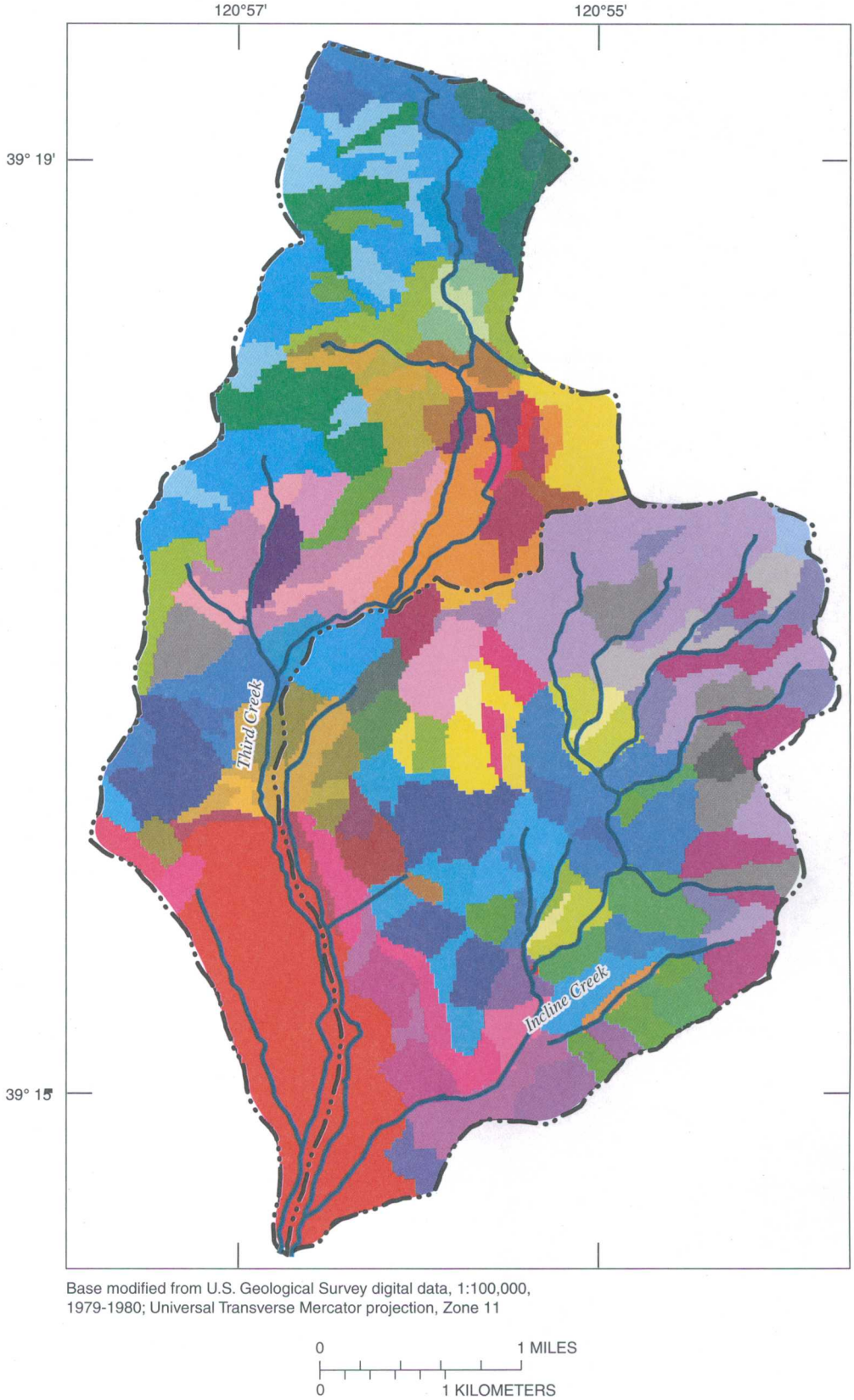


Figure 24. Digital classification of hydrologic response units for Third Creek and Incline Creek subbasins, Lake Tahoe Basin.

EXPLANATION

Hydrologic response units (HRU's) in Third Creek and Incline Creek subbasins

Altitude (feet above sea level)	Slope	Aspect	Land cover	Soil
HRU's common to both subbasins				
8,000	moderate	west	conifer	glacial sand
8,000	moderate	south	shrub	granitic sand
7,000	moderate	south	conifer	volcanic loam
7,000	moderate	south	conifer	granitic sand
7,000	moderate	east	conifer	granitic sand
7,000	moderate	south	urban	glacial sand
7,000	moderate	south	urban	glacial-volcanic loam
6,000	gentle	south	urban	glacial-volcanic loam
6,000	moderate	south	urban	glacial-volcanic loam
6,000	moderate	south	urban	glacial sand
HRU's unique to Incline Creek subbasin				
8,000	moderate	south	conifer	volcanic loam
8,000	gentle	south	conifer	volcanic loam
8,000	gentle	north	conifer	glacial sand
8,000	moderate	west	conifer	volcanic loam
8,000	moderate	east	conifer	volcanic loam
8,000	moderate	north	conifer	granitic sand
8,000	moderate	west	conifer	granitic sand
8,000	moderate	south	conifer	granitic sand
9,000	moderate	south	conifer	granitic sand
8,000	moderate	north	conifer	volcanic loam
8,000	moderate	west	shrub	granitic sand
8,000	moderate	south	rock	granitic sand
7,000	moderate	south	conifer	glacial sand
7,000	moderate	west	conifer	volcanic loam
7,000	moderate	south	shrub	granitic sand
7,000	moderate	west	conifer	glacial sand
7,000	moderate	south	shrub	volcanic loam
7,000	moderate	north	conifer	granitic sand
7,000	moderate	east	shrub	granitic sand
7,000	moderate	west	conifer	granitic sand
7,000	moderate	west	shrub	volcanic loam
7,000	moderate	west	shrub	granitic sand
7,000	moderate	south	rock	granitic sand
7,000	moderate	west	urban	glacial sand
7,000	moderate	east	conifer	volcanic loam
7,000	moderate	west	rock	granitic sand
7,000	moderate	west	shrub	rock
7,000	moderate	north	conifer	volcanic loam
7,000	moderate	south	urban	granitic sand
7,000	moderate	south	urban	volcanic loam
7,000	moderate	west	urban	volcanic loam
6,000	moderate	south	conifer	volcanic loam
6,000	moderate	west	conifer	volcanic loam
6,000	moderate	south	urban	volcanic loam
6,000	moderate	south	urban	granitic sand
6,000	moderate	west	urban	volcanic loam
6,000	gentle	south	urban	volcanic loam
6,000	gentle	south	urban	granitic sand
6,000	moderate	north	urban	granitic sand
7,000	moderate	north	urban	granitic sand

