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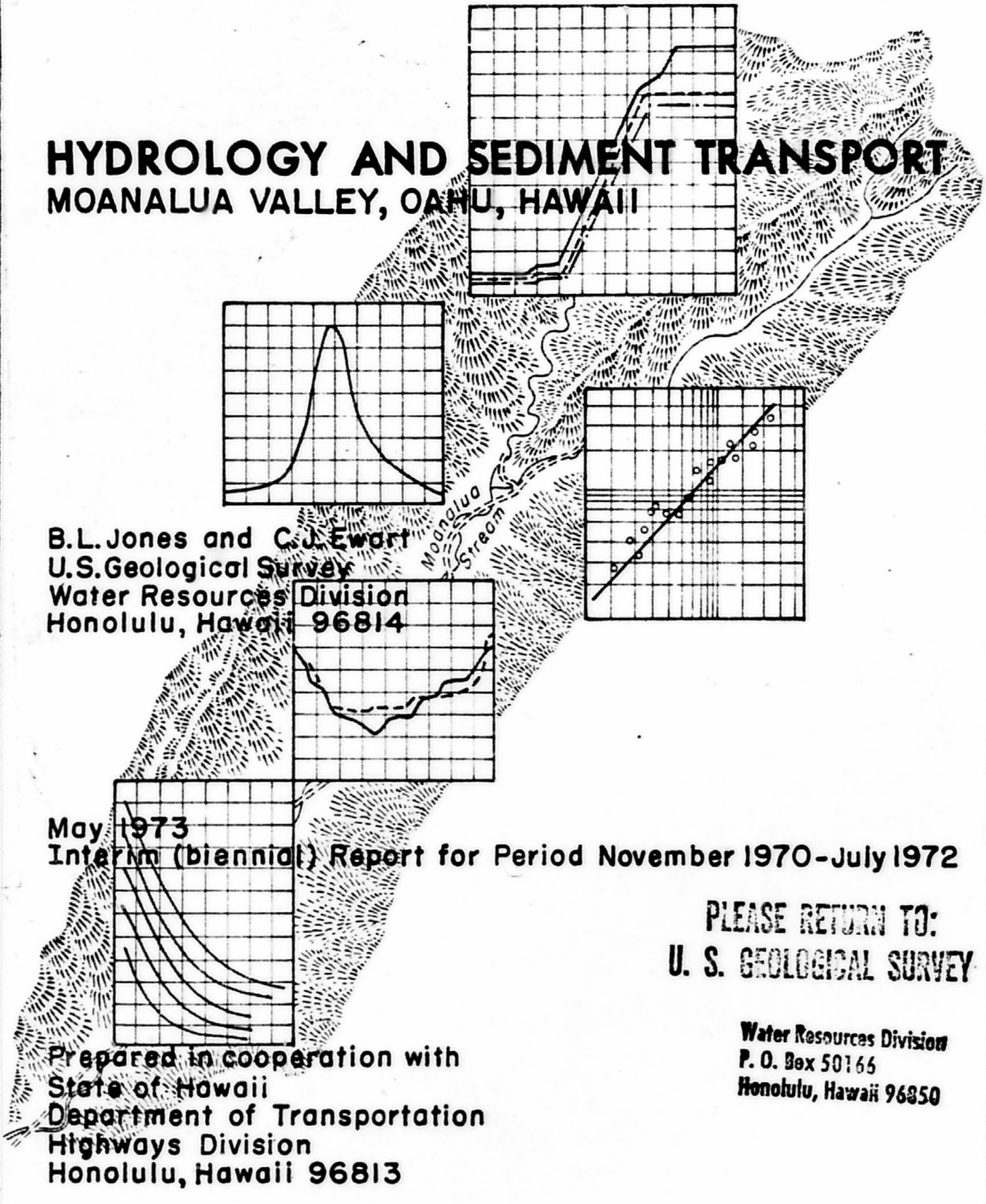
HYDROLOGY AND SEDIMENT TRANSPORT
MOANALUA VALLEY, OAHU, HAWAII



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May 1973
Interim (biennial) Report for Period November 1970-July 1972

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Cover design--James Y. Nitta

SUMMARY STATEMENT OF RESEARCH IMPLEMENTATION

The hydrologic investigations in Moanalua Valley are significant in both the distant and immediate future.

1. This will be the first such detailed study of a tropical watershed before, during, and after a major construction project. What is learned will have direct application to the planning of future projects.

2. During construction, the instrument network will be used to monitor the effects of activities, so that additional control measures can be taken, if needed.

3. The background data, which are the subject of this interim report, will be of immediate use in the final design of the project.

From the beginning, arrangements were made to provide data on a real-time basis to the Department of Transportation and to the consulting engineers.

Examples of information made available from the project files and summarized in this report include:

<u>Channel dimensions and configuration</u>.--The channel morphology of Moanalua Stream is the result of a long geologic process, in which the stream has reached a state of dynamic equilibrium with its surroundings. Knowledge of the dimensions will influence the design where stream realinement is necessary.

Debris production.--Observations of the sizes and quantities of material transported will influence both the location of debris-retention structures and the selection of material for channel stabilization.

Landslide processes.--The study has already indicated where large landslides have occurred in the past. This information will have a bearing on the final alinement, the protection of slopes, the selection of cut and fill sites, and foundation investigations.

Hydrology and hydraulics.--The detailed data collected thus far on rainfall and runoff have given a clearer picture of the hydrology of the basin as related to storms. Preliminary analyses of the data have resulted in an estimate of the 50-year flood, which can be used in the selection of the design flood. Hydrographs and rainfall mass curves from storms monitored during the report period can be used in the designing of drainage elements and location of possible retention structures.

Preliminary results on the attempt to use rainfall-runoff modeling techniques with the data collected thus far have been encouraging. In addition to the planned use of the model to establish the "before" hydrologic conditions, the model, in combination with a channel routing scheme, could be used to estimate the natural response of the basin subjected to the design storm.

The data gathered on future storms will be furnished to the Department of Transportation and the consulting engineers as soon as possible after the storm.

CONTENTS

ILLUSTRATIONS

Page.

TABLES

APPENDICES

HYDROLOGY AND SEDIMENT TRANSPORT, MOANALUA VALLEY, OAHU

FIRST BIENNIAL REPORT

By B. L. Jones and C. J. Ewart

ABSTRACT

The first 2 years of intensive data collection in Moanalua Valley have resulted in some observations concerning the rainfall-runoff and rainfall-sedimentation characteristics of the basin.

This initial study period has been concerned primarily with establishing a reliable hydrologic data-collection network. However, enough data have been collected to determine that rainfall within the valley shows extreme areal variations from one storm to another. An initial run on the U.S. Geological Survey small watershed model indicates some differences in basin characteristics in the two upper subregions. Results of model studies to date are encouraging. Flood routing with the Corps of Engineers' HEC-1 flood hydrograph package seems to be feasible. By preliminary estimates, the 50-year flood at gage 2282 would probably be between 5,500 and 6,000 cubic feet per second.

