APPLICATION OF THE PRECIPITATION-RUNOFF MODELING SYSTEM MODEL TO SIMULATE DRY SEASON RUNOFF FOR THREE WATERSHEDS IN SOUTH-CENTRAL GUAM

By Lenore Y. Nakama

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Conversion Factors

Multiply	By	To obtain
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
foot (ft)	0.3048	meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
inch (in.)	25.4	millimeter
inch per hour (in/h)	25.4	millimeter per hour
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
mile per hour (mi/h)	1.609	kilometer per hour
square mile (mi^2)	2.590	square kilometer

Temperature is given in degrees Fahrenheit (°F), which can be converted to degrees Celsius (°C) by using the equation:

$$°C = (°F - 32)/1.8$$

APPLICATION OF THE PRECIPITATION-RUNOFF MODELING SYSTEM MODEL TO SIMULATE DRY SEASON RUNOFF FOR THREE WATERSHEDS IN SOUTH-CENTRAL GUAM

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Abstract

The Precipitation-Runoff Modeling System model was calibrated and verified using existing hydrologic and climatic data for the Maulap and Imong River watersheds for simulation of dry season runoff from three gaged areas that contribute to the Fena Reservoir water supply. The model was applied to the Almagosa River watershed by transferring calibrated parameters and coefficients because data were not available for daily diversions of as much as 3.9 cubic feet per second of runoff at Almagosa Springs. Application of the model in the watershed of Fena Reservoir can provide a physically based method for estimating reservoir recharge during the dry season, January through May. Estimated recharge can be examined in relation to the effect of varying intensities of monthly reservoir-water production in order to identify a basis for the rational release of water.

Differences between simulated and observed monthly mean runoff for dry season months in the verification period (November 1980 through December 1981) ranged from –0.04 cubic feet per second (–3.51 percent) to 0.74 cubic feet per second (30.34 percent) at Maulap River and from 0.03 cubic feet per second (1.3 percent) to 1.19 cubic feet per second (27.95 percent) at Imong River. On the basis of runoff simulations for the four complete dry seasons included in the total calibration and verification periods (1981 and 1984–86), the total volume of runoff during the 5-month dry season can be predicted to within 20 percent of actual runoff at Maulap River, and to within 27 percent at Imong River.

INTRODUCTION

Fena Reservoir, located in south-central Guam (fig. 1), was constructed in 1951 by the U.S. Navy to provide a dependable water supply for Navy personnel and local citizens. The reservoir, which is under the management of the U.S. Navy Public Works Center in Guam, has a total storage capacity of about 7,100 acre-ft and provides a water supply of about 12,500 acre-ft/yr. Recharge is derived primarily from the runoff in three gaged rivers, the Maulap, Almagosa, and Imong Rivers, which drain about 75 percent of the Fena Valley watershed. Annually, the combined discharge of the three rivers averages about 15,000 acre-ft.

Because rainfall in the region is highly seasonal, the total quantity and timing of water available for replenishment of the reservoir also varies by season, and this is reflected in the records of monthly runoff and reservoir stage (fig. 2). During the dry season, which generally begins in January and persists through May, only about 15 to 25 percent of the total annual rainfall can be expected. Water levels in the reservoir gradually decline as daily withdrawals generally exceed the volume of runoff available for reservoir recharge. With the onset of the wet season (July through November), increases in rainfall, runoff, and reservoir water levels occur. In most years, wet-season runoff is adequate for complete replenishment of the reservoir. However, depending on factors such as quantity, distribution, and timing of rainfall during the preceding period, the volume of water stored in the reservoir and within subsurface zones of the surrounding drainage area may be insufficient to satisfy the daily demand for the duration of the dry season.

In 1983, a severe drought, in conjunction with the normal draft on the reservoir, caused the water level in the Fena Reservoir to drop to a record low of 21.86 ft below the spillway. For the first time since the completion of the dam in 1951, the reservoir did not fill

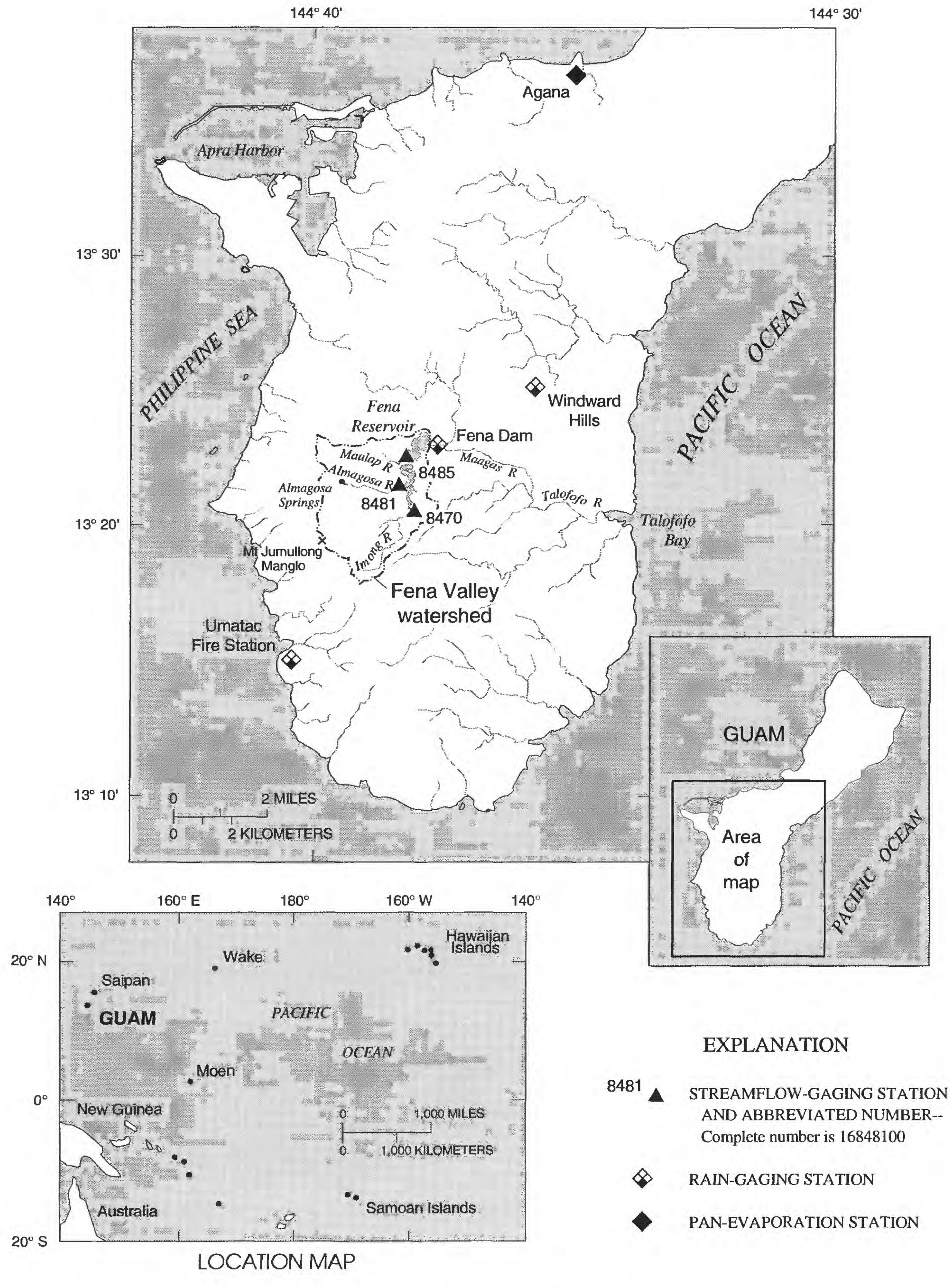

Figure 1. Location of the Fena Valley watershed and hydrologic data-collection stations.

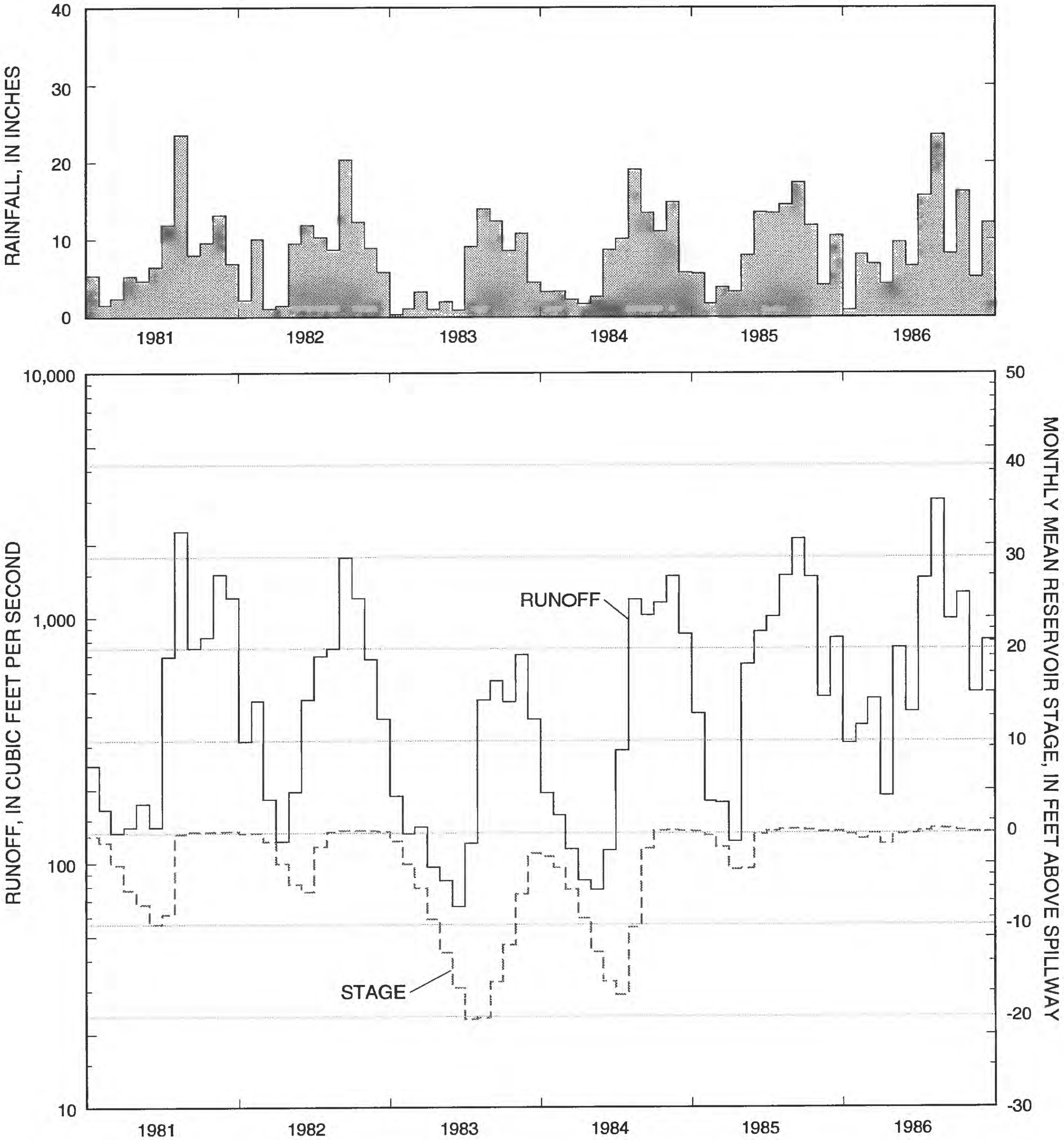

Figure 2. Monthly rainfall, monthly total runoff, and monthly mean stage of Fena Reservoir, 1981-86.

during the next rainy season, and strict water conservation measures were imposed (van der Brug, 1986). Because of the potential for water shortages, timely information on the anticipated reservoir inflow can be useful for management of the water supply.

The development of physically based rainfall-runoff models allows a variety of hydrologic questions and planning problems to be addressed. Each component of the hydrologic cycle is expressed in the form of known physical laws or empirical relations that have been based on observed, measurable watershed characteristics in order to reproduce the physical reality of the hydrologic system as closely as possible. The model's ability to simulate hydrologic response to normal and extreme minimum rainfall on the basis of antecedent moisture conditions and climate data, provides a physically based method for estimating streamflow volumes, rates, and time distribution. In 1990, the U.S. Geological Survey (USGS) entered into a cooperative agreement with the U.S. Navy to calibrate and verify the U.S. Geological Survey's Precipitation-Runoff Modeling System (PRMS) (Leavesley and others, 1983) for simulating runoff in gaged areas that contribute to the water supply of Fena Reservoir.

PURPOSE AND SCOPE

This report describes calibration and verification of PRMS for the Maulap and Imong River watersheds, application of the model to the Almagosa River watershed, and the accuracy of simulated runoff. Runoff simulations for dry season months, January through May, are described separately. In addition, an application of the results to the water-supply problem in Guam is also discussed. Existing hydrologic and climatic data, collected from February 1983 through February 1987, were used for model calibration. Fourteen months of existing data, from November 1980 through December 1981, were reserved for verification of the model. Recharge originating in ungaged areas (1.16 mi^2) is not addressed in this report.

DESCRIPTION OF THE STUDY AREA

The island of Guam is located near lat 13°28'N., long 144°45'W. in the tropical western Pacific Ocean. The island has an area of 212 mi^2 and is about 3,790 mi west-southwest of Hawaii. Guam is a U.S. territory and is the largest and southernmost of the Mariana Islands.

The watershed for Fena Reservoir is located in the volcanic uplands of southern Guam. All of the Fena Valley watershed lands are under the jurisdiction of the U.S. Navy. The drainage area upstream of the dam is 5.88 mi^2. Altitude of the land surface in the Fena Valley watershed ranges about from 111 ft at the dam spillway to 1,282 ft at Mt. Jumullong Manglo on the western drainage divide. The slopes of the land surface range from less than 15 percent to greater than 50 percent. Below the spillway, the Maagas River flows to the east and joins the Talofofo River before reaching the Pacific Ocean 5.5 mi downstream (fig. 1).

Three main rivers, the Almagosa, the Imong, and the Maulap drain 75 percent of the Fena Reservoir watershed. The area above the Maulap River streamflow-gaging station (16848500) is 1.15 mi^2. Altitude in the Maulap River watershed ranges from 130 ft at the gaging station to about 980 ft. The area above the Almagosa River streamflow-gaging station (16848100) is 1.32 mi^2. Altitude in the watershed ranges from 155 ft to about 1,240 ft. The area above the Imong River streamflow-gaging station (16847000) is 1.95 mi^2. Altitude ranges from 120 ft to 1,282 ft at the top of Mt. Jumullong Manglo.

CLIMATE

The climate of Guam is uniformly warm and humid throughout the year. Temperatures generally range from the mid-70's at night to the high 80's (Fahrenheit) during the day. Humidity commonly ranges between 60 and 100 percent, with the highest humidities occurring at night. Average annual rainfall ranges from 85 in. in coastal areas to 100 in. in the mountains of southern Guam.

Two distinct seasons characterize the climate. From January through May, conditions are generally dry. Of the total annual rainfall, only 15 to 20 percent usually occurs during this season, mostly in light and scattered showers. Tradewinds from the east blow 90 percent of the time during the dry season, and calms are rare. The rainy season usually begins in July and persists through November. Rainfall during this season is frequently prolonged and steady and accounts for an average of 65 percent of the total annual rainfall. Winds may blow from any direction, and calms are frequent. December and June are transitional; climatic conditions are variable from year to year. Typhoons generally occur during the rainy season and frequently bring daily rainfall of 6 to 10 in. and winds in excess of 75 mi/h (Blumenstock, 1959).

