APPLICATION OF THE PRECIPITATION-RUNOFF MODELING SYSTEM TO THE AH-SHI-SLE-PAH WASH WATERSHED, SAN JUAN COUNTY, NEW MEXICO

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CONTENTS

Page

Abstract 1

Introduction 1
- Purpose and scope 2
- Study area 2
- Data collection 4

General description of the precipitation-runoff modeling system 6
- Conceptual watershed system 6
- Watershed partitioning 9
- Daily and storm modes 10

Application of the precipitation-runoff modeling system at the Ah-shi-sle-pah Wash watershed 12
- Calibration 13
  - Daily mode 13
  - Storm mode 18
  - Verification 25
- Limitations 33

Conclusions 33

Selected references 35

FIGURES

Figure 1. Map showing location of Ah-shi-sle-pah Wash watershed and strippable coal in northwestern New Mexico 3

2. Map showing location of data-collection sites and stream network at Ah-shi-sle-pah Wash watershed 5

3. Schematic diagram of the conceptual watershed system and its inputs 7

4. Diagram showing flow-plane and channel-segment delineation of a basin 11

5. Map showing location of hydrologic-response units at Ah-shi-sle-pah Wash watershed 14

6. Bar graph and hydrographs showing rainfall and measured and simulated discharges at the Ah-shi-sle-pah Wash watershed during the storm on July 30-31, 1983 31

7. Bar graph and hydrographs showing rainfall and measured and simulated discharges at the Ah-shi-sle-pah Wash watershed during the storm on August 2-3, 1983 32

TABLES

Page

Table 1. Parameter values estimated or optimized at the Ah-shi-sle-pah Wash watershed for application of the precipitation-runoff modeling system in the daily mode 15

2. Equations for computation of ALPHA and RM from selected overland flow-plane characteristics and ALPHAC and RMC from selected channel-segment characteristics 21

3. Final parameter values for storm-mode simulation at Ah-shi-sle-pah Wash watershed 26

4. Summary of data from storm events used for calibration of the precipitation-runoff modeling system at the Ah-shi-sle-pah Wash watershed 28

5. Summary of data from storm events used for verification of the precipitation-runoff modeling system at the Ah-shi-sle-pah Wash watershed 30

CONVERSION FACTORS

For use of readers who prefer to use metric units, conversion factors for terms used in this report are listed below.

Multiply inch-pound units	By	To obtain metric units
mile	1.609	kilometer
square mile	640	acre
acre	0.4047	hectare
foot	0.3048	meter
foot per foot	1.00	meter per meter
foot per second	0.3048	meter per second
square foot	0.09290	square meter
cubic foot per second	0.02832	cubic meter per second
cubic foot per second per foot	0.09290	cubic meter per second per meter
inch	2.540	centimeter
inch per day	2.540	centimeter per day
inch per hour	2.540	centimeter per hour

Degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:

$$°C = 5/9(°F - 32)$$

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

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ABSTRACT

A deterministic precipitation-runoff model, the precipitation-runoff modeling system, was applied to the 8.21-square-mile drainage area of the Ah-shi-sle-pah Wash watershed in northwestern New Mexico (an arid climate). Emphasis was on calibrating model parameters in the storm mode using rainfall-runoff data collected at 5-minute intervals. The calibration periods were May through September of 1981 and 1982, and the verification period was May through September of 1983. Twelve storms (maximum approximately 5-year recurrence interval) were available for calibration and eight storms (maximum approximately 100-year recurrence interval) were available for verification. For calibration A (hydraulic conductivity estimated from onsite data and other storm-mode parameters optimized), the computed standard error of estimate was 50 percent for runoff volumes and 72 percent for peak discharges. Calibration B included hydraulic conductivity in the optimization, which reduced the standard error of estimate to 28 percent for runoff volumes and 50 percent for peak discharges. When optimized, the values for hydraulic conductivity were significantly smaller than the values estimated from onsite data. Optimized values for hydraulic conductivity resulted in reductions from 1.00 to 0.26 inch per hour and from 0.20 to 0.03 inch per hour for the two general soil groups in the calibrations. Simulated runoff volumes using seven of eight storms occurring during the verification period had a standard error of estimate of 40 percent for verification analysis A and 38 percent for verification analysis B. Simulated peak discharges had a standard error of estimate of 120 percent for verification A and 56 percent for verification B. Including the eighth storm, which had a relatively small magnitude, in the verification analyses more than doubled the standard error of estimating volumes and peaks.

INTRODUCTION

The impetus for this study originated when Congress passed the Surface Mining Control and Reclamation Act (Public Law 95-87) in 1977. The Act specifically addresses impacts of surface mining on hydrology. The Act states that before mining plans can be approved the plans have to show how the hydrologic balance of the mine area will be restored to premine conditions.

This study was conducted in cooperation with the U.S. Bureau of Land Management. It was one of several studies carried out in coal regions within the United States to calibrate and verify the precipitation-runoff modeling system with different physical and climatic conditions. Previous studies in the strippable coal-resource areas of northwestern New Mexico used regression techniques to estimate selected streamflow characteristics (Hejl, 1980 and 1984).

Purpose and Scope

The purpose of this study was to calibrate and verify the U.S. Geological Survey's precipitation-runoff modeling system using rainfall-runoff data collected in an arid climate. The model developed by Leavesley and others (1983) is described in this report. The data collected to calibrate the precipitation-runoff modeling system for the study area were precipitation, air temperature, solar radiation, and discharge (runoff) at the outlet of the basin. Also collected and compiled as input for the modeling system were soil, vegetation, land-surface-slope, and channel-slope characteristics. The calibration periods were May through September of 1981 and 1982, and the verification period was May through September of 1983.

Study Area

The 8.21-square-mile Ah-shi-sle-pah Wash watershed is in an intermontane area in northwestern New Mexico (fig. 1) that contains strippable coal in the Cretaceous Fruitland Formation. The average annual precipitation is about 10 inches (U.S. Weather Bureau, no date); snow rarely lasts more than a few days before melting. Streamflow is ephemeral. The arid climate supports sparse vegetation.

Mesas along the drainage divide make up about 10 percent of the study area. The sandy loam on the mesas supports sagebrush, a variety of short grasses, and a few piñon trees at the headwaters of the watershed.

About 50 percent of the study area is made up of steep, intricately dissected badlands adjacent to the mesas. The clays and shales of the badlands are almost barren, except for scattered lichen on the slopes and some brush and grasses in the drainage channels.

The remainder of the study area (about 40 percent) is a mixture of sand dunes, clinker (oxidized coal), and flat, silty-clay badlands outwash surfaces. The sand dunes, the most heavily vegetated areas, have a cover of brush and grass. The clinker and outwash surfaces support a sparse mixture of grass and scattered brush.

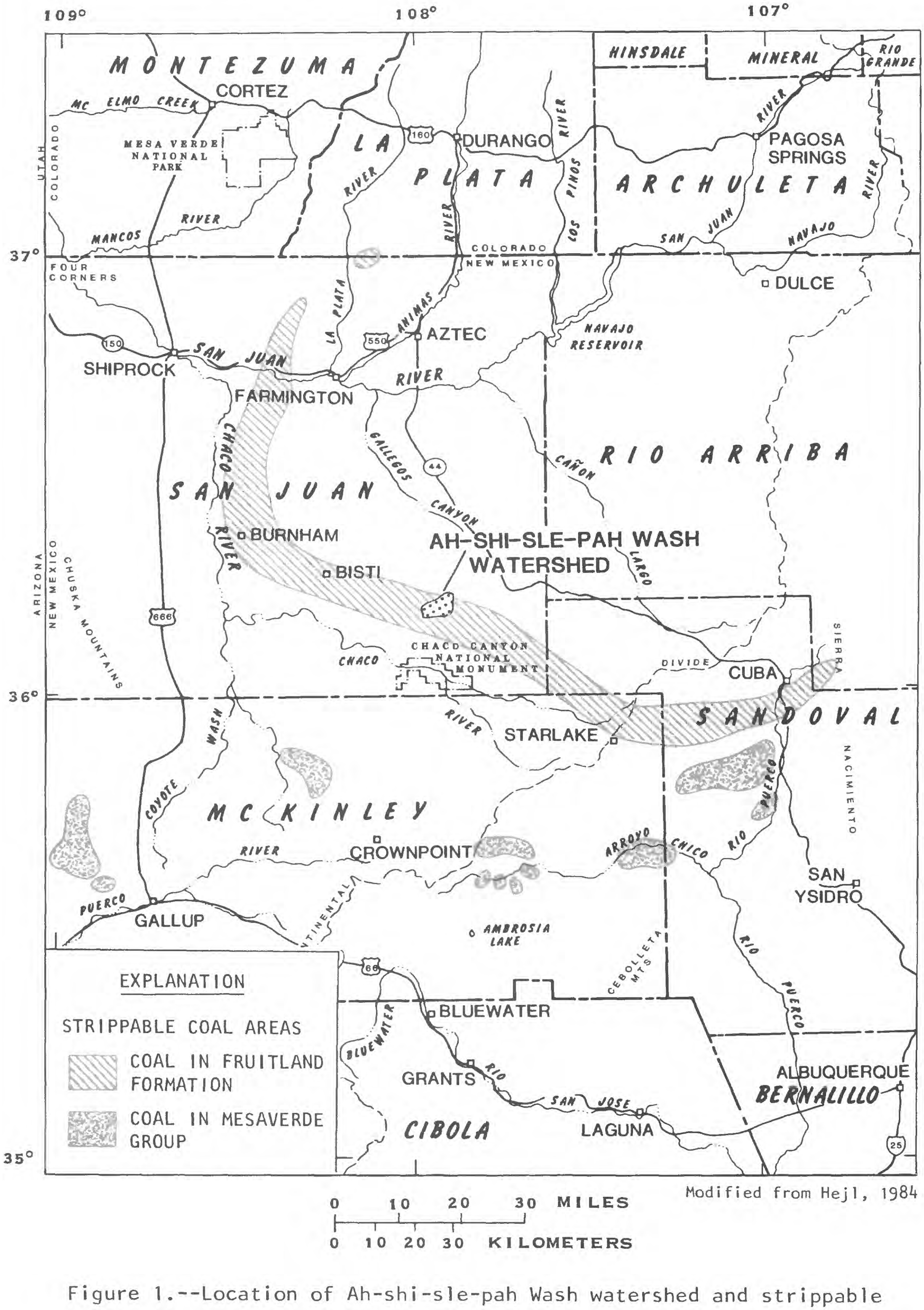


Figure 1.--Location of Ah-shi-sle-pah Wash watershed and strippable coal in northwestern New Mexico.

