HYDROLOGY AND SEDIMENT TRANSPORT
MOANALUA VALLEY, OAHU, HAWAII

By Patricia J. Shade

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CONVERSION TABLE

The following table may be used to convert measurements in the inch-pound system to the International System of Units (SI).

Multiply inch-pound units	By	To obtain SI (metric) units
Length		
inch (in)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
yard (yd)	0.9144	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
acre-foot (acre-ft)	1,233	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
gallon (gal)	3.785	liter (L)
Volume Per Unit Time (includes Flow)		
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

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ABSTRACT

This report analyzes the rainfall-runoff relationship and sediment transport in Moanalua Valley, Oahu, an undeveloped watershed in Hawaii. Rainfall, streamflow, and evaporation data as well as the physical characteristics of the basin were input to the Dawdy, Schaake, and Alley distributed routing rainfall-runoff model (DSA). The simulated hydrographs defined fairly accurately the very steep triangular shape of the flood flows observed in Moanalua. The model was calibrated and verified for this rural subtropical watershed indicating that on an event basis the average estimate of runoff is 35 percent of rainfall. A basin water balance computed using calibrated model parameter values, indicates an average of 7 million gallons per day (Mgal/d) recharge.

Sediment transport was determined from daily and intermittent suspended-sediment samples collected at two sites, and from debris basin surveys. The estimated mean annual sediment yield ranges between 500 and 1,050 tons per square mile per year (tons/mi^2/yr).

PURPOSE AND SCOPE

In November 1970, the State of Hawaii, Department of Transportation entered into a cooperative agreement with the U.S. Geological Survey to study the hydrologic and sedimentation characteristics of Moanalua Valley, Oahu. A major highway, H-3, was scheduled to be constructed through the length of the upper valley during the 10-year study. The highway would have had considerable impact on the physical characteristics of the stream and some of the valley slopes. However, in June of 1977, the highway project was cancelled. The purpose of this report, to analyze the rainfall-runoff relationship and sediment transport in the valley, nevertheless remains the same.

Rainfall, streamflow, and evaporation data have been collected since 1968 from an extensive instrumentation system. Data from 1968 to 1980 were used in a distributed routing model (DSA) to determine the percentage of rainfall that runs off as streamflow on an event basis. The model calculated reasonable soil-moisture-accounting and infiltration parameter values and appears to be transferable to other Hawaiian watersheds.

Both suspended-sediment and bedload data from 1968 to 1982 were analyzed to determine basin sediment yield. These analyses will serve as a basis for comparison and study in other Hawaiian watersheds.

BASIN PHYSIOGRAPHY

Moanalua Valley is typical of the many small watersheds that drain the mountains of the Hawaiian islands. Moanalua Stream drains the 3.34 square mile basin located on the leeward side of the Koolau Mountains. The long narrow valley (fig. 1) is bounded by steep, vegetated ridges which rise from 800 feet, above stream gaging station 16228200 (2282) near the mouth of the valley study area, to 2,800 feet in the headwaters along the Koolau Range. In the upland area a ridge forms two subbasins. A major tributary flows from each of the subregions gaged individually at stations 16227500 (2275) and 16227700 (2277). Streamflow is intermittent and channel losses during low flows are substantial, especially above the confluence. Elevations of the gaging stations, determined from topographic maps, range from about 230 feet, at station 2282, to approximately 660 feet at station 2275. Streambed slopes range from 0.01 to 0.05 in the lower reaches and exceed 0.20 in the headwaters. Mean slope of the main channel is about 0.027 ft/ft. Stream width increases irregularly from about 30 feet near the headwaters to approximately 100 feet at the debris basin near the urban boundary. Channel depth varies irregularly from about 3 to 6.5 feet. The stream is sinuous and has carved deep gouges around the erosional spurs protruding from the valley walls.

Although there are several native plant species present such as koa, hau, ohia lehua, and false staghorn fern (uluhe), much of the valley floor and slopes are covered with common grasses such as <u>Andropogon virginicus</u>, as well as the introduced species of guava, mango, Java plum, and Christmas berry. Even the steep ridges support some vegetation. A lack of rare native Hawaiian species is due to extended periods of grazing.

The lush vegetation is supported by two soil types described by the Soil Conservation Service in Foote and others (1972). The Kaena Series soil, a very fine montmorillonite clay derived from basalt, is the dominant soil type in the valley, and is found along the lower talus slopes and banks of almost the entire reach of the stream channel from the debris basin at station 2282 to just below the confluence of the upper basin tributaries near station 2275. The Hanalei Series soil, a fine silty clay soil derived from basalt alluvium, occupies some low-lying areas along the lower reaches of the stream between stations 2282 and 16228000 (2280) where there is periodic flooding. The remainder of the valley, the upper slopes, is classified as rocky mountainous land. Although the soil layer is thin in this area, dense vegetation thrives throughout the upland region.

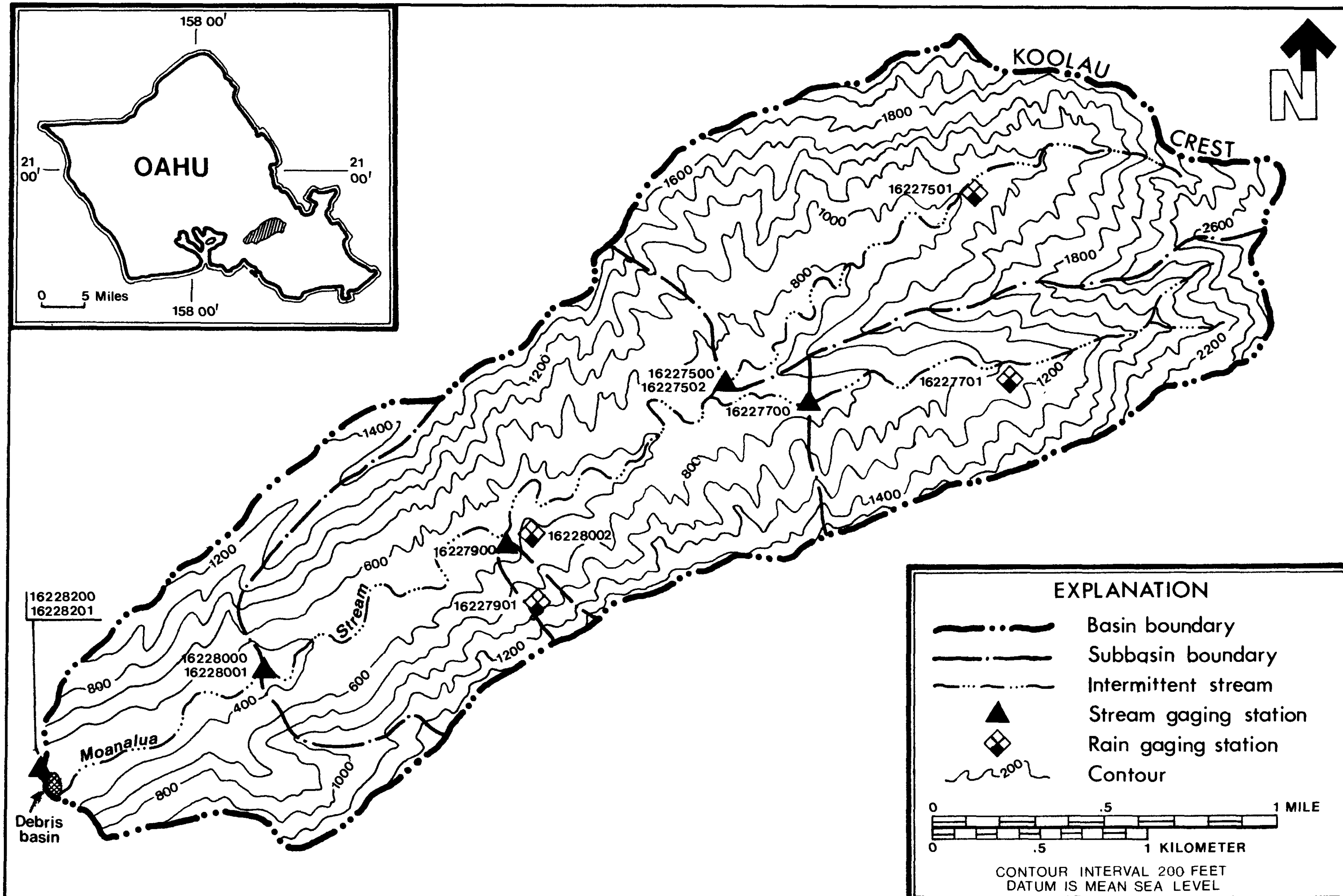

Figure 1. Locations of stream and rain gaging stations in Moanalua Valley.

RAINFALL

In Hawaii precipitation and climate are controlled by (1) latitude, which causes a warm mild climate; (2) the surrounding Pacific Ocean, which provides abundant moisture and moderate temperatures; (3) the location of the islands relative to major storm paths and the northeast Pacific high pressure center, which produces the prevailing tradewinds; and (4) the topography, which induces orographic rainfall. The northeast tradewinds prevail about 90 percent of the time from May to September and about 50 percent of the time during the winter months from October to April.

Rainfall is high and occurs throughout the year along the windward coasts and slopes where the tradewind air rises. In the leeward areas where the air descends, the climate is much drier, with most of the annual rainfall occurring during the winter when the tradewind regime is interrupted by storms moving to the north, or by local "Kona" storms where prevailing surface winds are from the south. This winter rainfall can be extremely intense, prolonged, and distributed island-wide, whereas, the tradewind rainfall generally affects only the windward and mountain areas.

Mean annual rainfall maps indicate extremes in distribution. Areas that receive 250 inches per year are within 10 miles of areas that receive less than 30 inches. This extreme variation in rainfall over short distances, necessitates a rain gage network with dense areal coverage.

In Moanalua the rainfall follows the tradewind distribution. The mean annual rainfall at upper elevations ranges from 130 inches per year at station 16227501 (7501) and 150 inches at station 16227701 (7701) to 65 inches at station 16228201 (8201) near the basin outlet. The difference in rainfall recorded in the headwaters at 7501 and 7701 and at the basin outlet at 8201 illustrates the rainfall variability even within a very small watershed. At higher elevations, rainfall is generally more intense than at the basin outlet where intense rainfall usually occurs only during the winter.

STREAMFLOW

Streamflow in Moanalua Valley is intermittent. There is no flow about 65 percent of the time in the reach between stations 2280 and 2282 at the basin outlet. In the upper reaches flow is more frequent, however periods of no flow exceeding two months occur occasionally.

Floods greater than 300 ft^3/s occur less than .15 percent of the time. The mean annual flood is 1,360 ft^3/s. Flood hydrographs have sharp peaks of short duration which is characteristic of Hawaiian streams draining undeveloped areas.

RAINFALL-RUNOFF MODELING ON OAHU

A review of the rainfall-runoff modeling literature in Hawaii reveals several problems: (1) Frequently models can not be adequately evaluated because reliable detailed input data are lacking (Fok, 1973, Phamwon, 1976, Jones and Ewart, 1973, Fok and others, 1977). (2) The rainfall-runoff relationship in undeveloped watersheds has not been thoroughly investigated. Undeveloped areas are important in water budget analysis because they supply a large portion of the ground-water recharge. In Hawaii, especially in the leeward basins, the ground-water is recharged largely as a result of individual storms. An event-type model can yield information regarding the amount of storm rainfall proportioned between runoff, evaporation and infiltration, as well as information for drainage system designs. (3) Most of the past modeling efforts used a black box approach where system response to an input is represented by a mathematical response function, such as the instantaneous unit hydrograph (Wu, 1969, Wang and others, 1970, Chong, 1974). The models calculate a peak discharge given that the amount of rainfall excess over a specified area is already known. This type of model does not simulate explicitly the processes of infiltration and evaporation.

The U.S. Geological Survey distributed routing rainfall-runoff model, DSA, developed by Dawdy, Schaake, and Alley (1978) treats a watershed as a time-invariant, nonlinear, distributed system. It consists of several submodels which simulate the physical mechanisms of the rainfall-runoff process; infiltration, soil moisture distribution, evaporation, overland and channel flow routing. The DSA model has been used on both urban and undeveloped watersheds in the continental United States with excellent results (Dawdy and others, 1978; Doyle and Miller, 1980; and Sloto, 1982). Based on the model structure and reported results, the DSA model was applied as an appropriate analytical tool in the study of the rainfall-runoff relationship in an undeveloped Hawaiian watershed.

INSTRUMENTATION

Moanalua Valley is the most intensively instrumented valley in Hawaii. For several years seven rainfall stations, five streamflow stations, one pan evaporation station, and two sediment-sampling stations were operated in cooperation with the Department of Transportation in the 3.34 mi^2 drainage area. The description of the instrumentation, period of record, and sampling interval can be found in table 1. Station locations are indicated on figure 1.

These sampling instruments provided a detailed data base of rainfall, evaporation, and hydrograph information that was used for model calibration and verification.