GEOLOGY

Much of southern Guam is underlain by volcanic rocks of Miocene age of the Umatac Formation. The formation is about 2,200 ft thick and consists of a sequence of volcanic rocks dipping gently to the east and minor interbedded limestone and calcareous shale. The formation is made up of four members: (1) the Facpi Volcanic Member, consisting of pillow basalt, massive flows, and flow-breccia; (2) the Maemong Limestone Member, consisting of fine- to coarse-grained limestone and bedded calcareous tuffaceous shale; (3) the Bolanos Pyroclastic Member, consisting of massively bedded tuff breccia that contains abundant fragments and cobbles of limestone, tuffaceous sandstone, and volcanic conglomerate; and (4) the Dandan Flow Member (Tracey and others, 1964). Outcrops of the formation cover 87 percent of the Fena Reservoir watershed.

At higher altitudes in the watershed, Alifan Limestone, also of Miocene Age, rests unconformably on the volcanic rocks (fig. 3). Originally 200 to 300 ft thick, the limestone cap is 2 to 3 mi^2 in area and is oriented in a north-south direction, extending to a maximum of 4 mi (Tracey and others, 1959). Alifan Limestone consists of massive coarse- to fine-grained recrystallized limestone characterized by dominance of coral fragments such as stick-like Porites and Acropora and by long calcite tubes formed by burrowing worms or gastropods (Tracey and others, 1964). In the Maulap and Almagosa River watersheds, Alifan Limestone underlies 20 percent and 31 percent of the areas. Within the limestone environment of the upper Almagosa River watershed, a sinkhole, greater than 50 ft in depth with an average diameter of about 1,500 ft, has formed. Alluvial clay fill covers the bottom of the sinkhole.

SOILS

The distribution and hydrologic properties of soils in the study area are described by the Soil Conservation Service (1988). In the Maulap, Almagosa, and Imong River watersheds, soils formed in residuum derived dominantly from tuff and tuff breccia are classified as shallow to very deep clay and silty clay soils (fig. 4). The silty clay soils of the Akina and Atate series are well-drained, deep to very deep (59 to 65 in.), and are moderate in permeability (0.2 to 2.0 in/hr) and available moisture capacity (0.07 to 0.2 in/in). At lower altitudes in the Imong River watershed, shallow clay soils of the Agfayan series, moderately slow in permeability (0.2 to 0.6 in/hr) and high in available moisture capacity (0.13 to 0.25 in/in), are intermingled with silty clay soils of the Akina series in an unpredictable pattern. In the Maulap and Almagosa River watersheds, soils formed in residuum derived from coralline limestone are classified as well-drained shallow (10 in.) extremely cobbly clay loam soils of the Ritidian series. These soils have moderately rapid permeability (2.0 to 6.0 in/hr) and very low available moisture capacity (0.05 to 0.08 in/in). The sinkhole in the Almagosa watershed is filled with deep (59 in.) clay soils of the Ylig series that formed in alluvium derived dominantly from volcanic rock. Permeability is moderately slow (0.5 to 1.5 in/hr) and available moisture capacity is high (0.15 to 0.20 in/in).

LAND USE

Land-use information was obtained from a vegetation survey of the Fena Valley watershed done by the [U.S.] Forest Service (Roger Skolmen, written commun., 1976). Because the area has been recognized as an important wildlife habitat, not much development has occurred. A variety of grasses grow in upland savannah areas. Shrubs and low trees are common where the savannahs grade into ravine forest vegetation. Coconut, pandanus, and banyan trees are common upperstory species in the forested areas; shrubs, ferns, and various grasses grow beneath. West of the reservoir, limestone plateaus support mixed, wet forests. Aerial photographs taken in 1988 by Perry Associates, Inc. indicate that the mapped boundaries between grasslands and ravine forests are relatively stable. The locations of forested areas, bare areas, grasslands, and areas covered predominantly by shrubs and low trees are shown in figure 5. Buildings, roads, and other impervious surfaces are nonexistent. The watershed is relatively undisturbed, except for areas where occasional wildfires occur.

HYDROLOGY

The Fena Reservoir watershed is located in the headwaters of the Talofofo River watershed. Most of the drainage area for the reservoir is underlain by volcanic rocks of the Umatac Formation. In the volcanic terrane, the land surface is typically steep and highly dissected by narrow, winding valleys, particularly in headwater areas. At higher altitudes in the Maulap and Almagosa River watersheds, Alifan Limestone forms a cap that overlies the volcanic rocks. The limestone has much higher permeability than the underlying volcanic rocks. Because downward percolation into the porous limestone is extremely rapid, slopes are long and plane, and no streams are present.

About 60 percent of the total annual rainfall runs off in the three main rivers, the Maulap, Almagosa, and Imong, that flow into Fena Reservoir. Vegetal

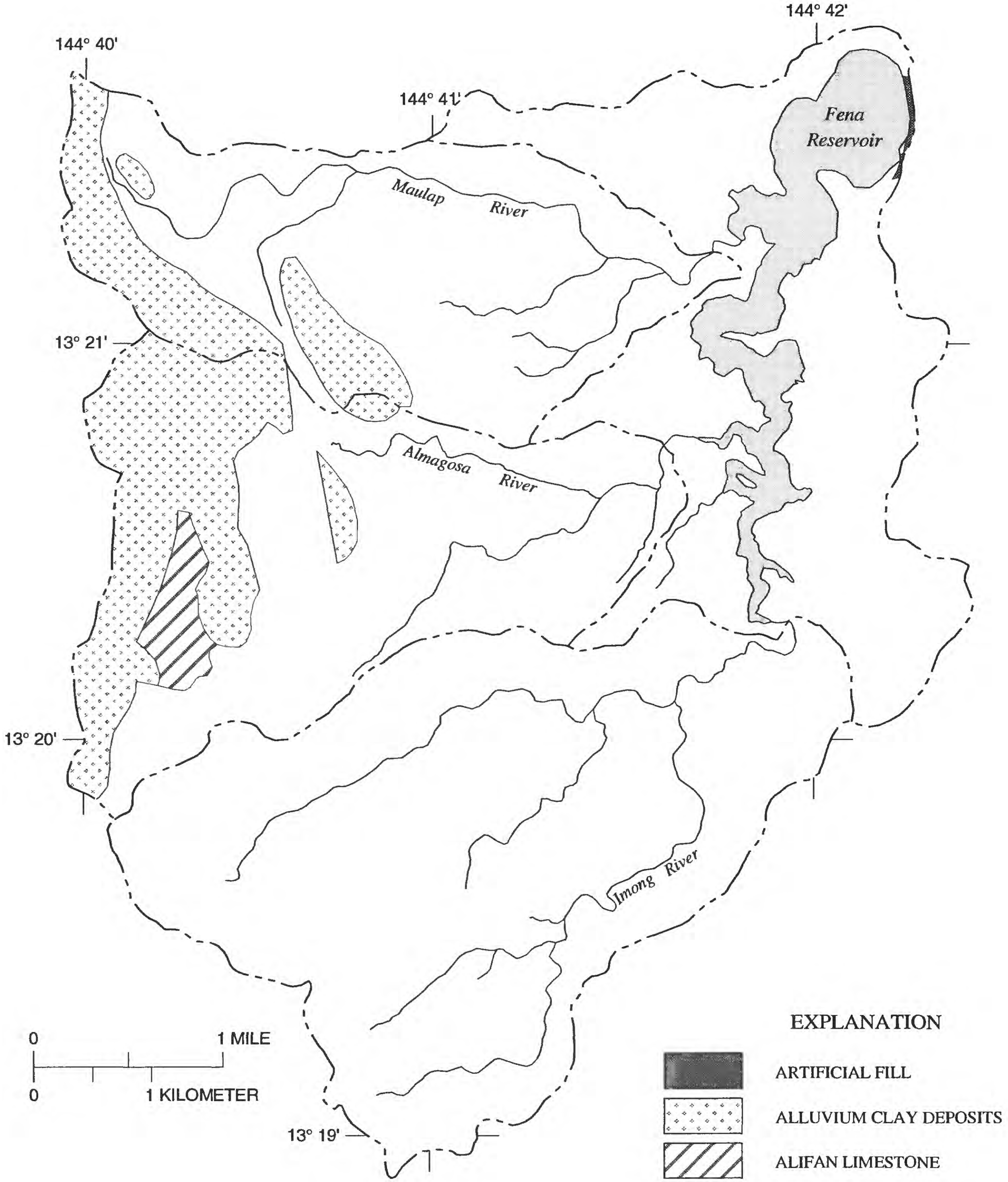

Figure 3. Generalized geology of Fena Valley watershed (modified from Tracey and others, 1964).

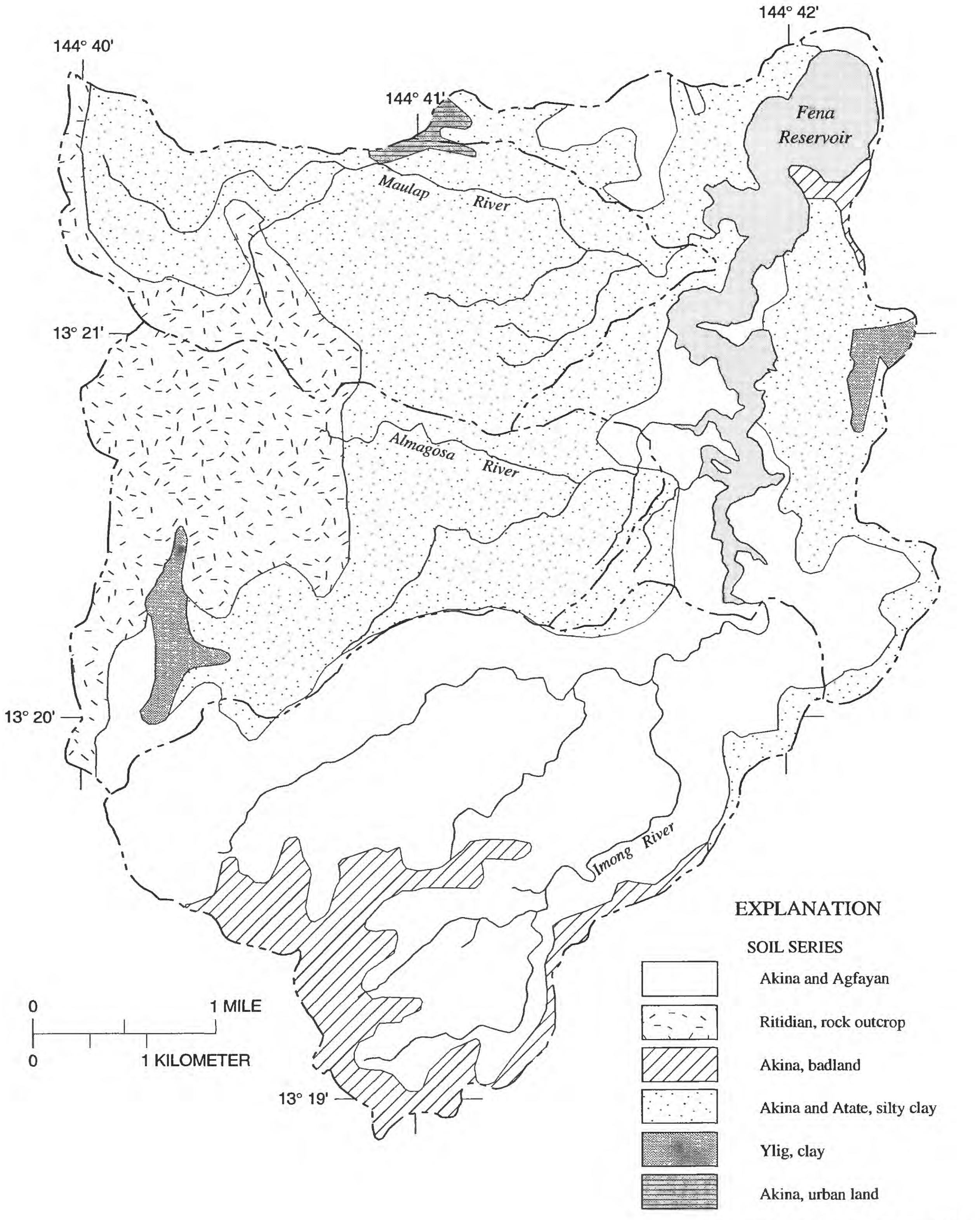

Figure 4. Distribution of soils in Fena Valley watershed (modified from Soil Conservation Service, 1988).

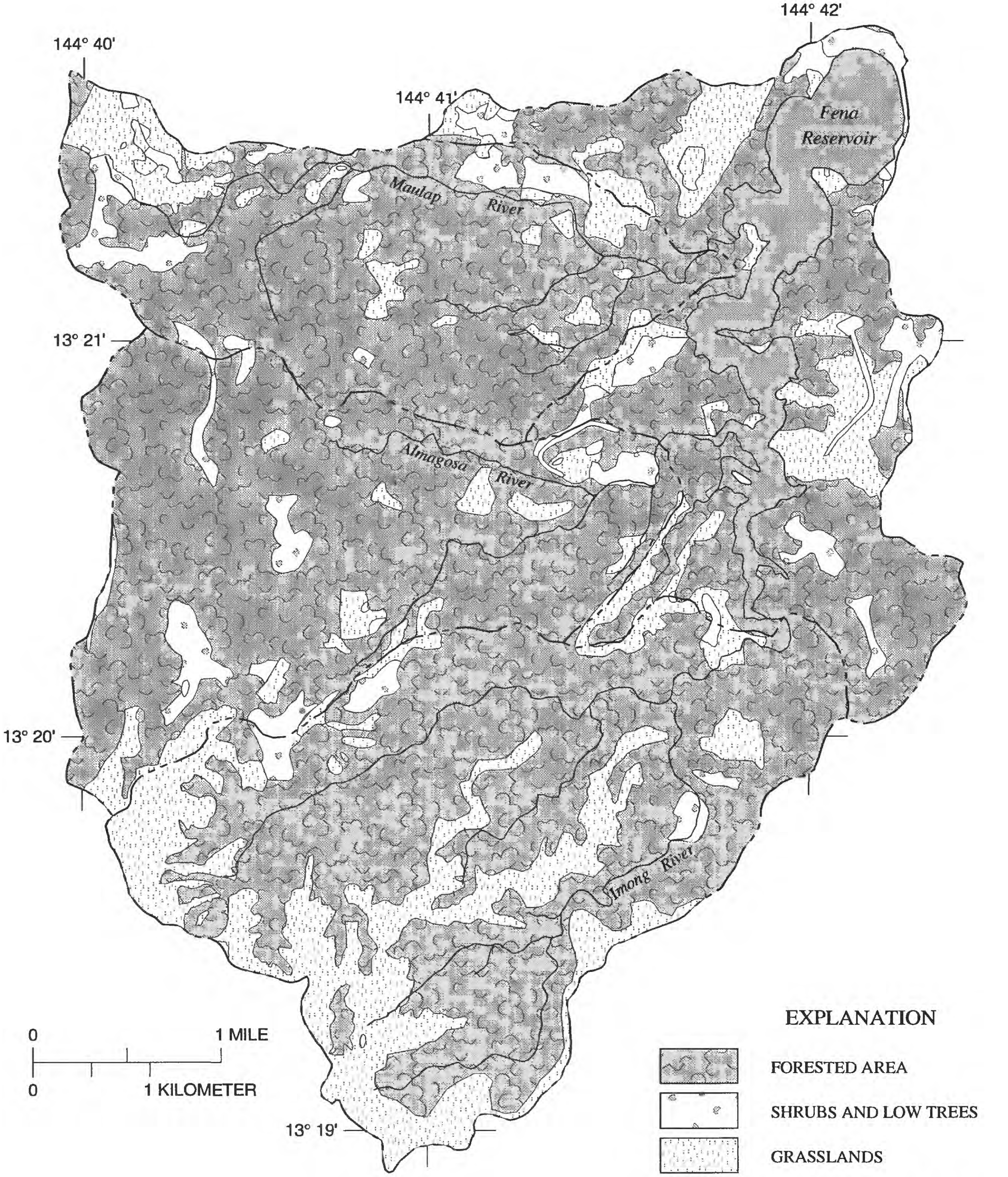

Figure 5. Vegetation unit boundaries in Fena Valley watershed (modified from Roger Skolman, (U.S.) Forest Service, written commun., 1976).

transpiration and evaporation account for the remaining quantity. Much of the watershed is forested, and these areas have generally high cover densities. Part of the rainfall is intercepted by the thick forest canopy and is eventually evaporated back into the atmosphere. Significant quantities of rainfall are also intercepted by the litter layer of organic material and debris that covers the forest floor. The litter layer forms a protective cover that serves to reduce evaporative losses from moist soils near the surface. Despite high humidities, evapotranspiration rates are high in the Fena Reservoir watershed because of moisture availability and warm air temperatures year-round. During the dry season, monthly rainfall of at least 4 in. is required to meet evapotranspiration needs and to prevent a decrease in the base-flow runoff (Ward and others, 1965).