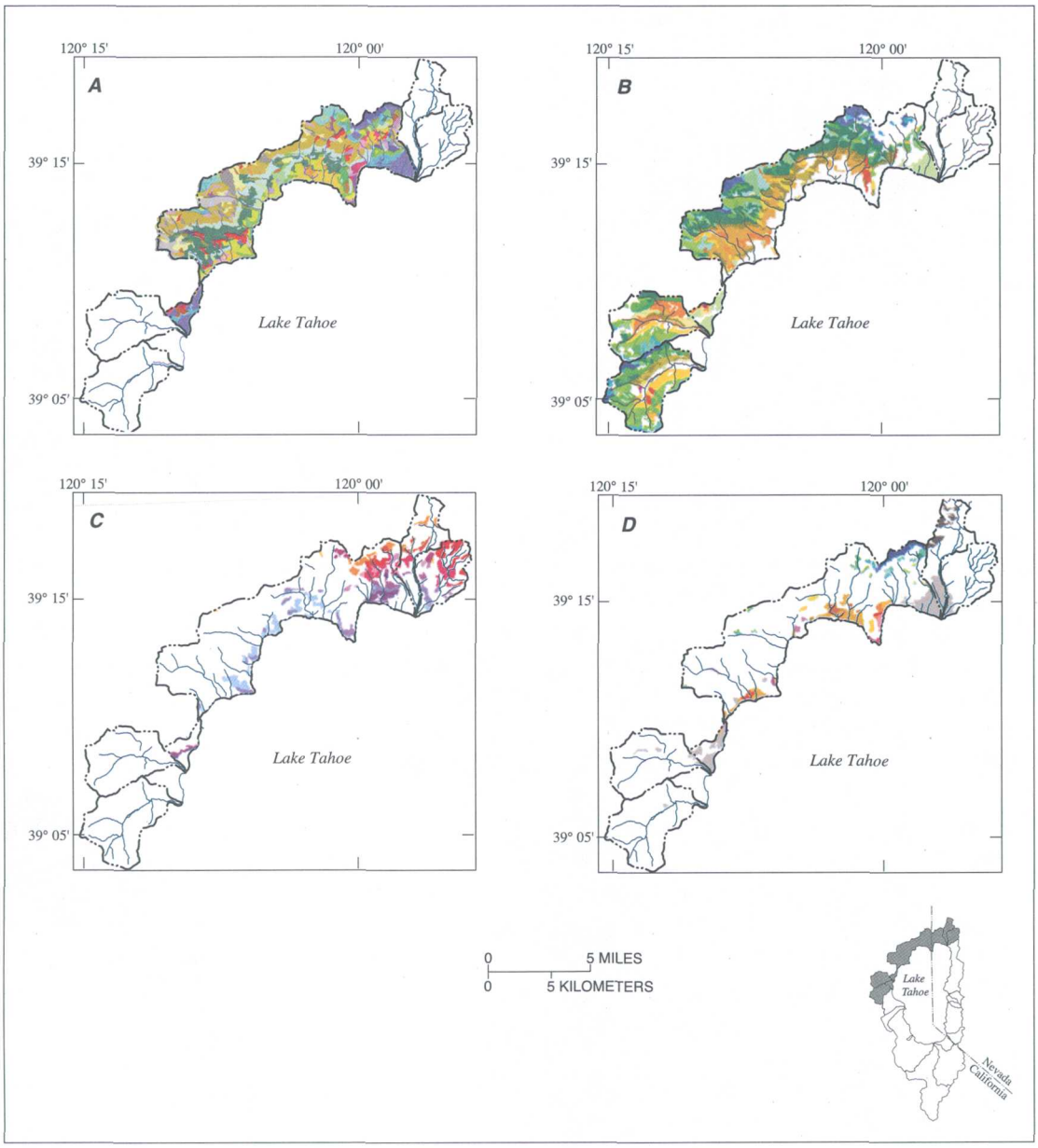
Figure 24. Continued.

