USE OF RAINFALL-SIMULATOR DATA IN PRECIPITATION-RUNOFF MODELING STUDIES

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CONVERSION FACTORS

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

Multiply	by	To obtain
inch (in)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
acre	4,047	square meter (m^2)
acre	0.4047	hectare
square inch (in^2)	6.452	square centimeter (cm^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09294	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
foot per second (ft/s)	0.3048	meter per second (m/s)
inch per hour (in/h)	25.40	millimeter per hour (mm/h)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
degree Fahrenheit (°F)	$\frac{(°F-32)}{1.8}$	degree Celsius (°C)

DEFINITIONS

FRIC	Surface roughness.
H_o	Pressure head at the entry surface.
HRU	Hydrologic response unit.
KSAT	Hydraulic conductivity of the transmission zone.
P	Effective pressure head at the wetting front.
PRMS	Precipitation runoff modeling system.
SURF	Surface retention capacity.
WINT	Uniform initial moisture content.
WWET	Uniform moisture content of the transmission zone above the wetting front.

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ABSTRACT

Results of a study using a rainfall simulator to define infiltration parameters for use in watershed modeling are presented. During 1981-82, a total of 23 rainfall-simulation runs were made on 5 small plots (about 2,500 square feet) located on 4 representative soil-vegetation types of the Willow Gulch watershed, located about 50 miles east of Denver, Colorado. During the summer of 1982, data for 3 observed rainfall-runoff events were recorded by gages on 4 of the plots. Runoff data from both simulator runs and observed rainstorms were used to develop best-fit parameters of the Green-Ampt infiltration equation.

In all fitting attempts, the hydraulic conductivity term, KSAT, grossly ontrolled the goodness of fit. High variability in soil-water uptake found from soil samples taken before and after simulator runs confirms the empirical nature of KSAT. Best-fit values are plot-average values that reflect both the limitations of the Green-Ampt equation, and the inherent (natural) variability of soil-water properties of field soils. Results of fitting KSAT to reproduce runoff from rainfall-simulator runs, and results of fitting KSAT to reproduce runoff from observed rainfall-runoff events are inconsistent. Summer runs on plots located in the upland area of ponderosa pine give little indication of runoff potential from observed rainstorms. In contrast, results for plots located in the lowland prairie area are in reasonable agreement with results from observed rainstorms. Fall runs on upland plots indicate that cooler soil temperatures may influence the infiltration process. In contrast, fall runs on lowland plots show no consistent effect of cooler soil temperatures; reasons for these anomalous results are unknown.

The drainage area of the North Fork Willow Gulch watershed was partitioned into homogeneous hydrologic-response units (HRUs), and a conceptual flow-routing network of plane and channel segments was developed to characterize required input to a precipitation-runoff modeling system, PRMS. The application of PRMS to three storms in 1982, using estimates of KSAT based on simulator runs, produced predicted runoff volumes that were 70 percent less than those observed in the first two cases and 40 percent more than that observed in the third case. Using estimates of KSAT based on observed rainfall events on plots 1-3 improved the prediction for two events, and degraded the result for the third event. Adjustments in KSAT specfications, and adjustments to the storm rainfall confirmed that accuracy of predicting peak flow rates is controlled by the amount of water that falls on the ground, and the amount of water that infiltrates. Runoff routing is adequately represented by the conceptual network of plane and channel segments.

INTRODUCTION

Prediction of overland flow generated by precipitation has been the object of intense study by hydrologists for many years. Although methods of prediction vary widely, the most commonly used method probably has been to relate flow characteristics to measurable features of drainage basins, such as area, relief, drainage density, and vegetative cover, and to extrapolate these relationships to larger areas of similar characteristics. Such studies necessarily require a long period to establish flow characteristics of the index watershed.

Advent of the high-speed digital computer has made possible the solution of numerous rainfall-runoff models that have been developed. One such model developed and being used by the U.S. Geological Survey is a physically based model known as PRMS (Precipitation-Runoff Modeling System) (Leavesley and others, written commun., 1983). PRMS is a modular design deterministic distributed-parameter modeling system developed to evaluate the impacts of various combinations of precipitation, climate, and land use on streamflow, sediment yields, and general basin hydrology. Surface runoff in this model is generated by precipitation excess resulting from application of the Green-Ampt infiltration equation.

For many years, researchers have used various types of infiltrometers to determine infiltration characteristics of soils. Most of this work has been concentrated on agricultural land, where the effect of soil treatments on water uptake is important for crop production. In 1971, the U.S. Geological Survey began development of a rainfall simulator that could be used on rangeland, to determine the effects of different land treatments on runoff and erosion (Lusby, 1977). This simulator was designed like a rainfall-runoff facility constructed at Colorado State University (Holland, 1969). The facility at Colorado State University was a permanently installed system, designed to study processes of runoff from an impervious surface, upon which various controlling factors could be imposed. The rainfall design of this system was adapted for use as a portable unit. One product of the simulation runs is determination of effective average infiltration, precipitation minus runoff, over areas of about 2,500 ft^2. These data need to be used on a broader scale than simple comparison of individual results; the use we describe is the definition of parameters used in the PRMS.

PURPOSE AND SCOPE

The primary purpose of the study is to determine if data on infiltration and runoff obtained from the U.S. Geological Survey rainfall simulator, are useful in defining parameters used in the PRMS, which is used to predict runoff from larger watersheds. Incidental to this purpose are determination of the spatial variability of the parameters measured over the simulation plots and over the watershed, and sensitivity of these parameters in predicting runoff.

METHODS OF STUDY

Study Plan

In every investigation of infiltration rates using manmade devices, the question is raised as to whether the results obtained are comparable to events occurring in natural rainstorms. The logical method of answering this question is to measure the results of both artificial and natural rainfall on the same site. To determine applicability of the study plot data to larger areas, the plots should be located within a larger gaged watershed. The study plan was to instrument such a watershed to measure precipitation, runoff, and sediment yield from rainfall-simulation plots, subwatersheds, and the total watershed, for a period long enough to obtain information on natural rainstorms. Simulated rainfall would be applied to the plots to obtain data for comparison with natural events.

Site Selection and Location

In 1978, a search was begun for a suitable watershed to instrument for study. Several criteria were considered for selection of a watershed: (1) Proximity to Denver (50 to 100 mi); (2) proper size (less than 5 mi^2); (3) necessary water supply; (4) reasonable homogeneity; (5) accessibility to equipment; (6) access provided by landowner; (7) reasonable occurrence of natural runoff; and (8) some historical record (preferably). Several areas were visited over the next 2 years, before a site was chosen in 1980.

The study watershed is at the headwaters of Willow Gulch, a tributary of Middle Fork Bijou Creek, about 20 mi south of Byers, Colorado, and about 50 mi east of Denver. A miscellaneous record station was operated at this site by the U.S. Geological Survey, Water Resources Division, Colorado District, from 1970 to 1979.

Description of the Study Watershed

The area is 1.7 mi^2, about 3 mi long and about 1 mi wide (maximum width) (fig. 1). The upper half of the watershed has many steep slopes with deeply incised channels. This part of the watershed contains numerous ponderosa pine interspersed with open areas of grass cover.

The lower half of the watershed has much gentler relief and nondescript drainage boundaries. Vegetation consists mostly of sod-forming grasses with numerous areas of yucca. The main drainage channel contains deep, coarse sand in its entire length. Altitude of the basin ranges from about 5,640 to 6,040 ft.

The entire watershed is underlain by the Dawson Arkose of Late Cretaceous and early Tertiary age (Bryant, 1981). The upper part of the watershed, generally the area containing the ponderosa pine, is underlain by arkosic sand-

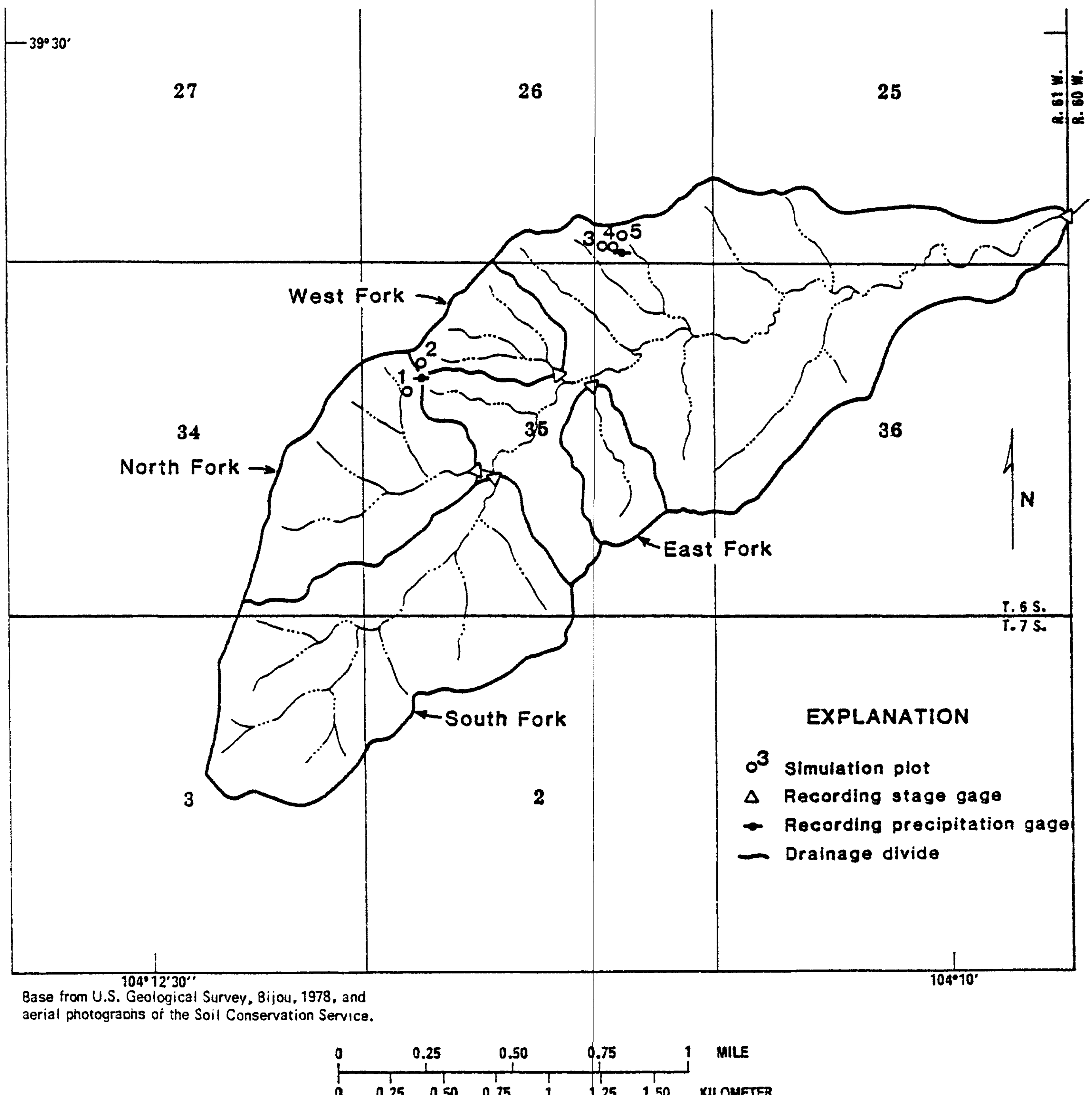


Figure 1.--Willow Gulch drainage basin and location of instrumentation.

stone and claystone facies, coarse to fine-grained, locally conglomeratic. According to the soil survey of Elbert County, Colorado, western part (Larsen, 1980), the soil in this area is Elbeth-Kettle Complex; these soils are formed in material from arkosic deposits. The lower part of the watershed is underlain by fine-grained sandstone, carbonaceous shale, and lignite facies (Bryant, 1981). Much of the north side of the lower part of the basin is Renohill-Louviers Complex soils. Renohill weathered from interbedded sandstone and shale; Louviers formed in material weathered from noncalcareous shale. The south side of the lower watershed is largely eolian material, Wiley-Baca loams, both soils formed in calcareous silty eolian material.

Climate at the Willow Gulch study area generally is characterized by dry, windy conditions. Average precipitation at Byers, about 20 mi north of Willow Gulch, is 15.4 in. Of this amount, about 56 percent occurs from April through July.

December has the least precipitation (0.37 in); May has the most precipitation (2.64 in). Temperatures during May and June are usually warm during the day and cool at night. During July and August, daytime temperatures are often between 90° and 100°F. The study area is fairly typical of the High Plains region of eastern Colorado, as far as wind movement is concerned: prevailing wind in the winter is from the northwest and blows a large part of the time; during summer months, air is often calm at night, but usually windy in the afternoon because of solar heating.

Vegetation at Willow Gulch is basically of two types: grassed and wooded. Within each type are numerous different kinds of grasses, forbs, and shrubs. The wooded area is at the upper end of the watershed, located on arkosic sandstone. This area is suitable for the growth of ponderosa pine; some grass grows beneath the pine trees, but grass is generally sparse. Small open areas containing good grass cover are scattered through the trees; the primary grass in most of these areas is blue gramma. A few shrubs grow along incised stream channels, where some water is available in deep sand. A few sites with sparse vegetation and steep slopes are included in this area.

The lower half of the watershed is almost entirely grass covered. Most of the area has a well-developed sod largely made up of blue gramma; however, numerous other grasses are present (figs. 2 and 3). These grasses include western wheatgrass, green needlegrass, bluegrass, Indian ricegrass, prairie junegrass, and sideoats gramma (Larsen, 1980). Clumps of large yucca are scattered throughout the area.

Delineation of Hydrologic-Response Units and Development of Test Plots

Reconnaissance of the Willow Gulch watershed indicates three major types of hydrologic-response units (HRUs). The upstream 40 percent of the watershed contains ponderosa pine and has steep slopes and deeply incised main channels. The lower part of the watershed has much gentler slopes and vegetative cover

Figure 2.--Grass cover on plot 1, Willow Gulch study watershed.

Figure 3.--Close-up view of sod cover on plot 3, Willow Gulch study watershed.

is either grass or grass mixed with yucca bushes. Two rainfall-simulation plots were established in the upper watershed; three plots were established in the lower watershed (fig. 1). Boundaries of lawn edging were installed around each plot. Size of the plots ranged from 2,099 to 2,720 ft^2. All plots were equipped with 1-in throat Parshall flumes, and digital recorders with a 5-min punch interval. A pressure transducer was installed in each flume and connected to a data logger that records stage at 1-min intervals, and activates a pumping sampler, at predetermined stage, for determination of sediment load. Data loggers also record rainfall at 1-min intervals, from 0.01-in tipping-bucket rain gages, located near plots 1-2 and near plots 3-5.

Several well-defined drainage basins exist within the watershed. Measuring sites were established on four of these tributaries (fig. 1): Supercritical 3-ft concrete flumes were constructed at the South Fork (303 acres) and North Fork (149 acres); Parshall flumes with 4-ft throats were installed at the West Fork (61 acres), and East Fork (53 acres). All flumes were equipped with digital recorders with 5-min punch intervals. The previously operated gaging station at the mouth of the basin is on the natural channel, which was rated by the step-backwater method and slope-area measurements. Dual digital punch recorders with 5-min interval measured rainfall and water stage at this location from 1970 to 1979 and 1981, 1982.

Development of Runoff Data from Rainfall Simulator

During 1981 and 1982, a total of 23 rainfall-simulation runs lasting from 30 to 60 min were made on the study plots (fig. 4). In July and August

Figure 4.--Rainfall simulator in operation, plot 2, Willow Gulch study watershed.

1981, two runs were made on each of the five plots. The first run on each plot was made on dry soil. The second run was made after the water in the soil had become distributed in the soil profile. In October 1981, another run was made on each plot to determine the effects of cooler weather, if any. During June, July, and August 1982, another run was made on each plot to verify previous findings, and to determine the effects of different rainfall rates. In October 1982, runs were made on plots 1 and 3 to observe runoff during the fall again.

Soil samples were taken before and after each run to determine soil moisture and bulk density; statistical summary of bulk density data is shown in table 1. Rainfall was measured during the run, using numerous

Table 1.--*Statistical summary of bulk density data*

[Values shown are mean (number of samples) / standard deviation]

Plot	Depth increment (inches)						
	0-2	2-4	4-6	6-8	8-12	12-16	16-20
1	1.21(76) / .19	1.41(76) / .24	1.50(74) / .21	1.49(65) / .19	1.44(48) / .19	1.58(43) / .26	1.71(32) / .26
2	1.20(67) / .22	1.28(67) / .22	1.34(62) / .24	1.29(52) / .24	1.41(32) / .19	1.48(31) / .19	1.68(30) / .18
3	1.11(64) / .21	1.23(64) / .20	1.18(56) / .17	1.13(45) / .15	1.23(34) / .16	1.37(28) / .17	--
4	1.07(49) / .16	1.13(45) / .15	1.27(32) / .22	1.22(21) / .18	1.31(14) / .12	1.41(14) / .07	--
5	1.02(50) / .16	1.07(50) / .18	1.14(38) / .24	1.21(22) / .21	1.25(13) / .20	1.36(13) / .24	--

storage gages within each plot (usually about 15) and two tipping-bucket rain gages (0.01 in per tip), recorded at 1-min intervals. During the run, staff gage readings were made each minute to compare with recorded stage measurements. Periodic volumetric measurements of outflow were made to verify discharge ratings. Samples of the outflow were taken to determine sediment concentration.

Model Application to Plot Runoff

A simplified, mathematical model of surface-runoff response to rainfall was developed from PRMS components and programmed for desk-top computer solution, to aid in the analysis of both naturally occurring and rainfall-simulator runoff events. The model is a conceptualization of reality, in that the plot is characterized to be a uniformly sloping infiltrating plane. Infiltration and overland-flow computations are coupled to give a more realistic simulation of the boundary conditions influencing infiltration, and also to account for infiltration after rainfall stops. In addition, a surface-retention storage effect, and the influence of ponded storage attenuation (resulting from training the flow to concentrate behind low dikes and thus pass through the measuring flume) are accounted for.

A simple, but widely used, approximation to the infiltration process was suggested over 70 years ago by Green and Ampt (1911), and is used to compute time- and space-varying infiltration rates. The consequence and formulation of the Green-Ampt infiltration equation was reviewed by Philip (1954); more recently, Morel-Seytoux and Khanji (1974) derived an infiltration equation of similar form without the stringent assumptions regarding the exact nature of the wetted profile. For vertical infiltration, the Green-Ampt equation is given as:

$$\frac{dI}{dt} = KSAT \left(\frac{H_o + P + L_f}{L_f} \right); \tag{1}$$

where

$\frac{dI}{dt}$ = infiltration rate, $\left[\frac{L}{T} \right]$;

KSAT = hydraulic conductivity of the transmission zone, $\left[\frac{L}{T} \right]$;

H_o = pressure head at the entry surface (the depth of ponded water), [L];

P = effective pressure head at the wetting front, [L]; and

L_f = length of the wetted zone, [L].

The equation can be transformed to express infiltration rate as a function of accumulated infiltration, I, by assuming a uniform initial moisture content, WINT, and a uniform moisture content of the transmission zone above the wetting front, WWET:

$$I = L_f \text{ (WWET - WINT)}; \tag{2}$$

and

$$\frac{dI}{dt} = K \left(1 + \frac{(H_o + P)(\text{WWET - WINT})}{I} \right). \tag{3}$$

There are many limitations to the use of the Green-Ampt equation in actual field conditions. For example, hydraulic conductivity, as well as other soil-water properties, is highly variable in space because of the heterogeneity of natural soils (Nielson and others, 1973). The parameters KSAT and P are, therefore, essentially empirical indices that must be found by experiment. The model is best suited to uniform, coarse-textured soil profiles where the wetting front is sharp and complications from surface crusting and air entrapment are absent. At best, it offers a frame of reference from which to evaluate the similarities and dissimilarities of both sprinkler-induced runoff and naturally occurring runoff events.

Overland-Flow Routing

Surface runoff is computed by using the kinematic-wave approximation to overland flow. The partial differential equation to be solved for the uniformly sloping, overland-flow plane is:

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = r - \frac{di}{dt}; \qquad (4)$$

where

- h = the depth of flow, ft;
- t = time, s;
- q = the rate of flow per unit width, $ft^3/s/ft$;
- x = distance down plane, ft;
- r = the rainfall rate, ft/s; and
- $\frac{di}{dt}$ = the infiltration rate, ft/s.

The relation between h and q for the kinematic wave is:

$$q = ah^m; \qquad (5)$$

where a and m are functions of overland-flow-plane characteristics. Assuming turbulent flow condition:

$$a = \frac{1.49}{FRIC} S^{\frac{1}{2}}; \qquad (6)$$

and

$$m = 1.67; \qquad (7)$$

where

S = the slope of the plane, ft/ft; and

FRIC = a roughness parameter similar to Manning's *n*, but scaled to reflect roughness elements quite different than those for typical open-channel flows.

The finite-difference numerical techniques developed by Leclerc and Schaake (1973), and described by Dawdy and others (1978), are used to approximate q(x,t) at discrete locations in the x-t plane. A rectangular grid of points spaced at intervals of time, Δt, and distance, Δx, is used.