GROUND WATER

Scant quantitative data exist for evaluating the hydraulic properties of the subsurface rocks in the Fena Reservoir. Except where otherwise indicated, the following description of the ground-water system is based on previous investigations done by Tracey and others (1959, 1964). Well data are not available in the vicinity of the Fena Valley watershed, however, some data are available for similar units in other locations on the island (Tracey and others, 1959).

In areas underlain by Alifan Limestone, soils are very shallow and well-drained, and seepage by downward percolation is extremely rapid. Residence time in the limestone is generally much shorter than in the volcanic rock, and during the wet season, a large part of the rainfall in the limestone terrane is routed quickly to a stream channel through subsurface pathways. Under intense or prolonged rainfall in the headwaters of the Almagosa River watershed, drainage can be directed to the sinkhole where water can pond for several days while entering the underlying rock. The limestone wastes by solution, forming fissures along joints and fractures and solution pipes. Locally, the ground-water drainage may be channeled along faults, joints, and breccia zones that intersect the watersheds. The water table is above the limestone-volcanic rock contact. Potentially large volumes of ground water can be concentrated at the contact. Perched water issues in copious springs located at the contact between the limestone and volcanic rocks. Almagosa Springs, which is the largest spring in southern Guam, contributes to flow in the Almagosa River and has been developed for municipal water supply; as much as 3.9 ft^3/s of runoff is removed daily from the spring.

The configuration of the water table in the volcanic terrane is not known in detail. However, in general, the water table slopes steeply towards streams and lowlands with discharge occurring at all altitudes, mostly at seeps and springs. The volcanic rock has been weathered to depths of 50 ft and greater. The upper few feet of weathered volcanic rock is commonly granular and friable, and is generally more permeable than that of the underlying material (Ward and others, 1965). Ground water in porous, weathered material is perched above the relatively impermeable unweathered rock. Seepage is slow in the weathered zone and extremely slow in the unweathered conglomerate at depth.

During the dry season, flow is sustained by slow seepage from a saturated zone of variable depth in the friable mantle that overlies the relatively impermeable volcanic rock and by numerous small perennial seeps and some springs that emerge from the base of the limestone cap, from joints, or from bedding planes in the volcanic rock.

SURFACE WATER

The conditions that determine streamflow characteristics are similar in all three watersheds, and this similarity is reflected in the annual hydrographs shown in figure 6. Runoff in all three rivers remains fairly constant throughout the dry season, sustained by ground-water discharge. During the rainy season, rapid increases and decreases in streamflow occur. Because of the relatively impermeable volcanic rocks and clay soils that underlie most of the Maulap and Almagosa River watersheds and the entire Imong River watershed, a large part of the wet season rainfall runs directly off.

Flow-duration curves, which show the frequency of flows at the three streamflow-gaging stations for a common period of record (1972–88), are shown in figure 7. In addition to the effect of drainage-area size, the curves reflect differences in the capacity of the watersheds to store and transmit water. Higher sustained base flows in the Imong River could indicate that the major part of flow during dry periods is derived from water stored in ground-water zones in the volcanic terrane. During years in which rainfall is substantially less than normal, monthly runoff per unit area is higher in the Imong River watershed for most months; this tendency can persist through the next year. During wet seasons that have rainfall in the normal range, monthly runoff per unit area may be higher in any watershed, depending on factors such as quantity, distribution, and timing of rainfall. The effects of water withdrawals at Almagosa Springs are reflected by a decrease in the duration of flows below 3.9 ft^3/s.

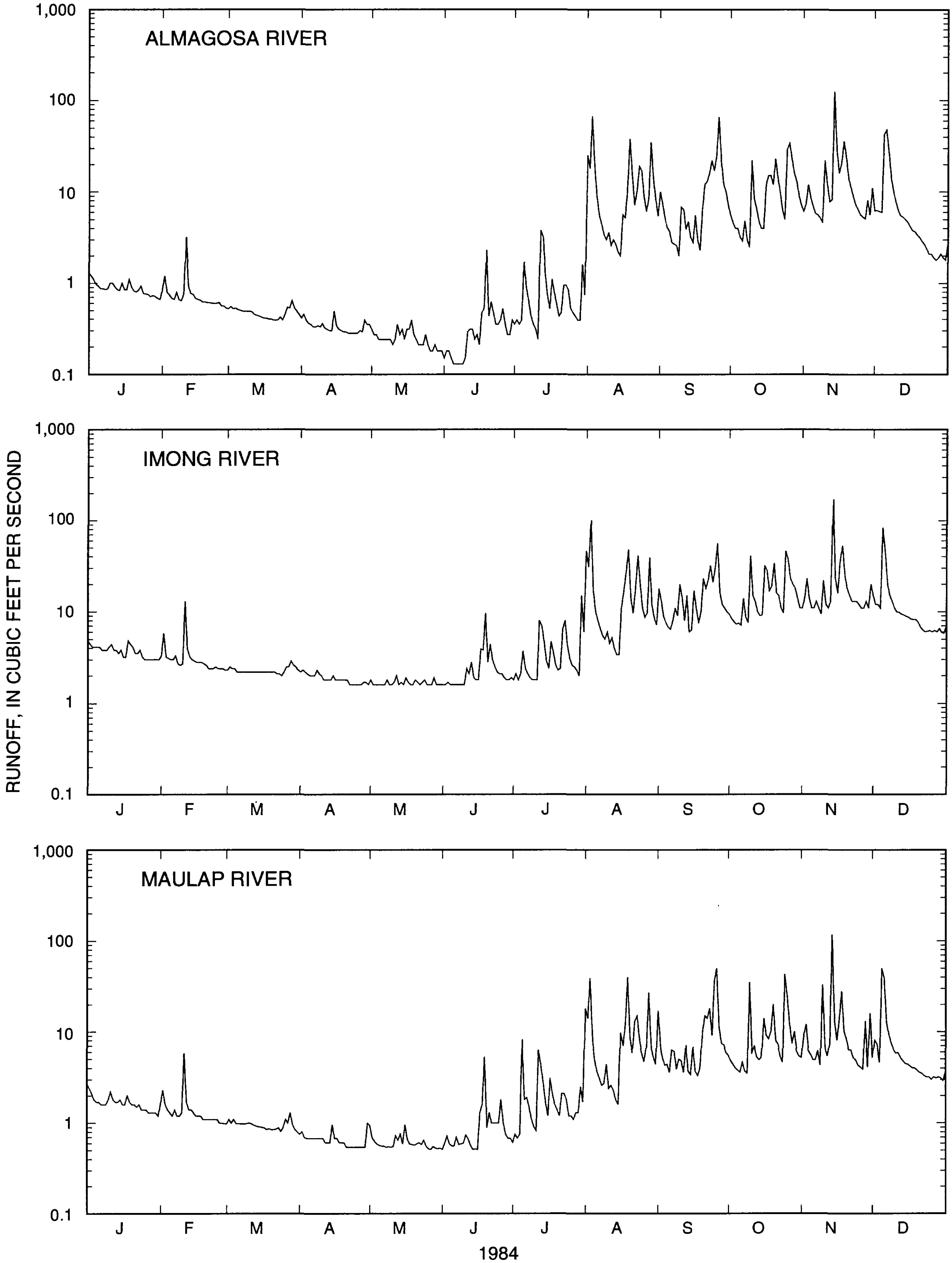

Figure 6. Daily mean runoff at Almagosa, Imong, and Maulap Rivers, 1984.

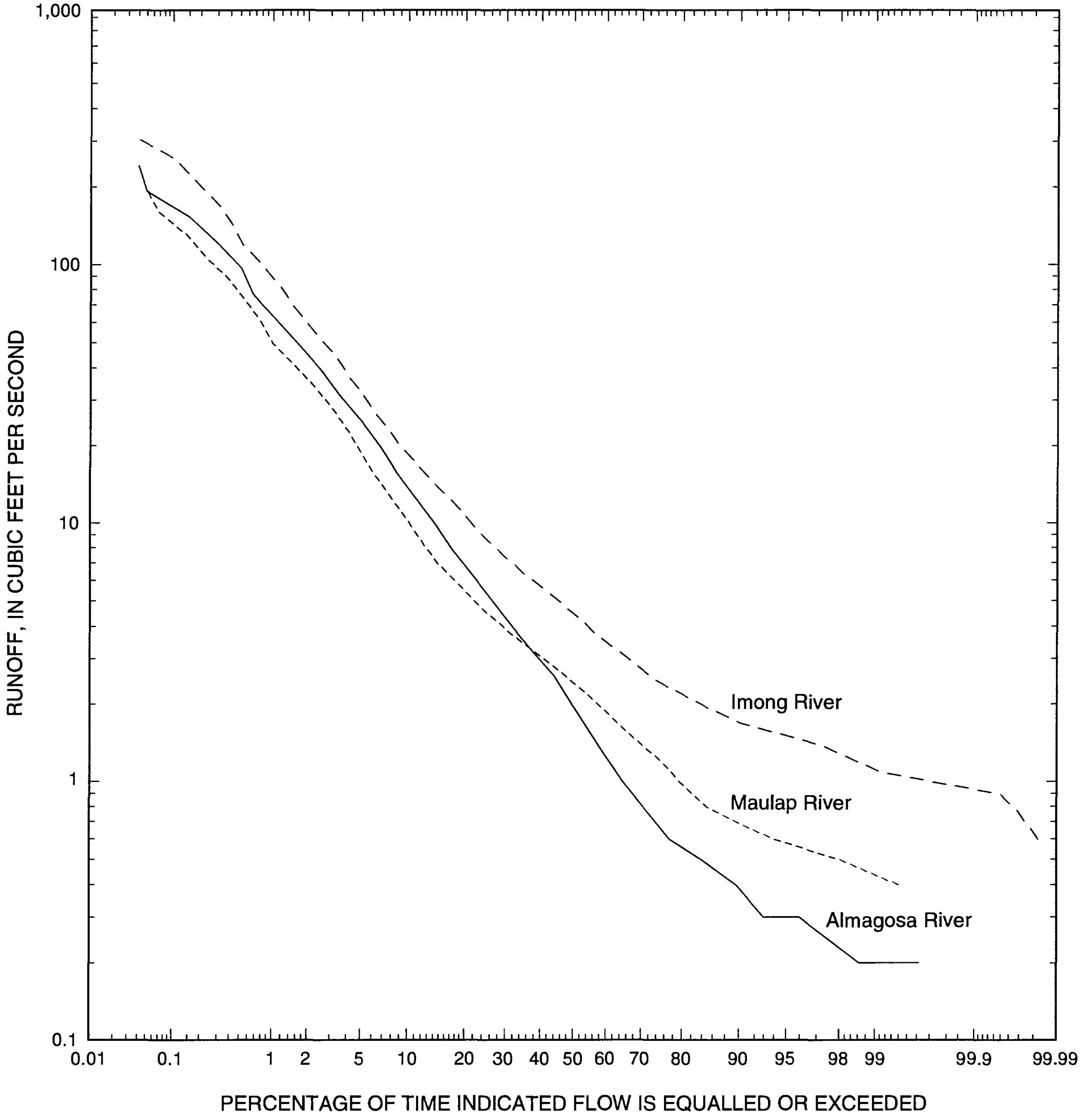

Figure 7. Flow-duration curves for Almagosa, Imong, and Maulap Rivers (based on period 1972-88).

APPLICATION OF PRECIPITATION-RUNOFF MODELING SYSTEM

Precipitation-Runoff Modeling System (PRMS) was calibrated in the daily-mode for the Maulap and Imong River watersheds, and then used to simulate dry season runoff for gaged areas that contribute to the water supply of the Fena Reservoir.

DESCRIPTION OF THE MODEL

PRMS is a deterministic, physically based modeling system that was developed to evaluate the effect of various combinations of precipitation, climate, and land use on watershed hydrologic response. Complete documentation for the program is available in the PRMS user's manual (Leavesley and others, 1983). Each component of the hydrologic cycle is expressed in the form of known physical laws or empirical relations that have been based on observed, measurable watershed characteristics in order to reproduce the physical reality of the hydrologic system as closely as possible. A moisture balance for each component in the hydrologic cycle is generated in a continuous-simulation approach. PRMS will simulate both daily mean flows and stormflow hydrographs. Data requirements and equations used for simulation in the daily-mode may differ for storm-mode simulation.

SYSTEM CONCEPTS

Physical heterogeneity within a watershed is accounted for by partitioning the watershed into units that have similar slopes, land use, soils, geology, and precipitation distribution. Each unit is then considered to be homogeneous with respect to its hydrologic response and is referred to as a hydrologic-response unit (HRU). A daily water balance and an energy balance are computed for each HRU and for the entire system.

A schematic diagram of the PRMS conceptual hydrologic system, modified to show the components used in modeling the Maulap, Almagosa, and Imong River watersheds, is shown in figure 8. The watersheds are treated as an interconnected series of reservoirs whose collective output produces the total system response. Gross precipitation is reduced by interception to become net precipitation. Daily infiltration, which varies as a function of soil characteristics, antecedent soil-moisture conditions, and precipitation volume, is computed as net precipitation minus surface runoff. For daily streamflow computations, surface runoff is computed using a contributing-area approach (Dickinson and Whiteley, 1970; Hewlett and Nutter, 1970). The central precept of this concept as applied to forested land is that rainfall generally infiltrates undisturbed forest soils and migrates downslope, resulting in lateral expansion of saturated zones along stream channels (Troendle, 1985). Surface runoff is then generated from rainfall falling on the saturated areas.

The soil-zone reservoir is treated as a two-layered system, the total depth of which is defined by the average rooting depth of the predominant vegetation. Water storage in the soil zone is increased by infiltration of rainfall. Evapotranspiration losses deplete the upper, or recharge zone, which is user-defined as to depth and water-storage characteristics. Moisture in the lower zone can be depleted only through transpiration.

Infiltration in excess of field capacity in the soil-zone reservoir is first used to satisfy recharge to the ground-water reservoir. The ground-water reservoir is a linear system and is the source of base flow. Seepage to the ground-water reservoir is assumed to have a maximum daily limit and occurs only on days when field capacity is exceeded in the soil-zone reservoir. Excess infiltration, available after the upper daily limit is satisfied, is routed to the subsurface reservoir.

The subsurface reservoir routes soil-water excess to the ground-water reservoir and to the stream channel. Seepage to the ground-water reservoir is computed daily as a function of a recharge-rate coefficient and the volume of water stored in the subsurface reservoir.