Data Collection

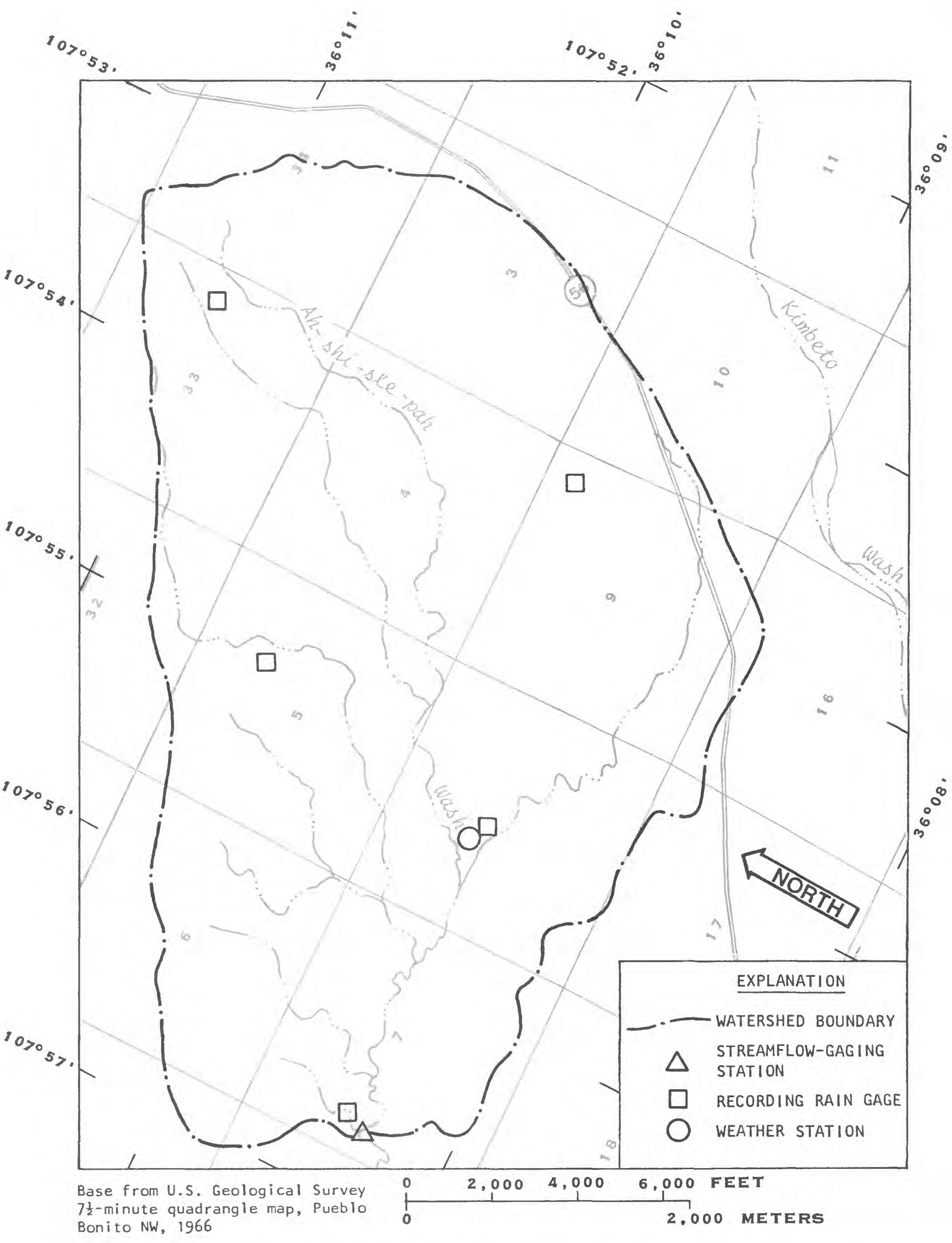
The Ah-shi-sle-pah Wash watershed was instrumented with a network of five recording rain gages, a weather station, and a streamflow-gaging station. The streamflow-gaging station, equipped with an automatic pump sampler, is located at the mouth (downstream end) of the 8.21 square miles of drainage area (fig. 2)

Rainfall and streamflow data were collected daily and at 5-minute intervals during storms. Snowfall and weather data (air temperature and solar radiation) were compiled on a daily basis, and water samples for sediment and chemical analyses at 15-minute intervals during storms. These data were collected from July 1978 through September 1983 and are available from the National Water-Data Storage and Retrieval System (WATSTORE), the central computerized repository of data collected by the U.S. Geological Survey. Records of daily discharge, chemical quality, and suspended sediment collected at Ah-shi-sle-pah Wash were published annually in "U.S. Geological Survey water-resources data for New Mexico" (1979-84).

The method of collecting rainfall data by using highway type II collectors and recording data on 16-channel digital punch paper, installed initially in July 1978, was found to be inadequate for calibrating the modeling system in the storm mode because of numerous occurrences of recorder stoppage (usually battery related) and wind effect on the shallow, rectangular rain-gage collector rings (assumed on the basis of comparisons with tipping-bucket rainfall collectors in concurrent operation at the five sites during the summer of 1981). This rainfall-recording equipment was replaced with tipping-bucket rainfall collectors and solid-state-storage recorders in May 1981. These collectors operated successfully to the termination of the data-collection period at the end of September 1983.

Soil samples were collected and vegetative-cover surveys made at 12 locations in the watershed by personnel of the U.S. Geological Survey Public Lands Hydrology Program (Lakewood, Colo.), assisted by Survey project personnel. Soil samples were obtained throughout the root zone (minimum depth of 1.5 feet to maximum depth of 10 feet) in July 1978 to define soil-moisture content near the wilting point, in May 1979 to define soil-moisture content near field capacity, and in July 1981 to define an intermediate soil-moisture content. Basin soil properties, soil-moisture storage characteristics, and vegetation characteristics were determined by personnel of the Public Lands Hydrology Program (R.F. Miller, written commun., 1982).

Infiltration and soil-detachability characteristics were determined from rainfall simulation at the 12 sites selected for soil samples and vegetative-cover surveys in June 1979 (Summer, 1981). The equipment used was a hand portable, rainfall-simulator infiltrometer developed by McQueen (1963). The rainfall simulator consists of a Plexiglas tube (wind screen), 55 inches long and 6 inches in diameter, with waterdrop formers at the top of the tube in the simulator head. Water trickling through the simulator head from an adjacent reservoir is converted into a stream of droplets. The user is able to control the intensity of the simulated rainfall. The infiltrometer consists of a 6-inch shallow-ring cylinder and suction pump to remove and collect simulated rainfall in excess of infiltration.



Base from U.S. Geological Survey 7½-minute quadrangle map, Pueblo Bonito NW, 1966

Figure 2.--Location of data-collection sites and stream network at Ah-shi-sle-pah Wash watershed.

The procedure consisted of running three infiltration experiments for 1 hour each at 12 representative soil sites within the study basin. The rainfall-simulation application rate was held constant at 5.5 inches per hour throughout each experiment. The simulated rainfall in excess of the infiltration rate was collected by the suction pump and no hydraulic head was allowed to develop in the infiltrometer cylinder. The total accumulated simulated-rainfall volume applied and runoff volume collected were recorded at 5-minute intervals. The infiltration from the experiments was computed as the rainfall volume applied minus the runoff volume collected. Total infiltration versus time was plotted at 5-minute intervals. After the infiltration rate became constant, usually after 10 to 20 minutes, the average slope of the plot was defined as the infiltration rate. Infiltrometer cylinders tend to overestimate infiltration rates unless large-diameter cylinders or large buffers are used (Bouwer, 1969, p. 460). The infiltration rate in these experiments included vertical and horizontal components. In this study, the assumption was made that the vertical infiltration rate is one-half the total infiltration rate measured in the experiments. This vertical infiltration rate was used during model calibration to estimate hydraulic conductivity.

