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Rainfall-Runoff and Water-Balance Models for Management of the Fena Valley Reservoir, Guam

Scientific Investigations Report 2004–5287

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

Cover: Spillway house at the Fena Valley Reservoir, Guam. (Photograph taken by Chiu W. Yeung, January 27, 2002.)

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Conversion Factors

Multiply	By	To obtain
acre	4,047	square meter
acre-foot (acre-ft)	0.3259	million gallons
acre-foot (acre-ft)	1,233	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second (ft^3/s)	448.8	gallon per minute
foot (ft)	0.3048	meter
inch (in.)	25.4	millimeter
inch per inch (in/in)	25.4	millimeter per millimeter
inch per hour (in/hr)	25.4	millimeter per hour
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
mile per hour (mi/hr)	1.609	kilometer per hour
million gallons (Mgal)	3.785	cubic meter
million gallons per day (Mgal/d)	0.04381	cubic meter per second
square mile (mi^2)	2.590	square kilometer

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

$$°C=(°F-32)/1.8$$

Datums

Vertical coordinate information is referenced relative to Guam mean sea level.

Horizontal coordinate information is referenced to the Guam Datum of 1963.

Acronyms

Acronym	Meaning
DEM	Digital Elevation Model
ENSO	El Nino Southern Oscillation
GIS	Geographic Information System
HRU	Hydrologic response unit
MMS	Modular Modeling System
NAS	Naval Air Station
PET	Potential evapotranspiration
PRMS	Precipitation-Runoff Modeling System
USGS	U.S. Geological Survey

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Rainfall-Runoff and Water-Balance Models for Management of the Fena Valley Reservoir, Guam

By Chiu W. Yeung

Abstract

The U.S. Geological Survey's Precipitation-Runoff Modeling System (PRMS) and a generalized water-balance model were calibrated and verified for use in estimating future availability of water in the Fena Valley Reservoir in response to various combinations of water withdrawal rates and rainfall conditions. Application of PRMS provides a physically based method for estimating runoff from the Fena Valley Watershed during the annual dry season, which extends from January through May. Runoff estimates from the PRMS are used as input to the water-balance model to estimate change in water levels and storage in the reservoir.

A previously published model was calibrated for the Maulap and Imong River watersheds using rainfall data collected outside of the watershed. That model was applied to the Almagosa River watershed by transferring calibrated parameters and coefficients because information on daily diversions at the Almagosa Springs upstream of the gaging station was not available at the time. Runoff from the ungaged land area was not modeled. For this study, the availability of Almagosa Springs diversion data allowed the calibration of PRMS for the Almagosa River watershed. Rainfall data collected at the Almagosa rain gage since 1992 also provided better estimates of rainfall distribution in the watershed. In addition, the discontinuation of pan-evaporation data collection in 1998 required a change in the evapotranspiration estimation method used in the PRMS model. These reasons prompted the update of the PRMS for the Fena Valley Watershed.

Simulated runoff volume from the PRMS compared reasonably with measured values for gaging stations on Maulap, Almagosa, and Imong Rivers, tributaries to the Fena Valley Reservoir. On the basis of monthly runoff simulation for the dry seasons included in the entire simulation period (1992–2001), the total volume of runoff can be predicted within -3.66 percent at Maulap River, within 5.37 percent at Almagosa River, and within 10.74 percent at Imong River. Month-end reservoir volumes simulated by the reservoir water-balance model for both calibration and verification periods compared closely with measured reservoir volumes. Errors for the calibration periods ranged from 4.51 percent [208.7 acre-feet (acre-ft) or 68.0 million gallons (Mgal)] to -5.90 percent (-317.8 acre-ft or -103.6 Mgal). For the verification periods, errors ranged from 1.69 percent (103.5 acre-ft or 33.7 Mgal) to -4.60 percent (-178.7 acre-ft or -58.2 Mgal). Monthly simulation bias ranged from -0.19 percent for the calibration period to -0.98 percent for the verification period; relative error ranged from -0.37 to -1.12 percent, respectively. Relatively small bias indicated that the model did not consistently overestimate or underestimate reservoir volume.

Introduction

In 1951, the U.S. Navy constructed the Fena Valley Reservoir in south-central Guam (fig. 1). It is the largest surface-water development on Guam, with a total storage capacity of 7,180 acre-ft (2,340 Mgal) (Nakama, 1992), which is equivalent to slightly more than an 8-month reserve at the current (2001) average water withdrawal rate of 8.9 Mgal/d. The reservoir captures runoff from the Fena Valley Watershed and is the primary source of water for Navy personnel and local citizens. The total drainage area of the watershed is about 5.86 mi^2. The three gaged tributaries to the Fena Valley Reservoir, Maulap, Almagosa, and Imong Rivers, drain about 75 percent of the watershed. The remaining land area of the watershed is ungaged. The combined annual streamflow of the three gaged tributaries averages about 15,000 acre-ft (4,890 Mgal).

Although rainfall is fairly abundant on Guam, where the mean annual total is about 100 in. (Lander, 1994), Fena Valley Reservoir experiences minor to severe water shortages almost every year because of the distinctive seasonal rainfall pattern (fig. 2). Rainfall during the wet season (July through November) normally generates sufficient runoff to replenish the reservoir to full capacity. However, dry season (January through May) rainfall typically contributes only 15 to 25 percent of the annual total. In response, reservoir water levels gradually decline as water withdrawals exceed the rate of reservoir recharge throughout the dry season. Prolonged absence of rainfall related to episodes of the El Nino Southern Oscillation (ENSO) phenomenon cause even more severe reductions in reservoir storage. ENSO events recur on an average of once every 4 years (Lander, 1994).

Base from U.S. Geological Survey
Island of Guam, 1:62,500, 1953.
1963 Guam datum

Figure 1. Location of the Fena Valley Watershed and hydrologic data-collection stations, Guam.

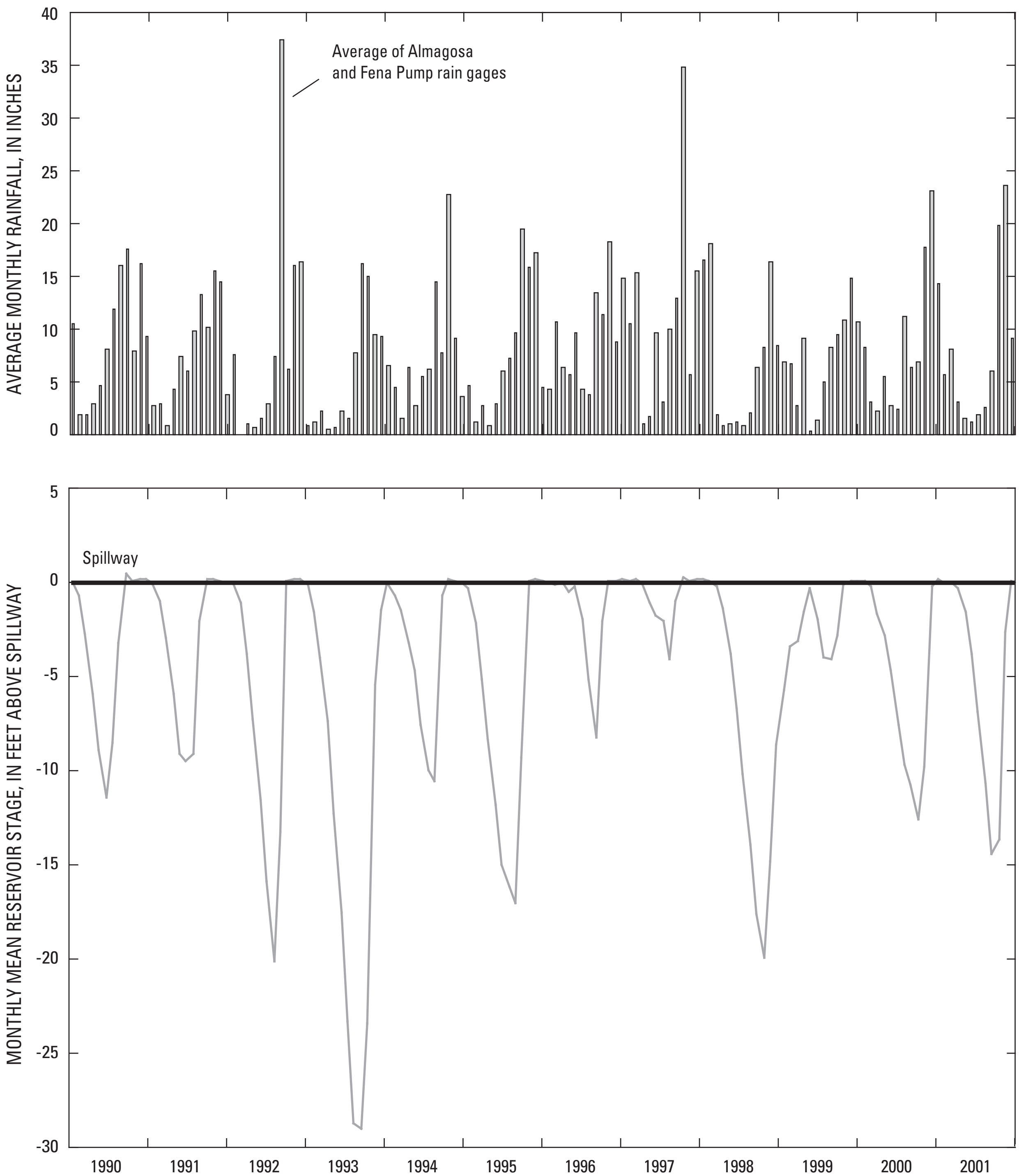


Figure 2. Average monthly rainfall and monthly mean reservoir stage of Fena Valley Reservoir, Guam, January 1990–September 2001.

Two fairly severe droughts occurred during ENSO events in the past decade, resulting in very steep declines of the reservoir water level. In 1993, the water level in the reservoir declined to a new record low of 31.56 ft below the spillway crest, 10 ft lower than the previously recorded low in 1983. This left the reservoir with only about 22 percent usable storage capacity remaining, a 54-day supply at the current average withdrawal rate of 8.9 Mgal/d. In 1998, another severe ENSO event caused the water level to decline to 21.03 ft below the spillway crest, leaving the reservoir with about 44 percent usable capacity remaining. The reservoir did not fill during the following wet season. Given the limited storage capacity of the reservoir relative to demand, the threat of more serious water shortages has always been a great concern.

In 1993, the U.S. Geological Survey (USGS), in cooperation with the U.S. Navy developed a numerical model of the Fena Valley Watershed to estimate the availability of reservoir recharge (Nakama, 1994) using the PRMS (Leavesley and others, 1983). The PRMS model of the Fena Valley Watershed developed by Nakama (1994) was subsequently used as a predictive tool in combination with a generalized reservoir water-balance model to estimate the change in monthly water levels in the reservoir in response to various combinations of water withdrawal options and rainfall projection scenarios. This two-step modeling procedure is illustrated in figure 3.

Limitations identified in the rainfall-runoff model developed by Nakama (1994), and the availability of improved and expanded data coverage in the watershed, supported the need for an update of the model. In addition, the reservoir water-balance model being used was generalized and had not been previously calibrated and documented. In 2001, the USGS entered into a cooperative agreement with the U.S. Navy to calibrate a new PRMS model of the Fena Valley Watershed, and to calibrate and verify a generalized reservoir water-balance model. These models will help the U.S. Navy to manage the limited water resources of the Fena Valley Watershed in a more effective manner.

Purpose and Scope

This report (1) describes the calibration and verification of an updated PRMS model of the Fena Valley Watershed, (2) describes the calibration and verification of a water-balance model for the Fena Valley Reservoir, (3) compares the updated PRMS model with the existing model developed by the USGS in 1993, and (4) identifies the uncertainties in the models. The data and methods used to develop the models also are discussed.

A PRMS model was developed for the Maulap, Almagosa, and Imong Rivers in the Fena Valley Watershed. In addition, a PRMS model was developed specifically for the ungaged land area in the Fena Valley Watershed not addressed in the previous USGS study (Nakama, 1994). Model development utilized data collected during 1992-2001.

Acknowledgments

Special acknowledgments are made to the following USGS scientists: George Leavesley and Lauren Hays for their assistance with model calibration and Steve Markstrom and Roland Viger for their assistance with building the PRMS model using the Modular Modeling System (MMS).

Description of Study Area

Guam, with an area of 212 mi^2, is the largest and southernmost of the Mariana Islands. The island is 28 mi long, 4 to 8 mi wide, and is in the tropical western Pacific Ocean east of the Philippine Sea (fig. 1). The Fena Valley Watershed, in the south-central part of the island, is deeply dissected by rivers and is underlain mostly by volcanic rocks. The resulting topography includes slopes ranging from less than 15 percent to greater than 50 percent. A nearly continuous mountain ridge constitutes the western drainage divide of the watershed. The watershed has a maximum relief exceeding 1,100 ft, with altitude ranging from 111 ft at the Fena Valley Reservoir outlet to 1,282 ft at the Mt. Jumullong Manglo.

The Fena Valley Watershed has a total drainage area of 5.86 mi^2. The three principal tributary rivers drain an area of 4.49 mi^2, or 75 percent of the total watershed area. Runoff has been concurrently monitored at USGS gaging stations located near the mouths of the three rivers since 1972. Topographical drainage areas upstream of the Maulap River gaging station (16848500), the Almagosa River gaging station (16848100), and the Imong River gaging station (16847000) are 1.18, 1.37, and 1.94 mi^2, respectively. The total ungaged land surface encompasses an area of 1.06 mi^2, which represents about 20 percent of the Fena Valley Watershed. The remaining 5 percent of the watershed area is the actual surface area of the Fena Valley Reservoir at full capacity. The USGS also operates a gaging station (16849000) near the dam spillway to record water level changes in the reservoir.

Runoff from the watershed captured in the Fena Valley Reservoir is an important source of domestic water supply for southern Guam. Runoff from the three gaged tributary rivers, with an annual combined discharge of about 15,000 acre-ft (4,890 Mgal), is the primary source of replenishment for the water supply in the reservoir. In addition, spring flows as much as 3.9 ft^3/s (2.5 Mgal/d) are diverted at the Almagosa Springs upstream of the Almagosa gaging station (fig. 1).

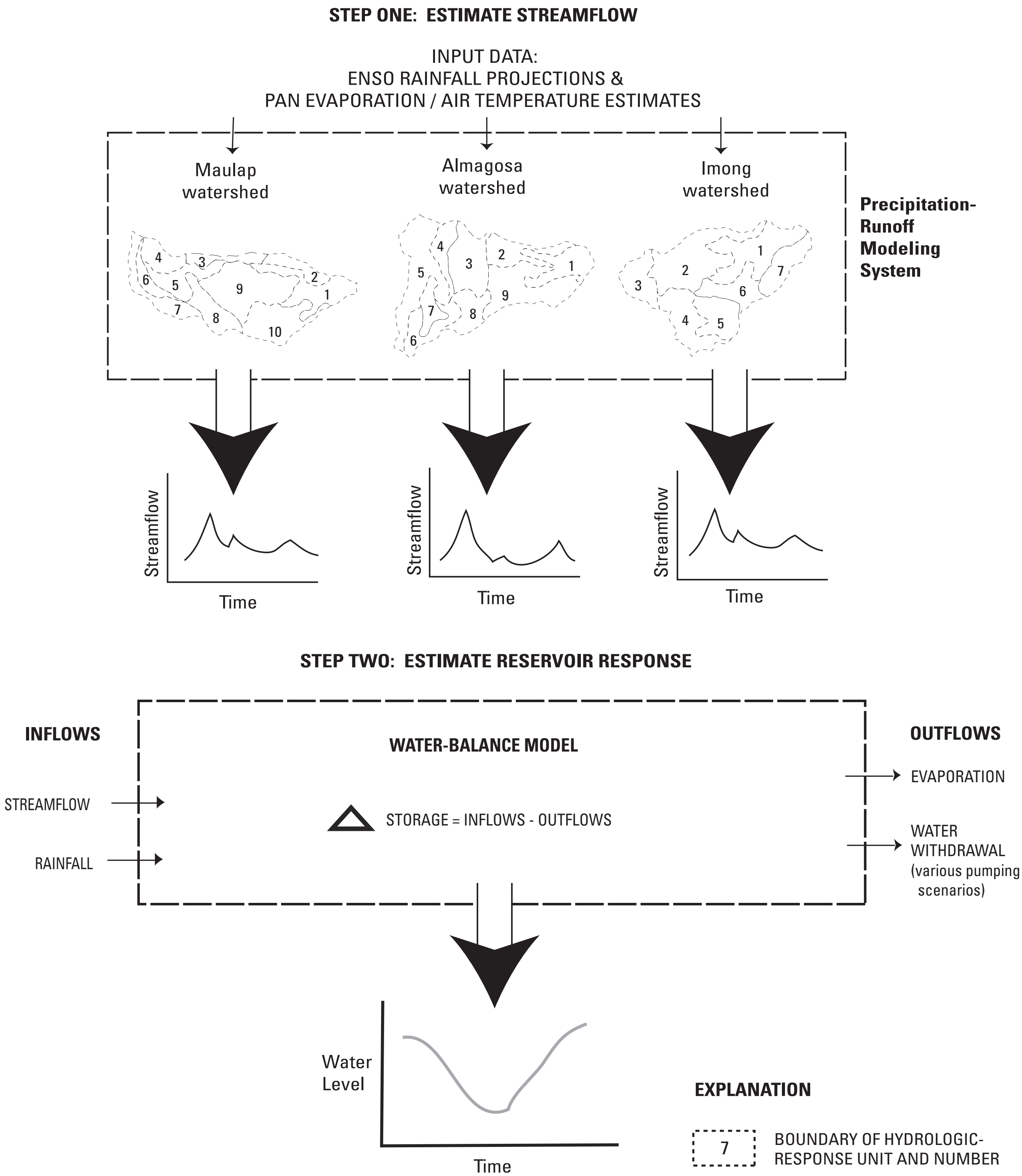


Figure 3. Two-step modeling procedure for Fena Valley Watershed, Guam.

Climate

The climate of Guam is mostly warm and humid throughout the year. Temperatures in degrees Fahrenheit typically are in the middle or high 80's in the afternoon and drop to 70's at night (fig. 4). Relative humidity ranges from 65 percent during the day to 100 percent at night. Rainfall varies spatially on the island owing to orographic effects (increases in rainfall with altitude) even though the mountains are relatively low (Lander, 1994). Mean annual rainfall is less than 90 in. on some coastal lowland areas and greater than 115 in. on mountainous areas in southern Guam (fig. 5). As temperature and humidity are fairly uniform throughout the year, the variations of wind and rainfall are what define the seasons in Guam.

Highly seasonal rainfall and wind patterns in the region provide Guam with distinctive wet and dry seasons. The island is subject to heavy rainfall during wet seasons and almost drought-like conditions during dry seasons. The dry season (January through May) is dominated by northeasterly trade winds with scattered and light showers (Lander, 1994). Rainfall during the dry season accounts for 15 to 20 percent of the total annual rainfall. Extended drought conditions are closely related to the recurrences of ENSO events. The wet season (July through November) accounts for an average of 65 percent of the annual rainfall. During the rainy season, westerly-moving storm systems and occasional typhoons bring heavy, steady rain and strong winds. Monthly rainfall total varies from less than 1 in. from February to April to more than 20 in. from August to November. The climate during the transitional months of December and June varies yearly.

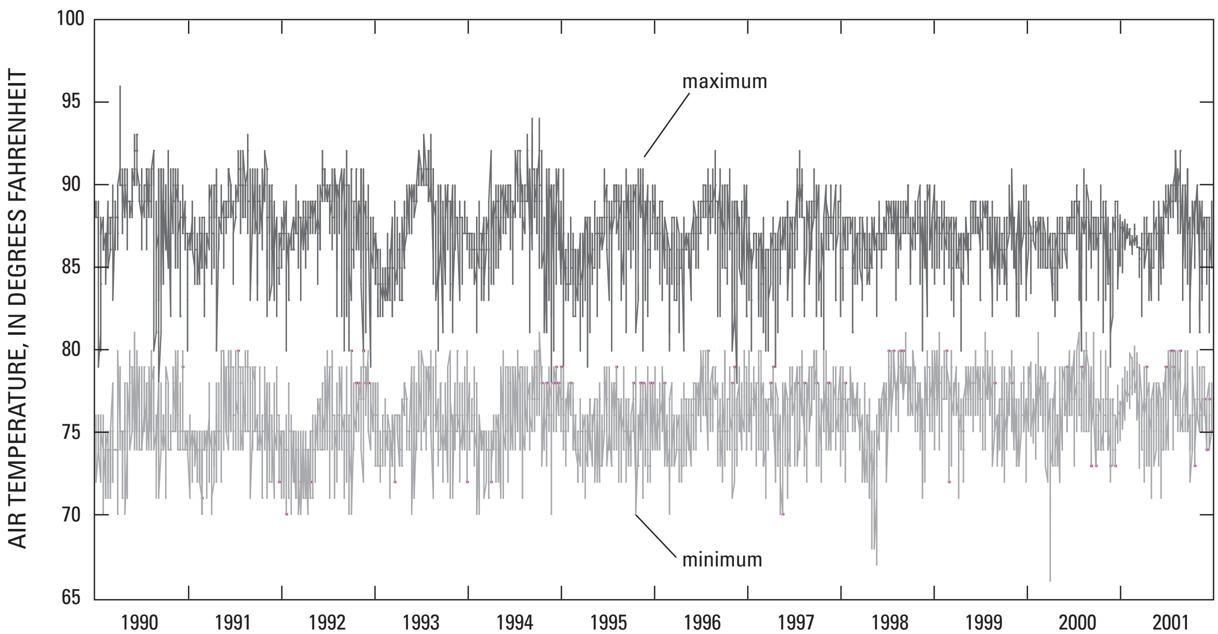
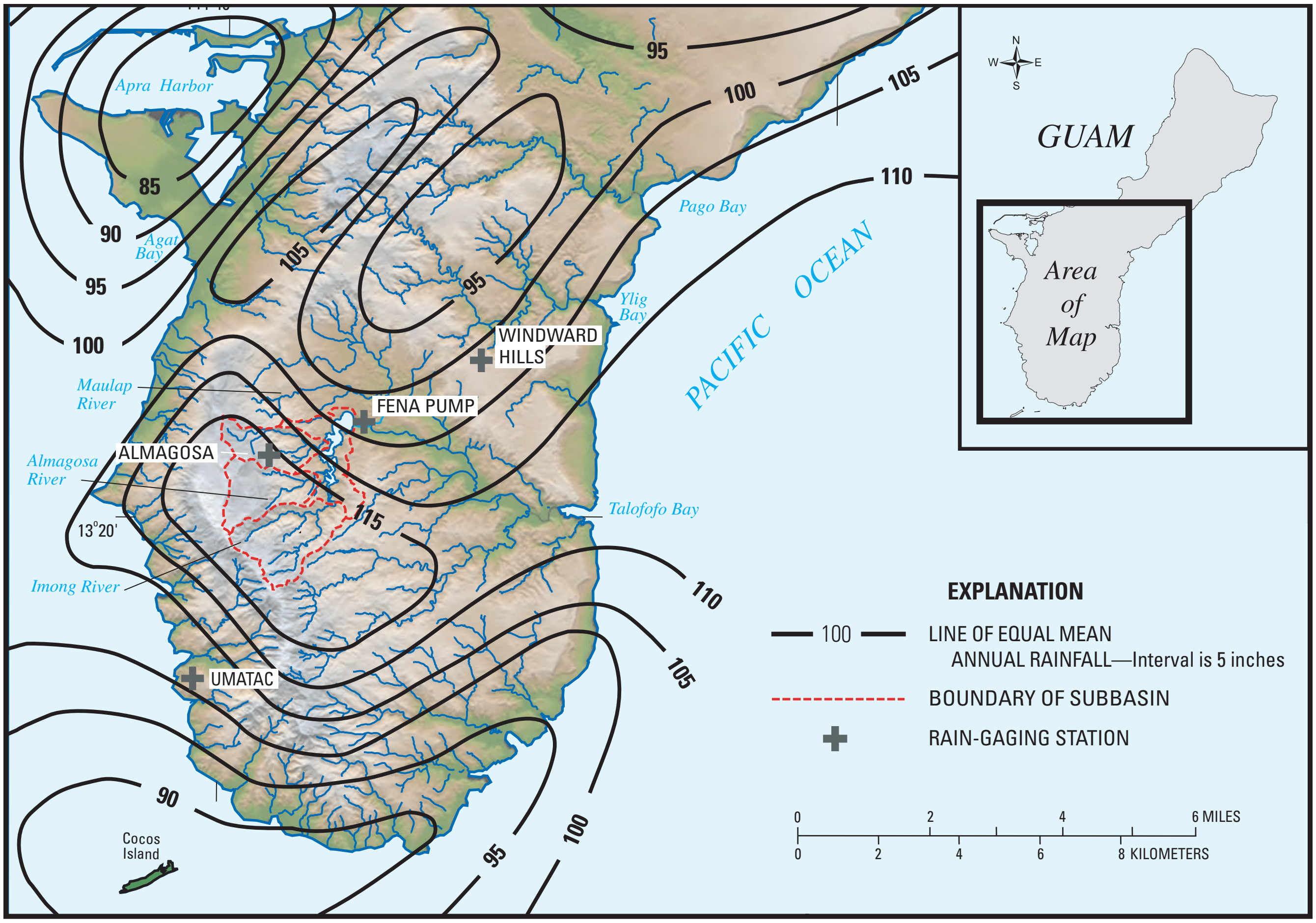


Figure 4. Daily maximum and minimum air temperatures, Naval Air Station Agana (National Climatic Data Center), Guam, 1990–2001.