The narrow, steep nature of Moanalua Valley results in very rapid concentration of runoff, with extremely sharp hydrograph peaks. Stream channel width ranges from about 20 feet in the headwaters to 35 feet near the downstream limit of the study area. Mean slope of the main stem is about 0.027 foot/foot.[1/]

[1/] Where not identified, units for slope are ft/ft.

Observations indicate that the stream transports very large particles (in excess of 2 feet in diameter) quite frequently. Detached fragments from old stone-arch bridges have been marked in the channel fill for use as tracers.

Only one storm has been analyzed for suspended-sediment discharge, but rough calculations indicate a possible suspended-sediment load of 12,000 tons for a storm similar to the design flow at gage 2282. This compares with a computed bedload discharge of 2,600 tons for the same flow.

Accumulation in the debris basin between October 2, 1969 and July 26, 1971, as measured by level survey, was 48,000 cubic feet or about 2,900 tons.

INTRODUCTION

In November 1970, the State of Hawaii, Department of Transportation entered into a cooperative agreement with the U.S. Geological Survey to study the hydrology and sedimentation characteristics of Moanalua Valley, Oahu. The primary purpose of this study is the analysis of rainfall-runoff and rainfall-sedimentation relations in a tropical watershed. During the 10-year study period, a major highway, H-3, is scheduled to be constructed the length of the upper valley. The highway will affect the stream and some of the valley slopes. An additional aim of the study is to determine the long-term impact of the highway on the basin hydrology. Data on runoff, sedimentation, and water quality will be collected before, during, and after highway construction. Hydrologic data and interpretations resulting from this study will be valuable for design of future projects in Hawaii-type environments.

This report is the first of a series of progress reports on the Moanalua Valley investigation. Additional reports are scheduled at about 2-year intervals for the life of the project. Table 1 is a brief summary of project status and aims.

The investigation is being conducted by personnel of the U.S. Geological Survey, under the direction of W. L. Burnham, district chief in charge of water-resources investigations, Honolulu.

Table 1. Status of Moanalua Project - July 1972

Work Elements Completed

Element	Coverage	Remarks
Project design	Definition of study objectives, scope, and techniques. Design of data collection network. Work plan-personnel assignments, cost estimates. Administration, funding details.	All elements firmly defined.
Data collection	Rainfall. Runoff. Suspended sediment. Evaporation.	Network installed and operational.
	Bedload.	Analysis of bed material-marked particles.
	Channel and debris basin surveys.	Ranges established-resurveyed.
Data analysis	Model studies.	Trial runs with U.S. Geological Survey model and HEC-1 flood package.
Progress report	November 1970 - July 1972.	Completed.

Table 1. Status of Moanalua Project - July 1972 (continued)

Work Elements in Progress

Element	Coverage	Remarks
Data collection	Network operation.	Routine maintenance and flood coverage, publication of basic data.[1]
	Channel studies.	Continuing surveys of channel and debris basin, observation of marked particles.[1]
	Watershed studies.	Data being collected on soils, slopes, landslides, vegetative cover, geology.[2]
Data analysis	Runoff studies.	More runs on U.S. Geological Survey model to firm up calibration. Parameter sensitivity tests. Selection of channel routing procedure. Investigation of HEC-1 flood package.[2]
	Sediment studies.	Analysis of results from bedload equation - comparison with observed movement and debris basin accumulations.[1]
	Watershed studies.	Analysis of aerial photographs - observations of changes. Field determination of areal extent of landslides.[1]

1/ Continuing basis for duration of project.

2/ Target date, July 1974.

Table 1. Status of Moanalua Project - July 1972 (continued)

Work Elements Planned

Element	Coverage	Remarks
Data collection	Network operation.	Continue operation, with emphasis on obtaining as many direct measurements as possible. Publish basic data in annual State report.1/
	Channel studies.	Expand cross-section network as needed. Establish survey reaches for study of dimensions and sediment movement. Systematically sample bed material to determine downstream changes in size, shape and specific gravity. Devise methods of obtaining bottom velocities if possible. Improve particle marking and tracing techniques.1/
	Hydrologic studies.	Conduct study of small tributary drainage area. Make series of seepage runs.2/
	Watershed studies.	Establish a system of documenting changes during study period with emphasis on slides and construction activities.1/

1/ Continuing basis for duration of project.

2/ Target date, December 1973.

Table 1. Status of Moanalua Project - July 1972 (continued)

Work Elements Planned (continued)

Element	Coverage	Remarks
Data analysis	Hydrology.	Construct stream-system model using U.S. Geological Survey rainfall-runoff component and adding routing and local inflow or use HEC-1 flood package. Investigate transferability of simulation results.2/
	Sedimentation.	Use bedload equations, adjusted to channel and debris-basin surveys to determine the significance of bedload transport. Use suspended sediment concentration as an input to U.S. Geological Survey model to determine significance of watershed hydrology in sediment transport. Analyze sediment data for trends during study period.1/
	Watershed studies.	Compare changing nature of watershed with hydrologic and sediment data. Attempt to determine general models of the relationships. Compare with similar results obtained elsewhere.1/
	Reporting procedure.	Biennial progress reports and final summary report.1/

1/ Continuing basis for duration of project.

2/ Target date, July 1974.

The data collection, servicing, maintenance, and operational capabilities are under the general supervision of the Honolulu subdistrict chief, Salwyn Chinn. The present reliability of the network has been achieved, in large part, through the conscientious efforts of Harold Sexton of the Honolulu subdistrict.

PHYSICAL SETTING

Moanalua Stream occupies a valley on the leeward slopes of the Koolau Range. The basin is narrow and steep, even by Oahu standards (fig. 1). In the lower reaches, the channel slopes are from 0.01 to 0.05, and in the headwaters slopes exceed 0.20. The stream is sinuous and deeply incised around the toes of alternating side slope ridges.

In the past two decades, a reach of approximately 1½ miles along Moanalua Valley upstream from Moanalua Road has been progressively urbanized. Single-unit dwellings dominate the valley floor and part of the lower slopes. The urban boundary is at the end of Ala Aolani Street. The stream channel is lined from this point to a debris dam approximately 450 feet upstream; and the lining continues downstream about 3,600 feet.

Above the urban boundary, the access road originally crossed the stream on stone-arch bridges, but many of these have deteriorated to an unusable condition. The present road, providing access for crews repairing power lines, crosses paved fords.