Two additional features are accounted for in the routing of overland flow: (1) The effect of irregular surface features causing the impoundment of small pockets or puddles of water that collectively produce a surface-retention-storage capacity; and (2) the effect of diversion dikes forming the downslope boundary of the plot. Overland flow can only occur when the effective surface-retention capacity is exceeded. Magnitude of this retention capacity is small (on the order of a few hundredths of an inch), but has been observed to exert an important influence on the time to runoff. Diversion or training dikes effectively pond water immediately above the measuring flume. This impoundment of surface water causes a slight but recognizable attenuation of the rising hydrograph, and also sustains the recession hydrograph after overland flow ceases. Ponded storage attenuation is modeled by a reservoir-routing technique that utilizes a storage-outflow relation of the form:

$$\text{Storage} = \text{KS} \cdot \text{Outflow}^{\text{KN}}; \qquad (8)$$

where KS and Kn are determined from a detailed survey of the plot area within the diversion dikes. The parameters used in the simulation model of plot runoff and the method of determination are summarized in table 2.

Table 2.--*Parameters used in simulation model of plot runoff*

Parameter	Meaning	Method of determination
KSAT	Hydraulic conductivity	Fit.
P	Effective pressure head at wet front	Do.
WWET	Moisture content of transmission zone	Sampled.
WINT	Initial moisture content	Do.
FRIC	Surface roughness	Fit.
S	Flow-plane slope	Measured.
m	Turbulent flow-routing parameter	Fixed (1.67).
SURF	Surface-retention storage, in inches	Fit.
KS, NS	Reservoir-routing parameters	Measured.

RESULTS OF MODEL CALIBRATION

Calibration Using Rainfall-Simulator Data

Model calibrations proceeded through a sequence of steps or phases, more or less predicated on data availability. Initially, available data from simulator runs of July, August, and October 1981 were analyzed on a trial-and-error basis. Adjustment of Green-Ampt infiltration parameters, surface-retention capacity, and surface-roughness coefficient were made to gain insight into the sensitivity of parameters and to best reproduce individual runoff events. These adjustments and their influence on runoff volume and hydrograph shape readily can be determined by using both the speed and graphics capability of the desk-top computer.

Results of the trial-and-error approach of fitting runoff for the summer and fall runs of 1981 for the upland ponderosa area (plots 1 and 2) are shown in figures 5 and 6. Simulation runs shown in figures 5A, 5B, and 6A were intended to represent application of a uniform rainfall intensity of about 2 in/h. Simulation runs shown in figures 5C, 6B, and 6C were intended to represent variable (step-function) rates of rainfall application. Tipping-bucket rain gages were used to approximate the time-varying rainfall rates. Observed discharge is shown by the "+" symbol and simulated response by the continuous solid line. End of rainfall is shown by the vertical dashed line rising from the time-axis. The time- and rate-axes are scaled to a common magnitude for ease in comparing relative magnitude and response characteristics.

In these fitting attempts, as in the majority of all fitting attempts, the hydraulic conductivity term, KSAT, grossly controlled the goodness of fit. The other parameters exerted a second-order influence affecting the shape and timing of the rising hydrograph. Surface-retention capacity, SURF, generally can be adjusted for good agreement between simulated and observed time of rise. However, the range in value and absolute magnitude of this parameter is small, from about 0.05 to 0.10 in. The pressure-head parameter, P, and surface roughness, FRIC, affect the shape of the rising limb of simulated hydrographs. Magnitude of P is very small (0.1 in of water) and approximately the same order of magnitude as the depth of flow, H_o. Values of P commonly reported are in range of 5 to 50 in of water. Roughness values are in general agreement with values for shortgrass prairie, reported by Woolhiser and others (1970).

Results of sensitivity analyses of parameters involved in the infiltration equation are shown in figure 7. These data were obtained by varying the value of each parameter from 30 percent less to 30 percent more than the value for the parameter obtained in the best-fit simulation, while holding the other parameters at their best-fit value. Resulting runoff for each simulation then was recorded. Sensitivity of calculated runoff to applied rainfall is also shown in figure 7. These data were obtained by holding all parameters at their best-fit values and varying applied rainfall from 20 percent less to 20 percent more than the measured rainfall for that run. Of the parameters used in fitting simulated runoff to observed runoff, KSAT is by far the most

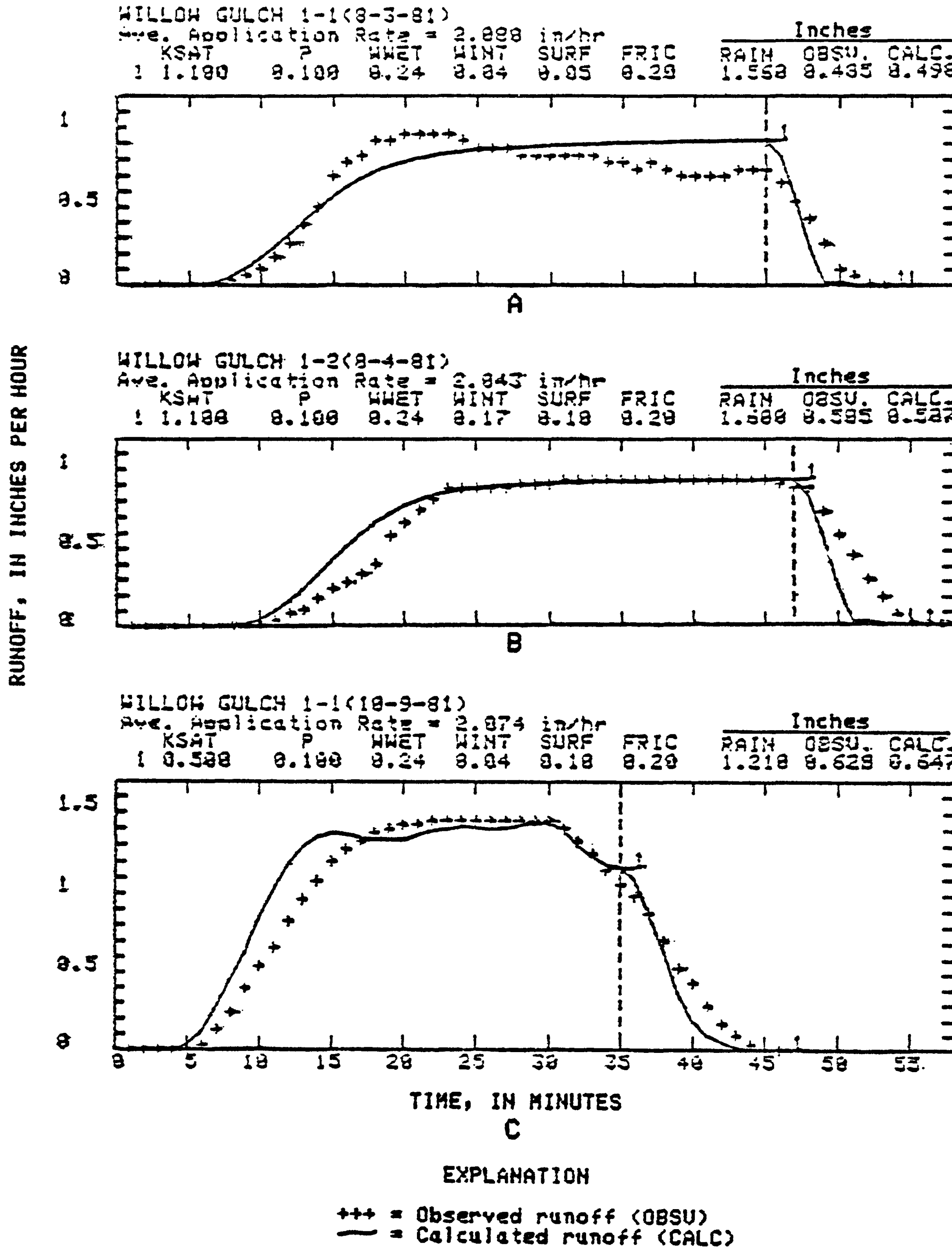


Figure 5.--Model calibration of simulator runs, plot 1, 1981.

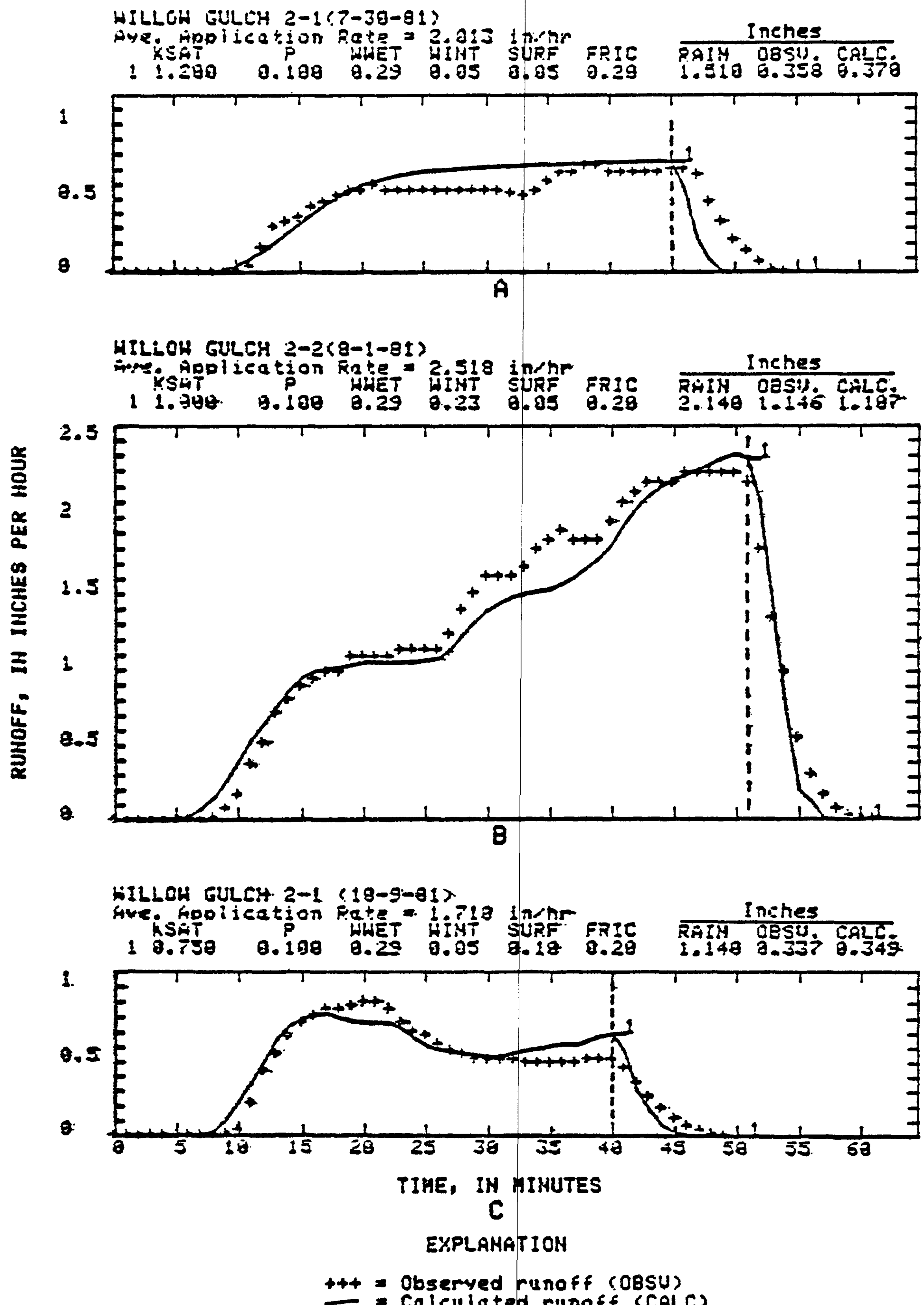


Figure 6.--Model calibration of simulator runs, plot 2, 1981.

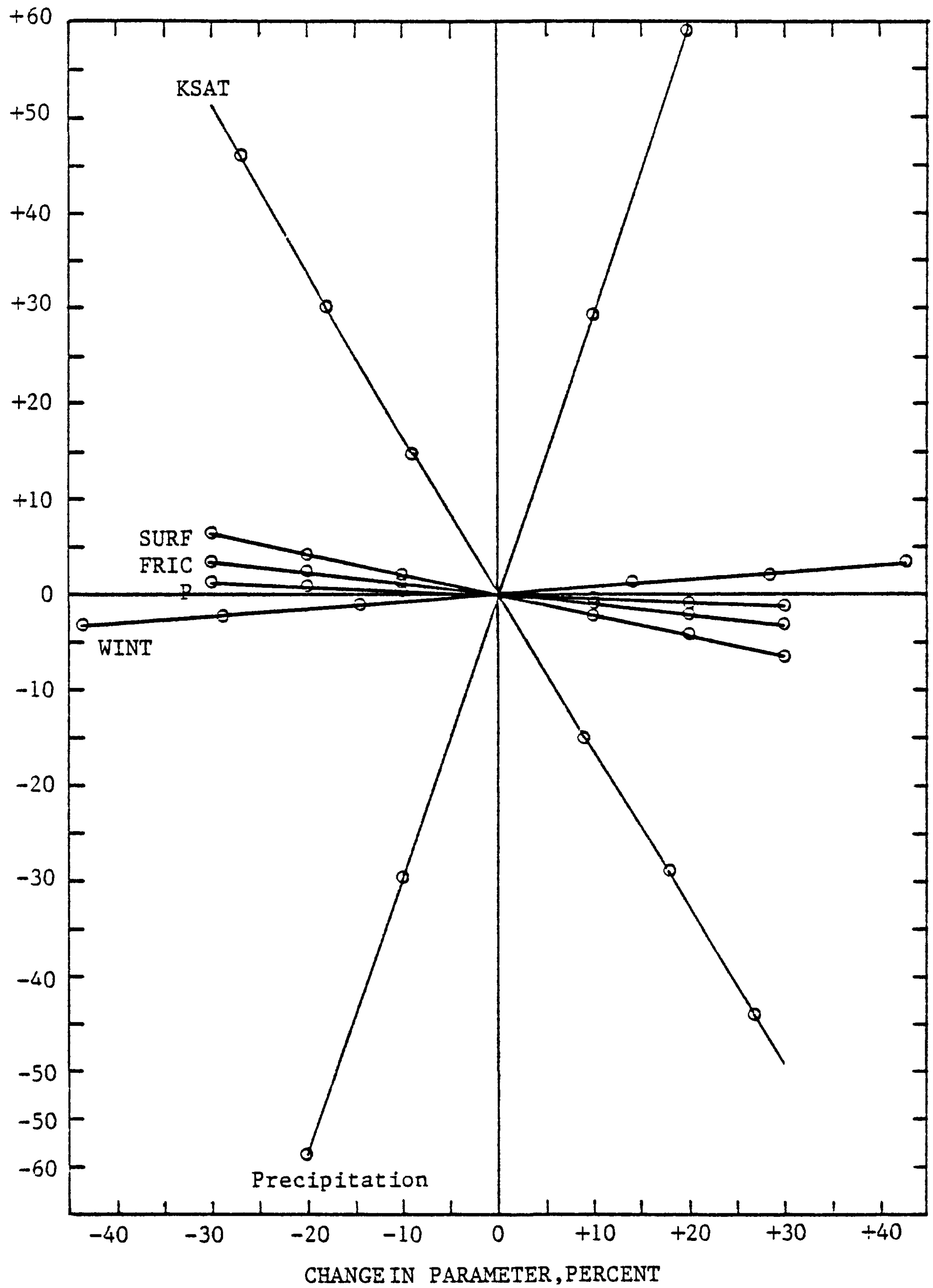


Figure 7.--Sensitivity of calculated runoff to changes in model parameters and precipitation.

sensitive. A -30 percent to +30 percent change in KSAT produced a +48 percent to -53 percent change in computed runoff. The next most sensitive parameter is surface-retention capacity (SURF). A -30 percent to +30 percent change in SURF resulted in a +6 percent to -6 percent change in runoff. Changes of -30 percent to +30 percent in the other parameters resulted in less than 5 percent changes in runoff.

The precipitation section of figure 7 illustrates the sensitivity of model output to errors in precipitation input. A -20 percent to +20 percent change in precipitation results in a -59 percent to +59 percent change in runoff. The precipitation input to model calibration runs is a constant, measured value. The sensitivity analysis is included here to demonstrate the effect of possible errors in precipitation measurements on larger watersheds. On all simulator runs on plots 1-4, water applied was measured in from 10 to 15 rain gages. The average standard error of the mean precipitation for all simulator runs was 2.3 percent.

Examples of the effect of changes in all parameters used in developing best-fit curves are shown in figures 8 through 12. Changes in KSAT (fig. 8) affected not only the shape of the rising hydrograph; the change in infiltration rate throughout the run created large differences in volume of runoff. Changes in P and FRIC affect the shape of the rising hydrograph, but create very small changes in runoff volume (figs. 9, 12). The surface-retention parameter is a direct subtraction from applied water before runoff can begin (fig. 11). Therefore, it affects the timing of initial runoff. Affect of errors in determination of initial moisture content is shown in figure 10. The rising hydrograph is changed slightly, but runoff volumes are changed very little. Although the fitting of calculated runoff to observed runoff through the adjustment of parameters in the model is somewhat subjective, it appears that a fairly unique set of parameters is obtained when calculated runoff matches observed runoff.

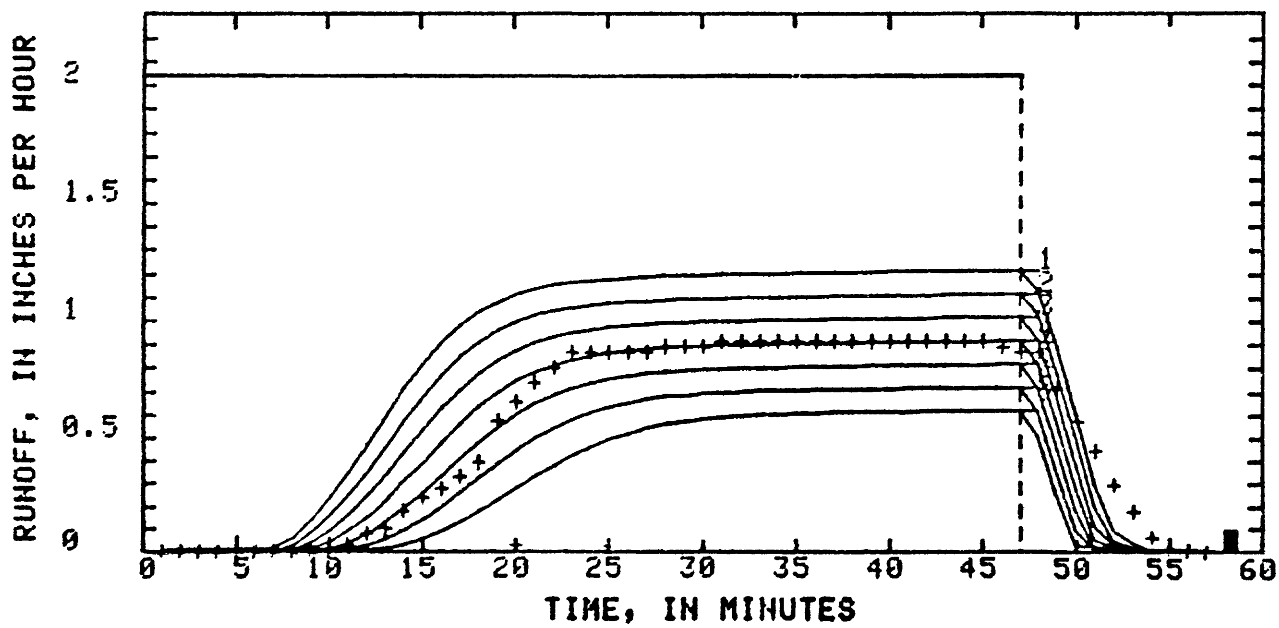
A large reduction in the hydraulic conductivity term is required to reproduce observed runoff for the October runs (figs. 5 and 6). Values of about 1 to 1.2 in/h fit the summer runs, and values of 0.5 and 0.75 are required for the October runs. Antecedent soil-moisture content for the October runs was similar to that for the dry runs of summer: on the order of 0.05 (5 percent of volume). However, temperature of surface soil was considerably less in October (about 50°F) than during the summer runs (70 to 80°F). Hydraulic conductivity is a function of many factors, including viscosity of water. The effect of lower soil temperatures on viscosity of water is in approximate agreement with the reductions in conductivity required to fit the October runs. Viscosity of water at 75°F is 1.92, and at 50°F is 2.74, or an increase of 42 percent. KSAT needed to fit summer runs was about 1.1; KSAT needed for fall runs was about 0.6, or a decrease of 45 percent.