Base from U.S. Geological Survey
Island of Guam, 1:62,500, 1953.
Elevation from Digital Elevation Model, 1:24,000
1963 Guam datum

Figure 5. Mean annual rainfall distribution, southern Guam, 1950-99.
(Modified from Charles Guard, Water and Environmental Research Institute, University of Guam, written commun, 2000.)

Geology[1]

The geology underlying the Fena Valley Watershed is fairly uniform (fig. 6). The watershed is predominantly underlain by low permeability volcanic rocks of Miocene age of the Umatac Formation, except in the elevated areas near the western drainage boundary where the much higher permeability Alifan Limestone, also of Miocene age, rests unconformably on gently sloping volcanic rocks. The volcanic rocks cover about 87 percent of the Fena Valley Watershed. The Umatac Formation is about 2,200 ft thick and is made up of four members: the Facpi Volcanic Member, the Maemong Limestone Member, the Bolanos Pyroclastic Member, and the Dandan Flow Member (Tracey and others, 1964). The Alifan Limestone underlies 20 and 31 percent of the Maulap and Almagosa River watersheds.

The limestone contains thin bodies of high-level ground water that are perched on low permeability volcanic rocks. During the wet season, a large part of the rainfall perched in the limestone is routed quickly to stream channels through subsurface pathways. Perched water discharges primarily as springs at contacts between the limestone and volcanic rocks. Almagosa Springs, which is the largest spring in southern Guam, contributes flow to the Almagosa River. The Navy diverts as much as about 3.9 ft^3/s (2.5 Mgal/d) from the springs for water supply. Within the limestone area of the upper Almagosa River watershed, a sinkhole greater than 50 ft in depth has formed. Alluvial clay deposits cover the bottom of the sinkhole. Further detailed descriptions of the Umatac Formation and the Alifan Limestone in the watershed are available in Tracey and others (1964).

Soils[1]

A survey conducted by the Soil Conservation Service (Young, 1988) provides descriptions of the spatial distribution and hydrologic properties of soils in the Fena Valley Watershed. The surficial soil consists of various series classified as shallow to very deep clay and silty clay soils. The permeability of the soils ranges from moderate to rapid. Soils over volcanic rocks are generally lower in permeability and higher in available water-holding capacity than soils over limestone.

The distribution of the soils in the Fena Valley Watershed is shown in figure 7. The silty clay soils of the Akina and Atate series in all the watersheds are well drained and deep to very deep (59 to 65 in.). They are of moderate permeability (0.2 to 2.0 in/hr), with available moisture capacity ranging from 0.07 to 0.2 in/in. These soils formed in residuum derived dominantly from tuff and tuff breccia. At lower altitudes in the Imong River watershed, shallow clay soils of the Agfayan series, moderately low in permeability (0.2 to 0.6 in/hr) and high in available moisture capacity (0.13 to 0.25 in/in), are intermixed with silty clay soils of the Akina series. In the Maulap and Almagosa River watersheds, the well-drained and shallow (up to 10 in.) soils over the Alifan Limestone are moderately high in permeability (2.0 to 6.0 in/hr) and very low in water-holding capacity (0.05 to 0.08 in/in). These soils are classified as the extremely cobbly clay loam soils of the Ritidian series, which are formed in residuum derived from coralline limestone. The sinkhole in the Almagosa watershed is filled with deep (up to 59 in.) clay soils of the Ylig series that formed in alluvium derived dominantly from volcanic rock. Permeability is moderately low (0.5 to 1.5 in/hr) and available water-holding capacity is high (0.15 to 0.20 in/in).

Vegetation[1]

The abundant rainfall over southern Guam helps to keep the Fena Valley Watershed lushly vegetated. The vegetation consists primarily of forested areas with scattered patches of grasslands, shrubs, and low trees (fig. 8). The multi-strata ravine forest is diverse, consisting of two or more canopy layers (Kinvig and others, 2001). Coconut, pandanus, and banyan trees are common upper story species in the ravine forest; shorter woody trees, tall shrubs, ferns, and various grasses grow beneath the upper layer. Shallow soils on limestone ridge tops west of the reservoir support various uncommon plant species. A variety of grasses grow in upland savannah areas. Shrubs and low trees are common where savannahs grade into ravine forest vegetation.

Runoff Characteristics

Seasonal rainfall patterns and the underlying geology heavily influence runoff characteristics in the Fena Valley Watershed. The Maulap, Almagosa, and Imong River watersheds have similar rainfall patterns and geology, which are reflected in the runoff hydrographs (fig. 9). Seasonal rainfall on Guam produces distinctive seasonal runoff patterns and reservoir response (fig. 10). With little rainfall during the dry season, runoff is fairly constant, sustained by the slow discharge of ground water stored in the volcanic terrain. With highly variable and at times intense rainfall during the wet season, runoff is flashy owing to the small drainage areas with steep slopes and low permeability volcanic rocks underlying the watershed. The volcanic terrain absorbs water at a low rate and a large part of the wet season rainfall runs off directly to the rivers. Average runoff for the three gaged watersheds during the wet season (July through November) typically ranges from 67 to 84 percent of annual runoff while the dry season runoff (January through May) is typically 9 to 22 percent of annual runoff.

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[1]Nakama (1994) provides summaries of the geology, soils, and land use of the study area. The sections on geology, soils, and vegetation are largely taken from this report.

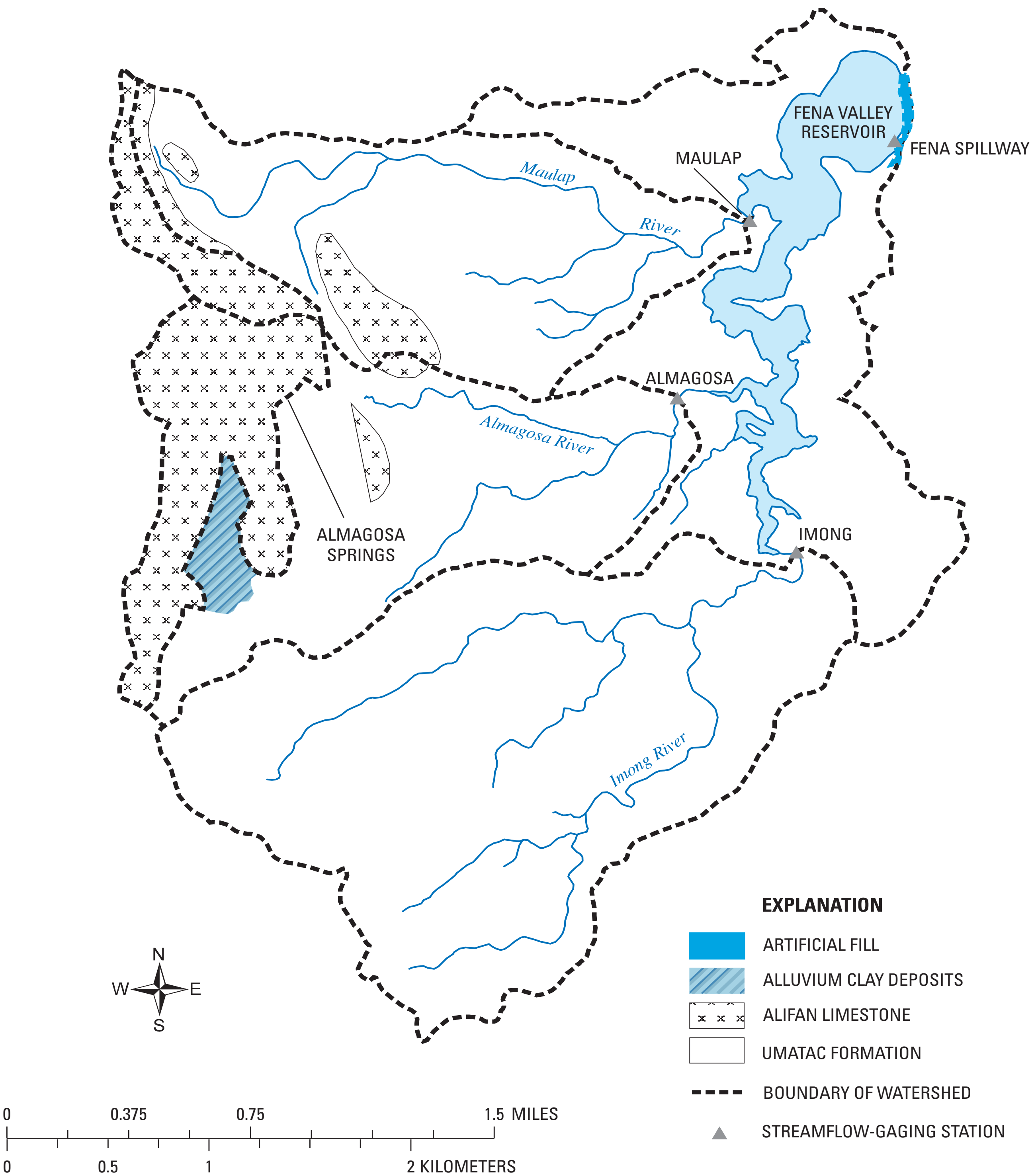

Figure 6. Generalized geology of Fena Valley Watershed, Guam. (Modified from Tracey and others, 1964; Nakama, 1994.)

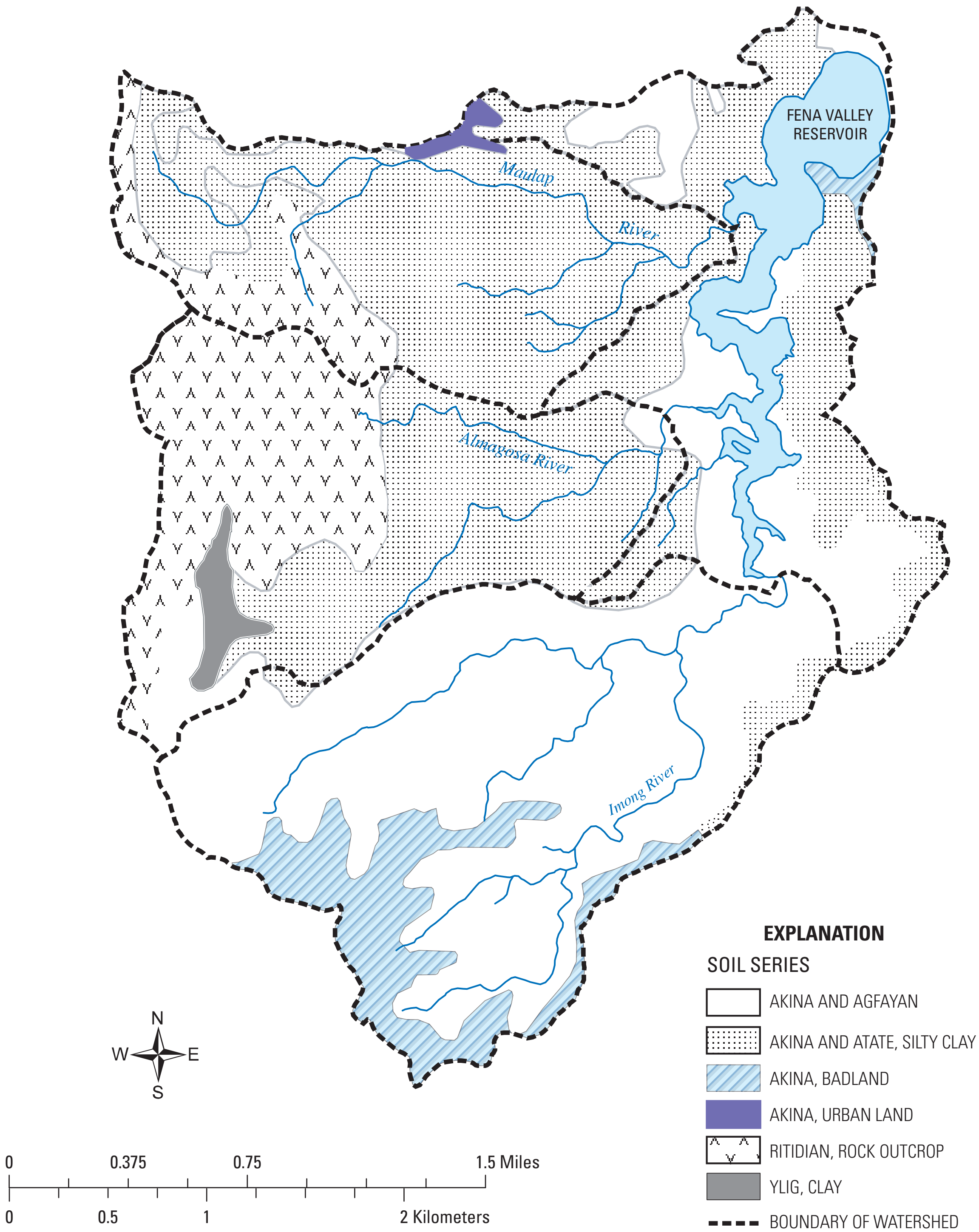

Figure 7. Distribution of soils in Fena Valley Watershed, Guam. (Modified from Young, 1988; and Nakama, 1994.)

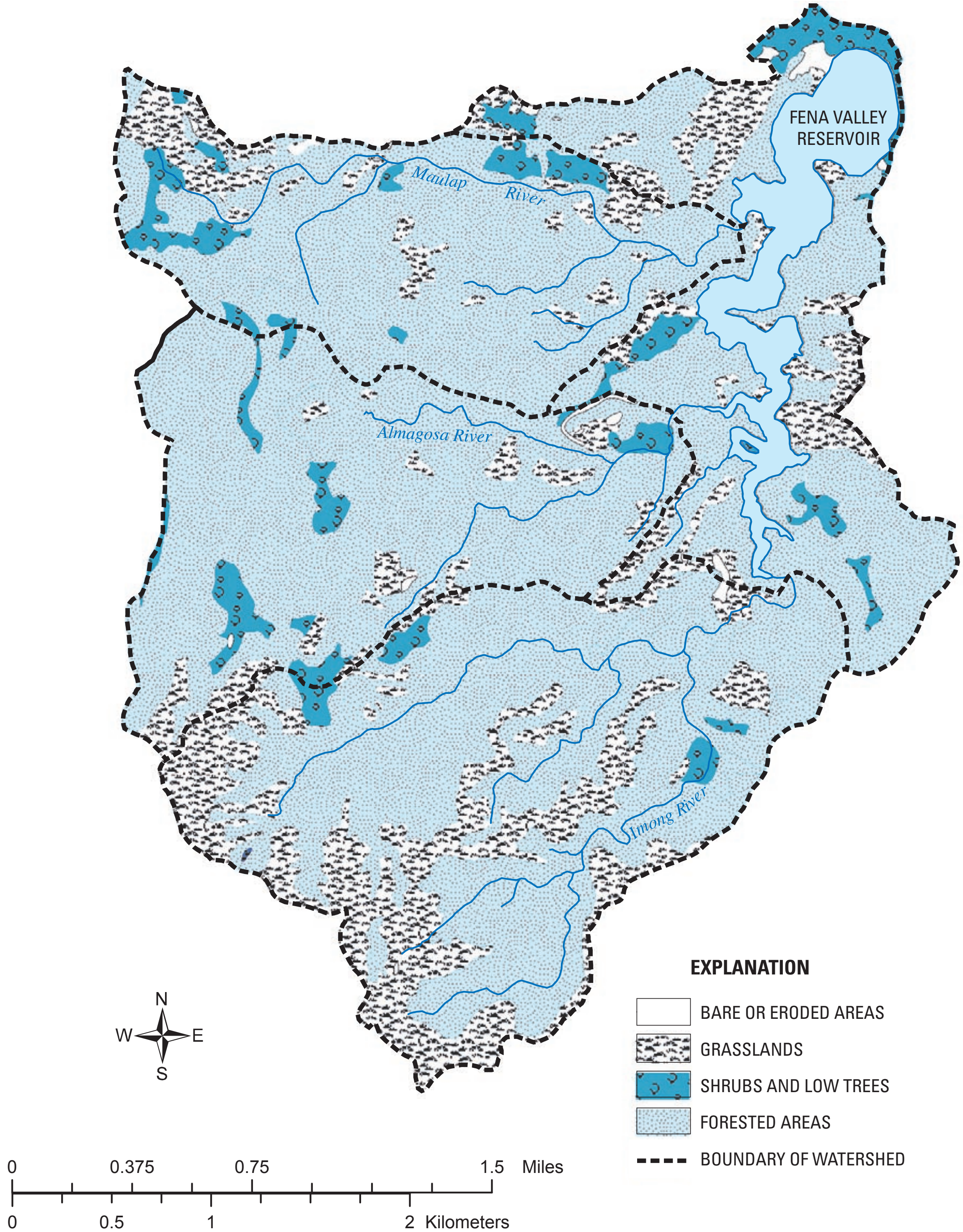

Figure 8. Vegetation unit boundaries in Fena Valley Watershed, Guam. (Modified from Roger Skolman, U.S. Forest Service, written commun., 1976; and Nakama, 1994.)

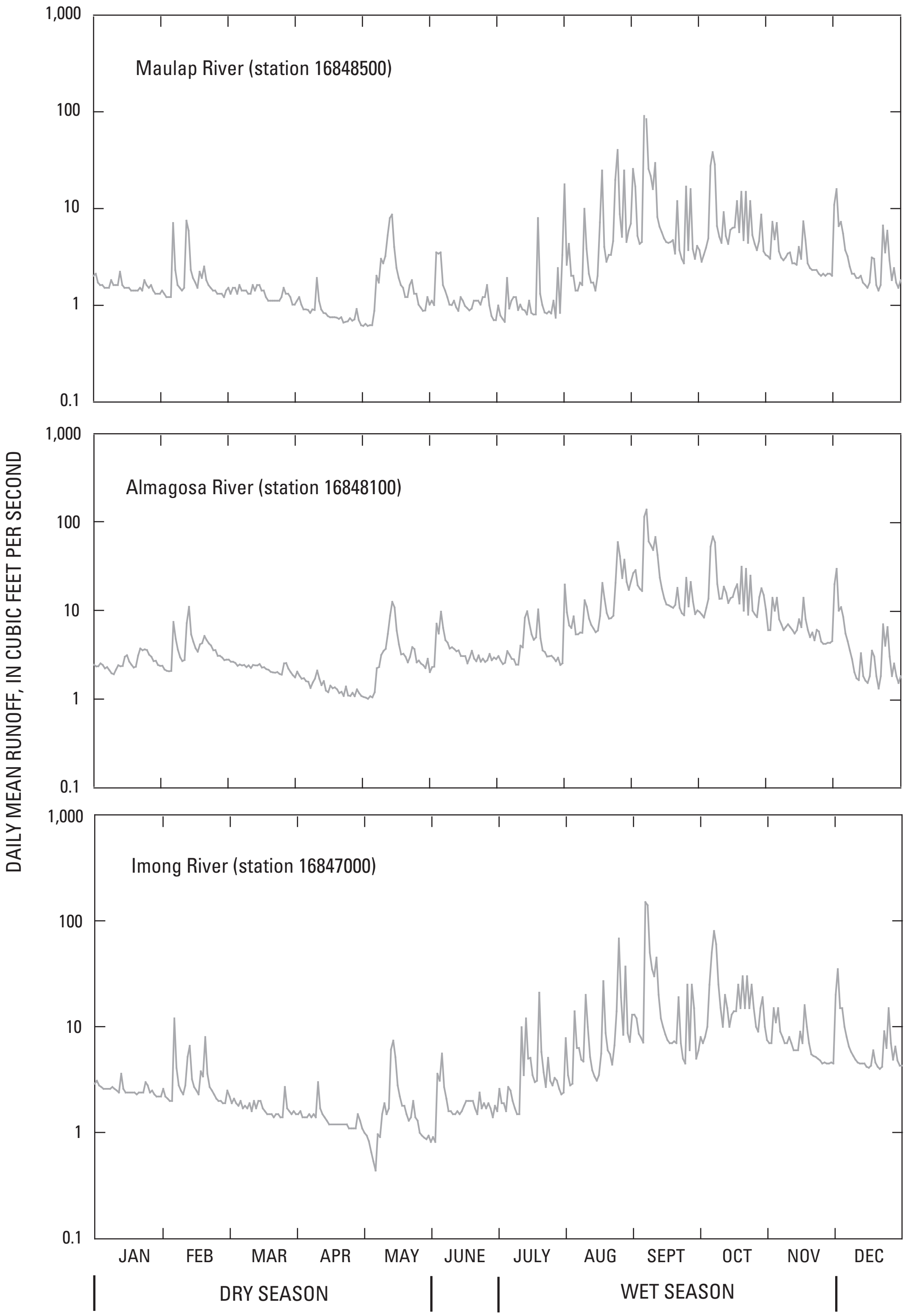

Figure 9. Daily mean runoff at Maulap, Almagosa, and Imong Rivers, Guam, 2000.

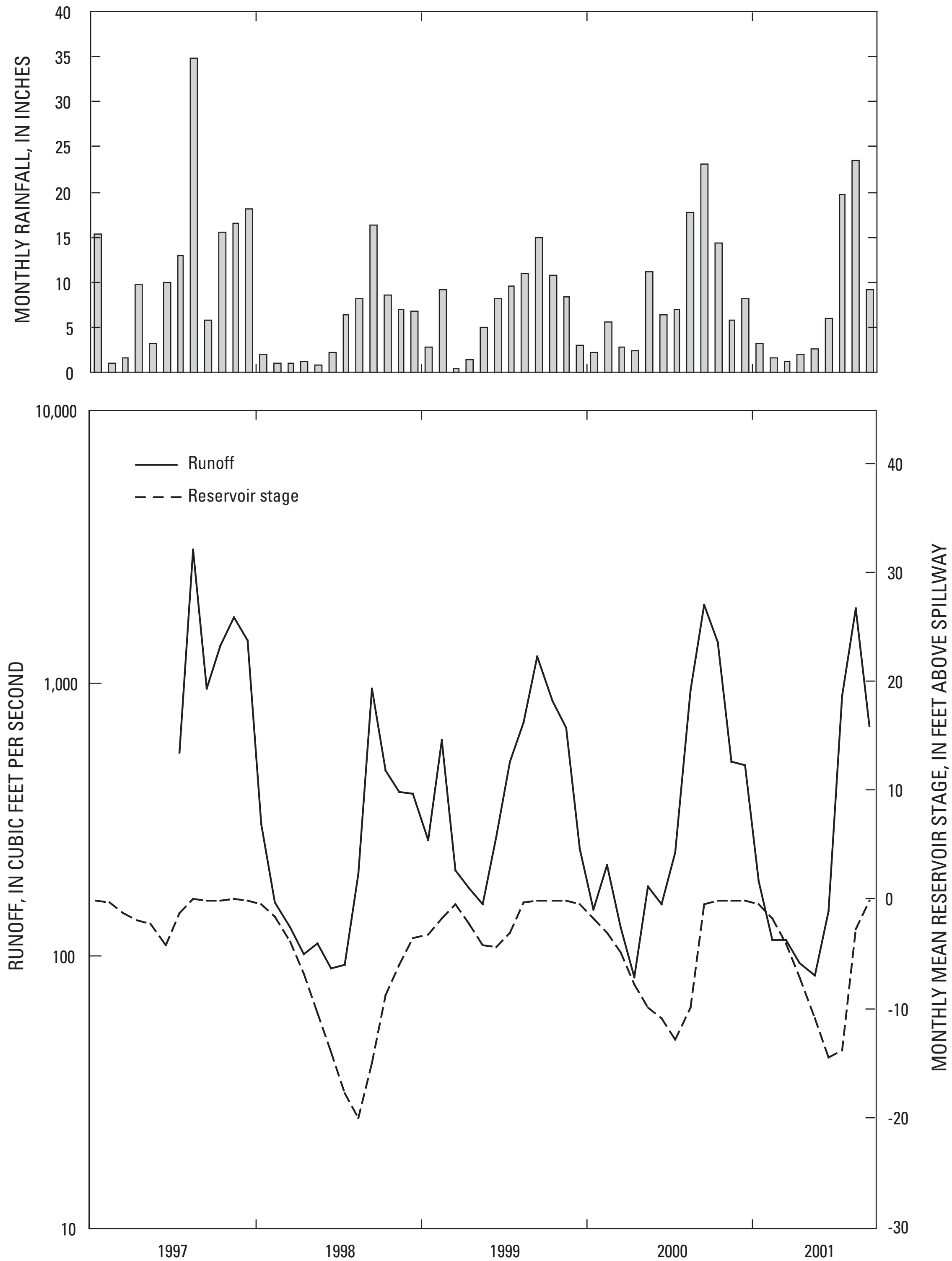

Figure 10. Monthly rainfall (average of Almagosa and Fena Pump), monthly total runoff (from Maulap, Almagosa, and Imong Rivers), and monthly mean reservoir stage of Fena Valley Reservoir (from Fena Dam spillway), Guam, January 1997 – September 2001.