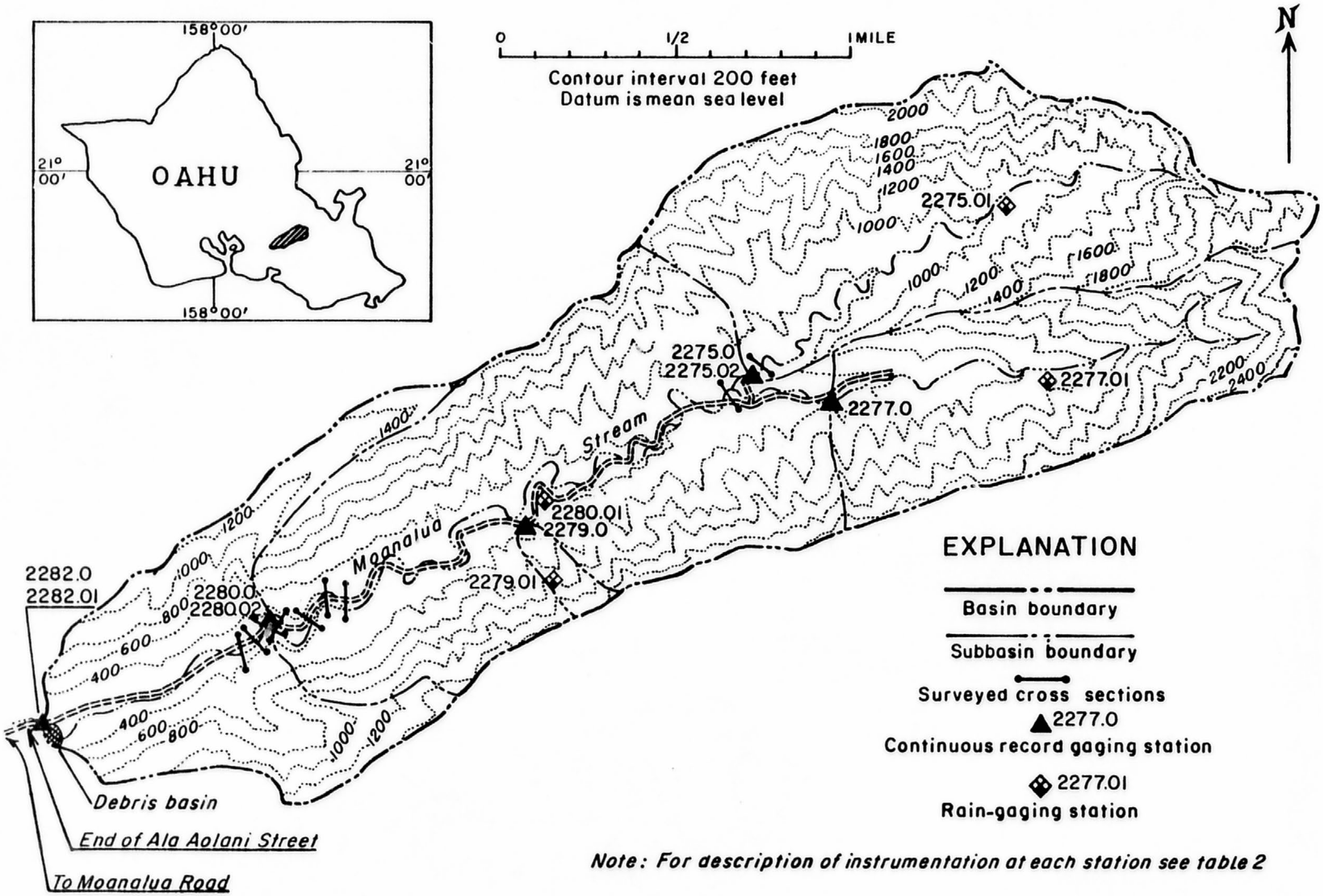

Figure 1. Map of Moanalua Valley showing subbasin boundaries and gaging-station locations.

In the last 100 years, the valley has been largely deforested, and vegetation now includes many introduced species. The first mile of the valley floor, above the urban boundary, is covered with a growth of grass, koa haole, and other shrubs and plants. Lamoureux (1972), has made a detailed survey of the flora and vegetation along the proposed route of Interstate H-3.

HYDROLOGIC DATA NETWORK

The study area proper is the part of Moanalua Valley upstream from the urban boundary, an area of approximately 3.5 square miles (fig. 1). Within this area, instrumentation includes seven rain gages, five stream gages, three automatic-sediment samplers, and one evaporation gage (table 2). Deposition in the debris basin is measured by spirit-level surveys, and similar surveys are made of numerous cross-sections along the stream channel. Debris movement also is monitored by tracing the downstream progress of marked particles in the streambed.

Suspended-sediment concentration is monitored during significant storm events at the three locations listed in table 2. Samples also are collected intermittently at each of the stream-gaging sites. Because suspended-sediment discharge is closely related to such watershed factors as soils, slope, and cover conditions, any changes in suspended-sediment discharge will indicate the degree to which construction activities affect the watershed. Further, comparison of suspended-sediment discharge rates before, during, and after construction can give valuable information as to the manner in which a tropical watershed recovers after a disturbance.

Table 2. Type of data collected, and instrumentation in Moanalua Valley

Station no.	Type of data collected	Instrumentation 1/	Period of record
16-2275.0 D.A.=0.94 sq.mi.	Streamflow, evaporation, suspended sediment and rainfall.	Fischer-Porter digital recorder with 5-minute punch interval, USPS-67 automatic sediment sampler, evaporation pan and water-supply system, and Leupold and Stevens Type "F" recorder.	October 1968 to present 2/.
16-2275.01	Rainfall (intensity and duration).	Fischer-Porter digital recorder with 5-minute punch interval.	October 1968 to present.
16-2275.02	do.	do.	Do.
16-2277.0 D.A.=0.62 sq.mi.	Streamflow.	do.	Do.
16-2277.01	Rainfall (intensity and duration).	do.	Do.
16-2279.0 D.A.=0.03 sq.mi.	Streamflow and suspended sediment.	Stevens A-35 continuous recorder and Jones automatic sediment sampler.	April 1972 to present.

1/ The use of brand names in this report is for identification only and does not imply endorsement by the U.S. Geological Survey.

2/ To July 31, 1972.

Table 2. Type of data collected, and instrumentation in Moanalua Valley (cont.)

Station no.	Type of data collected	Instrumentation	Period of record
16-2279.01	Rainfall (intensity and duration).	Fischer-Porter digital recorder with 5-minute punch interval.	April 1972 to present.
16-2280.0 D.A. = 2.73 sq. mi.	Streamflow, rainfall (intensity and duration)	Fischer-Porter digital recorder with 5-minute punch interval tipping-bucket rain-gage attachment, and Stevens A-35 continuous recorder.	June 1926 to present.
16-2280.01	Rainfall (intensity and duration).	Fischer-Porter digital recorder with 5-minute punch interval.	October 1968 to present.
16-2282.0 D.A. = 3.34 sq. mi.	Streamflow and suspended sediment.	Fischer-Porter digital recorder with 5-minute punch interval and a binary decimal transmitter, USPS-67 automatic sediment sampler.	Do.
16-2282.01	Rainfall (intensity and duration).	Fischer-Porter digital recorder with 5-minute punch interval.	Do.

In general, the gaging stations most affected by highway construction should be 2282[2], 2280, and 2275, in that order. Gage 2277 should be affected for a short time, during construction of a small flood-control dam. The gage on the unnamed tributary (2279) is expected to measure streamflow and sediment loads unaffected by construction and will serve as an index of conditions on similar first-order tributaries draining the valley side slopes.

During the period covered by this report, the emphasis was on installation, modification, and calibration of the automatic sediment-sampling equipment. There has been a steady improvement in reliability of the sampling equipment and since March 1972, sample coverage of storms has been satisfactory. The data network is now considered to be fully operational on a systematic and routine basis.