The moisture content of surface-soil samples (0 to 2 in) taken before and after simulation runs are the basis for assigning values to the initial moisture content, WINT, and transmission zone moisture content, WWET. The

WILLOW GULCH 1-2(8-4-81)

Ave. Application Rate = 2.043 in/hr

	KSAT	P	HWET	WINT	SURF	FRIC	Inches RAIN	Inches OBSV.	Inches CALC.
1	0.800	0.100	0.24	0.17	0.10	0.20	1.600	0.505	0.733
2	0.900	0.100	0.24	0.17	0.10	0.20	1.600	0.505	0.655
3	1.000	0.100	0.24	0.17	0.10	0.20	1.600	0.505	0.578
4	1.100	0.100	0.24	0.17	0.10	0.20	1.600	0.505	0.503
5	1.200	0.100	0.24	0.17	0.10	0.20	1.600	0.505	0.429
6	1.300	0.100	0.24	0.17	0.10	0.20	1.600	0.505	0.355
7	1.400	0.100	0.24	0.17	0.10	0.20	1.600	0.505	0.283



EXPLANATION

+++ = Observed runoff (OBSV)

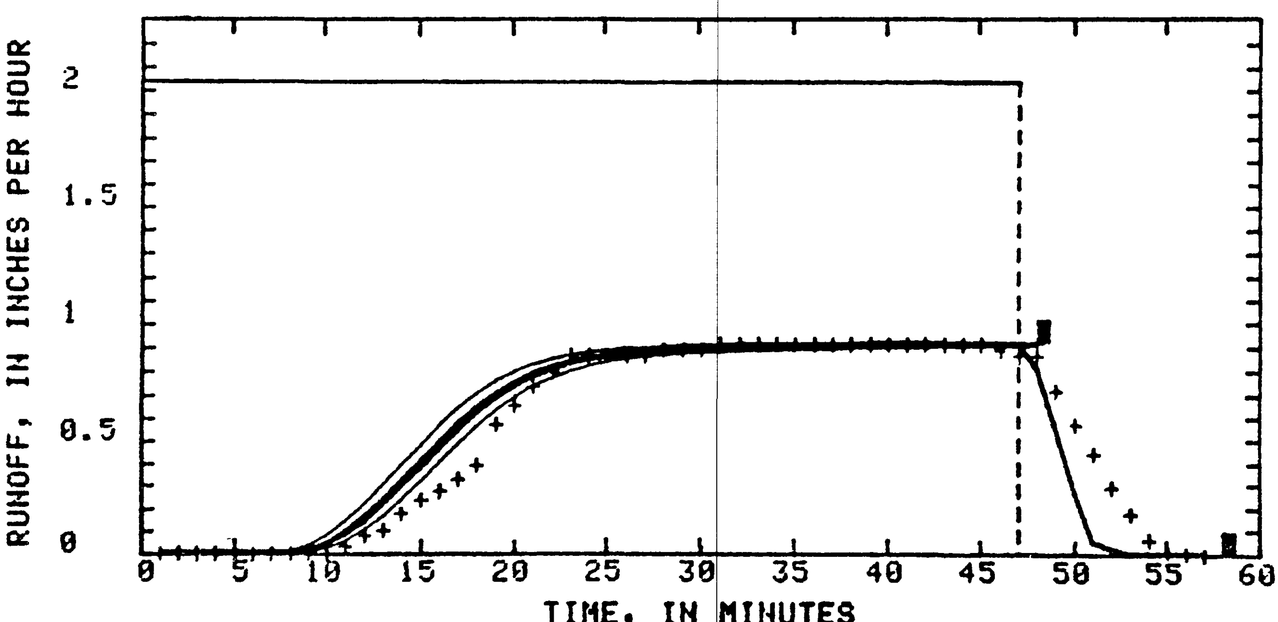
—— = Calculated runoff (CALC)

Figure 8.--Sensitivity of calculated runoff to changes in KSAT.

WILLOW GULCH 1-2(8-4-81)

Ave. Application Rate = 2.043 in/hr

	KSAT	P	WWET	WINT	SURF	FRIC	RAIN (Inches)	OBSV. (Inches)	CALC. (Inches)
1	1.10	0.10	0.24	0.17	0.10	0.20	1.600	0.505	0.503
2	1.10	0.09	0.24	0.17	0.10	0.20	1.600	0.505	0.505
3	1.10	0.08	0.24	0.17	0.10	0.20	1.600	0.505	0.507
4	1.10	0.07	0.24	0.17	0.10	0.20	1.600	0.505	0.509
5	1.10	0	0.24	0.17	0.10	0.20	1.600	0.505	0.524
6	1.10	0.11	0.24	0.17	0.10	0.20	1.600	0.505	0.501
7	1.10	0.12	0.24	0.17	0.10	0.20	1.600	0.505	0.499
8	1.10	0.13	0.24	0.17	0.10	0.20	1.600	0.505	0.497
9	1.10	0.20	0.24	0.17	0.10	0.20	1.600	0.505	0.483



EXPLANATION

+++ = Observed runoff (OBSV)

—— = Calculated runoff (CALC)

Figure 9.--Sensitivity of calculated runoff to changes in P.

WILLOW GULCH 1-2(8-4-81)
Ave. Application Rate = 2.043 in/hr

	KSAT	P	WWET	WINT	SURF	FRIC	Inches		
							RAIN	OBSV.	CALC.
1	1.100	0.100	0.24	0.14	0.10	0.20	1.600	0.505	0.487
2	1.100	0.100	0.24	0.15	0.10	0.20	1.600	0.505	0.492
3	1.100	0.100	0.24	0.16	0.10	0.20	1.600	0.505	0.498
4	1.100	0.100	0.24	0.17	0.10	0.20	1.600	0.505	0.503
5	1.100	0.100	0.24	0.18	0.10	0.20	1.600	0.505	0.509
6	1.100	0.100	0.24	0.19	0.10	0.20	1.600	0.505	0.514
7	1.100	0.100	0.24	0.20	0.10	0.20	1.600	0.505	0.520

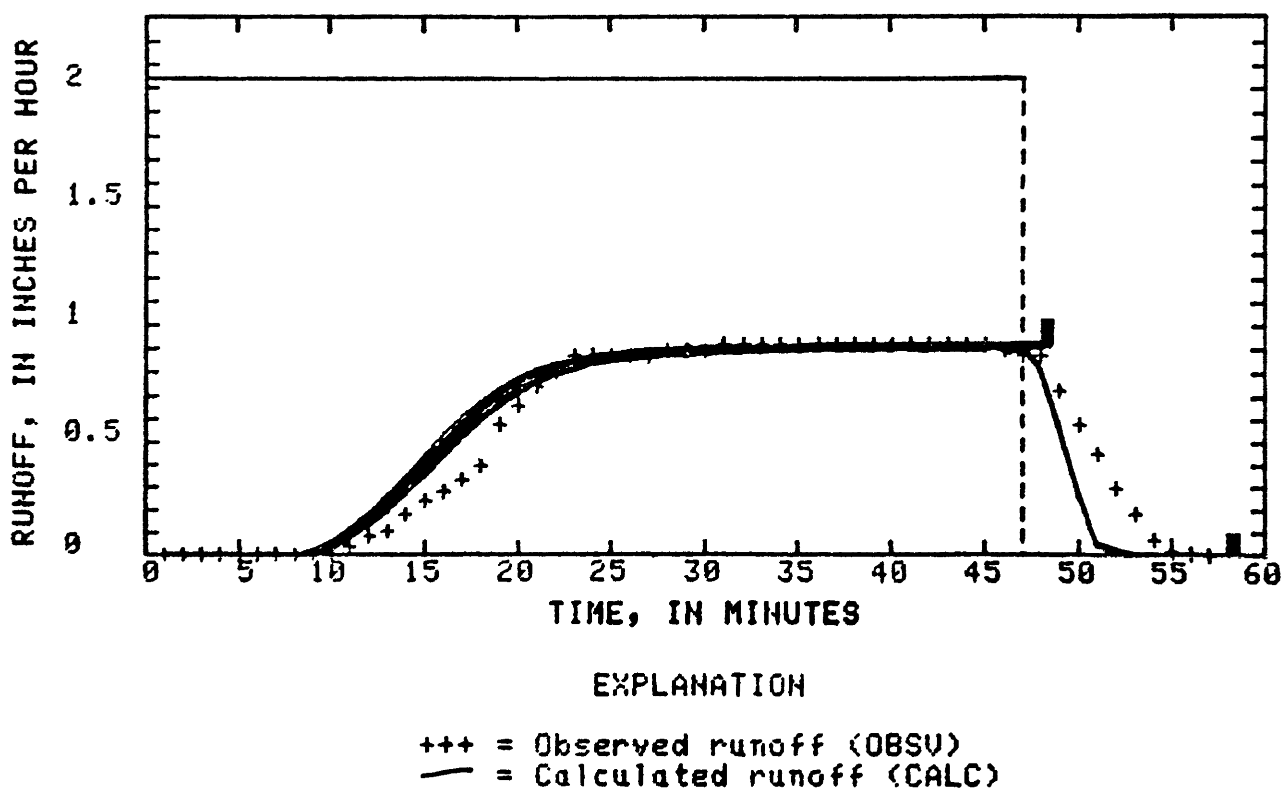
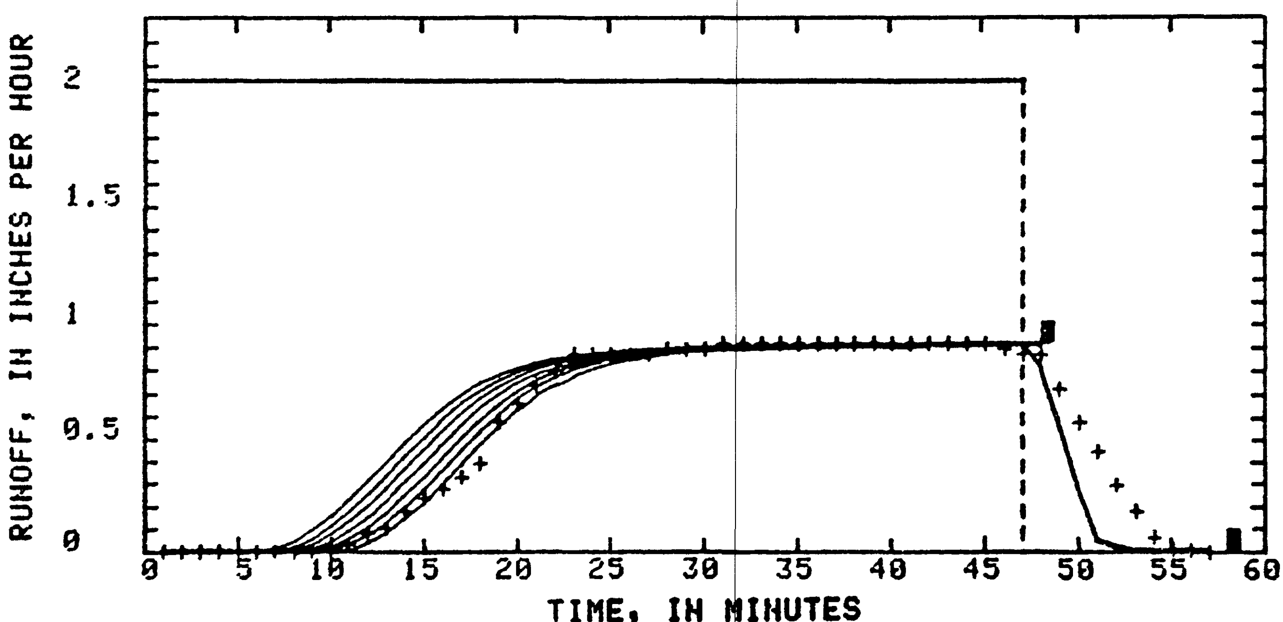


Figure 10.--Sensitivity of calculated runoff to changes in WINT.

WILLOW GULCH 1-2(8-4-81)
Ave. Application Rate = 2.043 in/hr

	KSAT	P	WWET	WINT	SURF	FRIC	Inches		
							RAIN	OBSV.	CALC.
1	1.10	0.100	0.24	0.17	0.10	0.20	1.600	0.505	0.503
2	1.10	0.100	0.24	0.17	0.09	0.20	1.600	0.505	0.514
3	1.10	0.100	0.24	0.17	0.08	0.20	1.600	0.505	0.524
4	1.10	0.100	0.24	0.17	0.07	0.20	1.600	0.505	0.535
5	1.10	0.100	0.24	0.17	0.11	0.20	1.600	0.505	0.492
6	1.10	0.100	0.24	0.17	0.12	0.20	1.600	0.505	0.482
7	1.10	0.100	0.24	0.17	0.13	0.20	1.600	0.505	0.471



EXPLANATION

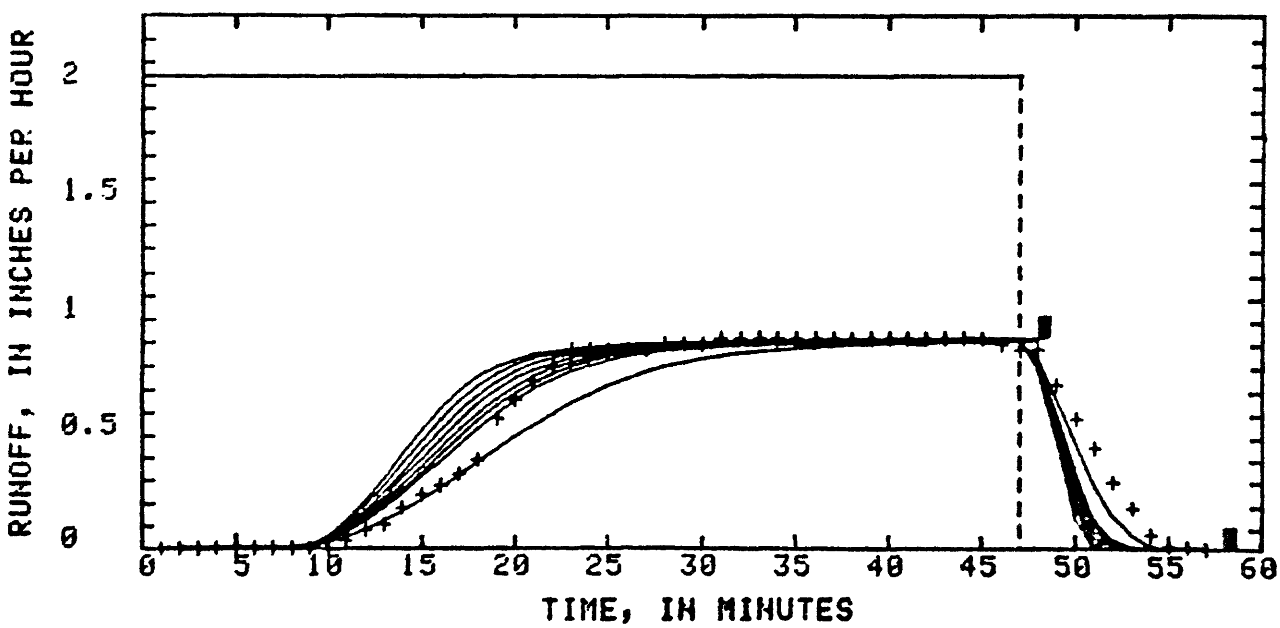
+++ = Observed runoff (OBSV)
—— = Calculated runoff (CALC)

Figure 11.--Sensitivity of calculated runoff to changes in SURF.

WILLOW GULCH 1-2(8-4-81)

Ave. Application Rate = 2.043 in/hr

	KSAT	P	WWET	WINT	SURF	FRIC	Inches RAIN	Inches OBSV.	Inches CALC.
1	1.100	0.100	0.24	0.17	0.10	0.20	1.600	0.505	0.503
2	1.100	0.100	0.24	0.17	0.10	0.18	1.600	0.505	0.509
3	1.100	0.100	0.24	0.17	0.10	0.16	1.600	0.505	0.514
4	1.100	0.100	0.24	0.17	0.10	0.14	1.600	0.505	0.520
5	1.100	0.100	0.24	0.17	0.10	0.22	1.600	0.505	0.498
6	1.100	0.100	0.24	0.17	0.10	0.24	1.600	0.505	0.493
7	1.100	0.100	0.24	0.17	0.10	0.26	1.600	0.505	0.488
8	1.100	0.100	0.24	0.17	0.10	0.40	1.600	0.505	0.457



EXPLANATION

+++ = Observed runoff (OBSV)

—— = Calculated runoff (CALC)

Figure 12.--Sensitivity of calculated runoff to changes in FRIC.

before- and after-run moisture contents of these soil samples show relatively low spatial variability. Standard deviations are about 1 to 2 percent by volume for before-dry-run moisture contents (figs. 5A and 6A) and about 4 percent by volume for before-wet-runs (figs. 5B and 6B). Standard deviation of after-run moisture contents ranged from about 2 to 5 percent by volume. Spatial variability in after-run moisture content increases rapidly with depth, especially for dry antecedent conditions, and indicates a highly irregular wetting front and high variability in cumulative infiltration from point to point. Moisture storage in the 0- to 20-in soil profile before and after the August 3, 1981, run (fig. 5A) is shown in table 3. The data only

Table 3.--*Moisture storage in the 0- to 20-inch soil profile before and after simulator run of August 3, 1981, plot 1*

[Results in inches]

Hole	Before	After	Change[1/]
1	1.44	3.72	2.28
2	1.52	2.60	1.08
3	1.60	2.70	1.10
4	1.41	1.74	.33
5	1.35	3.33	1.98
6	1.51	2.97	1.46
Mean	1.47	2.84	1.37
Standard deviation.	.09	.69	.70

[1/]Values are only approximate; see text.

indicate an approximate change in moisture storage, because augering is a destructive sampling technique and cannot be repeated at the same location. After-run samples were located within about 8 to 10 in of the before-run sample location on the same contour. The data shown in table 3 indicate a large variation in point-to-point infiltration; this large variation in infiltration reflects the large variation in depth of penetration, rather than large differences in wet-up moisture content.

After-run moisture content of surface soils of about 45 to 50 percent of saturation are lower than values normally reported or accepted as appropriate for ponded infiltration into homogeneous soils in the absence of a surface crust. Rapid drainage and redistribution of soil water, occurring before samples could be taken, may be a factor in explaining the low moisture contents; however, a crusting phenomenon may exist. In addition, the soils are typically layered in the vertical, and are either bare or vegetated on the surface, all complicating factors controlling the entry of water into the soil profile. Best-fit parameter values of this simple characterization of the infiltration-surface-runoff process are plot-average values; they reflect the limitations of the model as well as the natural variability inherent in field soils, roughness elements, and surface-retention characteristics.

Results of the best-fit approach to reproduce individual simulator runs made in 1981 for plots 3-5 (representative of the lowland prairie area) are shown in figures 13 through 15. Plot 5 is located in an area of high clay content where the soil typically shrinks and produces a maze of surface cracks when it is dry. The cracking phenomenon negates a meaningful application of the Green-Ampt infiltration equation, except possibly under high antecedent moisture conditions when the cracks have healed, and the expanding nature of clay lattices has more or less stabilized. Results for plot 5 (fig. 15) are presented primarily to show the dramatic effect of surface cracking on observed runoff. Both the conductivity term and surface roughness take on high values to simulate the effect of cracking on runoff.

As in the case for the upland plots, results shown in figures 13 and 14 indicate a consistent hierarchy of parameter significance. Hydraulic conductivity is the most significant; wet-front pressure, surface-retention capacity, and surface roughness are secondary. In addition, the relative magnitude of fitted parameters is similar for the summer runs. Values of KSAT in the range of 1.0 to 1.3 in/h fit all summer runs on plots 1-4. However, the apparent effect of cooler soil temperatures in the fall, and the associated large reductions in hydraulic conductivity required to fit runoff from plots 1 and 2, were not confirmed by the fall runs on plots 3 and 4. Values of KSAT in the range of 1.0 to 1.3 in/h adequately reproduce the fall runs on plots 3 and 4. The best-fit values of KSAT for the various runs are summarized in table 4.

Table 4.--*Summary of fitted values of hydraulic conductivity for rainfall-simulator runs of 1981*

[Results in inches per hour]

Run sequence (soil condition)	Plots				
	1	2	3	4	5
Summer (dry)	1.10	1.20	1.30	1.00	1.60
Summer (wet)	1.10	1.00	1.00	1.10	1.50
Fall (dry)	.50	.75	1.00	1.30	1.60

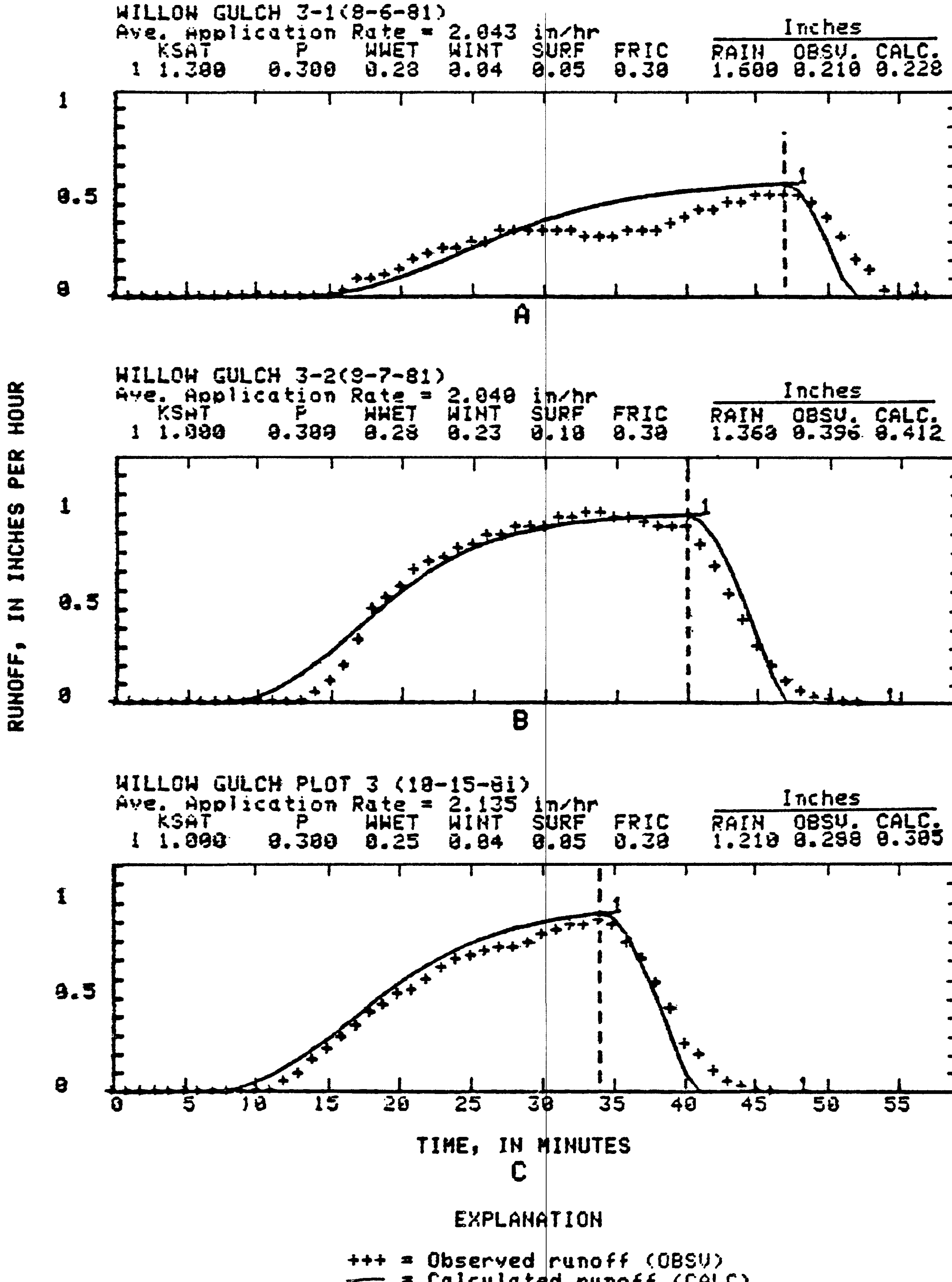


Figure 13.--Model calibration of simulator runs, plot 3, 1981.