GENERAL DESCRIPTION OF THE PRECIPITATION-RUNOFF MODELING SYSTEM

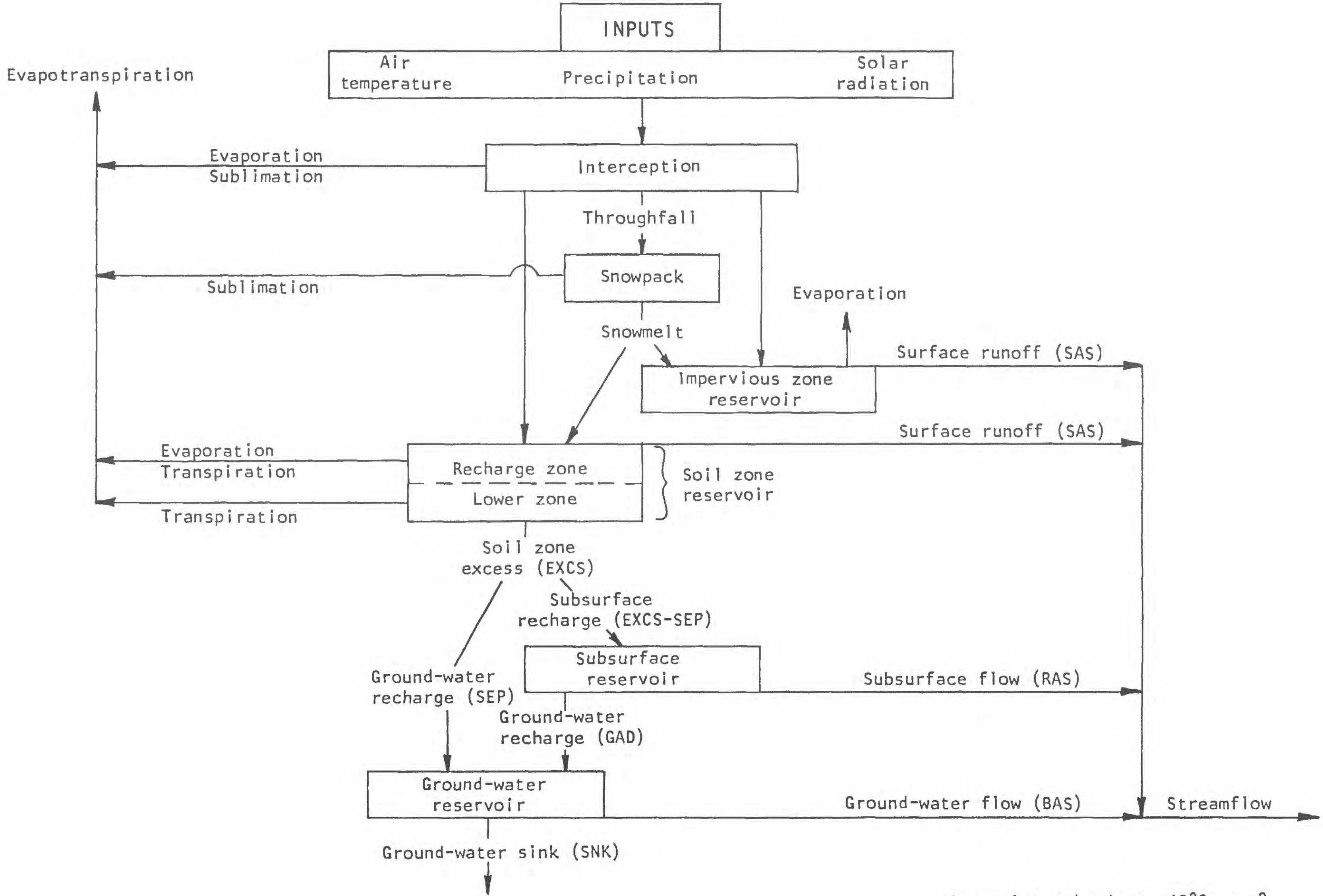
The precipitation-runoff modeling system of Leavesley and others (1983) was developed to simulate runoff for a wide range of hydrologic conditions. Some components of the system are not applicable to the arid Ah-shi-sle-pah Wash watershed and are not included here.

The following description of a conceptual watershed system was extracted from the user's manual by Leavesley and others (1983, p. 7-9). All additions or clarifications added to the user's manual are enclosed in brackets.

Conceptual Watershed System

> The watershed system and its inputs are schematically depicted in figure 2 [fig. 3 in this report]. System inputs are precipitation, air temperature, and solar radiation. Precipitation in the form of rain, snow, or a mixture of both is reduced by interception and becomes net precipitation delivered to the watershed surface. The energy inputs of temperature and solar radiation drive the processes of evaporation, transpiration, sublimation, and snowmelt. The watershed system is conceptualized as a series of reservoirs whose outputs combine to produce the total system response.

* * * * * * *



Leavesley and others, 1983, p. 8

Figure 3.--Schematic diagram of the conceptual watershed system and its inputs.

The soil-zone reservoir represents that part of the soil mantle that can lose water through the processes of evaporation and transpiration. Average rooting depth of the predominant vegetation covering the soil surface defines the depth of this zone. Water storage in the soil zone is increased by infiltration of rainfall and snowmelt and depleted by evapotranspiration. Maximum retention storage occurs at field capacity [quantity of water held by soil against the pull of gravity]; minimum storage (assumed to be zero) occurs at wilting point. The soil zone is treated as a two-layered system. The upper layer is termed the recharge zone and is user-defined as to depth and water-storage characteristics. Losses from the recharge zone are assumed to occur from evaporation and transpiration; losses from the lower zone occur only through transpiration.

The computation of infiltration into the soil zone is dependent on whether the input source is rain or snowmelt. All snowmelt is assumed to infiltrate until field capacity is reached. At field capacity, any additional snowmelt is apportioned between infiltration and surface runoff. At field capacity the soil zone is assumed to have a maximum daily snowmelt-infiltration capacity (SRX). All snowmelt in excess of SRX contributes to surface runoff. Infiltration in excess of field capacity (EXCS) first is used to satisfy recharge to the ground-water reservoir (SEP). SEP is assumed to have a maximum daily limit. Excess infiltration, available after SEP is satisfied, becomes recharge to the subsurface reservoir. Water available for infiltration as the result of a rain-on-snow event is treated as snowmelt if the snowpack is not depleted, and as rainfall if the snowpack is depleted.

For rainfall with no snowcover, the volume infiltrating the soil zone is computed as a function of soil characteristics, antecedent soil-moisture conditions, and storm size. For daily-flow computations, the volume of rain that becomes surface runoff is computed using a contributing-area concept. Daily infiltration is computed as net precipitation less surface runoff. For stormflow-hydrograph generation, infiltration is computed using a form of the Green and Ampt equation (Philip, 1954). Surface runoff for these events is net precipitation less computed infiltration. Infiltration in excess of field capacity is treated the same as daily infiltration.

The subsurface reservoir performs the routing of soil-water excess that percolates to shallow ground-water zones near stream channels or that moves downslope from point of infiltration to some point of discharge above the water table. Subsurface flow (RAS) is considered to be water in the saturated-unsaturated and ground-water zones that is available for relatively rapid movement to a channel system. The subsurface reservoir can be defined either as linear or nonlinear.

Recharge to the ground-water reservoir can occur from the soil zone (SEP) and the subsurface reservoir (GAD). SEP has a daily upper limit and occurs only when field capacity is exceeded in the soil zone. GAD is computed daily as a function of a recharge rate coefficient (RSEP) and the volume of water stored in the subsurface reservoir. The ground-water reservoir is a linear reservoir and is the source of all baseflow (BAS). Movement of water through the ground-water system to points beyond the area of interest or measurement can be handled by flow to a ground-water sink (GSNK) which is computed as a function of storage in the ground-water reservoir.

Streamflow is the sum of SAS, RAS, and BAS. For daily flow simulations, no channel routing is done. [Streamflow at the study basin for this report is the sum of surface runoff and subsurface flow. The streamflow is ephemeral.]

Watershed Partitioning

The distributed-parameter modeling capability is provided by partitioning a watershed into 'homogeneous' units. Watershed partitioning can be done on the basis of characteristics such as slope, aspect, elevation, vegetation type, soil type, and precipitation distribution. Each watershed unit delineated is considered to be homogeneous with respect to these characteristics. Partitioning provides the ability to account for spatial and temporal variations of basin physical and hydrologic characteristics, climatic variables, and system response. It also provides the ability to impose land-use or climatic changes on parts or all of a basin. Evaluation can then be made of the impacts of such changes on the hydrology of each unit and the total basin.

Two levels of partitioning are available. The first level divides the basin on the basis of some or all of the physical characteristics mentioned above. The resulting units are called hydrologic-response units (HRU's), and each is considered homogeneous with respect to its hydrologic response. A water balance and an energy balance are computed daily for each HRU. The sum of the responses of all HRU's, weighted on a unit-area basis, produces the daily system response and streamflow from a basin.

The conceptual watershed system shown in figure 2 [fig. 3] could be defined for each HRU. However, for most small watersheds, one soil-zone reservoir is defined for each HRU, while one ground-water reservoir is defined for the entire watershed. One or more subsurface reservoirs are defined, depending on variations in soils and geology.

PRMS [precipitation-runoff modeling system] will handle a maximum of 50 HRU's. The number and location of HRU's for any given basin are a function of the number of physical characteristics used in the partitioning scheme, the number and location of precipitation gages available, and the problem to be addressed by the model. There are no hard and fast rules for partitioning currently available; this is an area to be addressed by further research. However, the number of HRU's delineated will influence the calibration fit of many of the model components (Leavesley and Striffler, 1978). A general rule of thumb currently used for daily-flow computations for most problems is not to create HRU's smaller than 4 to 5 percent of the total basin area. Exception would occur if an area smaller than this would have significant influence on streamflow or on general basin hydrology. A common tendency is to overpartition. Therefore, it is recommended that test runs be made at a few levels of partitioning to get a feel for the influence of the numbers of HRU's on model daily-flow response.

A second level of partitioning is available for storm hydrograph simulation. The watershed can be conceptualized as a series of interconnected flow planes and channel segments. Surface runoff is routed over the flow planes into the channel segments; channel flow is routed through the watershed channel system. An HRU can be considered the equivalent of a flow plane, or it can be delineated into a number of flow planes. Delineation of a basin into six overland flow planes and three channel segments is shown in figure 3 [fig. 4 in this report]. Overland flow planes have a width equal to the adjacent channel segment and an equivalent length which, when multiplied by the width, gives the area of the natural basin segment. PRMS will handle a total of 50 overland flow plane and 50 channel segments.