INPUT-DATA REQUIREMENTS

For simulation of daily mean flows in an area such as the Fena Valley watershed, where all precipitation occurs as rain, input data required by PRMS include daily rainfall and daily pan evaporation. Daily pan-evaporation data were obtained from the National Weather Service climate station at Agana (fig. 1), about 8 mi north of the Maulap River watershed. Daily rainfall on each watershed was estimated by averaging daily rainfall observations at Fena Dam, Windward Hills, and Umatac Fire Station (fig. 1). The weighing-bucket rain gage at Fena Dam was installed in January 1980 by the National Weather Service and is located near the dam spillway at an altitude of about 60 ft. The rain gages at Windward Hills and Umatac Fire Station are maintained by the USGS and provide a continuous graphical record of rainfall at the two sites. The Windward Hills rain gage was installed in February 1974 and is located about 2.5 mi northeast of the dam

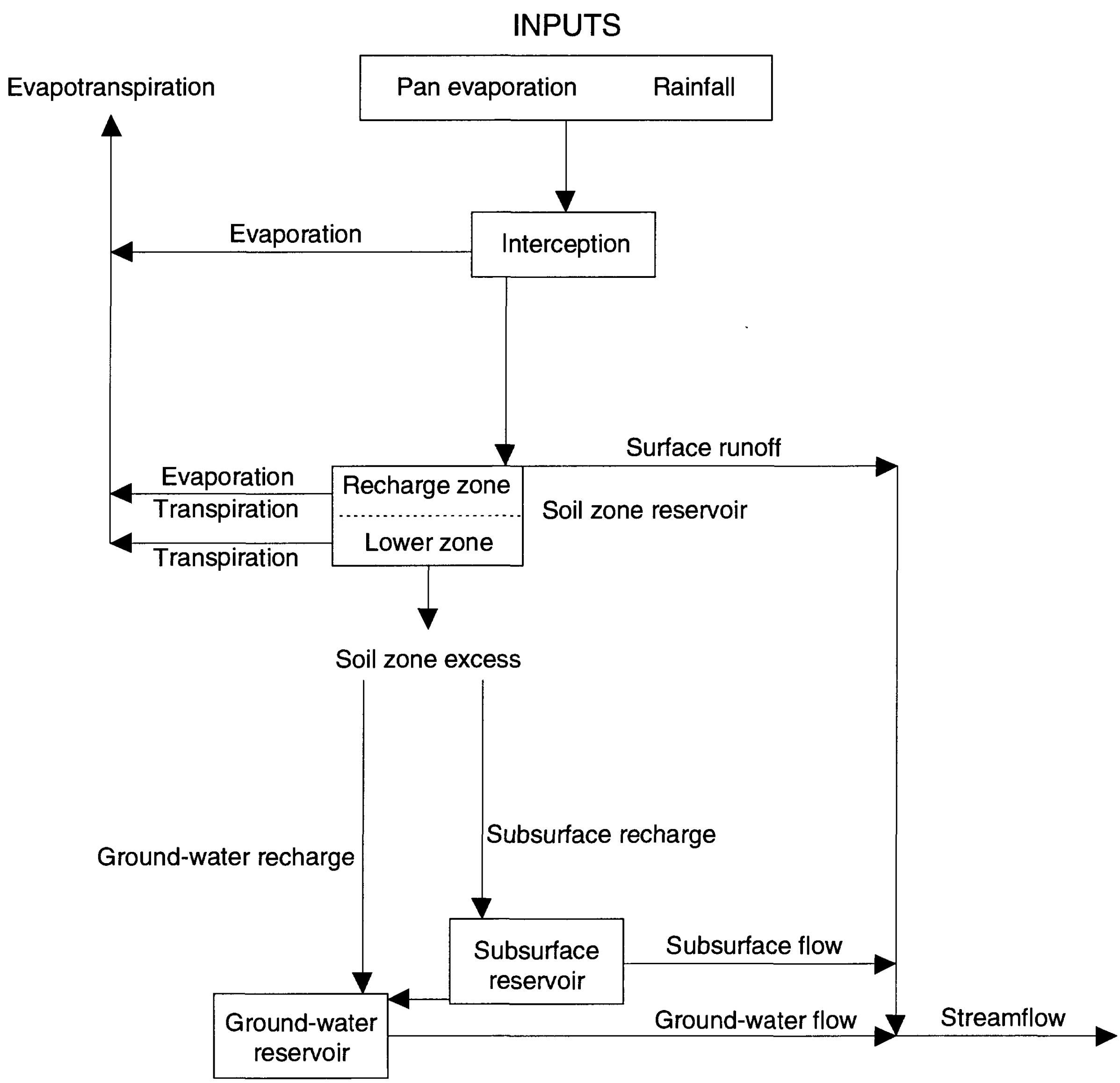

Figure 8. Diagram of the conceptual hydrologic system used in Precipitation-Runoff Modeling System to simulate runoff (modified from Leavesley and others, 1983).

spillway at an altitude of 340 ft. The rain gage at Umatac Fire Station was installed in December 1978 and is located about 1.75 mi southwest of the Imong River watershed at an altitude of 15 ft.

Although the Fena Dam rain gage is closest to the study area, fluctuations in measured streamflow were not always explained by rainfall at Fena Dam. Because of inconsistencies in the rainfall-runoff relation, the timing of rainfall collected during 1981–87 at surrounding rain gages was analyzed in relation to the timing of fluctuations in measured runoff. Results indicated that the timing of rainfall at Fena Dam, Windward Hills, and Umatac Fire Station correlated best with the timing of fluctuations in measured runoff. Although reasonably correlated with respect to the timing of the rainfall, rainfall volumes at the three sites could be extremely variable, particularly during storms. Wet season rainfall at the three sites varied by as much as 4.6 in., and differences of as much as 3 in. were not uncommon. On December 27, 1986, the difference in daily rainfall at Umatac Fire Station and Windward Hills was more than 8 in. (fig. 9). Differences in daily rainfall at the three sites were not explained by altitude differences. At an altitude of 340 ft, the Windward Hills rain gage was the highest rain gage in southern Guam that had daily data for a period concurrent with Fena Dam rain gage. Orographic effects were not reflected in rainfall collected at Windward Hills, probably because the altitude at the rain gage (340 ft) is not high enough.

Because no correlation to either watershed topography or orientation was exhibited, data from the three gages were averaged to estimate rainfall on the study watershed. Although averaging tends to dampen rainfall extremes, particularly when the daily variability in rainfall is large, the average values are considered the best available estimates of daily rainfall in the study area.

Physiographic data were obtained from 7 1/2-minute USGS topographic maps (1968, photo-revised 1975). Soils data were compiled from detailed soil unit maps (Soil Conservation Service, 1988). Soil textures, depths, and available moisture capacities were determined from soil property tables (Soil Conservation Service, 1988). Results of additional soil sampling and analysis, obtained during 1991, were used to further define the hydrologic properties of watershed soils (Chris Smith, [U.S.] Forest Service, oral commun., 1991). Geologic information was obtained from a map produced by Tracey and others (1964) at a scale of 1:50,000. Information on the type, distribution, and cover density of the predominant vegetation was obtained from a vegetation survey of the Fena Reservoir watershed done by the [U.S.] Forest Service (Roger Skolmen, written commun., 1976), 7 1/2-minute USGS topographic maps, aerial photographs, and field observations.

MODEL CALIBRATION AND VERIFICATION

Calibration involves fitting the simulated flow hydrograph to the observed flow hydrograph. During this process, sensitive parameters and coefficients requiring estimation are adjusted from their initial values within a reasonable range of values. The procedure involves making a series of iterative model runs during which parameters and coefficients undergo slight perturbations until the best fit between observed and simulated values is achieved.

Daily streamflow data were used to calibrate the models. Complete records of the daily streamflow values used in this study are available in the annual USGS Water Resources Data publications for Hawaii and the Pacific (Chinn and others, 1983–1988; U.S. Geological Survey, 1981–82). Streamflow-gaging station 16848500 on the Maulap River is located 100 ft upstream of Fena Reservoir at lat 13°21'14"N., long 144°41'44"E. Streamflow-gaging station 16848100 on the Almagosa River is located 400 ft upstream from the reservoir at lat 13°20'43"N., long 144°41'36"E. Both gaging stations were established in 1972. As much as 3.9 ft^3/s of runoff is diverted from the watershed at Almagosa Springs. Streamflow-gaging station 16847000 on the Imong River was established in 1960 and is located 500 ft upstream of the reservoir at lat 13°20'17" N., long 144°41'55"E.

Selection of the time period for which to calibrate the models was based on several factors. Time periods with large gaps in the input data sets were avoided to reduce the necessity of having to either re-initialize the model or rely on synthetic input data. A wide range in observed daily runoff volumes was also desired. Calibration over a range of climatic and hydrologic conditions provides confidence in prediction at more levels within the flow distribution.

On the basis of these criteria, 4 years of existing streamflow data, measured from February 1983 to February 1987, were used to calibrate the Imong and Maulap watershed models. During this time, several periods of extreme climatologic conditions occurred. Beginning in late 1982, until mid-1983, prolonged dry conditions resulted in a minimum extreme for the period of record at the Maulap River station. By June

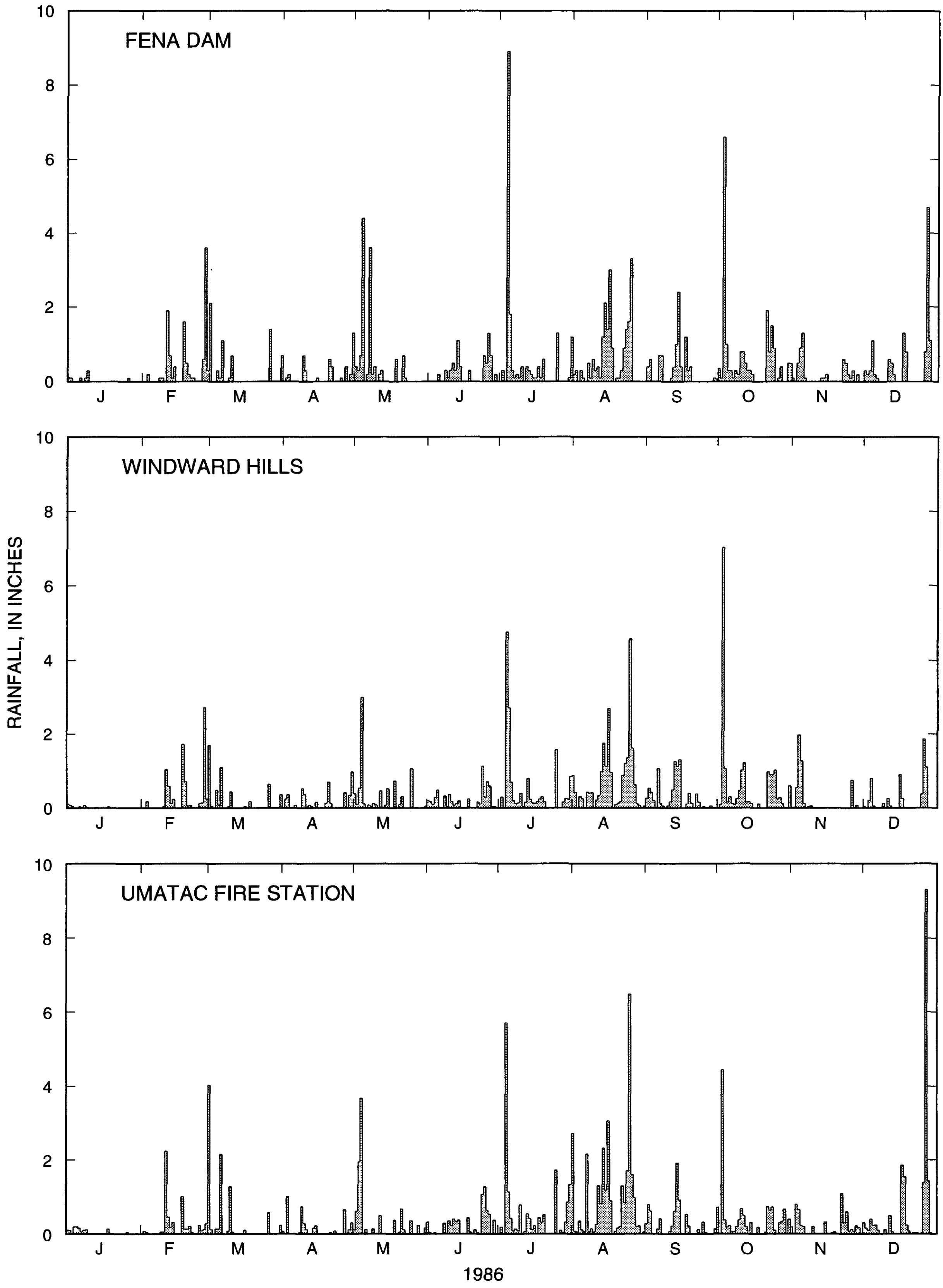

Figure 9. Daily rainfall at rain gages at Fena Dam, Windward Hills, and Umatac Fire Station, 1986.

30, 1983, daily mean streamflow in the Maulap River had dropped to 0.31 ft^3/s, the lowest recorded minimum flow since establishment of the gaging station in January 1972. New record minimum flows were not set at the Imong and Almagosa gaging stations. Wetter than normal conditions occurred in 1986 and during the first few months in 1987. The largest daily rainfall amount for the calibration period occurred on December 27, 1986 when 9.3 in. of rain was recorded at the Umatac Fire Station rain gage; mean runoff from the Maulap River for that day was estimated at 103 ft^3/s. The seasonal variation in flow and the cycles of wet and dry periods are illustrated by the monthly mean runoff measured at the Maulap River gaging station during 1980–87 (fig. 10).

Verification consisted of applying the calibrated models to a period outside the calibration period and evaluating model performance. Fourteen months of existing data, measured from November 1980 through December 1981, were reserved for verification purposes. Hydrologic conditions were wetter than normal during most of this period and during most of the preceding year.

CALIBRATION PROCEDURE

Spatial variations in the conditions that determine the hydrologic response of an area were analyzed in order to partition each of the watersheds into a number of smaller hydrologic response units. The major criteria used in the delineation of hydrologic-response units were differences in geology, soils, and land cover. The watersheds were also partitioned so that HRUs in one watershed corresponded to HRUs in the other watersheds, allowing calibrated parameters and coefficients to be transferred. On the basis of this analysis, the Maulap River watershed was partitioned into ten HRUs; the Almagosa River watershed into nine; and the Imong River watershed into seven HRUs (fig. 11). Many of the parameters used to describe the physical characteristics of each HRU represent measurable watershed characteristics. These values were defined by existing data extracted from topographic, soil, land use, and geologic maps, as well as from published streamflow records, climatological reports, soil surveys, and previous investigations. Heterogeneity within individual HRUs was resolved by computing areally weighted averages. Physical characteristics of the HRUs for each modeled area are listed in table 1.

Initial values for parameters and coefficients not defined by existing data were determined using techniques outlined in the PRMS user's manual (Leavesley and others, 1983), and from field observations, previous investigations, and published hydrologic and climatologic records. Parameters and coefficients which required estimation included those used to determine subsurface and ground-water reservoir recharge and outflow rates, the expansion of contributing areas for surface runoff, vegetal interception, and correction factors for model input data. Sensitivity testing indicated that the coefficient used to compute the rate of ground-water outflow was the most sensitive during the dry season.

Because of the homogeneity in the underlying geology, model calibration was first done for the Imong River watershed. One ground-water reservoir and one subsurface reservoir were used to describe the ground-water system in the watershed. Observed wet season recession curves and measured base flow were used to compute the coefficient which controls the rate of outflow from the ground-water reservoir. The slope of the recession curve following individual storm days was used to adjust the coefficients which compute the rate of outflow from the subsurface reservoir and seepage from the subsurface reservoir to the ground-water reservoir.

Daily pan-evaporation data were adjusted downward by about 30 percent until simulated monthly evapotranspiration losses fell into a reasonable range (2 to 4 in.). Observed annual runoff volumes were compared with simulated runoff volumes to estimate correction factors for rainfall data. Consistent underpredictions of annual runoff volumes indicated that more moisture input to the system was required. Rainfall data were corrected for probable deficiencies in rain-gage catch. Topographic information and the timing and magnitude of observed daily streamflow were used to adjust the parameters controlling the expansion of contributing areas for surface runoff. Streamflow response to rainfall at the beginning of a period of rainfall was used to adjust vegetal interception storage volumes. Initial water storage in the soil, subsurface, and ground-water reservoirs was determined from observed streamflow data and from preliminary model runs. Values generated by the model following several iterative cycles were used to estimate initial storage volumes.