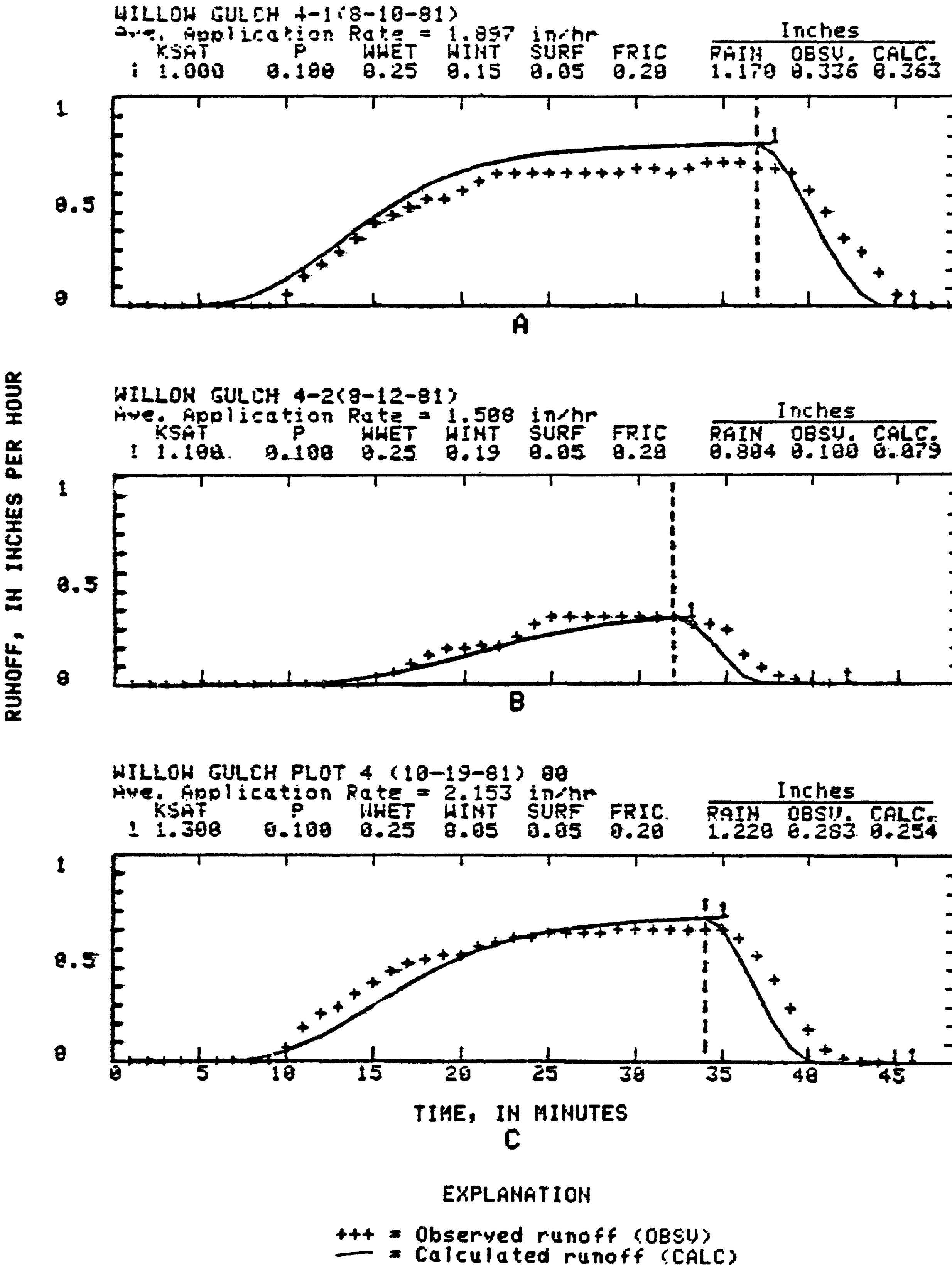


Figure 14.--Model calibration of simulator runs, plot 4, 1981.

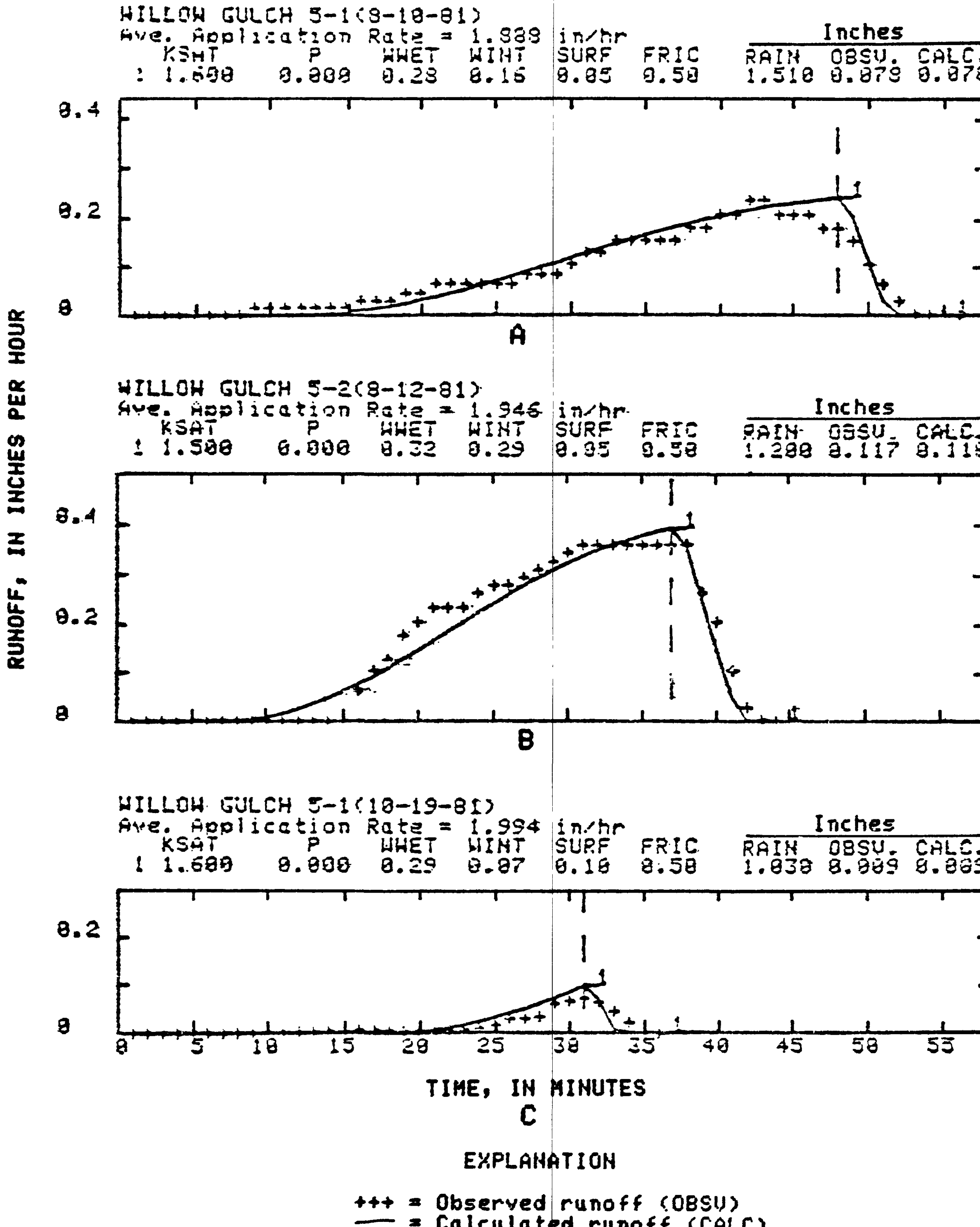


Figure 15.--Model calibration of simulator runs, plot 5, 1981.

Rainfall-simulator runs made during 1982 were conducted to investigate the influence of variable rainfall intensity on runoff, and to confirm the trends in fitted values of hydraulic conductivity determined from the 1981 experiments. Prevailing weather conditions during the spring and summer of 1982 presented a substantially different set of antecedent soil-moisture conditions than those of the summer of 1981. Frequent showers and thunderstorms were typical of the 1982 summer season, as opposed to the extremely dry conditions of 1981. Only one rainfall-similation run conducted during the summer of 1982 could be considered as having a dry antecedent condition. The results of the sequence of runs conducted in 1982 are depicted in figures 16, 17, and 18. Comparative summer runs on the upland ponderosa area are shown in figure 16; similar results for plots 3-5 in the lowland prairie area are shown in figure 17; and comparative runs on plots 1 and 3 made during the fall are shown in figure 18.

Results of fitting parameters for plot 1 data (fig. 16A) and the second run on plot 2 (fig. 16C) show close correspondence between observed and computed runoff. A large discrepancy between observed and computed runoff is evident for the first run on plot 2 (fig. 16B). The computed response rises too rapidly and overpredicts the slowly rising limb of the observed hydrograph. Computed results do not start to converge to the observed runoff rate until about 30 minutes into the run. Soil temperature at 0.5 in depth was 102°F at the start of this run. Near-surface soil temperature dropped to about 87°F after 15 minutes of 2 in/h rain application and then stabilized at 77°F at 35 minutes into the run; (rainfall rate increased from 2 to 4 in/h at 27 minutes, then dropped back to 2 in/h at 39 minutes). Soil temperature at 0.5 in depth also was high, 96°F, at the start of the second run on plot 2 (fig. 16C). However, the temperature dropped very rapidly to 84°F after 6 minutes of 4 in/h rain application and changed little for the duration of the run. Soil temperature at the start of the run on plot 1 (fig. 16A) was about 85°F, dropped to 76°F after 12 minutes of 2 in/h rainfall application, and changed little thereafter.

The best-fit parameter values for the summer runs on plot 2 (figs. 16B and 16C) compare reasonably well with those developed from 1981 data. Values for KSAT in the range of 1.0 to 1.2 apply to all four summer runs. Hydraulic conductivity is the controlling parameter as noted in the fitting of 1981 simulator results. The fitted result for the run shown in figure 16B could be improved by an increase in the surface-retention capacity to about 0.2 in; however, the value of 0.05 in seems more appropriate and consistent with other results. The fitted value for KSAT of 1.5 in/h shown in figure 16A (plot 1) is higher than previously determined values from the summer runs of 1981.

A more intensive before- and after-run soil-sampling effort than that of the previous summer was undertaken for the June 23 and July 8, 1982 runs on plots 1 and 2 (figs. 16A and 16B). Results shown in table 5 demonstrate very pronounced variability in cumulative infiltration from point to point. Point-to-point variability in water uptake is related to depth of wetting rather than to large differences in degree of saturation, which is a confirmation of previous results.

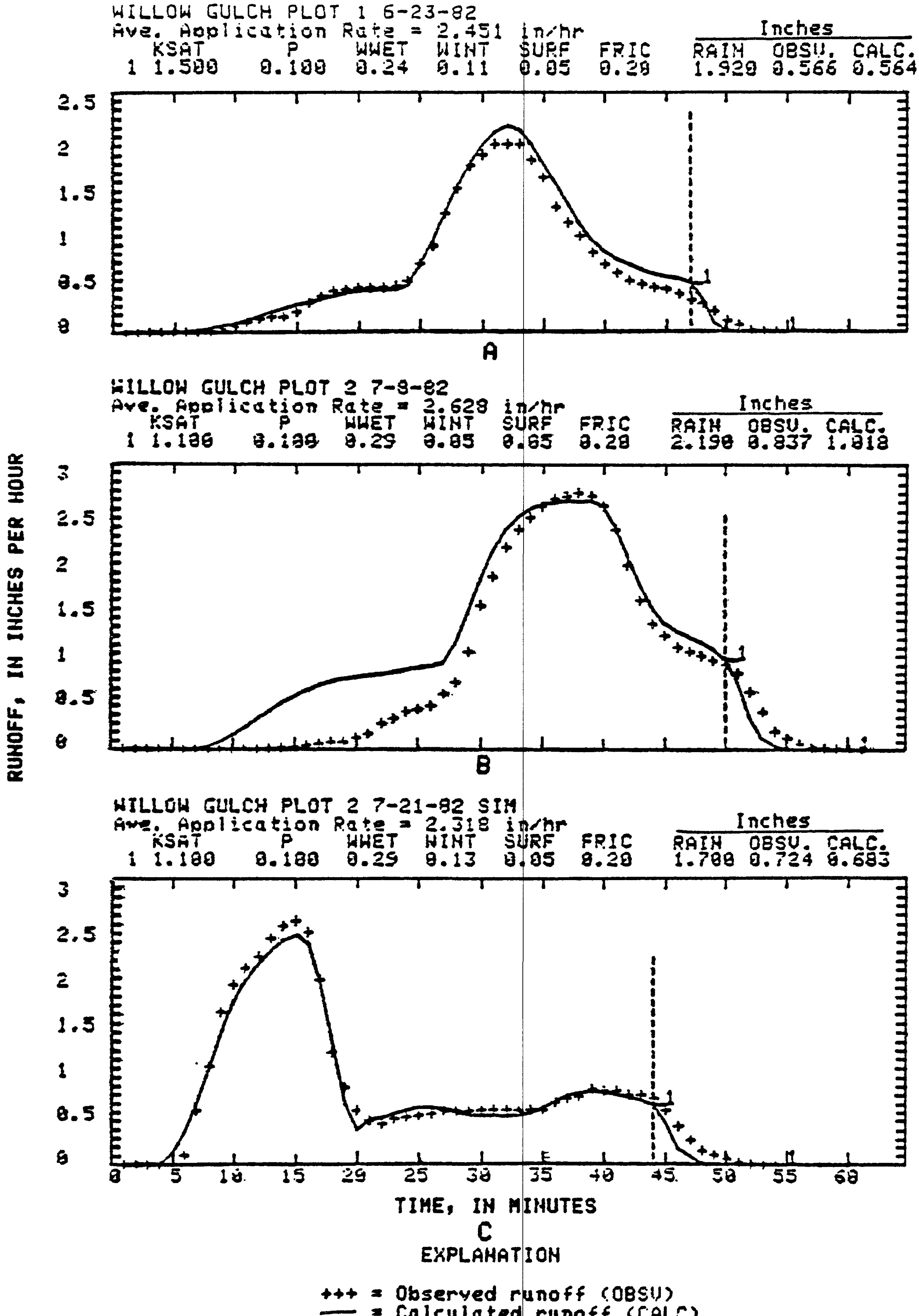


Figure 16.--Model calibration of simulator runs, plots 1 and 2, summer 1982.

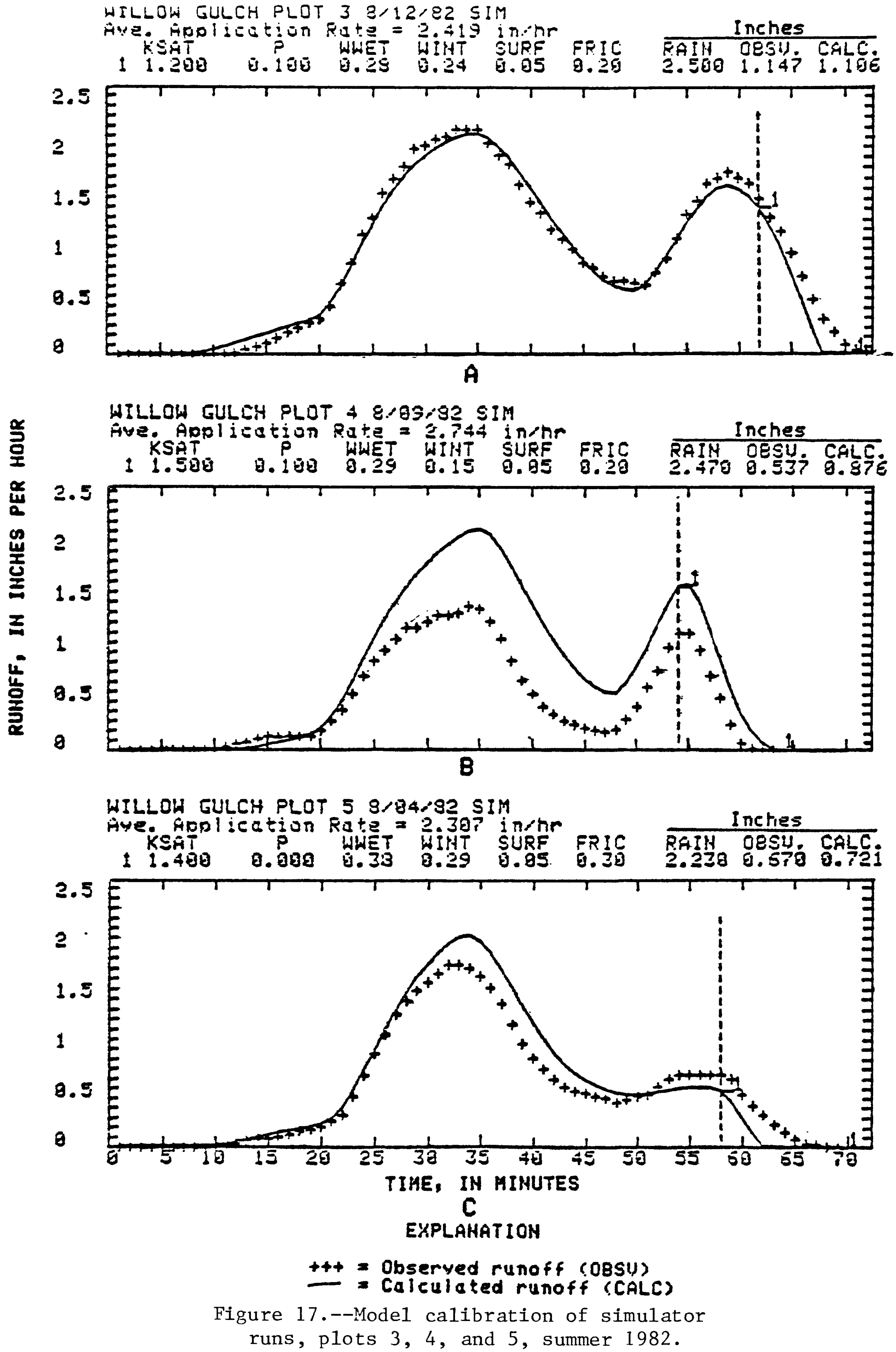


Figure 17.--Model calibration of simulator runs, plots 3, 4, and 5, summer 1982.