Table 1. Type of data collected and instrumentation in Moanalua Valley

Station No.	Drainage Area (Square miles)	Elevation (feet)	Streamflow	Rainfall	Evaporation	Suspended sediment	Instrumentation	Period of record
16227500	0.94	660	X				Digital recorder, 5-min. interval.	Oct. 1968-Apr. 1978.
						X	Automatic sampler, daily samples to Sept. 1976, intermittent thereafter.	Oct. 1971-Apr. 1978.
					X		Evaporation pan, water-supply system, and graphic recorder to April 1978. Digital recorder thereafter.	Oct. 1968-present.
16227501		1,100		X			Digital recorder, 5-min. interval to Jan. 1978, 15-min. interval thereafter.	Oct. 1968-present.
16227502		660		X			Digital recorder, 5-min. interval to Jan. 1978, 15-min. interval thereafter.	Oct. 1968-present.
16227700	.62	700	X				Digital recorder 5-min. interval.	Oct. 1968-Apr. 1978.
16227701		1,150		X			Digital recorder, 5-min. interval to Mar. 1978, 15-min. interval thereafter.	Oct. 1968-present.
16227900	.03	540	X				Graphic continuous recorder.	Apr. 1972-Mar. 1978.
16227901		950		X			Digital recorder, 5-min. interval to Mar. 1978, 15-min. interval thereafter.	Apr. 1972-present.
16228000	2.73	338	X				Graphic continuous recorder to Feb. 1970, digital recorder, 5-min. interval to Sept. 1974, 15-min. interval to Mar. 1978, continuous graphic recorder thereafter.	June 1926-present.
16228001		338		X			Cumulative-storage rain gage to Dec. 1964, tipping-bucket rain-gage attachment, and graphic continuous recorder thereafter.	June 1926-present.
16228002		580		X			Digital recorder, 5-min. interval.	Oct. 1968-Mar. 1978.
16228200	3.34	230	X			X	Digital recorder, 5-min. interval to Mar. 1978, graphic continuous recorder thereafter. A binary decimal transmitter, automatic sediment sampler, with graphic continuous recorder, intermittent samples (Oct. 1968-June 1980). Automatic sediment sampler, intermittent samples (July 1980-present).	Oct. 1968-present.
16228201		230		X			Digital recorder, 5-min. interval.	Oct. 1968-June 1978.

MODEL APPLICATION

Rainfall-Runoff Model Structure

The DSA model was used to analyze data from the Moanalua precipitation, evaporation, and streamflow-gaging network. For this study, the model input was daily pan evaporation and rainfall data from three rain gages at 5- or 15-minute intervals and the model output was the simulated runoff hydrograph.

The DSA combines the soil-moisture-accounting and rainfall-excess components of a model developed by Dawdy and others (1972) with the kinematic-wave routing components of a model developed by Leclerc and Schaake (1973). These components are comprised of equations that approximate the physical laws governing the rainfall-runoff process. Hydrologic factors include the effects of antecedent soil-moisture conditions, evapotranspiration, overland-flow slope, roughness and area, and channel slope, area and roughness. The model consists of a soil-moisture-accounting component, a rainfall-excess component, a routing component, and a soil moisture and infiltration parameter-optimization component. The following model description is largely from Dawdy and others (1978).

Soil-moisture-accounting component

The soil-moisture-accounting component determines the effect of antecedent moisture conditions on infiltration. Four parameters (table 2) are contained in this component which distribute the moisture within the soil column and determine evapotranspiration from the soil. Soil moisture is set up as a two-layered system. The upper part, surface-moisture storage (SMS), is wetted by infiltration. The other part, antecedent base-moisture storage (BMS), has a maximum storage value (BMSN) which is the soil-moisture storage at field capacity. Zero storage in BMS is assumed to represent wilting-point conditions.

On modeled storm days, moisture is added to SMS based on the Philip (1954) infiltration equation. Distribution of soil moisture between SMS and BMS is controlled by a constant drainage-rate parameter (DRN). Evapotranspiration takes place from SMS based on moisture availability, otherwise from BMS, at a rate determined by a pan-evaporation coefficient (EVC). This coefficient, when multiplied by pan data, estimates potential evapotranspiration. On other than modeled storm days, a proportion of daily rainfall, determined by the parameter RR, infiltrates into the soil.

The combination of the four parameters, BMSN, DRN, EVC and RR, determines the amount of moisture that will infiltrate into the soil and the amount that will be lost from the system due to evapotranspiration. Thus, from inputs of daily rainfall and pan-evaporation data, amounts of surface- and base-moisture storage can be calculated, which are essential to the calculation of rainfall excess.

Table 2. Model Parameters

Soil-Moisture Accounting

Parameters

BMSN	Soil-moisture storage at field capacity (in.).
DRN	A constant drainage rate for redistribution of soil moisture between saturated moisture storage (SMS) and antecedent base-moisture storage (BMS), (in./d).
EVC	A pan coefficient for converting measured pan evaporation to potential evapotranspiration.
RR	The proportion of daily rainfall that infiltrates into the soil for the period of simulation excluding modeled storm days.

Infiltration

PSP	Suction at wetted front for soil moisture at field capacity (in. of pressure).
KSAT	The effective saturated value of hydraulic conductivity (in./hr).
RGF	Ratio of suction at the wetting front for soil moisture at wilting point to that at field capacity.

Rainfall-excess component

Three types of drainage surfaces can be modeled: effective impervious, noneffective impervious, and pervious surfaces. As the project area is undeveloped, it was modeled as a pervious surface.

A point-potential infiltration rate is calculated by the Philip (1954) equation to determine from rainfall totals and intensities the rainfall excess. The capillary potential (soil suction) at the wetting front (PS) varies with the initial soil-moisture condition over the range from field capacity to wilting point. This point-potential infiltration, which occurs at varying rates throughout the basin, is converted to net infiltration over the whole basin by a set of equations developed by Crawford and Linsley (1966). These equations, according to Dawdy and others (1972), eliminate the absolute threshold value for infiltration. Thus, there is some runoff from any volume of rainfall, although for low-intensity rain where antecedent soil conditions are dry, the runoff is very small. The major justification for these equations is that it aids the modeling of runoff volumes for the smaller, low-intensity storms.

Routing component

The drainage basin is divided into any combination of channel, overland flow, reservoir, or nodal segments. This is a flexible process for representing the essential basin properties affecting runoff. A channel segment may receive upstream inflow from up to three other segments and lateral inflow from as many as four overland-flow segments. Excess rainfall is uniformly distributed as lateral inflow into overland-flow segments. Overland-flow segments are described by length, roughness, slope, and percent perviousness, and channel segments by length, slope, roughness, and width. Kinematic wave theory is applied for both channel and overland-flow routing.

Optimization component

Given observed rainfall and runoff data, the soil-moisture and infiltration parameters for the drainage basin are optimized by Rosenbrock's (1960) technique. The model is assigned an initial set of bounded parameter values. The optimization method revises the parameter magnitudes and computes the objective function which is the sum of the squared deviations of the logarithms of computed and measured storm-runoff volumes. If the revisions of the parameter values result in an improvement in the objective function, the revised set of values is accepted; if not, the method returns to the previous best set of parameter values. The process develops a nonlinear least-squares solution.

Drainage Basin Segmentation

Moanalua Valley is divided into four channel and eight overland flow segments. Slope, area, and length measurements were made from topographic maps. Values for roughness and channel widths were obtained from field cross-sections; maximum channel widths were used. Within each segment the physical characteristics are assumed to be homogeneous (tables 3 and 4).

Natural drainage paths dictated by the basin topography, ridgelines, and the stream channel, were used to delineate the boundaries of most overland-flow segments (fig. 2). Major changes in roughness or slope within each segment were also considered in determining boundaries.

Parameter Optimization - Model Calibration

Five-minute-interval data for 20 calibration storms were input for soil-moisture-accounting and infiltration parameter optimization. The 20 storms represented a range of antecedent moisture conditions, rainfall totals and intensities, peak flows, and runoff volumes. Optimizing on such a range of event characteristics produced realistic parameter values which will fit the rainfall characteristics and antecedent moisture conditions that occur in the basin.

Limits between which each parameter value fluctuated were established based on guidelines presented in the model documentation (Dawdy and others, 1978) and on field research done in Hawaii (Rotert, 1977, Ahuja and El-Swaify, 1979, Chong, 1979, Chang, 1968, Ekern, 1966, and Green and others, 1981). All seven parameters were optimized for the 20 calibration storms. Each run was evaluated by comparing the observed and simulated volumes for each event. Subsequent runs were made until there was an acceptable fit for 85 percent of the storms using the criteria from Doyle and Miller (1980); less than 50 percent error if simulated volume or peak is less than observed, and less than 100 percent error if simulated volume or peak is greater than observed. Simulated and observed hydrograph shape and time to peak were also compared.

Storms 5 and 6 did not meet the criteria for peak discharge and storm 19 failed to meet the criteria for both volume and peak flow. The failures may have been due to the very wet antecedent conditions for storm 6, the very dry antecedent conditions for storm 19, and possible data measurement errors for storm 5.

Table 3. Overland flow-segment characteristics

Segment Number	Channel drainage segment	Area (mi^2)	Length[1/] (ft)	Slope (ft/ft)
OVF 5	CH 1	0.59	1939	0.47
OVF 6	CH 1	.35	1163	.47
OVF 7	CH 2	.23	982	.49
OVF 8	CH 2	.39	1637	.49
OVF 9	CH 3	.55	1320	.50
OV 10	CH 3	.63	1390	.47
OV 11	CH 4	.30	2084	.41
OV 12	CH 4	.31	2154	.47

1/ Length of overland flow segments is computed as the area, in square feet, divided by the length, in feet, of the channel segment into which the overland flow segment contributes lateral inflow.

Perviousness is 100 percent and roughness, Manning n, is 0.4 for all overland flow segments.

Table 4. Channel-segment characteristics

Segment Number	Upstream inflow segment	Length (ft)	Slope (ft/ft)	Manning n	Width (ft)
CH 1		8,448	0.15	0.052	45
CH 2		6,600	.23	.067	21
CH 3	CH 1, CH 2	12,170	.03	.050	50
CH 4	CH 3	4,013	.03	.040	29

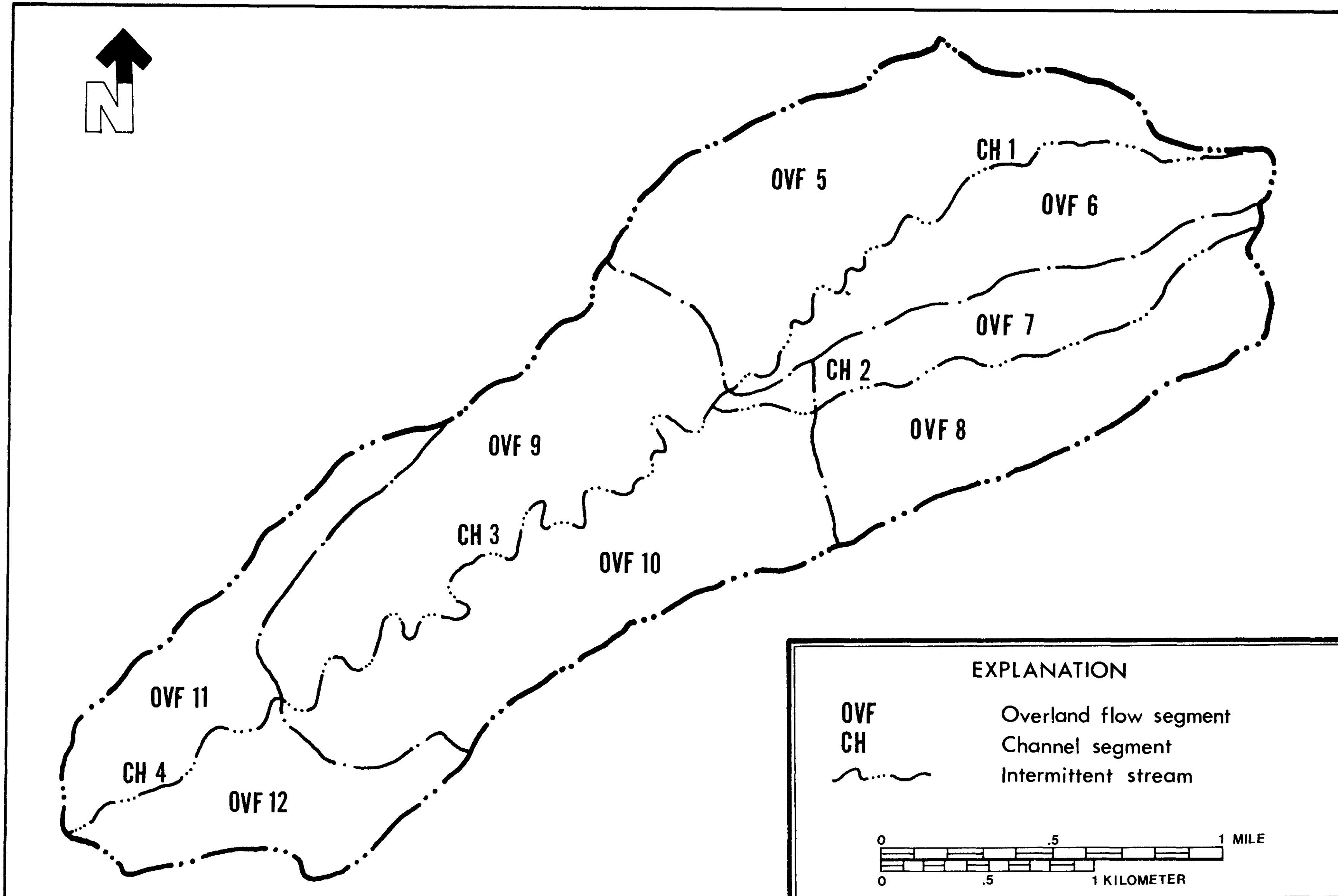

Figure 2. Moanalua Valley showing overland flow and channel segmentation.

A sensitivity analysis indicated that the PSP and KSAT parameters are highly interactive, and that simulated runoff volumes are highly sensitive to changes in the PSP, KSAT, and DRN parameter values. One hundred percent increases in PSP, KSAT, and DRN caused decreases of more than 40 percent in runoff volumes for many events.

For a 100 percent decrease in the BMSN parameter value, the resulting simulated runoff volumes for most events were not significantly affected. A similar decrease in the RR value caused a 100 percent decrease in simulated volumes for a few events, and others remained unchanged. The EVC and RGF parameters were least sensitive as 100 percent increases and decreases in their values did not cause significant changes in the simulated runoff volumes for any events.

Some basin parameters such as channel and overland flow slopes, and Manning n values were also adjusted to yield better hydrograph matches. For example, a decrease in channel Manning n values generally increased the simulated peak flows; significantly for the higher peak flow events. This is a sensitive model parameter and can be adjusted to "fine tune" the model. Several runs were made until the above criteria were met for observed and simulated peak flows and hydrograph shapes.