Daily and Storm Modes

A model selected or developed from the PRMS library can simulate basin hydrology on both a daily and a storm time scale. The daily mode simulates hydrologic components as daily average or total values. Streamflow is computed as a mean daily flow. The storm mode simulates selected hydrologic components at time intervals shorter than a day. The minimum time interval is 1 minute. The storm mode is used to compute infiltration, surface-water runoff, and sediment yield from selected rainfall events.

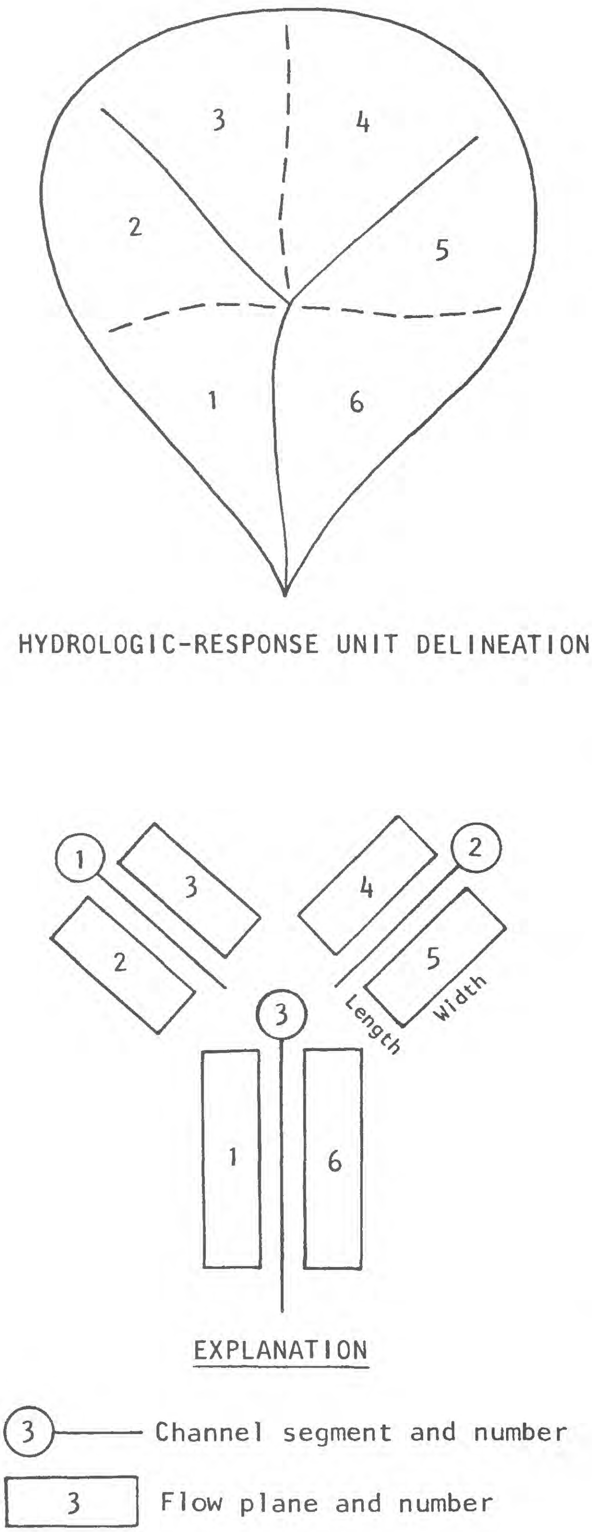


Figure 4.--Flow-plane and channel-segment delineation of a basin (Leavesley and others, 1983, p. 11).

Data required for daily simulations are input to the model one water year at a time. Included in the input are the dates of storm periods within the water year * * *. The model operates in a daily mode until it reaches one of these dates. It then shifts to the storm mode and inputs the data available for that date. A stormflow hydrograph and sediment-concentration graph can be simulated for that day at a time interval selected by the user. At the end of the storm day, control is returned to selected daily components for updating to insure storm- and daily-mode compatibility and to compute mean daily streamflow. If the storm period is more than 1 day in length, then control returns to the storm mode and another day of data is input. Subsequent storm days of data are read and used in this manner until the storm period terminates. The model then returns to the full daily-mode sequence.

Summaries can be output both for daily and for storm simulations. Daily-mode computations can be summarized on a daily, monthly, and annual basis. Storm-mode computations can be summarized for the full storm period and at a user-selected time interval.

APPLICATION OF THE PRECIPITATION-RUNOFF MODELING SYSTEM AT THE AH-SHI-SLE-PAH WASH WATERSHED

The precipitation-runoff modeling system includes components (computer subroutines) to simulate hydrologic characteristics of a basin influenced by climatic- and land-phase parameters. Emphasis during development of the modeling system was on emulating hydrologic processes using physical laws or empirical relations with measurable climatic data and watershed characteristics. The climatic phase included parameters such as precipitation, air temperature, and solar radiation. The land phase included parameters such as soils, vegetation, and physiography.

A distributed-parameter approach was used to account for variations in soil, vegetative cover, flow-plane and channel slope, aspect, altitude, and precipitation. The watershed was partitioned into homogeneous subunits or subareas called hydrologic-response units, and parameter values were selected for the subareas to account for variations. For storm-hydrograph simulation, each hydrologic-response unit was partitioned into conceptualized series of flow planes and channel segments.

Model parameters were optimized and tested for sensitivity. The optimization process attempts to automatically adjust user-selected parameters to improve agreement between measured and predicted runoff by minimizing the value of an objective function selected by the user. The sensitivity analysis evaluates the extent to which uncertainty in the parameters results in uncertainty in the predicted runoff. The analysis also assesses the magnitude of parameter errors and parameter intercorrelations when optimization is performed.

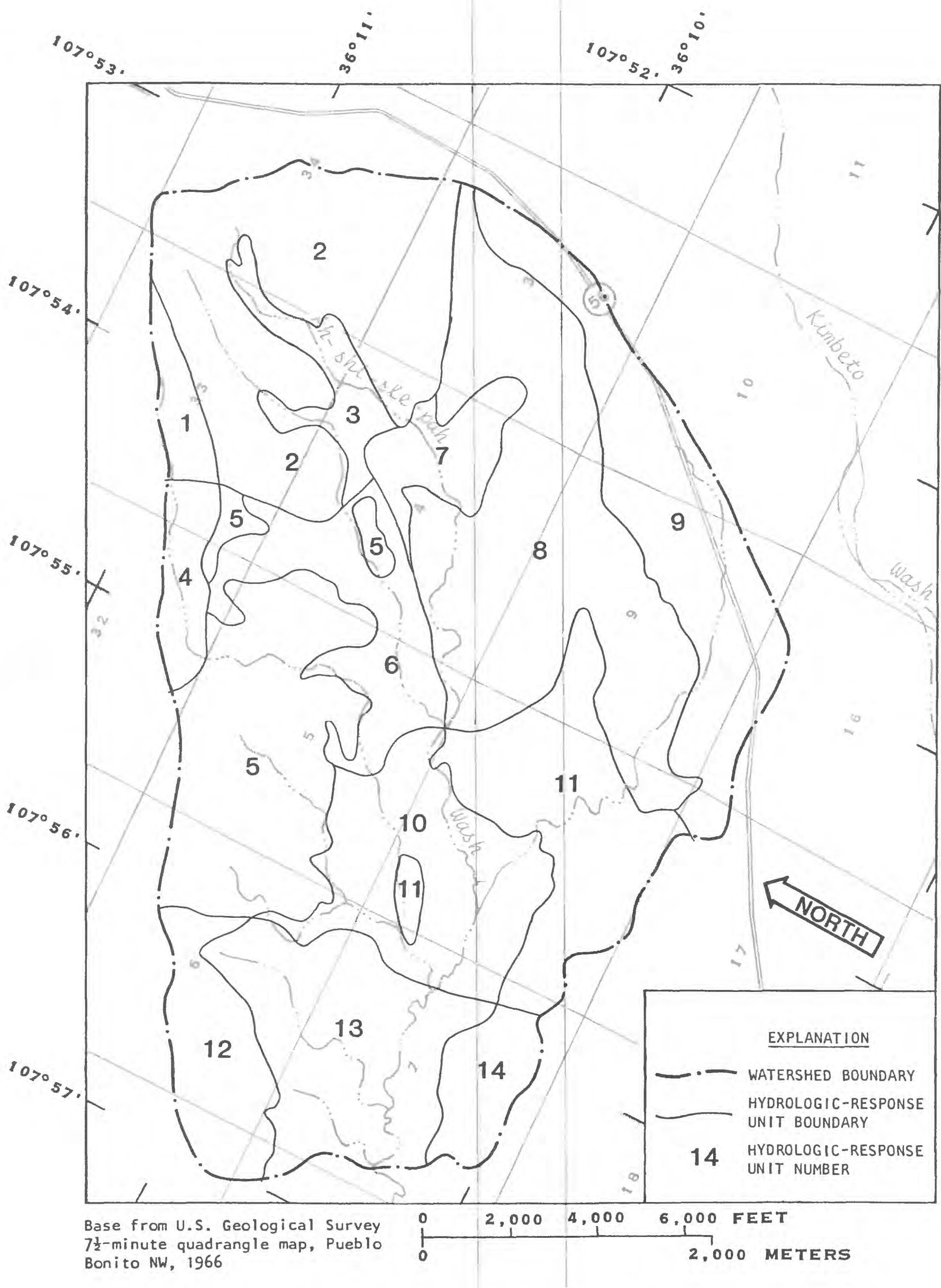
Calibration

The Ah-shi-sle-pah Wash watershed was partitioned into 14 hydrologic-response units. The boundaries of the units are shown in figure 5. Each hydrologic-response unit was assumed to be homogeneous with respect to its soil, vegetative cover, slope, aspect, altitude, and precipitation distribution. The precipitation for each hydrologic-response unit was assumed to be that measured at the nearest rain gage. Hydrologic-response units 5 and 11 are not contiguous areas.