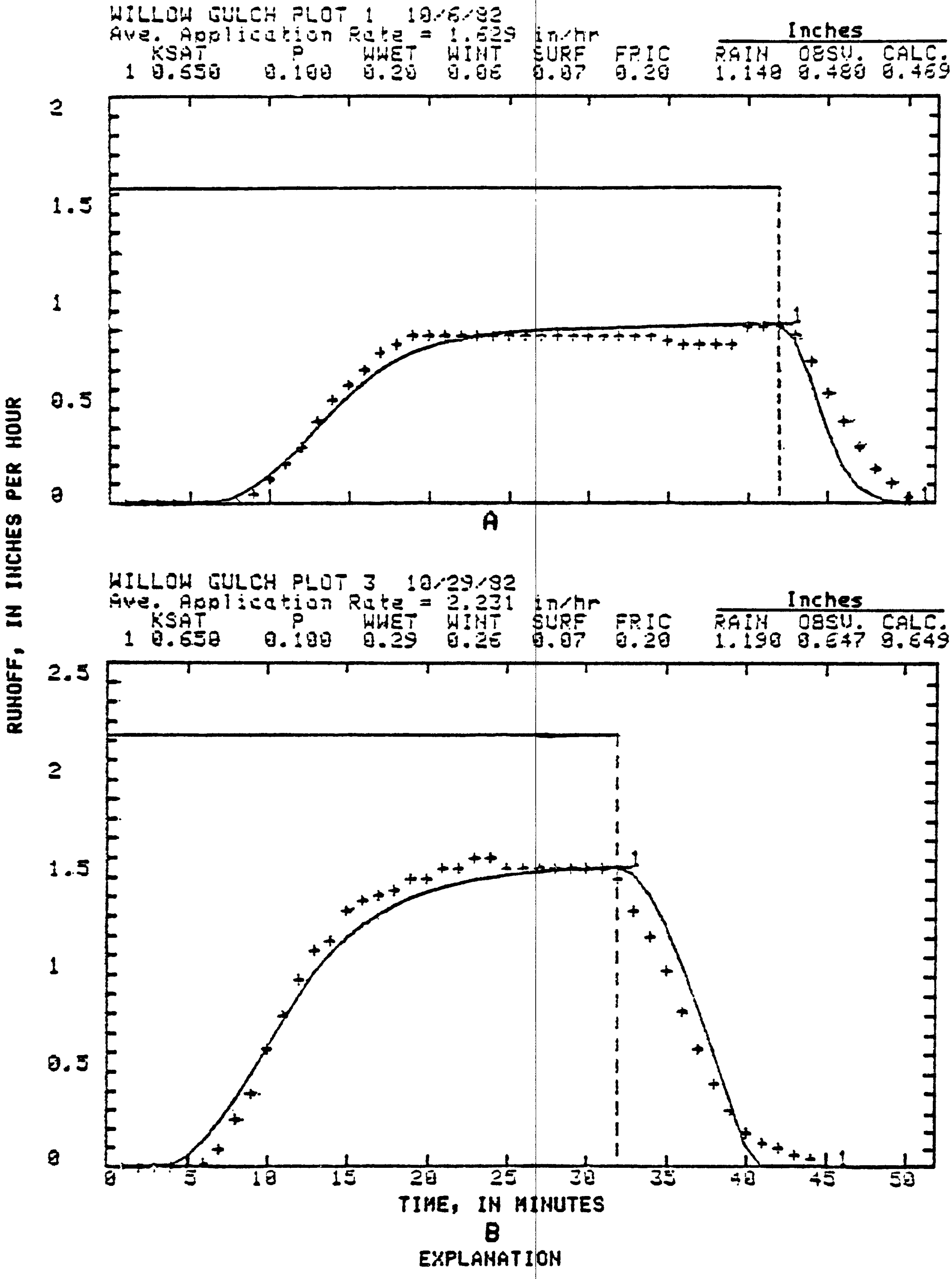


Figure 18.--Model calibration of simulator runs, plots 1 and 3, fall 1982.

Table 5.--*Moisture storage in the 0- to 20-inch soil profile before and after simulator runs*

[Results are in inches]

Hole	Plot 1 (6-23-82)			Plot 2 (7-8-82)		
	Before run	After run	Change[1/]	Before run	After run	Change[1/]
1	2.69	3.47	0.78	2.17	2.97	0.80
2	2.75	4.06	1.31	2.74	3.27	.53
3	2.25	2.71	.46	2.00	3.14	1.14
4	2.72	3.49	.77	2.63	3.22	.59
5	2.81	4.74	1.93	3.11	4.33	1.22
6	2.63	5.00	2.37	2.37	3.76	1.41
7	2.61	3.31	.70	2.55	4.29	1.74
8	3.10	4.00	.90	2.13	3.36	1.29
9	2.92	4.42	1.50	1.89	5.49	3.57
10	2.80	4.30	1.50	1.95	2.50	.55
11	2.55	2.74	.19	2.45	3.10	.65
Mean	2.71	3.84	1.12	2.36	3.58	1.22
Standard deviation.	.22	.76	.66	.38	.83	.87

[1/]Values are only approximate. Replicate samples cannot be taken from the same location (see text).

Results of the sequence of runs made in early August 1982 on plots 3-5 are shown in figure 17. These rainfall-simulator runs were conducted during a period of frequent rain showers and thunderstorms starting the evening of July 26 and continuing almost daily through August 12. Antecedent soil moisture was quite high, especially for the runs on plots 3 and 5 (fig. 17A and 17C). Severe cracking of the surface soil of plot 5, found during the previous summer, was absent. The soil was uniformly moist and near field capacity (the moisture content at which drainage by gravity ceases) to a depth of about 4 in, and drier below. Soils on plot 3 were near field capacity to a depth of about 8 in, and drier below. Soils on plot 4 were drier than those on plots 3 and 5, but were uniformly moist to a depth of about 10 in, and drier below.

The computed response for plot 3 (fig. 17A) is in close agreement with observed runoff. In addition, the fitted value for hydraulic conductivity of 1.2 in/h is in line with the fitted value for hydraulic conductivity determined from the simulator runs of 1981. Results for plot 4 (fig. 17B) are very poor, and in no way representative of those previously experienced. The observed runoff data show a subtle but possibly significant flattening of the rising hydrograph, starting at about 25 minutes into the run. From this point on, the deviation between observed and computed runoff gives the general appearance of the action of a sink, or diversion of flow. Surface features of plot 4 are very irregular; large dish-shaped clumps of yucca dot the ground surface. These yucca areas are characteristically porous, and are interlaced with rodent holes and rotted root chambers. In several instances, these clumps of yucca are located on rather flat drainage divides between gentle swales. Under high rates of surface runoff, these low divides may become inundated and the yucca area may act as a sink. One large area of yucca is located directly upslope from the measuring flume. Surface runoff normally divides just above this clump and flows laterally into the training dikes. It is quite possible that a large diversion of low and loss of runoff occurred into the area of yucca during this run. The lower than anticipated runoff prompted a sampling of the soil profile a few feet downslope from the suspected intake area. The soil was uniformly wet (near field capacity) to the depth of the auger handle (40 in). Sampling on the general plot area showed much shallower depths of water penetration, rarely exceeding 12 in. Other reasons for the discrepancy between observed and computed response could be invoked; however, the fact remains that adjustment of model parameters cannot account for apparent threshold effects exhibited in observed runoff.

Observed results for plot 5 show the pronounced influence of high antecedent soil moisture and the absence of surface cracks on runoff (fig. 17C). In contrast to the dry conditions of 1981, plot 5 is reasonably well behaved under wet conditions and produces runoff that is comparable to that from plots 3 and 4. As shown in figure 17C, the computed results are reasonably close to the observed runoff. The large value of surface roughness, required to fit the cracked surface condition of 1981, has been reduced to a more realistic value.

Results of simulation runs made on plots 1 and 3 during October 1982 are shown in figure 18. The antecedent soil-moisture condition for these fall runs was higher than the previous year, especially so for the run on plot 3. The near surface (0 to 2 in) moisture content for the run on plot 1 was similar to that of 1981, but the soils were more moist at depth in 1982. The run of plot 3 was scheduled for October 7, but it had to be repeatedly postponed because of wind, rain, and snow and was not made until October 29. Antecedent soil moisture at this time was the highest observed for any of the runs on plot 3. In addition, soil temperature was quite low, 34°F at the surface, and increased slightly with depth.

Fitted results for both runs are in close agreement with observed runoff (fig. 18). The value of KSAT for plot 1 is comparable to that found the previous fall (0.5 in/h for 1981; 0.65 in/h for 1982). The fitted value of KSAT for plot 3 had to be reduced from the 1981 value of 1.0 in/h to match observed runoff.

The range (where available) in fitted values of hydraulic conductivity for summer and fall runs is shown in table 6. Data from summer runs show little in the way of significant differences in the runoff potential between plots 1-4. Data from fall runs indicate some resemblance to an ordering or ranking of runoff potential, in the same ordering as the plot-sequence number.

Table 6.--*Range in fitted values of hydraulic conductivity for summer and fall runs*

[Results in inches per hour. Values in parentheses indicate ranges not available.]

Runs	Plots				
	1	2	3	4	5
Summer	1.1-1.5	1.0-1.2	1.0-1.3	1.0-1.5	1.5-1.6
Fall	0.5-0.65	(0.75)	0.65-1.0	(1.30)	(1.4)

Calibration Using Observed Rainfall-Runoff Data

Three rainfall-runoff events are available for analysis: June 25, July 26, and August 10, 1982. Stage-recorder malfunction and plot failures hamper the usefulness of these data; but, overall, these available data give valuable insight into natural runoff characteristics. The largest runoff-producing event occurred the evening of June 25, when rainfall intensities in the range of 5 and 6 in/h were recorded by tipping-bucket rain gages, located near plot 2 in the upland ponderosa area, and near plot 4 in the lowland prairie area. During this event, plots 1, 3, 4, and 5 overflowed their downslope diversion dikes. Perimeter edging around the plots also failed to divert surface runoff from upslope; only plot 2 withstood the excessive runoff during this event. Unfortunately, the pressure transducer malfunctioned, and observed stage data are poor. No record of stage is available for this event, or the event of July 26 for plot 5; both the digital punch and pressure transducer were inoperative. A summary of available data is shown in table 7.

Table 7.--*Summary of available data for three rainfall-runoff events during 1982*

Date	Rainfall (inches)	Runoff (inches)		Rainfall (inches)	Runoff (inches)		
		Plot 1	Plot 2		Plot 3	Plot 4	Plot 5
June 25	1.58	[1/] 1.42	[2/] 1.07	1.44	[1/] 0.54	[1/] 0.42	---
July 26	1.20	.65	.48	.81	.06	.08	---
August 10	.74	.50	.45	.85	.16	.16	0.10

[1/] Plot boundaries failed during this event, runoff unreliable (see text).

[2/] Stage record poor, runoff questionable (see text).

Results of trial-and-error adjustment of model parameters to best-fit observed runoff data for plots 1-4 are shown in figures 19 through 22. Records of precipitation producing these runoff events are shown in figure 23. Hydraulic conductivity is the controlling parameter, as in the case of fitting rainfall-simulator data. The pressure term, surface-retention capacity, and surface roughness are of secondary importance. Attempts to fit KSAT for the June 25 event were conditioned on matching the rising limb of observed hydrographs; the plot boundaries failed and runoff volumes were unreliable. Other fittings were conditioned on both the shape and volume of runoff.

Similarity in observed runoff response for each storm event for plots 1 and 2 (figs. 19 and 20), and then again for plots 3 and 4 (figs. 21 and 22), reflects the differences in rainfall-intensity patterns for each storm, for each location. For example, the observed (and computed) hydrographs for plots 1 and 2 show two peaks for the event of July 26; those for plots 3 and 4 show only one. Results are in harmony with observed rainfall-intensity patterns. Observed data show that rainfall-intensity patterns change significantly over short distances (gages 3,000 ft apart) for these summer thunderstorms.

Apparent consistency in matching hydrograph shape makes the observed results for plots 1 and 2 for the August 10 event seem out of place (figs. 19C and 20C). Observed data from both plots show a rapid early rise in runoff to about 1.5 in/h. It is unlikely that the pressure transducers on both plots 1 and 2 overregistered this early rise; it is more likely that the rain gage failed to catch an early burst of rainfall. In any case, the fitted value of KSAT is conditioned to fit the general shape and volume of runoff, and not the early rise.

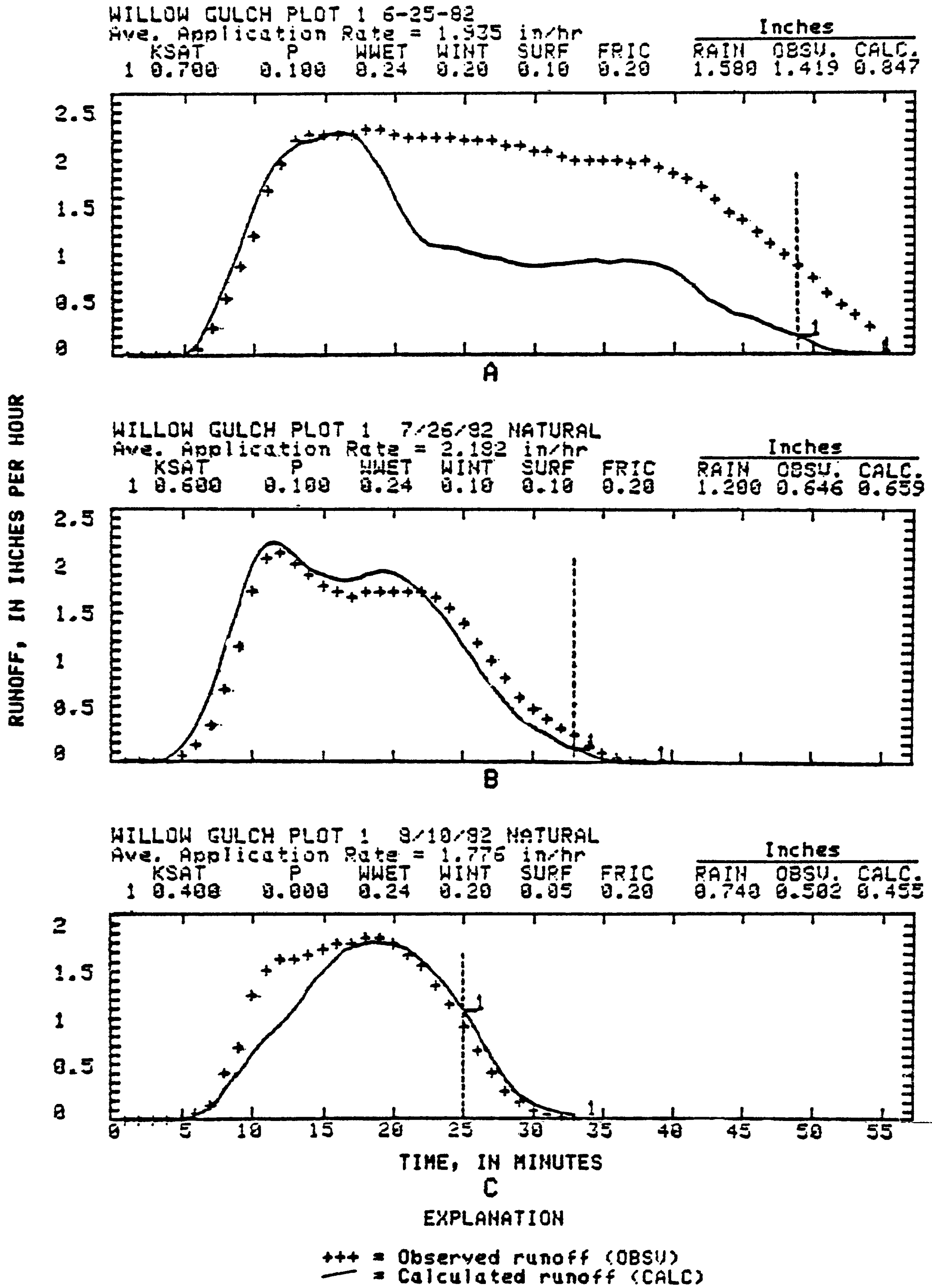


Figure 19.--Model calibration using observed data, plot 1.

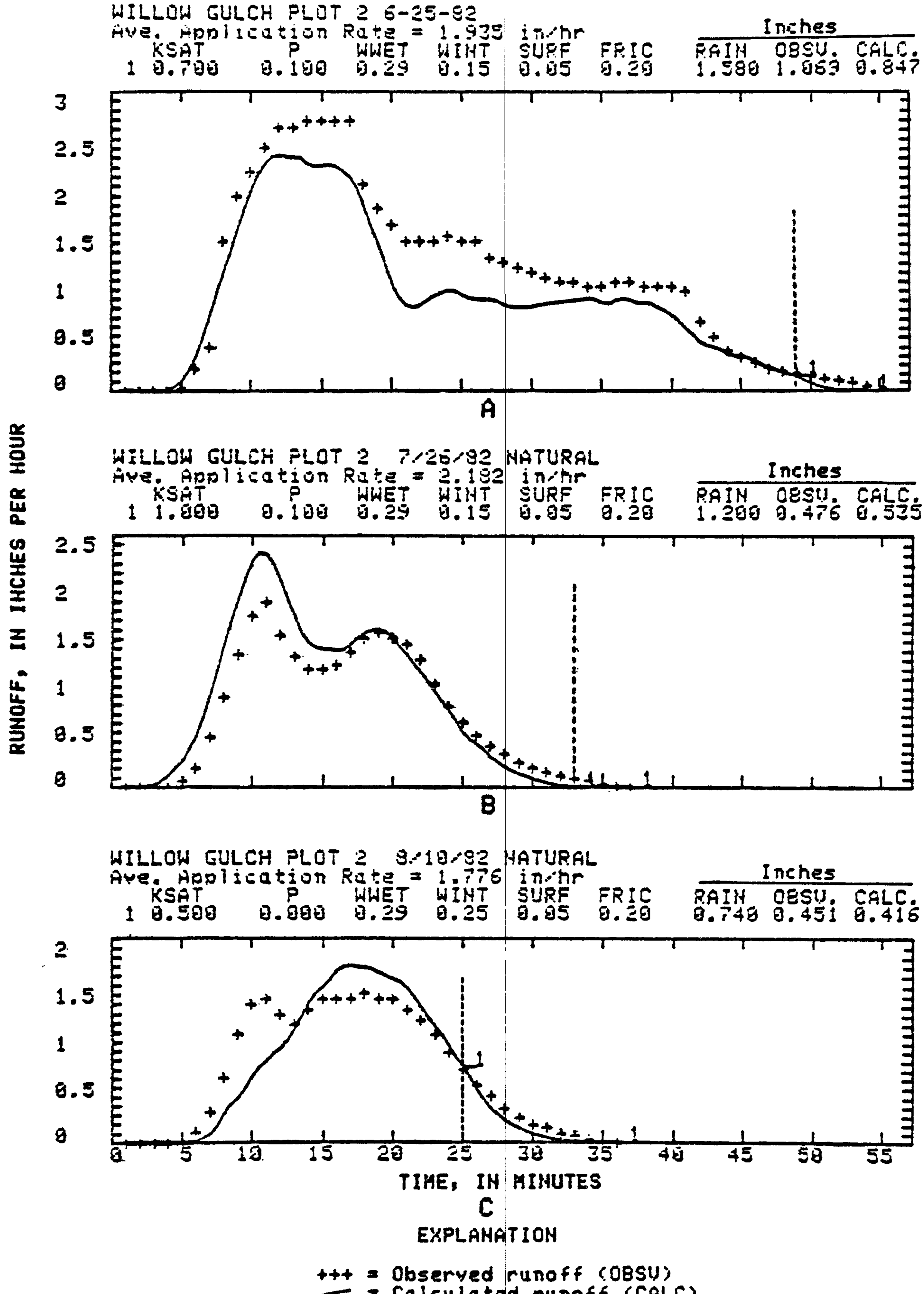


Figure 20.--Model calibration using observed data, plot 2.

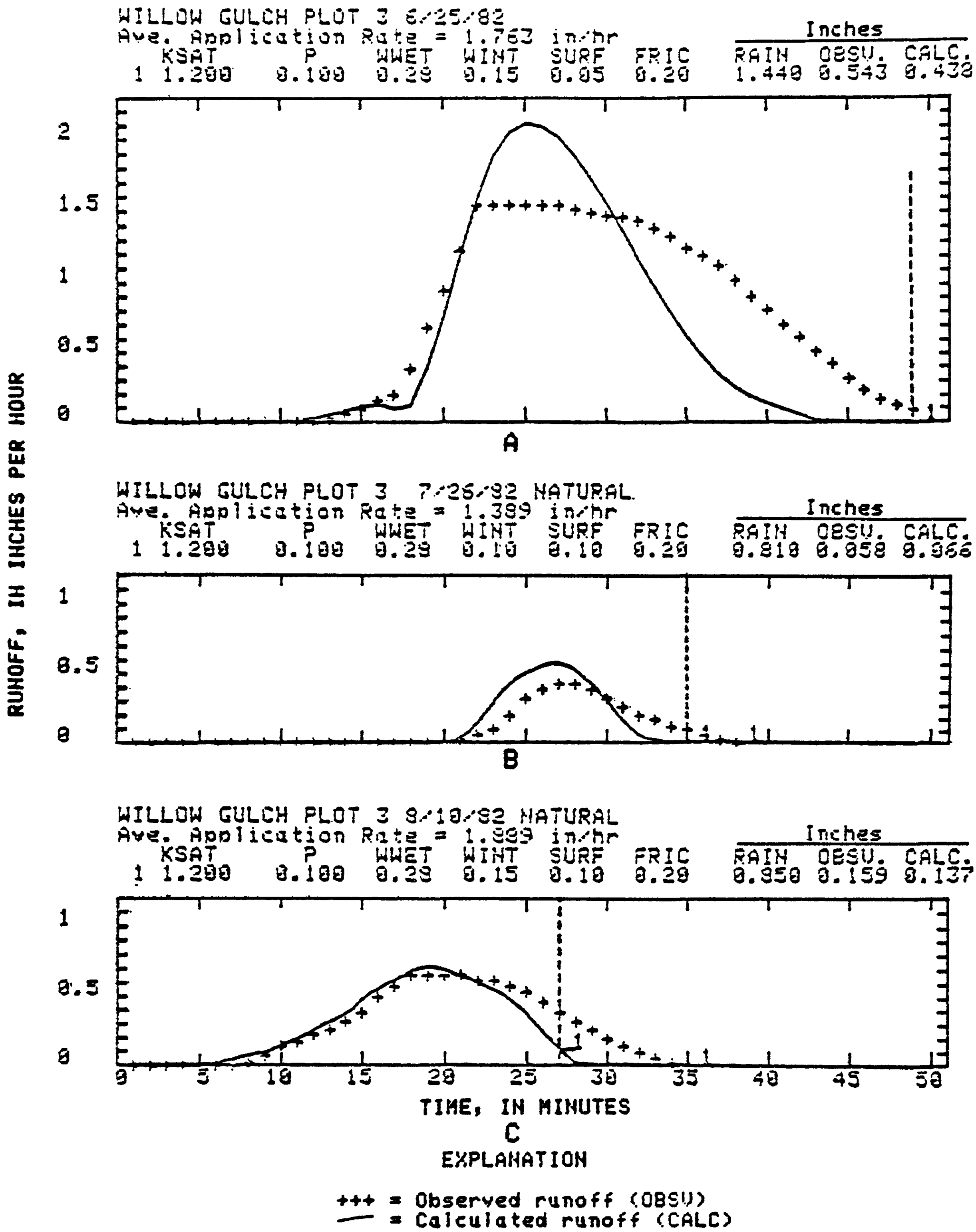


Figure 21.--Model calibration using observed data, plot 3.