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[2] To facilitate text reference to gages, the four-digit gage numbers, rather than names, will be used. In tables and figures, gages are referred to by both name and complete number, i.e.: 16-2280.01 identifies the part of the United States, (16), the gage number, (2280), and the rain gage, (01), at or near the gage site, Moanalua Stream near Honolulu.

DATA-COLLECTION METHODS

Streamflow

Streamflow is monitored continuously at five locations (fig. 1) within the study area. The physical apparatus for obtaining systematic records of streamflow consists of a suitable shelter, a stilling well, an intake system connecting the well to the stream, and a mechanism to record the water level in the stilling well. Because water level in the stilling well corresponds to that of the stream, a record is produced of stream stage. The stage, or gage height, is simply the height of the water surface above a datum (referred to mean sea level or arbitrary), which corresponds to the zero point of the gage.

Gage height is converted to discharge by means of a derived stage-discharge relationship or rating curve. A rating curve is usually developed by making a series of flow measurements and relating discharges to the gage heights observed during the times of the measurements. Stage-discharge relations for stations on natural stream channels may shift because of channel changes and ratings must continuously be reviewed and revised as more discharge measurements are made.

Four of the five streamflow stations in the project area are located on natural channels; the exception (station 2282) is located on a section of lined channel. The rating for this station has been computed theoretically and verified by measurements.

Because access to the valley often is impossible during storms and because high-water measuring facilities are lacking, the higher discharge part of the rating curve must be defined by indirect measurements.

The methods employed to determine peak discharge for this study are the slope-area method, computation of flow over weir (2280), and velocity-area studies. At the time of this report, four indirect measurements have been made at stations within the project area.

The recording mechanisms used at stations 2275, 2277, 2280, and 2282 are Fischer-Porter digital recorders, which record gage height as a series of punches in a 16-channel paper tape. A timer activates the punch cycle of the recorder at 5-minute intervals. At station 2282, a binary decimal transmitter has been connected to the stage recorder and to a telephone. When called from another telephone, the device transmits the gage height as a series of signals. The recording mechanism at station 2279 is a Stevens A-35 continuous recorder, which gives an expanded graphical record from which gage heights can be read for 5-minute intervals.

Rainfall

Rainfall is monitored continuously at seven locations (fig. 1) within the project area. Three of the rainfall stations (2275.02, 2280.02, 2282.01) are located at stream-gage locations and four are separate installations. At all sites, rainfall is intercepted by standard 8-inch Weather Bureau receivers and is routed to a calibrated storage tank. The water level in the storage tank is recorded at 5-minute intervals by a Fischer-Porter digital recorder. The recording process is exactly the same as described earlier for the streamflow stations.

Evaporation

A continuous record of evaporation is obtained at gaging station 2275 (fig. 1). An evaporation pan is situated on the roof of the gage shelter and a calibrated storage tank is located in the shelter. A pump raises the water from the storage tank to the pan and a Stevens Type F recorder monitors the water level in the storage tank. A float switch in the pan triggers the pump, which provides a fresh supply of water to the pan when evaporation lowers the water level. Rainfall also is measured at station 2275.

The major effort during the first 2 years of this study was, by necessity, devoted to the installation, elimination of problems, and modification of the existing hydrologic network. One of the major concerns in the operation of the network is that of proper timing. Because of the quick response of Hawaii's small, steep drainage basins to rainfall excess, and the high rainfall intensities associated with major storms, a small time interval was considered necessary to adequately define the rainfall-runoff relations for Moanalua Valley. Estimates of basin lag based on records of similar small basins in Hawaii indicated a time interval of about 5 minutes would be adequate. A number of different timing devices have been tried and tests on others are being carried out on a continuing basis. The existing network is now considered to be fully operational on a 5-minute recording-interval basis. The entire data network is serviced every 25 to 28 days and immediately after storms.

Suspended-Sediment Sampling

Suspended-sediment samples are collected at frequent intervals during periods of runoff to determine the sediment concentration. Sediment concentration and the flow at the time of sampling are used to compute the sediment discharge. The method is described briefly in the analytical section of this report and fully in Porterfield (1972).

Manual samples of suspended sediment are collected with standard samplers developed by the Federal Inter-Agency Sedimentation Project of the U.S. Inter-Agency Committee on Water Resources (1966). Figure 2 shows one of the samplers. Each sampler has a nozzle and a sample-container cavity. The sampler is hydrodynamically designed to admit a representative filament of the water-sediment mixture.

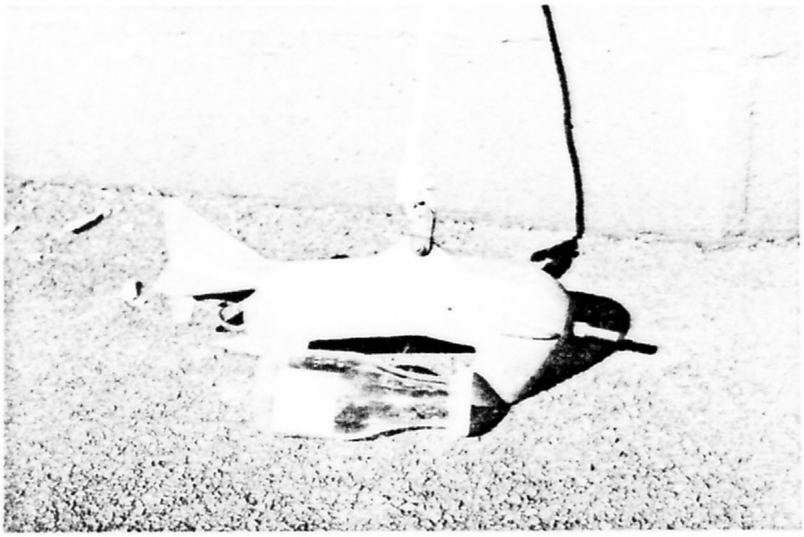

Figure 2. Suspended-sediment sampler,
U.S. DH-59 hand sampler.

Automatic sampling equipment is being used in Moanalua Valley, because access is difficult during flood periods, and because stream rises and recessions occur with great rapidity. The automatic samplers are basically systems for pumping discrete samples from the stream into a series of containers. One sampler of this type is illustrated in figure 3. Others are described in U.S. Inter-Agency Committee on Water Resources (1962) and by Guy and Norman (1970).

Samples are collected manually as frequently as possible to check and calibrate the automatic equipment.

Suspended-sediment samples also are analyzed to determine the particle-size distribution. Usually, a special sample must be collected because size analysis requires a larger volume of sediment than does concentration analysis. The collection techniques and equipment are the same for both types of samples.

Bed-Material Sampling

Material forming a streambed reflects the past history of the stream. The size, shape, and weight of particles also indicate the present hydraulic properties of the stream. To date, this study has been concerned with the size and specific gravity of bed material as a means of estimating critical diameter and rate of bedload discharge. Future plans include sampling and analysis of other bed-material characteristics.