EXPLANATION

Hydrologic response units (HRU's) in Third Creek and Incline Creek subbasins

Altitude (feet above sea level)	Slope	Aspect	Land cover	Soil
HRU's unique to Third Creek subbasin				
9,000	moderate	south	rock	glacial-volcanic loam
9,000	moderate	south	conifer	glacial-volcanic loam
9,000	moderate	east	rock	glacial-volcanic loam
9,000	moderate	east	conifer	glacial-volcanic loam
9,000	moderate	west	conifers	glacial-volcanic loam
9,000	moderate	west	conifer	rock
9,000	moderate	south	conifer	rock
9,000	moderate	east	conifer	rock
9,000	moderate	south	conifer	volcanic loam
9,000	moderate	west	conifer	volcanic loam
9,000	moderate	north	conifer	rock
9,000	steep	east	conifer	rock
9,000	steep	south	conifer	rock
8,000	moderate	south	conifer	glacial-volcanic loam
8,000	moderate	south	grass	rock
8,000	moderate	south	grass	glacial-volcanic loam
8,000	gentle	south	grass	rock
8,000	moderate	east	conifer	rock
8,000	gentle	north	conifer	glacial-volcanic loam
8,000	moderate	south	conifer	glacial sand
8,000	moderate	north	conifer	rock
8,000	gentle	south	conifer	glacial sand
8,000	moderate	north	conifer	glacial sand
8,000	gentle	south	shrub	glacial sand
8,000	moderate	west	shrub	glacial sand
8,000	0	level	water	not mapped
8,000	moderate	south	shrub	rocky soil
9,000	moderate	west	conifer	rocky soil
8,000	steep	south	shrub	rocky soil
8,000	steep	west	shrub	rocky soil
7,000	steep	south	shrub	rocky soil
7,000	moderate	south	conifer	rocky soil
7,000	gentle	south	urban	glacial-volcanic loam
7,000	moderate	east	urban	volcanic loam

Figure 24. *Continued.*



Base modified from U.S. Geological Survey digital data, 1:100,000,1979-1980 and NRCS and USFS data, 1:24,000, 1974; Universal Transverse Mercator projection, Zone 11

Figure 25. Digital classification of hydrologic response units (HRU's) for ungaged area 11 and associated index subbasins. *(A)* HRU distribution for ungaged area 11. *(B)* Similar HRU's for ungaged area 11 and for Ward Creek and Blackwood Creek subbasins. *(C)* Similar HRU's for ungaged area 11 and for Third Creek and Incline Creek subbasins. *(D)* HRU's in ungaged area 11 not matched to either Ward-Blackwood Creek pair or Third Creek–Incline Creek pair (see fig. 1*B*).

The nondistributed-parameter values were obtained from one or more of the gaged subbasins. The selection was based on geographic proximity (to avoid climatic conditions different from those associated with the subbasins to which the HRU's were matched) and hydrogeologic similarities. Specifically, Ward Creek was the template for ungaged area 11; Third Creek and Incline Creek for ungaged area 12; Glenbrook Creek and Trout Creek for ungaged area 14; Trout Creek for ungaged area 15 (with adjustments made to reflect less ground-water contribution than that modeled for Trout Creek); General Creek and the Upper Truckee River for ungaged area 16; and Ward Creek and General Creek for ungaged area 17.

Estimating Uncertainty in Ungaged Runoff

Many assumptions were inherent in modeling 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 in a hydrologically similar manner 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 general hydrogeologic characteristics obtained from previous studies (Thodal, 1997; Cartier and others, 1994; Harrill, 1977; Burnett, 1971). The ungaged areas constitute multiple drainage basins adjacent to one another, not single drainage areas as are the gaged subbasins. Transferring parameter values, particularly the nondistributed-parameter values from the gaged model to the ungaged models, generally assumes that the hydrogeologic characteristics of the gaged subbasins are similar to those of each of the tributaries within the ungaged area. This uniformity is not assumed for the ungaged areas.

The "uncertainty" associated with the simulated runoff for the ungaged areas is assumed to be at best within the range of error computed for the associated gaged template subbasin or subbasins, as listed in tables 4–6, and not from the prevalidation modeling results for the validation models as discussed in the section "Error Analysis." For example, ungaged area 12 was indexed to the Incline-Third Creek subbasin pair. Ungaged area 12 is predominantly decomposed granite with very little of the ground-water bearing sediments present in lower part of the Third and Incline Creek subbasins. Therefore the ground-water routing parameters were adjusted to accommodate this difference, as well as to account for the minor diversion out of Marlette Lake.

A weighed error factor (the sum of the product of the percent subbasin area and its associated error) was computed for the gaged and ungaged areas. Using the errors listed in table 4 for the full modeling period of record, the daily mean error for the total gaged subbasin portion of the Lake Tahoe drainage area is estimated to be +29 percent; the uncertainty associated with the total ungaged area ranged from +12 to +36 percent.

Simulated streamflow from ungaged areas also was evaluated using three different indices: (1) seasonal distribution of runoff, using monthly comparisons of percent of total annual runoff; (2) runoff per square mile (cubic feet per second per square mile), which allows for comparison of runoff from watersheds of different sizes (Black, 1996, p. 219); and (3) runoff efficiencies, expressed as percent of precipitation yielding runoff. The first was computed on monthly intervals, the second and third indices were computed on annual time intervals. Table 7 summarizes simulated and observed annual runoff disaggregated to monthly percents for the full modeling period of record, for the index (gaged) subbasins and simulated runoff the ungaged areas. In general, the seasonal aggregates representing spring snowmelt tend to be undersimulated when compared to the gaged (index) subbasins, while simulated baseflow approximates the index base flow.