Parameter values for each response unit were estimated from data collected from the watershed and extrapolated on the basis of topographic-map and aerial-photograph interpretations. These parameters included characteristics of soils, vegetation, and physiography. Water-holding capacity for the soil root zone was estimated as the difference between maximum soil moisture (field capacity) and minimum soil moisture (wilting point) determined from the soil samples at 12 sites. The precipitation-runoff modeling system treats the root zone as two zones: the upper and lower soil zones. The soil zone is defined as the maximum depth at which roots were measured during soil sampling. The upper soil zone was assumed to consist of the top one-third of the root zone. Vegetative-cover types, density, and inteception storage were estimated from surveys provided by R.F. Miller (written commun., 1982) and extrapolated on the basis of field reconnaissance. Flow-plane slopes, hydrologic-response-unit aspects, and channel shapes and slopes were estimated from field-reconnaissance data and from the U.S. Geological Survey Pueblo Bonito NW 7½-minute quadrangle topographic map (scale 1:24,000; contour interval 20 feet). Parameters were selectively chosen for inclusion in table 1 to show the range in values in the 14 response units measured or estimated for application of the modeling system at the watershed. Most of the parameters in table 1 are representative of measurable watershed characteristics.

Daily Mode

After selection of the initial parameter values, a daily sensitivity analysis was used to identify parameters that had the most effect on predicting daily runoff during the model-calibration periods, May through September of 1981 and 1982. The parameters, maximum available water-holding capacity of soil-recharge zone (REMX), minimum possible contributing area as a proportion of total hydrologic-response-unit area (SCN), and air-temperature evapotranspiration coefficient (CTS), were identified as having the most significance in predicting daily runoff and their values were computed by the model in the order listed during optimization. The model was insensitive to other parameters. The sensitivity or insensitivity of the model to parameters could have been the result of (1) measurement errors inherent in data collection; (2) the length of the data-collection period available for analysis; (3) the model's inadequate representation of arid climates; (4) poorly determined parameter values; or (5) a combination of these factors.



Base from U.S. Geological Survey 7½-minute quadrangle map, Pueblo Bonito NW, 1966

Figure 5.--Location of hydrologic-response units at Ah-shi-sle-pah Wash watershed.

Table 1.—Parameter values estimated or optimized at the Ah-shi-sle-pah Wash watershed for application of the precipitation-runoff modeling system in the daily mode

[* indicates that parameter values obtained from optimization procedure]

Parameter	Definition	Range in values in 14 hydrologic-response units
ISOIL	Soil type: sand = 1, loam = 2, clay = 3	2-3
SMAX	Maximum available water-holding capacity in soil profile, in inches	2.70-4.00
SMAV	Current available water in soil profile, in inches	1.35-2.00
REMX*	Maximum available water-holding capacity of soil-recharge zone, in inches	0.10-0.40
RECHR	Current available water-holding capacity of soil-recharge zone, in inches	0.05-0.20
SRX	Maximum daily snowmelt-infiltration capacity of soil profile, in inches	0.50-1.00
SCX	Maximum possible contributing area as proportion of total hydrologic-response-unit area (decimal form)	0.08
SCN*	Minimum possible contributing area as proportion of total hydrologic-response-unit area (decimal form)	0.012-0.030
SEP	Maximum daily recharge from soil-moisture excess to designated ground-water reservoir, in inches per day	0.0
DARU	Drainage area for hydrologic-response unit, in acres	84-804
SLP	Average slope of hydrologic-response unit (decimal form)	0.030-0.200
(ASPECT)	Horizontal (H), north (N), south (S), east (E), and west (W)	H,N,W, & S

Table 1.—Parameter values estimated or optimized at the Ah-shi-sle-pah Wash watershed for application of the precipitation-runoff modeling system in the daily mode—Concluded

Parameter	Definition	Range in values in 14 hydrologic-response units
ELV	Mean altitude of hydrologic-response unit, in feet above sea level	6,200-6,500
CTS*	Air-temperature evapotranspiration coefficient	0.0167
ICOV	Predominant vegetation-cover type: bare, grasses, shrubs, and trees	Bare, grasses, and shrubs
COVDNS	Summer vegetation-cover density (decimal form)	0.0-0.40
COVDNW	Winter vegetation-cover density (decimal form)	0.0-0.30
TRNCF	Transmission coefficient for shortwave radiation through the winter-vegetation canopy (decimal form)	0.80-1.00
SNST	Interception storage capacity of major winter vegetation for snow, in inches water equivalent	0.0-0.01
RNSTS	Summer rain-interception storage capacity of major vegetation, in inches	0.0-0.2
RNSTW	Winter rain-interception storage capacity of major vegetation, in inches	0.0-0.02
ITST	Month to look for start of transpiration (1-12)	4
ITND	Month that transpiration ends (1-12)	11

Optimization was performed on maximum available water-holding capacity, minimum possible contributing area, and air-temperature evapotranspiration coefficient because the model was most sensitive to these parameters and required the least amount of adjustment to improve agreement between measured and predicted runoff. The precipitation-runoff modeling system components, using the parameters that follow, are summarized from the user's manual (Leavesley and others, 1983, p. 21-27).

The procedure using the air-temperature evapotranspiration coefficient (CTS) computes potential evapotranspiration (PET) as follows:

$$PET = CTS(MO) \times (TAVF - CTX) \times RIN \tag{1}$$

where PET = potential evapotranspiration, in inches per day;
CTS(MO) = an air-temperature evapotranspiration coefficient for the month (MO assumed to have constant value from May through September);
TAVF = daily mean air temperature, in degrees Fahrenheit;
CTX = an air-temperature coefficient; and
RIN = daily solar radiation, in inches of evaporation potential.

The maximum moisture storage and minimum possible contributing area were used to compute daily surface runoff using the contributing-area concept. The percentage of a hydrologic-response unit contributing to surface runoff was computed as a linear function of antecedent soil moisture and rainfall amount as follows:

$$CAP = SCN + [(SCX - SCN) \times (\frac{RECHR}{REMX})] \tag{2}$$

where CAP = contributing area, expressed as a decimal form of the total area;
SCX = maximum possible contributing area (decimal form);
SCN = minimum possible contributing area (decimal form);
RECHR = current moisture storage in the recharge zone of the soil profile, in inches; and
REMX = maximum moisture storage in the recharge zone of the soil profile, in inches.

Surface runoff is computed by:

$$SRO = CAP \times PTN \tag{3}$$

where SRO = surface runoff, in inches; and
PTN = daily net precipitation, in inches.

A means of model evaluation is the comparison between measured and simulated runoff values. Using optimized values for maximum available water-holding capacity in the recharge zone of the soil profile (REMX), minimum possible contributing area (SCN), and air-temperature evapotranspiration coefficient (CTS), the measured runoff during May through September of 1981 and 1982 was 1.62 inches versus 1.54 inches predicted with the model calibrated in the daily mode. The total predicted runoff was within 5 percent for the period; however, predicting daily runoff accurately was not possible. A probable cause could have been the variability of rainfall in 24 hours or storms occurring over a 2-day period.

Model components using baseflow and snowmelt were not applicable at Ah-shi-sle-pah Wash. Streamflow is ephemeral, and at no time during the data-collection period did snow accumulate into a snowpack as required for snowmelt-runoff simulation.

Storm Mode

Model emphasis was on calibrating the precipitation-runoff modeling system at Ah-shi-sle-pah Wash in the storm mode (5-minute interval). The calibration in the daily mode was necessary to establish daily soil-moisture conditions prior to calibrating parameters in the storm mode. Thunderstorms during May through September generally are responsible for producing storm runoff. Rainfall and runoff data were collected at 5-minute intervals for 12 significant storms during May through September of 1981 and 1982, the calibration period. Runoff volumes ranged from 0.02 to 0.28 inch, and peak discharges ranged from 54 to 688 cubic feet per second, with a maximum recurrence interval of approximately 5 years (Hejl, 1984).

Storm-runoff volumes (in inches) are computed by the model using the procedures described below. The hydrologic-response units are the same as defined for the daily-mode calibration (fig. 5). Storm-runoff volume is a function of net rainfall (PTN) and net infiltration (FIN). Infiltration during storms is computed using a variation of the Green-Ampt equation (Green and Ampt, 1911) and is summarized from the user's manual (Leavesley and others, 1983, p. 24-25) as follows:

$$FR = KSAT \times (1.0 + \frac{PS}{SMS}) \qquad (4)$$

where FR = point infiltration, in inches per hour;
KSAT = hydraulic conductivity of the transmission zone, in inches per hour;
PS = effective value of the product of capillary drive and moisture deficit, in inches; and
SMS = current value of accumulated infiltration, in inches.

The effective value of the product of capillary drive and moisture deficit (PS, in inches) is expressed as:

$$PS = PSP \times [RGF - (RGF - 1) \times (\frac{RECHR}{REMX})] \qquad (5)$$

where PSP = value of the product of capillary drive and moisture deficit at field capacity, in inches;
RGF = ratio of the combined effects of capillary drive and moisture deficit from the wilting point to that at field capacity (dimensionless);
RECHR = current moisture storage in the recharge zone of the soil profile, in inches; and
REMX = maximum moisture storage in the recharge zone of the soil profile, in inches.