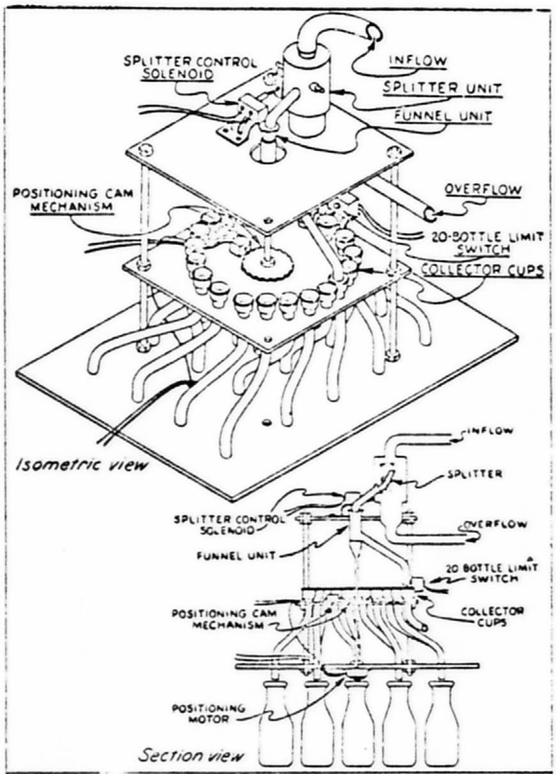

Figure 3. Automatic pumping sampler mechanism.

Particle-Size Distribution

Bed material in Moanalua Stream ranges from smaller than 1 mm (millimeter) in diameter to particles larger than 1000 mm. Analysis of such a wide range of particle sizes by sieve methods is impractical. A point count procedure was adopted using vertical photographs and the optical particle-size analysis technique described by Ritter and Helley (1969). The optical analyzer is basically a light source, which directs a beam through the photograph being analyzed. An iris is adjusted by the machine operator so that the diameter of a spot of light corresponds to a particle diameter and a switch is pressed, mechanically marking the particle as having been counted. At the same time, a linkage records the iris setting in one of a series of counters. Summation of the number of particles in individual counters and application of a scale factor results in a size-distribution table for particles in the photograph. Figure 4 shows a typical vertical photograph of bed material. The tape shown in the photograph is used to determine the scale factor.

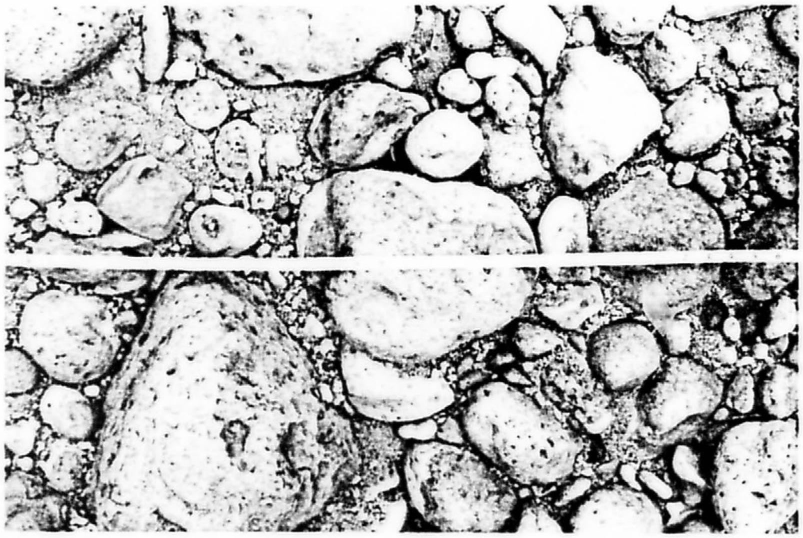

Figure 4. Vertical photograph showing bed material in Moanalua Stream.

Specific Gravity

Sixteen bed-material samples were collected at random for laboratory specific-gravity determinations. These samples were of four basic types:

(1) Dense dike rocks or ponded basalts.

(2) Flow basalts with few or no vesicles.

(3) Vesicular basalts, with a wide range of vesicle size and abundance.

(4) Porphyritic basalt, with numerous large feldspar phenocrysts.

In general, the four types can be represented by the following ranges of specific gravities:

(1) Dense: 2.89 - 2.92; average 2.90.

(2) Flows: 2.76 - 2.79; average 2.78.

(3) Porphyritic: 2.59 - 2.66; average 2.62.

(4) Vesicular: 2.07 - 2.32; average 2.20.

Grids were drawn on vertical photographs of the bed material, and rock type was identified at about 100 grid intersections on each photograph. The number of intersections touching each rock type was multiplied by the representative specific gravity and the sum of these products divided by the total count was taken as the average specific gravity.

Channel Morphology

Cross-section surveys have been conducted at nine locations along the stream (fig. 1). The locations selected are situated such that highway construction will not directly affect the channel. At each site a level reference line was established between two end points (marks on rocks, blazes on trees), and a level rod was used to determine the distance between the streambed and a tape stretched tightly between the reference points.

Stream profiles were plotted from the latest maps along the highway route.

Additional detailed information is available from the indirect discharge measurements made in the past near gaging sites. These measurements require surveys of several closely-spaced cross sections between high-water marks.

A detailed survey was made at the 2280 gage site in 1941, when a model of the gage control was built and tested.

Resurveys of all these sites will be made on a regular basis.

Debris-Basin Surveys

Accumulation in the debris basin is determined by level surveys along parallel ranges across the basin. Each cross section is plotted, and the area below a reference elevation is determined by planimeter. The net change in area between surveys is taken as being a prism extending half way to each adjacent range, and the total volume of these prisms is the net filling. Future plans call for programming this information on a digital computer. More detailed analysis of the distribution of fill can then be obtained with a reasonable effort.

Successive vertical and oblique photographs of the basin are obtained at the time of survey to document the filling process and to aid in analyzing characteristics of the fill material.

Tracers for Coarse-Material Movement

Detached fragments of the old stone-arch bridges serve as excellent tracers of bedload transport. These are boulders or aggregates of boulders originally derived from the bed or banks. Traces of the mortar used in bridge construction make these fragments easily identifiable in the channel fill.

Tabular fragments of concrete broken from the pavement of stream fords also are found in the channel. These are initially very angular, so they are of particular value in determining progressive rates of rounding versus distance from the source.

Particles to be traced have been painted a characteristic color and number, corresponding to the stream reach and location, respectively. Each particle is listed on a file card with detailed description of rock type, dimensions and distance to reference marks. After each significant storm, observations are made of the distance moved (or absence from original location) and the information is entered on the file card.

Watershed Factors

Physical factors peculiar to a particular watershed or group of watersheds may greatly modify the interrelationships between rainfall, evaporation, runoff, and sedimentation. In order to transfer the results of this study to other locations, the importance of the physical setting must be evaluated. Unfortunately, the full impact of watershed factors cannot be known in advance, but many past studies have shown that among the physical factors affecting the hydrology and sedimentation of a watershed are the geology, soils, topography, and vegetative cover conditions. Knowledge of past and present watershed conditions is being gained by study of maps, reports, and aerial photographs, by field surveys and photography and by personal inquiry of individuals who may have knowledge of such past occurrences as forest fires, grading, or landslides.