Flow-duration curves of unit runoff for the Maulap, Almagosa, and Imong Rivers for a common period of record (1990–2001) are shown in figure 11. A flow-duration curve shows the percentage of time-specified discharges were equaled or exceeded during a given period. Similarities in slope and how closely the curves plot at the high end reflect similarities of high-flow characteristics among the three rivers. The distribution of high flows is controlled largely by the rainfall, the physiography, and the vegetation cover of the watershed. The low ends of the flow-duration curves, which diverge slightly, reflect the effect of geology on low flow. Because Maulap and Almagosa Rivers drain similar geologic formations, curves 1 and 3 have nearly the same slope throughout the low end of the curve. Daily flow from the spring diversions was added to the daily flow measured at Almagosa gaging station to eliminate the effects of flow diversions. The decrease in curve 2 in comparison to curve 3 reflects the effects of the spring diversions at Almagosa Springs on Almagosa River runoff. The spring diversions have substantially decreased base flow in the Almagosa River and are highly influential at medium and low flows, but the influence diminishes at higher flows.

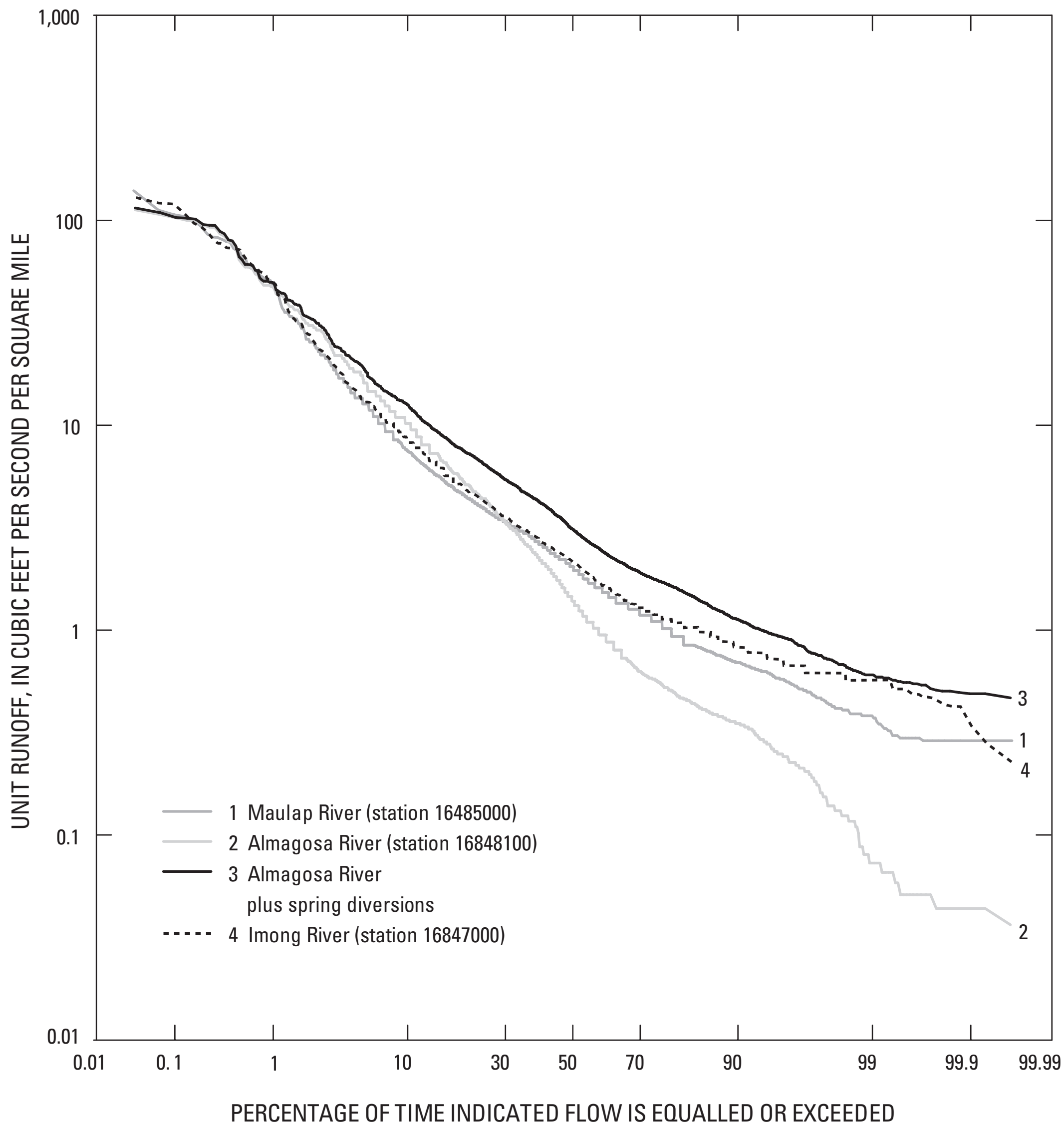

Figure 11. Flow-duration curves for Maulap, Almagosa, Imong Rivers and Almagosa River plus spring diversions, Guam (based on period 1990–2001).

Rainfall-Runoff Model

Fena Valley Watershed has a complex mix of soils, geology, vegetation, topography, and rainfall patterns. The interaction of this complex mix of watershed characteristics controls the processes involved with generating runoff from rainfall. In this study, the primary objective was to account for these processes by using the PRMS in order to accurately simulate monthly dry season runoff in the three gaged river watersheds and the ungaged land area that drain into the Fena Valley Reservoir. Model performance in wet seasons was less of a concern for water management because the reservoir normally remains at full capacity during that time of year.

Description of Precipitation-Runoff Modeling System

PRMS is a modular, physically based, distributed-parameter modeling system developed to assess the effects of watershed characteristics on watershed hydrologic response. A PRMS model is composed of various user-selected modules that simulate different components of the hydrologic cycle. PRMS is physically based in that each component of the hydrologic system is simulated with known physical laws or empirical relations formulated on the basis of measurable watershed characteristics. The distributed-parameter and watershed partitioning features of the PRMS are designed to account for the spatial variation in watershed characteristics. A watershed is partitioned into small units within which the slope, land use, soil, geology, and precipitation distribution is similar. The hydrologic response within each unit is assumed to be homogeneous, and each unit is referred to as a hydrologic response unit (HRU). Heterogeneity within an individual HRU is accounted for by computing areally weighted averages for each characteristic. A daily water balance and energy balance are computed for each HRU and daily total watershed response is the areally weighted sum of the responses of all HRUs.

PRMS can be run in daily and storm mode time scales. The daily mode simulates daily average runoff and the storm mode simulates runoff at time intervals that may be shorter than a day. Because monthly runoff was the desired input for the reservoir water-balance model, it was not necessary to simulate runoff at time intervals less than a day. Therefore, the PRMS model was run in the daily mode and calibrated and verified based on its ability to simulate monthly runoff. In daily mode, daily rainfall and pan evaporation or air temperature data are required as input.

PRMS conceptualizes a watershed as an interconnected series of reservoirs, including interception storage in the vegetation canopy and storages in the soil zone, subsurface reservoir, and ground-water reservoir (fig. 12). Flows going into and out of the PRMS reservoirs represent various processes of the hydrologic cycle. Total system response or streamflow is the sum of surface, subsurface, and ground-water flow. Complete documentation for the modeling system is available in the PRMS user's manual (Leavesley and others, 1983). The following paragraphs from Nakama (1994) detail the conceptualization of the Fena Valley Watershed system by the PRMS.

> *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 (Hewlett and Nutter, 1970; Dickinson and Whiteley, 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.*

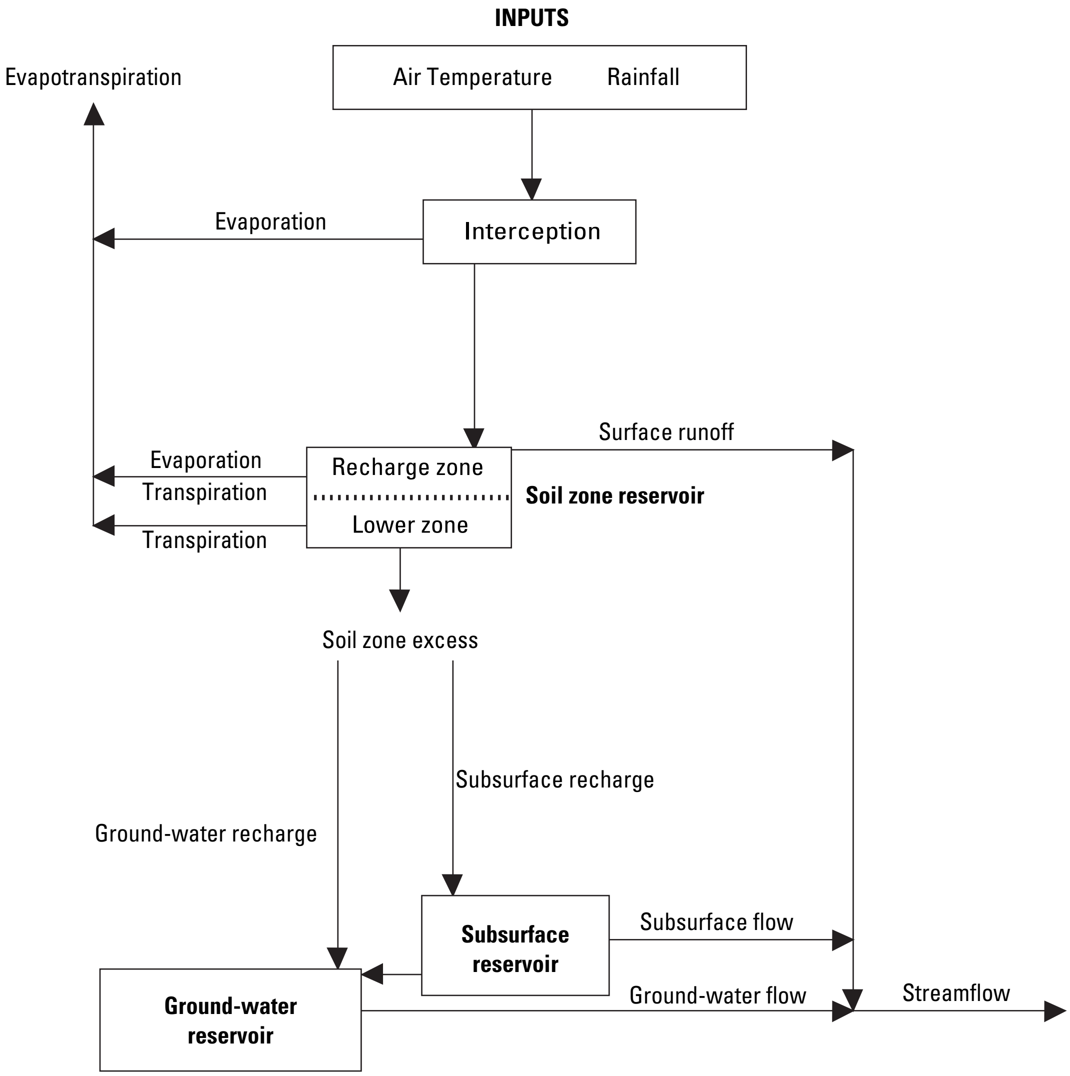

Figure 12. Conceptual hydrologic system used in the Precipitation-Runoff Modeling System for the Fena Valley Watershed, Guam.
(Modified from Leavesley and others, 1983.)

Background Data

PRMS was calibrated and verified using daily-mode flow simulation. Measured daily mean runoff data were used to calibrate and verify model simulations for the three gaged watersheds, the Maulap, Almagos, and Imong Rivers. Measured climate data including daily rainfall and maximum and minimum air temperatures were used as model input. Physiographic data were used to describe the distribution of the physical characteristics of each watershed.

Runoff Data

Since 1972, the USGS has concurrently operated streamflow gaging stations near the mouths of the Maulap, Almagosa, and Imong Rivers to provide a continuous record of inflow to the Fena Valley Reservoir (fig. 1). The Maulap River gaging station (16848500) is 100 ft upstream of the Fena Valley Reservoir at latitude 13°21’14” N., longitude 144°41’44”E. The Almagosa River gaging station (16848100) is 400 ft upstream of the reservoir at latitude 13°20’43” N., longitude 144°41’36” E. The Imong River gaging station (16847000) is 500 ft upstream of the reservoir at latitude 13°20’17” N. longitude 144°41’55” E.

Measured daily runoff data from the Maulap and Imong River gaging stations were used directly with no adjustments. Runoff data from the Almagosa River gaging station, however, do not reflect natural runoff conditions because of the upstream diversions at the Almagosa Springs (fig. 1). As much as 3.9 ft^3/s (2.5 Mgal/d) of runoff is diverted daily from the springs. Almagosa River flows continuously from its headwaters downstream to the USGS gaging station. Therefore, it was assumed that diversion of a given volume of flow at Almagosa Springs would result in an equal reduction in flow downstream at the gaging station. Daily flow data for the spring diversions, provided by the U.S. Navy, was added to the daily flow measured at Almagosa River gaging station to eliminate the effects of flow diversions and to simulate natural runoff conditions.

The accuracy ratings on the USGS streamflow data from the Maulap, Almagosa, and Imong River gaging stations (1992–2001) ranged from fair to poor. A fair rating indicates that about 95 percent of the daily flow data are within 15 percent of their actual values; poor rating indicates that records do not meet fair rating criteria. Accuracy associated with the U.S. Navy flow data for the Almagosa Springs diversion is not known.

Climate Data

The two climate-data inputs required for the PRMS application are (1) daily total rainfall and (2) either daily pan evaporation or maximum and minimum air temperatures. Rainfall data provide the timing and volume of water input to the watershed being modeled. Pan evaporation or air temperature data are used to estimate evapotranspiration losses from the watershed.

Rainfall

In the previous PRMS modeling study of the Fena Valley Watershed (Nakama, 1994), daily rainfall on the watershed was estimated by using an arithmetic average of daily rainfall measurements from two USGS rain gages at Windward Hills and Umatac and a National Weather Service (NWS) rain gage at Fena Dam (fig. 1). None of these rain gages, however, are within the watershed area of the Fena Valley Reservoir. The Windward Hills gage is at an altitude of 365 ft about 2.5 mi northeast of the Fena Valley Reservoir dam. The Umatac gage is at an altitude of 180 ft about 1.75 mi southwest of the Imong River. The Fena Dam gage is near the dam spillway at an altitude of about 60 ft. In October 1993, the USGS installed a rain gage at Fena Reservoir pumping station (fig. 1) to replace the nearby Fena Dam rain gage. In June 1992, the USGS installed a rain gage adjacent to the access road to the Almagosa Springs (fig. 1). The Almagosa rain gage currently is the only rain gage operated within the Fena Valley Watershed and it is at an altitude of about 600 ft, or 250 ft higher than the three rain gages used in the previous PRMS modeling study (Nakama, 1994).

The timing of rainfall collected at the four USGS rain gages (Almagosa, Fena Pump, Windward Hills, and Umatac) generally is similar although rainfall volumes vary among sites (fig. 13). Rainfall variation with altitude was examined by plotting the altitude of the gages and the corresponding monthly rainfall values. Results indicated no strong rainfall-altitude relations in the data, probably because the altitude differences among gages are not great. Because orographic effects were not reflected in the data, the arithmetic-average rainfall from the Almagosa and Fena Pump gages was used to estimate daily rainfall on the Fena Valley Watershed. Data from Almagosa and Fena Pump were selected because these two gages are closest to the study area and therefore would provide more accurate volume and temporal descriptions of rainfall than would data from the Windward Hills and Umatac rain gages. Although this averaging procedure tends to lower rainfall extremes, Nakama (1994) considered the average value the best available estimate of daily rainfall over relatively small drainage basins with limited rain gage coverage. Missing rainfall data for the Almagosa and Fena Pump gages were estimated using a linear-regression model developed with the most closely correlated of the four adjacent USGS rain gages.

Evapotranspiration

PRMS provides a variety of procedures for computing daily estimates of potential evapotranspiration (PET) based on the use of either daily pan evaporation or air temperature data. In the previous PRMS modeling study, Nakama (1994) used daily pan evaporation data obtained from the NWS climate station (914229) (fig. 1) at Taguac about 17 mi northeast of the Maulap River watershed. The NWS climate station has been in operation since September 1944 but was discontinued in April 1998.

The Hamon (1961) method was selected to estimate PET in this study, because pan-evaporation data from the NWS Taguac station are no longer available. The Hamon method computes PET as a function of daily mean air temperature and possible hours of sunshine. The required daily maximum and minimum air temperatures were obtained from the NWS station at the Naval Air Station (NAS) Agana (914226) (fig. 1), about 11 mi northeast of the Maulap River watershed. Because air temperature across the island of Guam varies very little, air temperature in the study area should be well represented by data from the NAS Agana station, and no adjustments to the data were made. Although pan-evaporation data were not directly used in the model, pan-evaporation data were used to identify seasonal variations in potential evapotranspiration during the calibration process. Accuracies associated with the pan-evaporation data and air temperature data are not known.

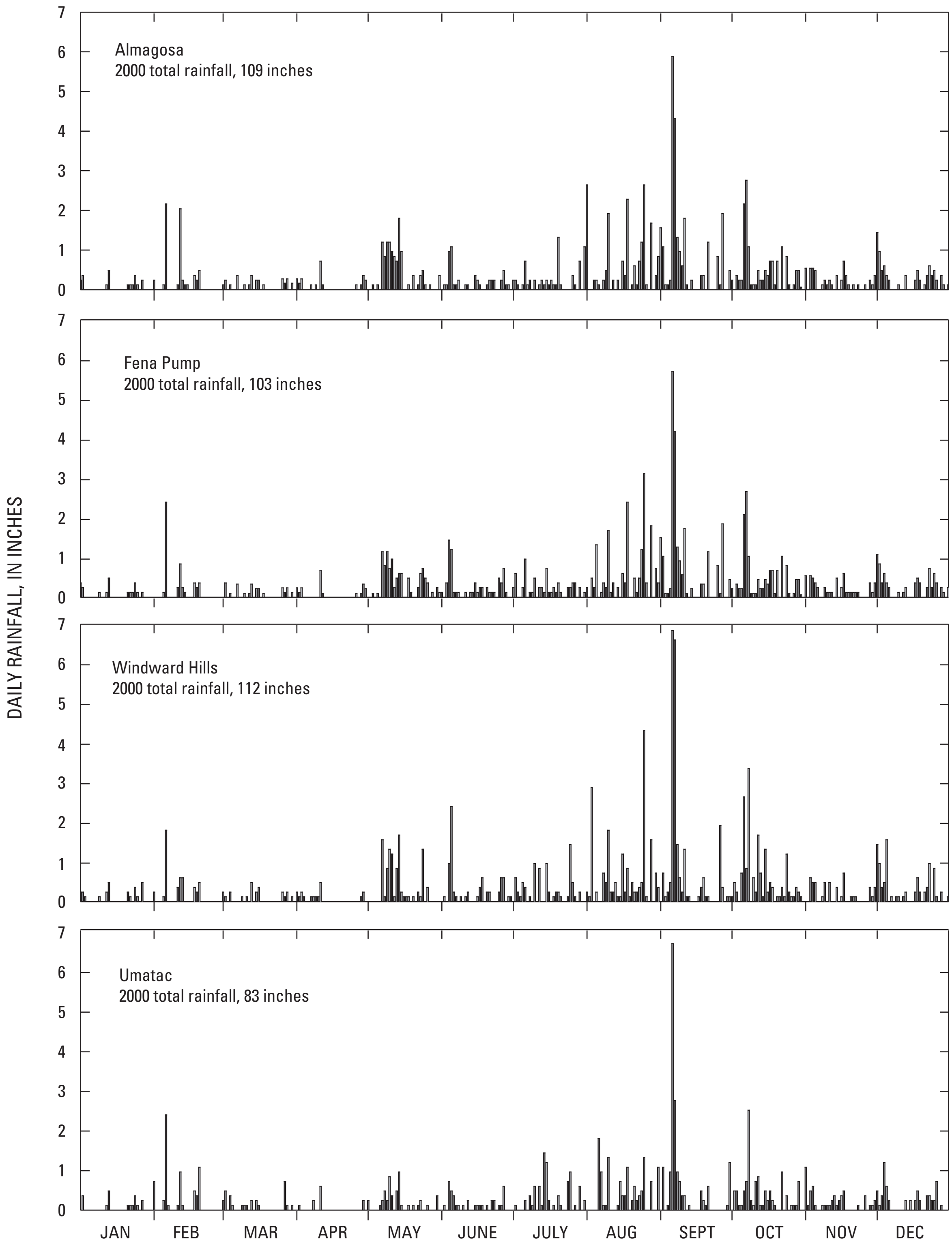

Figure 13. Daily rainfall at rain gages at Almagosa, Fena Pump, Windward Hills, and Umatac, Guam, 2000.

Physiographic Data

Physiographic data were compiled to describe the spatial variations of watershed characteristics. Geologic information for the geology data layer (fig. 6) was derived from the 1:50,000-scale geology map of Guam produced by Tracey and others (1964). The soils data layer (fig. 7) was compiled from the 1:25,000-scale detailed soil unit maps, and information on various physical properties of the soils was obtained from soil property tables (Young, 1988). The determination of cover density and delineation of the predominant vegetation were based on a vegetation survey of the Fena Valley Watershed done by the [U.S.] Forest Service (Roger Skolmen, written commun., 1976), 1:24,000-scale USGS topographic maps, aerial photographs, and field observations. Digital data layers for the three major watershed characteristics—geology, soils, and vegetation—were created by Nakama (1994) using ARC-INFO, a geographic information system (GIS) tool. These three data layers were used in this study because no current information was available to update the layers. Other physical watershed characteristics, including basin area, slope, aspect, and elevation, were derived from the USGS 10-m Digital Elevation Model (DEM) for Guam.

Selection of Calibration and Verification Periods

Daily time-series of runoff and climate data (discussed above) for 1990–2001 were used for this study. The availability of concurrent runoff and climate data primarily dictated the selection of the time periods used for model calibration and verification. As illustrated in figure 14, the availability of the measured runoff and Almagosa rainfall data (gage installed in 1992) limited the calibration periods for the Maulap and Imong River watersheds to July 1992 through February 1994, and for the Almagosa River watershed to February 1993 through April 1994. The selected periods represented climatic and hydrologic conditions ranging from normal to extremely dry. In 1992, about 100 in. of rain fell in the study area, and in 1993, one of the driest years associated with the occurrence of a severe ENSO event, only about 70 in. of rain fell. Two other independent periods with concurrent runoff and climate data were reserved for model verification to evaluate model performance. Data for August 1997 through August 1998 and for October 1999 through September 2001 were used in model verification for Maulap and Imong River watersheds, and data for April 1997 through August 1998 and for October 1999 through September 2001 were used in

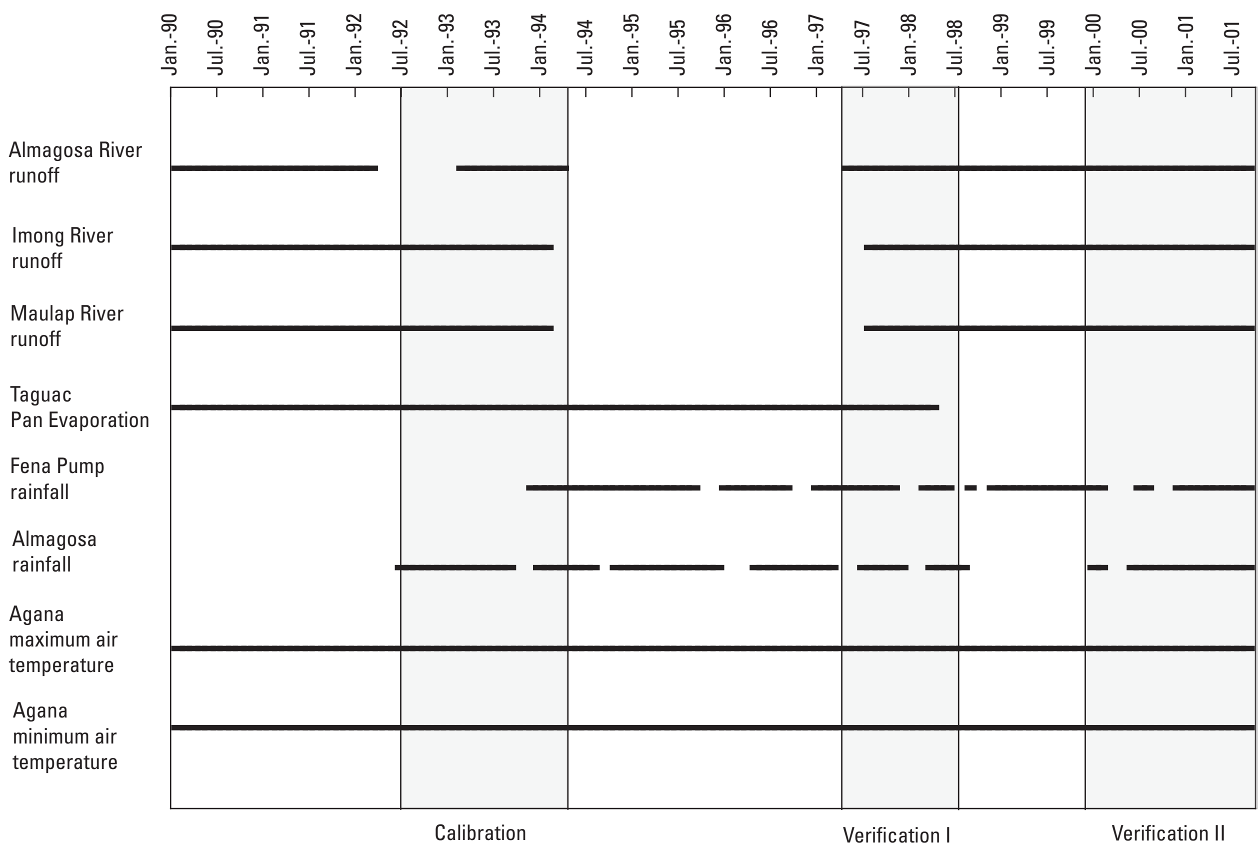

Figure 14. Periods with complete data used in the development of the Precipitation-Runoff Modeling System models for the Fena Valley Watershed, Guam, January 1990 through September 2001.

model verification for Almagosa River watershed. The first verification period represented a transition from extremely wet to extremely dry hydrologic conditions. About 140 in. of rain fell in 1997, and a very severe ENSO event, during which only 60 in. fell, occurred in 1998. The second verification period represented average hydrologic conditions, with about 100 in. of rain falling in both 2000 and 2001.