Table 5 lists the optimized parameter values. Table 6 lists all calibration storm rainfall characteristics and observed versus simulated results. Figure 3 displays representative hydrographs.

Table 5. Optimized parameter values

Parameter	20 Storms 5 minute interval data
BMSN (in.)	9.75
DRN (in./d)	1.09
EVC	0.62
RR	0.99
PSP (in.)	1.95
KSAT (in./hr)	0.45
RGF	17.09
Objective function	4.63

Table 6. Model calibration results and storm characteristics

Storm No.	Storm duration	Observed rainfall stations (in.) 7501	7502	8201	Mean rain (in.)	Maximum intensity stations (in./hour) 7501	7502	8201	10-day antecedent rain (in.)	Observed runoff volume (in.)	Simulated runoff volume (in.)	Percent error[1/]	Observed peak (ft^3/s)	Simulated peak (ft^3s)	Percent error[1/]	Runoff / rainfall (percent)
1	11/28-30/68	8.3	9.9	6.7	8.3	1.8	2.2	0.8	3.6	1.95	1.95	0	1,090	910	-17	23
2	12/24-25/68	6.2	6.0	3.7	5.3	2.3	2.4	2.2	6.0	1.61	2.88	+79	1,390	2,320	+67	30
3	1/2-3/69	7.5	7.7	6.5	7.2	1.6	1.5	1.7	6.5	1.15	2.26	+97	927	1,030	+11	16
4	2/1/69	15.4	11.9	4.9	10.7	3.4	3.0	1.1	7.3	3.88	7.19	+85	2,980	2,020	-32	36
5	12/27-28/69	6.1	5.6	1.2	4.3	1.7	1.3	0.3	6.8	1.09	1.37	+25	540	1,640	+203	26
6	1/3/70	7.5	7.1	0.9	5.2	2.1	1.6	0.2	15.3	1.69	3.03	+79	878	1,920	+118	33
7	7/25-26/70	9.2	15.4	12.1	12.2	3.0	4.0	2.0	5.1	5.15	8.02	+56	2,740	2,640	-3	42
8	11/25-26/70	9.7	4.8	3.0	5.8	3.5	1.2	0.5	8.7	3.84	3.09	-20	2,180	1,920	-12	66
9	11/29/70	3.7	3.3	0.4	2.5	1.5	1.1	0.4	11.8	1.16	0.76	-34	844	428	-49	46
10	4/5-6/71	5.3	5.4	0.8	3.8	2.6	2.4	0.2	4.0	1.28	2.01	+57	1,820	1,920	-12	34
11	4/23-24/71	8.8	6.9	2.6	6.1	1.3	1.4	0.4	11.3	3.86	2.75	-29	1,240	1,920	+5	63
12	1/22-24/72	13.9	12.9	3.4	10.1	1.8	2.0	1.0	1.4	3.63	3.72	+3	1,170	1,920	+64	36
13	2/18/72	4.9	4.7	0.9	3.5	0.6	0.6	0.1	1.8	0.30	0.32	+6	100	74	-26	9
14	4/14-15/72	3.4	3.5	4.7	3.9	0.9	1.1	1.6	5.7	0.46	0.88	+93	278	406	+46	12
15	11/12/73	5.1	6.3	2.2	4.5	1.3	1.0	0.3	1.8	1.29	1.46	+14	353	646	+83	29
16	4/18-20/74	11.4	13.7	11.1	12.1	1.8	1.8	4.0	4.5	6.08	4.31	-29	2,200	1,800	-18	50
17	5/14/74	4.0	2.6	0.3	2.3	1.3	1.3	0.2	2.6	0.84	1.12	+33	948	830	-13	37
18	11/20-21/74	11.5	12.0	7.6	10.4	1.7	1.5	1.6	4.6	5.01	2.61	-48	1,420	1,590	+12	48
19	1/11-12/75	7.3	4.2	5.2	5.6	0.8	0.4	0.5	0.8	2.40	0.81	-66	455	190	-58	43
20	11/24-27/75	13.3	13.0	9.3	11.9	1.5	1.4	2.8	2.3	5.09	3.88	-24	1,470	1,600	+9	43

1/ Percent error = $\frac{\text{Observed - simulated}}{\text{Observed}}$

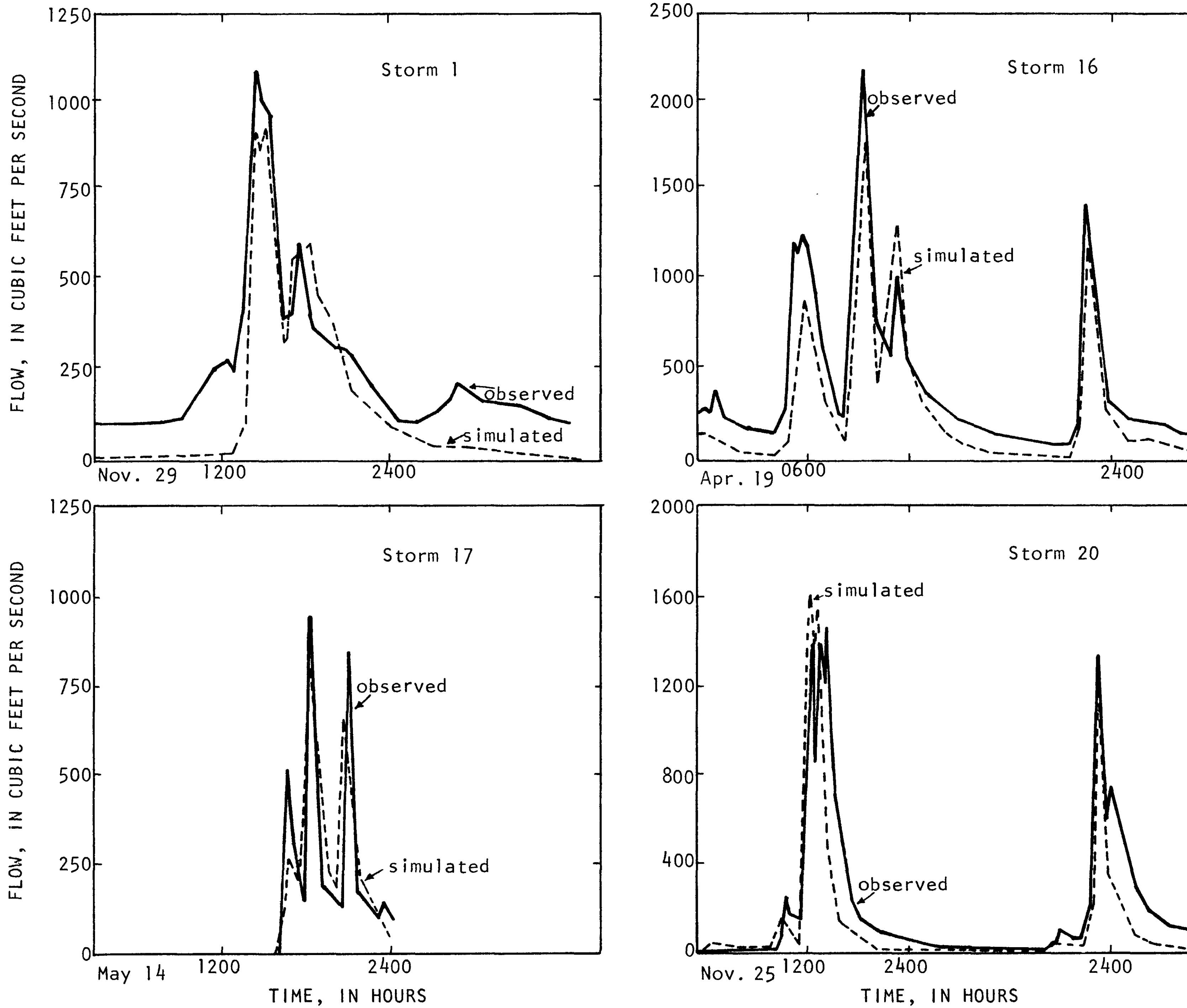

Figure 3. Calibration storm hydrographs.

Validity of DSA model parameter values

The value of the model results is substantially dependent on the validity of the soil-moisture-accounting and infiltration parameter values which quantify the physical processes. The data available for comparison are from experiments done on soils with somewhat different characteristics than those found in Moanalua Valley. The following studies indicate the model parameter values fall within a range of reasonable values.

The DSA optimized saturated hydraulic conductivity, KSAT, is 0.45 in./hour. Both the Kaena and Hanalei Series soils found in Moanalua Valley are fine-textured and contain a large amount of montmorillonite. They have lower permeabilities, 0.06-0.63 in./hour and 0.63-2.0 in./hour, respectively, as compared with Wahiawa and Tantalus Series soils (1.0-6.3 in./hour) according to the Soil Conservation Service (Foote and others, 1972).

Rotert (1977) presented saturated hydraulic conductivities of 0.63-0.689 and 1.063-3.228 in./hour for Wahiawa Series silty clays at two different sites. Ahuja and El-Swaify (1979) continuously monitored soil moisture, rainfall, and runoff on a forested plot. Their analysis indicated conductivities of 0.315-0.945 in./hour for cores of Tantalus Series silty clay.

The model value for suction at the wetted front at field capacity, parameter PSP, is 1.95. From the RGF parameter value of 17.09, suction at the wilting point equals 33.33 inches. Chong's study (1979) provides a general comparison as he calculated wetting front potentials for soil-water contents at less than field capacity ranging from 7.22 to 19.01 inches for Molokai and Lahaina Series soils. These soils are well-aggregated and well-drained with a silty clay texture, and have higher permeabilities (0.63-2.0 in./hr) than the predominant Kaena Series soils found in Moanalua Valley.

The model optimized pan coefficient, EVC, is 0.62. Because of the type of pan and the natural ground cover in Moanalua Valley, the following provide only a general comparison. Chang (1968) found pan coefficients to vary from .40 to 1.10 for sugarcane in different stages of growth, using a class-A pan. Ekern (1966) found that the evapotranspiration rate of Bermuda grass under optimum moisture conditions was essentially the same as class-A pan evaporation.

The optimized RR value, 0.99, indicates that 99 percent of daily rainfall, exclusive of large storm days, infiltrates into the soil. This value appears reasonable as the rainfall and associated streamflow data indicate that generally there is either no flow or very low flow, less than 1 ft^3/s mean daily discharge, for daily rainfalls less than one inch when antecedent conditions are dry.

The optimized DRN value is 1.09 which indicates that the drainage rate between the two-layered soil system is about 1 inch per day. This value can not be evaluated on a physical basis, as there is no soil thickness indicated for these two soil layers.

The model BMSN value of 9.75 inches indicates the field-capacity moisture storage of an active soil zone. The lack of comparable data requires an indirect method to determine the validity of this value. Green and others (1981) calculated volumetric soil-moisture suctions from undisturbed Lahaina, Molokai, and Wahiawa Series soil cores. If field capacity occurs at a suction of 1.9 inches (PSP value), then the data from Green and others (1981) can be extrapolated to indicate a soil moisture at field capacity of 0.53 cm^3/cm^3 (fig. 4). The model calculates BMSN with a soil depth assumed to equal the depth of the root zone. Selecting 18 inches (45.72 cm) as a reasonable root depth, the value for volumetric soil moisture at field capacity (0.53 cm^3/cm^3) by Green and others converts to 0.53 $cm/^3cm^3$ x 45.72 cm = 24.23 cm or 9.54 inches.

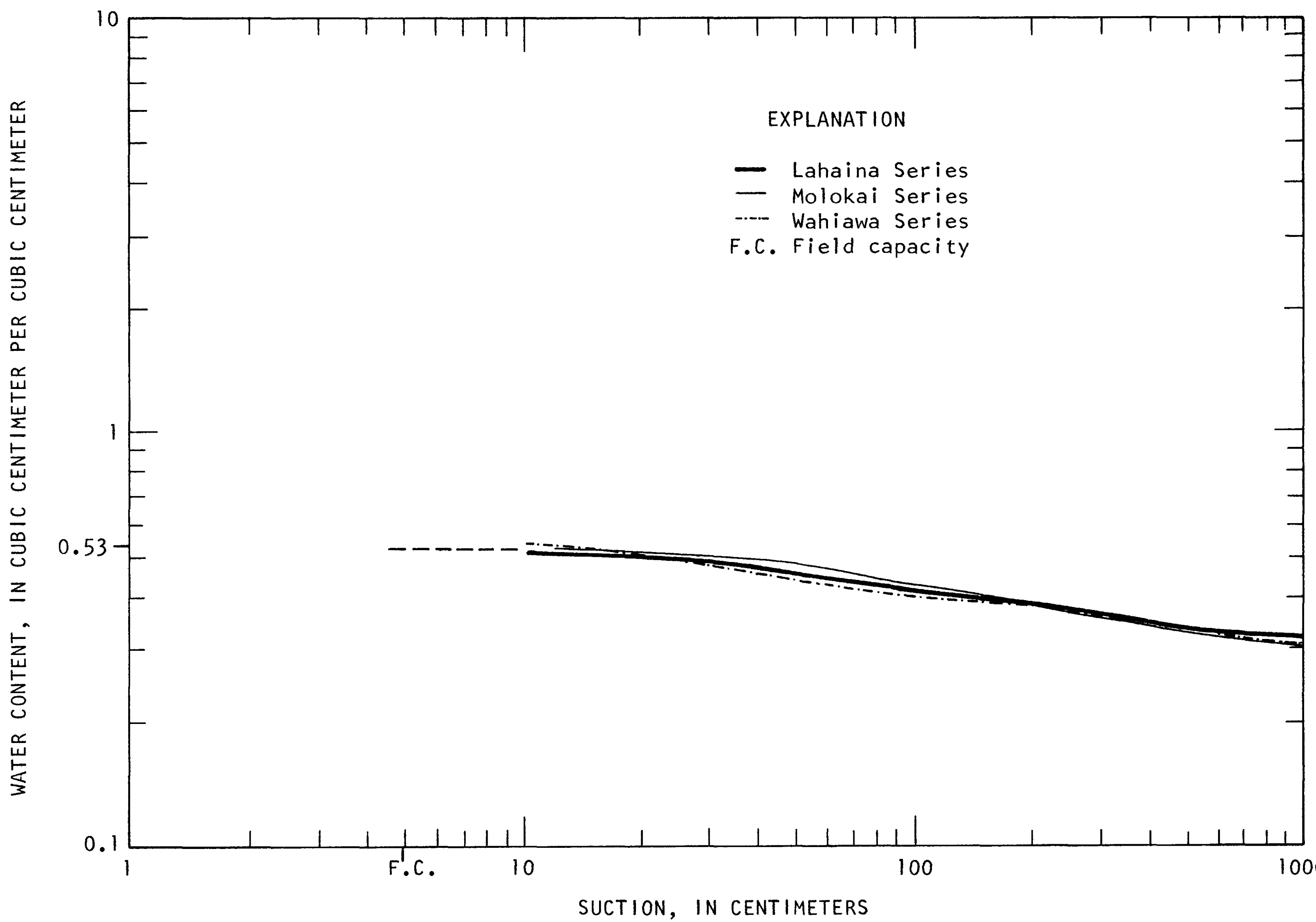

Figure 4. Relationship between soil-water content and soil suction.