Net infiltration (FIN, in inches per hour) is computed assuming that infiltration capacity varies linearly from zero to FR as:

$$FIN = PTN - \frac{PTN^2}{2FR} \quad \text{if} \quad PTN < FR \qquad (6)$$

or

$$FIN = \frac{FR}{2} \quad \text{if} \quad PTN \geq FR. \qquad (7)$$

Storm-runoff volume or rainfall excess (QR) is net rainfall minus net infiltration:

$$QR = PTN - FIN. \qquad (8)$$

Net infiltration (FIN) enters the recharge zone as the current value of accumulated infiltration (SMS) for the purpose of computing point infiltration in equation 4. During periods when net rainfall (PTN) is equal to zero, the current value of accumulated infiltration is reduced at a rate that is computed by a constant drainage rate for redistribution of soil moisture (DRN) times hydraulic-conductivity and evapotranspiration losses.

Distribution of storm runoff is implemented by additional partitioning of each hydrologic-response unit into a series of interconnected flow planes and channel segments. This component of the precipitation-runoff modeling system that simulates storm hydrographs is summarized from the user's manual (Leavesley and others, 1983, p. 28, 30, 34-46). Overland flow computations were performed using rainfall excess computed in equation 8 as inflow to flow planes. All overland flow planes delineated on a response unit use the same rainfall-excess trace and must discharge to a channel segment. Surface runoff for storm-mode simulation is computed using kinematic-wave approximation to overland flow. The partial differential equation solved for each overland flow-plane segment is:

$$re = \frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} \qquad (9)$$

where re = rate of rainfall-excess inflow, in feet per second;
h = depth of flow, in feet;
q = rate of flow per unit width, in cubic feet per second per foot;
t = time, in seconds; and
x = distance down the flow plane, in feet.

The relation between h and q is given as:

$$q = ALPHA \times h^{RM} \qquad (10)$$

where ALPHA and RM = functions of overland flow-plane characteristics.

Values for ALPHA and RM may be computed from selected overland flow-plane characteristics using equations given in table 2 or may be overridden by user-defined values. The technique used to approximate q(x,t) at discrete locations in the x-t flow-plane segment is described by Dawdy and others (1978). Points in a rectangular grid were spaced at intervals of time (Δt) and distance (Δx). Values of Δt and Δx were varied from segment to segment, as required to maintain computational stability and to produce desired resolution in computed results.

Table 2.—Equations for computation of ALPHA and RM from selected overland flow-plane charateristics and ALPHAC and RMC from selected channel-segment characteristics (modified from Leavesley and others, 1983, p. 30)

[SLOPE (I) is slope, in feet per feet; FRN (I) is roughness parameter]

Type of segment	Equations for computation		Definition of PARAM	
			PARAM (I,1)	PARAM (I,2)
	ALPHA	**RM**		
External specification of ALPHA and RM.	PARAM (I,1)	PARAM (I,2)	ALPHA	RM
Overland flow (turbulent).	$\frac{1.49 \times \sqrt{\text{SLOPE (I)}}}{\text{FRN (I)}}$	1.67	—	—
Overland flow (laminar).	$\frac{64.4 \times \text{SLOPE (I)}}{0.0000141 \times \text{FRN (I)}}$	3.00	—	—
Junction.	—	—	—	—
	ALPHAC	**RMC**		
Rectangular cross section.	$\frac{1.49 \times \sqrt{\text{SLOPE (I)}}}{\text{FRN (I)} \times \text{PARAM (I,1)}^{2/3}}$	1.67	Width	—
Triangular cross section.	$\frac{1.18 \times \sqrt{\text{SLOPE (I)}}}{\text{FRN (I)}} \times \left[\frac{\sqrt{\text{PARAM (I,1)} + \text{PARAM (I,2)}}}{\sqrt{[\text{PARAM (I,1)}]^2 + 1} + \sqrt{[\text{PARAM (I,2)}]^2 + 1}}\right]^{2/3}$	1.33	Width from left bank to center at 1-foot depth	Width from right bank to center at 1-foot depth

The overland flow from the flow planes is routed into channel segments. The channel segments can receive upstream inflow from as many as three other segments and lateral inflow from as many as two overland flow planes (left bank and right bank). The inflow hydrograph to a channel segment and the lateral inflow per unit length of channel times channel length serve as the input or driving functions for channel-segment computations. Channel-flow routing uses a finite-difference approximation of the continuity equation:

$$q = \frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} \tag{11}$$

and the kinematic-wave approximation relating discharge and cross-sectional area of flow:

$$Q = ALPHAC \times A^{RMC} \tag{12}$$

where q = lateral inflow per unit length of channel, in cubic feet per second per foot;
A = area of flow, in square feet;
Q = flow rate, in cubic feet per second;
t = time, in seconds;
x = distance down channel, in feet; and
ALPHAC and RMC = functions of channel-segment characteristics.

The kinematic-wave parameters ALPHAC and RMC for channel flow can be computed from selected channel characteristics using equations given in table 2, specified by the user, or estimated for channel segments using Manning's equation if the wetted perimeter, W, can be expressed as a power function of the area:

$$W = c \times A^{d} \tag{13}$$

where W = wetted perimeter, in feet; and
c and d = constants.

Defining the hydraulic radius (R) as:

$$R = \frac{A}{W} = \frac{A^{(1-d)}}{c}, \tag{14}$$

then Manning's equation for the flow rate is:

$$Q = A \times V = \frac{1.49 \sqrt{S}}{n \times c^{2/3}} A^{(5/3 - 2d/3)} \qquad (15)$$

where V = flow velocity, in feet per second;
n = a roughness coefficient (Manning's "n"); and
S = slope, in feet per feet; and all other terms are as previously defined.

Then

$$ALPHAC = \frac{1.49 \sqrt{S}}{n \times c^{2/3}} \qquad (16)$$

and

$$RMC = \frac{5}{3} - \frac{2}{3} d. \qquad (17)$$

The numeric technique described by Dawdy and others (1978) is used to approximate Q(x,t) at discrete locations in the x-t plane of the channel segment. This technique requires that time and space steps (Δt and Δx) that are used in the numerical computations be selected on the frequency-response characteristics (time to equilibrium) of the "fastest" channel segment and the largest expected lateral-inflow rate. An alternate method for selecting time and space steps for channel segments with predominantly upstream flow can be an estimation using a linear-stability criterion (Woolhiser and others, 1970) as follows:

$$\frac{\Delta x}{\Delta t} \geqq ALPHAC \times RMC \times AM^{(RMC-1)} \qquad (18)$$

where AM = a maximum expected cross-sectional area of flow.

Two approaches were used in the calibration of the precipitation-runoff modeling system in the storm mode. During calibration A, values of hydraulic conductivity that were estimated onsite were used and other storm-mode parameters were optimized. Calibration B consisted of optimization of hydraulic conductivity and reoptimization of the parameters optimized in calibration A.

Calibration A was based on the assumption that the hydraulic conductivity of the transmission zone (KSAT) could be estimated from onsite data. Characteristics of soils for storm-mode simulation were lumped into two general groups for estimating hydraulic conductivity and optimizing other storm-mode parameters. The effort was to reduce the number of parameters and to keep the number of degrees of freedom as large as possible because only 12 storms were available for optimization. Hydraulic conductivity was estimated to average 0.20 inch per hour for the steep badlands with clay-shale soils that make up about one-half of the area and 1.00 inch per hour for the more permeable parts of the watershed.

Parameters were adjusted by optimization to minimize the value of an objective function. The objective function used was the sum of the squared differences between the logarithms of observed and predicted runoff values. The Rosenbrock optimization technique (Rosenbrock, 1960) was used to adjust values of parameters for the product of capillary drive and moisture deficit at field capacity (PSP), the ratio of the combined effects of capillary drive and moisture deficit from the wilting point to that at field capacity (RGF), and the maximum available water-holding capacity of the soil-recharge zone (REMX). The parameters were introduced into the optimization computations in the order listed above. The values for REMX did not change from the optimized values obtained from the daily-mode calibration.

Calibration of peak discharges was accomplished by optimization of values for ALPHA and RM, functions of overland flow characteristics for the kinematic-wave theory. The initial values for ALPHA and RM were estimated on the basis of slope and roughness of the flow-plane surfaces using equations in table 2. Each of the 14 values of ALPHA was decreased by 5 percent from the initial value as a result of optimization. The same procedure was used to obtain optimized values for RM, which resulted in a decrease of 25 percent from the initial value. Optimization of ALPHAC and RMC, functions of channel characteristics for kinematic-wave routing, did not improve the fit between measured and predicted peak discharges.

Because of the limited number of storms available, only one to two parameters were optimized at a time. The parameters were reoptimized until no significant changes occurred in the parameter values.

Calibration B consisted of introducing hydraulic conductivity first in the optimization and following with reoptimizing the same parameters, in the same order, that were optimized in calibration A. The goal of calibration B was to determine if the match between measured and estimated runoff volumes and peak discharges could be improved by including hydraulic conductivity in the optimization. The initial values of hydraulic conductivity estimated from onsite data were 0.20 inch per hour for the steep badlands and 1.00 inch per hour for the more permeable parts of the watershed. The optimized values of hydraulic conductivity were 0.03 inch per hour for the steep badlands and 0.26 inch per hour for the more permeable parts of the watershed. The values for the product of capillary drive and moisture deficit at field capacity (PSP) and the ratio of combined effects of capillary drive and moisture deficit from the wilting point to that at field capacity (RGF) were significantly larger than those from calibration A. Reoptimization of daily-mode values for maximum available moisture storage in the recharge zone of the soil profile (REMX) in calibration B, as in calibration A, did not improve the fit between measured and predicted values. Optimized values for ALPHA and RM, functions of overland flow characteristics, from calibration B deviated plus 14 percent and minus 33 percent, respectively, from the onsite estimated values. Optimization of onsite estimated values for ALPHAC and RMC, functions of channel-segment characteristics, did not improve the fit between measured and estimated peak discharges in calibration B. The final parameter values for calibrations A and B are shown in table 3.