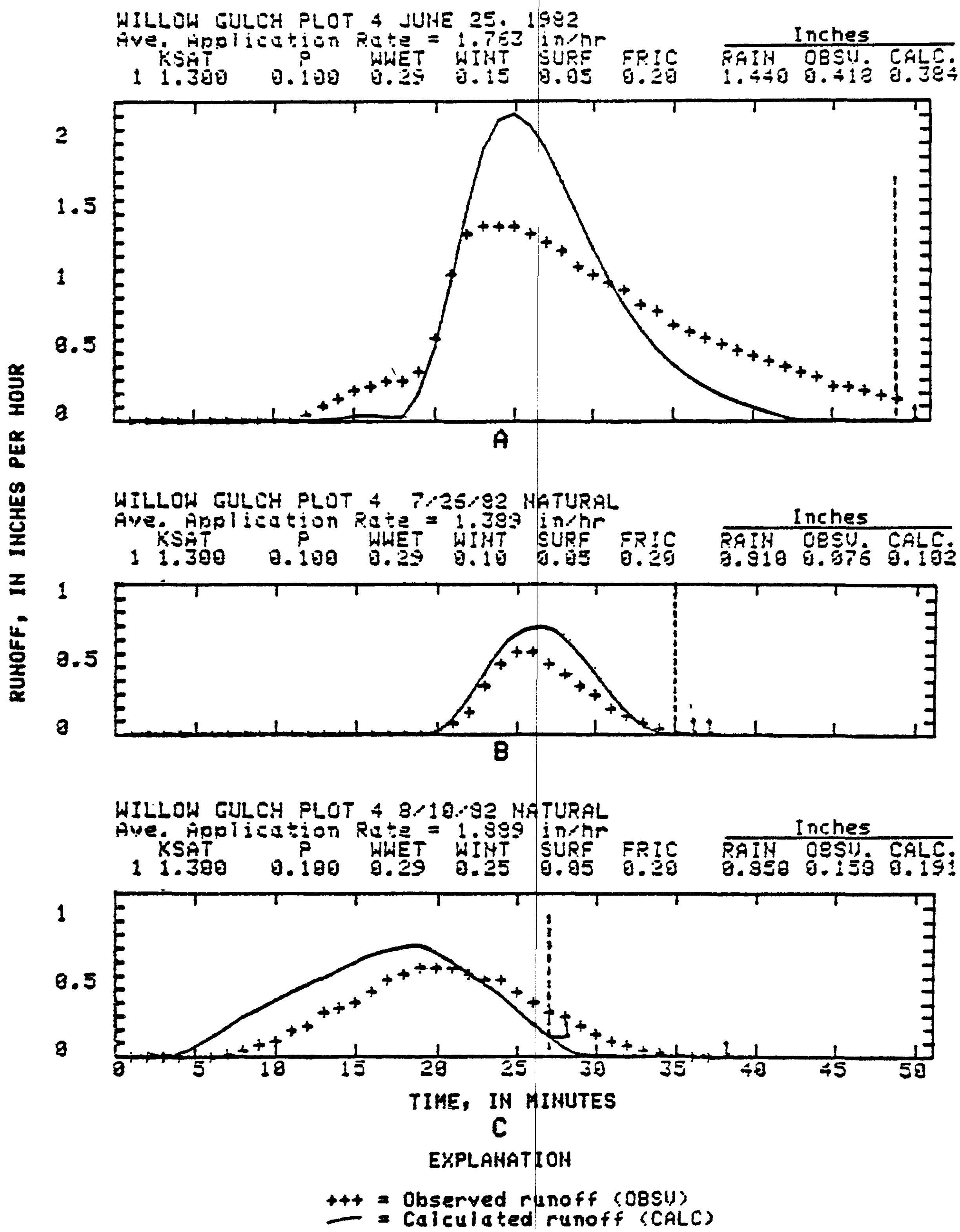
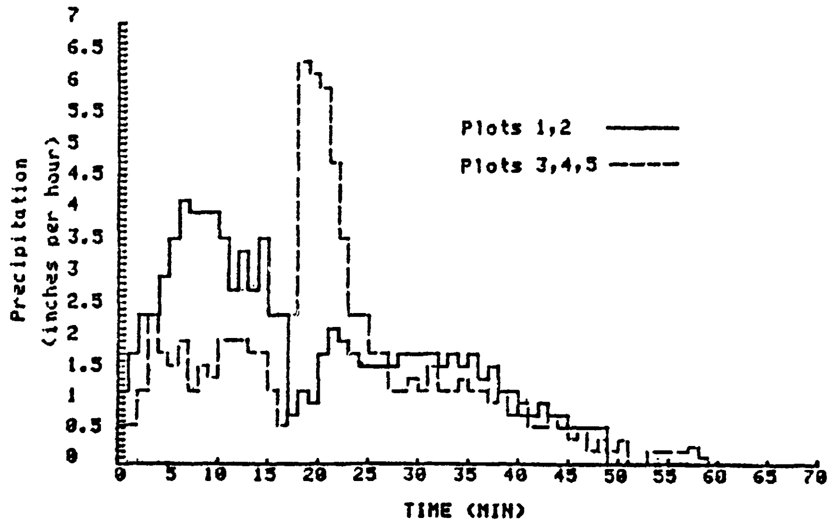
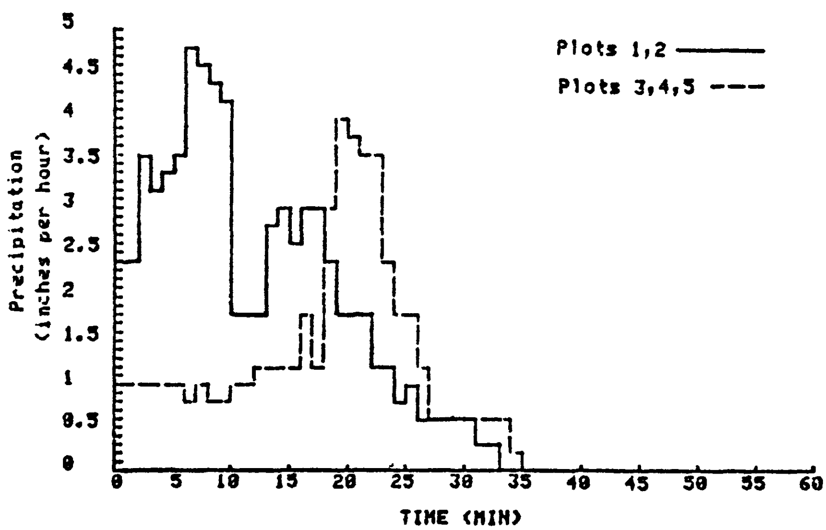


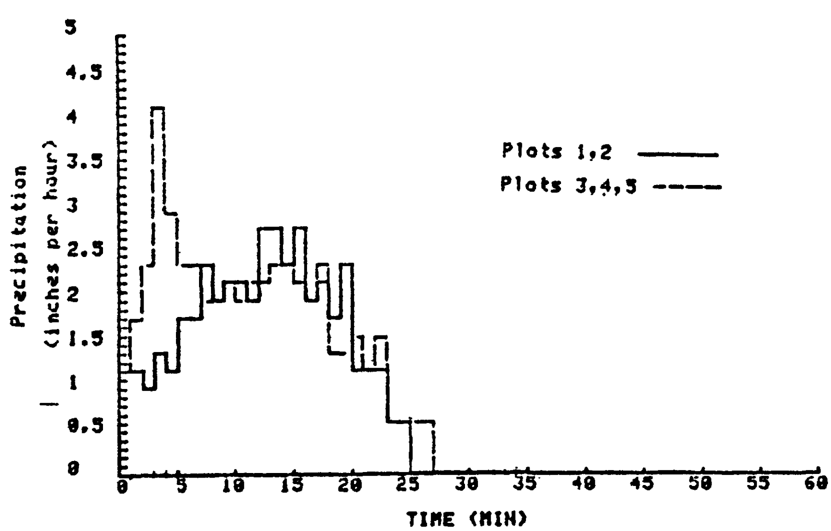
Figure 22.--Model calibration using observed data, plot 4.



--Precipitation at Willow Gulch, June 25, 1982



--Precipitation at Willow Gulch, July 26, 1982



--Precipitation at Willow Gulch, August 10, 1982

Figure 23.--Precipitation in observed storms at Willow Gulch, 1982.

A summary of the fitted values of hydraulic conductivity is shown in table 8. Repeated values of 1.2 and 1.3 in/h shown for plots 3 and 4 are

Table 8.--*Summary of fitted values of hydraulic conductivity for observed rainfall-runoff events during 1982*

[Results in inches per hour]

Date	Plots			
	1	2	3	4
June 25	0.7	0.7	1.2	1.3
July 26	.6	1.0	1.2	1.3
August 10	.4	.5	1.2	1.3

somewhat misleading. They could be refined in the second decimal place to show variability, but the differences between observed and computed volumes of runoff are too small to warrant this refinement. Results of fitting KSAT values to reproduce natural runoff events show a consistent hierarchy or rank of runoff potential. Plot 1 ranks first, followed in order by plots 2, 3, and 4.

Comparison of Results of Plot Calibrations

Results of fitting KSAT values to reproduce runoff from rainfall-simulator runs, and results of fitting KSAT values to reproduce runoff from observed rainfall-runoff events are inconsistent, particularly for plots 1 and 2, the high-runoff producers. Summer runs on these two plots give little indication of the runoff potential from natural rainstorms, whereas those for plots 3 and 4 are in line with observed runoff potential. Fitting results for fall rainfall-simulator runs on plots 1 and 2 required large reductions in the magnitude of KSAT; these results were in line with fitted results based on observed rainfall-runoff events. With the exception of the October 29 1982, simulator run on plot 3 (a very extreme antecedent condition), large reductions in KSAT were not required to fit the fall runs on plots 3 and 4. Results of fitting hydraulic conductivity to reproduce both rainfall-simulator data and observed rainfall-runoff events are summarized in table 9.

WATERSHED MODELING--NORTH FORK WILLOW GULCH

Partitioning the Watershed

The distributed-parameter modeling capability of PRMS (precipitation-runoff modeling system) allows a watershed to be partitioned into homogeneous

Table 9.--*Range in fitted values of hydraulic conductivity for both rainfall-simulator runs and observed rainfall-runoff events*

[Results in inches per hour. Values in parentheses indicate ranges not available.]

Source of data	Plots			
	1	2	3	4
Simulator (summer).	1.1-1.5	1.1-1.2	1.0-1.3	1.0-1.5
Simulator (fall).	0.5-0.65	(0.75)	0.65-1.0	(1.3)
Observed events (summer).	0.4-0.7	0.5-1.0	(1.2)	(1.3)

HRUs (hydrologic-response units). Each HRU is considered to be homogeneous with respect to the factors affecting runoff, such as slope, vegetation type, and infiltration characteristics. Two levels of partitioning are available: the first level considers the hydrologic characteristics just listed; the second level describes the drainage network in terms of overland-flow plane and channel segments, for the purpose of routing flow.

The drainage area of the North Fork watershed was partitioned into four HRUs, based on vegetative cover, soil type, and slope (fig. 24). Areal photographs, field reconnaissance, and a U.S. Geological Survey quadrangle map (Bijou, Colorado) were used to delineate the area of each HRU. HRU 1 is grass-covered, with gentle slopes and soils typical of those on plots 1 and 2. HRU 2 is the same as 1, but is considerably steeper. HRU 3 is the area with ponderosa pine and grass cover, has steep slopes with incised channels, and has soils typical of those on plots 1 and 2. HRU 4 is relatively steep and is mostly grass-covered; the soils are intermixed: soils typical of plots 1, 2, and 3 are represented. Each HRU was assigned parameter values derived from simulator plots.

The watershed then was partitioned into subbasins, and the area of each HRU within each subbasin was determined (fig. 24). From this subbasin delineation, a conceptual drainage network of channel segments and overland-flow planes was developed (fig. 25). Each rectangle represents an overland-flow plane, of HRU type 1, 2, 3, or 4, contributing to a channel segment. To reduce the number of overland-flow plane segments required to conceptualize the drainage network, the length, slope, roughness, and surface-retention capacity were assigned representative values based on the four HRU types.

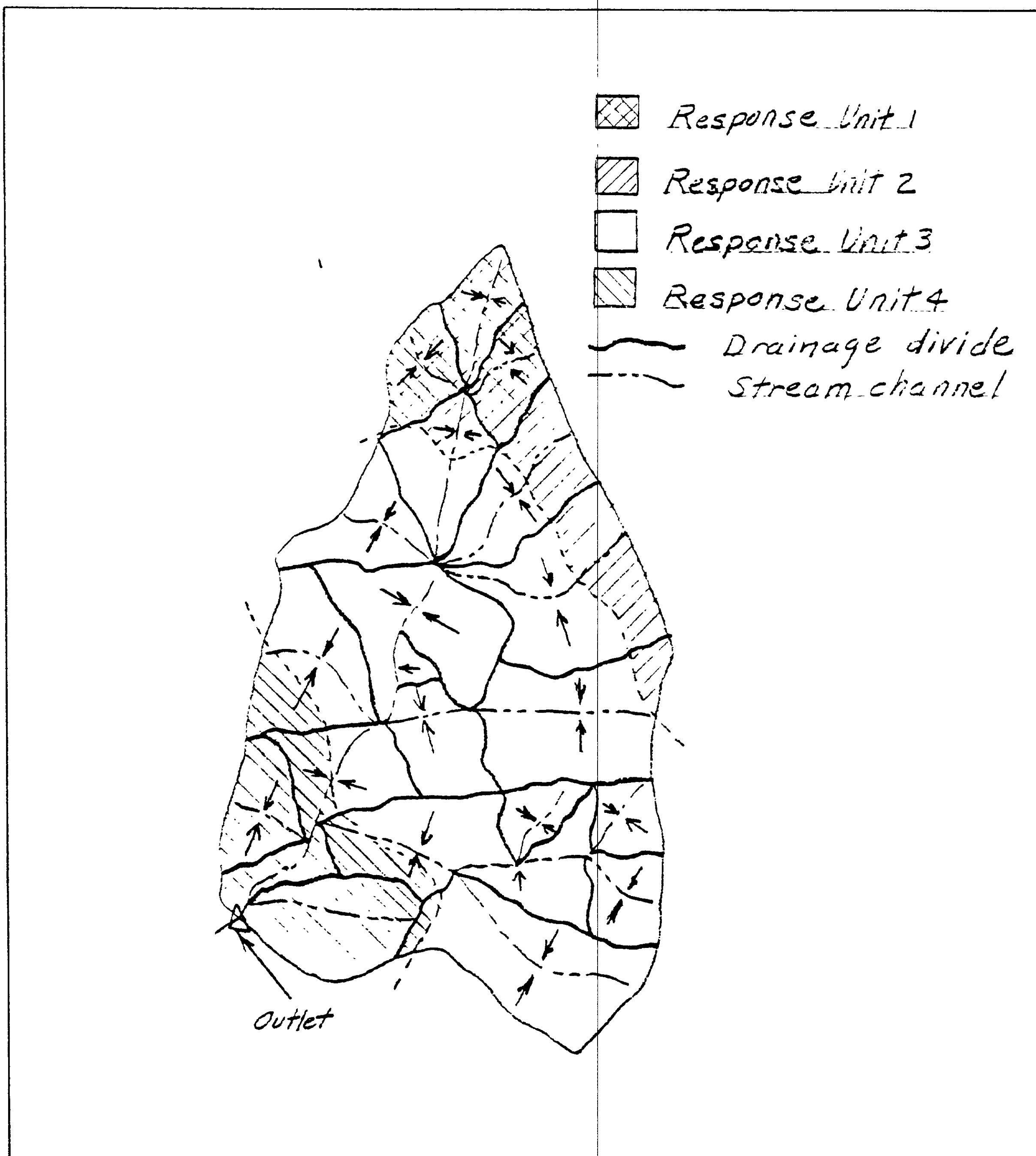


Figure 24.--North Fork Willow Gulch showing hydrologic-response units, subbasins, and drainage network.

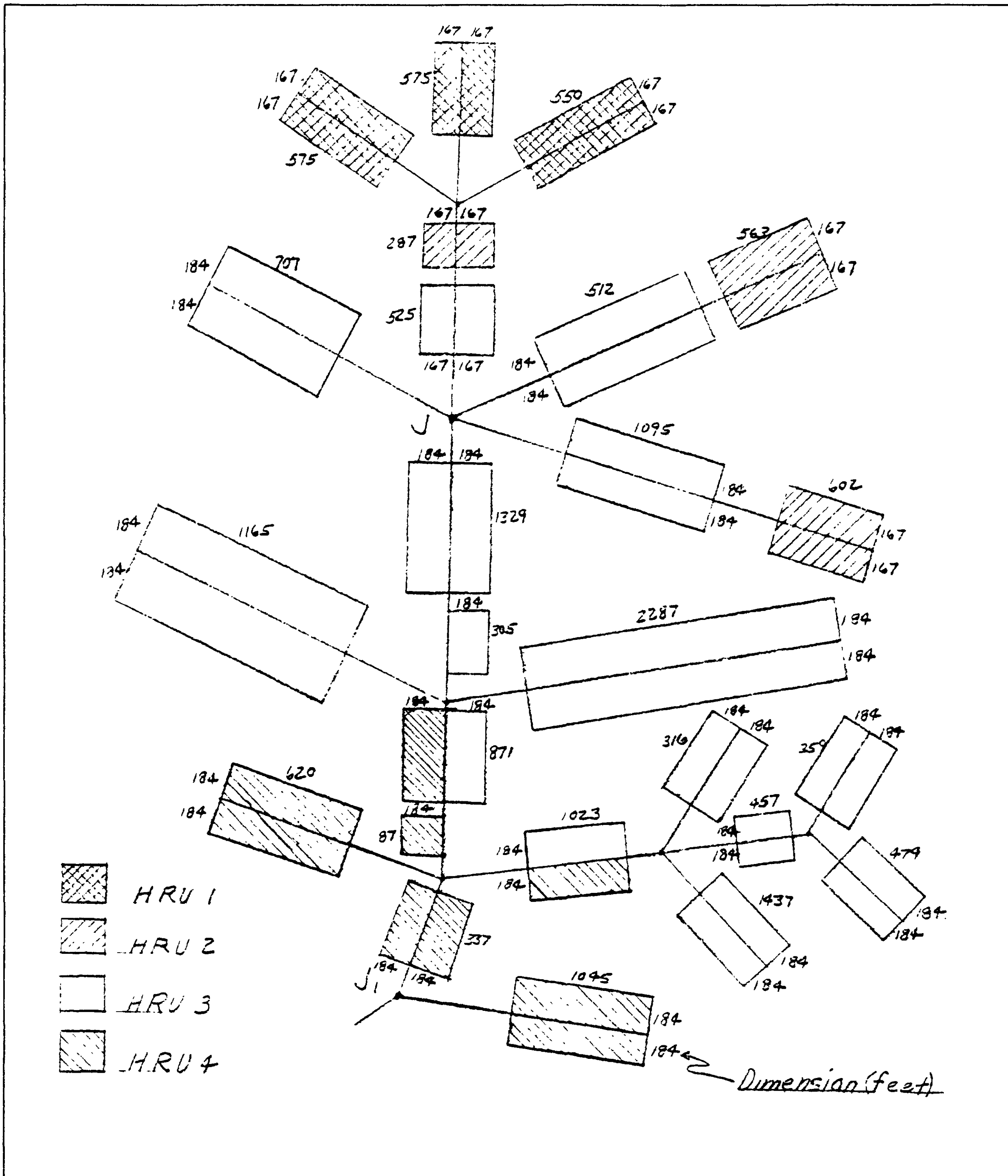


Figure 25.--Conceptual view of North Fork Willow Gulch watershed showing flow planes, channel segments, and junctions.

The length of each channel segment was determined and a characteristic shape, slope, and roughness was assigned. Infiltration and moisture-accounting parameters of each HRU and flow-routing characteristics of associated overland-flow plane and channel segments were input to the model. Model computations then were performed on individual planes, using observed rainfall and estimates of potential evapotranspiration. HRUs 1-3 and their associated overland-flow plane segments were assigned parameter values, typified by results obtained from simulator plots 1 and 2. Parameters for HRU 4 were typified by a melding of parameters for plots 1, 2, and 3. Model results are largely controlled by KSAT, through its dominant influence on computed volumes of runoff. Hydrograph shape and timing are influenced by both infiltration computations and the routing specifications described by the network of planes on channel segments.

Comparison of Observed and Simulated Runoff Events

Three storms that could be modeled occurred on June 25, July 26, and August 10, 1982. As discussed previously, the hydraulic-conductivity term in the infiltration equation largely controls the final results. Two sets of model results were developed for each of these storm events. The first uses estimates of KSAT values based on results of rainfall-simulator runs on plots 1, 2, and 3; the second is based on estimates from results of observed rainfall-runoff events on plots 1, 2, and 3. The value of KSAT for summer simulation runs on plots 1 and 2 ranged from 1.1 to 1.5 in/h, and for fall simulation runs on plots 1 and 2 ranged from 0.5 to 0.75 in/h. An intermediate value of 1.0 in/h was selected to be representative of the simulator value for HRUs 1-3. The value of KSAT for plot 3 ranged from 1.0 to 1.3 in/h for summer runs and from 0.65 to 1.0 in/h for fall runs. A value of 1.1 in/h was selected for the simulator value for HRU 4. Values of KSAT for plots 1 and 2, based on observed rainfall-runoff events, ranged from 0.4 to 1.0 in/h; a value of KSAT for plot 3 of about 1.2 in/h was indicated. A value of 0.5 in/h was selected to be representative of the natural value for HRUs 1-3, and a natural value of 0.8 in/h was selected for HRU 4.