Model Verification

With the soil-moisture, infiltration, and flow-routing parameters calibrated, the model was verified using 10 events with data recorded at 15-minute intervals. These events took place after the downstream rain gage, 8201 (fig. 5), which supplied data for the calibration runs, was discontinued. The next closest recording rain gage was 16227901 (7901), located about 1-1/2 miles upstream on the south ridge of the valley at an elevation of 950 feet (fig. 6). Changing the source and distribution of point rainfall over the basin should indicate if the model parameter values have accurately defined the basin's hydrologic characteristics. The results of this test are summarized in table 7.

These verification storms reproduced both volumes and peaks within the range of error established by the calibration storms. The simulated volumes and peak flows for the two largest storms are well within the calibration criteria, although some of the very small storms are not. The rainfall-runoff relationship indicated by the last column of Table 7 is also consistent with the relationship established by the calibration storms. Figure 7 demonstrates that the hydrograph shape and time to peak for several floods have been preserved.

Storm No. 5 produced a 50-year flood as determined by the Water Resources Council log-Pearson Type III frequency analysis. The error between observed and simulated volumes was +9-percent and between observed and simulated peak flows was -32-percent. This was a prolonged storm, March 16-19, 1980, with extreme rainfall intensities. The reasonably accurate simulation of such a large flood as well as smaller floods, is a good indication that the model is calibrated for the basin.

These results indicate that further model adjustment is not necessary as there is no trend in either the magnitude or direction of errors between observed and simulated runoff volumes and peak flows. There are however, several explanations for these errors.

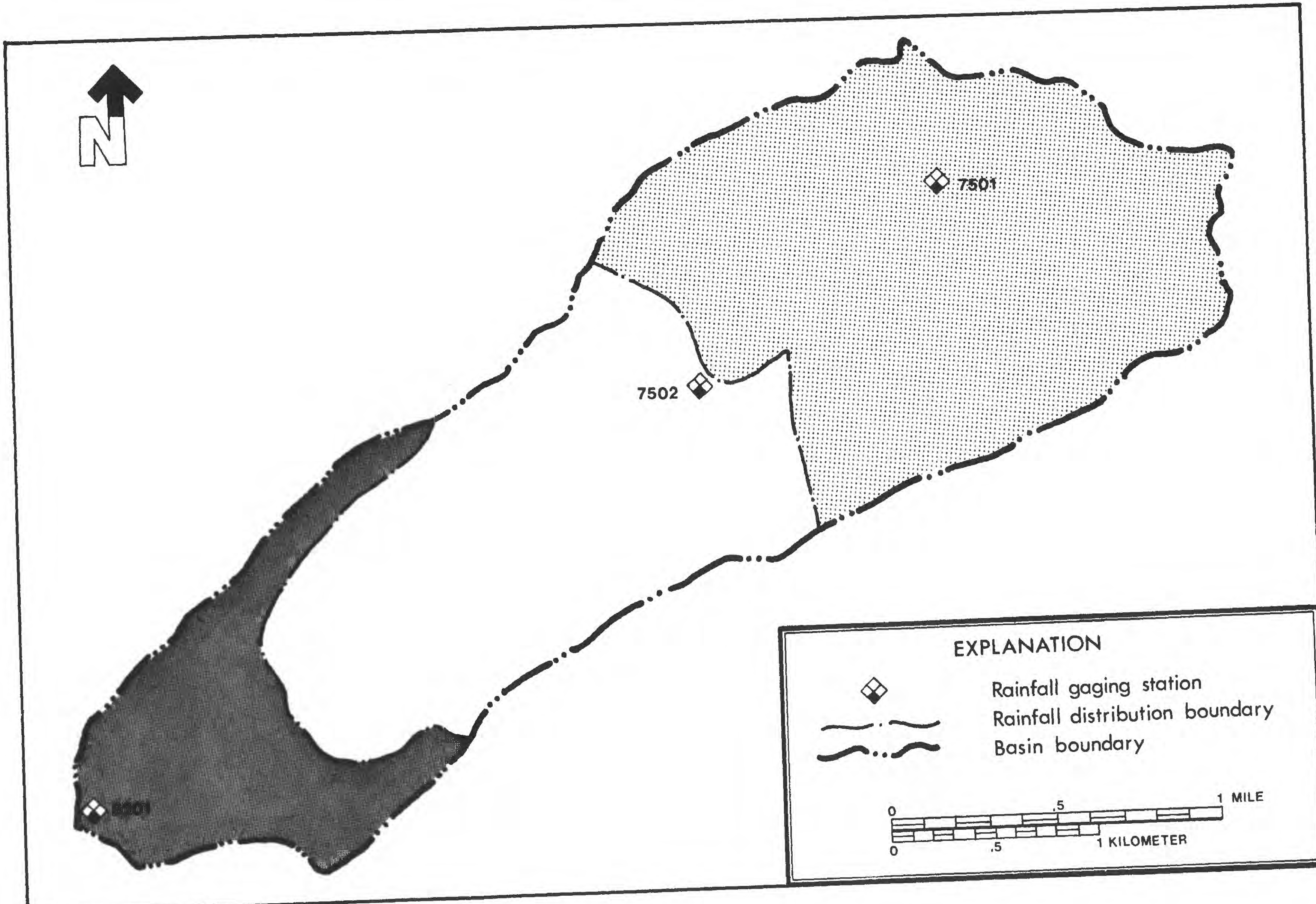

Figure 5. Distribution of model calibration 5-minute interval rainfall data.

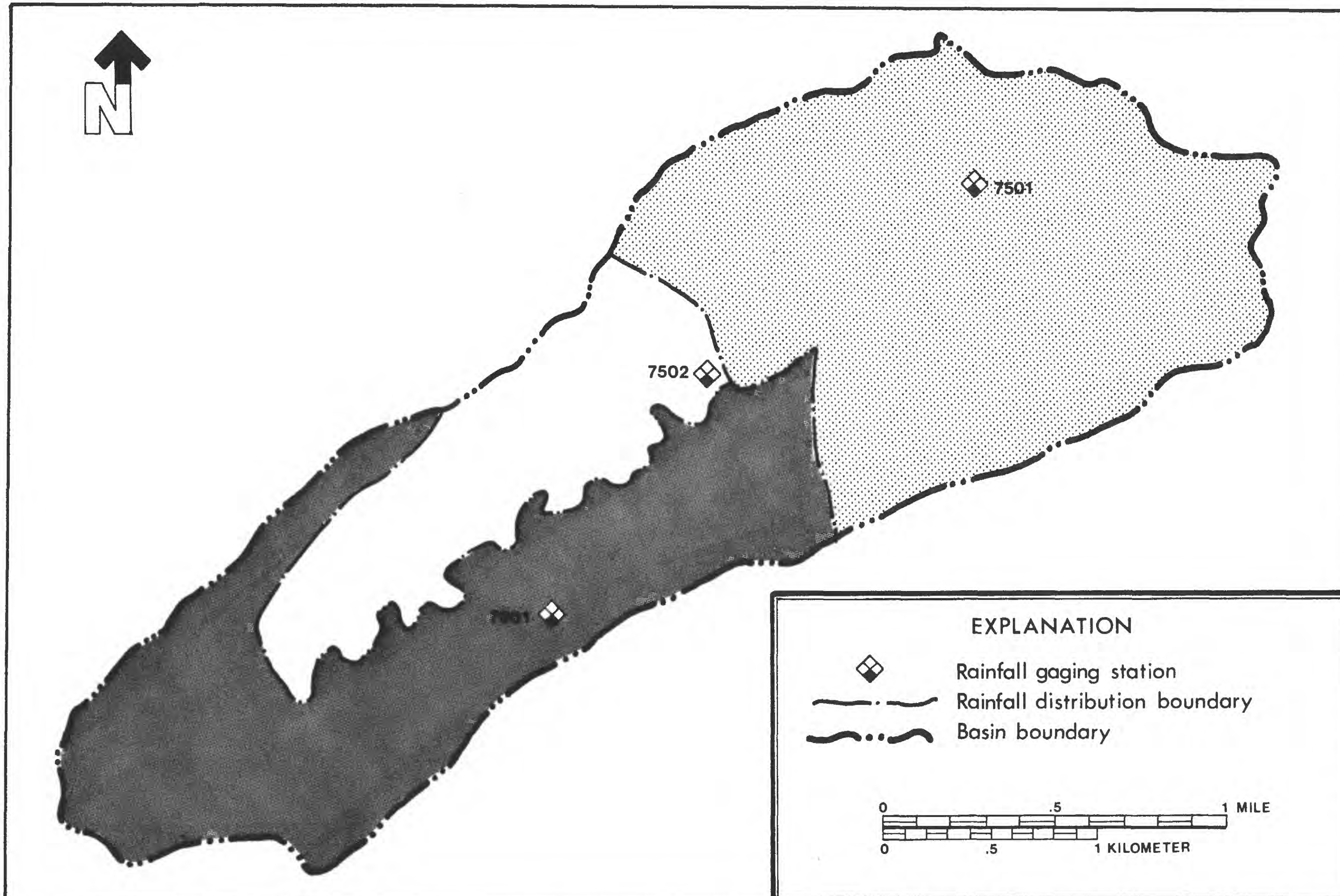

Figure 6. Distribution of model verification 15-minute interval rainfall data.

Table 7. Results of model verification test

Storm No.	Date	Observed rainfall stations (in.) 7501	7502	7901	Mean rain (in.)	Maximum intensity stations (in./hour) 7501	7502	7901	10-day antecedent rain (in.)	Observed volume (in.)	Simulated volume (in.)	Percent error 1/	Observed peak (ft^3/s)	Simulated peak (ft^3s)	Percent error 1/	Runoff/rainfall (percent)
1	6/28/78	6.1	5.3	3.5	5.0	0.9	0.7	0.5	6.5	1.75	1.18	-33	516	493	- 4	35
2	1/11-15/79	16.7	14.9	10.4	14	1.0	1.0	0.6	1.8	7.83	2.5	-68	962	640	-33	56
3	12/24-25/79	8.6	8.1	5.7	7.5	2.4	2.3	1.8	0.9	1.81	3.17	+75	1,570	2,410	+54	24
4	1/8-10/80	11.3	11.8	12.2	11.8	2.1	2.4	2.5	4.9	4.97	3.25	-35	2,330	2,410	+ 3	42
5	3/16-19/80	28.5	24.0	16.1	22.9	5.0	4.6	4.3	6.4	10.86	11.81	+ 9	4,860	3,310	-32	47
6	4/15/80	4.0	3.1	1.7	2.9	1.9	1.3	0.6	6.1	0.47	0.79	+68	331	956	+189	16
7	5/25-26/80	3.6	3.9	2.2	3.2	0.6	0.7	0.3	5.3	0.16	0.22	+38	91	45	-51	5
8	5/28-29/80	2.6	2.9	2.8	2.8	1.3	1.4	1.1	6.5	0.80	0.59	-26	558	497	-11	29
9	6/13-15/80	4.9	5.0	4.6	4.8	0.9	0.9	0.6	3.2	1.02	0.22	-78	435	73	-83	21
10	7/6-7/80	3.5	3.1	2.1	2.9	0.6	0.4	0.4	4.2	0.26	0.12	-54	97	21	-78	9