Differences in runoff efficiencies per square mile (table 8) between the ungaged areas and their respective index subbasins were within 20 percent for all the ungaged areas (except for ungaged areas 11, 15, and 17 which were less than 7 percent). The runoff per square mile for ungaged area 16 was 56 percent greater than the average for Upper Truckee River and Trout Creek, but only 28 percent greater than for General Creek. This difference was attributed to large areas of bedrock in the upland part of the General Creek subbasin that yielded more runoff per square mile, similar to the extensive granitic bedrock over most of ungaged area 16 above an altitude of 7,000 ft.

In general, runoff efficiencies computed for the ungaged areas were similar to their respective index subbasins. Typically, differences of more than 20 percent for wet and dry periods within a given subbasin are

Table 8. Simulated inflow to Lake Tahoe by gaged subbasins and ungaged areas, California and Nevada

[Abbreviations: mi^2, square mile; $(ft^3/s)/mi^2$, cubic feet per second per square mile]

Subbasin or area (fig. 1*B*)	Drainage area (mi^2) [1]	Percentage of total area tributary to Lake Tahoe	Mean annual discharge per unit of tributary area [$(ft^3/s)/mi^2$]	Percentage of total mean annual inflow to lake
Blackwood Creek	11.1	3.6	1,167	6.0
Ward Creek	9.7	3.1	1,001	4.4
Third Creek	6.1	2.0	477	1.3
Incline Creek	6.7	2.2	422	1.3
Glenbrook Creek	4.1	1.3	143	.3
Logan House Creek	2.1	.7	77	.1
Trout Creek	41.0	13.3	322	6.0
Upper Truckee River	56.4	18.3	670	17.3
General Creek	7.6	2.5	829	2.9
Ungaged area 11	40.6	13.2	969	18.0
Ungaged area 12	23.0	7.5	335	3.5
Ungaged area 14	18.3	6.0	259	2.2
Ungaged area 15	12.4	4.0	530	3.0
Ungaged area 16	53.3	17.2	1,146	28.0
Ungaged area 17	11.9	3.9	1,047	5.7
Ungaged and unmodeled areas [2]	3.8	1.2	--	--
TOTALS	308.1	100	9,394	100

[1] Drainage areas were computed from digital 1:24,000 scale USGS topographic maps. Total of drainage areas listed herein differs from published drainage area due to exclusion in this report of lakes within subbasins and ungaged areas and, to a lesser extent, to rounding.

[2] Consist of two intervening areas, one between Ward Creek and Blackwood Creek, and the other between Glenbrook Creek and Logan House Creek (see fig. 1*B*).

attributed to the increased storage capacity during dry periods. The exception appears to be in subbasins that have extensive bedrock and thus less subsurface storage capacity, resulting in little difference in runoff efficiencies for wet and dry years. For example, runoff efficiencies for wet years for ungaged area 16 are about 80 percent, whereas runoff efficiencies for the dry 1987–92 period averaged about 70 percent.

LIMITATIONS OF THE MODEL AND OF ITS APPLICATION TO A LAKE TAHOE WATER BUDGET

Model uncertainties arise because of simplifications made in the PRMS representations of some of the hydrologic processes. These various sources of uncertainty are discussed in this section. In addition, limitations associated with a simulated water budget for Lake Tahoe also are discussed.

Modeling Uncertainties

Calibration problems with the model for the Lake Tahoe Basin appear to be due primarily to difficulties in modeling the form of precipitation. Simulating the actual form of precipitation is particularly a problem for middle-altitude zones (most of the Lake Tahoe Basin area) where winter storms carry a mix of rain and snow. In middle-altitude basins, such as in this study, winter temperatures stay near freezing over large areas. This makes these basins more sensitive to changes in cool-season temperatures. The 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 snow-threshold value that is suitable for many storms but may be too warm for others. Rapid, intermittent snowmelt also is facilitated or initiated in the warm snowpacks of the Sierra Nevada when rain falls on the snow. In turn, simulated snow accumulation or snowmelt rates may be

affected, especially during warm storms that are large precipitation contributors in the Sierra Nevada (Cayan and Riddle, 1992). In addition, monthly lapse rates for temperature do not reflect the variability in 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 constant winter snowmelt for most alpine basins; whereas, in actuality, winter snowmelt in the Lake Tahoe Basin is intermittent and results in less overall spring-melt streamflow. For most simulations, maintaining a spring snowpack while modeling the late fall/early winter rain-on-snow often results in a longer-than-observed spring snowmelt period, which produces more streamflow later in the year. Conversely, adjusting the temperature-dependent parameters to better model the rain-on-snow events commonly result in less-than-observed spring snowmelt runoff.

Losses from the snowpack by sublimation probably are 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 Lake Tahoe Basin. The Emerald Lake Basin has virtually no vegetation cover and, thus, no shading of the snowpack from the canopy, which would reduce snowpack losses from 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 need to be considered. PRMS assumes that no sublimation occurs while plants are transpiring; however, for moderate-to-high altitude watersheds where transpiration begins in late March to early April (when significant snowpack is still present, particularly for higher-than-normal precipitation years), sublimation may be underestimated.

The net short-wave and long-wave components of the snowpack energy budget critically depend on estimates of winter canopy-cover density (eq. 1) so that 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 were derived from the 1978 timber-type data source used in the HRU delineation (Cartier and others, 1994). 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.