A summary of the results from calibrations A and B is given in table 4. Table 4 also includes information on weighted rainfall and maximum point rainfall for selected 5- to 60-minute durations measured at the five rain gages in the watershed. The standard error of estimate (mean of squared differences between the logarithms of measured and predicted runoff values converted to percent) of the runoff volumes is 50 percent for calibration A and 28 percent for calibration B. The standard error of estimate of the peak discharges is 72 percent for calibration A and 50 percent for calibration B.

Verification

The verification analyses were made using storms that occurred from May through September 1983, independent of the calibration period. The storms had a range in runoff volume from 0.02 to 1.27 inches and a range in peak discharge from 52 to 3,350 cubic feet per second, the maximum discharge, which has approximately a 100-year recurrence interval (table 5) (Hejl, 1984). The results of the verification analyses A and B using parameter values from calibrations A and B, respectively, are shown in table 5. Simulations of runoff volumes and peak discharges from the storm that occurred on June 27-28, 1983, were poor. Detailed examination of the data for this storm did not reveal any abnormality in the measured rainfall or runoff data. For the remaining seven storms, the standard error of estimate for computing runoff volumes is 40 percent for verification A and 38 percent for verification B. For the peak discharges, the standard error of estimate is 120 percent for verification A and 56 percent for verification B. Inclusion of the June 27-28, 1983, storm more than doubles the standard error of estimate for verifications A and B. Bar graphs of measured rainfall (average of five sites in watershed) and hydrographs of measured discharge and simulated discharges from verification analyses A and B for selected storms at the 8.21-square-mile drainage area of the Ah-shi-sle-pah Wash watershed are shown in figures 6 and 7.

Table 3.—Final parameter values for storm-mode simulation at Ah-shi-sle-pah Wash watershed

[HRU, hydrologic-response unit number; KSAT, hydraulic conductivity of the transmission zone, in inches per hour; PSP, value of the product of capillary drive and moisture deficit at field capacity, in inches; RGF, ratio of the combined effects of capillary drive and moisture deficit from wilting point to that at field capacity; REMX, maximum moisture storage in the recharge zone of the soil profile, in inches; ALPHA and RM, functions of overland flow-plane characteristics]

			CALIBRATION A			
HRU	KSAT	PSP	RGF	REMX	ALPHA	RM
1	1.000	0.001	0.002	0.400	2.18	1.25
2	.200	.069	10.000	.100	5.45	1.25
3	1.000	.001	.002	.400	3.27	1.25
4	1.000	.001	.002	.400	4.59	1.25
5	.200	.069	10.000	.100	4.68	1.25
6	1.000	.001	.002	.400	2.48	1.25
7	1.000	.001	.002	.400	3.27	1.25
8	.200	.069	10.000	.100	5.41	1.25
9	1.000	.001	.002	.400	2.64	1.25
10	1.000	.001	.002	.400	2.96	1.25
11	.200	.069	10.000	.100	2.96	1.25
12	.200	.069	10.000	.100	4.67	1.25
13	1.000	.001	.002	.400	2.96	1.25
14	.200	.069	10.000	.100	5.54	1.25

Table 3.--Final parameter values for storm-mode simulation at Ah-shi-sle-pah Wash watershed--Concluded

HRU	KSAT	PSP	CALIBRATION B RGF	REMX	ALPHA	RM
1	0.260	0.060	0.620	0.400	2.63	1.12
2	.030	2.100	37.000	.100	6.57	1.12
3	.260	.060	.620	.400	3.95	1.12
4	.260	.060	.620	.400	5.53	1.12
5	.030	2.100	37.000	.100	5.64	1.12
6	.260	.060	.620	.400	2.98	1.12
7	.260	.060	.620	.400	3.95	1.12
8	.030	2.100	37.000	.100	6.52	1.12
9	.260	.060	.620	.400	3.18	1.12
10	.260	.060	.620	.400	3.57	1.12
11	.030	2.100	37.000	.100	3.57	1.12
12	.030	2.100	37.000	.100	5.64	1.12
13	.260	.060	.620	.400	3.57	1.12
14	.030	2.100	37.000	.100	6.68	1.12

Table 4.--Summary of data from storm events used for calibration of the precipitation-runoff modeling system at the Ah-shi-sle-pah Wash watershed

[CA, calibration A; CB, calibration B]

Date of storm	Weighted rainfall totals, in inches	Maximum rainfall, in inches, for stated duration, in minutes				Runoff volumes, in inches			Peak discharges, in cubic feet per second		
		5	15	30	60	Measured	Predicted CA	Predicted CB	Measured	Predicted CA	Predicted CB
1981											
June 3	0.256	0.13	0.24	0.27	0.28	0.02	0.05	0.05	59	75	72
August 31	.360	.34	.48	.52	.53	.12	.20	.12	310	738	348
September 5	.219	.08	.19	.25	.26	.02	.02	.02	60	43	36
September 7	.128	.04	.09	.12	.12	.04	.02	.02	132	90	103

Table 4.--Summary of data from storm events used for calibration of the precipitation-runoff modeling system at the Ah-shi-sle-pah Wash watershed--Concluded

Date of storm	Weighted rainfall totals, in inches	Maximum rainfall, in inches, for stated duration, in minutes				Runoff volumes, in inches			Peak discharges, in cubic feet per second		
		5	15	30	60	Measured	Predicted CA	Predicted CB	Measured	Predicted CA	Predicted CB
1982											
July 18-19	0.341	0.13	0.30	0.39	0.43	0.06	0.09	0.08	156	221	152
July 27-28	.682	.14	.34	.46	.78	.18	.16	.18	295	288	298
July 30-31	.596	.39	.69	.96	.99	.28	.32	.24	688	1,200	714
August 22-23	.386	.23	.55	.60	.60	.11	.18	.18	304	577	314
August 23-24	.249	.17	.25	.29	.29	.10	.09	.08	247	243	223
August 24	.252	.11	.24	.25	.25	.07	.05	.05	111	76	45
September 11	.210	.05	.08	.13	.18	.03	.02	.02	54	17	22
September 11-12	.334	.10	.24	.36	.39	.17	.10	.23	310	252	604

Table 5.—Summary of data from storm events used for verification of the precipitation-runoff modeling system at the Ah-shi-sle-pah Wash watershed

[VA, verification A using parameter values from calibration A; VB, verification B using parameter values from calibration B]

Date of storm	Weighted rainfall totals, in inches	Maximum rainfall, in inches, for stated duration, in minutes				Runoff volumes, in inches			Peak discharges, in cubic feet per second		
		5	15	30	60	Measured	Predicted VA	Predicted VB	Measured	Predicted VA	Predicted VB
1983											
May 20	0.299	0.05	0.12	0.20	0.24	0.03	0.02	0.03	102	32	48
June 23-24	.228	.09	.13	.15	.25	.02	.02	.03	52	35	47
June 27-28	.522	.23	.52	.79	.91	.06	.29	.22	170	1,350	688
July 23	.278	.11	.32	.36	.37	.03	.06	.06	130	113	115
July 25-26	.480	.22	.44	.80	.98	.17	.24	.17	396	1,100	761
July 30-31	.206	.21	.45	.46	.47	.09	.10	.07	242	365	152
August 2-3	.387	.16	.34	.56	.65	.16	.09	.09	321	474	352
August 3	1.629	.46	1.03	1.47	1.80	1.27	1.15	1.28	3,350	5,460	6,100