1/ Percent error = $\frac{\text{Observed - simulated}}{\text{Observed}}$

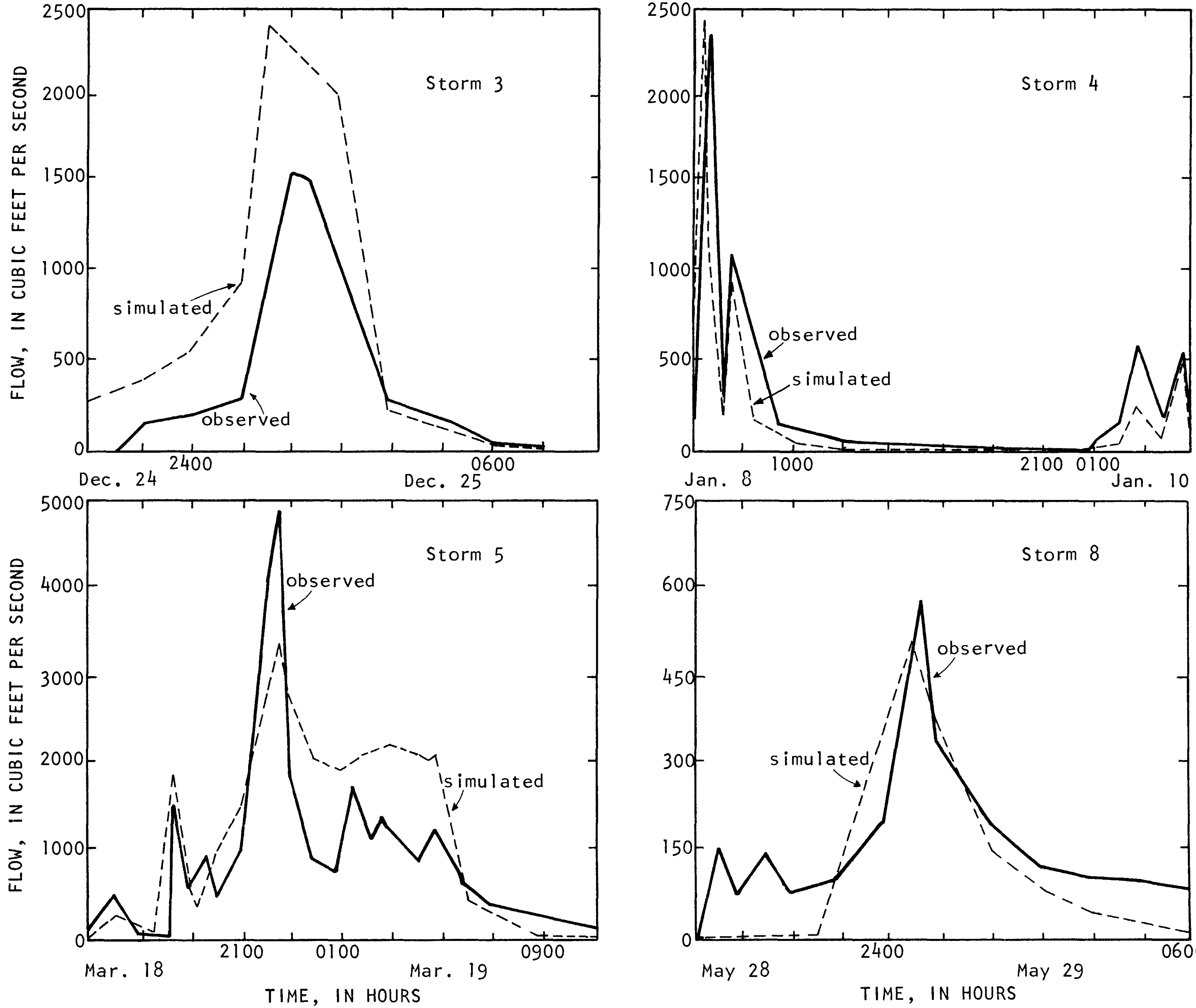

Figure 7. Verification storm hydrographs.

MODEL EVALUATION

Model Assumptions--Sources of Error

Several assumptions are made in modeling which introduce error into the resulting hydrographs. There are instances where simulated and observed peaks and hydrograph shapes do not coincide. The following discussion will attempt to explain several reasons for these discrepancies.

The assumption that point rainfall (rain gage data) is distributed homogeneously over the segments may be the major source of error. When considering the limited dimensions of intense storm cells that develop over Oahu, the model's spatially uniform distribution of rainfall cannot match the actual occurrence of rainfall.

Another source of error is in the assumptions of the kinematic wave-routing component of the model. The α parameter, in the kinematic wave equation, which is related to the velocity of the flow, is computed from the Manning formula. It is a function of the slope of the water-surface, which is assumed equal to the bed slope. The magnitude of α, because it is related to wave velocity, may be a function of the mean depth of water and, consequently, a function of the storm intensity (Leclerc and Schaake, 1973). For each segment the α parameter is held constant throughout each storm, and from storm to storm. Clearly, wave velocity and mean water depth vary within a storm, as well as between storms. Holding this parameter constant introduces error in the timing of the rising limb of the simulated hydrographs. The effect of this source of error on the modeling results was slight as shown by the generally good fit between simulated and observed hydrographs (figs. 3 and 7).

In addition, the kinematic-wave method is applicable only when the Froude number is less than two. As the Froude number is directly related to the mean-flow velocity, which is dependent upon roughness and slope, the kinematic-wave approximation may not be applicable for determining discharge in the two very steep upper-basin areas where the calculated Froude number is 2.5. As mean, model-calibrated values for slope and roughness are used in the calculation of the Froude number, there is an amount of error present in the Froude number itself. To the extent that the calculated Froude numbers are correct, and are less than or slightly greater than two for each of the sub-basins, the use of the kinematic-wave method for modeling discharge in Moanalua Valley is justified, although possibly near its limit of applicability and potentially introducing error into the modeled hydrographs.

The segmentation of the basin is a simplified representation of the real valley structure. Although care was taken to characterize each segment with accurate measurements of slope, roughness, and area, error will remain in the representation. The problem is compounded during flow routing. Every individual drainage path is not modeled, and thus, only the combined behavior of the basin's complex processes is represented. Some of the deviations of the simulated hydrographs may be the result of this oversimplification, but the generally good fit indicates the model has successfully integrated these processes.

Another source of error is in the ability of the soil-moisture-accounting and infiltration parameters to accurately represent the volume of water infiltrated. Optimized parameter values are average values for the basin and are an index to, rather than a measure of, the underlying physical systems (Dawdy and others, 1972). Due to the complexity of the actual physical processes, the parameter values are not unique, in that a different set of values could be found that also produce model results in agreement with hydrologic data. It is necessary to keep the values realistic so that the simulated hydrographs will be the result of modeling actual physical processes.

Summary of Model Results

The results of the DSA model application to Moanalua Valley indicate the model successfully simulated the rainfall-runoff relationship in a small undeveloped Hawaiian watershed. Because the DSA model is a distributed parametric model, it can adequately model the extreme variability in rainfall intensities and distributions, and basin physical characteristics. Physically based soil-moisture-accounting and infiltration model parameter values have been established.

The error between observed and simulated runoff volumes and peak flows was 35 percent or less for 50 percent of the events modeled. Many of the simulated hydrographs, conform well to the observed hydrographs in terms of hydrograph shape and timing of the rising and recession limbs. Results indicate that the DSA model is capable of simulating multiple-peak storms as large as a 50-year flood well within the calibration criteria.

The analysis of the modeled storms indicates that the average ratio of runoff to rainfall is approximately 35 percent.

The success of the model application to Moanalua Valley, and the establishment of physically-based model parameter values, indicate high transferability potential to other Hawaiian watersheds.

Model Transferability

The transferability of the DSA model is not limited by the lack of long-term data. Because the rainfall-runoff relationship in Moanalua Valley has been successfully modeled, it is likely that the results can be transferred to other Hawaiian watersheds. To obtain simulated hydrographs from ungaged basins, the Moanalua soil-moisture-accounting and infiltration parameter values can be used with adjustments depending on the comparability of the soils, ground cover, and other basin characteristics.

A range of parameter values also could be determined by modeling other gaged small basins with similar soil types. Results of the Moanalua model calibration can guide the parameter optimization and model fine-tuning for these basins.

BASIN WATER BALANCE

The components of a water balance are rainfall, runoff, evapotranspiration, ground-water recharge, and change in soil-moisture storage. Recognizing that runoff and ground-water recharge in an undeveloped Hawaiian basin generally occur only when there is a significant amount of rainfall, as opposed to a short light drizzle, and that modeling the major storms that occurred during a twelve year period has supplied a good estimate of the rainfall-runoff relationship, a water balance for the basin was calculated based on the model input data and results.

The averaged monthly rainfall totals from stations 7501, 7502, 7701, 8001, and 8201 are listed on Table 8. Each month's value represents the average rainfall over the basin and is input as the rainfall component. The model calibration and verification storms indicate that the runoff-rainfall ratio from various rainfall-intensity events averages 35 percent. Therefore, 35 percent of each rainfall value represents the runoff component of the water balance.

For evapotranspiration the potential rate is calculated by multiplying the pan coefficient model parameter, 0.62, by the total monthly recorded pan data listed on Table 8. Actual evapotranspiration is maintained at the potential rate as long as soil moisture content is high. As the soil dries out, the actual evapotranspiration rate will be less than the potential rate.

To calculate the change in soil moisture storage the amount of water the soil can store is estimated. This amount, maximum soil storage, equals the available water in the soil (field capacity minus wilting point) multiplied by an average soil thickness (depth of the root zone). Water in excess of field capacity will recharge the ground water. Water content less than wilting point will be tightly held in the soil unavailable for evapotranspiration. The value for suction at field-capacity, PSP, determined by the model is 1.9 inches. From figure 4, 1.9 inches (4.8 cm of suction) indicates a water content of .53 cm^3/cm^3. Calculated from the model parameter RGF, soil suction at the wilting point is 33 inches. Using figure 4, 33 inches (84 cm of suction) indicates a water content at wilting point of .43 cm^3/cm^3. Using 18 inches as a reasonable soil thickness, maximum soil storage equals: (.53 - .43) x 18 = 1.8 inches. In support of figure 4, the range of available water capacity for the Lahaina, Molokai, and Wahiawa Series soils equals that of the predominant Kaena Series soil found in Moanalua Valley (Foote and others, 1972).

Table 8. Mean monthly rainfall from stations 7501, 7502, 7701, 8001 and 8201 in inches

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						Rainfall						
1970	12.28	2.02	3.82	10.42	8.16	7.30	21.10	6.26	6.08	8.90	26.32	10.78
1971	11.78	4.42	13.42	23.94	7.54	6.48	2.84	2.84	5.80	3.64	10.00	9.90
1972	14.74	10.56	5.28	12.56	4.98	4.10	6.88	6.56	3.50	7.30	7.28	6.58
1973	2.42	9.54	9.70	11.30	8.54	5.34	10.06	4.38	4.84	10.58	12.88	8.00
1974	13.20	7.96	9.52	20.58	12.38	8.58	7.42	4.22	10.06	9.90	16.38	6.38
1975	16.98	7.40	10.58	6.90	5.44	3.28	5.68	4.10	2.10	7.52	16.70	5.80
1976	7.44	9.26	14.90	13.26	4.32	4.22	8.30	3.46	5.70	6.24.	6.46	2.24
1977	2.00	6.24	11.10	13.82	11.80	8.46	5.54	5.06	4.26	3.22	7.20	5.06
						Pan evaporation from station 7500						
1970	1.90	4.16	4.28	1.91	3.63	3.94	3.00	2.65	3.19	2.09	1.11	2.33
1971	1.53	2.47	2.11	2.13	3.58	4.49	5.58	4.61	2.83	3.16	1.64	2.14
1972	3.26	2.94	4.24	1.57	3.51	3.36	3.84	4.73	5.06	3.28	2.35	2.41
1973	3.41	2.58	1.14	2.28	2.88	3.78	3.04	3.17	3.75	2.33	1.60	2.50
1974	1.01	1.91	3.25	2.16	2.51	2.63	3.27	3.26	3.34	2.83	1.99	2.16
1975	1.45	2.28	2.24	2.69	4.08	3.46	4.68	4.53	4.18	3.66	1.65	3.96
1976	2.20	1.33	1.54	1.95	3.12	3.34	2.84	4.88	3.86	3.55	3.34	4.18
1977	4.68	3.04	2.30	1.81	2.59	3.27	4.63	4.07	3.48	2.99	2.12	3.89

Recharge was computed using these data in the following equation:

Rainfall - Runoff - Change in soil storage - Evapotranspiration = Recharge

This water budget was calculated on a monthly basis for eight years using: the mean of the monthly rainfall totals from five rain gages; 35 percent of this mean value for runoff; the monthly pan evaporation total multiplied by the pan coefficient, 0.62, for potential evapotranspiration; and 1.8 inches for the value of maximum soil storage. For each month the value of rainfall minus runoff is added to soil storage. This amount of soil storage is compared to the value of PE (potential evapotranspiration). If the amount in soil storage is greater than PE, then AE (actual evapotranspiration) equals PE. If the remainder in soil storage exceeds the maximum soil capacity, the difference goes to recharge. If the amount in storage is less than PE, then AE equals the amount in storage, the soil moisture goes to zero, and there is no recharge.

Calculating the water balance on a monthly basis allows for the variation in soil-moisture storage during the wet and dry seasons, and when performed for several years with real data, assesses the water balance for the basin on an annual basis. The calculated mean annual recharge to the ground water by this method was 43 inches over the basin per year or 7 Mgal/d.

SEDIMENT TRANSPORT

Suspended-sediment discharge

To discuss sediment discharge it is important to recognize the products of chemical weathering in Hawaii. Basically, climatic conditions in Hawaii are very favorable for chemical decomposition of rocks, and the mineral composition of the rocks is such that most of the minerals are readily decomposed. Also, quartz, a resistant rock-forming mineral found in continental areas, is essentially absent from the rocks of Hawaii. Thus, in Moanalua the products of erosion are predominantly very fine montmorillonite clay and fine silty clay soils, and the suspended-sediment discharge is dominated by clay and silt size particles with very little sand as shown in the one available particle-size analysis (table 9).

Table 9. Particle-size analysis of suspended-sediment at 16228200

Percent finer than the size (in mm) indicated						
Particle size						
Clay		Silt			Sand	
0.002	0.004	0.016	0.062	0.125	0.250	0.500
33	46	80	93	98	100	100

The fine particles (less than .062 mm in diameter) move at essentially the same velocity as the water and are transported, suspended in the flow by the upward components of turbulence, or by colloidal suspension in the case of very fine particles. Because most streams are capable of transporting large quantities of fine sediment, suspended-sediment concentration in a stream is largely a function of the availability of fine sediment for transport, rather than the stream's transport capacity.

Daily and instantaneous suspended-sediment samples have been collected at two sites within Moanalua Valley. Daily suspended-sediment data from station 2275 have been published in the U.S. Geological Survey annual reports (1973-1977) and indicate the sediment discharge from a small sub-basin (table 10).