AVAILABLE DATA

The following section summarizes the types of hydrologic data available as a result of the past activities of the U.S. Geological Survey in Moanalua Valley. Only part of the data will be presented or summarized in this report, because of the sheer volume represented. Readers requiring more detailed information for special purposes are invited to contact the Honolulu office of the U.S. Geological Survey.

Streamflow

Daily records of discharge are available for all five gaging stations in the study area. Records for station 2280 date back to June 1926; records for stations 2275, 2277, and 2282 begin in October 1968; and records for station 2279, the most recent addition to the network, begin in April 1972. Periods of record for the entire data network are shown in table 2.

Daily discharge records for three stations, 2275, 2277, and 2280, are published on an annual basis in the U.S. Geological Survey's release "Water Resources Data for Hawaii and other Pacific Areas". Prior to 1961, daily records for station 2280 were published annually in the U.S. Geological Survey Water-Supply Paper series, "Surface-Water Supply of the U.S.". Annual peak discharges for station 2280 for water years 1927-72 are listed in the U.S. Geological Survey's annual progress report entitled, "An Investigation of Floods in Hawaii" (Nakahara and Ewart, 1972). These data are summarized in table 6.

Discharge records of storm runoff are available for most stations for the dates shown in table 2. Records of runoff can be made available at 5-minute intervals. For this report, the five largest storms, in terms of peak discharge at station 2282, were selected for analyses. These storm dates are December 25, 1968, February 1, 1969, July 25, 1970, November 25-26, 1970, and April 5-6, 1971, and they will be covered in detail in the analytical section of the report. Other detailed data available include the rating curve for each station and current-meter and indirect measurements made to define the rating.

Rainfall

Rainfall records are available for the seven recording gages in the study area. The periods of record are shown in table 2. For rainfall data collected since October 1968, computer printout sheets are available showing rainfall quantity at 5-minute intervals with daily totals for each station. Prior to that date, rainfall was tabulated on a daily basis at station 2280. Rainfall mass curves for selected storms are compared in the analytical section of this report.

Evaporation

Pan evaporation records from the installation at station 2275 are available and can be tabulated for daily, weekly, or monthly amounts. The record is intermittent, due to equipment difficulties, especially during the early stages of the project. These difficulties have been largely overcome, and later records appear to be reliable. The primary use for the evaporation data is as input into the moisture-accounting process of the U.S. Geological Survey's rainfall-runoff model. Both the model and the role of pan evaporation data will be discussed in the analytical section of this report.

Suspended Sediment

Appendix 1 is a summary of all suspended-sediment data available to July 1972. Instantaneous sediment discharges were computed as the product of the discharge, in cfs (cubic feet per second), suspended-sediment concentration, in mg/l (milligrams per liter), and a coefficient (0.0027), which converts the result to conventional units of tons per day. Thus, suspended-sediment discharges listed in the table represent the time rate of sediment transport for the water discharge and concentration at the instant of sample collection. Computation of the sediment load for a particular period requires the incremental addition, or integration, of the water discharge and concentration products, (Porterfield, 1972). A storm-load computation is shown in the analytical section of this report.

Particle-Size Distribution

One particle-size analysis of suspended sediment is available (table 3). The analysis indicates a size distribution similar to that at other locations on Oahu (Jones, Nakahara, and Chinn, 1971, p. 30).

Bed Material

Particle-Size Distribution

Seven vertical photographs were analyzed and the composite particle-size distribution was used in the bedload computations in this report. Table 4 summarizes the particle-size information.

Specific Gravity

Average specific gravity from analysis of four bed material photographs was 2.62, sufficiently close to 2.65 to allow use of bedload equations in standard form. Obviously, as the study progresses, methodology will be refined, so that differences in specific gravity, particle, size and particle shape can be taken into account.

Table 3. Particle-size analysis of suspended sediment, Moanalua Stream near Aiea (2282)

Date	Time	Water temperature (°C)	Discharge (cfs)	Concentration (mg/l)	Sediment discharge (tons/day)
Nov. 27, 1970	1730	21.0	227	1240	760

Date	Time	Particle size, percent finer than the size (in mm) indicated: (Clay) 0.002	(Clay) 0.004	(Silt) 0.016	(Silt) 0.062	(Sand) 0.125	(Sand) 0.250	(Sand) 0.500
Nov. 27, 1970	1730	33	46	80	93	98	100	100

Table 4. Size distribution of bed material, Moanalua Stream. Volumetric composite of seven vertical photographs, as determined by particle counts.

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

ANALYTICAL RESULTS

As the previous sections of this report indicate, numerous lines of investigation and data collection are being pursued in the overall study of Moanalua Valley. The following section presents some analyses of the data collected during the first report period. Although data are available in additional categories, they are not considered to be adequate for meaningful analysis at this time. Since the project began in November 1970, only a few significant flows have occurred. Of these, even fewer were completely covered by suspended-sediment samples. At present (July 1972), the number and range of storms receiving comprehensive coverage is extremely limited.

Selected Storms

During October 1968 - March 1972, there were 13 storms which resulted in a peak flow of 500 cfs (cubic feet per second) or greater, as measured at station 2282. The five largest of these storms, in terms of peak produced at station 2282, were selected for analysis in this report. These five storms occurred on December 25, 1968, February 1, 1969, July 25, 1970, November 25-26, 1970, and April 5-6, 1971. For purposes of this report, the data for each storm are presented in a series of illustrations (plates 1-15) which, for ease of use, are located in a pocket attached to the back cover of the report. The series for each storm include hydrographs and rainfall mass curves at 30-minute intervals, a table of 10-day antecedent rainfalls, a set of rainfall mass curves at 5-minute intervals, and a set of superimposed hydrographs at 30-minute intervals. Because of equipment malfunctions, various data are missing for some storms and estimates have been made, in most instances.

Storm Rainfall

Annual rainfall variations in space and time are extreme in Hawaii. Variations of rainfall during a storm within a valley such as Moanalua can also be pronounced. The rainfall mass curves for the five storms included in this report are examples. Variation in storm totals range from 1.6 inches for the storm of December 25, 1968 to 10.7 inches for the February 1, 1969 storm. A fairly uniform rainfall over the valley is indicated by the data for the December storm. The storm of February 1, 1969, which produced 15.3 inches and 15.0 inches at rain gages 2275.01 and 2277.01, respectively, but only 4.6 inches at rain gage 2282.01, was produced by a type of meteorological situation (low-pressure area overlying a layer of moist trade winds) that has resulted in some of windward Oahu's heaviest downpours. The storm of July 25, 1970 was a result of a shifting of normal summer air-circulation patterns. The storms of November 1970 and April 1971 were of the thunderstorm type and most of the intense rainfall occurred at the higher elevations. Rainfall diminished significantly from the higher to lower elevations in the valley for the February, November, and April storms. The July storm appeared to be most intense over the middle part of the valley.

The 10-day antecedent rainfall listed for each station is greater in the higher elevations, but the daily variations are not as pronounced as those that occur during storm periods. This would seem to indicate that the frequent small showers are more uniformly distributed.