Final values for the coefficients describing the characteristics of flow through the volcanic rock in the Imong watershed were transferred to similar HRUs in the Maulap and Almagosa River watersheds. Historic records of daily streamflow measured at Almagosa

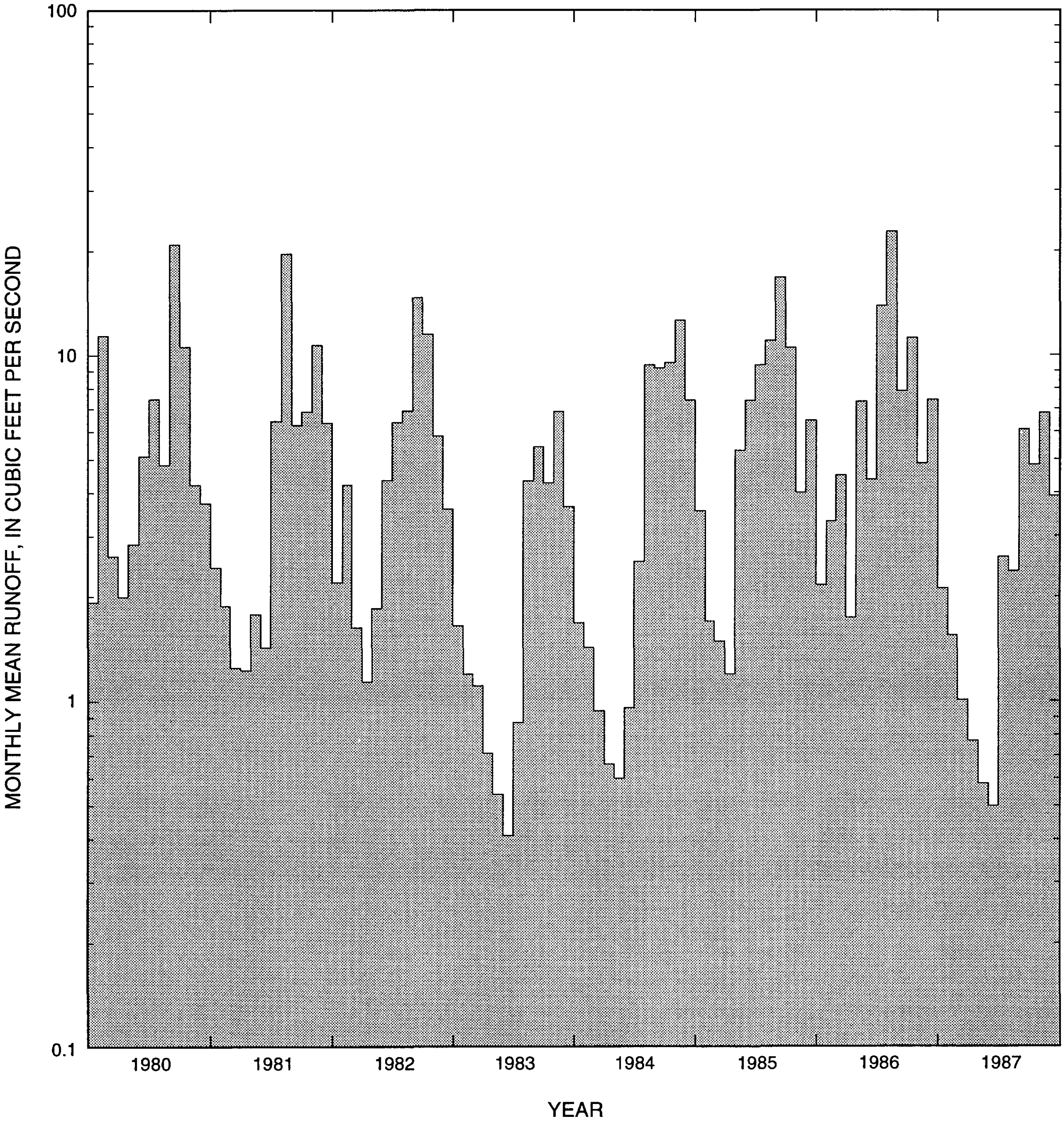

Figure 10. Seasonal variation in monthly mean runoff at Maulap River, 1980-87.

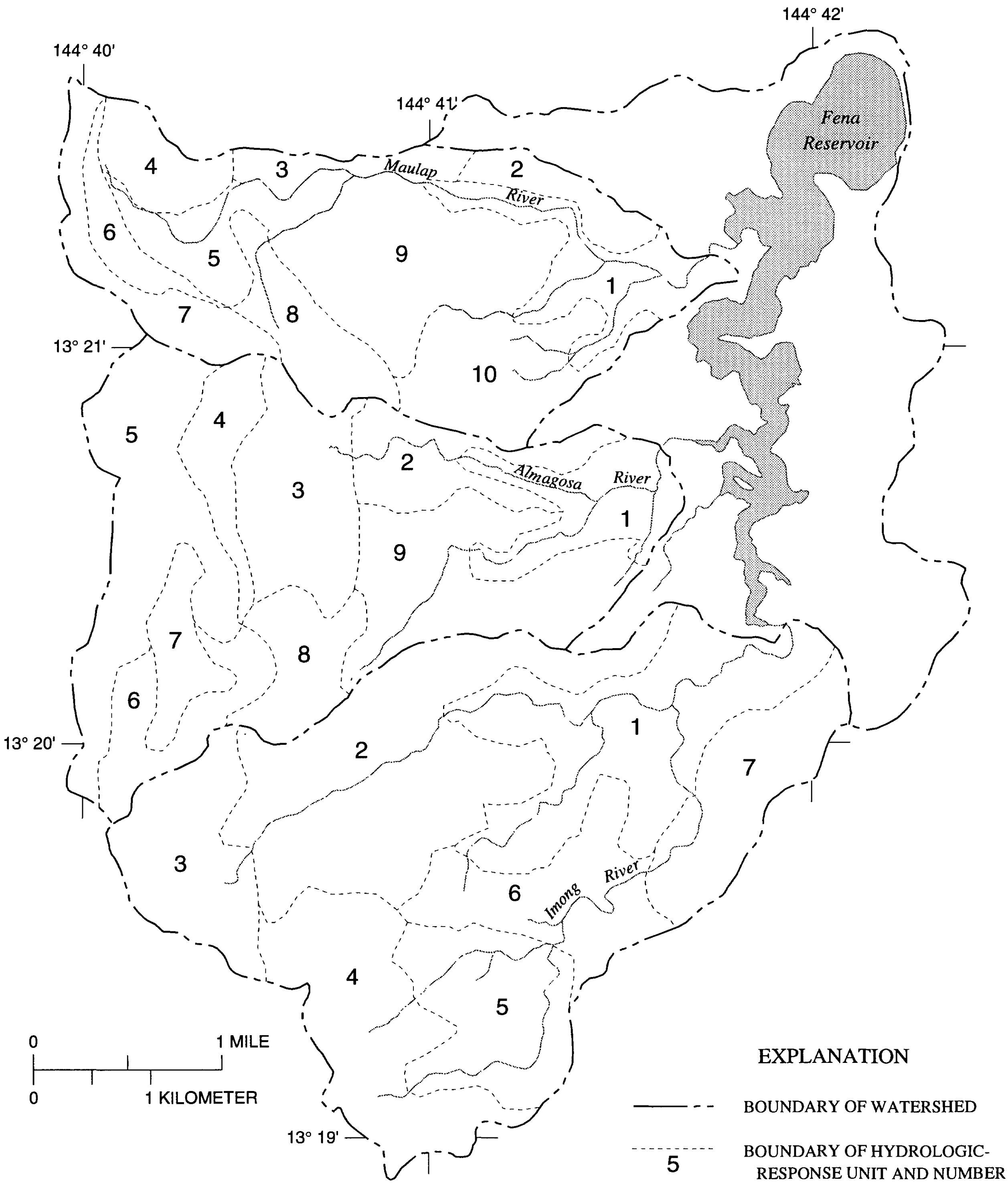

Figure 11. Hydrologic-response units in the Fena Valley watershed.

Table 1. Selected physical characteristics used for delineation of hydrologic-response units

[station is streamflow-gaging station]

Hydrologic response unit (fig. 11)	Area (acres)	Maximum soil water-holding capacity (inches)	Average slope	Vegetation cover density
		Maulap River station 16848500		
1	93	5.95	0.13	0.78
2	39	5.95	.25	.65
3	34	5.95	.23	.78
4	49	3.90	.13	.55
5	69	5.95	.13	.78
6	31	3.90	.24	.65
7	67	.44	.25	.78
8	70	.44	.13	.78
9	173	5.95	.20	.78
10	113	5.95	.14	.78
		Almagosa River station 16848100		
1	89	5.95	0.17	0.78
2	79	5.95	.21	.78
3	123	.44	.16	.78
4	53	.44	.29	.78
5	183	.44	.23	.78
6	71	3.90	.19	.55
7	44	5.40	.12	.65
8	66	5.95	.17	.70
9	166	5.95	.23	.78
		Imong River station 16847000		
1	239	5.95	0.23	0.78
2	316	5.95	.34	.78
3	121	3.90	.26	.55
4	180	3.90	.20	.55
5	136	5.95	.29	.78
6	125	3.90	.21	.55
7	121	5.95	.24	.78

Springs during 1952–58 (Carson and Leak, 1959) indicated that there are considerable differences in the hydrologic response of areas underlain by Alifan Limestone and those underlain by the Umatac Formation. Therefore, two ground-water reservoirs and two subsurface reservoirs were used to describe the ground-water system in the Maulap and Almagosa River watersheds. Streamflow records for Almagosa Springs were used to determine reservoir recharge and outflow rates in areas underlain by limestone. Calibration of the Maulap watershed model proceeded in the same manner as that described for the Imong watershed model.

The runoff records for the Almagosa River do not include daily diversions of as much as 3.9 ft^3/s at Almagosa Springs; therefore, the hydrologic response of the limestone environment in the headwaters of the watershed is not accurately reflected in the measured streamflow record. Because of the lack of reliable observed data for the Almagosa River watershed, calibration of the model was not possible. With respect to regional conditions determining streamflow characteristics, such as climate, physiography, land use, and subsoil material, a high degree of similarity exists between the Almagosa River watershed and the two adjacent watersheds. Therefore, the Almagosa watershed model was constructed by direct transfer of parameters and coefficients identified during calibration of the Imong and Maulap watershed models. No adjustments were made to transferred coefficients. The flow coefficients of the subsurface and ground-water reservoirs in each watershed are summarized in table 2. Definitions and values for all the parameters and coefficients used for daily runoff computations are given in supplemental data tables A through D (at end of report).

RESULTS OF MODEL CALIBRATION AND VERIFICATION

Graphs of rainfall, observed runoff, and runoff simulated by PRMS at the three streamflow-gaging stations for selected years in the calibration and verification period are shown in figures 12 through 17. Simulated and observed hydrographs in figures 12 through 17 can be examined in relation to the variability in daily rainfall at the three rain gages (shown in fig. 9) and in relation to estimated daily rainfall on each study watershed. The data were plotted using a logarithmic scale to emphasize variations between observed and simulated runoff during periods of low flow, when the need for runoff information is greatest.

Table 2. Coefficients used to define the flow characteristics of subsurface and ground-water reservoirs

[station is streamflow-gaging station]

RCB is ground-water-flow routing coefficient
RCF is subsurface-flow routing coefficient
RCP is subsurface-flow routing coefficient
RSEP is the coefficient used in computing the seepage rate from the subsurface reservoir to the ground-water reservoir
RESMX is the coefficient for computing seepage from the subsurface reservoir to its designated ground-water reservoir, assigned a constant value of 1.00 for each watershed
REXP is the exponent for computing seepage from subsurface reservoir to its designated ground-water reservoir, assigned a constant value of 1.00 for each watershed

Reservoir	Coefficient for routing ground water to channel[1]	Coefficients for routing subsurface flow to channel[2]		Coefficients for routing subsurface flow to the ground-water reservoir[3]		
	RCB	RCF	RCP	RSEP	RESMX	REXP
		Maulap River station 16848500				
Volcanic	.0052	.0034	.0090	.008	1.00	1.00
Limestone	.7800	.0040	.0058	.780	1.00	1.00
		Almagosa River station 16848100				
Volcanic	.0052	.0034	.0090	.008	1.00	1.00
Limestone	.7800	.0040	.0058	.780	1.00	1.00
		Imong River station 16847000				
Volcanic	.0052	.0034	.0090	.008	1.00	1.00

[1]Coefficient used in the equation:

$$BAS = RCB \times GW$$

where BAS is the rate of outflow from the ground-water reservoir and
GW is the storage volume in the ground-water reservoir

[2]Coefficients used in the equation:

$$\frac{d(RES)}{dt} = INFLOW - (RCF \times RES) - (RCP \times RES^2)$$

where RES is the storage volume in the subsurface reservoir and
INFLOW is the rate of inflow to the subsurface reservoir

[3]Coefficients used in the equation:

$$GAD = RSEP \times \left(\frac{RES}{RESMX}\right)^{REXP}$$

where GAD is water moved from a subsurface reservoir to a ground-water reservoir and
RES is the current storage in the subsurface reservoir

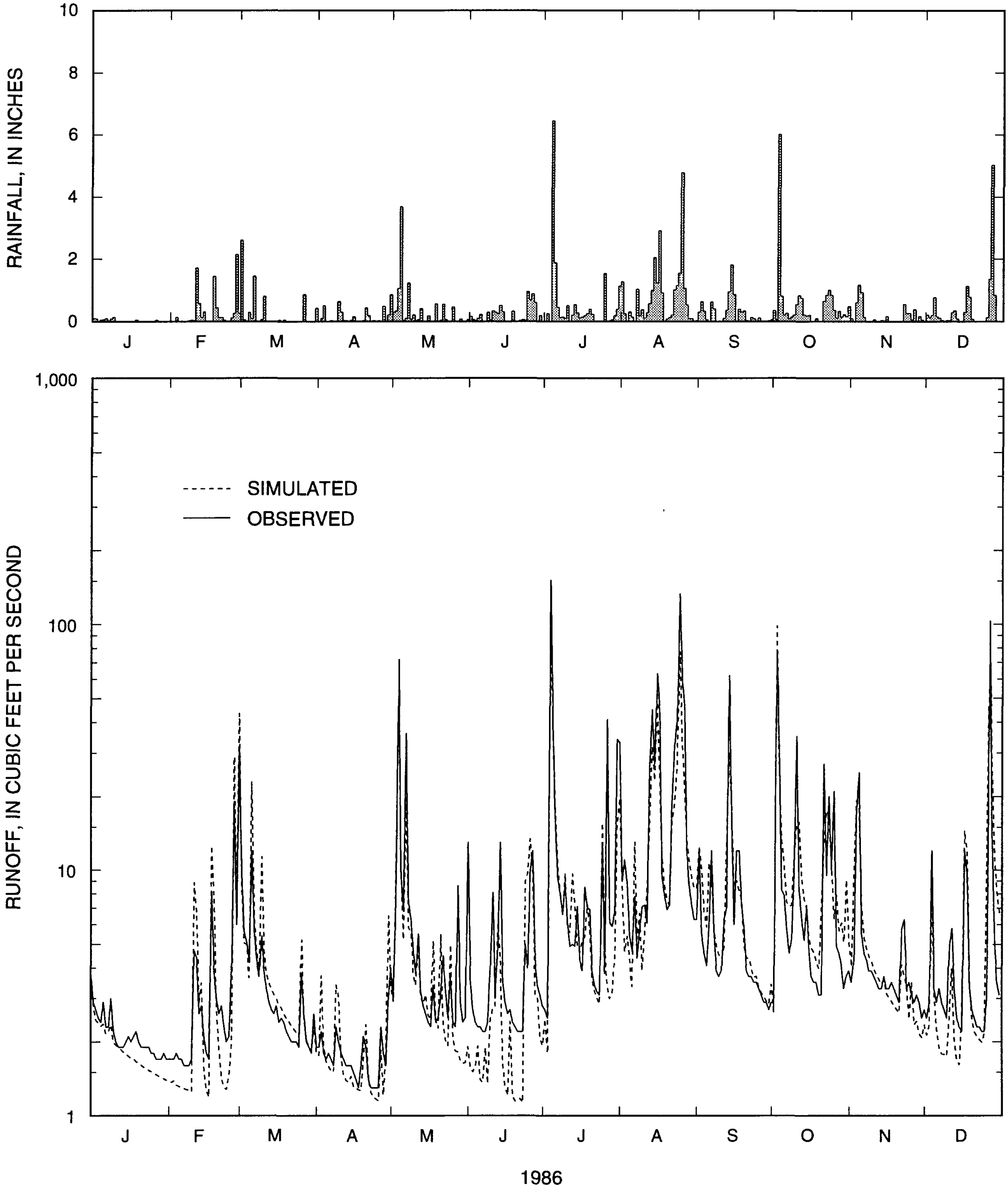

Figure 12. Rainfall, simulated runoff, and observed runoff at Maulap River, 1986.