Table 10. Annual suspended-sediment discharge, in tons per year, at station 16227500, drainage area 0.94 mi^2

1973	1974	1975	1976	1977
23.04	364.86	83.12	181.09	26.04

The mean annual subbasin yield equals 144 $tons/mi^2/yr$.

Intermittent instantaneous suspended-sediment samples have been collected at the basin outlet station 2282 from 1972 to 1982. These data are used in computing storm loads and developing a suspended-sediment transport curve.

A suspended-sediment transport curve (fig. 8) represents the average relationship between water discharge, and suspended-sediment discharge, calculated by:

Instantaneous streamflow (ft^3/s)
X Instantaneous sediment concentration (mg/L)
X 0.0027 (unit conversion factor)
= suspended-sediment discharge (tons/day).

The upper data points were fit by a class-average line, and points below a sediment discharge of 58 tons/day were fit by eye.

Figure 8 and a flow-duration curve for station 2282 (fig. 9) were used in the flow-duration sediment-rating-curve method (Miller, 1951) to calculate the mean annual suspended-sediment discharge and yield for the basin. A flow-duration curve is a cumulative frequency curve that shows the percentage of time within the total period of record that a specified daily discharge was equalled or exceeded. It combines, in one curve, the flow characteristics of a stream throughout the range of discharge without regard to the sequence of occurrence.

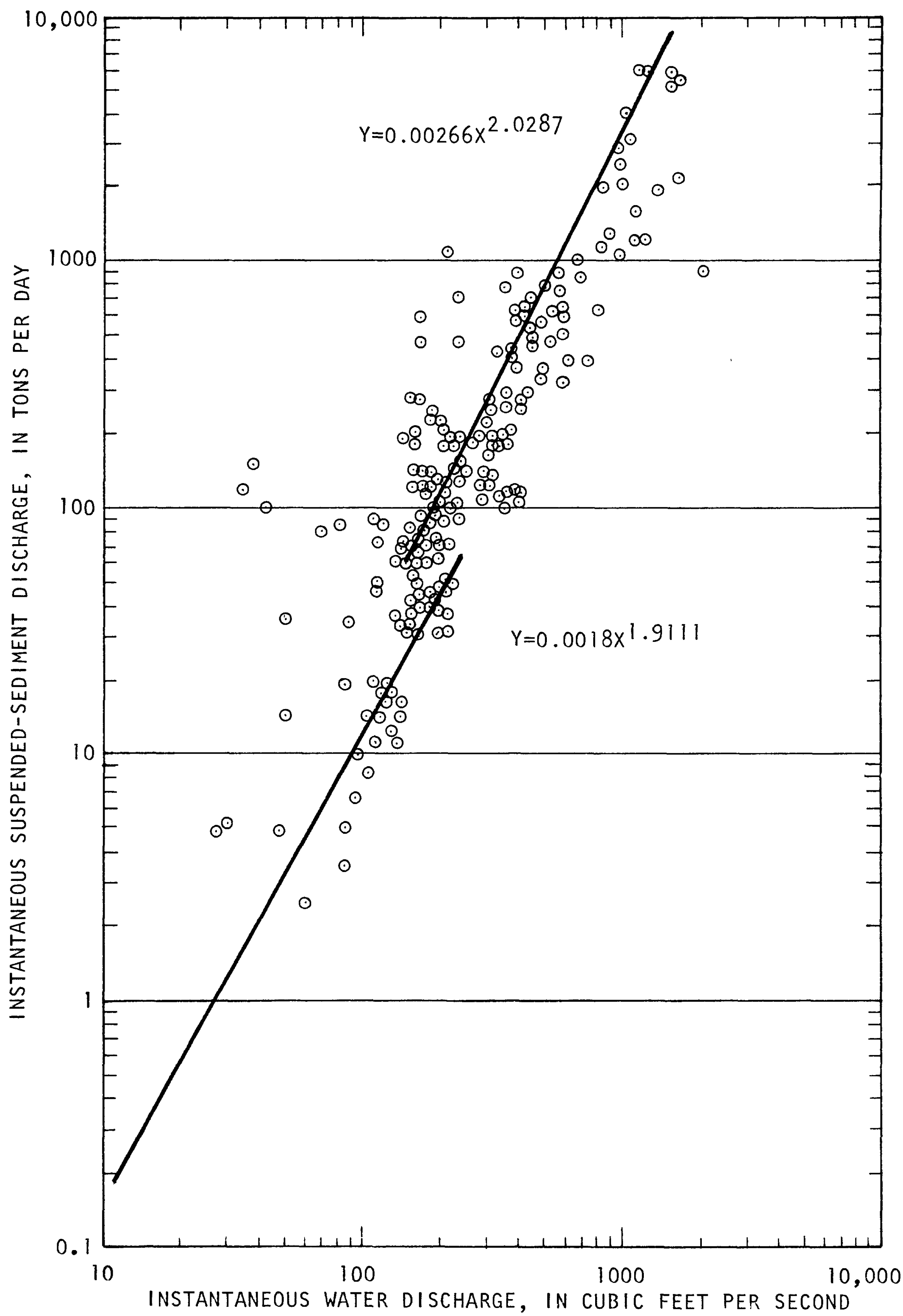

Figure 8. Instantaneous suspended-sediment transport curve for station 16228200.

The flow-duration curve (fig. 9) has been modified, as in Jones and others (1971), to account for higher flows of short duration, less than one day. The high-flow portion of the curve represents the flows that transport the bulk of the sediment, and the smallest increment of time represented on the curve is one day. As indicated by the hydrographs presented earlier (figs. 3 and 7), and the 1971 study, flood peaks in Oahu streams usually persist for two hours or less. The mean annual flood, therefore, with a recurrence interval of two years, approximates the 0.01- percent frequency on the duration curve because 2/(2 X 365 X 24) = 0.011 percent. To extend the flow-duration curve for Moanalua Stream, the mean annual flood (1,360 ft^3/s determined by the log-Pearson Type III method) is plotted as the 0.01 percentile on the duration curve, and a dashed line drawn from that point tangent to the curve.

To calculate the mean annual water discharge (4,122 acre-ft/yr), the mean flow for each range of water discharge is multiplied by the corresponding percentage of time that the flow occurs (table 11 cols. 2 x 4). The sum of these products is multiplied by 365.25 and a unit conversion factor (1.9835).

To obtain the basin mean annual suspended-sediment discharge (902 tons/yr), sediment discharge for the mid-point of each water-discharge range (table 11, col. 3) is read from the sediment transport curves and listed in column 5 of table 11. The mean annual suspended-sediment discharge, in tons per year for the period of record of the flow-duration curve, is determined by the sum of the products of the time interval and sediment discharge (table 11, columns 2 x 5) multiplied by 365.25.

The mean annual suspended-sediment yield, obtained by dividing 902 tons by the drainage area, 3.34 mi^2, is 270 $tons/mi^2/yr$.

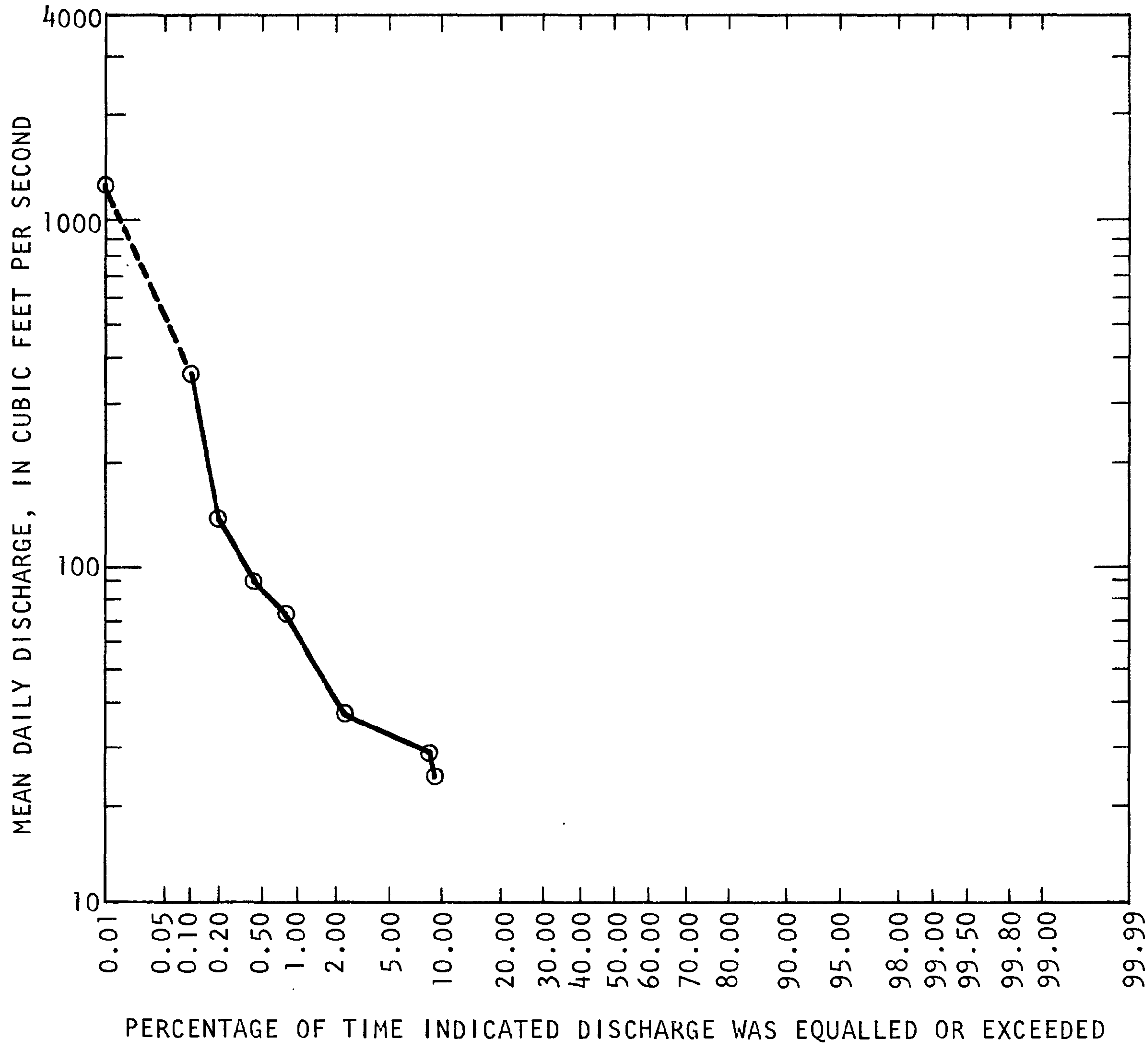

Figure 9. Flow-duration curve for Moanalua Stream at station 16228200 (October 1969 to September 1977).

Table 11. Estimate of mean annual suspended-sediment discharge for Moanalua Stream

Duration table of mean daily discharge at station 2282
and corresponding suspended-sediment discharge
for October 1969 to September 1977

Col. 1 percent limits	Col. 2 percent interval	Col. 3 percent mid. ord.	Col. 4 Q_w ft^3/s	Col. 5 Q_s tons/day	Q_w Cols. $\frac{2 \times 4}{100}$	Q_s Cols. $\frac{2 \times 5}{100}$
0.00-0.02	0.02	0.01	1,360	6,050	0.27	1.21
0.02-0.04	0.02	0.03	900	2,618	0.18	.52
0.04-0.06	0.02	0.05	500	795	0.10	.16
0.06-0.10	0.04	0.08	370	431	0.15	.17
0.10-0.20	0.10	0.15	210	137	0.21	.14
0.20-0.50	0.30	0.35	125	19	0.38	.06
0.50-1.00	0.5	0.75	72	6.5	0.36	.03
1.00-2.00	1.0	1.50	47	2.9	0.47	.03
2.00-5.00	3.0	3.50	35	1.6	1.05	.05
5-10	5.0	7.5	31	1.3	1.55	.07
10-15	5.0	12.5	19	0.5	0.95	.03
15-15.5	0.5	15.2	4	0.03	0.02	0
			Totals		5.69	2.47

Mean annual discharge for October 1969 to September 1977:
$Q_w = 5.69 \times 365.25 \times 1.9835 = 4{,}122$ acre-ft/yr

Mean annual suspended sediment discharge:
$Q_s = 2.47 \times 365.25 = 902$ tons/yr

Mean annual suspended sediment yield:
$902/3.34 = 270$ tons/mi^2/yr

Storm-Load Computation

Because most of the streamflow and sediment discharge occur as a result of individual events, suspended-sediment loads have been computed for several storms. A suspended-sediment concentration rating curve was prepared from instantaneous measurements of streamflow and suspended-sediment concentrations (fig. 10). This figure, along with the hydrographs and trends established by available instantaneous sediment samples, were used to estimate sediment concentrations when samples were not taken (the dashed lines on figures 11 to 13).

For a storm-load computation, instantaneous measurements of streamflow and the calculated suspended-sediment discharge are integrated to yield an estimate of the daily suspended-sediment discharge by:

Instantaneous streamflow (ft^3/s)
X Instantaneous suspended-sediment concentration (mg/L)
X 0.0001125 = tons/hr.

The storm load is the sum of the hourly sediment loads.

Figure 11 is a plot of the hydrograph and sediment concentration curve for a storm on April 19, 1974. Concentration estimates for periods with no sediment data were made from figure 10 and an analysis of the hysteresis effect indicated by portions of other storm graphs when there is adequate data. The calculated suspended-sediment storm load is 975 tons for April 19. This represents 108 percent of the computed mean annual suspended-sediment discharge. This was a 5-year flood, and that it transported, in a single day, more than the total mean annual suspended-sediment discharge is characteristic of small undeveloped Hawaiian watersheds; that is, most of the annual sediment load is transported by a few large storms.