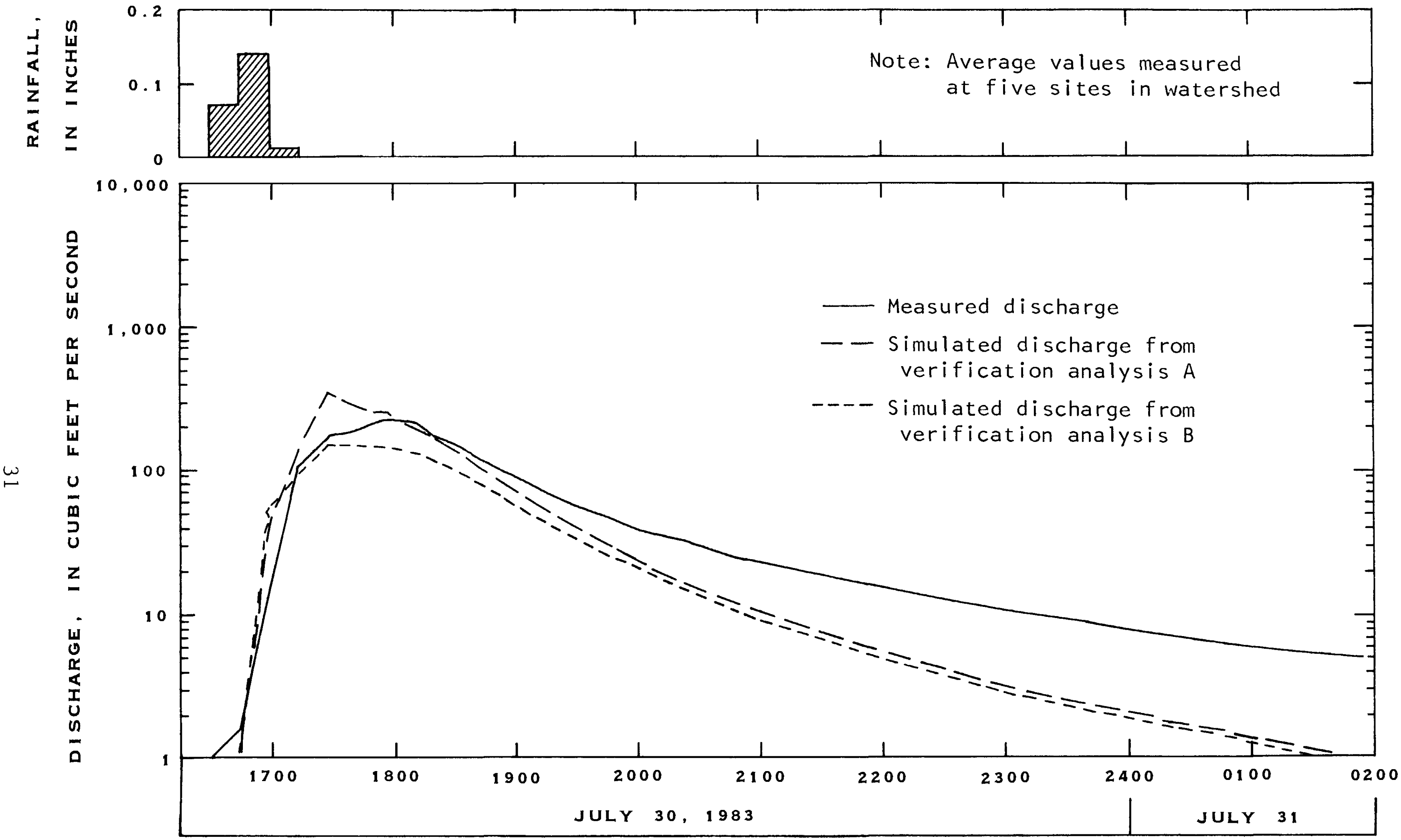


Figure 6.--Rainfall and measured and simulated discharges at the Ah-shi-sle-pah Wash watershed during the storm on July 30-31, 1983.

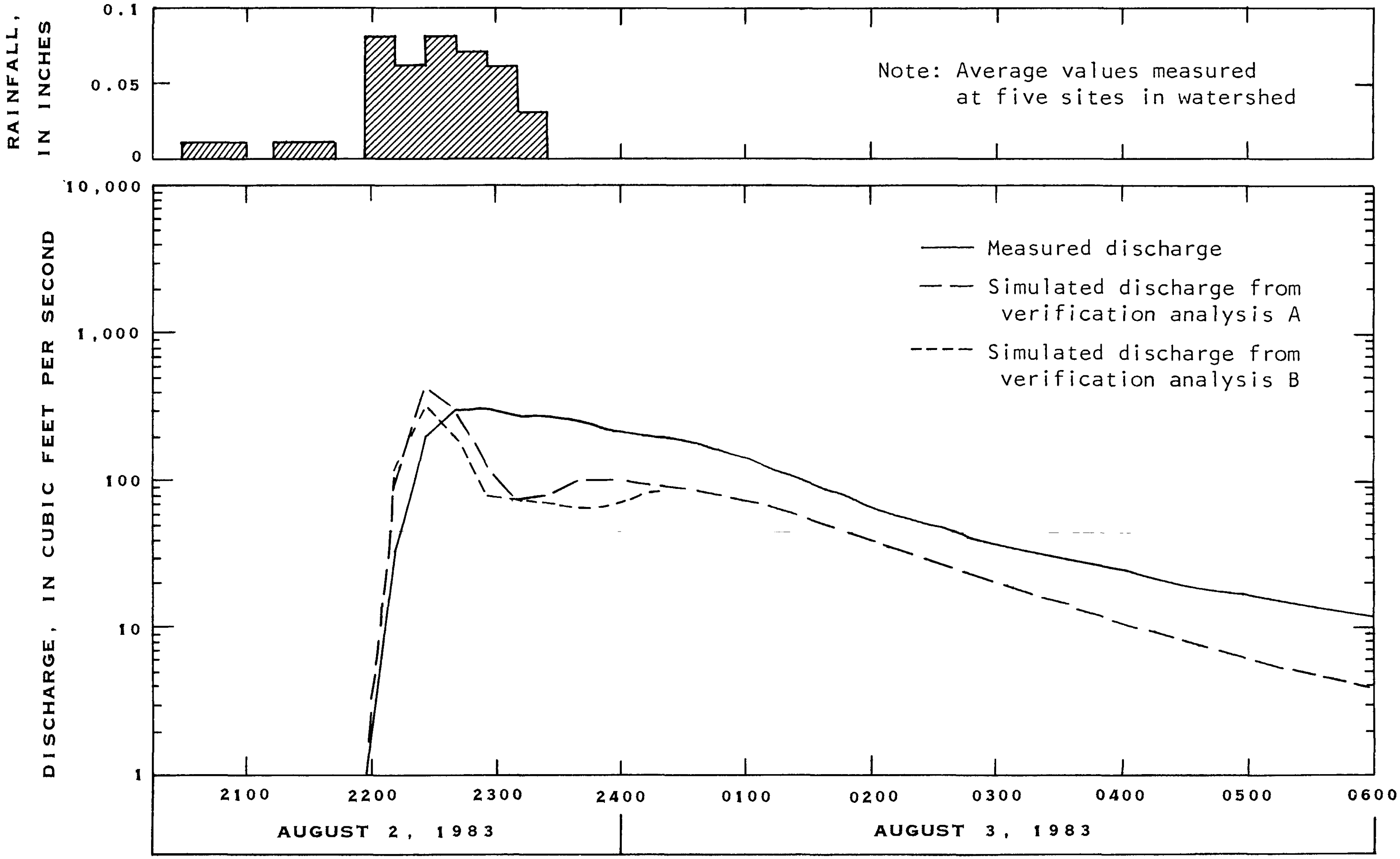


Figure 7.--Rainfall and measured and simulated discharges at the Ah-shi-sle-pah Wash watershed during the storm on August 2-3, 1983.

Limitations

Considerable effort was expended in attempts to calibrate the precipitation-runoff modeling system in the storm mode before successful calibrations were accomplished. The initial values of the product of capillary drive and moisture deficit at field capacity (PSP) and the ratio of the combined effects of capillary drive and moisture deficit from the wilting point to that at field capacity (RGF) are critical for obtaining a successful calibration when optimizing these parameters. Optimized values for hydraulic conductivity were significantly smaller than the values estimated from onsite data. The probable cause for the difficulty in obtaining successful calibrations in the storm mode may have been that an insufficient number of storms were available or that these storms represented a limited range in conditions for a meaningful identification of parameter values. The transferability of parameter values obtained during the calibration of the precipitation-runoff modeling system at the Ah-shi-sle-pah Wash watershed to other basins has not been tested. Additional study is needed before applications are made using the precipitation-runoff modeling system in the arid climate of northwestern New Mexico.

CONCLUSIONS

This study was conducted to address impacts of surface mining on hydrology after Congress passed the Surface Mining Control and Reclamation Act (Public Law 95-87) in 1977. The Act states that before mining plans can be approved the plans have to show how the hydrologic balance of the mine area will be restored to premining conditions. This study, conducted in cooperation with the U.S. Bureau of Land Management, was one of several studies carried out in coal regions within the United States to calibrate and verify the U.S. Geological Survey's precipitation-runoff modeling system with different physical and climatic conditions. The 8.21-square-mile Ah-shi-sle-pah Wash watershed is in an arid, intermontane area in northwestern New Mexico that contains strippable coal in the Cretaceous Fruitland Formation.

The precipitation-runoff modeling system was developed to simulate the hydrologic system using physical and empirical relations to permit the user to input measurable watershed characteristics for selected parameters. This physical-process hydrological model uses a distributed-parameter approach to enable partitioning of a watershed into units based on characteristics such as soil, vegetation, slope, aspect, altitude, and precipitation distribution.

The driving variables used to calibrate the precipitation-runoff modeling system at the Ah-shi-sle-pah Wash watershed were daily precipitation, unit (5-minute increment) precipitation, maximum and minimum daily air temperatures, and solar radiation. Emphasis was placed on calibrating the model in the storm mode. Twelve storms were available for the calibration period May through September of 1981 and 1982. These storms had runoff volumes ranging from 0.02 to 0.28 inch and peak discharges ranging from 54 to 688 cubic feet per second. The maximum peak discharge available for the calibration had a recurrence interval of approximately 5 years.

Two approaches to calibration were used. Calibration A was based on estimated values for hydraulic conductivity from onsite data and the optimization of other storm-mode parameters; calibration B included hydraulic conductivity in addition to parameters optimized in calibration A. The value for hydraulic conductivity when optimized was significantly smaller than that estimated from onsite data. The standard error of estimate in fitting runoff volumes was 50 percent for calibration A and 28 percent for calibration B. The standard error of estimate for peak discharges was 72 percent for calibration A and 50 percent for calibration B.

Eight storms occurring from May through September 1983 were available for the verification analyses. The runoff volumes ranged from 0.02 to 1.27 inches, and peak discharges ranged from 52 to 3,350 cubic feet per second. The maximum peak discharge available for the verification analyses had a recurrence interval of approximately 100 years. Runoff volumes using seven of eight storms occurring during the verification period were simulated and had a standard error of estimate of 40 percent for verification A and 38 percent for verification B; simulated peak discharges had a standard error of estimate of 120 percent for verification A and 56 percent for verification B. Including the eighth storm, which had a relatively small magnitude in the verification analyses, more than doubled the standard error of estimates for runoff volumes and peak discharges from verifications A and B. Additional study is needed before applications are made using the precipitation-runoff modeling system in the arid climate of northwestern New Mexico.

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