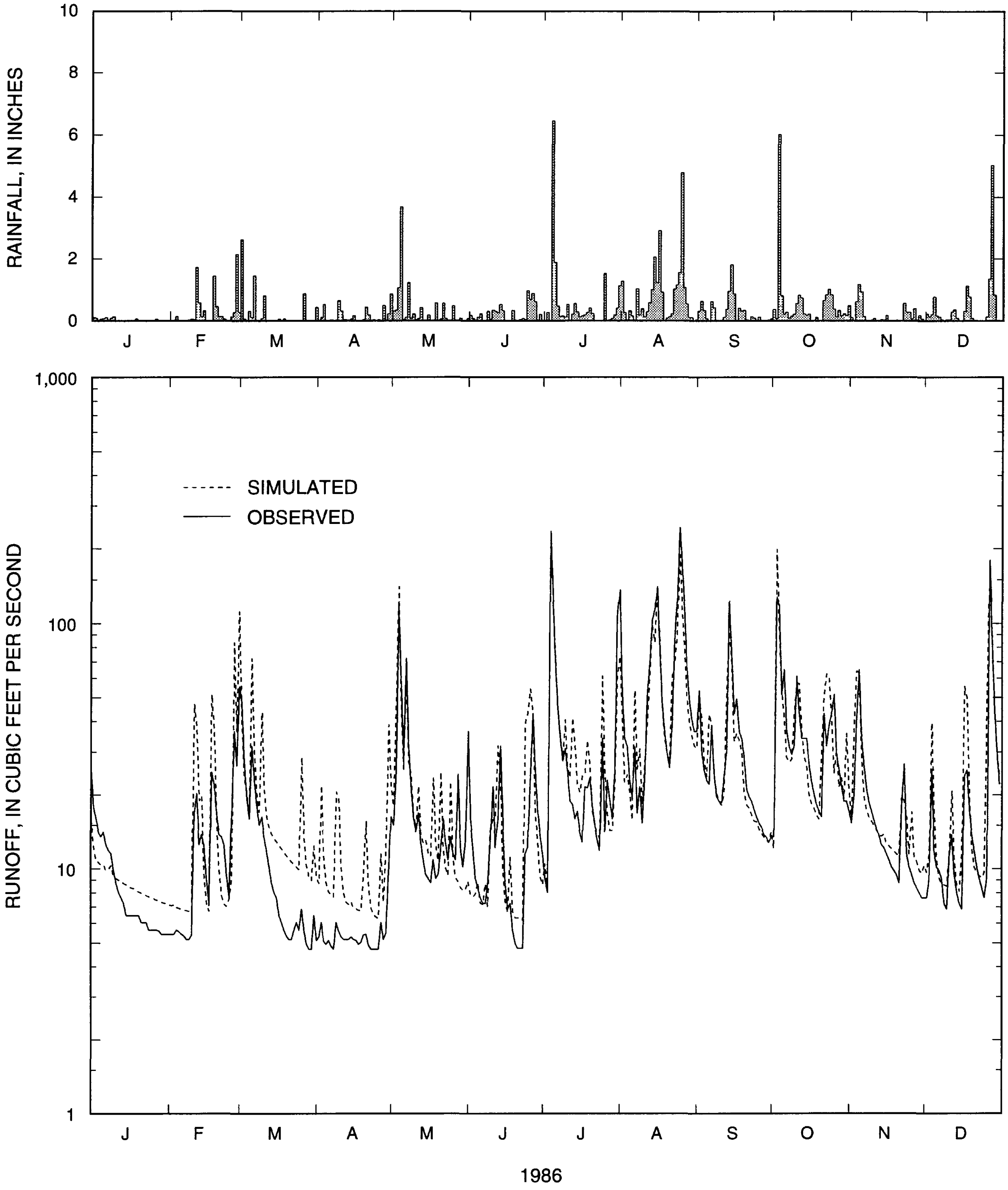

Figure 13. Rainfall, simulated runoff, and observed runoff at Almagosa River, 1986.

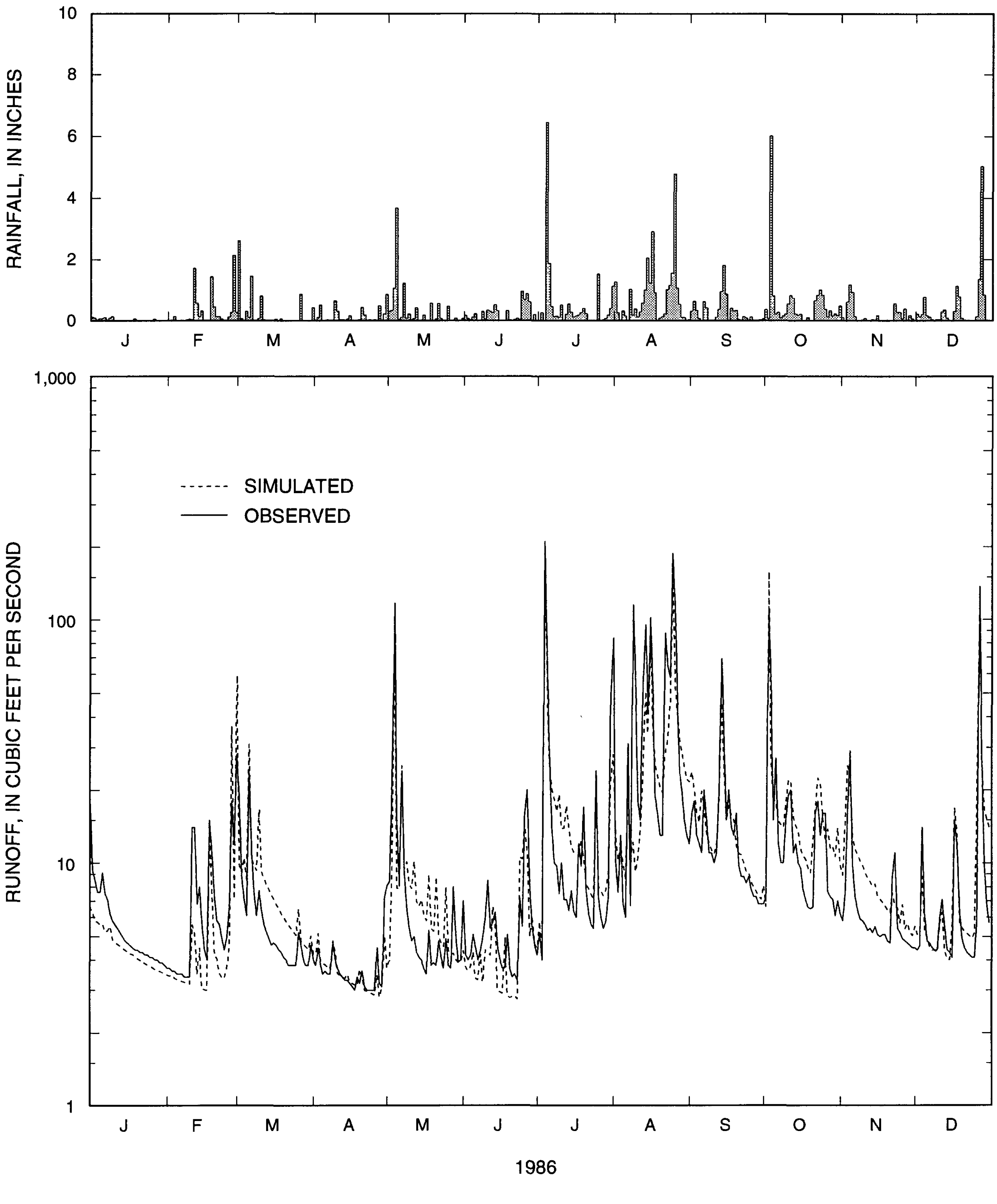

Figure 14. Rainfall, simulated runoff, and observed runoff at Imong River, 1986.

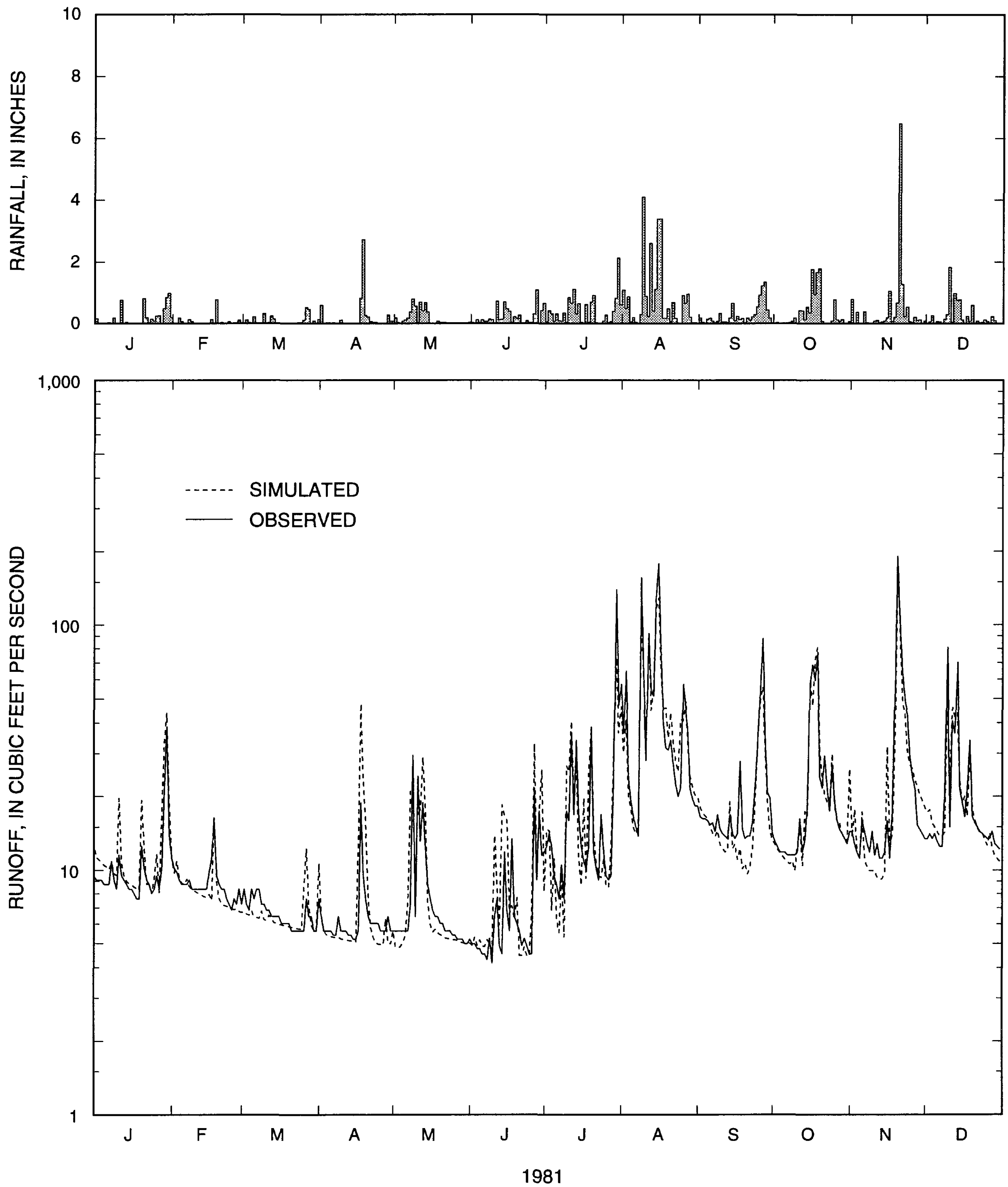

Figure 15. Rainfall, simulated runoff, and observed runoff at Maulap River, 1981.

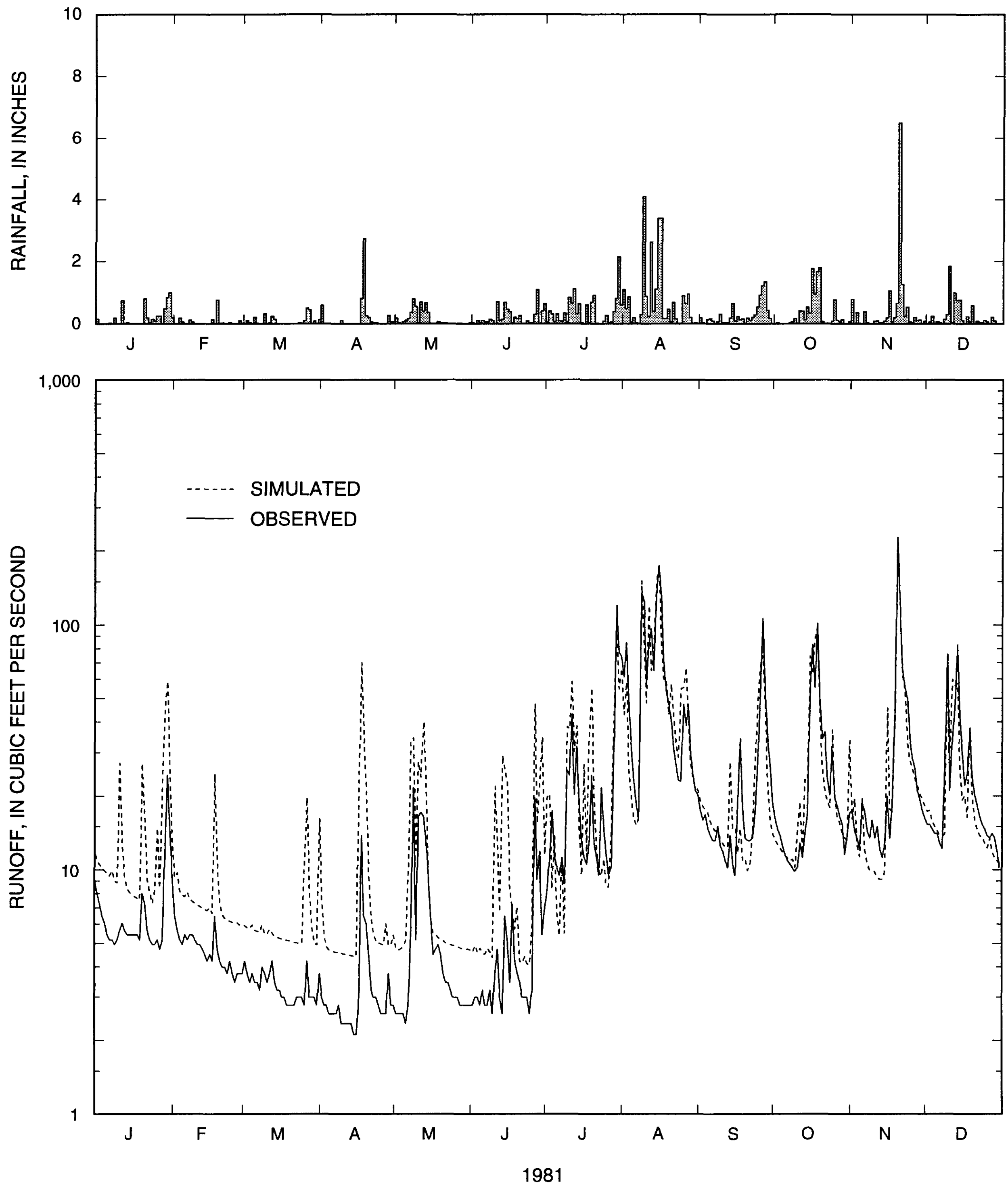

Figure 16. Rainfall, simulated runoff, and observed runoff at Almagosa River, 1981.