River basins are dynamic systems. Land-cover type and density, and the percentage of impervious urban areas are static parameters in PRMS and, therefore, reflect land cover or development existing at the time data were collected or when the digital maps were compiled. Population growth in the Lake Tahoe Basin since the late 1970's, when the land-cover data base was compiled, has substantially increased the land-surface area classified as urban. Urban areas are classified in PRMS as impervious. PRMS assumes that, on impervious surfaces, water that is not lost to surface evaporation becomes overland flow directly to the stream channel. Storm-flow routing is not accounted for in PRMS, nor is the loss of subsurface storage to ground-water pumping. PRMS is designed to simulate runoff from bedrock watersheds with little to no surface-water/ground-water interaction. Several subbasins modeled—Third Creek, Incline Creek, Upper Truckee River, and Trout Creek—in the Lake Tahoe Basin have substantial sedimentary units known to store significant amounts of ground water (Thodal, 1997). The installation and monitoring of shallow wells adjacent to the outlet streamflow gages would help to better understand the contributions of snowmelt runoff to ground-water flow and ground-water/surface-water interactions.

Model Limitations Associated With Application to a Lake Water Budget

The reservoir-routing module of HSPF was used to construct a model for simulating lake-storage volumes for Lake Tahoe. The model used total tributary inflow, which in turn was computed for this study by summing the simulated streamflow time series from the gaged and ungaged areas. The scope of this analysis, however, was not to do a detailed evaluation of the water budget of Lake Tahoe, but rather to simulate lake-storage volumes and to determine the sensitivity of the water-budget components to error. Typically, lake water budgets consist of the following hydrologic components: precipitation on and evaporation from the lake surface, tributary inflow, ground-water discharge

into or out of the lake, and stream outflow. Of these components, precipitation, inflow, and ground-water seepage into the lake contribute to increased lake volume, whereas evaporation, outflow, and seepage out of the basin are considered losses. Generally, evaporation is computed as a residual term and seepage out of the lake is considered negligible.

Despite the great interest in Lake Tahoe, data from numerous hydrologic and limnology studies are inadequate for determining lake water budgets for time intervals less than annual. This includes insufficient data on tributary inflow and on lake-surface evaporation and precipitation. Previous water-budget studies used precipitation-runoff relations to account for inflow from the ungaged areas (Dugan and McGaugey, 1974; Crippen and Pavelka, 1970; and McGauhey and others, 1963). Myrup and others (1979) used data from three of the gaging stations (Blackwood and Trout Creeks and Upper Truckee River) and applied a factor of 2.5 to the summation of monthly inflow from these three tributaries to account for total lake inflow.

Evaporation from Lake Tahoe has been previously estimated from data collected using a standard Class-A pan near Tahoe City, or computed as a residual. Pan-evaporation data have been collected intermittently at Tahoe City since 1916 by the NWS and the Bureau of Reclamation. Data typically were collected for the May–October period, although winter-evaporation estimates were reported by McGauhey and others (1963) for the period 1916–30. Pan-evaporation rates were adjusted with pan coefficients, averaging 0.70, when used in water-budget computations. Because of differences in wind and thermal regimes of pans and lakes, Winter (1981) cautions against the use of pan coefficients for time intervals less than annual, stating that monthly estimates can differ from the commonly used coefficient of 0.7 by more than 100 percent. Precipitation on Lake Tahoe was estimated from isohyetal lines over the lake (Dugan and McGauhey, 1974; Crippen and Pavelka, 1970; and McGauhey and others, 1963). Myrup and others (1979) used the average of precipitation reported for long-term weather stations at Glenbrook, Nev., and Tahoe City, Calif., and distributed that over the area of the lake.

HSPF is a continuous watershed model designed to simulate water-quantity and water-quality processes. Only the flow-routing component of HSPF was used in this analysis. Lake-storage volumes are computed in HSPF using relations between lake-surface elevations and storage. Computing a lake water budget in HSPF required generating daily time series for total tributary inflow, stream outflow, precipitation on the lake, and lake-surface evaporation. Tributary inflow was simulated using PRMS, as described earlier in the report. Total inflow averaged 409,000 acre-ft annually for the period 1980-96, within the range estimated by Thodal (1997, table 5). The USGS streamflow gage at Tahoe City measures outflow from Lake Tahoe as regulated by the dam at Tahoe City. Daily precipitation totals for three lake-side climate sites (Tahoe City, Glenbrook, and Fallen Leaf; table 2) were averaged and the time series used in HSPF as an estimate of lake-surface precipitation. Annual precipitation from this time series averaged 27 in.

Two evaporation time series were generated, one from the Tahoe City pan-evaporation data for 1916–56 (McGauhey and others, 1963) and the second from the Boca Reservoir pan-evaporation station in the Truckee River Basin. Annual pan evaporation for the Tahoe City station averaged 38 in/yr. The Tahoe City station is thought to yield low readings due to its locale; however, this has not been substantiated by published analysis. Preliminary water-budget simulations in the this study, using the Tahoe City data, suggested that lake-surface evaporation was grossly underestimated; therefore, modified evaporation data from Boca Reservoir was used instead. The Boca pan-evaporation data were adjusted by Rod Hall (Sierra Hydrotech, written commun., 1994) with monthly pan coefficients that ranged from 0.74 to 1.00. Monthly sums were disaggregated to daily mean values and a time series generated to correspond to water years 1981–96 modeling period. Annual evaporation averaged 47 in/yr for the Boca data. The Boca evaporation time series is referred to in this report as the Boca-adjusted evaporation data to avoid confusion with the pan-evaporation data measured at Boca Reservoir.