Figure 12 is a plot of the hydrograph and sediment concentration for a storm on November 21, 1974. Several periods were estimated using figure 10. The calculated suspended storm load, 583 tons, represents 65 percent of the mean annual suspended-sediment discharge.

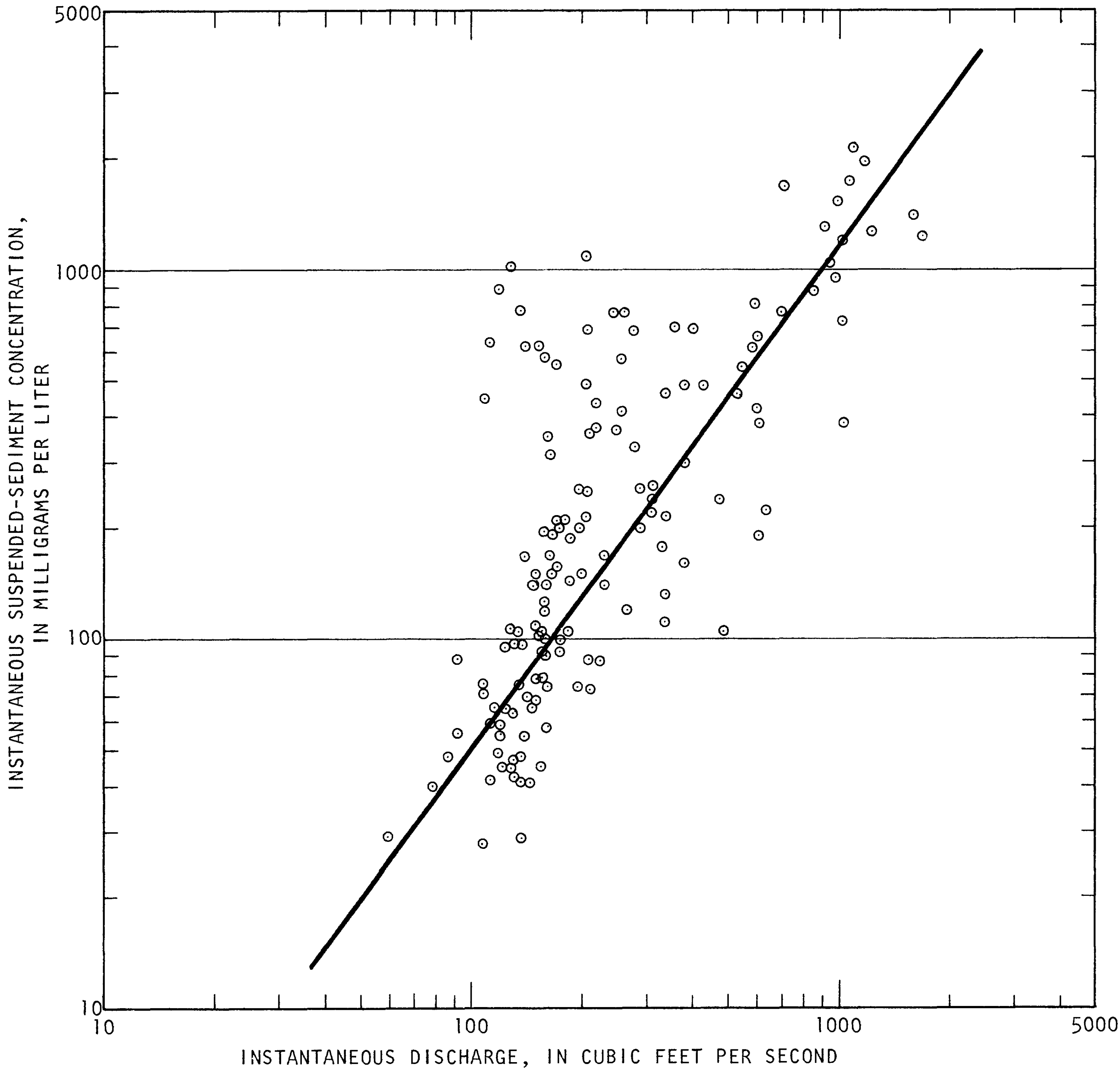

Figure 10. Instantaneous sediment-concentration rating curve for station 16228200.

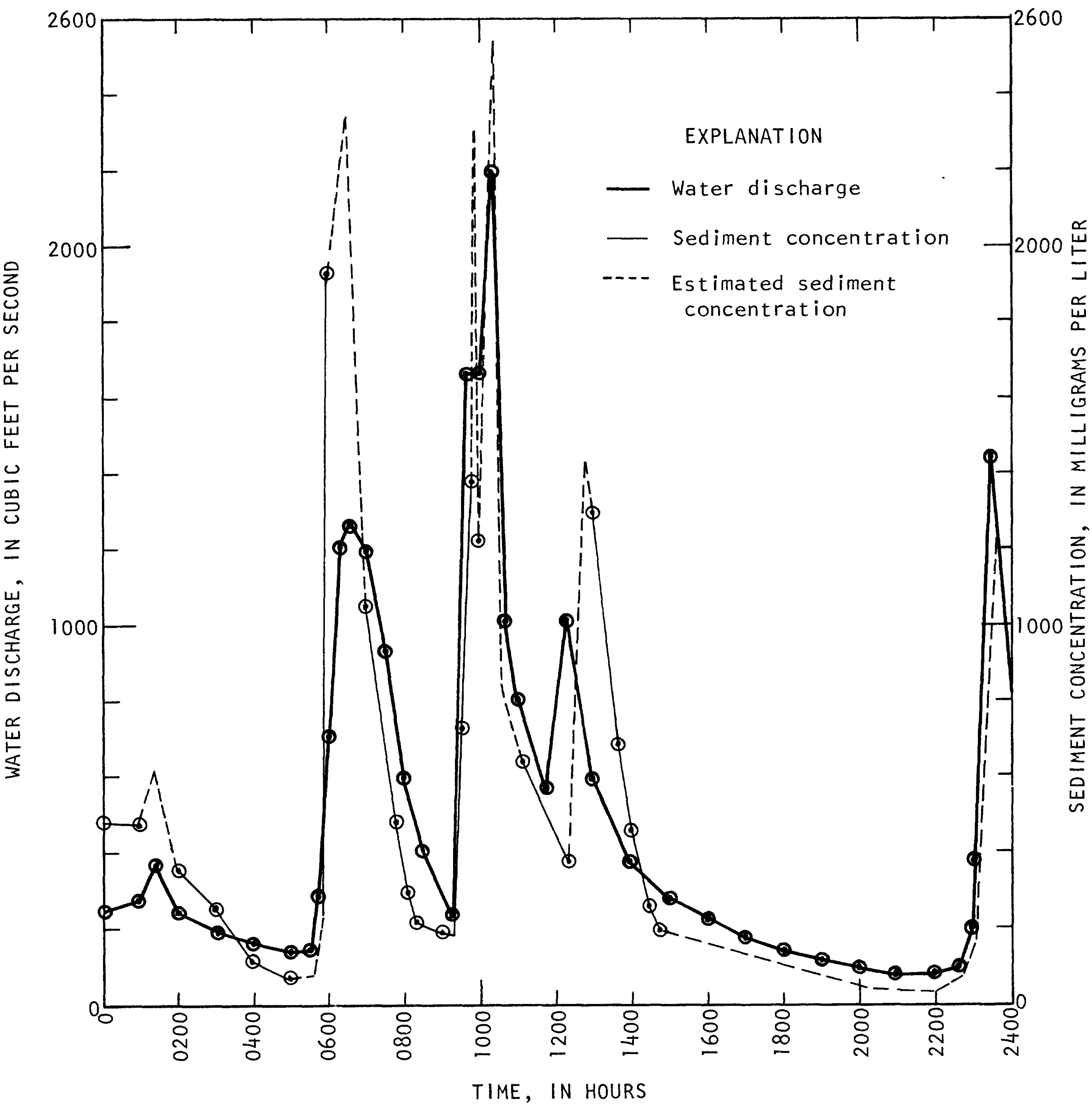

Figure 11. Water discharge and suspended-sediment concentration for April 19, 1974 at station 16228200.

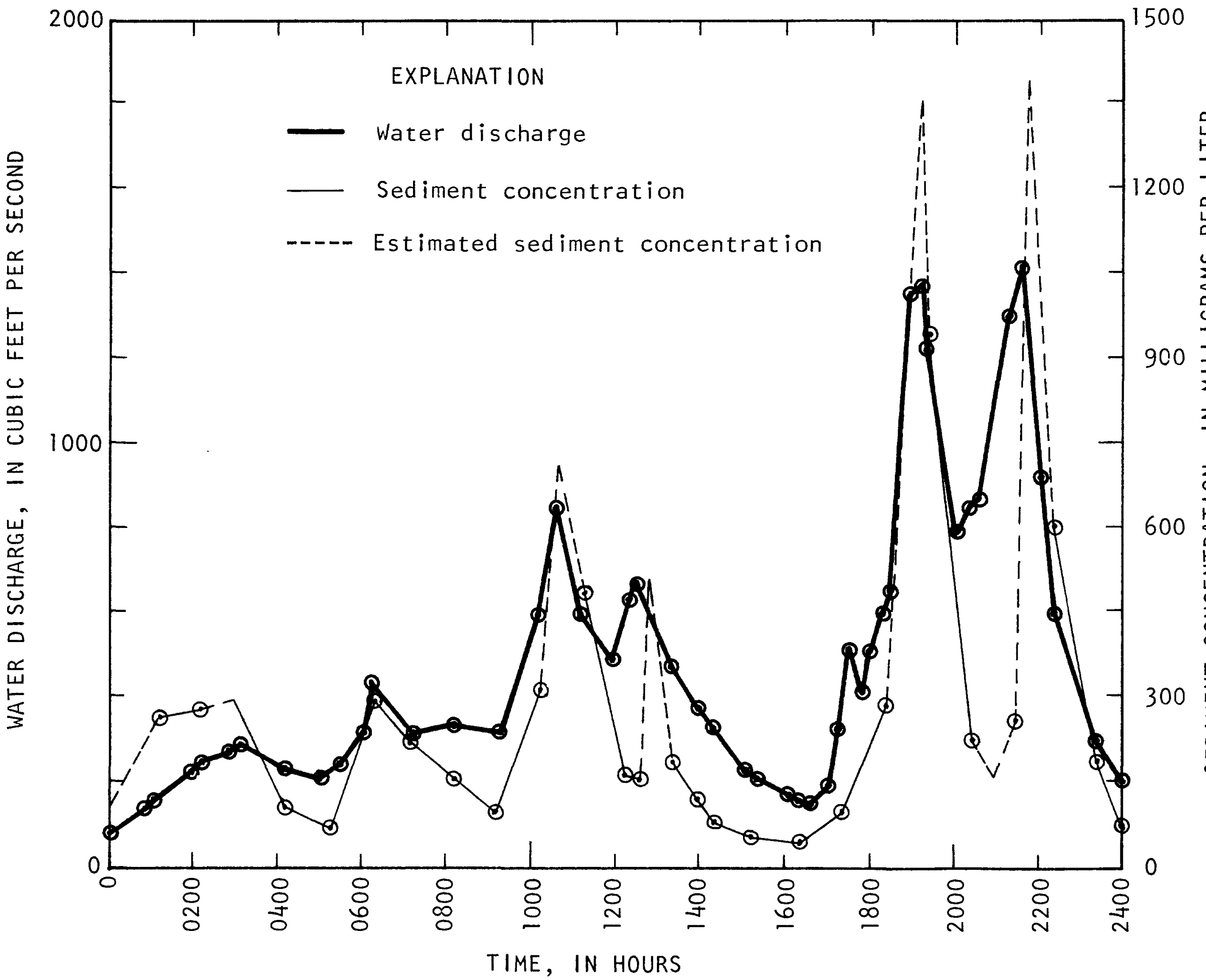

Figure 12. Water discharge and suspended-sediment concentration for November 21, 1974 at station 16228200.

Figure 13 is a plot of the streamflow and suspended-sediment concentration for January 20-21, 1982. Maximum rainfall intensities were at least 1.0 in./hr at all rain gage locations. The graph indicates the typical effect of high-intensity short-duration rainfall on stream discharge and sediment concentration for a small-drainage-basin stream having low or no base flow. The concentration rises rapidly and peaks at or slightly after the discharge peak, and generally decreases faster than the recession in water discharge. The duration of the concentration peak is usually less than that of the water-discharge peak and the concentration does not increase prior to the increase in water discharge.

There are a few short intervals with no concentration data. Concentrations for these periods were estimated from figure 10 and trends established by the sediment concentration samples and hydrograph. The calculated storm load, 586 tons, is 65 percent of the mean annual suspended-sediment discharge.