The recording rain gage near the upper end of North Fork Willow Gulch measured 1.58 in of rain during the storm of June 25; results of modeling this storm are shown in figures 26 and 27. Peak and volume of runoff are grossly underestimated by both the simulator and natural KSAT specifications. Observed runoff is a very large percentage of rainfall (78 percent).

The storm of July 26 produced 1.20 in of rain; model results for this storm are shown in figures 28 and 29. Parameter specification based on simulator data slightly overestimated both the peak flow and volume of observed runoff. Specifications based on natural events more than doubled the observed peak and volume of runoff.

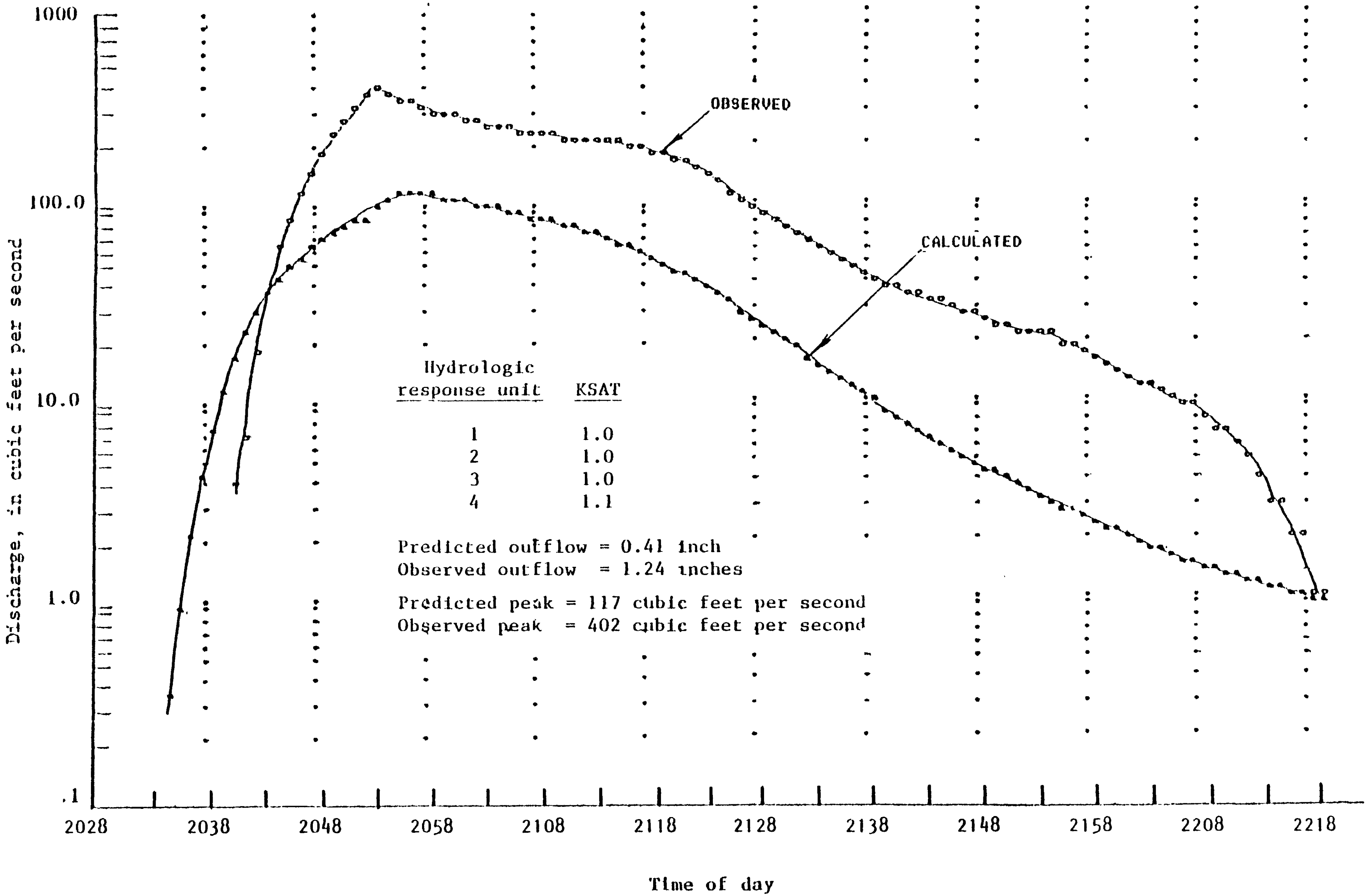


Figure 26.--Modeling results of North Fork Willow Gulch, June 25, 1982, using parameters from simulation runs on plots.

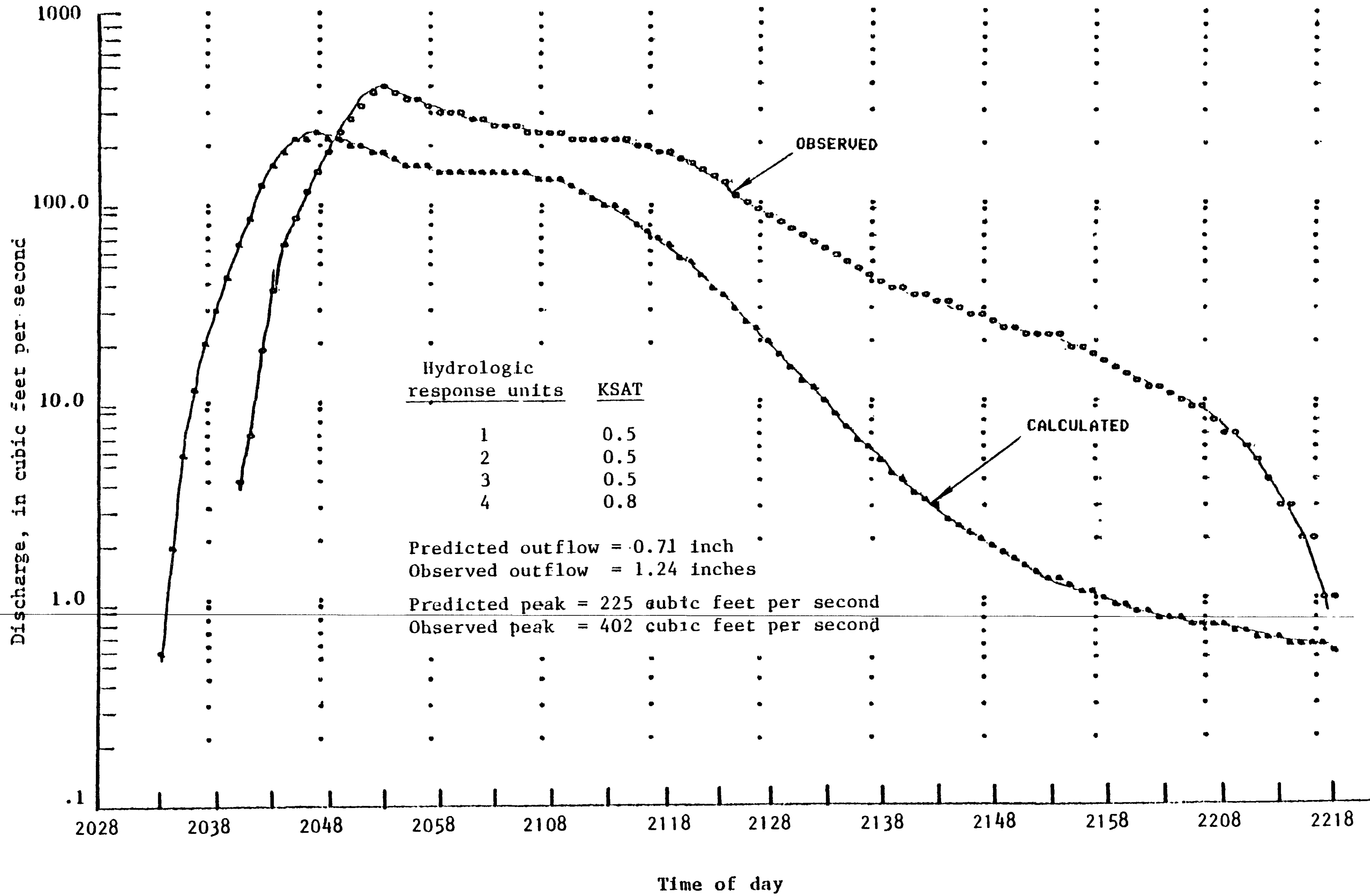


Figure 27.--Modeling results of North Fork Willow Gulch, June 25, 1982, using parameters from storm data on plots.

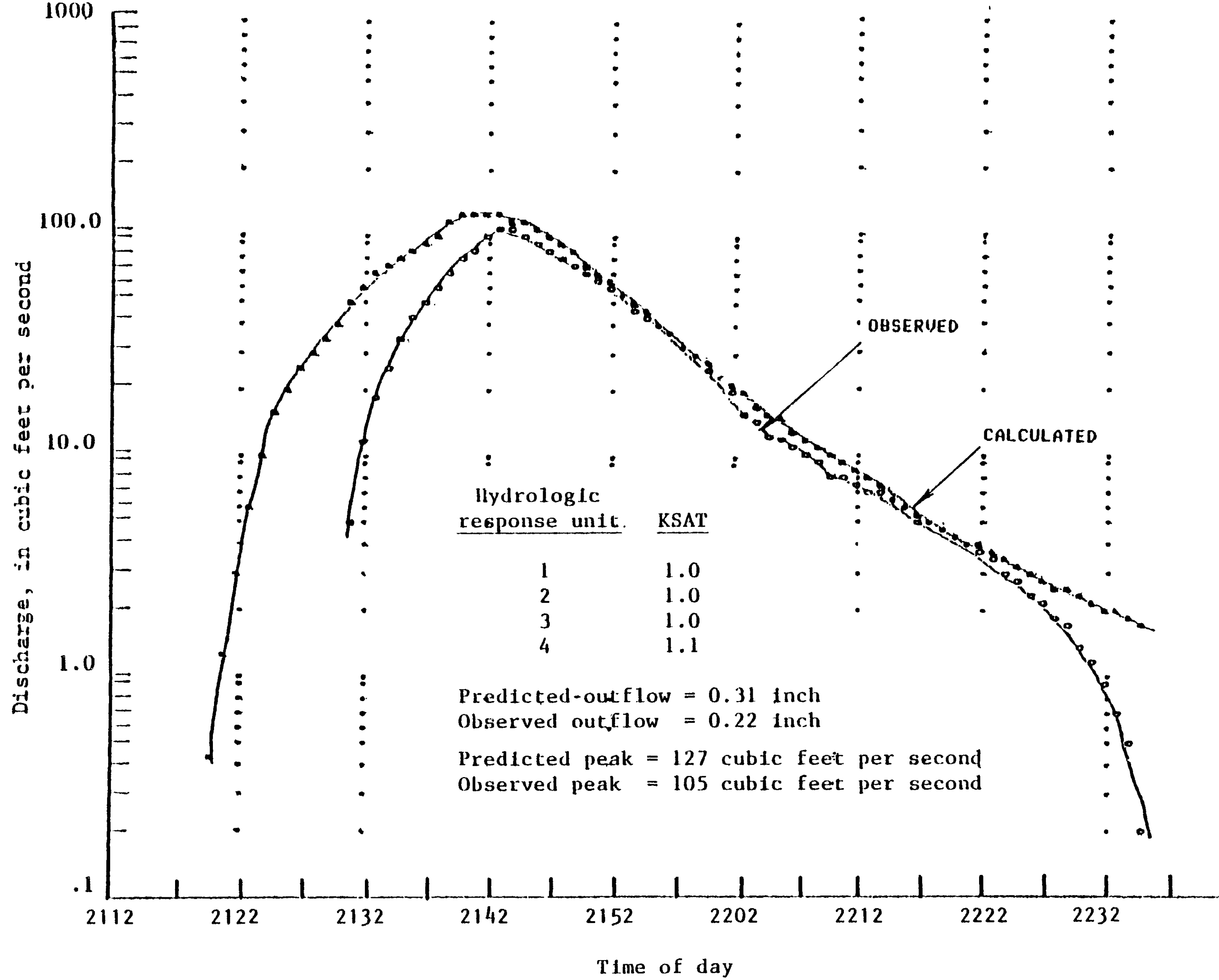


Figure 28.--Modeling results of North Fork Willow Gulch, July 26, 1982, using parameters from simulation runs on plots.

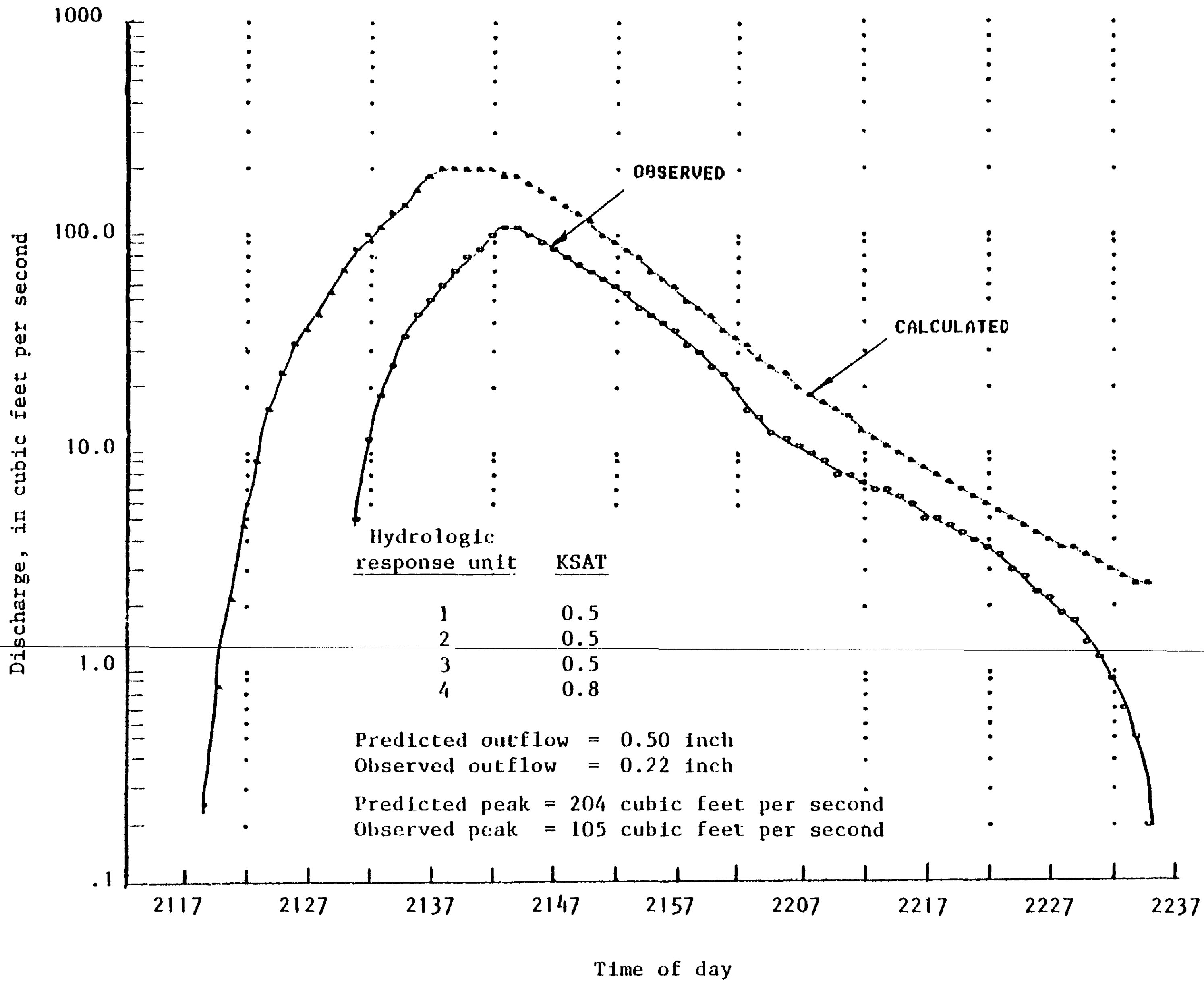


Figure 29.--Modeling results of North Fork Willow Gulch, July 26, 1982, using parameters from storm data on plots.

The storm of August 10 produced 0.74 in of rain; results for this storm are shown in figures 30 and 31. Both the observed volume and peak were underestimated by about 70 percent using simulator parameter specifications. Using the natural parameters, volume was underestimated by 28 percent and peak by 37 percent. A summary of these modeling results is shown in table 10.

Sources of Error

As shown in figures 26 through 31, the general shape and timing of modeled hydrographs is in fair agreement with the shape and timing of observed hydrographs. The major source of error in reproducing the observed hydrograph is the prediction error in runoff volume. A good prediction of the runoff volume is contingent on many factors; the two most significant factors are: (1) An accurate representation of storm rainfall, and (2) an accurate computation of infiltration losses (a function of KSAT). The effect on model results of changing the specifications of KSAT values and of adjusting storm rainfall are shown in figures 32, 33, and 34. For the June 25 event shown in figure 32, KSAT values were lowered from the natural specification, and storm rainfall was increased by 40 percent. The predicted volume is 12 percent more, and the predicted peak is 9 percent less than the observed values. Results of modeling the July 26 event using simulator parameters, and a 10-percent reduction in storm rainfall are shown in figure 33. The predicted and observed runoff volumes are the same; the predicted peak is 18 percent less than the observed. Observed hydrographs for both the June 25 and July 26 storm events show the observed rise lagging the predicted rise by about 6 minutes. On June 14, a tornado crossed the watershed of the North Fork and deposited many trees in the drainageways (fig. 35). Flood waters of the storm of June 25 carried one of these trees into the approach section of the measuring flume where it became lodged (fig. 36). These trees may have partially dammed the channels and slowed the runoff. Model results for the August 10 storm are shown in figure 34; KSAT values are lowered, (as was done for the June 25 storm), and storm rainfall is increased by 10 percent. Predicted runoff volume is 7 percent larger, and predicted peak is 6 percent smaller, than observed values.

Results of the foregoing adjustments were included to demonstrate sensitivity of the model to possible variations in rainfall input and KSAT parameter. Rainfall data from one gage located on the edge of the watershed could vary considerably from total rainfall on the watershed.

RESULTS AND CONCLUSIONS

Runoff data from both simulator runs and observed rainstorms on plots were used to develop best-fit parameters of the Green-Ampt infiltration equation. In all fitting attempts, the hydraulic conductivity term, KSAT, grossly controlled the goodness of fit. High variability in soil-water

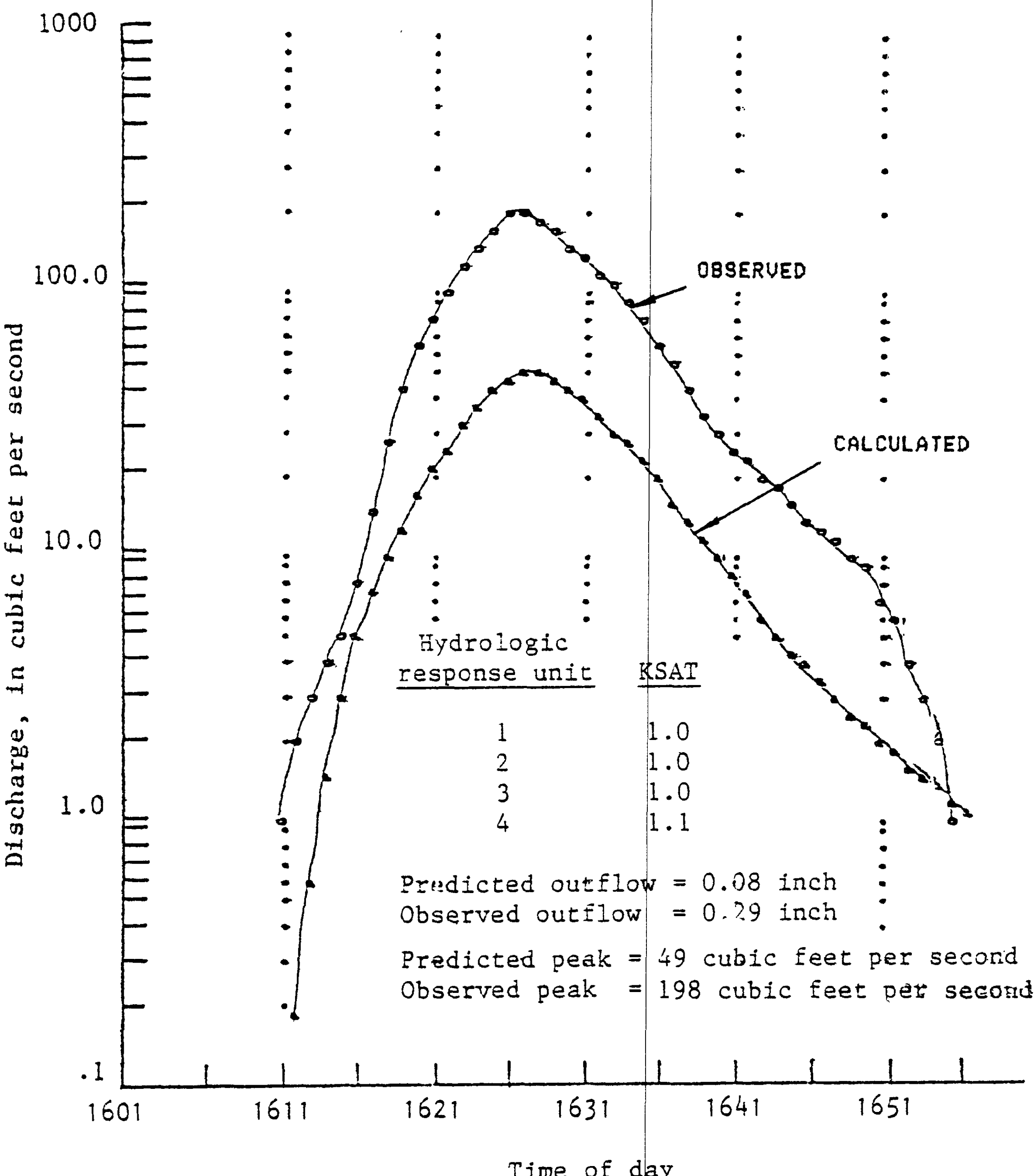


Figure 30.--Modeling results of North Fork Willow Gulch, August 10, 1982, using parameters from simulation runs on plots.