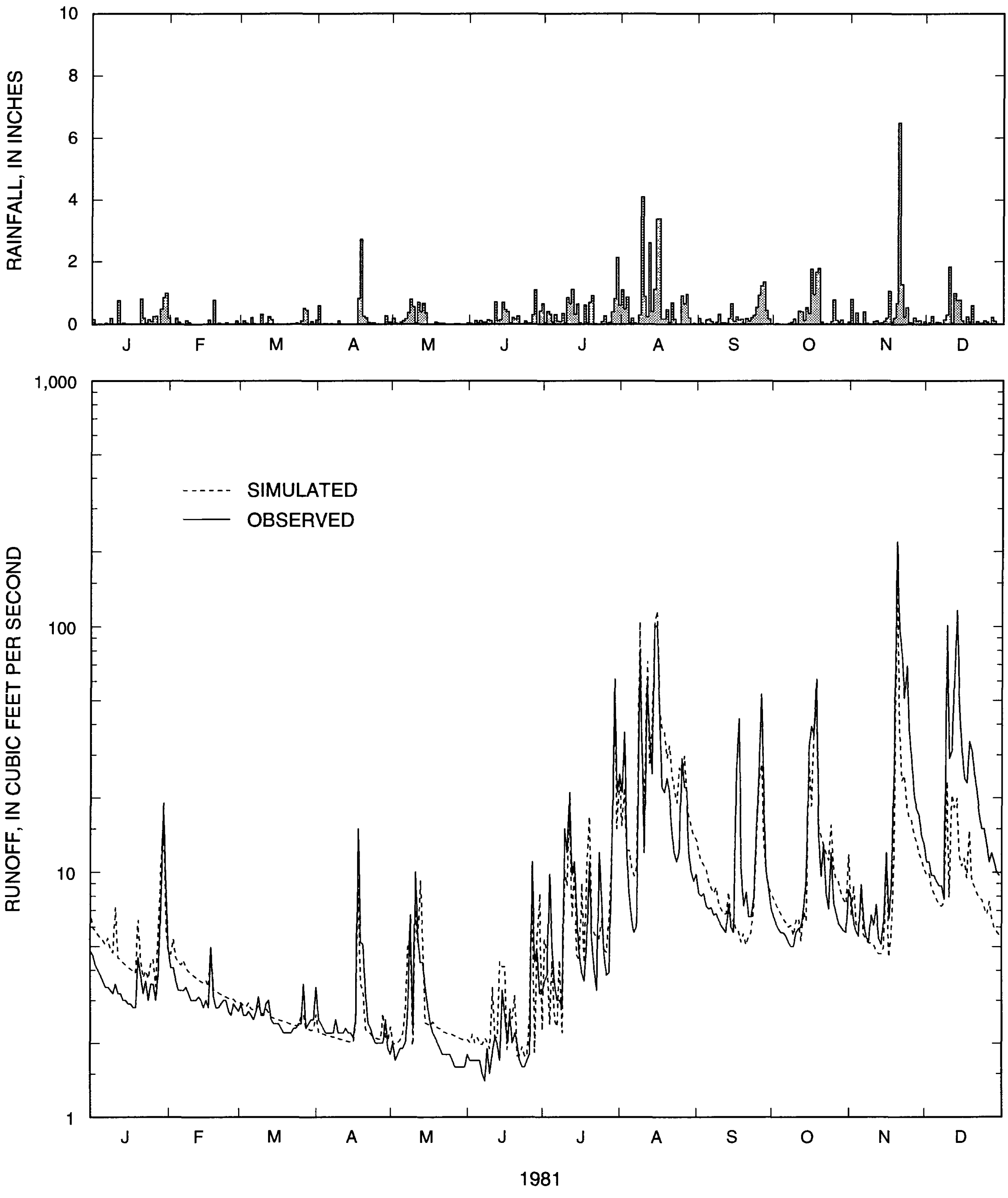

Figure 17. Rainfall, simulated runoff, and observed runoff at Imong River, 1981.

Observed and simulated hydrographs for the Almagosa River were included to show the results of transferring calibrated parameters and coefficients. As indicated in the hydrographs, errors in simulated runoff are most obvious during the dry season. These results were consistent for the period of simulated record and are probably related to diversions at Almagosa Springs. Because the measured record could not be corrected for spring diversions, the following discussion will focus primarily on results of modeling in the Maulap and Imong River watersheds.

Selected statistics that describe model accuracy for the calibration and verification periods are summarized in table 3. The coefficient of determination, which measures the fraction of the total runoff variation explained by using the model, was 0.77 for the Maulap River watershed and 0.74 for the Imong River when computed for daily runoff during the calibration period. For the verification period, this statistic was similar or improved at the two stations. The statistic can be computed for both daily and monthly mean runoff. The daily variability in the rainfall data is smoothed over by using the larger time-step, resulting in a better monthly statistic for the period.

Mean errors, expressed as a percentage of mean observed runoff, indicated that runoff was underpredicted at both sites for the two periods of simulated record. The mean error, which increased at both sites during the verification period, was greatest at the Imong River (14.3 percent). A summary of observed and simulated runoff volumes for selected years in the calibration and verification period is given in table 4, which shows underpredictions of as much as 16.33 in. (–18.35 percent) on an annual basis. Although rainfall data were corrected as much as possible without compromising model accuracy during the dry season, the water balance indicates inadequate estimates of rainfall. Inconsistent results in 1984 at both Maulap and Imong Rivers may be related to extreme dry conditions in 1983.

The summary of observed and simulated mean monthly runoff at the two stations in table 5 indicates that, in general, large underpredictions occurred during the wetter months (July through November). The average of the simulated mean monthly runoff for the wet season at both stations is less than observed values for both periods. Underpredictions during the wet season are most likely related to rainfall error. The spatial variability of rainfall is generally greater during larger storms, and averaging rainfall observations tends to dampen extremes. The uncertainty of orographic

Table 3. Selected statistics describing model accuracy

[station is streamflow-gaging station; mean errors are expressed as a percentage of mean observed runoff]

	Daily coefficient of determin-ation	Monthly coefficient of determin-ation	Daily runoff: Mean error (percent)	Daily runoff: Mean absolute error (percent)
Maulap River station 16848500				
Calibration	0.77	0.91	0.4	35.5
Verification	.88	.98	5.2	26.4
Almagosa River station 16848100				
Calibration	.69	.85	–21.7	53.0
Verification	.83	.97	–12.1	43.7
Imong River station 16847000				
Calibration	.74	.88	2.4	33.8
Verification	.70	.83	14.3	35.8

Table 4. Summary of observed and simulated annual runoff and associated error, 1981 and 1984-86

[station is streamflow-gaging station]

Year	Observed runoff (inches)	Simulated runoff (inches)	Difference between simulated and observed (percent)
Maulap River station 16848500			
1981	65.48	61.31	–6.37
1984	55.87	62.70	12.22
1985	77.49	70.53	–8.98
1986	90.43	79.43	–12.16
Almagosa River station 16848100			
1981	61.24	68.46	11.79
1984	50.92	69.94	37.35
1985	74.60	77.65	4.09
1986	84.22	88.54	5.13
Imong River station 16847000			
1981	76.27	63.80	–16.34
1984	60.70	65.74	8.30
1985	89.00	72.67	–18.35
1986	89.18	83.27	–6.63

Table 5. Summary of observed and simulated mean monthly runoff and associated error for Maulap and Imong watersheds during calibration and verification

[station is streamflow-gaging station; ft^3/s, cubic foot per second]

Month	Calibration Mean monthly runoff Observed (ft^3/s)	Calibration Mean monthly runoff Simulated (ft^3/s)	Calibration Error (percent)	Verification Mean monthly runoff Observed (ft^3/s)	Verification Mean monthly runoff Simulated (ft^3/s)	Verification Error (percent)
Maulap River station 16848500						
January	2.38	2.54	7	2.43	3.17	30
February	1.84	1.93	5	1.88	1.74	–7
March	2.01	2.28	13	1.26	1.21	–4
April	1.08	1.15	6	1.23	1.90	54
May	3.45	2.74	–21	1.78	1.95	10
June	3.28	3.95	20	1.43	2.09	46
July	6.67	5.88	–12	6.46	5.25	–19
August	11.88	11.72	–1	19.75	17.36	–12
September	9.82	9.88	1	6.27	4.97	–21
October	8.89	9.07	2	6.87	6.83	–1
November	7.08	7.22	2	7.48	6.97	–7
December	6.23	6.05	–3	5.05	5.08	1
Imong River station 16847000						
January	5.20	5.26	1	4.27	5.46	28
February	3.94	3.68	–7	3.23	3.77	17
March	3.91	4.37	12	2.55	2.58	1
April	2.47	2.47	0	2.92	2.48	–15
May	5.80	4.57	–21	2.67	2.98	12
June	5.85	6.03	3	2.42	2.92	21
July	10.11	10.13	0	9.03	8.17	–10
August	22.80	21.52	–6	27.49	32.94	20
September	17.56	17.55	0	11.92	9.43	–21
October	15.85	15.15	–4	11.68	11.72	2
November	11.91	12.43	4	18.18	12.84	–29
December	10.79	10.39	–4	16.10	8.79	–45

effects at higher altitudes would also result in inadequate estimates of rainfall in the watersheds.

Errors in simulated mean monthly runoff for the calibration period ranged from 1 percent (0.06 ft^3/s) to –21 percent (–0.71 ft^3/s) at Maulap River, and from 0 percent to –21 percent (–1.23 ft^3/s) at Imong River. Errors computed for the verification period were larger than those for the calibration period, and this is explained in part by the number of monthly observations included in each analysis. The models were calibrated on a substantially longer period of record than that for verification, and positive and negative residuals may compensate each other. Verification period errors in simulated mean monthly runoff ranged from 1 percent (0.03 ft^3/s) to 54 percent (0.67 ft^3/s) at Maulap River and from 1 percent (0.03 ft^3/s) to –45 percent (–7.31 ft^3/s) at Imong River. The large monthly error computed for April at Maulap River is discussed in the following section.

On an individual-month basis, the difference between observed and simulated monthly mean runoff for the calibration period ranged from 0 ft^3/s to –6.63 ft^3/s (–29 percent) at Maulap River and from –0.01 ft^3/s (less than –1 percent) to –15.08 ft^3/s (–34 percent) at Imong River. For the verification period, monthly mean runoff errors ranged from –0.04 ft^3/s (–1 percent) to –2.39 ft^3/s (–12 percent) at Maulap River and from 0.02 ft^3/s (less than 1 percent) to –15.10 ft^3/s (–60 percent) at Imong River. The large difference in monthly mean runoff at Imong River, which occurred in December 1981, is believed to be caused by inadequate estimates of rainfall in the watershed. During December 1981, estimated rainfall on the Imong watershed was about 7 in.; however, the observed monthly runoff for the watershed was about 15 in. This ratio between rainfall and runoff is not supported by the historic record of monthly rainfall and runoff information. Modeled response indicates that a localized storm most likely occurred in the Imong River watershed during December 1981.

SIMULATION OF DRY SEASON RUNOFF

Although the calibration period provided a fairly wide range of flows on which to test the models, extreme high flows remain untested; however, for this study, reliable simulations of dry season flows were of greater concern. Observed and simulated monthly mean runoff at Maulap and Imong Rivers are summarized in table 6 for the dry season (January through May). For the calibration period, the largest difference between observed and simulated monthly mean runoff was in May 1985 at both Maulap and Imong Rivers. Mean runoff for the month was underpredicted by –1.57 ft^3/s (–29.6 percent) at Maulap River and by –4.25 ft^3/s (–45.1 percent) at Imong River. Daily rainfall at the Windward Hills and Umatac Fire Station rain gages was extremely variable during the month (fig. 18). Under these rainfall conditions, the method for estimating rainfall tends to dampen rainfall extremes, resulting in inadequate estimates of rainfall. Rainfall records at Fena Dam were missing from May 15 through the end of the month, and because most of the runoff-producing rainfall occurred in the latter part of the month, rainfall at Fena Dam is not shown in figure 18. Observed rainfall extremes were smoothed-over by averaging, which resulted in estimates of rainfall that were probably less than actual rainfall on the watersheds.

Errors in simulated monthly mean runoff were largest in January 1987 at both the Maulap River (51.7 percent) and Imong River (55.6 percent) for the calibration period. Although rainfall at the three rain gages showed similar characteristics for the month, rainfall during the previous month did not. On December 27, 1986, more than 9 in. of rain was recorded at Umatac Fire Station, while only about 1 in. fell at Windward Hills. Estimated rainfall during December was most likely greater than what actually fell on the watersheds, resulting in a base-flow rate that was much larger than observed.

Verification of the model for simulation of dry season runoff indicated monthly errors for Maulap River that ranged from –3.51 percent (–0.04 ft^3/s) in March to 54.77 percent (0.67 ft^3/s) in April of 1981. During April 1981, the volume error (–0.65 in.) is within the variation in monthly rainfall observed at the Umatac Fire Station rain gage (4.55 in.) and the Fena Dam rain gage (5.90 in.). For the Imong River, errors in simulated monthly runoff ranged from 1.3 percent (0.03 ft^3/s) in March to 27.95 percent (1.19 ft^3/s) in January.

Total rainfall, observed runoff volumes, and simulated runoff volumes during the dry seasons (January through May) for 1981 and 1984–86 are summarized in table 7. For the four dry seasons, the largest differences between simulated and observed runoff volumes during the dry season, expressed as a percentage of observed volumes, were –19.46 percent (2.5 in.) at Maulap River, and –26.56 percent (3.9 in.) at Imong River.