Several other factors also were considered when selecting time periods for model calibration and verification. A continuous period of data was desired to avoid the need for reinitialization of the model or for using synthetic input data. The purpose of model initialization is to estimate initial conditions in the watershed at the beginning of a simulation period. Wide variability of runoff also was desired so that a wide range of hydrologic processes would be represented in the data set (Sorooshian and Gupta, 1995). Most importantly, both calibration and verification periods were selected to include an ENSO period because model performance for periods of drought is of great concern.

Model Building Using the Modular Modeling System

The model-building phase of this study included delineating divides and HRUs for each watershed, computing physical basin characteristics using the USGS DEM, and building the PRMS model using the MMS (Leavesley and others, 1996). The PRMS is currently implemented within the MMS. The MMS supports various model-building tools that were used in this study. The pre-modeling component of MMS, GIS Weasel (Viger and others, 2000), was used for delineation of divides and HRUs for each watershed and the computation of watershed characteristics. Xmbuild, an interactive model-building component of the MMS, was used to build an air temperature-based PRMS model. A diagram illustrating the module configuration used in the implementation of the PRMS in the MMS is shown in figure 15.

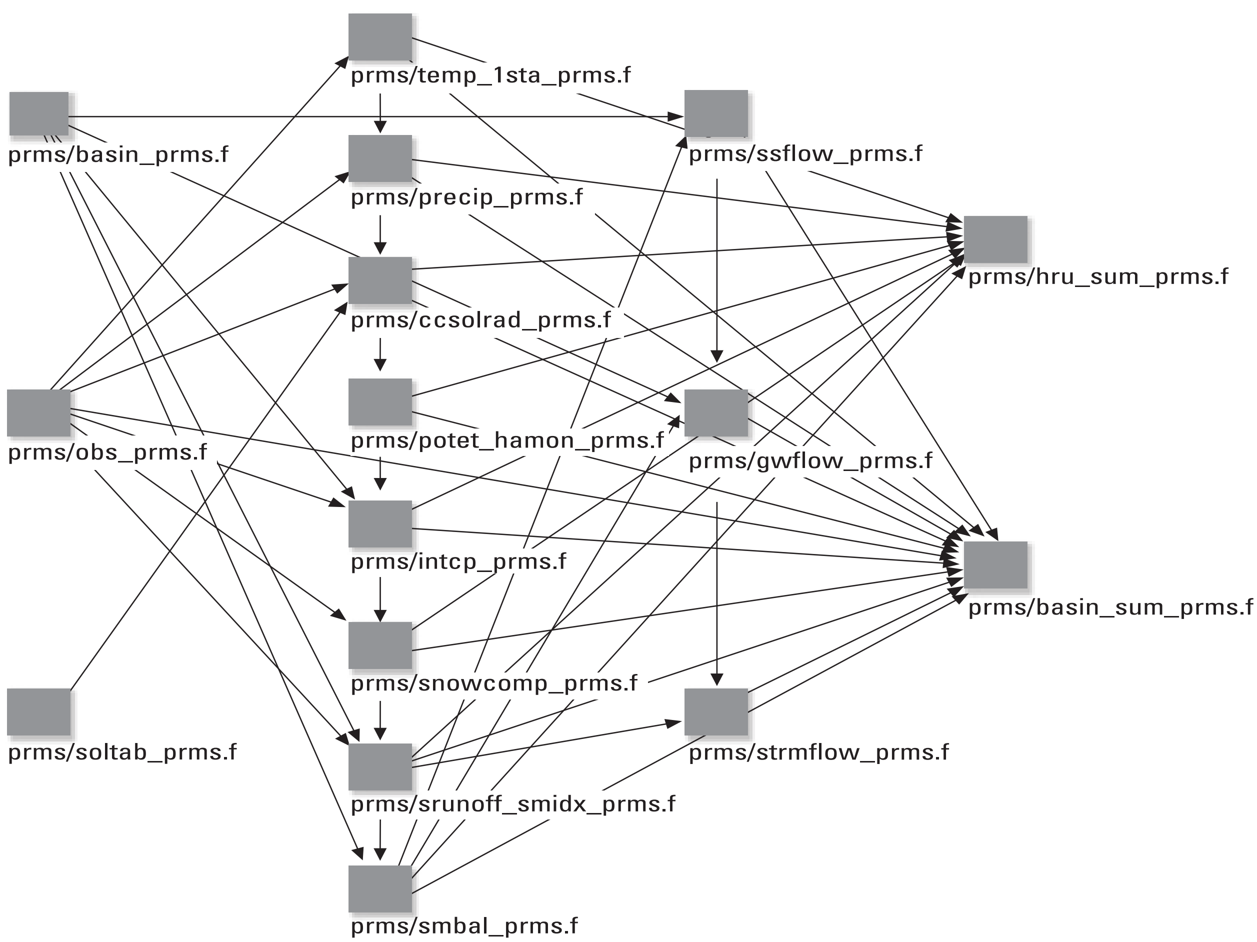

Figure 15. Specific modules linked to implement the Precipitation-Runoff Modeling System in the Modular Modeling System for the Fena Valley Watershed, Guam.

Watershed Delineation

Drainage boundaries for the three gaged watersheds and the ungaged areas were delineated from the 10-m USGS DEM using the automated procedure in the GIS Weasel (Viger and others, 2000). Accuracy of the delineated divides was compared with manually delineated divides (Nakama, 1994). Small discrepancies between the automated and manual delineations were identified and modifications were made to resolve them based on topographic information obtained from the 1:24,000-scale USGS topographic maps of Agat and Talofofo (1968, photo-revised 1975).

Characterization and Delineation of Hydrologic Response Units

Watershed heterogeneity was accounted for by partitioning the watershed into smaller areas known as HRUs. Because all major land-characteristic data layers available were from the previous modeling study (Nakama, 1994), updated HRU delineation for the Maulap, Almagosa, and Imong River watersheds was not necessary. The Maulap River watershed was partitioned into ten HRUs, the Almagosa River watershed into nine, and the Imong River watershed into seven (fig. 16). A tenth HRU was added to the Almagosa watershed as part of the calibration process (see model calibration section). The partitioning was based primarily on watershed characteristics such as geology, soils, and vegetation type (Nakama, 1994). Vegetation differences were considered less important in the determination of HRU boundaries, because hydrologic response is more sensitive to soil and geologic-unit type when using daily-mode simulations. The elevation range within each HRU was restricted to not more than about 300 ft. Because of the uniformity of the underlying geology in the Imong River watershed, one subsurface reservoir and one ground-water reservoir were used to describe the ground-water system. In other words, excess soil-zone water from each of the seven HRUs in the Imong River watershed is routed into the same subsurface and ground-water reservoirs (fig. 12). Two ground-water reservoirs and two subsurface reservoirs were used to describe the ground-water system in the Maulap and Almagosa River watersheds. Excess soil-zone water from HRUs in areas where the subsurface geology is Alifan Limestone is routed to one set of subsurface and ground-water reservoirs in both the Maulap and Almagosa River watersheds. Excess soil-zone water from HRUs in areas where the subsurface geology is Umatac volcanics is routed to a second set of subsurface and ground-water reservoirs in each watershed.

Similar HRU delineation procedures and criteria were applied to the ungaged areas so that HRUs in these areas and the three gaged watersheds corresponded with each other. This correspondence allows calibrated parameters and coefficients for HRUs in the gaged watersheds to be transferred to comparable HRUs in the ungaged areas. Using GIS Weasel, the three digital data layers were merged into a composite data layer (fig. 17) and HRUs for the ungaged areas were delineated by grouping areas having similar watershed characteristics. As a result, the ungaged watershed areas were partitioned into ten HRUs. The Fena Valley Reservoir was not included in the ungaged areas modeled using PRMS (fig. 16). One set of subsurface and ground-water reservoirs was used to describe the ground-water system in the ungaged watershed areas.

Model Parameterization

Model parameters in PRMS can be classified into two basic types: distributed and non-distributed. Many of the distributed parameters describe the physical characteristics of individual HRUs and represent measurable watershed characteristics such as drainage area, slope, soil type, cover type, and cover density. Distributed parameters also describe components and processes of the hydrologic cycle on or within an HRU. Non-distributed parameters are watershed-wide characteristics such as temperature, rainfall, and ground-water and subsurface routing coefficients, which apply over the entire watershed. Descriptions of the major distributed (HRU-related) and non-distributed parameters used in the PRMS model for the Fena Valley Watershed are listed in table 1.

In this study, initial estimates of parameter and coefficient values for the three gaged watersheds were taken largely from the previous PRMS modeling study (Nakama, 1994), except for the physical parameters. Physical parameter values were recomputed for all watersheds because basin delineations were modified from the divides used by Nakama (1994). Physical watershed characteristics including basin area, slope, and elevation were derived from the USGS DEM using GIS Weasel (Viger and others, 2000). The HRU physical characteristics values are summarized in table 2.

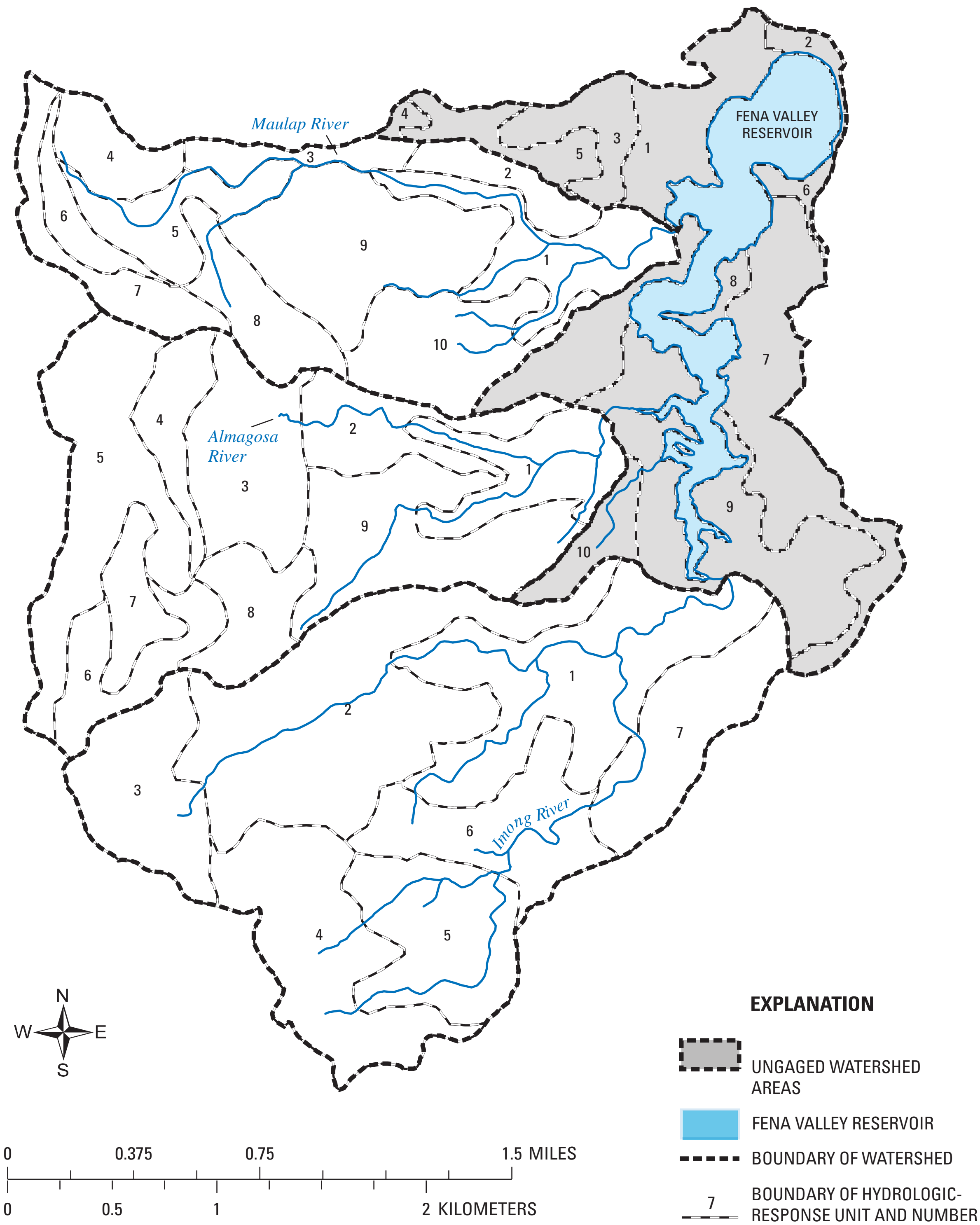

Figure 16. Hydrologic response units in the Fena Valley Watershed, Guam. (Modified from Nakama, 1994.)

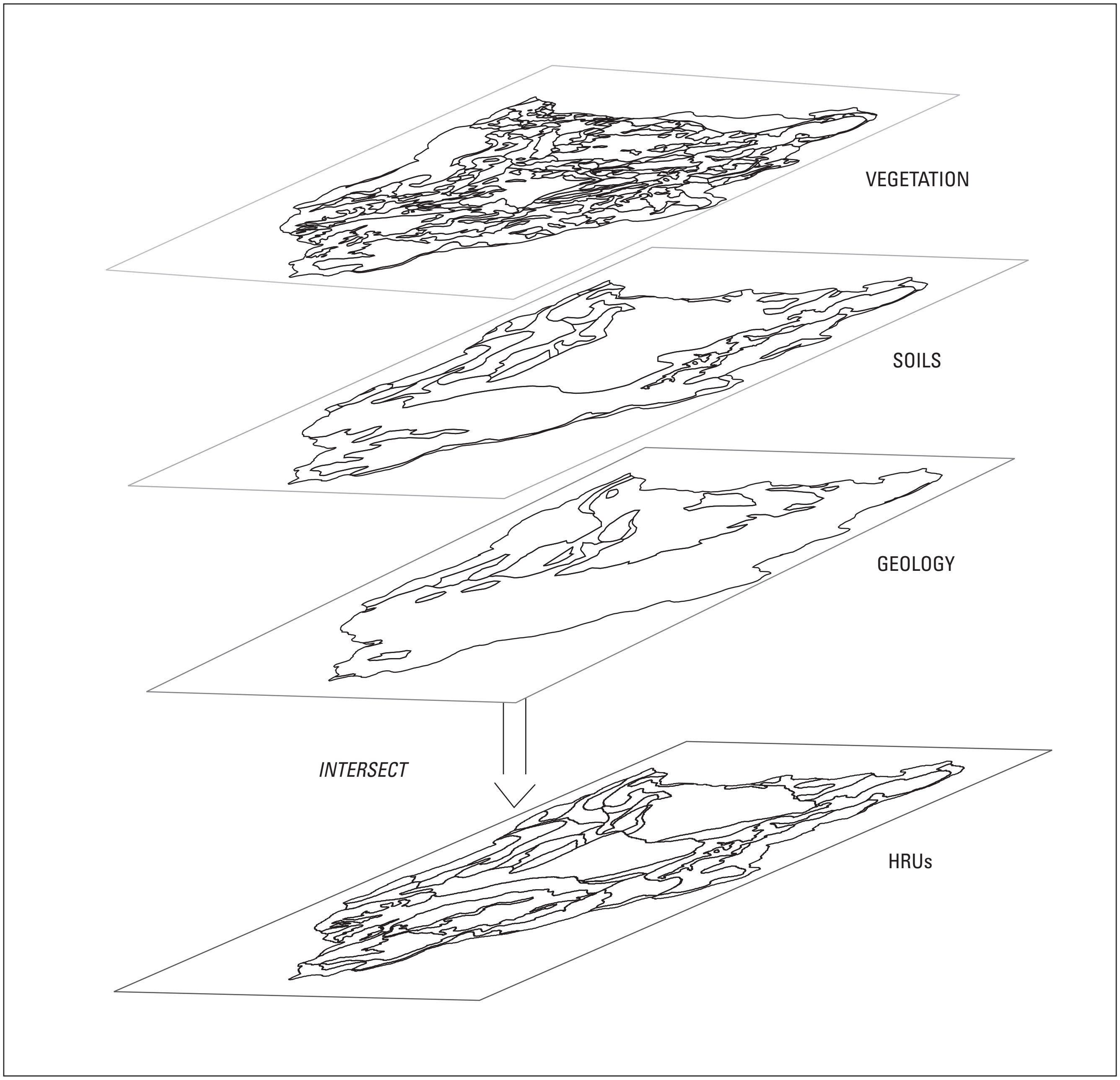

Figure 17. Merging of data layers to create hydrologic response units (HRUs) for a watershed.

Table 1. List of distributed and nondistributed parameters used in the Precipitation-Runoff Modeling System for the Fena Valley Watershed, Guam.

[**Abbreviation:** PRMS, Precipitation-Runoff Modeling System. MMS, Modular Modeling System. HRU, hydrologic response unit]

PRMS-MMS Model parameter	Equivalent PRMS Model parameter	Description of parameter
		Distributed (HRU-dependent) parameters
CAREA_MAX	SCX	Maximum area contributing to surface runoff (in decimal percent of HRU_AREA)
COV_TYPE	ICOV	Vegetation cover type (tree, shrub, grass, or bare)
COVDEN_SUM	COVDNS	Vegetation cover density (in percent) for summer
COVDEN_WIN	COVDNW	Vegetation cover density (in percent) for winter
HRU_AREA	DARU	HRU area (in acres)
HRU_ELEV	ELV	Mean HRU altitude (in feet)
HRU_GWRES	KGW	Index number for ground-water reservoir
HRU_PSTA	IDS	Index number of the precipitation station used to compute rain and snow on HRU
HRU_RADPL	IRD	Index number of the solar radiation plane
HRU_SLOPE	SLP	HRU slope in decimal percent (vertical feet/horizontal feet)
HRU_SSRES	KRES	Index number of the subsurface reservoir receiving excess water from the HRU soil zone
HRU_TSTA	KTS	Index number of the temperature station used to compute HRU temperatures
SMIDX_COEF	SCN	Coefficient in non-linear contributing area algorithm (for computing surface runoff)
SMIDX_EXP	SC1	Exponent in non-linear contributing area algorithm (for computing surface runoff)
SOIL2GW_MAX	SEP	Maximum amount of soil water excess for an HRU that is routed directly to the associated ground-water reservoir each day (in inches)
SOIL_MOIST_INIT	SMAV	Initial value of available water in soil profile (in inches)
SOIL_MOIST_MAX	SMAX	Maximum available water holding capacity of soil profile (in inches)
SOIL-RECHR_INIT	RECHR	Initial value for available water in the soil recharge zone, in upper soil zone (in inches)
SOIL_RECHR_MAX	REMX	Maximum value for available water in the soil recharge zone (in inches)
SOIL_TYPE	ISOIL	HRU soil type (sand, loam, clay)
SRAIN_INTCP	RNSTS	Summer interception storage capacity for the major vegetation type on an HRU (in inches)
WRAIN_INTCP	RNSTW	Winter rain interception storage capacity for the major vegetation type on an HRU (in inches)
		Selected nondistributed (basin-wide) parameters Temperature/rainfall related
HAMON_COEF	CTS	Air temperature coefficient for evapotranspiration computation for months 1-12
RAIN_ADJ	DRCOR	Monthly factor to adjust measured rainfall in each HRU
		Ground-water routing related
GWFLOW_COEF	RCB	Ground-water routing coefficient to obtain ground-water flow contribution to streamflow
GWSTOR_INIT	GW	Storage in each ground-water reservoir at the beginning of the simulation (in inches)
		Subsurface routing related
SSR2GW_RATE	RSEP	Coefficient to route water from the subsurface to ground-water reservoir
SSRCOEF_LIN	RCF	Linear subsurface routing coefficient to route subsurface storage to streamflow
SSRCOEF_SQ	RCP	Non-linear subsurface routing coefficient to route subsurface storage to streamflow
SSSTOR_INIT	RES	Initial storage for each subsurface reservoir (in inches)

Table 2. Physical characteristics of hydrologic response units for the Fena Valley Watershed, Guam.

[**Almagosa River watershed:** Hydrologic response unit 10 was added to account for additional ground-water flow from limestone areas. Parameter definitions are shown in table 1]

Hydrologic-response unit	COV_TYPE	HRU_AREA (acres)	HRU_ELEV (feet)	HRU_GWRES	HRU_SLOPE (feet/feet)	HRU_SSRES	SOIL_TYPE
			Maulap River watershed				
1	Trees	103.53	216	1	0.219	1	Clay
2	Shrubs	40.92	292	1	.312	1	Clay
3	Trees	35.46	516	1	.346	1	Clay
4	Grasses	49.79	779	1	.212	1	Clay
5	Trees	69.95	701	1	.189	1	Clay
6	Shrubs	32.15	815	2	.242	1	Clay
7	Trees	67.00	936	2	.237	2	Clay
8	Trees	70.78	707	2	.197	2	Clay
9	Trees	173.74	504	1	.274	1	Clay
10	Trees	113.17	400	1	.221	1	Clay
			Almagosa River watershed				
1	Trees	89.85	281	1	0.252	1	Clay
2	Trees	80.83	501	1	.231	1	Clay
3	Trees	124.61	748	1	.204	2	Clay
4	Trees	53.37	875	2	.324	2	Clay
5	Trees	180.78	989	2	.234	2	Clay
6	Grasses	71.41	988	1	.230	1	Clay
7	Shrubs	44.97	883	1	.078	1	Clay
8	Shrubs	66.69	874	1	.212	1	Clay
9	Trees	166.32	488	1	.314	1	Clay
10	Trees	250.00	1,061	2	.170	2	Clay
			Imong River watershed				
1	Trees	239.54	266	1	0.322	1	Clay
2	Trees	317.87	556	1	.446	1	Clay
3	Grasses	120.09	965	1	.363	1	Clay
4	Grasses	179.17	988	1	.233	1	Clay
5	Trees	136.45	694	1	.387	1	Clay
6	Grasses	125.58	533	1	.311	1	Clay
7	Trees	121.10	361	1	.307	1	Clay
			Ungaged watershed areas				
1	Grasses	151.47	218	1	0.192	1	Clay
2	Shrubs	13.34	144	1	.134	1	Clay
3	Trees	49.40	244	1	.145	1	Clay
4	Grasses	6.50	462	1	.115	1	Clay
5	Trees	43.19	352	1	.234	1	Clay
6	Trees	14.97	156	1	.247	1	Clay
7	Trees	164.91	241	1	.201	1	Clay
8	Trees	13.39	144	1	.300	1	Clay
9	Trees	186.71	216	1	.276	1	Clay
10	Grasses	37.21	322	1	.307	1	Clay

Model Calibration, Verification, and Results

The purpose of model calibration was to estimate realistic model parameter and coefficient values for the three gaged watersheds so that the PRMS model closely simulates the hydrologic processes of the watershed. The values were adjusted upward or downward manually between each model run. The first step in the calibration process was to adjust climatic model coefficients such as the rainfall correction factor (RAIN_ADJ) and monthly air temperature coefficient for PET computation (HAMON_COEF) until the simulated total runoff volume was within 5 percent of measured runoff. Subsequently, a sensitivity analysis was performed to identify which of the parameters had the most influence on runoff simulation. Model parameters and coefficients identified by the sensitivity analysis were then manually adjusted to adequately simulate the shape of storm hydrographs and base-flow recession curves. Not all model parameters were adjusted in the calibration process. Measurable physical characteristics such as drainage area, average elevation, and slope were not adjusted (table 2). Finally, an auto-calibration procedure contained within the PRMS was applied to evaluate if further improvement could be made to the manually calibrated model.

Calibration Objective

Prolonged dry conditions during the ENSO events of 1993 and 1998 resulted in extremely low levels of runoff in the Maulap, Almagosa, and Imong Rivers, which led to alarmingly low water levels in the Fena Valley Reservoir (fig. 2). Annual rainfall during these 2 years was about 70 and 60 percent of average. To better assess the availability of water for reservoir storage and use during these extremely dry climatic conditions, the focus of the calibration efforts in this study was on the dry season runoff. Accuracy in the simulation of wet season runoff was therefore considered of secondary importance.

Water-Budget Adjustments

The PRMS model was run on a continuous basis throughout the simulation period (1990–2001), and the first few years (1990–1992) prior to the calibration period were used to establish initial conditions of key parameters such as soil moisture and storage in the subsurface and ground-water reservoirs.