HSPF reservoir model runs made with the Boca-adjusted evaporation data set, in combination with the lake-surface precipitation time series, indicate how sensitive Lake Tahoe is to these two components of the water budget. Figure 26 shows the observed lake-storage volume and simulated volumes that use (1) PRMS-generated inflow, (2) the three-site precipitation average, (3) the Boca-adjusted evaporation data, and (4) outflow measured on the Truckee River, downstream from the Lake Tahoe dam at Tahoe City. Lake-storage volume for purposes of this analysis is defined as the volume of water between the 6,219.0-ft and 6,229.1-ft lake elevations. The Lake Tahoe elevation-volume rat-

ing considers flows below the rim (6,223 ft) as "negative" storage. Because HSPF cannot simulate negative storage, a minimum elevation of 6,219.0 ft (more than 1 foot below the lowest recorded elevation of 6,220.26 ft) was assigned "0" storage (fig. 26). The lake volume between the rim and the maximum permissible elevation by Federal Court decree, at 6,229.1 ft (744,600 acre-ft; Bostic and others, 1997), added to the lake volume between the rim and the arbitrary zero-storage elevation, at 6,219.0 ft (482,720 acre-ft), yields a maximum observed-storage volume (black line in fig. 26) of 1,227,320 acre-ft.

Lake-surface daily totals for precipitation and evaporation were arbitrarily decreased or increased, respectively to determine their relative sensitivity in simulating lake-storage volumes. Simulation 1 (green line) represents lake storage using 50 percent of the daily precipitation and 100 percent lake-surface evaporation; simulation 2 (red line) uses 67 percent of the daily precipitation and 120 percent of the lake-surface evaporation; and simulation 3 uses 67 percent of the daily precipitation and 100 percent lake-surface evaporation. Simulation 1 and simulation 2 consistently underestimated lake storage from early spring of 1983 through the remaining simulation period, with no storage simulated for periods in 1988, 1990-91, and 1992. Though considerably better than the previous two runs, simulation 3 (blue line) resulted in periods of overestimation during 1980–83 and 1989–96, and periods of underestimation during 1983-88. HSPF was adjusted to simulate more volume than the decreed maximum (at 6,229.1 ft) to allow the simulation to run through water year 1996. However, even with this increased volume, simulation 3 exceeded the adjusted limit of 1,500,000 acre-ft in March 1996.

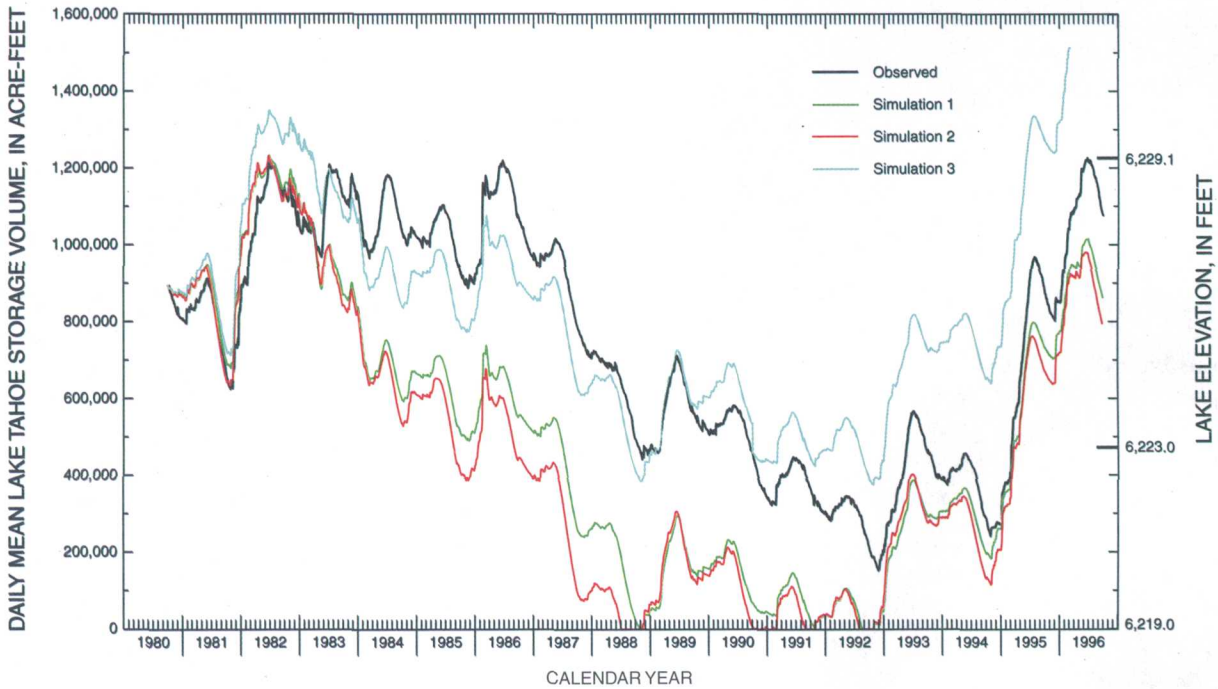


Figure 26. Simulated and observed daily mean lake-storage volumes, Lake Tahoe for the period 1980–96. Observed storage is the volume of water in Lake Tahoe between the 6,219.0-ft and 6,229.1-ft lake elevations. All three simulations used the same PRMS inflow data, the three-site precipitation average time series for lake-surface precipitation, and the Boca-adjusted evaporation time-series data for lake-surface evaporation. Simulation 1 used 50 percent of the precipitation and 100 percent of the lake-surface evaporation; simulation 2 used 67 percent of the precipitation and 120 percent of the lake-surface evaporation; and simulation 3 used 67 percent of the precipitation and 100 percent of the lake-surface evaporation. Lake elevations shown on the right axis represent the minimum lake elevation for storage computation (6,219 ft), the natural rim (6,223 ft), and the maximum lake elevation by Federal Court decree (6,229.1 ft).