Because of the complex wind patterns created by the topography, the exposure of the rain gage is a problem, especially in the higher elevations of the valley. The errors in rainfall interception attributable to these local wind regimes cannot completely be eliminated regardless of location. The existing rain-gage network in Moanalua Valley is subject to these errors, the magnitude of which is difficult to determine.

The density of gages within the valley and the short (5-minute) recording interval incorporated in the existing network gives adequate coverage of storms.

Storm Hydrographs

Data on the storm hydrographs for the five selected events are presented as a series of plates. Plates 6, 7, 8, and 10 are superimposed hydrographs from each of the gaging stations at 30-minute intervals plotted on semilogarithmic paper. Plate 9 is the series of hydrographs for the storm of November 25-26, 1970 plotted on rectangular coordinates at 5-minute intervals. The illustrations on plates 11-15 are arithmetic plots and consist of the storm hydrograph, and mass-rainfall curve at 30-minute intervals for the storm event, and the 10-day antecent rainfall for the four subregions in the project area. An arbitrary 10-day period was used for listing antecedent rainfall.

The storm hydrographs for Moanalua Stream and its main tributary (plates 11-15) are of a steep triangular shape with very sharp rising limbs and steep recession slopes. Because of the steep side and channel slopes and the narrow basin configuration found in Moanalua Valley, the time of concentration is short and, hence, time to peak is short, especially for the two upstream subregions (2275.0 and 2277.0). The responsiveness of the two small subregions to rainfall excess is indicated by the short time to peak, which is of the order of 30-45 minutes. The November 25-26, 1970 hydrograph plotted at 5-minute intervals shows a series of jagged peaks and valleys within short time periods indicating quick response to variations in basin runoff. A plot of the hydrograph using a 30-minute time interval tends to smooth out much of the jaggedness.

For these five storms, the hydrograph shape is essentially translated downstream from the confluence of the two main tributaries with an increase in the peak caused by the lateral inflow from numerous side channels.

For each of the five storms, peak flow occurs earliest at the smaller subregion (2277.0). The time difference between peaks at 2277.0 and those at 2275.0 ranged from 5 to 15 minutes. Stations 2275.0 and 2277.0 are 400 and 1,700 feet upstream of the confluence, respectively. Assuming an equal velocity of the flood crest and a 5-minute differential in peaks at the stations, the two flows should arrive at the confluence at about the same time, or at least within a 5-minute interval.

The storms of November 1970 and April 1971 were primarily upper-basin storms with little rain in the mid to lower reaches. Using the time of peak of 2275 as a base, the travel time of the flood crest from the confluence to station 2282 was 40 and 30 minutes for the November and April storms, respectively. The stream-channel distance between the two points is approximately 17,000 feet, which indicates average flood-crest velocities of about 7 and 9 feet per second.

The time differential was 25 minutes for the December 1968 storm and 40 minutes for the February 1969 storm. A time differential of 2 hours and 15 minutes between the peak at the confluence and that at 2282 was observed for the July 25, 1970 storm. This longer interval can be attributed to a significant amount of runoff in the intervening area, primarily from the two large tributaries, which enter the main stream just below station 2280.

Storm-runoff data for the five storms used in the report are shown in table 5. The runoff volumes were computed at 5-minute intervals, and because the antecedent baseflow was small or nonexistent, an arbitrary straight line was used to separate the surface runoff. Variations in runoff volumes over the four subregions can be attributed primarily to differences in rainfall. However, when comparing the runoff volumes of the two upper basin subregions (2275 and 2277) for periods of essentially equal rainfall, some differences attributable to basin characteristics can be noted. Data for gages 2275.01 and 2277.01 during the February 1, 1969 storm indicated fairly uniform rainfall conditions at both stations, and if it is assumed that the rainfall registered at the lower station (2275.02) is also applicable to the lower part of the watershed of 2277, then the rainfall for this storm can be considered equal for both subregions. Antecedent conditions were also similar. The runoff volumes computed for this storm show a difference of 2.7 inches, with 2275 being the larger. Also, data for the December 25, 1968 storm show that at 2275 the runoff was about twice the amount at 2277. The rainfall from this storm also was equally distributed, and the antecedent rainfall for each gage was similar. A large variation in rainfall was observed for the July 25, 1970 storm but the hydrograph record was not available for 2275, so a comparison cannot be made for this storm.

Table 5. Storm-runoff data for stream-gaging locations in Moanalua Valley

Date	Stations	Peak discharge (cfs)	Time of peak (hrs)	Volume computation interval (hrs)	Runoff volume (in)
12-25-68	2277.0	504	0620	12-25 (2400-1000)	1.30
	2275.0	755	0635	12-25 (2400-1500)	2.62
	2280.0	1,260	*0630	12-25 (2400-2400)	1.91*
	2282.0	1,435	0700	12-25 (2400-2400)	1.94
2-1-69	2277.0	892	1610	2-1 (0900-2400)	4.65
	2275.0	1,200	1615	2-1 (0800-2400)	7.31
	2280.0	1,980	1630	2-1 (0900)-2-2 (1200)	5.12
	2282.0	2,950	1655	2-1 (0900)-2-2 (1200)	4.94
7-25-70	2277.0	680	1910	7-25(1700)-7-26(0600)	5.25
	2275.0	820	*1930		4.94*
	2280.0	1,910	2030	7-25(1800)-7-26(1200)	4.23
	2282.0	2,736	2135	7-25(1800)-7-26(1500)	5.75
11-25,26-70	2277.0	790	2400	11-25(2100)-11-26(0600)	2.94
	2275.0	1,512	0010	11-25(2100)-11-26(0900)	4.96
	2280.0	1,690	0035	11-25(2100)-11-26(1500)	2.34
	2282.0	2,180	0050	11-25(2700)-11-26(1500)	2.24
4-5,6-71	2277.0	886	2340	4-5(2200)-4-6(0300)	1.88
	2275.0	720	2345	4-5(2200)-4-6(0600)	1.69
	2280.0	1,440	0010	4-5(2200)-4-6(0900)	1.11
	2282.0	1,820	0015	4-5(2200)-4-6(1500)	1.17

* Estimated.

There were significant differences between the amount and intensity of rainfall for the November 25-26, 1970 storm at stations 2275.01 and 2277.01, with 2275.01 recording a higher 1-hour intensity and a greater total amount. The volume of runoff at station 2275.0 was 1.7 times greater than that recorded at station 2277.0. Rainfall variations may have accounted for a major part of the difference in this case.
The antecedent conditions for this storm were comparable. Because of equipment failure, the rain gage at 2275.01 was not functioning during the April 5, 1971 storm. Storm-runoff computations showed 2277.0 to have a slightly higher volume.

The excess in the volume of runoff observed at the 2275.0 gaging station over that for station 2277.0 for those storms having about equal rainfall intensities and durations and similar antecedent conditions can possibly be explained by unknown variations in rainfall, but perhaps, there is a significant difference in the values of the saturated hydraulic conductivity between the basins. The latter is considered to be more likely, but the solution will require further study.

For the five storms documented in this report, there does not appear to be any correlation between the observed flood peaks and the runoff volumes for any of the stations, due probably to variations in rainfall during storm periods and varying antecedent conditions.