The first step of PRMS model calibration focused on the parameters that control computation of PET and rainfall distribution. The monthly Hamon coefficients (HAMON_COEF) and rainfall correction factors (RAIN_ADJ) were adjusted until simulated total runoff was within 5 percent of measured total runoff for the calibration period. The HAMON_COEF and RAIN_ADJ parameters are two of the most important controls on the amount of water entering and leaving a watershed. HAMON_COEF was varied to reflect seasonal patterns of the evapotranspiration losses. RAIN_ADJ was adjusted to account for the influences of spatial variation in rainfall, and gage-catch efficiency (Leavesley and others, 1983).

The initial monthly HAMON_COEF applied in the temperature-based Hamon evapotranspiration formula (Hamon, 1961) were selected to reflect the seasonal variation in pan-evaporation data (fig. 18) and were adjusted until the temperature-based annual PET agreed reasonably with the pan-evaporation based annual PET. The pan-evaporation based PET was computed using a pan-adjustment coefficient of 0.7 (Nakama, 1994). The monthly HAMON_COEF were further adjusted until simulated monthly evapotranspiration losses fell into a reasonable range of 2 to 4 in. (Nakama, 1994).

Rainfall input to each individual HRU was adjusted until the simulated runoff in each of the watersheds was within 5 percent of the measured runoff. The rainfall within each watershed was uniformly adjusted by a constant factor. Annual runoff volumes were consistently overestimated with the RAIN_ADJ value of 1.15, which was used in the previous PRMS model calibration study (Nakama, 1994). As a result, a RAIN-ADJ value of 1.05 was selected for the Imong and Almagosa River watersheds and, a value of 1.0 was used for the Maulap River watershed. The slightly lower RAIN_ADJ value applied to the Maulap River watershed was consistent with the slightly lower annual rainfall received in that watershed, as indicated in figure 5. The 115-in. mean annual rainfall line encloses most of the Almagosa and Imong River watersheds, whereas parts of the Maulap River watershed are areas where the mean rainfall is between 100 and 115 in.

Initial PRMS model calibration results for the Almagosa River watershed indicated that simulated runoff volumes were much lower than measured runoff volumes. To achieve a proper water balance, either RAIN_ADJ had to be increased significantly to increase rainfall going into the watershed or HAMON_COEF had to be decreased to reduce the amount of water leaving the watershed through evapotranspiration. Adjustments of the magnitude required to achieve a proper water balance, however, would result in factor values not consistent with the adjacent hydrologically similar watersheds.

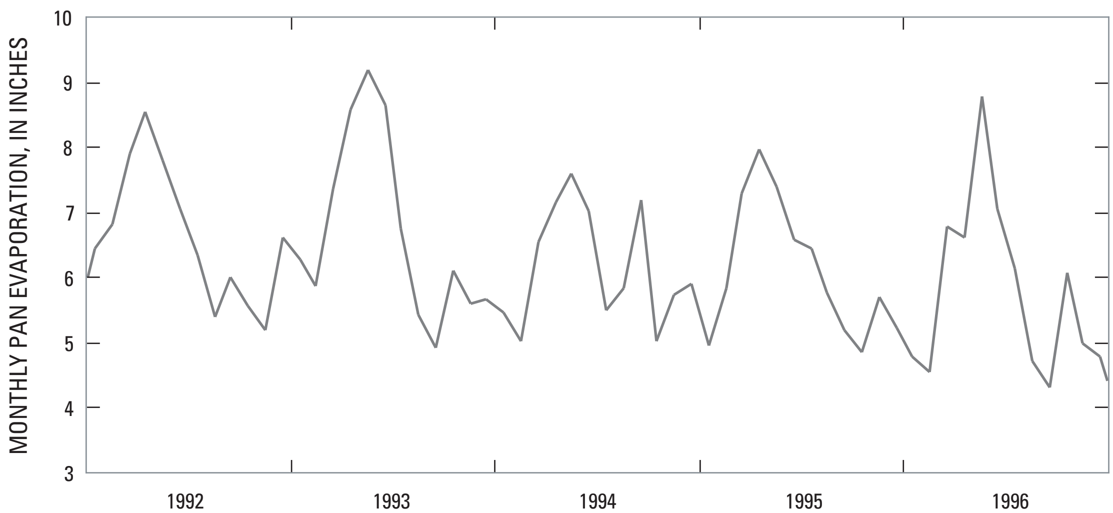

Figure 18. Seasonal variation in monthly pan evaporation data, Taguac, Guam, 1992–96.

The exact hydrologic drainage boundary of the Almagosa River watershed is uncertain in areas where the limestone terrain (fig. 6) exerts a significant influence on the movement of ground water. Two lines of evidence indicate that the ground-water flow system contributing to surface-water runoff in the Almagsoa River watershed may be larger than the topographically defined surface-water basin. First, of the total of 1,560 acres of limestone terrain in the region (fig. 19), only about 16 percent lies within the Almagosa River watershed. Yet ground-water discharge at the Almagosa Springs (among dozens of other springs in the region) accounted for almost 50 percent of the total spring flow produced by the total limestone area (Ward and others, 1965). The disproportionate contribution may indicate that additional limestone areas are contributing to the Almagosa Springs. Second, as shown in the geologic cross section map (fig. 19), the contact between limestone and volcanic rocks (beyond the surface-drainage divide) appears to slope slightly toward the Almagosa River watershed. This suggests that subsurface water moving along this contact would preferentially flow from adjacent areas into the Almagosa River watershed.

To more accurately define the ground-water system in the Almagosa River watershed, an additional HRU was included in the PRMS model. The added HRU intercepts subsurface and ground-water flows from the extended limestone terrain located beyond the topographically defined Almagosa River watershed boundaries. Parameters were set to prevent surface runoff contribution from this additional HRU to the Almagosa River watershed. Because the exact delineation of the HRU was not known, its area was determined using the PRMS in a trial and error manner. To achieve agreement between the simulated total runoff volume and the measured total runoff volume in the Almagosa River watershed, the area of the added HRU was determined to be 250 acres.

Parameter Adjustments

A sensitivity routine in the PRMS (Leavesley and others, 1983) was used to identify model parameters for which small changes in values could cause large changes in modeling results. In the Maulap, Almagosa, and Imong River watersheds, model results were most sensitive to a parameter controlling expansion of contributing areas for surface runoff (SMIDX_EXP) and a parameter describing the soil moisture capacity of the soil profiles (SOIL_MOIST_MAX) during both wet and dry seasons. Model results also were fairly sensitive to a surface-runoff-related parameter (CAREA_MAX) during the wet season and parameters related to subsurface and ground-water flows (GWFLOW_COEF, SOIL2GW_MAX, SSR2GW_RATE, and SSRCOEF_SQ) in the dry season.

A trial-and-error adjustment of the parameters to which the model was sensitive was performed to adjust the volume and timing of the simulated runoff hydrograph. The timing and magnitude of measured hydrograph peaks were used to adjust parameters controlling expansion of contributing areas for surface runoff and parameters describing soil moisture. The shape of the base-flow recession was used to adjust parameters related to subsurface and ground-water flows.

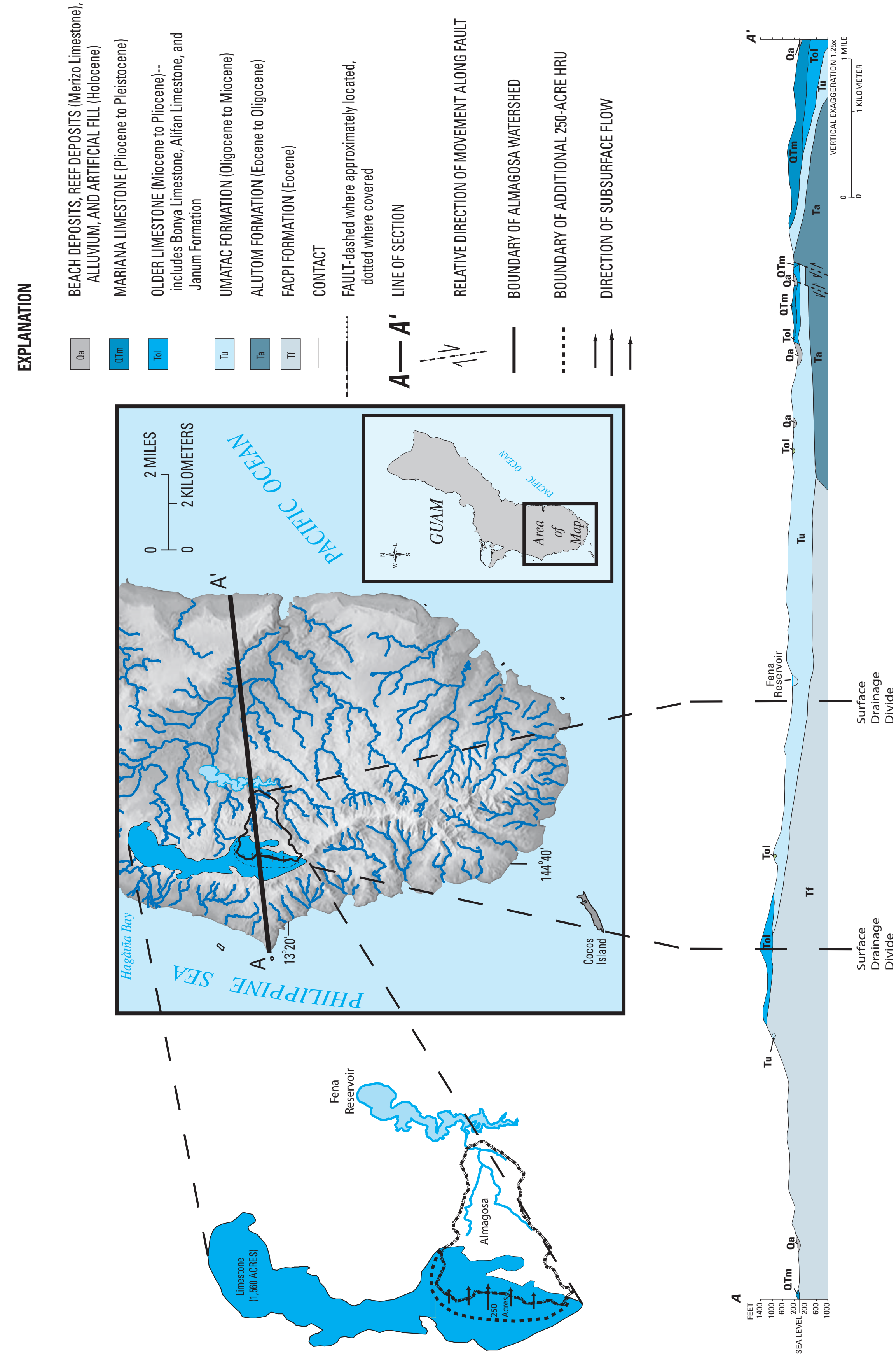

Figure 19. Almagosa River watershed, Guam. (Modified from Tracey and others, 1964.)

The manual calibration process was facilitated by the use of an interactive interface supported by the MMS. Measured and simulated runoff hydrographs were visually compared after each parameter adjustment. Statistical comparisons of flow volume, distribution of errors during dry season months, and coefficient of efficiency (Nash and Sutcliffe, 1970) also were examined to determine if adjustments improved model simulations. The process was repeated several times before values of parameters were accepted as final for use in the calibrated model. Lastly, an automated calibration technique developed by Rosenbrock (1960) that is an option in the PRMS was performed to examine if further improvement could be achieved. Because the automated calibration technique did not significantly improve model results, no further adjustments were made to the manually calibrated parameter values. The automated calibration technique is briefly described in the PRMS manual (Leavesley and others, 1983).

A high degree of similarity exists between watershed characteristics in the ungaged areas and in the three gaged river watersheds. As a result, transfer of calibrated model coefficients and parameters from the gaged to the ungaged areas is considered reasonable and valid. When parameter values for similar watershed characteristics differed, average values from the three gaged watersheds were used. No further adjustment was made to the transferred values. The calibrated values for all parameters and coefficients used for daily runoff computations for all three gaged watersheds and the ungaged area are listed in tables 3 through 7.

Table 3. Parameters and coefficients for daily-mode runoff computation for Maulap River Watershed, Guam.

[**Reservoir:** Volcanic ground-water and subsurface reservoirs are specified by index numbers HRU_GWRES and HRU_SSRES of 1 (see table 2). Limestone ground-water and subsurface reservoirs are specified by index numbers HRU_GWRES and HRU_SSRES of 2 (see table 2). Parameter definitions are shown in table 1]

Parameter or coefficient	Hydrologic-response unit									
	1	2	3	4	5	6	7	8	9	10
CAREA_MAX	0.791	0.703	0.703	0.703	0.703	0.527	0.264	0.264	0.703	0.703
COVDEN_SUM	.78	.65	.78	.55	.78	.65	.78	.78	.78	.78
COVDEN_WIN	.78	.65	.78	.55	.78	.65	.78	.78	.78	.78
SMIDX_COEF	.0018	.0018	.0018	.0018	.0018	.0015	.0015	.0015	.0018	.0018
SMIDX_EXP	.262	.244	.255	.285	.255	.244	.244	.244	.255	.255
SOIL2GW_MAX	.064	.144	.064	.200	.064	.600	.600	.600	.064	.064
SOIL_MOIST_INIT	2.70	2.70	2.70	1.80	2.70	1.80	.09	.09	2.70	2.70
SOIL_MOIST_MAX	7.646	7.646	7.646	5.012	7.646	5.012	1.809	1.809	7.646	7.646
SOIL_RECHR_INIT	.30	.30	.30	.30	.30	.30	.05	.05	.30	.30
SOIL_RECHR_MAX	1.95	1.95	1.95	2.25	1.95	2.25	.66	.66	1.95	1.95
SRAIN_INTCP	.09	.06	.09	.05	.09	.06	.08	.09	.08	.09
WRAIN_INTCP	.09	.06	.09	.05	.09	.06	.08	.09	.08	.09
	Reservoir									
	Volcanic	Limestone								
GWFLOW_COEF	0.009	0.050								
GWSTOR_INIT	7.0	1.3								
SSR2GW_RATE	.016	.25								
SSRCOEF_LIN	.0017	.0060								
SSRCOEF_SQ	.005	.200								
SSSTOR_INIT	2.0	.0								

Table 4. Parameters and coefficients for daily-mode runoff computation for Almagosa River Watershed, Guam.

[**Reservoir:** Volcanic ground-water and subsurface reservoirs are specified by index numbers HRU_GWRES and HRU_SSRES of 1 (see table 2). Limestone ground-water and subsurface reservoirs are specified by index numbers HRU_GWRES and HRU_SSRES of 2 (see table 2). Parameter definitions are shown in table 1]

Parameter or coefficient	Hydrologic-response unit									
	1	2	3	4	5	6	7	8	9	10
CAREA_MAX	0.671	0.596	0.447	0.223	0.223	0.596	0.373	0.596	0.596	0.001
COVDEN_SUM	.78	.78	.78	.78	.78	.55	.65	.70	.78	.78
COVDEN_WIN	.78	.78	.78	.78	.78	.55	.65	.70	.78	.78
SMIDX_COEF	.0018	.0018	.0018	.0015	.0015	.0018	.0015	.0018	.0018	.0010
SMIDX_EXP	.282	.274	.242	.225	.225	.307	.225	.250	.274	.001
SOIL2GW_MAX	.064	.064	.600	.600	.600	.200	.400	.144	.064	.600
SOIL_MOIST_INIT	1.725	1.806	.444	.401	.400	1.086	1.580	1.716	1.805	.531
SOIL_MOIST_MAX	7.463	7.463	1.771	1.771	1.771	4.892	6.773	7.463	7.463	1.771
SOIL_RECHR_INIT	.30	.30	.05	.05	.05	.30	.30	.30	.30	.05
SOIL_RECHR_MAX	1.95	1.95	.66	.66	.66	2.25	2.10	1.95	1.95	.66
SRAIN_INTCP	.09	.09	.09	.09	.09	.05	.06	.08	.09	.09
WRAIN_INTCP	.09	.09	.09	.09	.09	.05	.06	.08	.09	.09
	Reservoir									
	Volcanic	Limestone								
GWFLOW_COEF	0.0108	0.0210								
GWSTOR_INIT	8.9	7.3								
SSR2GW_RATE	.025	.200								
SSRCOEF_LIN	.0017	.006								
SSRCOEF_SQ	.005	.250								
SSSTOR_INIT	1.7	.0								

Table 5. Parameters and coefficients for daily-mode runoff computation for Imong River Watershed, Guam.

[**Reservoir:** Volcanic ground-water and subsurface reservoirs are specified by index numbers HRU_GWRES and HRU_SSRES of 1 (see table 2). Parameter definitions are shown in table 1]

Parameter or coefficient	Hydrologic-response unit						
	1	2	3	4	5	6	7
CAREA_MAX	0.659	0.586	0.586	0.586	0.586	0.586	0.586
COVDEN_SUM	.78	.78	.55	.55	.78	.55	.78
COVDEN_WIN	.78	.78	.55	.55	.78	.55	.78
SMIDX_COEF	.0018	.0018	.0018	.0018	.0018	.0018	.0018
SMIDX_EXP	.271	.264	.295	.295	.264	.295	.264
SOIL2GW_MAX	.066	.066	.206	.206	.066	.206	.066
SOIL_MOIST_INIT	1.969	1.969	1.159	1.159	1.969	1.159	1.969
SOIL_MOIST_MAX	7.645	7.645	5.011	5.011	7.645	5.011	7.645
SOIL_RECHR_INIT	.30	.30	.30	.30	.30	.30	.30
SOIL_RECHR_MAX	1.69	1.69	1.95	1.95	1.69	1.95	1.69
SRAIN_INTCP	.09	.09	.05	.05	.09	.05	.09
WRAIN_INTCP	.09	.09	.05	.05	.09	.05	.09
	Reservoir						
	Volcanic						
GWFLOW_COEF	0.0152						
GWSTOR_INIT	6.4						
SSR2GW_RATE	.025						
SSRCOEF_LIN	.0017						
SSRCOEF_SQ	.005						
SSSTOR_INIT	1.7						

Table 6. Parameters and coefficients for daily-model runoff computation defined for ungaged areas, Fena Valley Watershed, Guam.

[**Reservoir:** Volcanic ground-water and subsurface reservoirs are specified by index numbers HRU_GWRES and HRU_SSRES of 1 (see table 2). Parameter definitions are shown in table 1]

Parameter or coefficient	Hydrologic-response unit									
	1	2	3	4	5	6	7	8	9	10
CAREA_MAX	0.703	0.683	0.532	0.683	0.683	0.532	0.683	0.532	0.532	0.703
COVDEN_SUM	.55	.65	.78	.78	.78	.78	.78	.78	.78	.67
COVDEN_WIN	.55	.65	.78	.78	.78	.78	.78	.78	.78	.67
SMIDX_COEF	.0018	.0018	.0018	.0018	.0018	.0018	.0018	.0018	.0018	.0018
SMIDX_EXP	.260	.290	.290	.240	.260	.310	.260	.290	.290	.305
SOIL2GW_MAX	.064	.12	.12	.05	.064	.375	.064	.12	.12	.064
SOIL_MOIST_INIT	1.969	1.969	1.969	1.435	1.969	1.159	1.969	1.969	1.969	1.969
SOIL_MOIST_MAX	7.555	7.645	7.645	5.813	7.555	5.011	7.555	7.645	7.645	7.555
SOIL_RECHR_INIT	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30
SOIL_RECHR_MAX	1.95	1.95	1.95	2.25	1.95	2.25	1.95	1.95	1.95	1.95
SRAIN_INTCP	.06	.06	.09	.06	.08	.08	.07	.09	.08	.08
WRAIN_INTCP	.06	.06	.09	.06	.08	.08	.07	.09	.08	.08
	Reservoir									
	Volcanic									
GWFLOW_COEF	0.013									
GWSTOR_INIT	7.4									
SSR2GW_RATE	.0231									
SSRCOEF_LIN	.0017									
SSRCOEF_SQ	.005									
SSSTOR_INIT	1.8									

Table 7. Monthly air temperature coefficients for evapotranspiration computation, HAMON_COEF, for gaged and ungaged watersheds in the Fena Valley Watershed, Guam.

Month	Watershed			
	Maulap	Almagosa	Imong	Ungaged
Jan.	0.0062	0.0055	0.0058	0.0055
Feb.	.0068	.0065	.0068	.0065
Mar.	.0079	.0075	.0078	.0075
Apr.	.0085	.0075	.0081	.0075
May	.0085	.0080	.0083	.0080
June	.0079	.0070	.0073	.0070
July	.0066	.0060	.0066	.0060
Aug.	.0057	.0050	.0053	.0050
Sept.	.0068	.0065	.0068	.0065
Oct.	.0062	.0055	.0058	.0055
Nov.	.0062	.0058	.0061	.0058
Dec.	.0063	.0060	.0063	.0060

Simulation Results

Simulation results from the updated PRMS model were examined both graphically and statistically. Comparisons of simulated and measured streamflow hydrographs for the calibration and verification periods for the three gaged watersheds are presented in figures 20–25. A semi-logarithmic scale was used in the plots to emphasize low flows during the dry season, when water availability is of greatest concern.

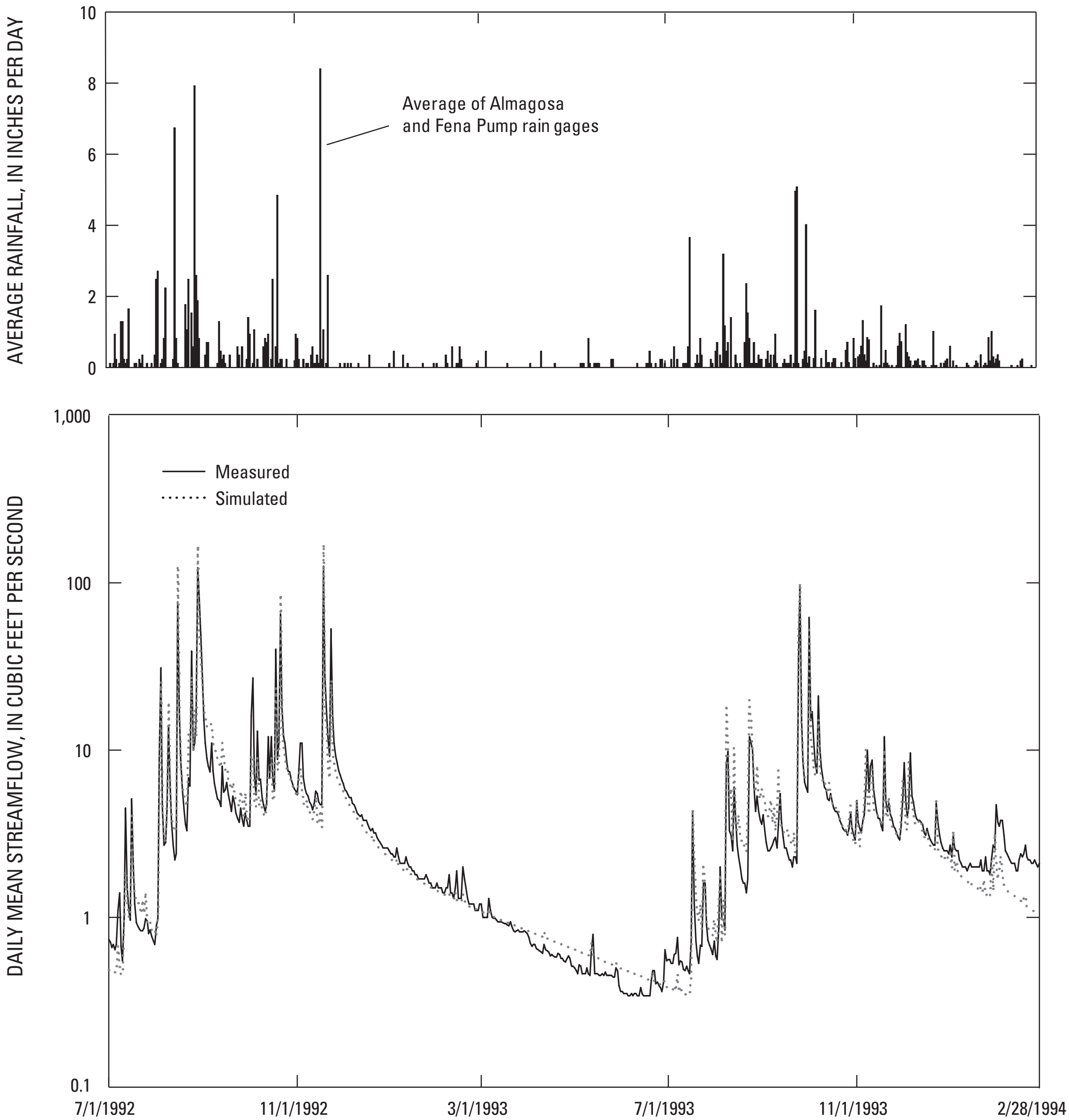

Figure 20. Measured average daily rainfall and measured and simulated daily streamflow for the calibration period at Maulap River watershed, Guam, July 1, 1992 – February 28, 1994.