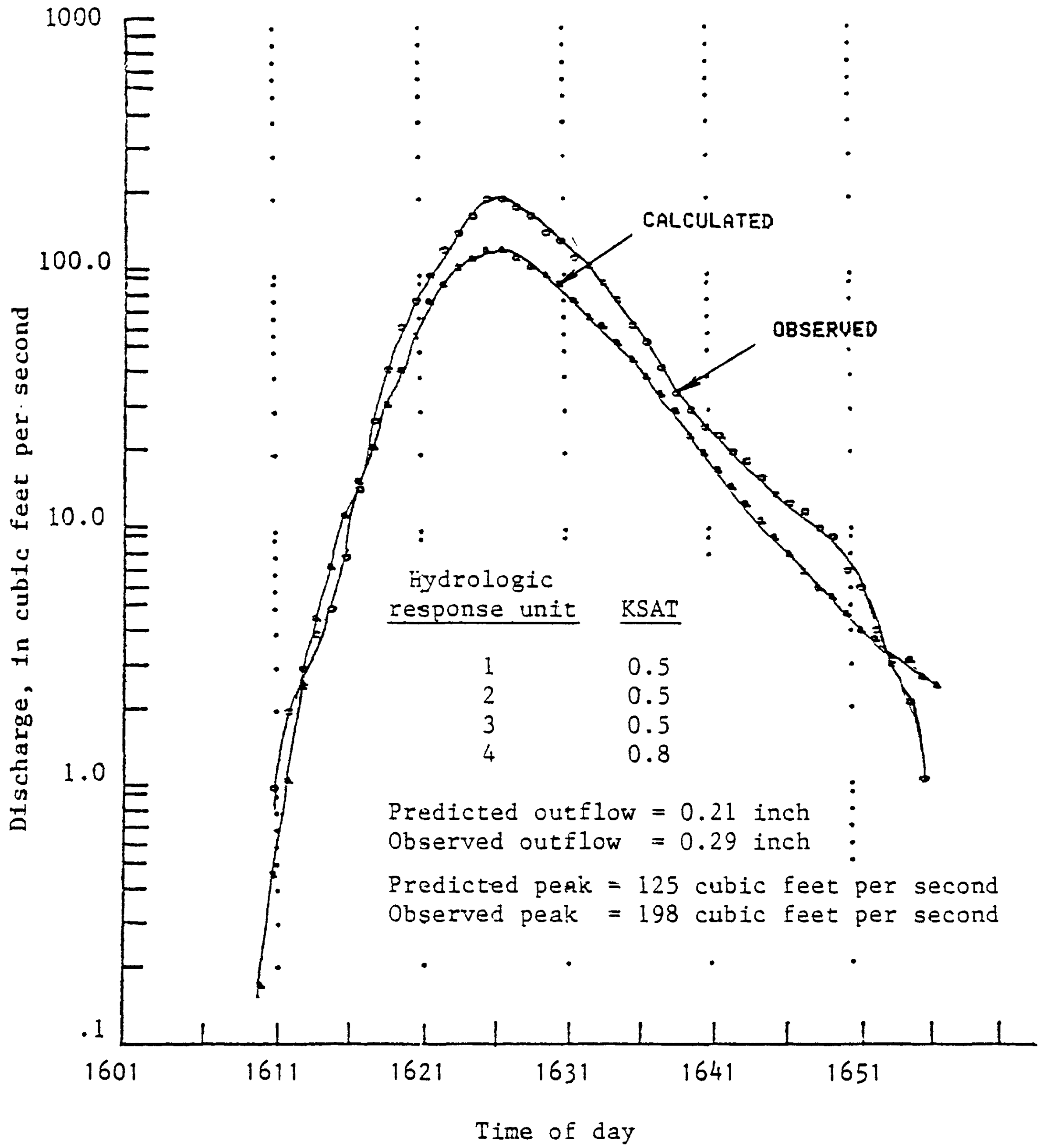


Figure 31.--Modeling results of North Fork Willow Gulch, August 10, 1982, using parameters from storm data on plots.

Table 10.--*Summary of predicted and observed runoff and peak flow from rainstorms, North Fork Willow Gulch, 1982*

[CASE 1, simulator KSAT specification; CASE 2, natural KSAT specification, see text]

	June 25		July 26		August 10	
	CASE 1	CASE 2	CASE 1	CASE 2	CASE 1	CASE 2
Runoff (inches)						
Predicted	0.41	0.71	0.31	0.50	0.08	0.21
Observed	1.24	1.24	.22	.22	.29	.29
Difference (units/percent)	-.83/-67	-.53/-43	+.09/+41	+.28/+155	-.21/-72	-.08/-29
Peak (cubic feet per second)						
Predicted	117	225	127	204	49	125
Observed	402	402	105	105	198	198
Difference (units/percent)	-285/-71	-177/-44	+22/+21	+99/+94	-148/-75	-73/-37

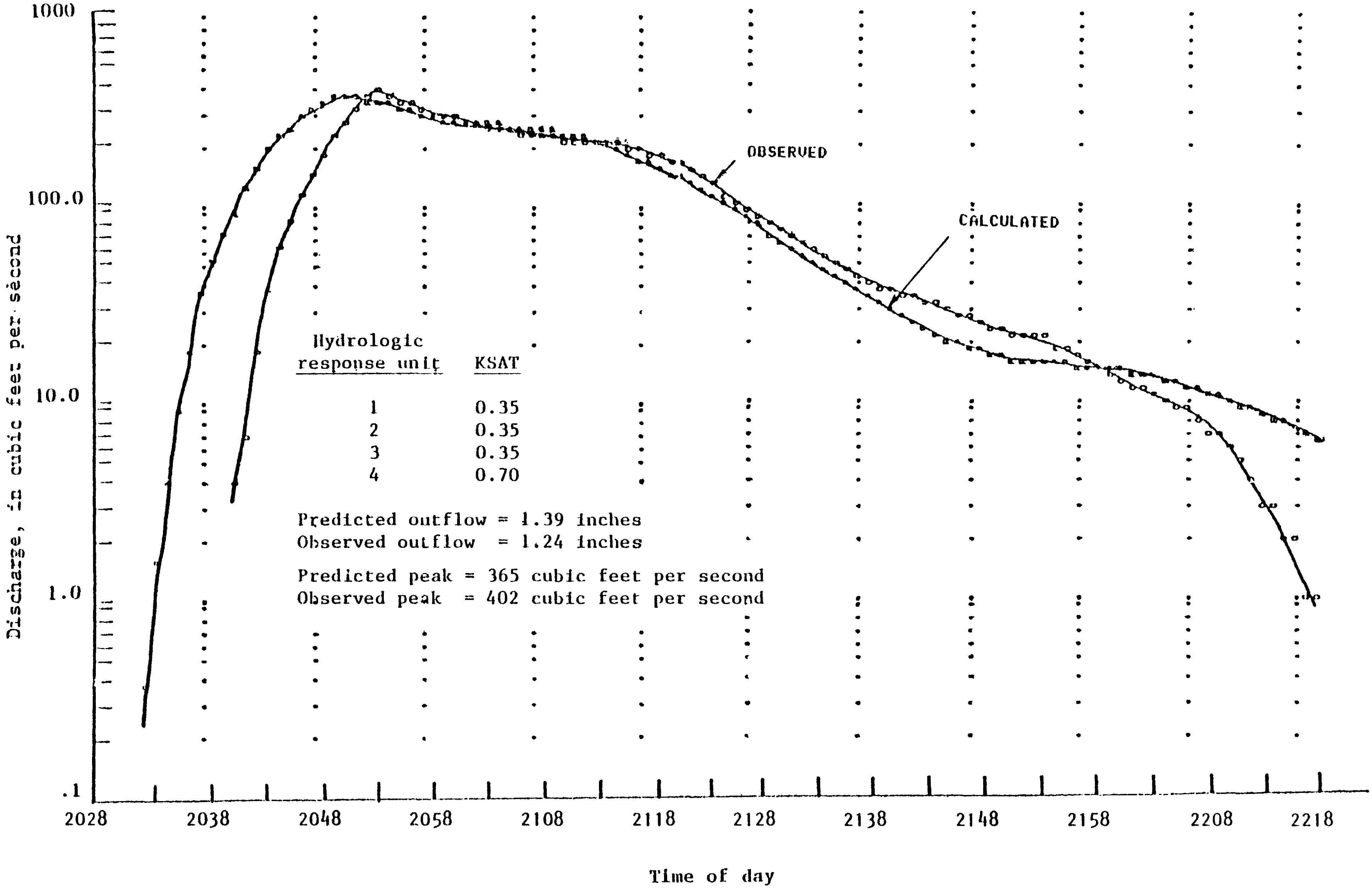


Figure 32.--Modeling results of North Fork Willow Gulch, June 25, 1982. KSAT parameter lowered slightly and precipitation raised 40 percent.

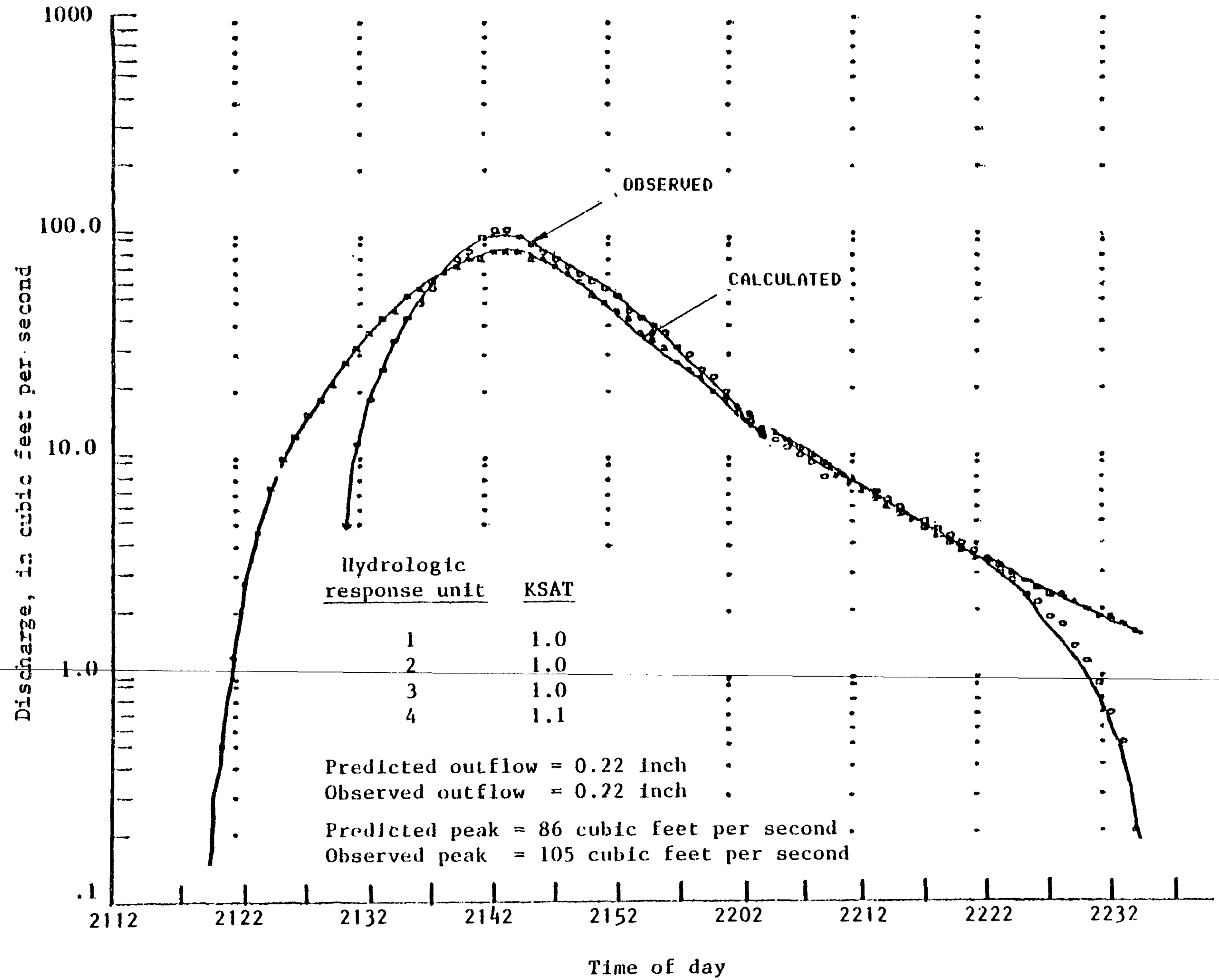


Figure 33.--Modeling results of North Fork Willow Gulch, July 26, 1982. KSAT parameter obtained from simulation plots and precipitation lowered 10 percent.

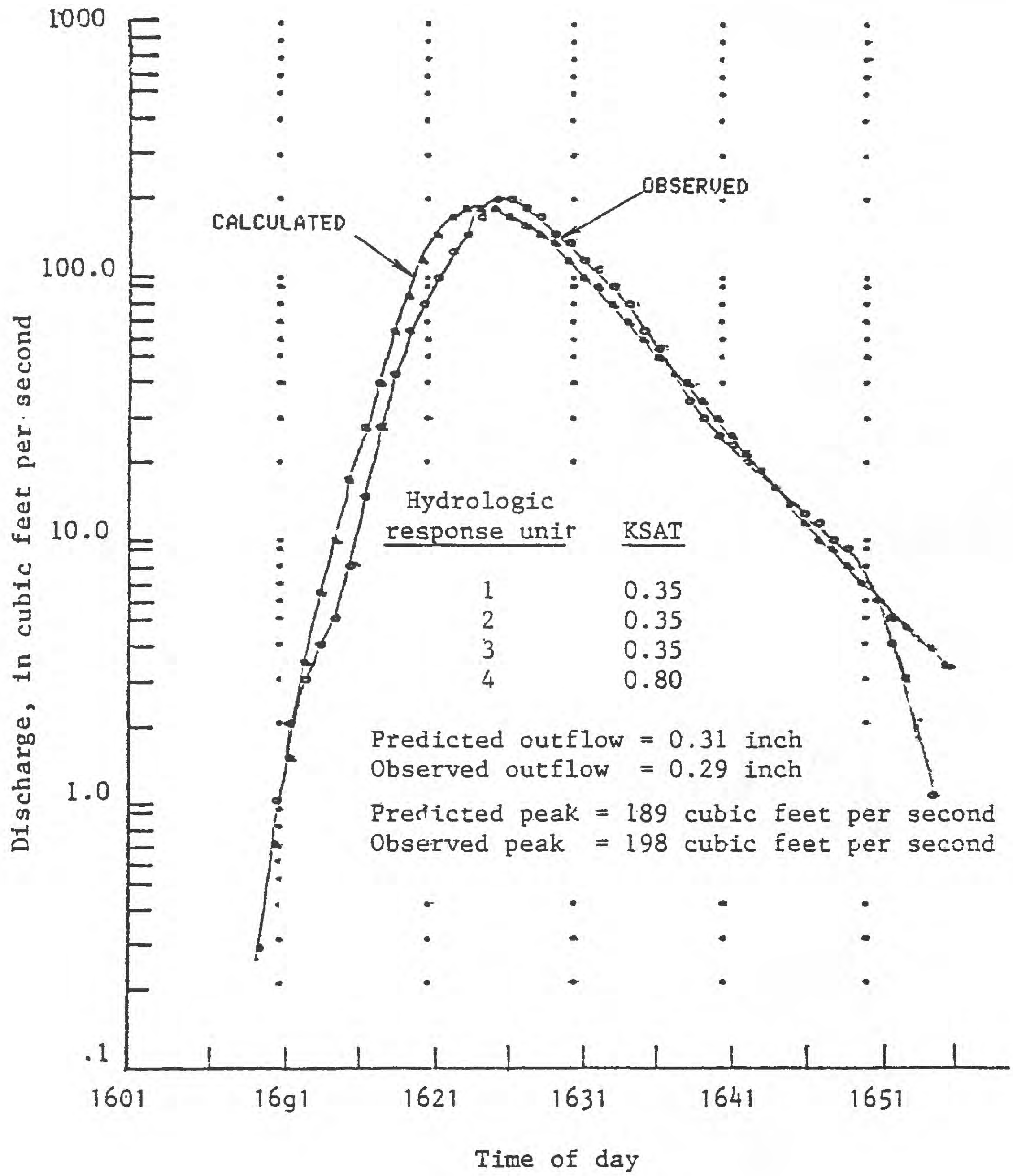


Figure 34.--Modeling results of North Fork Willow Gulch, August 10, 1982. KSAT parameter lowered slightly and precipitation raised by 10 percent.

Figure 35.--Trees deposited in channels by tornado.

Figure 36.--Tree lodged above supercritical flow flume on North Fork Willow Gulch.

uptake found from soil samples taken before and after simulator runs confirms the empirical nature of KSAT. Best-fit values are plot-average values that reflect both the limitation of the equation and the inherent variability of soil-water properties of field soils.

Results of fitting KSAT to reproduce runoff from rainfall-simulator runs, and results from fitting KSAT to reproduce runoff from observed rainfall events on the plots, are inconsistent. Fitted values of KSAT for rainfall-simulator runs conducted on plots 1 and 2 during the summers of 1981-82 show little resemblance to values for observed summer rainstorms of 1982. In contrast, results for plots 3 and 4 are in reasonable agreement with results from observed rainstorms. Fall runs on plots 1 and 2 indicate that cooler soil temperatures may influence the infiltration process. In contrast, fall runs on plots 3 and 4 show no consistent effect of cooler soil temperatures; the October 29, 1982 run on plot 3 is a very extreme case; frost occurred the previous night. Reasons for these anomalous results are unknown; however, the implication of a site-specific effect is apparent. Some speculation on reasons for these differences might provide the basis for future study.

The effect of the dissimilarity between artificial and natural raindrops is not known. Natural rainstorms have varying rates, accompanied by varying size of drops. The rainfall simulator is designed to operate at a rate of 2 in/h. Any change in rates is achieved by adding or subtracting sprinklers. Output from each sprinkler remains the same, and drop size is unchanged. Neff (1979) determined that the rainfall simulator, at a rate of 2 in/h, produced maximum size drops considerably smaller than those occurring in natural rainfall at the same rate. Total kinetic energy at 2 in/h is about 40 percent of that from natural storms. The effect of these differences on the infiltration process (the crusting phenomenon) is poorly understood. Studies aimed at identifying the conditions under which a surface crust tends to develop and influence the infiltration process would give valuable insight into where, when, and if the rainfall-simulator could be used to quantify natural infiltration characteristics.

Atmospheric conditions during simulator runs often are considerably different than atmospheric conditions in rainstorms. Regional temperature during rainstorms usually drops sharply; regional temperature during simulator runs remains fairly constant. Rainstorms occur at different times of day; in eastern Colorado, summer storms most often occur in late afternoon or evening hours. Because of wind conditions, simulator runs were conducted in the morning or at midday. The effect of different ambient soil temperatures and the difference between natural and artificial rain temperatures on the dynamics of heat and water flux in the soil profile may have an important influence on water uptake. Several simulator runs made in the fall indicate a site-selective temperature effect. Studies aimed at resolving this apparent anomaly and its relationship to a crusting phenomenon are needed.

Considerable uncertainty exists regarding the adequacy of simulator data for determination of parameters for use in rainfall-runoff modeling. Apparent differences between hydraulic conductivity values developed from the simulator and those from rainstorms for some plots, and not for others, is not explained easily. The scarcity of data from observed rainfall-runoff events, and the difficulties encountered in collecting good data provide a poor foundation on which to base final conclusions; additional data on observed rainfall-runoff events on simulator plots are needed.

The application of PRMS to three storms on North Fork Willow Gulch in 1982, using estimates of KSAT obtained from rainfall-simulator runs on plots, produced predicted runoff volumes that were about 70 percent less than those observed in two cases, and 40 percent more than that observed in the third case. Estimates of KSAT obtained from observed rainfall-runoff events on plots improved the prediction for two events, and degraded the result for the third. Adjustments in the KSAT specfication and adjustments to storm rainfall produced close agreement between predicted and observed runoff volumes, peak flow rates, and hydrograph shape. This exercise in parameter adjustment only confirms the fact that accuracy of predicting peak-flow rates is dominantly controlled by the amount of water that falls on the ground, and how much infiltrates. Runoff routing is represented adequately by the conceptual network of plane and channel segments used in PRMS. The problem of the amount of water that falls on the ground is logistic and economic; it could be resolved with more recording rain gages. The problem of the amount of water that infiltrates can only be solved by a better understanding of the onsite infiltration process and by the development of better models based on this understanding.

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