The graphical results underscore the need for more definitive water-budget studies for Lake Tahoe. In simulating lake storage, deviations from observed storage levels result when one or more of the lake water-budget components has bias over extended periods. Differences between the observed and simulated storage traces shown were not caused by errors (bias) in inflow alone, but were exacerbated by errors associated with the evaporation and precipitation components of the water budgets. Errors in modeling lake volumes also may arise in volume-stage relations, the quality of bathymetric maps used to compute lake volumes (Winter, 1981), and the accuracy with which the HSPF lake-reservoir model replicates the physical characteristics of Lake Tahoe.

Individual models described in this report may be useful for smaller-scale studies associated with the subbasins. Results from the aggregated models may be useful in other large-scale studies, including water-budget investigations and analyzing the relative effects of changes in land use. However, until the uncertainty in the lake-surface precipitation and evaporation is reduced, the models in this document are not recommended for use to simulate storage in Lake Tahoe.

SUMMARY AND CONCLUSIONS

The U.S. Geological Survey's watershed model, PRMS, was used to simulate streamflow from nine gaged subbasins and six ungaged areas composed of multiple ungaged tributaries in the Lake Tahoe 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. HRU's were delineated for the study subbasins using an integrated GIS containing raster and vector-based data interpolated on 30-m (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 based on groupings of the source data. This method uses the definition of HRU's as discrete land units with similar sets of hydrologic properties regardless of location. The physical properties affecting streamflow are quantified at the HRU level. Computer programs developed to aid users in reconstructing the HRU digital-data layer allow for incorporating updates and corrections into the digital data base as new data becomes available.

Data on mean monthly precipitation from 19 climate sites in the Tahoe–Truckee River Basins were plotted against altitude to estimate the precipitation lapse rates from the long-term regional means. No strong, consistent precipitation-altitude relations were evident, especially during the winter months when most of the annual precipitation occurs. The rain-shadow effect of the Sierra Nevada influences precipitation at the sites as much as altitude. The result of the principal component analysis indicated that 93 percent of the monthly precipitation variability is shared among all of the sites, once seasonality is removed. For the remaining 7 percent, a second principal component analysis was computed, once the shared component was removed. The results of this climate analysis appear to refute an assumption that, on a regional scale, natural clusters of synchronized precipitation variation exist in the Tahoe–Truckee Basins. Instead, these basins evidently are small enough so that monthly precipitation variations are either shared or effectively random. Because precipitation mean and variance distributions were controlled at larger or smaller scales than described by historical data, the decision was made here to drive the models with local observations of precipitation with daily, rather than monthly, spatial distributions.

The Lake Tahoe Basin is characterized by moderate-altitude subbasins sensitive to adjustments made to nondistributed, temperature-dependent parameters. Possible basin-wide temperature inversions may skew the temperature lapse rates used in the model. When temperature-dependent model parameters are adjusted to simulate late fall and early winter runoff, more of the snowpack at the higher altitudes was melted than observed runoff indicated. Conversely, when calibration is adjusted so that spring snowpack is maintained, some of the simulated snowpack lingered later than what the observed snow-water equivalence data indicated, often producing more summer runoff than was observed. Simulation bias for daily mean streamflow ranged from -9 to 0 percent for the calibration period and from -5 to +8 percent for the verification and validation periods; relative error ranged from +1 to +38 percent and from -5 to +74 percent for the calibration and verification periods, respectively. Simulation bias for annual mean streamflow ranged from -5 to +4 per-

cent and relative error ranged from -1 to +18 percent. Runoff from Logan House Creek is diverted upstream from the gage and data were not available to reconstruct runoff for modeling use. Runoff diverted during below-average precipitation years from the Upper Truckee River watershed was not accounted for during modeling, nor were the effects of routing urban runoff in the urban areas, of ground-water pumping, or of diversions upstream from Echo Lake. In general, runoff from the gaged subbasins during dry or under-average precipitation years was oversimulated.

A GIS and a RDB program allowed for objective and time-efficient identification of similar HRU's between the gaged and ungaged areas and facilitated the construction of the PRMS models for the ungaged areas. The gaged subbasins were loosely defined as "paired-subbasins" for purposes of testing the transfer of calibrated model parameters to adjacent uncalibrated (validation) subbasins. Physiographic differences prohibited consideration of all but the Ward Creek and Blackwood Creek pair as truly similar, paired subbasins. However, the fact that both subbasins were not physiographically identical allowed for a higher match of HRU's in the ungaged areas. HRU-distributed parameter values generally are transferrable when physiographic conditions are similar. Nondistributed parameter values from the index subbasins were transferrable when hydroclimatic conditions were similar. The most sensitive nondistributed parameters that were regionalized were the subsurface and ground-water routing coefficients, and the monthly temperature-dependent parameters. These parameters affect runoff timing, the shape of the baseflow recession part of the hydrograph, and the overall seasonal distribution of runoff.

Simulated streamflow from ungaged areas was evaluated using three different indices: (1) flow expressed as cubic feet per second per square mile to permit comparison of runoff from watersheds of different sizes; (2) runoff efficiencies or percentages of precipitation yielding runoff; and (3) seasonal distribution of streamflow using comparisons of monthly percentage of total annual streamflow. Comparison of ungaged runoff indices to those of the associated gaged subbasins indicates that the ungaged areas have similar runoff proportions and seasonal distributions. The uncertainty associated with the simulated runoff for the ungaged areas is assumed to be within the range of error computed for the associated gaged "index" subbasin(s), because the ungaged areas and their respective gaged, index subbasins have similar hydrologic and climatic characteristics. No field work was done nor were any data collected in the ungaged areas to verify this assumption. The mapping of HRU's and transfer of model parameters from gaged to ungaged areas assumes that the digital data base adequately characterizes the dominant physiographic and land-cover features, and more importantly, that the dominant hydrologic processes are identified and correctly simulated. Error attributed to the digital physiographic data were not computed and, for purposes of evaluating runoff, is considered to be insignificant.