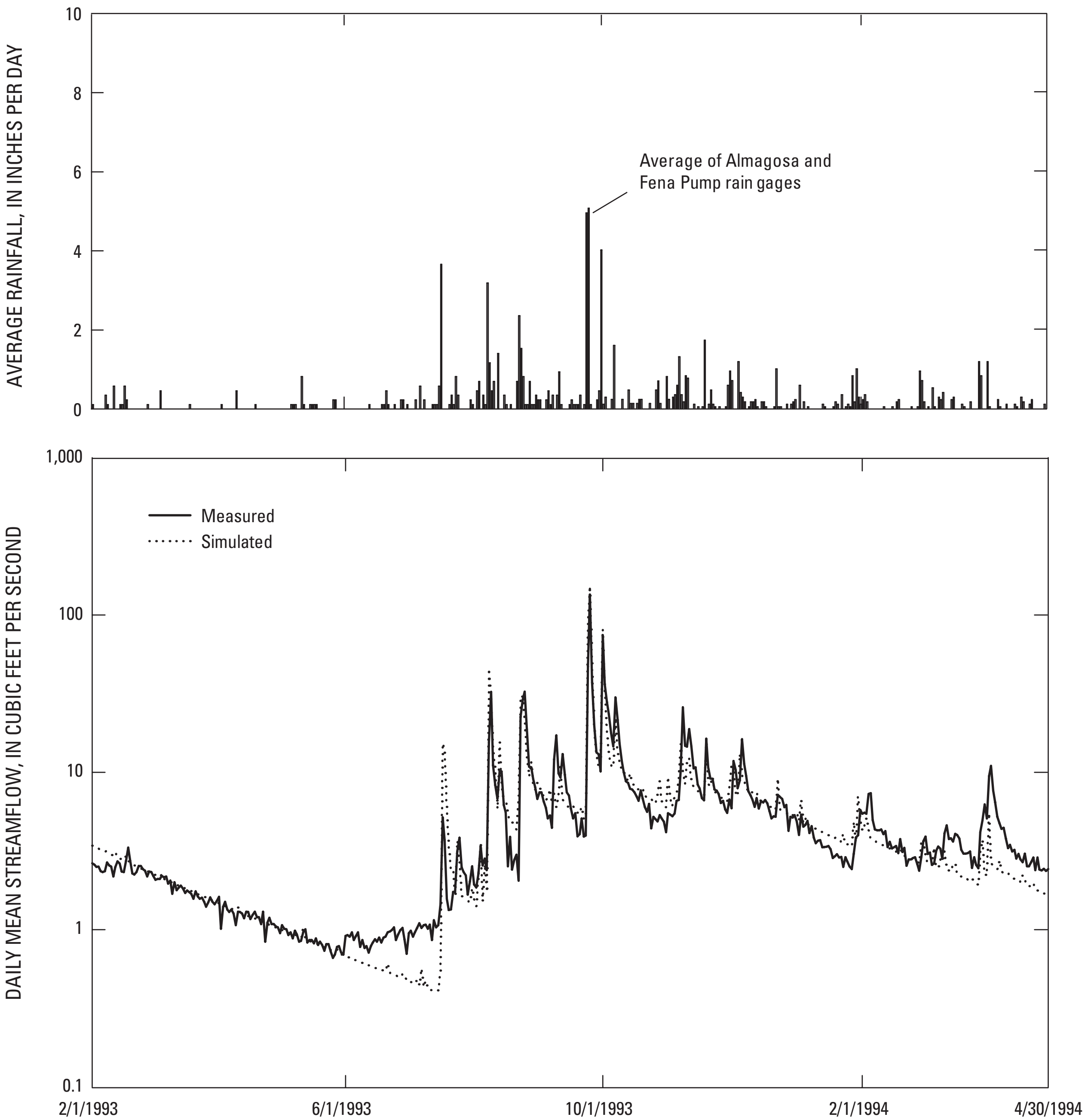

Figure 21. Measured average daily rainfall and measured and simulated daily streamflow for the calibration period at Almagosa River watershed, Guam, February 1, 1993 – April 30, 1994.

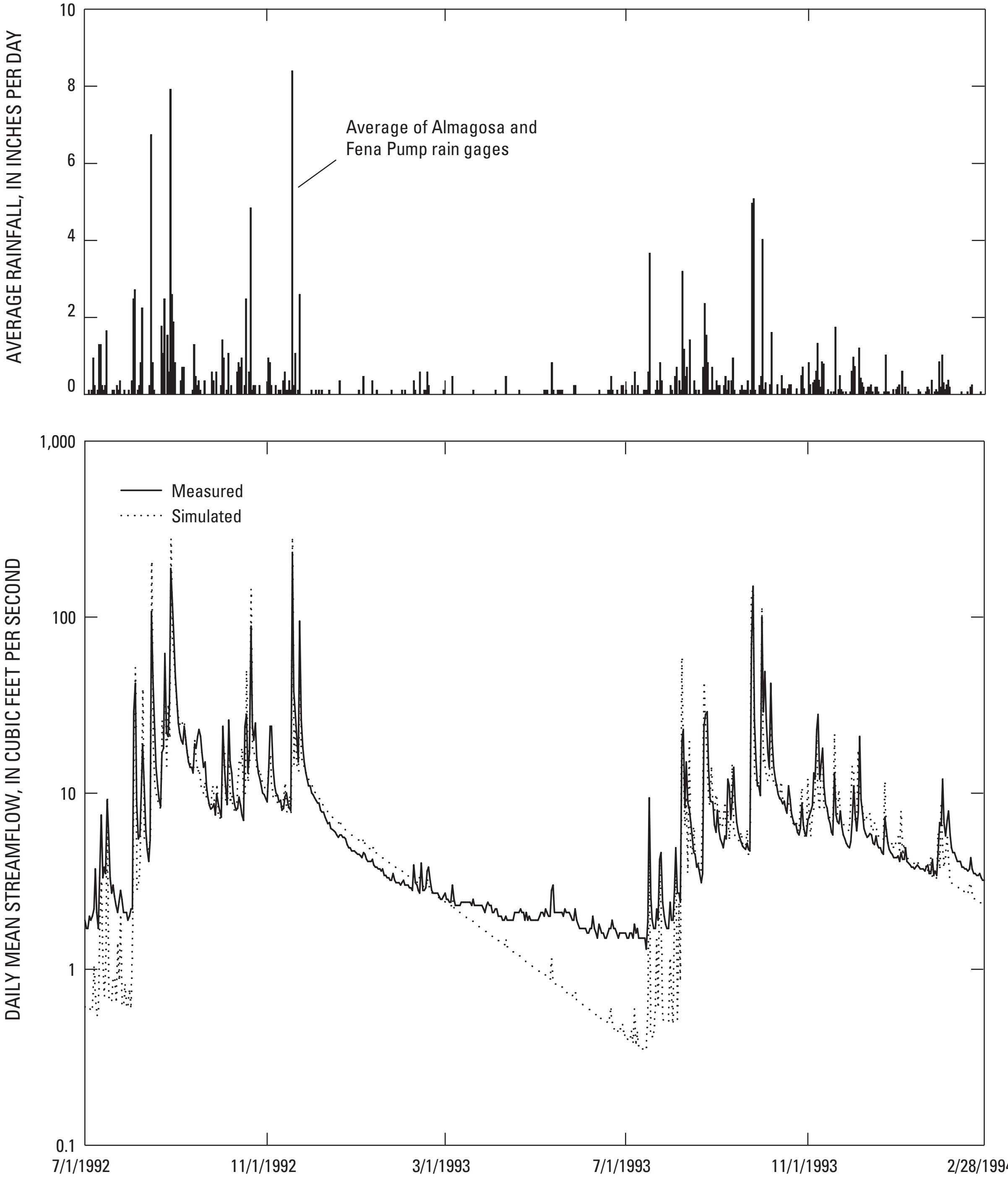

Figure 22. Measured average daily rainfall and measured and simulated daily streamflow for the calibration period at Imong River watershed, Guam, July 1, 1992 – February 28, 1994.

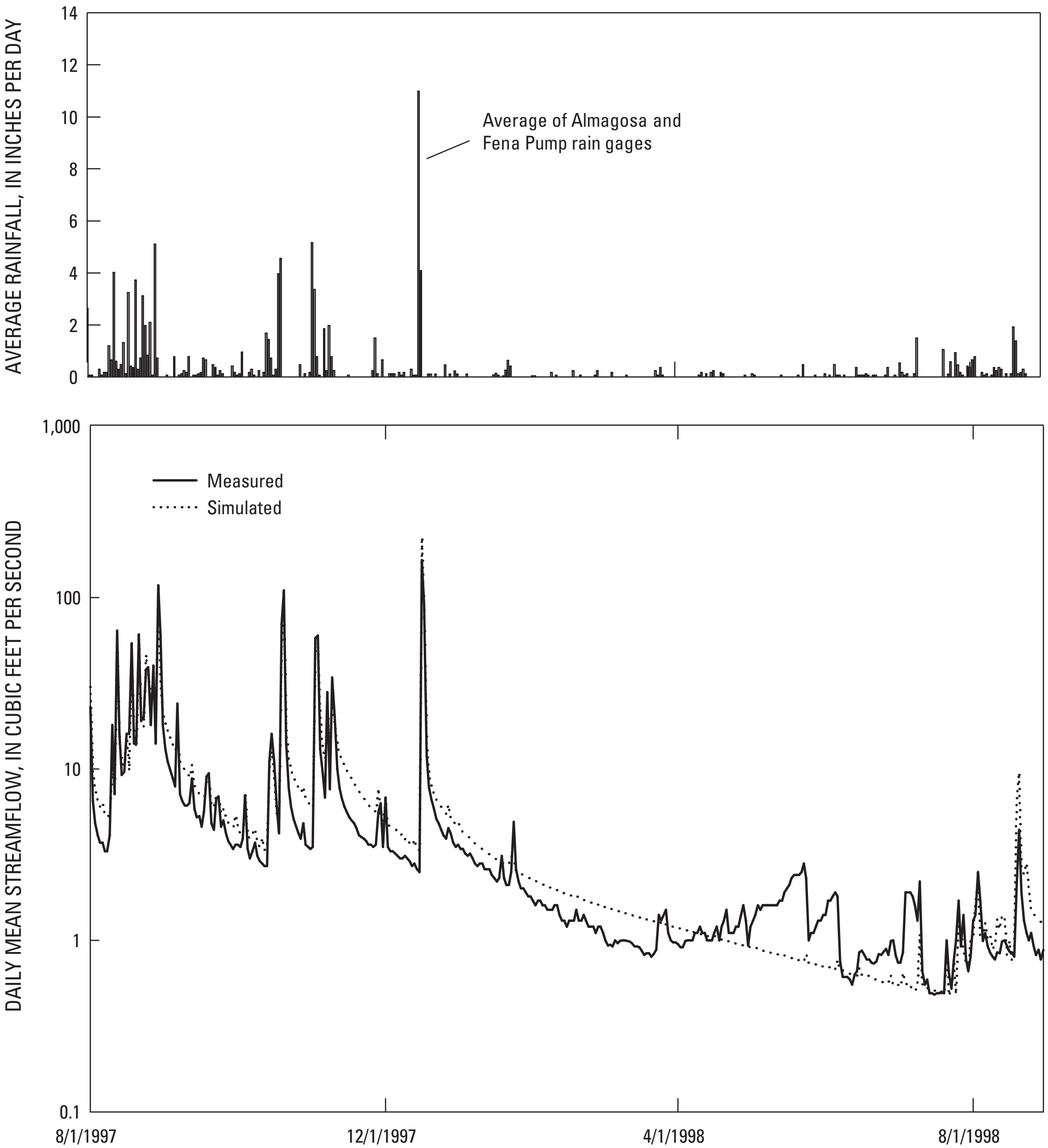

Figure 23. Measured average daily rainfall and measured and simulated daily streamflow for the verification period at Maulap River watershed, Guam, August 1, 1997 – August 30, 1998.

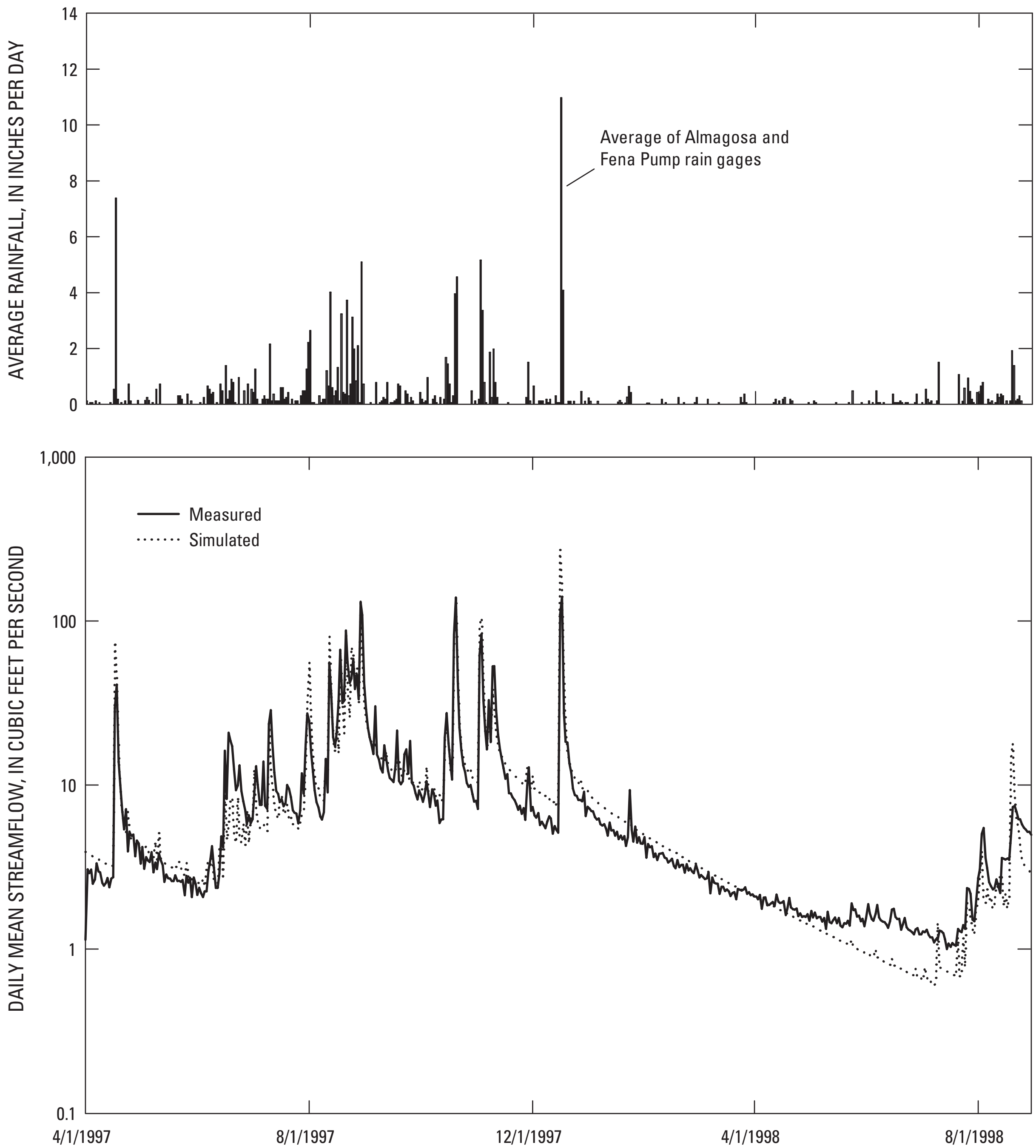

Figure 24. Measured average daily rainfall and measured and simulated daily streamflow for the verification period at Almagosa River watershed, Guam, April 1, 1997 – August 30, 1998.

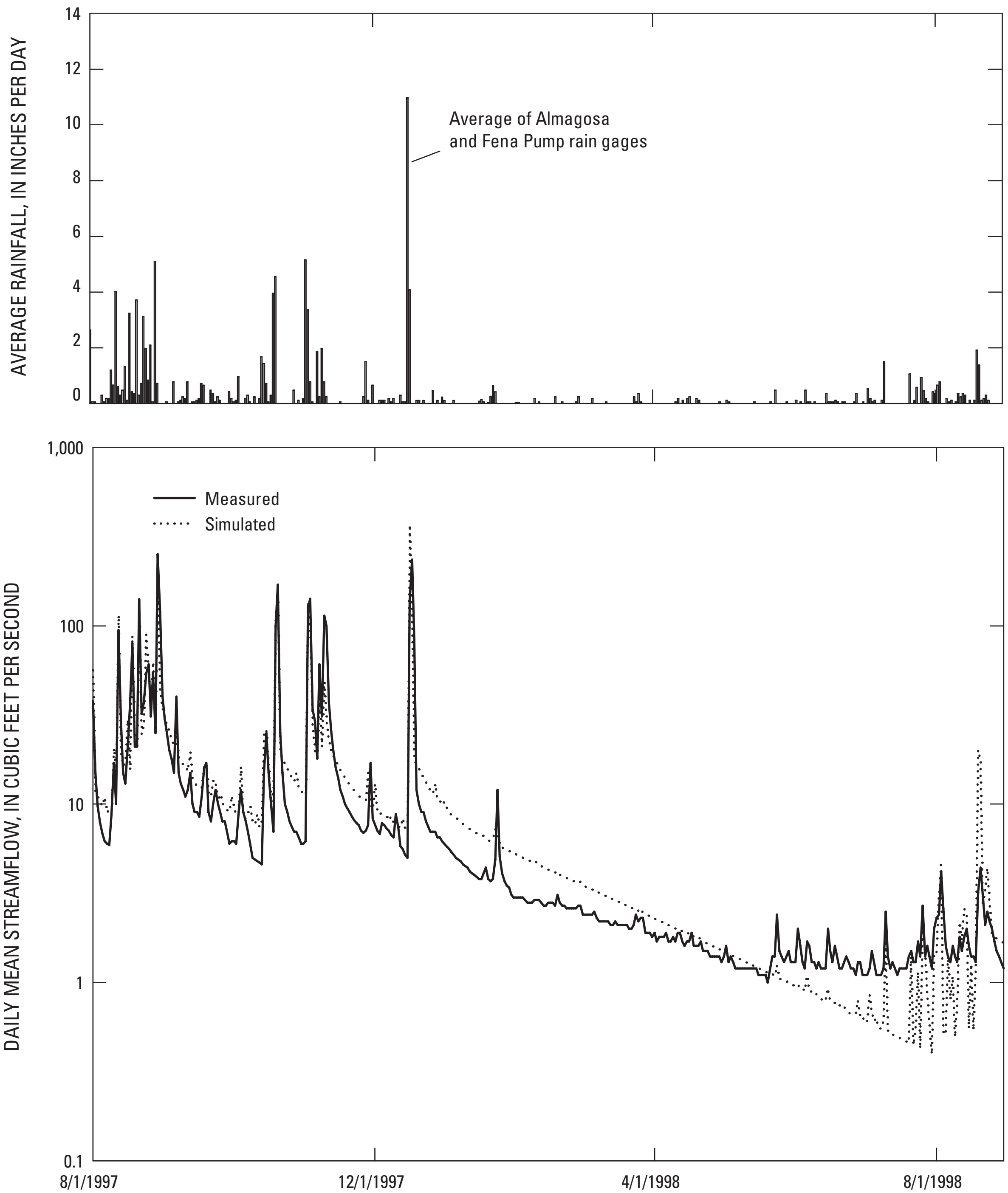

Figure 25. Measured average daily rainfall and measured and simulated daily streamflow for the verification period at Imong River watershed, Guam, August 1, 1997 – August 30, 1998.

Overall, the PRMS model simulated the timing and volume of streamflow for the three gaged watersheds reasonably well. Errors for the verification period were expected to be larger than those for the calibration period. The PRMS model was calibrated to obtain the best fit to the calibration period data while the verification period results represent an independent assessment of model utility. The model is sometimes limited in its ability to simulate the shape of complex base-flow recession hydrographs. Runoff at the onset of wet season (June – August) generally was underestimated, especially for the Imong River watershed. The underestimation may be the result of not having sufficient recharge to the ground-water and subsurface reservoirs to sustain base flow in May and June. This may be attributed to the size of soil storage used in the model because water moves to the ground-water and subsurface reservoirs only after satisfying the available water-holding capacity of the soil profile.

Statistical summaries of the accuracy of simulated daily and monthly mean streamflow for calibration, verification, and the entire simulation periods are shown in tables 8 and 9. Relative error in percent was selected as the measure of prediction error. Bias and a simple over-simulation rate in percent (number of overestimated months divided by the total number of monthly simulations) were computed to determine whether the model consistently overestimated or underestimated runoff. The coefficient of efficiency (Nash and Sutcliffe, 1970) was examined as a measure of the overall quality of model fit, with a value of 1 representing a perfect fit. The coefficient of efficiency is a widely used measure, which is analogous to the coefficient of multiple determination, R^2, used in regression analysis (Leavesley and others, 1983).

The accuracy of monthly simulation results is especially important because the reservoir water-balance model is run using a monthly time step with monthly runoff totals as input. The following discussion of the accuracy of model simulations is therefore focused primarily on monthly results. The PRMS model simulated runoff volume on a monthly scale for all three watersheds reasonably well. The monthly coefficient of efficiency for the entire simulation period was greater than 0.90 for all three watersheds (table 9). Relative errors and bias for the entire simulation period ranged from a low of -0.94 and 0.31 percent in the Almagosa River watershed to a high of 4.29 and 5.98 percent in the Imong River watershed. Over-simulation rates were very close to 50 percent for all three watersheds. Overall, simulation errors were lowest in the Almagosa River watershed.

Simulation errors for the Imong River watershed were greater than errors associated with the other two watersheds. A summary of measured and simulated runoff volumes for each simulation period (table 10) indicated that the runoff volume for the Imong River watershed was overestimated by 17.4 percent for the second verification period, whereas

Table 8. Errors in simulated daily mean streamflow for gaged watersheds in the Fena Valley Watershed, Guam.

Period	Relative error[1] (percent)	Bias[2] (percent)	Coefficient of efficiency[3]
Maulap River watershed			
Calibration (07-01-92 to 02-28-94)	2.58	0.46	0.84
Verification I (08-01-97 to 08-31-98)	13.72	6.70	.91
Verification II (10-01-99 to 09-30-2001)	18.29	8.40	.88
Entire period	11.74	5.09	.88
Almagosa River watershed			
Calibration (02-01-93 to 04-30-94)	-1.55	-0.64	0.85
Verification I (04-01-97 to 08-31-98)	-.10	5.00	.70
Verification II (10-01-99 to 09-30-2001)	11.56	-2.72	.87
Entire period	4.52	.48	.79
Imong River watershed			
Calibration (07-01-92 to 02-28-94)	-14.5	-2.26	0.78
Verification I (08-01-97 to 08-31-98)	16.62	3.31	.65
Verification II (10-01-99 to 09-30-2001)	27.10	17.62	.83
Entire period	10.13	6.16	.72

[1] Relative error: $\sum_{i=1}^{n}(e_i / O_i) / N \times 100.$

$$e_i = S_i - O_i,$$

where,

S_i is simulated runoff for day i
O_i is measured runoff for day i
N is number of measured values.

[2] Bias, as a percentage of mean measured runoff, $= \left(\sum_{i=1}^{n} e_i / \sum_{i=1}^{n} O_i \right) \times 100.$

[3] Coefficient of efficiency $= 1 - \left(\sum_{i=1}^{n} e_i^{\,2} / \sum_{i=1}^{n} e_{m_i}^{\,2} \right).$

$e_{m_i} = O_i - \overline{O}$, where $\overline{O}$ is mean measured runoff for full period of simulation.

Table 9. Errors in simulated daily mean streamflow for gaged watersheds in the Fena Valley Watershed, Guam.

Period	Relative error[1] (percent)	Bias[2] (percent)	Over-simulation rate (percent)	Coefficient of efficiency[3]
Maulap River watershed				
Calibration (07-01-92 to 02-28-94)	0.77	0.28	45.0	0.96
Verification I (08-01-97 to 08-31-98)	4.14	6.47	53.8	.97
Verification II (10-01-99 to 09-30-2001)	5.85	8.20	50.0	.93
Entire period	3.68	4.90	49.1	.96
Almagosa River watershed				
Calibration (02-01-93 to 04-30-94)	-3.23	-0.84	46.7	0.96
Verification I (04-01-97 to 08-31-98)	-1.94	4.82	47.1	.93
Verification II (10-01-99 to 09-30-2001)	1.20	-2.88	41.7	.96
Entire period	-.94	.31	44.6	.95
Imong River watershed				
Calibration (07-01-92 to 02-28-94)	-13.90	-2.42	45.0	0.97
Verification I (08-01-97 to 08-31-98)	9.32	3.13	61.5	.96
Verification II (10-01-99 to 09-30-2001)	16.72	17.42	62.5	.88
Entire period	4.29	5.98	56.1	.94

[1]Relative error: $\sum_{i=1}^{n}(e_i / O_i)/N \times 100.$

$$e_i = S_i - O_i,$$

where,

S_i is simulated runoff for month i
O_i is measured runoff for month i
N is number of measured values.

[2]Bias, as a percentage of mean measured runoff, $= \left(\sum_{i=1}^{n} e_i / \sum_{i=1}^{n} O_i\right) \times 100.$

[3]Coefficient of efficiency $= 1 - \left(\sum_{i=1}^{n} e_i^{2} / \sum_{i=1}^{n} e_{m_i}^{2}\right).$

$e_{m_i} = O_i - \overline{O}$, where $\overline{O}$ is mean measured runoff for full period of simulation.

the Maulap and Almagosa River watersheds were within 8.2 and -2.9 percent for the same period. The rainfall data used to calibrate the PRMS model are from rain gages located closer to the Maulap and Almagosa River watersheds than to the Imong River watershed and therefore may not always accurately represent rainfall conditions for the Imong River watershed. The accuracy of the measured streamflow data for Imong River also was questionable during a portion of the second verification period from September 6, 2000 to February 26, 2001, because the data were estimated and therefore rated poor. The PRMS model for the Imong River watershed did, however, compute total runoff volume within 6.0 percent over the entire simulation period. The model for the Maulap and Almagosa River watersheds computed total runoff volume within 4.9 and 0.3 percent over the entire simulation period.