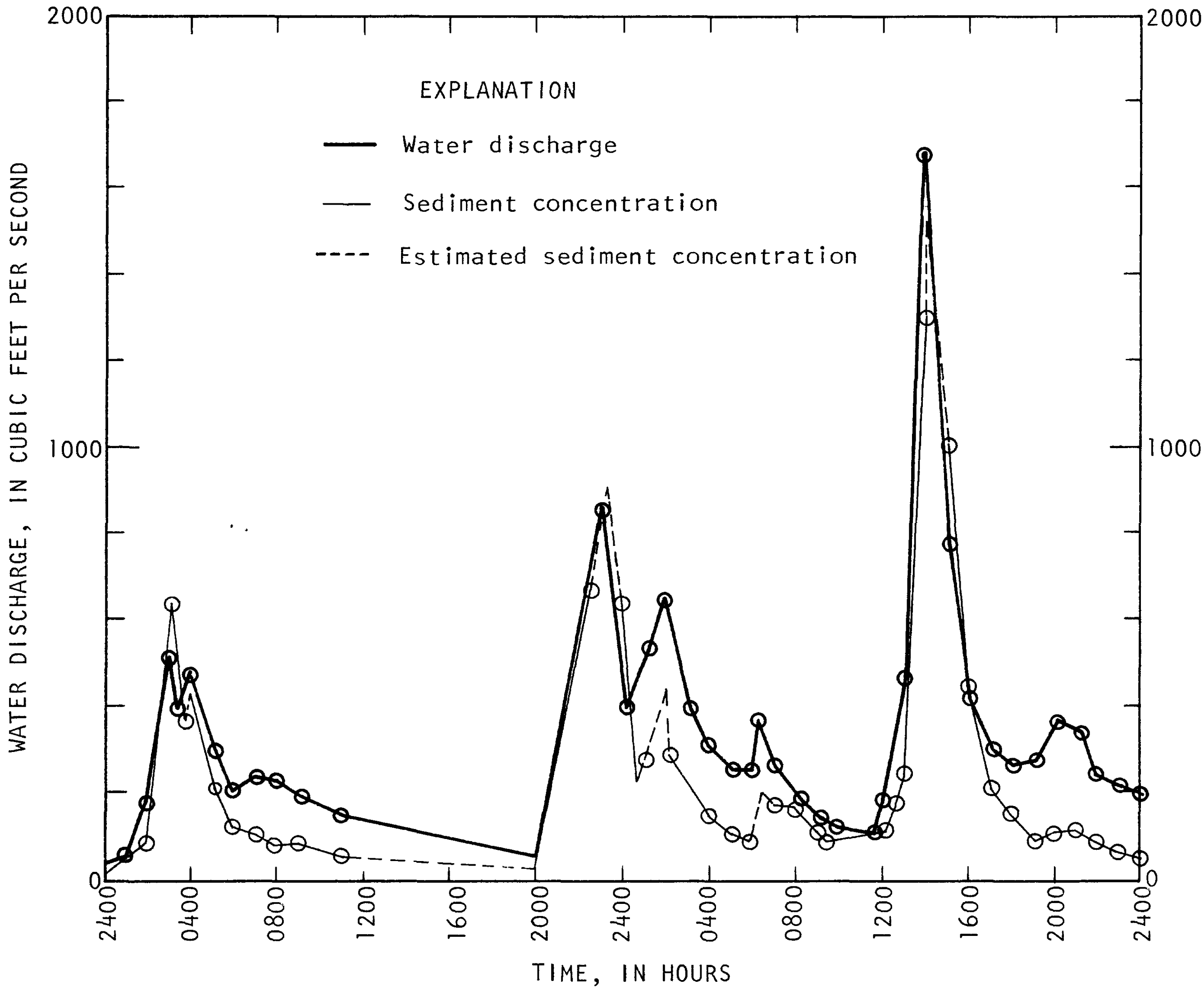

Figure 13. Water discharge and suspended-sediment concentration for January 20-21, 1982 at station 16228200.

Bedload Computation

Bedload is that part of the sediment load that moves by rolling, slipping, or sliding along the streambed. Bedload consists predominantly of coarse (sand size or larger) particles, mostly having fall diameters greater than .062 mm. In Moanalua Stream, bedload is largely composed of material in the channel and on the banks of the stream. Table 12 indicates that seventy-five percent of this material is in a size range greater than 64 mm (Jones and Ewart, 1973).

The rate of bedload discharge is predominantly a function of the size, shape, and specific gravity of the sediment and flow hydraulics. In contrast to suspended-sediment discharge, a stream transports as much coarse sediment as it is able to for a given flow condition.

Two methods are used to estimate mean annual bedload discharge. Jones and Ewart (1973) used the Schoklitsch equation to compute bedload discharge and develop a bedload-transport curve (fig. 14) at station 2280, approximately 3/4 mile upstream of the basin outlet. Due to (1) the lack of bed material samples at station 2282, (2) the location of station 2282 downstream of the debris basin, and (3) the concrete-lined channel at station 2282, it is believed that the bedload-transport curve developed at station 2280 best represents the bedload-transport conditions in the basin. To offset the likely underestimate of bedload transport for the basin by performing calculations at station 2280, 3/4 mile upstream of the basin outlet, the transport curve was applied to the flow-duration curve for the basin-outlet station 2282 following the same procedure used to calculate mean annual suspended-sediment discharge. The mean annual bedload discharge at station 2282 is 2,615 tons/year (table 13).

The other method used to estimate bedload discharge was to calculate the accumulated volume of material at the debris basin just upstream from station 2282. From visual inspection and according to the engineers, sediment specialist, and hydrologists involved with the dam's construction, a conservative estimate of trap efficiency of the debris basin is 80 percent. The basin does not function as a settling basin. However, due to the nature of the rocks and the products of weathering in Moanalua, the sand-size component of the bed-material load is thought to be negligible.

Table 12. Size distribution of bed material in Moanalua Stream

Volumetric composite of seven vertical photographs, as determined by particle counts.[1/]

Size range (mm)	Mean diameter (mm)	Percent in range, by volume	Cumulative percent
0 - 8	4	2.9	2.9
8 - 11	10	.1	3.0
11 - 16	14	.9	3.9
16 - 23	19	2.3	6.2
23 - 32	27	3.2	9.4
32 - 45	39	5.6	15.0
45 - 64	55	9.6	24.6
64 - 90	77	15.3	39.9
90 - 128	109	20.6	60.5
128 - 181	155	16.6	77.1
181 - 256	219	6.0	83.1
256 - 362	309	16.9	100.0

1/ From Jones and Ewart, 1973.

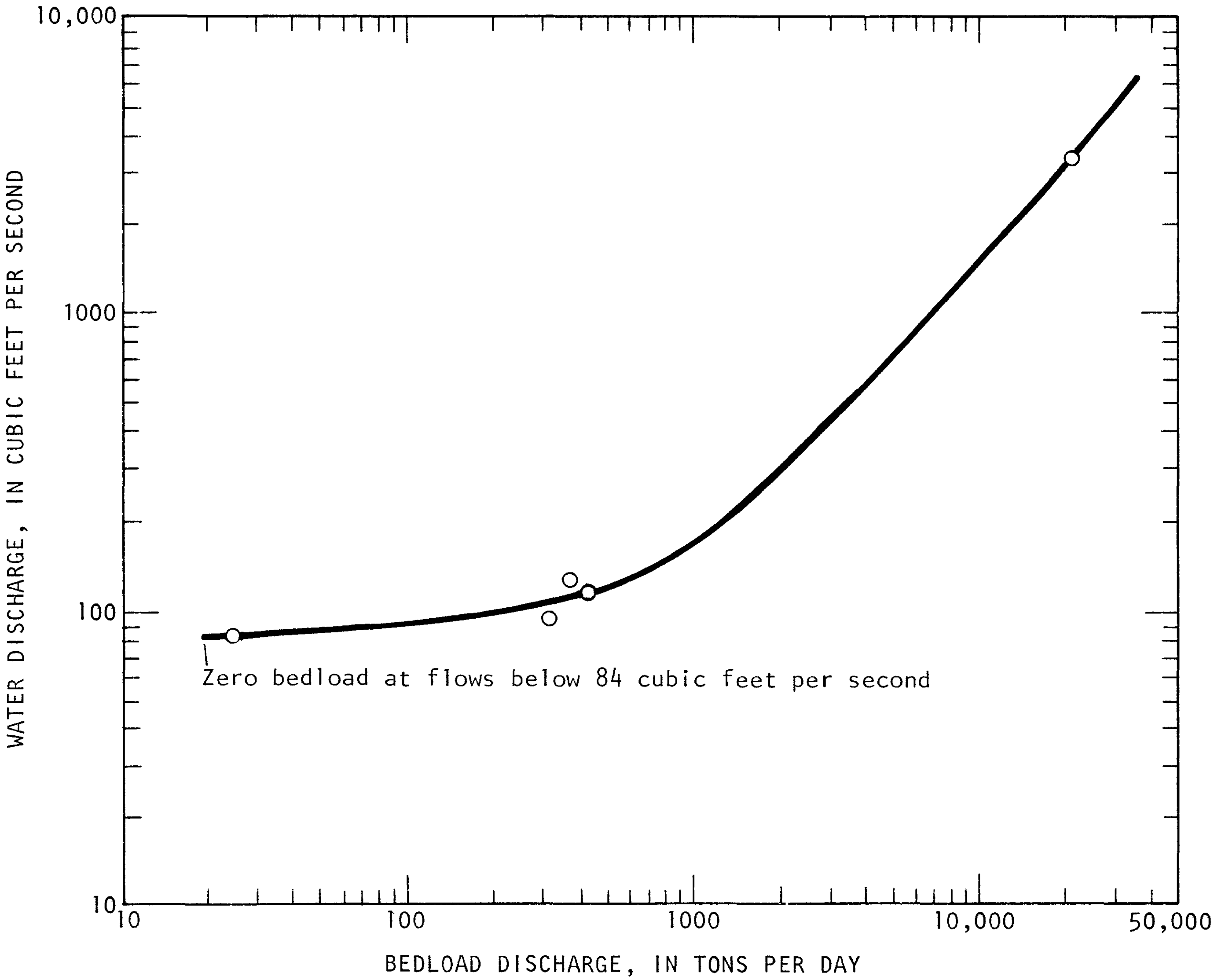

Figure 14. Bedload-transport curve, computed from discharge measurements at station 16228000 and the Schoklitsch (1934) equation.[1]

[1] From Jones and Ewart, 1973.

Table 13. Estimate of mean annual bedload discharge for Moanalua Stream

Duration table of mean daily discharge at station 2282 and corresponding bedload discharge at station 2280

Col. 1 percent limits	Col. 2 percent interval	Col. 3 percent mid. ord.	Col. 4 Q_w ft^3/s	Col. 5 Q_s tons/day	Q_w Cols. $\frac{2 \times 4}{100}$	Q_s Cols. $\frac{2 \times 5}{100}$
0.00-0.02	0.02	0.01	1,360	8,500	0.27	1.70
0.02-0.04	0.02	0.03	900	6,300	0.18	1.26
0.04-0.06	0.02	0.05	500	3,500	0.10	.70
0.06-0.10	0.04	0.08	370	2,500	0.15	1.0
0.10-0.20	0.10	0.15	210	1,300	0.21	1.3
0.20-0.50	0.30	0.35	125	400	0.38	1.2
0.50-1.00	0.5	0.75	72	0	0.36	0
1.00-2.00	1.0	1.50	47	0	0.47	0
2.00-5.00	3.0	3.50	35	0	1.05	0
5-10	5.0	7.5	31	0	1.55	0
10-15	5.0	12.5	19	0	0.95	0
15-15.5	0.5	15.2	4	0	0.02	0
			Totals		5.69	7.16

Mean annual bedload discharge:
Q_b = 7.16 x 365.25 = 2,615 tons/yr

Mean annual bedload yield:
2,615/3.34 = 783 tons/mi^2/yr

Five level surveys of the basin were conducted between October 1969 and April 1980. Each cross section was plotted and the area under the curve calculated by Simpson's one-third rule method (Davis and Foote, 1953). The net change in volume between surveys is added to yield the total volume of material for the period (table 14).

The results of the last survey (December 1975 to April 1980) show an accumulated net volume for approximately a 4-1/2-year period. December 1975 through December 1979 was a fairly dry period during which no significant storms occurred. Yet, the calculated accumulated net volume of fill is almost four times that of the previous survey which spanned 2-1/3 years. This accumulation of coarse sediment is thought to be due, in large part, to the floods in January (peak flow of 2,300 ft^3/s) and March (peak flow of 4,864 ft^3/s) 1980, the latter being a 50-year flood. The mean annual bedload discharge from the debris basin method for October 1969 through April 1980 (10.6 years) is 13,450 ft^3 or 740 tons.

The results calculated from the Schoklitsch equation and the debris basin surveys establishes a range of mean annual bedload discharge from 740 to 2,615 tons/yr. Combined with the mean annual suspended-sediment discharge (902 tons), the total mean annual discharge ranges from 1,642 to 3,517 tons/year. The estimated total mean annual sediment yield ranges from 492 to 1,053 $tons/mi^2/yr$. These values are reasonable in comparison with the estimated yields for other leeward streams on Oahu (Jones and others, 1971).

Table 14. Results of debris basin surveys

Period	Cumulative volume of fill (ft^3)	Volume of fill for individual period (ft^3)	Weight of fill[1/] for individual period (tons)
10/2/69-8/7/70	34,000	34,000	1,870
8/8/70-7/26/71	48,000	14,000	770
7/27/71-8/9/73	54,300	6,300	350
8/10/73-12/3/75	66,900	12,600	690
12/4/75-4/30/80	114,060[2/]	47,160	2,594

1/ The weight of fill is calculated assuming a deposited unit weight of 110 $pounds/ft^3$ as in Jones and Ewart (1973).

2/ It is assumed that 114,060 ft^3 represents 80 percent of the total bed material volume.

CONCLUSIONS

This study was made to describe the hydrologic and sedimentation characteristics of Moanalua Valley, a small leeward undeveloped basin on the Island of Oahu, Hawaii. The major portion of the study was devoted to the analysis of the rainfall-runoff relationship by the application of a distributed routing model which was calibrated and verified for the basin. Sources of error have been discussed to explain the differences in simulated and observed hydrographs. The successful application of the DSA model to Moanalua Valley indicates its applicability to a sub-tropical watershed and transferability potential. The DSA model is a valuable engineering tool. It can be used to predict hydrographs resulting from a wide range of rainfall durations and intensities anywhere along a stream channel.

Model results indicate that on an event basis, the average rainfall lost to runoff is 35 percent. A basin water balance indicates an average of 7 Mgal/d recharging the ground-water supply.

The analysis of the available sediment data resulted in estimates of suspended-sediment yields for a subbasin, and the entire watershed. Together with estimates of bedload, the mean annual sediment yield for Moanalua basin ranges between 492 and 1,053 tons/mi^2/yr. This estimate compares favorably with calculated yields for other leeward Oahu basins.

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