In simulating storage volumes for Lake Tahoe, 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 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. Despite the uncertainties in the Lake Tahoe water-budget components, simulated inflow to the lake from the gaged and ungaged areas, which averaged 409,000 acre-ft annually, was compatible with previously determined mean annual inflow estimates. However, until the uncertainty in lake-surface precipitation and evaporation are reduced, it is not recommended that the models in this document be used to simulate storage volumes in Lake Tahoe. The models discussed in this report can be used in aggregate to provide total tributary inflow to Lake Tahoe. Inflow data can then be further used to simulate storage operations, as an aid in policy development or for near-term decision support.

Because of model and data limitations, the results presented herein for the ungaged areas should only be considered initial estimates of runoff, yet should provide a sound basis for more detailed simulations. These models were calibrated under a specific set of environmental conditions and assumptions (meteorological, physiographic, hydrologic, and land use). The advantage of a distributed-parameter model might not be apparent until the model is needed to simulate new climatic/cover/terrain conditions not used in the original calibration. Changing conditions, particularly changes in land-cover type and density, or climate, or the incorporation of new subsurface or ground-water use information, would require updated model-input data and, possibly, recalibration to the new set of conditions.

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Appendix

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

File	Size (bytes)	Description
blck_adj_climateQ.mms	1,869,148	Daily precipitation and temperature adjusted for each HRU, and observed streamflow - Ward Creek model input.
ward_adj_climateQ.mms	1,608,370	Daily precipitation and temperature adjusted for each HRU, and observed streamflow - Blackwood Creek model input.
third_adj_climateQ.mms	1,831,904	Daily precipitation and temperature adjusted for each HRU, and observed streamflow - Third Creek model input.
incline_adj_climateQ.mms	2,092,686	Daily precipitation and temperature adjusted for each HRU, and observed streamflow - Incline Creek model input.
glenbrk_adj_climateQ.mms	1,459,363	Daily precipitation and temperature adjusted for each HRU, and observed streamflow - Glenbrook Creek model input.
logan_adj_climateQ.mms	1,012,314	Daily precipitation and temperature adjusted for each HRU, and observed streamflow - Logan House Creek model input.
trout_adj_climateQ.mms	5,147,498	Daily precipitation and temperature adjusted for each HRU, and observed streamflow - Trout Creek model input.
utr_adj_climateQ.mms	6,451,415	Daily precipitation and temperature adjusted for each HRU, and observed streamflow - Upper Truckee River model input.
general_adj_climateQ.mms	1,459,350	Daily precipitation and temperature adjusted for each HRU, and observed streamflow - General Creek model input.
tcp11_adj_climateQ.mms	3,161,780	Daily precipitation and temperature adjusted for each HRU, and observed streamflow - Ungaged area 11 model input
tcp12_adj_climateQ.mms	3,126,721	Daily precipitation and temperature adjusted for each HRU, and observed streamflow - Ungaged area 12 model input
tcp14_adj_climateQ.mms	2,320,248	Daily precipitation and temperature adjusted for each HRU, and observed streamflow - Ungaged area 14 model input.
tcp15_adj_climateQ.mms	2,109,868	Daily precipitation and temperature adjusted for each HRU, and observed streamflow - Ungaged area 15 model input.

Appendix. Name, size, and description of files used in precipitation-runoff simulations for the Lake Tahoe Basin, California and Nevada [1]—Continued

File	Size (bytes)	Description
tcp16_adj_climateQ.mms	5,265,629	Daily precipitation and temperature adjusted for each HRU, and observed streamflow - Ungaged area 16 model input.
tcp17_adj_climateQ.mms	2,004,668	Daily precipitation and temperature adjusted for each HRU, and observed streamflow - Ungaged area 17model input.
blck_final_param.file	53,921	PRMS parameter input file for Blackwood Creek.
ward_final_param.file	46,352	PRMS parameter input file for Ward Creek.
third_final_param.file	52,847	PRMS parameter input file for Third Creek.
incl_final_param.file	60,361	PRMS parameter input file for Incline Creek.
glenbrk_final_param.file	42,121	PRMS parameter input file for Glenbrook Creek.
logan_final_param.file	29,250	PRMS parameter input file for Logan House Creek.
trout_final_param.file	148,584	PRMS parameter input file for Trout Creek.
utr_final_param.file	185,963	PRMS parameter input file for Upper Truckee River.
general_final_param.file	41,997	PRMS parameter input file for General Creek.
tcp11_param.file	96,852	PRMS parameter input file for Ungaged area 11.
tcp12_param.file	95,910	PRMS parameter input file for Ungaged area 12.
tcp14_param.file	71,224	PRMS parameter input file for Ungaged area 14.
tcp15_param.file	64,673	PRMS parameter input file for Ungaged area 15.
tcp16_param.file	161,495	PRMS parameter input file for Ungaged area 16.
tcp17_param.file	61,462	PRMS parameter input file for Ungaged area 17.

[1] For more information, please contact the U.S. Geological Survey, Carson City, Nev., at (775) 887-7649, or e-mail request to <usgsinfo_nv@usgs.gov>.

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U.S. Department of the Interior
1849•1999

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