Table 10. Summary of measured and simulated cumulative runoff for the gaged watersheds in the Fena Valley Watershed, Guam.

[**Runoff:** Measured inches of runoff = total volume of runoff/area of watershed. Percentage of difference = 100 × (Simulated – Measured)/Measured]

Period	Runoff		
	Measured (inches)	Simulated (inches)	Percentage of difference
Maulap River watershed			
Calibration (07-01-92 to 02-28-94)	91.37	91.63	0.3
Verification I (08-01-97 to 08-31-98)	73.68	78.45	6.5
Verification II (10-01-99 to 09-30-2001)	92.72	100.32	8.2
Entire period	257.77	270.40	4.9
Almagosa River watershed			
Calibration (02-01-93 to 04-30-94)	48.11	47.71	-0.8
Verification I (04-01-97 to 08-31-98)	99.90	104.71	4.8
Verification II (10-01-99 to 09-30-2001)	124.02	120.45	-2.9
Entire period	272.03	272.87	.3
Imong River watershed			
Calibration (07-01-92 to 02-28-94)	104.68	102.15	-2.4
Verification I (08-01-97 to 08-31-98)	83.27	85.88	3.1
Verification II (10-01-99 to 09-30-2001)	97.61	114.61	17.4
Entire period	285.56	302.64	6.0

Dry Season Runoff Simulation

In this study, the focus of the calibration of the PRMS model was primarily on dry-season conditions. Measured and simulated monthly mean runoff for the dry season (January through May) from the three gaged watersheds are summarized in table 11. The differences between measured and simulated monthly mean runoff for the Maulap River watershed ranged from -44.9 percent (February 1994) to 19.7 percent (April 1993) in the calibration period and from -53.2 percent (May 1998) to 75.0 percent (January 2001) in the verification period. For the Almagosa River watershed, the differences ranged from -43.5 (April 1994) to 20.5 percent (January 1994) in the calibration period and from -29.4 (May 2001) to 39.4 percent (January 2001) in the verification period. Consistent with the previous analysis, monthly mean runoff simulations for the dry seasons at the Imong River generally were poorer than those for the Maulap and Almagosa Rivers. For the Imong River watershed, the differences ranged from -60.1 percent (May 1993) to 19.6 percent (January 1993) in the calibration period and from -25.8 percent (May 2001) to 87.0 percent (May 2000) in the verification period.

The large overestimation error during May 2000 for the Imong River watershed probably is related to error in the rainfall estimate. Rainfall input to the PRMS model is estimated by averaging data collected from Fena pump and Almagosa rain gages. During May 2000, the average from these gages probably overestimated rainfall in the Imong River watershed located farther south. Measured rainfall records at four USGS rain gages indicated a localized storm occurred in the northern part of the study area in May 2000. Monthly total rainfall at the Windward Hills, Fena pump, and Almagosa rain gages averaged about 11 in.; farther to the south, the Umatac rain gage received only about 5 in.

Total measured and simulated runoff volumes during the dry seasons for each simulation period are summarized in table 12. The PRMS model simulated the total volume of dry season runoff for the entire simulation period at Maulap and Almagosa River watersheds within -3.66 and 5.37 percent. Simulation error for the Imong River watershed was higher at 10.74 percent but it was still within the limit of the accuracy of the measured streamflow record. Over-simulation rates for all three watersheds were close to 50 percent, which indicated that the positive and negative errors were distributed evenly.

Comparison to Previous Model

This section summarizes limitations identified in the previous PRMS model of the Fena Valley Watershed developed by Nakama (1994) and the modifications implemented as part of this study to address these limitations and to improve model performance. First, the previous model for the Almagosa River watershed was based on model parameters transferred from the adjacent Maulap and Imong River watersheds and the model was not calibrated and verified specifically for the Almagosa River watershed. The diversion data for the Almagosa Springs available for this study allowed the adjustment of measured Almagosa River flow data to reflect natural runoff conditions necessary for model calibration. Second, the availability of diversion data also facilitated the improvement of the PRMS model for the Almagosa River watershed to simulate ground-water contribution from areas of limestone terrain that lie outside of the topographically based divide for the Almagosa River watershed. Third, no rainfall data were available in the Fena Valley Watershed when the previous PRMS model for Maulap and Imong River watersheds was calibrated. Data from the Almagosa rain gage was incorporated in this study to correct this limitation. Fourth, ungaged areas of the watershed were not modeled by Nakama (1994). Development of the PRMS for the ungaged areas improved the estimation of total watershed runoff draining into the reservoir. Lastly, the updated PRMS model was improved by calibrating to current hydrologic conditions in the watershed, including an extreme ENSO event in both the calibration and verification periods.

One of the original objectives of the study was to compare the performances of the previous (original) and updated (current) versions of the PRMS model to evaluate which one provides better estimates of runoff. However, due to the limited availability of rainfall data from the new Almagosa rain gage (from June 1992) and pan-evaporation data (up to April 1998), the common period (fig. 14) for which all data required to run the two models concurrently were available was too short to make a meaningful comparison. Because the updated model was specifically calibrated using data collected from mid-1992 to mid-1994, it would not be appropriate to compare model results using this period. The only remaining common period for which all available data allowed running the two versions of the model concurrently was from August 1997 to April 1998, and there are only four dry season months in this period.

Table 11. Summary of measured and simulated dry season monthly mean runoff and associated error for the gaged watersheds in the Fena Valley Watershed, Guam.

[**Monthly mean runoff:** Percentage of difference = 100 × (Simulated - Measured) / Measured. **Abbreviations:** ft^3/s, cubic feet per second; n/a, not available]

Month	Monthly mean runoff								
	Maulap watershed			Almagosa watershed			Imong watershed		
	Measured (ft^3/s)	Simulated (ft^3/s)	Percentage of difference	Measured (ft^3/s)	Simulated (ft^3/s)	Percentage of difference	Measured (ft^3/s)	Simulated (ft^3/s)	Percentage of difference
Calibration period									
1993									
Jan.	1.93	1.78	-7.8	n/a	n/a	n/a	3.73	4.46	19.6
Feb.	1.40	1.26	-10.0	2.41	2.75	14.1	2.97	3.00	1.0
Mar.	.93	.95	2.2	1.76	1.81	2.8	2.38	1.97	-17.2
Apr.	.61	.73	19.7	1.19	1.20	.8	2.02	1.28	-36.6
May	.48	.57	18.8	.82	.82	.0	2.08	.83	-60.1
1994									
Jan.	2.26	1.78	-21.2	3.51	4.23	20.5	4.36	4.38	0.5
Feb.	2.45	1.35	-44.9	3.82	3.27	-14.4	4.33	2.98	-31.2
Mar.	n/a	n/a	n/a	3.35	2.48	-26.0	n/a	n/a	n/a
Apr.	n/a	n/a	n/a	3.79	2.14	-43.5	n/a	n/a	n/a
Verification period									
1997									
Apr.	n/a	n/a	n/a	6.25	8.31	33.0	n/a	n/a	n/a
May	n/a	n/a	n/a	2.96	3.43	15.9	n/a	n/a	n/a
1998									
Jan.	2.59	3.12	20.5	5.48	6.57	19.9	4.50	6.91	53.6
Feb.	1.39	1.87	34.5	3.48	4.02	15.5	2.79	4.31	54.5
Mar.	1.00	1.37	37.0	2.41	2.63	9.1	2.18	2.88	32.1
Apr.	1.12	1.04	-7.1	1.85	1.73	-6.5	1.65	1.88	13.9
May	1.71	.80	-53.2	1.53	1.16	-24.2	1.31	1.22	-6.9
2000									
Jan.	1.57	1.45	-7.1	2.62	3.49	33.2	2.56	3.52	37.5
Feb.	2.13	1.52	-28.6	3.98	3.31	-16.8	3.31	3.01	-9.1
Mar.	1.33	.96	-27.8	2.29	2.13	-7.0	1.77	1.76	-.6
Apr.	.86	.66	-23.3	1.42	1.35	-4.9	1.38	1.13	-18.1
May	2.06	2.04	-1.0	3.47	3.85	11.0	1.77	3.31	87.0
2001									
Jan.	1.32	2.31	75.0	3.93	5.48	39.4	3.51	5.35	52.4
Feb.	.85	1.42	67.1	2.90	3.43	18.3	2.45	3.36	37.1
Mar.	.85	1.04	22.4	2.21	2.25	1.8	2.16	2.22	2.8
Apr.	.96	.79	-17.7	1.64	1.49	-9.1	1.63	1.44	-11.7
May	.72	.62	-13.9	1.43	1.01	-29.4	1.28	.95	-25.8

Table 12. Total measured and simulated dry season runoff for the gaged watersheds in the Fena Valley Watershed, Guam.

[**Runoff:** Measured inches of runoff = total volume of runoff/area of watershed. Percentage of difference = 100 × (Simulated - Measured)/Measured]

Period	Runoff			
	Measured (inches)	Simulated (inches)	Percentage of difference	Over-simulation rate (percent)
Maulap River watershed				
Calibration (07-01-92 to 02-28-94)	9.45	7.95	-15.84	42.9
Verification I (08-01-97 to 08-31-98)	7.46	7.79	4.37	60.0
Verification II (10-01-99 to 09-30-2001)	12.08	12.19	0.90	30.0
Entire period	28.99	27.93	-3.66	40.9
Almagosa River watershed				
Calibration (02-01-93 to 04-30-94)	13.00	11.75	-9.61	50.0
Verification I (04-01-97 to 08-31-98)	15.27	17.71	15.98	70.0
Verification II (10-01-99 to 09-30-2001)	16.51	17.72	7.35	50.0
Entire period	44.78	47.18	5.37	56.0
Imong River watershed				
Calibration (07-01-92 to 02-28-94)	12.56	10.86	-13.53	42.9
Verification I (08-01-97 to 08-31-98)	7.20	9.93	37.89	80.0
Verification II (10-01-99 to 09-30-2001)	12.67	15.12	19.36	50.0
Entire period	32.43	35.91	10.74	54.5

Although results of the previous and updated models are not directly comparable, the average monthly coefficients of determination for the previous model and the coefficients of efficiency for the updated model provide some measure of comparison. In the previous USGS modeling study, the average monthly coefficients of determination for the Maulap, Almagosa, and Imong River watersheds were 0.94, 0.91, and 0.86, respectively (table 3 in Nakama, 1994). In the study reported here, the coefficients of efficiency for the entire period for the Maulap, Almagosa, and Imong River watersheds were 0.96, 0.95, and 0.94, respectively (table 9). Values for the updated model were all higher than those from the previous model. In addition, the estimate of runoff for the entire watershed undoubtedly improved as a result of the model calibration for the Almagosa watershed and the extension of the model to the ungaged areas. Total runoff from these two areas accounted for about 43 percent of total watershed area contributing runoff to the reservoir.

Model Uncertainties

Model simulation results are subject to various sources of uncertainty. Some uncertainties are inherent in the model structure and some are due to errors in the calibration input data and parameter estimates. Examples of inherent uncertainties in the PRMS model include simulations that oversimplify complex hydrologic processes and the failure of HRUs to adequately describe the heterogeneity of watershed characteristics. Most physically based models cannot fully account for the complexity and heterogeneity of processes occurring in the watershed (Hornberger and others, 1985).

The accuracy of the model calibration is dependent on the accuracy of the input data. Errors associated with the assumed distribution of rainfall over the watershed affect model results. For example, overestimation of rainfall on the Imong River watershed during May 2000 likely resulted in an overestimation of streamflow. In December 2000, the USGS installed a rain gage at Mount Jumullong Manglo, which is very close to the Imong River watershed. Data collected at this gage may provide better estimates of rainfall distribution in the Imong River watershed, and rainfall may be spatially distributed in the study watershed to improve simulation results. It also should be noted that the applicability of the model outside the range of flow conditions that occurred during the calibration and verification periods is uncertain.

The possible changes of vegetation type, density, and canopy interception as a result of two recent typhoons in 2002 were not addressed in this study. None of the model parameter values were changed to reflect the modified conditions. It is reasonable to assume, however, that changes in vegetation associated with the typhoons were of short duration, because Guam is located in a tropical setting and recovery of vegetation after storms is a rapid process.

Water-Balance Model

Seasonal fluctuations of water levels in Fena Valley Reservoir are controlled primarily by the magnitude of tributary inflows, timing of direct rainfall, and volume of water withdrawals from the reservoir. A generalized water-balance model can be used to describe how water levels in the Fena Valley Reservoir respond to various simulated inflow and outflow scenarios.

Description of Model

The water-balance model developed for Fena Valley Reservoir simply accounts for the interactions between various forms of water going into and out of the reservoir over monthly intervals. Fennessey (1995) determined that a monthly time step provides accurate reservoir-yield estimates. The model is based on a simple water-balance equation:

$$\text{CHANGE IN STORAGE} = \text{INFLOW} + \text{PRECIPITATION} - \text{OUTFLOW} - \text{EVAPORATION}\ . \quad (1)$$

The components of the reservoir water-balance model are shown in figure 26. Inflow components include direct runoff from the three gaged tributary rivers (draining 75 percent of the watershed), direct runoff from the ungaged land area (20 percent of the watershed area), and direct rainfall on the reservoir water surface (5 percent). Outflows from the reservoir include daily withdrawals for water supply, and direct evaporation from the water surface of the reservoir. Limited understanding of ground-water exchange in Fena Valley Reservoir prevented the estimation of the loss or gain of ground water. Ground-water inflow and outflow was assumed negligible relative to other inflow and outflow components. The low permeability of the clayey soil and volcanic rocks underlying the reservoir probably do not allow for appreciable water exchange between the reservoir and the ground-water body.

Model Development and Data

Data required for an accurate calibration of the water-balance model are reservoir bathymetry, reservoir-wide average evaporation, reservoir-wide average rainfall, monthly water levels, tributary inflows, and water-withdrawal data.

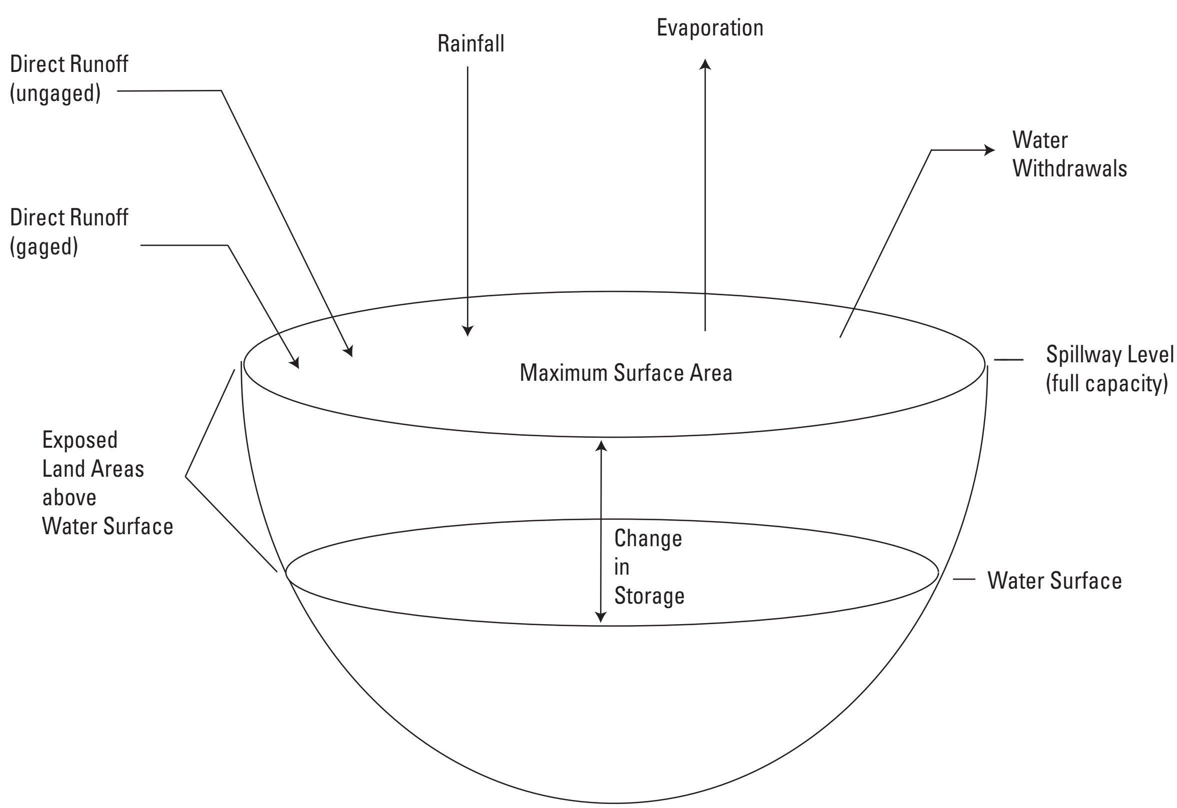

Figure 26. Components of water-balance model for the Fena Valley Reservoir, Guam.

The USGS conducted a bathymetric survey of the Fena Valley Reservoir in 1990 (Nakama, 1992). Relations between reservoir water level and water surface area and water level and storage volume were developed (fig. 27) on the basis of the survey. The water-balance model incorporated these relations to convert simulated month-end storage volume to water level and to determine month-end reservoir surface area.

Information pertaining to evaporation losses from the Fena Valley Reservoir is limited. Because pan-evaporation data are no longer collected near the reservoir, PET generated from the PRMS model, using the Hamon (1961) method, was applied in the water-balance model. The simulated monthly PET rate was multiplied by the corresponding month-end reservoir surface area to estimate volume of reservoir evaporation loss for the following month.

Rain falling on the water surface of the reservoir was considered direct inflow. The same average rainfall used in the PRMS model was applied directly to estimate rainfall inflow in the water-balance model. Monthly rainfall was estimated using the arithmetic average of the rainfall collected at the Almagosa and Fena pump rain gages with a rainfall adjustment factor applied. Data were averaged to account for the spatial variability of rainfall. Direct inflow to the reservoir from rainfall was computed as the monthly average rainfall times the maximum water-surface area of the reservoir. Maximum water-surface area was computed as the area when the water level in the reservoir was at the spillway crest. The water-surface area was held constant in the computations because according to field observations during dry seasons, reservoir land area above the water surface and below spillway level remained nearly saturated. It was assumed that all rain falling on these saturated areas ran off and contributed directly to reservoir inflow.

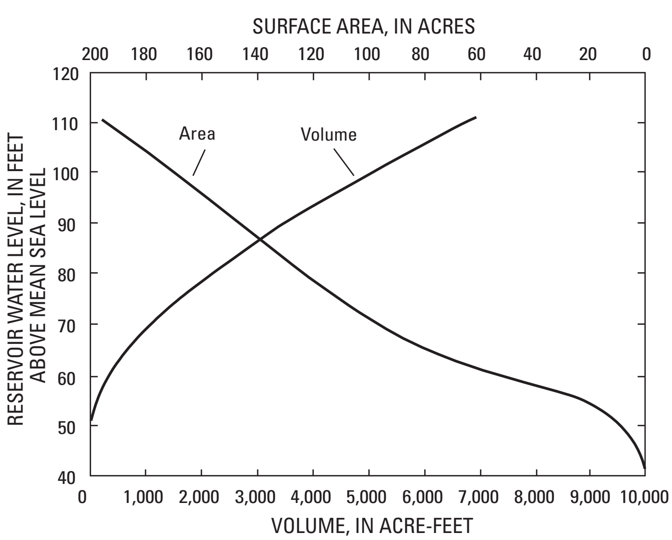

Figure 27. Water level-surface area and water level-capacity curves for the Fena Valley Reservoir, Guam, 1990 (Nakama, 1992).

Data for the remainder of the inflow and outflow components in the water-balance model, including gaged and ungaged direct runoff and water withdrawals, were applied without adjustment. Gaged, direct runoff was computed as the recorded runoff from the three gaged rivers. Adjustment was not necessary for the Almagosa River runoff data because recorded runoff at the gage reflected actual runoff going into the reservoir. Direct runoff from the ungaged land area was estimated using the PRMS model. Monthly total withdrawal data were metered and available from the Navy Public Works Center on Guam. Accuracy of the recorded withdrawal data is not known.

Actual month-end reservoir volumes were compared with the simulated month-end reservoir volumes to assess the accuracy of the water-balance model. Reservoir volume (water storage) was computed using month-end water level measurements collected at the USGS reservoir water-level gage and the documented relation between water level and reservoir storage volume (Nakama, 1992). The USGS gage (16849000) is near the Fena dam spillway at latitude 13°21’28”N., longitude 144°42’12”E (fig. 1). The accuracy ratings of the measured water-level data were mostly “good”.

The monthly reservoir water-balance computations are summarized in the following steps:

1. Given the reservoir water level at the beginning of a month, determine the initial reservoir volume (*Vi*) and surface area for the month using relations illustrated in figure 27.
2. Compute the reservoir evaporation volume for the month (*E*) based on initial surface area times the estimated evaporation rate for the month as computed by the PRMS model.
3. Determine the volume of water withdrawn (*W*) from the reservoir during the month based on data recorded by the Navy Public Works Center, Guam.
4. Estimate the volume of rain falling directly on the reservoir (*R*) during the month based on the surface area of the reservoir at spillway level times the monthly average rainfall.
5. Determine the volume of direct runoff input to the reservoir from the gaged watersheds using data from the three gaged rivers (*Sg*).
6. Determine the volume of direct runoff input to the reservoir from the ungaged areas using output from the PRMS model (*Su*).
7. Determine volume of water in the reservoir at the end of the month (V_f) using the reservoir water-balance equation:

$$V_f = V_i + R + S_g + S_u - E - W. \quad (2)$$

Model Calibration, Verification, and Results

The periods selected for calibration and verification of the water-balance model were dictated by the availability of concurrent data, similar to procedures used for the rainfall-runoff model. Periods of missing streamflow data and periods of questionable withdrawal data (due to pump-meter failure) limited model calibration and verification to four discontinuous periods between 1990 and 2001. Data for the periods January 1990 through January 1992 and May 1993 through February 1994 were used for model calibration, and data for the periods August 1997 through August 1998 and September 2000 through September 2001 were used for model verification. Calibration and verification periods were selected so that each included a drought period. The ability of the water-balance model to accurately simulate steep water-level declines during extreme dry conditions is critical to its utility as a management tool.

A relatively simple process was used to calibrate the water-balance model. Among all the water-balance components, direct evaporation and rainfall were the most uncertain and difficult to estimate. Because other components were comparatively well known, calibration involved adjusting only the correction coefficients associated with direct water-surface evaporation and rainfall. The coefficients were adjusted manually in a trial and error manner to fit simulated reservoir volumes to observed reservoir volumes. Calibration results indicated a rainfall correction coefficient of 1.05, which is similar to the adjustment applied in the rainfall-runoff model. A coefficient of 0.8 was applied to PET to estimate reservoir evaporation. The coefficient was expected to be close to 1.0 because evaporation from a large water surface is considered to be approximately equivalent to PET (Jones, 1992).