Table 7. Total rainfall, observed runoff, and simulated runoff during dry seasons, 1981 and 1984-86

[Station is streamflow-gaging station]

Year	Rainfall (inches)	Observed runoff (inches)	Simulated runoff (inches)	Difference between simulated and observed (percent)
Maulap River station 16848500				
1981	19.43	8.32	9.78	17.55
1984	13.18	5.17	5.72	10.64
1985	22.46	13.00	10.47	–19.46
1986	26.69	18.63	18.76	0.70
Almagosa River station 16848100				
1981	19.38	3.67	10.00	172.48
1984	13.15	2.21	5.60	153.39
1985	22.40	9.88	11.91	20.55
1986	29.62	13.58	20.00	47.28
Imong River station 16847000				
1981	19.42	9.05	10.00	10.49
1984	13.17	7.41	7.37	–0.54
1985	22.43	14.76	10.84	–26.56
1986	29.67	19.41	19.28	–0.67

Table 6. Summary of observed and simulated monthly mean runoff and associated error for Maulap and Imong River watersheds during the dry season

[ft^3/s, cubic feet per second; %, percent]

Month	Maulap River Monthly mean runoff Observed (ft^3/s)	Simulated (ft^3/s)	Difference (ft^3/s)	Error (%)	Imong River Monthly mean runoff Observed (ft^3/s)	Simulated (ft^3/s)	Difference (ft^3/s)	Error (%)
Calibration Period								
1983								
February	1.20	1.23	0.03	2.5	3.01	3.07	0.06	2.0
March	1.11	1.25	0.15	13.5	2.93	2.78	–0.15	–5.1
April	0.71	0.72	0.01	1.4	2.2	2.23	0.03	1.4
May	0.54	0.61	0.07	13.0	1.93	1.91	–0.02	–1.0
1984								
January	1.68	2.09	0.42	25.0	3.71	4.17	0.46	12.4
February	1.43	1.53	0.1	7.0	3.24	2.95	–0.29	–9.0
March	0.95	0.94	–0.01	–1.1	2.28	2.18	–0.1	–4.4
April	0.66	0.68	0.02	3.0	1.85	1.8	–0.04	–2.2
May	0.60	0.60	0.0	0.0	1.67	1.54	–0.13	–7.8
1985								
January	3.55	2.99	–0.55	–15.5	6.69	5.19	–1.5	–22.4
February	1.7	1.33	–0.38	–22.4	3.59	3.29	–0.3	–8.4
March	1.49	1.31	–0.18	–12.1	3.37	2.71	–0.66	–19.6
April	1.2	1.32	0.12	10.0	2.18	2.26	0.08	3.7
May	5.3	3.73	–1.57	–29.6	9.42	5.17	–4.25	–45.1
1986								
January	2.16	1.89	–0.27	–12.5	5.84	4.56	–1.28	–21.9
February	3.31	3.83	0.51	15.4	6.7	5.43	–1.28	–19.1
March	4.49	5.62	1.13	25.2	7.07	9.82	2.75	38.9
April	1.74	1.87	0.13	7.5	3.63	3.59	–0.04	–1.1
May	7.34	6.01	–1.33	–18.1	10.16	9.65	–0.51	–5.0
1987								
January	2.11	3.20	1.09	51.7	4.57	7.11	2.54	55.6
February	1.55	1.72	0.17	11.0	3.17	3.65	0.48	15.1
Verification Period								
1981								
January	2.43	3.17	0.74	30.34	4.27	5.46	1.19	27.95
February	1.88	1.74	–0.14	–7.5	3.23	3.77	0.54	16.82
March	1.26	1.21	–0.04	–3.51	2.55	2.58	0.03	1.3
April	1.23	1.9	0.67	54.77	2.92	2.48	–0.43	–14.88
May	1.78	1.95	0.17	9.26	2.67	2.98	0.31	11.61

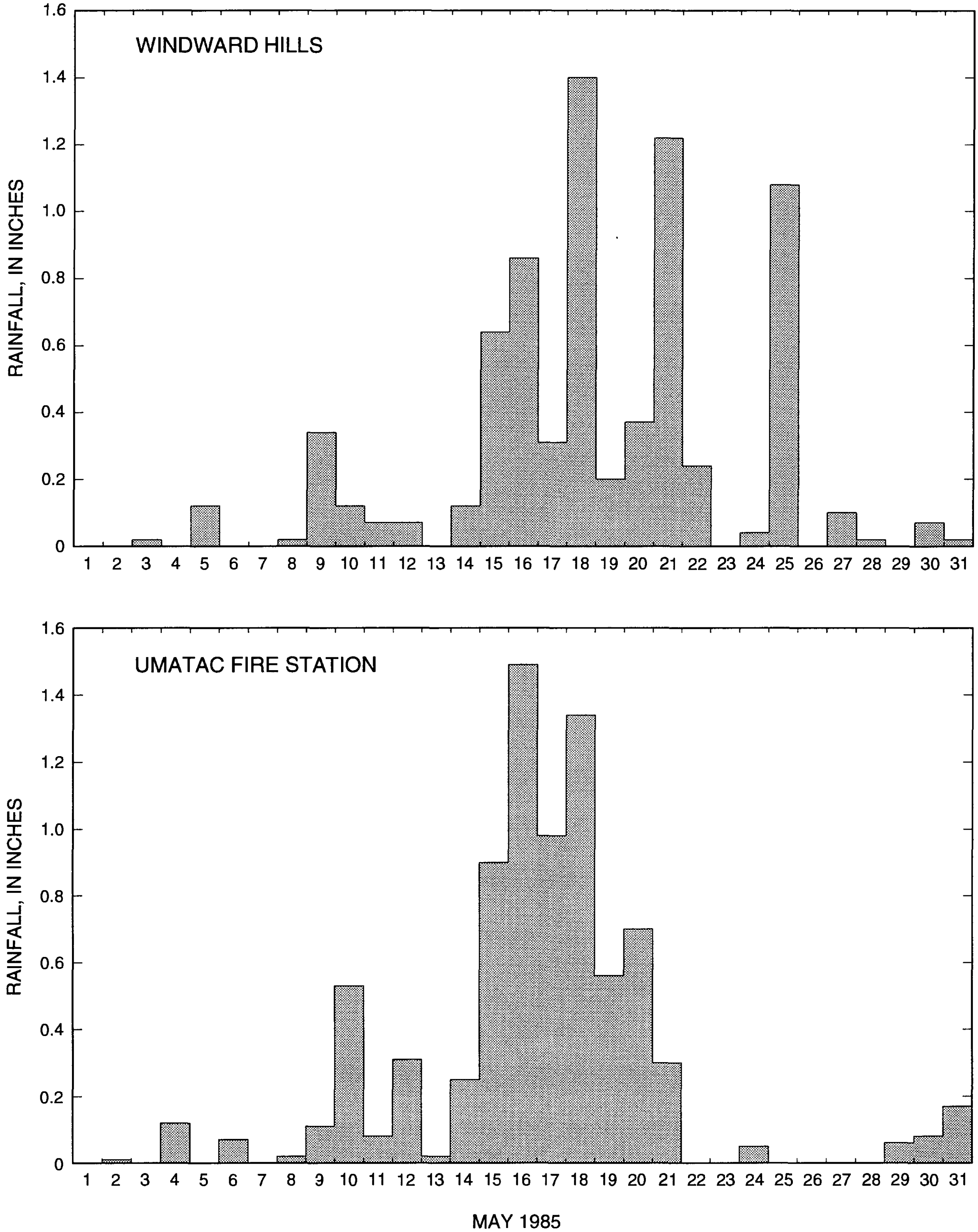

Figure 18. Daily rainfall at rain gages at Windward Hills and Umatac Fire Station, May 1985.

SUMMARY AND CONCLUSIONS

Existing data were used to calibrate and verify the Precipitation-Runoff Modeling System model (PRMS) for the Maulap and Imong River watersheds for simulating runoff during the dry season. PRMS was applied in the Almagosa River watershed by transferring parameters and coefficients calibrated streamflow data from gages on the Maulap and Imong Rivers. Because information was not available on daily withdrawals at Almagosa Springs, located in the headwaters of the Almagosa River, model performance in the Almagosa River watershed could not be evaluated.

Models calibrated for the Maulap and Imong River watersheds explained more than 70 percent of the total daily runoff variation at the two gages, based on the period of simulated record. Following calibration, errors in simulated mean monthly runoff ranged from 1 percent to –21 percent of observed monthly means at Maulap River, and from 0 to –21 percent of observed means at Imong River. In verifying the models, increased errors for most months may be explained, in part, by the lesser number of months used in computing the statistic. The largest error in simulated monthly runoff was in April 1981 (54 percent) at Maulap River and in December (–45 percent) at Imong River.

Simulated runoff was less than observed runoff for most years and for the total period. Volume errors were greatest during the wet season and are most likely the result of rainfall error. Because rainfall data were not collected in the study area, rainfall was estimated by averaging rainfall observations from three surrounding rain gages. Where the variability in daily rainfall is large, this method would tend to dampen rainfall extremes, resulting in inadequate estimates of rainfall. Analysis of the rainfall at the three sites indicated that variability is greatest during large, wet season storms. Orographic effects, which could not be estimated from the available data due to the relatively low altitude of existing rain gages, would also result in inadequate rainfall. The U.S. Geological Survey installed a rain gage in the Almagosa River watershed in June 1992 at an altitude of about 600 ft. Data collected at this gage may provide better estimates of rainfall distribution in the study watershed.

For the calibration period, simulations of monthly mean runoff during the dry season (January to May) yielded errors that ranged from 0 to greater than 50 percent (2.54 ft^3/s) of the observed runoff for the month. Errors in simulated monthly mean runoff, which were largest in January 1987 at both Maulap River (51.7 percent) and Imong River (55.6 percent), are most likely the result of rainfall errors in the previous month. One December 27, 1986 rainfall at the Umatac Fire Station and Windward Hills rain gages differed by more than 8 in. On the basis of verification of the models for the 1981 dry season, errors in simulated monthly mean runoff of as much as 54 percent may occur at Maulap River watershed. Although the error in simulated monthly mean runoff is large relative to the observed monthly mean, differences in monthly mean runoff at Maulap River were less than 0.74 ft^3/s for all months. Errors in simulated monthly mean runoff at Imong River ranged from 1.3 percent (0.03 ft^3/s) to 27.95 percent (1.19 ft^3/s) of the observed monthly mean for the 1981 dry season. On the basis of runoff simulations for the four complete dry seasons included in the total calibration and verification periods, the total volume of runoff during the 5-month dry season can be predicted to within 20 percent of actual runoff at Maulap River, and to within 27 percent at Imong River.

The results of this study can be applied to water-supply problems in Guam by providing physically based estimates of monthly runoff into the reservoir; these estimates can then be used to estimate total water availability during the dry season. Runoff response to a variety of management-specified scenarios of rainfall—which can include normal, minimum, and worst-case conditions—can be used to project reservoir recharge for the succeeding period. These estimates of recharge can be examined in relation to the effect of varying intensities of monthly reservoir production in order to identify a basis for the rational release of water. Results of modeling in the Maulap and Imong River watersheds can be used to estimate contributions from ungaged areas. In addition, the volume of water diverted at Almagosa Springs is currently being measured, which can now allow calibration of PRMS to the Almagosa River watershed. In effect, estimates of runoff for the entire Fena Reservoir watershed can soon become available for use in formulation of management during periods of extremely dry weather.

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Supplemental Data

Table A. Parameters and coefficients used for daily runoff computations

Parameter or coefficient acronym	Parameter or coefficient definition
COVDNS	summer vegetation cover density (decimal).
COVDNW	winter vegetation cover density (decimal).
DRCOR	daily precipitation correction factor, assigned a constant value of 1.15 for each watershed.
EVC	evaporation pan coefficient, assigned a constant value of 0.70 for each month and each watershed.
GSNK	coefficient used in computing the seepage rate from the ground-water reservoir to a ground-water sink, assigned a constant value of 0.0 for each watershed.
GW	initial storage in each ground-water flow routing reservoir (inches).
RCB	ground-water-flow routing coefficient.
RCF	subsurface-flow routing coefficient.
RCP	subsurface-flow routing coefficient
RECHR	current available water-holding capacity of soil recharge zone (inches).
REMX	maximum available water-holding capacity of soil recharge zone (inches).
REXP	exponent for computing seepage from subsurface reservoir to its designated ground-water reservoir, assigned a constant value of 1.00 for each watershed.
RES	initial storage in each subsurface flow routing reservoir (inches).
RESMX	coefficient for computing seepage from the subsurface reservoir to its designated ground-water reservoir, assigned a constant value of 1.00 for each watershed.
RNSTS	interception-storage capacity of major summer vegetation (inches).
RNSTW	interception-storage capacity of major winter vegetation (inches).
RSEP	coefficient used in computing the seepage rate from the subsurface reservoir to the ground-water reservoir.
SEP	maximum daily recharge from soil-moisture excess to designated ground-water reservoir (inches per day).
SC1	exponent in contributing area-moisture index relationship.
SCN	coefficient in contributing area-moisture index relationship.
SMAV	current available water-holding capacity of soil profile (inches).
SMAX	maximum available water-holding capacity of soil profile (inches).

Table B. Parameters and coefficients for daily runoff computations defined by calibration for Maulap River watershed

[See table A for parameter and coefficient definitions]

Parameter or coefficient	Hydrologic-response unit									
	1	2	3	4	5	6	7	8	9	10
Predominant cover type	Trees	Shrubs	Trees	Grass	Trees	Shrubs	Trees	Trees	Trees	Trees
COVDNS	0.78	0.65	0.78	0.55	0.78	0.65	0.78	0.78	0.78	0.78
COVDNW	.78	.65	.78	.55	.78	.65	.78	.78	.78	.78
RNSTS	.09	.06	.09	.05	.09	.06	.08	.09	.08	.09
RNSTW	.09	.06	.09	.05	.09	.06	.08	.09	.08	.09
SMAX	5.95	5.95	5.95	3.90	5.95	3.90	.44	.44	5.95	5.95
SMAV	1.50	1.50	1.50	1.00	1.50	1.00	.05	.05	1.50	1.50
REMX	1.30	1.30	1.30	1.50	1.30	1.50	.44	.44	1.30	1.30
RECHR	.30	.30	.30	.30	.30	.30	.05	.05	.30	.30
SCN	.0018	.0018	.0018	.0018	.0018	.0015	.0015	.0015	.0018	.0018
SC1	.35	.31	.34	.38	.34	.28	.28	.28	.34	.34
SEP	.08	.18	.08	.25	.08	.90	.90	.90	.08	.08
RSEP	.008	.008	.008	.008	.008	.008	.78	.78	.008	.008
RES	0	0	0	0	0	0	0	0	0	0
GW	7.0	7.0	7.0	7.0	7.0	0	0	0	7.0	7.0
RCF	.0034	.0034	.0034	.0034	.0034	.0034	.004	.004	.0034	.0034
RCP	.009	.009	.009	.009	.009	.009	.0058	.0058	.009	.009
RCB	.0052	.0052	.0052	.0052	.0052	.78	.78	.78	.0052	.0052

Table C. Parameters and coefficients for daily runoff computations defined by calibration for Imong River watershed

[See table A for parameter and coefficient definitions]

Parameter or coefficient	Hydrologic-response unit						
	1	2	3	4	5	6	7
Predominant cover type	Trees	Trees	Grass	Grass	Trees	Grass	Trees
COVDNS	0.78	0.78	0.55	0.55	0.78	0.55	0.78
COVDNW	.78	.78	.55	.55	.78	.55	.78
RNSTS	.09	.09	.05	.05	.09	.05	.09
RNSTW	.09	.09	.05	.05	.09	.05	.09
SMAX	5.95	5.95	3.90	3.90	5.95	3.90	5.95
SMAV	1.50	1.50	1.00	1.00	1.50	1.00	1.50
REMX	1.30	1.30	1.50	1.50	1.30	1.50	1.30
RECHR	.30	.30	.30	.30	.30	.30	.30
SCN	.0018	.0018	.0018	.0018	.0018	.0018	.0018
SC1	.35	.34	.38	.38	.34	.38	.34
SEP	.08	.08	.25	.25	.08	.25	.08
RSEP	.008	.008	.008	.008	.008	.008	.008
RES	0	0	0	0	0	0	0
GW	8.7	8.7	8.7	8.7	8.7	8.7	8.7
RCF	.0034	.0034	.0034	.0034	.0034	.0034	.0034
RCP	.009	.009	.009	.009	.009	.009	.009
RCB	.0052	.0052	.0052	.0052	.0052	.0052	.0052

Table D. Parameters and coefficients for daily runoff computations defined by calibration for Almagosa River watershed

[See table A for parameter and coefficient definitions]

Parameter or coefficient	Hydrologic-response unit								
	1	2	3	4	5	6	7	8	9
Predominant cover type	Trees	Trees	Trees	Trees	Trees	Grass	Shrubs	Shrubs	Trees
COVDNS	0.78	0.78	0.78	0.78	0.78	0.55	0.65	0.70	0.78
COVDNW	.78	.78	.78	.78	.78	.55	.65	.70	.78
RNSTS	.09	.09	.09	.09	.09	.05	.06	.08	.09
RNSTW	.09	.09	.09	.09	.09	.05	.06	.08	.09
SMAX	5.95	5.95	.44	.44	.44	3.90	5.40	5.95	5.95
SMAV	.80	.80	0	0	0	.30	.80	.80	.80
REMX	1.30	1.30	.44	.44	.44	1.50	1.40	1.30	1.30
RECHR	0	0	0	0	0	0	0	0	0
SCN	.0018	.0018	.0018	.0015	.0015	.0018	.0005	.0018	.0018
SC1	.35	.34	.30	.28	.28	.38	.28	.31	.34
SEP	.08	.08	.90	.90	.90	.25	.90	.18	.08
RSEP	.008	.008	.008	.78	.78	.008	.78	.008	.008
RES	0	0	0	0	0	0	0	0	0
GW	4.8	4.8	0	0	0	4.8	0	4.8	4.8
RCF	.0034	.0034	.0034	.004	.004	.0034	.004	.0034	.0034
RCP	.009	.009	.009	.0058	.0058	.009	.0058	.009	.009
RCB	.0052	.0052	.78	.78	.78	.0052	.78	.0052	.0052