Monthly results for the calibration and verification periods are presented graphically in figures 28-29. The water-balance model generally simulated monthly reservoir

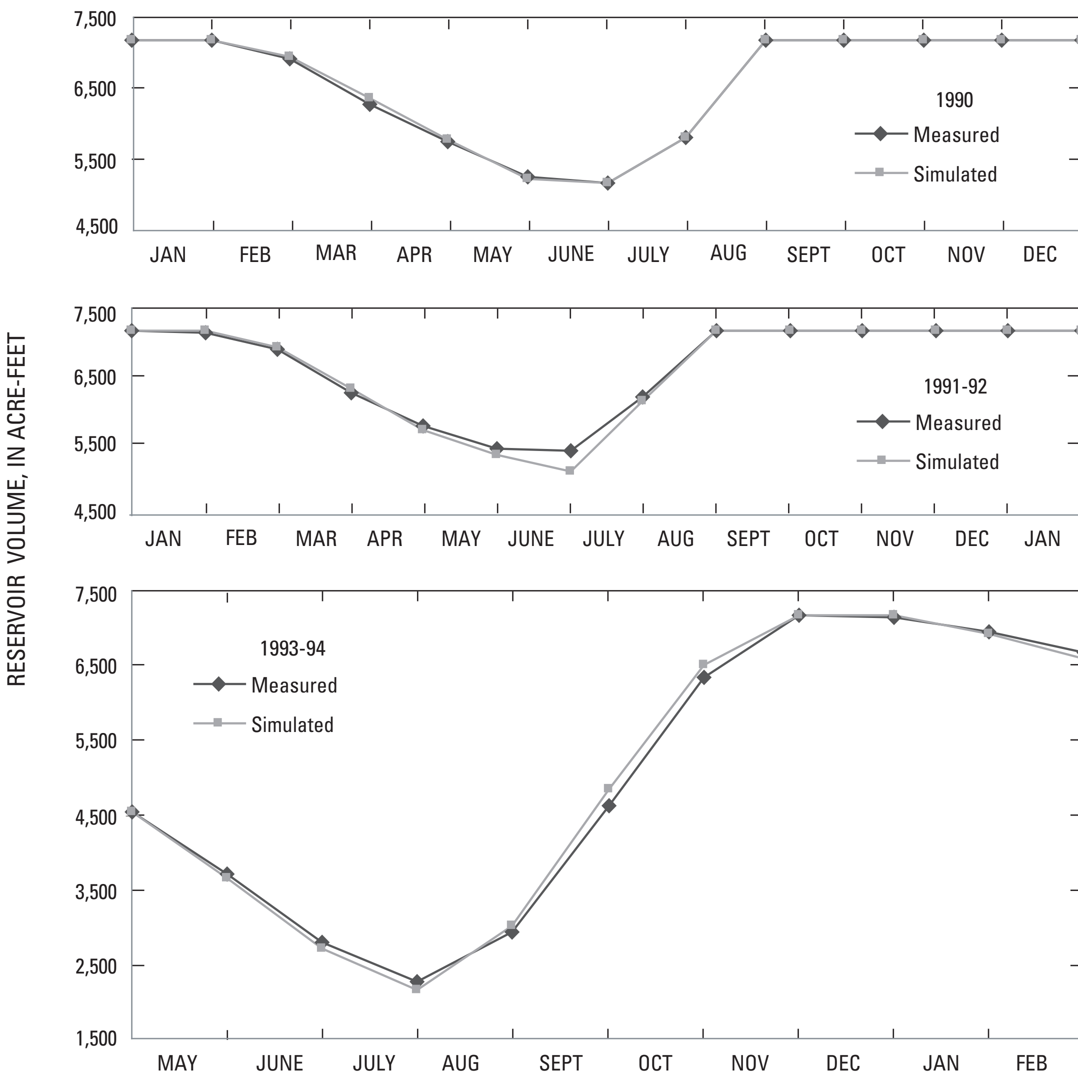

Figure 28. Measured and simulated month-end reservoir volume for the calibration periods, Fena Valley Reservoir, Guam, January 1990 – January 1992 and May 1993 – February 1994.

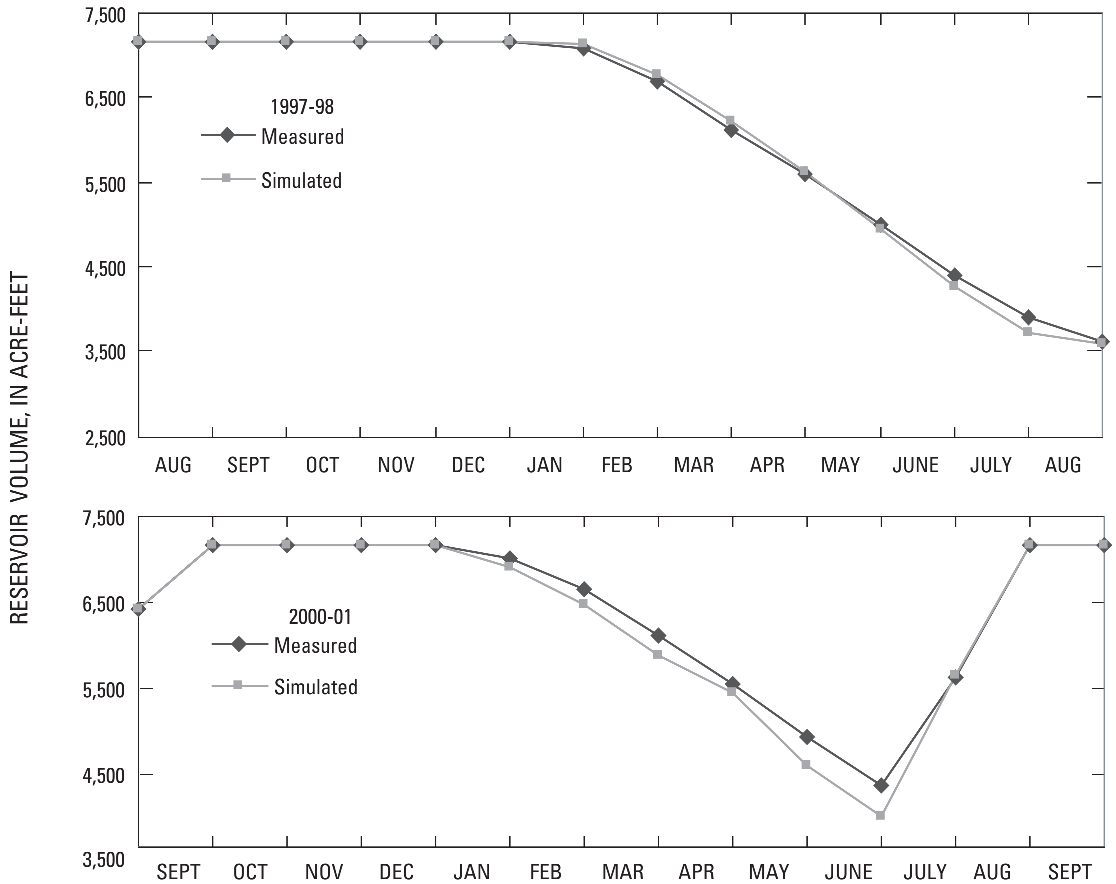

Figure 29. Measured and simulated month-end reservoir volume for the verification periods, Fena Valley Reservoir, Guam, August 1997 – August 1998 and September 2000 – September 2001.

storage volume with reasonable accuracy. For the calibration periods, errors associated with month-end reservoir-storage simulation for individual months ranged from 4.51 percent (208.7 acre-ft or 68.0 Mgal) to -5.90 percent (-317.8 acre-ft or -103.6 Mgal). For the verification periods, errors for individual months ranged from 1.69 percent (103.5 acre-ft or 33.7 Mgal) to -4.60 percent (-178.7 acre-ft or -58.2 Mgal). Bias and relative errors also were computed to evaluate model performance during both calibration and verification periods. Results are summarized in table 13. Monthly simulation bias ranged from -0.19 percent for the calibration period to -0.98 percent for the verification period; relative error ranged from -0.37 to -1.12 percent for the calibration and verification periods. Relatively small bias indicated that the model did not consistently overestimate or underestimate reservoir storage volume. Out of the 38 monthly simulations, 18 (47 percent) of the simulations resulted in overestimation, 19 (50 percent) resulted in underestimation, and 1 (3 percent) had zero error. Water-balance model errors did not display any systematic patterns, therefore supporting the assumption that ground-water inflows and outflows were negligible relative to other model components.

It should be noted that the above error analysis did not include the entire simulation period. Wet season months when observed water levels were above the spillway crest level or volumes above storage capacity of 7,180 acre-ft (2,340 Mgal) (Nakama, 1992) were not considered. Simulation above spillway crest level was not conducted because measured bathymetric information was available only up to spillway crest level and flow-over-spillway data were not available. The model assumed any simulated volume greater than the reservoir capacity to be 7,180 acre-ft (2,340 Mgal). In addition, simulated month-end volumes for May 2001 and June 2001 were not included in the error analysis because reservoir water levels from the USGS gaging station for those months were estimated.

Table 13. Errors in simulated month-end storage volume in the Fena Valley Reservoir, Guam.

Period	Relative error[1] (percent)	Bias[2] (percent)	Over-simulation rate (percent)
Calibration	-0.37	-0.19	52
Verification	-1.12	-.98	38
Entire period	-.63	-.46	47

[1]Relative error: $\sum_{i=1}^{n}(e_i / O_i) / N \times 100.$

$$e_i = S_i - O_i,$$

where,

S_i is simulated storage volume for month i
O_i is measured storage volume for month i
N is number of measured values.

[2]Bias, as a percentage of mean measured storage volume =

$$\left(\sum_{i=1}^{n} e_i / \sum_{i=1}^{n} O_i\right) \times 100.$$

Model Uncertainties

Although the water-balance equation is fairly simple, measures of accuracy regarding hydrologic phenomena are very complex. The difference between simulated and measured reservoir volume reflects errors associated with measuring tributary inflow, change in storage, and water withdrawal; estimating runoff from ungaged areas, rainfall and reservoir evaporation; and neglecting flow between the reservoir and the ground-water body. Lacking meteorological measurements over the reservoir surface, evaporation was the most difficult component to quantify and had the highest uncertainty among all water-balance components. Because evaporation is less than 7 percent of total outflow (table 14), errors associated with evaporation, however, are considered to have a relatively small effect on overall simulation results.

In terms of magnitude, the two largest water-budget components in the water-balance model are total watershed runoff and water withdrawal. The magnitude of these two components varies seasonally (fig. 30). Total watershed runoff, which is the sum of gaged tributary inflow and simulated ungaged area runoff, is significantly greater than the other components during the wet season. As a result, total inflow during the wet season is overwhelmingly greater than total outflow and the reservoir remains at full capacity during most of the wet season. The accuracies of rainfall and evaporation estimates during the wet season are therefore not very critical from a reservoir management perspective. From the onset of the dry season, reservoir volumes start to decline as total runoff decreases and water withdrawals become more significant (fig. 30). Water withdrawals normally account for a large part of total outflow (95 percent), so a small error could have a significant effect on the simulation results. This implies that the accuracy of the model calibration during the dry season is highly dependent on the accuracy of the water-withdrawal data.

Table 14. Water budget for the Fena Valley Reservoir during calibration and verification periods.

Period	Inflows (percentage of total inflow)		Outflows (percentage of total outflow)	
	Total runoff	Direct rainfall	Evapo-ration	Water with-drawals
Calibration				
Jan. 1990 to Jan. 1992	92.41	7.59	6.25	93.75
May 1993 to Feb. 1994	89.48	10.52	5.00	95.00
Verification				
Aug. 1997 to Aug. 1998	92.55	7.45	6.42	93.58
Sept. 2000 to Sept. 2001	91.19	8.81	6.44	93.56

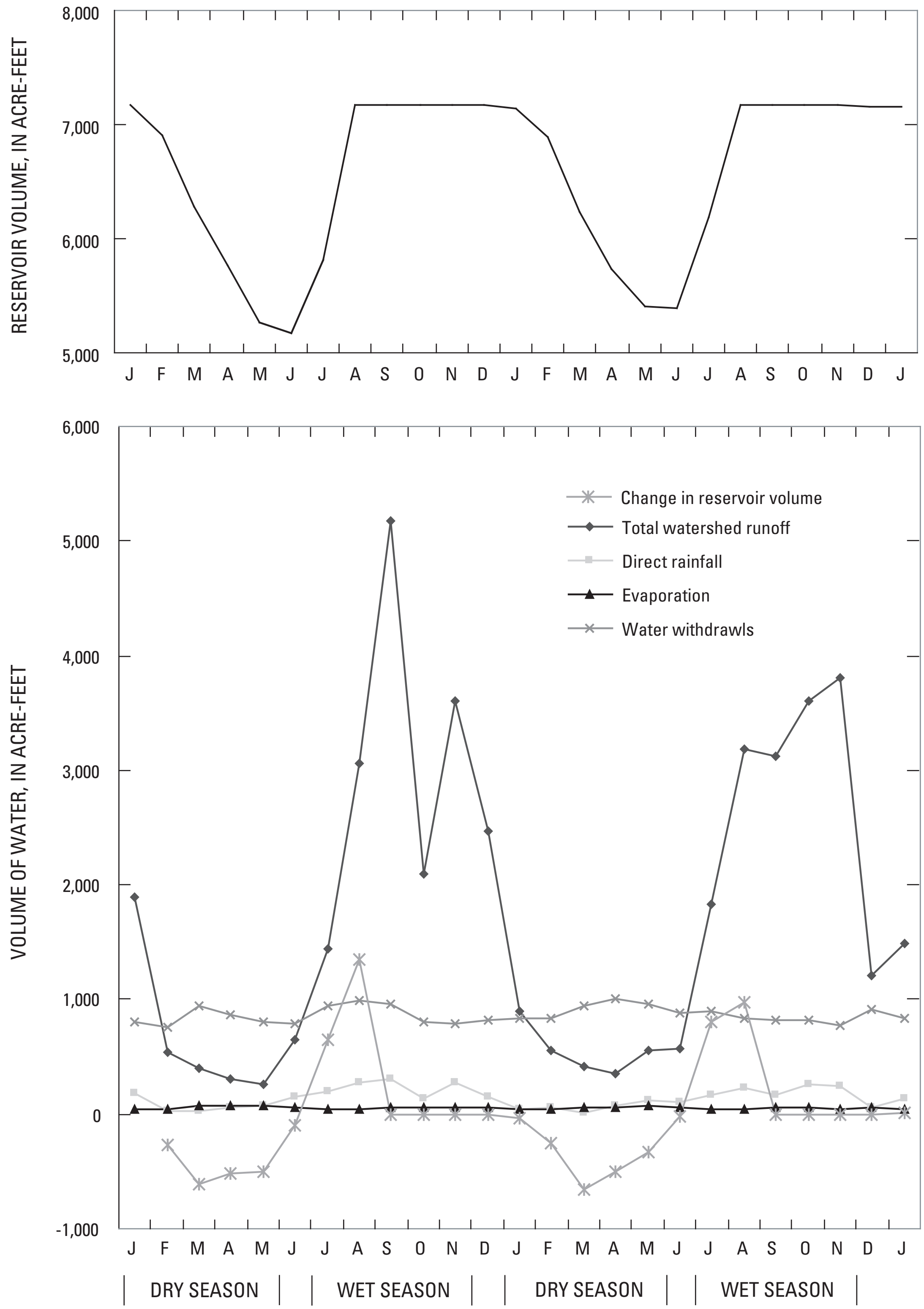

Figure 30. Monthly reservoir volume and water budget, Fena Valley Reservoir, January 1990 – January 2001.

Application and Evaluation of the Two-Step Modeling Procedure

The two-step modeling procedure (fig. 3) documented in this report is used as a management tool by the U.S. Navy to estimate the response of Fena Valley Reservoir to a variety of rainfall and water-withdrawal scenarios. The first step involves application of the PRMS to estimate monthly total runoff for the three gaged watersheds and ungaged areas in the Fena Valley Watershed. The second step involves use of the monthly runoff and potential evapotranspiration estimates from the PRMS as input to the water-balance model to estimate water-level changes in the reservoir. Estimates of future water availability in the reservoir vary depending on the range of rainfall and water-withdrawal scenarios being evaluated.

Rainfall scenarios commonly applied in the PRMS and water-balance models are long-term average monthly rainfall and current ENSO rainfall projections provided by the Pacific ENSO Application Center at the University of Hawaii[2]. ENSO rainfall projections are reported as a percentage of long-term average monthly rainfall. The long-term average monthly rainfall for the updated models was computed using the entire period of record for Almagosa and Fena Pump rain gages. Because of relatively short period of record (1990–2001) available for these two gages, the average monthly values were adjusted to represent long-term conditions using data from the adjacent Windward Hill rain gage, which was operated from 1974 to 2001. The adjusted long-term average monthly rainfall values can be used directly in the water-balance model because it is applied on a monthly time step. The PRMS model, however, is applied on a daily time step and requires daily rainfall data to compute monthly runoff and potential evapotranspiration estimates. Monthly rainfall projections are partitioned into daily time steps by following historical rainfall patterns recorded at the Almagosa and Fena Pump rain gages. The pattern used to partition rainfall projections for the month of June, for example, is based on the June during which the recorded rainfall at either gage was the closest to the adjusted long-term average June rainfall. The same technique is applied to each of the remaining months. This method assumes that historical rainfall pattern at the Almagosa and Fena Pump rain gages are reasonable representations of daily rainfall patterns for the monthly rainfall projections being modeled.

Earlier parts of this report focus on the accuracies of the PRMS and water-balance models individually. Measured daily rainfall was used as input in the evaluation of the PRMS model, and measured monthly rainfall and runoff data were used as input in the evaluation of the water-balance model. To evaluate the performance of the two-step modeling procedure as a whole, runoff simulated using the PRMS model was used as input in the water-balance model. Daily rainfall applied in the PRMS model was simulated by distributing the measured monthly total using the method as discussed above.

Periods in 1993 and 1998, each including an ENSO event, were selected for the evaluation of the two-step modeling procedure. Monthly reservoir storage volumes computed using both measured and simulated daily rainfall were compared to measured reservoir storage volumes (fig. 31). Differences between computed results using measured and simulated rainfall were used to indicate errors associated with using simulated rainfall patterns in the modeling procedure. The modeling procedure performed reasonably well when measured rainfall patterns were used. Results based on simulated rainfall were reasonably close to results based on measured rainfall in the 1993 evaluation period. Computations based on simulated rainfall, however, consistently overestimated reservoir storage volumes in the 1998 evaluation period. Overall in the two evaluation periods, monthly reservoir storage volumes computed from measured and simulated rainfall patterns were estimated within 13.80 percent (316.4 acre-ft or 103.1 Mgal) and 16.90 percent (611.3 acre-ft or 199.2 Mgal), respectively, of the observed reservoir storage volumes. It should be noted, however, that this does not measure the actual forecast capabilities of the procedure because the accuracy of a forecast is heavily dependent on the accuracy of rainfall and water-withdrawal projections being applied.

[2] The Pacific ENSO Update is a bulletin produced quarterly and is edited by Rebercca Schneider. This bulletin can be accessed at URL http://lumahai.soest.hawaii.edu/Enso/subdir/update.dir/update.html.

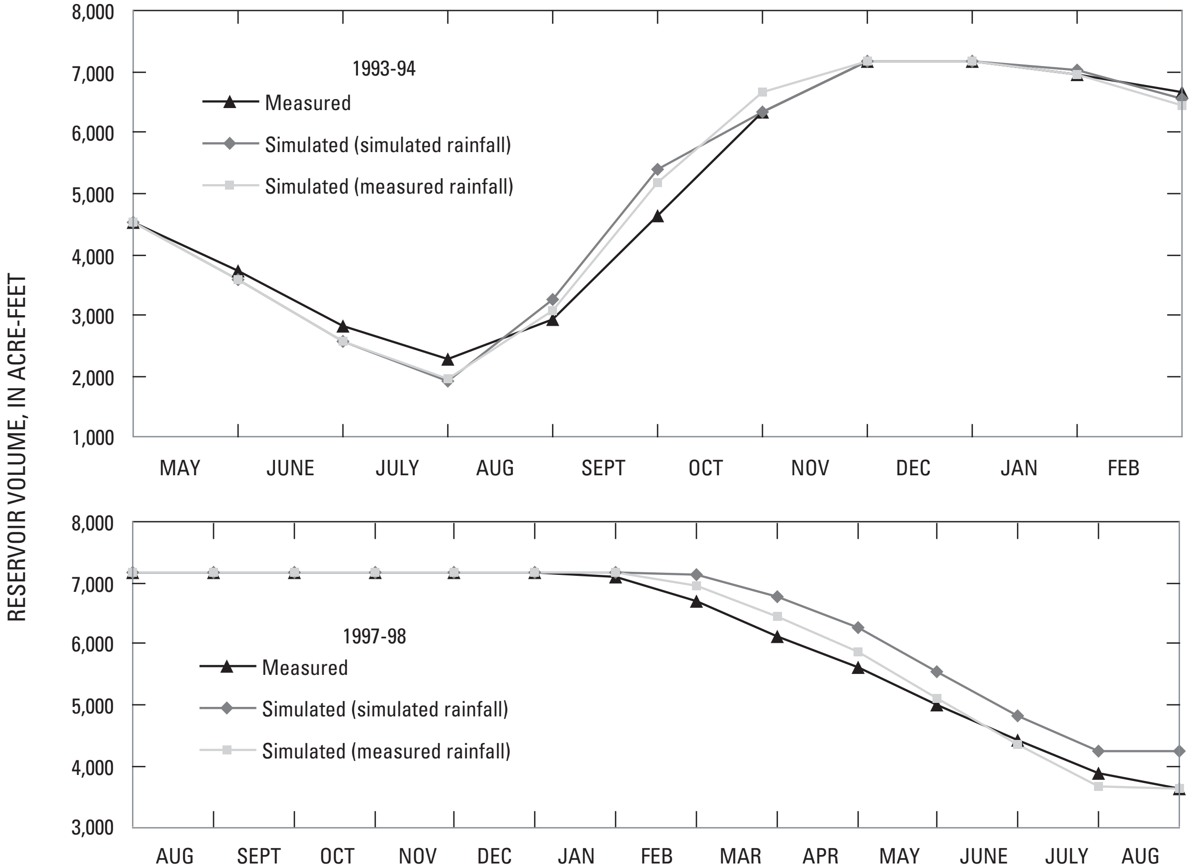

Figure 31. Measured and simulated month-end reservoir volume for the evaluation periods, Fena Valley Reservoir, Guam, May 1993 – February 1994 and August 1997 – August 1998.

Summary and Conclusions

A two-step modeling procedure developed by the U.S. Geological Survey (USGS) will allow estimates of monthly water levels in the Fena Valley Reservoir in response to various combinations of water-withdrawal rates and rainfall conditions. The first step in this predictive modeling procedure involves the use of the USGS Precipitation Rainfall Modeling System (PRMS), a physically based, distributed-parameter, watershed model designed to analyze the effects of rainfall, temperature, and land use on watershed runoff. The second step of the procedure is to use runoff estimates from the PRMS models as input to a generalized water-balance model to estimate changes in water levels in the reservoir.

An earlier PRMS model for the Fena Valley Watershed had at least three limitations: (1) rainfall data were not available in the watershed, (2) the model was not calibrated for the Almagosa River watershed because information on daily diversions at the Almagosa Springs upstream of the gaging station was not available, and (3) runoff from the ungaged areas was not modeled. The current study and updated model addressed all three of these limitations.

Given the critical nature of water-supply management decisions being made regarding the Fena Valley Reservoir, it is essential that the validity of the rainfall-runoff and water-balance models be routinely updated and verified to reflect current hydrologic conditions. As rainfall data at Almagosa rain gage (located within the watershed) and Almagosa Springs diversion data became available, improvements to the models were possible. For this study, the PRMS, currently implemented in the Modular Modeling System (MMS), was updated and recalibrated for the Maulap and Imong River watersheds, and also was calibrated for the first time for the Almagosa River watershed. The PRMS was applied to the ungaged areas by transferring model coefficients and parameters from the three adjacent watersheds.

Calibration of the model for the Almagosa River watershed required special considerations because of the uncertainties of ground-water exchange in the limestone terrain areas of the watershed. The surface-drainage divide commonly is used to define the contribution area for both surface and subsurface runoff computations. Preliminary model calibration on the Almagosa River watershed and other hydrologic evidence indicated, however, that the ground-water flow system contributing water to the watershed extends beyond the topographically defined surface-drainage divide. To more accurately represent the ground-water system of the Almagosa River watershed, it was determined that an additional hydrologic response unit with an area of 250 acres, to intercept subsurface flow from the area of limestone terrain beyond the watershed divide, was necessary to achieve agreement between simulated and measured runoff volumes.

Graphical and statistical analyses of monthly measured and simulated runoff for the three gaged rivers indicated reasonable PRMS model performance. Model performance in the ungaged areas could not be evaluated. For the Maulap, Almagosa, and Imong River watersheds, bias in simulating monthly mean runoff ranged from -2.42 to 0.28 percent for the calibration period and from -2.88 to 17.42 percent for the two verification periods; relative error ranged from -13.90 to 0.77 percent for the calibration period and from -1.94 to 16.72 percent for the two verification periods. For the entire simulation period (1992–2001), monthly mean runoff bias ranged from 0.31 to 5.98 percent, relative error ranged from -0.94 to 4.29 percent, and the coefficient of efficiency ranged from 0.94 to 0.96. The total runoff volume error for the entire simulation period ranged from 0.3 to 6.0 percent.

Because reliable simulations of dry season flows were of greatest concern, the focus of the PRMS model calibration was on dry season conditions. Dry season model results for the entire simulation period indicated that runoff can be predicted within -3.66 percent in the Maulap River watershed, within 5.37 percent in the Almagosa River watershed, and within 10.74 percent in the Imong River watershed. Although model error for the Imong River watershed was higher than for the other gaged watersheds, the results were still within the limits of the accuracy of the streamflow records used to develop the model.

The month-end reservoir volumes simulated by the water-balance model for both calibration and verification periods compared closely with observed reservoir volumes. Errors associated with the simulation of month-end reservoir storage for individual months in the calibration periods ranged from 4.51 percent (208.7 acre-ft or 68.0 Mgal) to -5.90 percent (-317.8 acre-ft or -103.6 Mgal). Errors for individual months in the verification periods ranged from 1.69 percent (103.5 acre-ft or 33.7 Mgal) to -4.60 percent (-178.7 acre-ft or -58.2 Mgal). Monthly simulation bias ranged from -0.19 percent for the calibration periods to -0.98 percent for the verification periods; relative error ranged from -0.37 to -1.12 percent for the calibration and verification periods. Relatively small bias indicated that the model did not consistently overestimate or underestimate reservoir volume.

The PRMS model of the Fena Valley Watershed developed as part of this study represents a reliable tool for estimating runoff contributions to the Fena Valley Reservoir. The PRMS model, in conjunction with the reservoir water-balance model also developed in this study, provide accurate and reliable estimates of future availability of water supply in the Fena Valley Reservoir depending on a broad range of likely climatic and water-withdrawal scenarios. This information is critical to the U.S. Navy to make timely decisions to determine the amount of water that can reliably be withdrawn from the reservoir.

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