Flood-Peak Correlation

The correlation between the flood peaks observed at station 2280 and those observed at station 2282 is shown in figure 5. Thirteen storms occurring between October 1968 and March 1972 were used in the analysis. All peaks had a discharge of at least 500 cfs at station 2282. A best-fit line (A) and a line (B) weighted to favor the four highest peaks were drawn. The scatter of points reflects the rainfall variability attributable to each storm.

Using these curves, the 50-year recurrence-interval design flood (Parsons, Brinckerhoff-Hirota Associates, 1967, p. 4, app. B) of 3,900 cfs for station 2280 would yield discharges of 4,700 and 5,200 cfs for station 2282 using the best-fit (A) and weighted line (B), respectively.

Table 6 lists the annual peak discharges for station 2280 on a water-year basis for 1927-72.

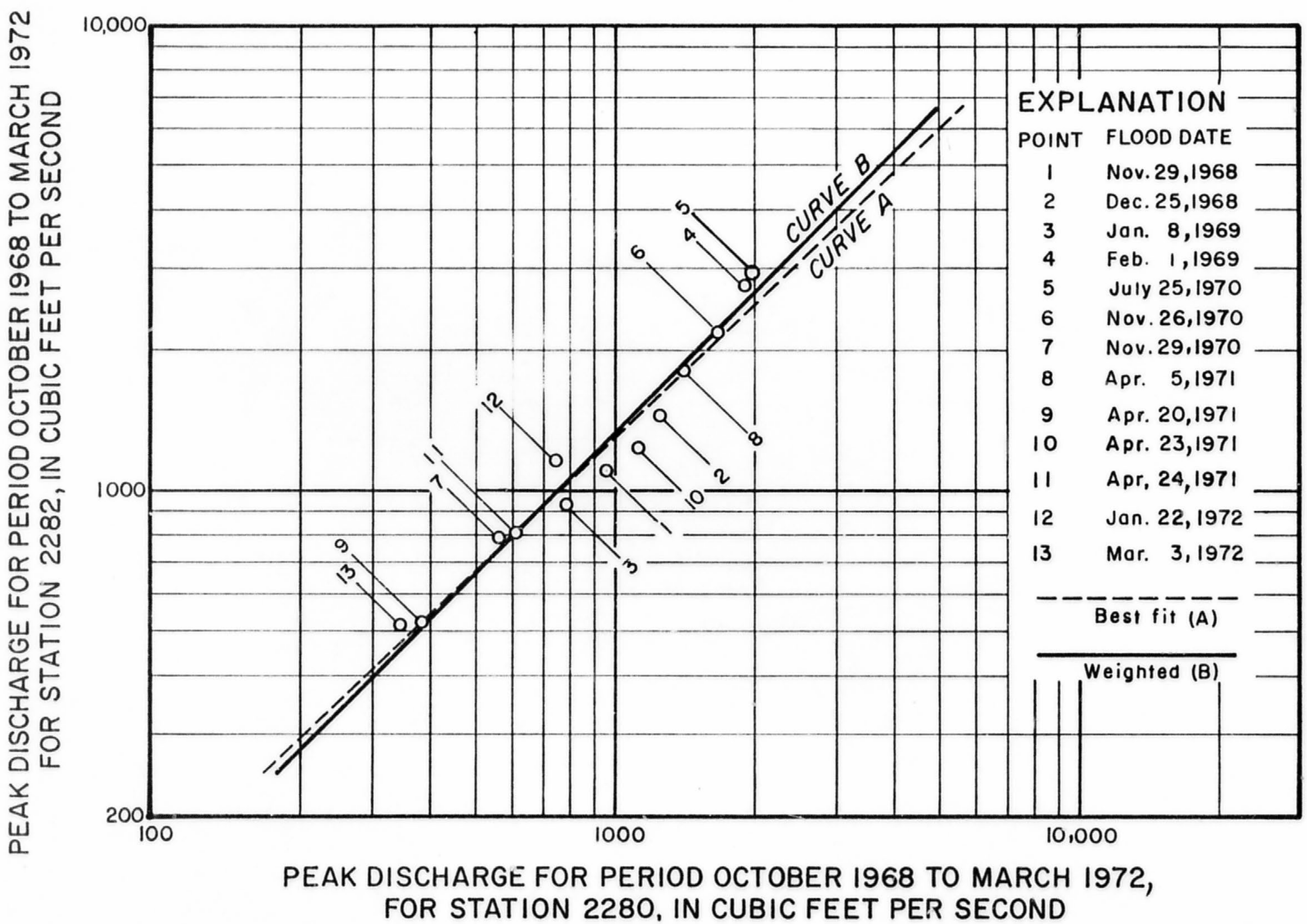

Figure 5. Relationship of instantaneous peak discharges between stations 2280 and 2282.

Table 6. Peak discharges, water years 1927-72, for Moanalua Stream near Honolulu (2280)*

Water year	Date	Gage height (ft)	Discharge (cfs)	Water year	Date	Gage height (ft)	Discharge (cfs)
1927	5-16-27	8.48	2,210	1952	3-26-52	7.26	1,460
1928	11-19-27	8.48	2,210	1953	11- 2-52	3.21	263
1929	4-18-29	3.07	237	1954	7-29-54	3.39	306
1930	9-18-30	7.90	1,810	1955	2-23-55	6.52	1,080
1931	11-18-30	11.58	4,580	1956	2-25-56	6.36	1,040
1932	2-28-32	8.54	2,210	1957	11-30-56	4.73	596
1933	3- 3-33	6.41	1,040	1958	3- 5-58	7.42	1,520
1934	4-26-34	6.18	975	1959	10-23-58	9.46	3,000
1935	2-27-35	9.09	2,660	1960	5-14-60	8.79	1,900
1936	8-12-36	7.82	1,750	1961	12-30-60	7.94	1,200
1937	1- 1-37	7.73	1,700	1962	3-12-62	5.45	538
1938	11-25-37	6.10	1,200	1963	5-14-63	11.82	3,370
1939	3- 5-39	8.16	2,000	1964	10- 4-63	7.29	1,020
1940	11- 8-39	6.26	1,010	1965	5- 2-65	8.36	1,440
1941	8- 8-41	6.37	1,190	1966	12-14-65	9.20	1,810
1942	9-14-42	7.10	1,350	1967	8- 9-67	7.98	1,250
1943	1-13-43	7.99	1,870	1968	12- 9-67	9.07	1,740
1944	12- 5-43	2.89	203	1969	2- 1-69	9.56	1,980
1945	11- 9-44	3.00	223	1970	7-25-70	9.42	1,910
1946	1-25-46	3.02	227	1971	11-26-70	8.86	1,630
1947	3-29-47	4.93	650	1972	1-22-72	5.92	750
1948	1-27-48	6.10	944				
1949	1-16-49	6.52	1,080				
1950	1-22-50	5.36	743				
1951	12- 3-50	8.24	2,000				

* From Nakahara and Ewart, 1972, p. 51.

The 50-year recurrence-interval flood for station 2280 was estimated at 5,600 cfs by the U.S. Corps of Engineers (State of Hawaii, Dept. Land and Nat. Resources, 1972). By use of the Storm Drainage Standards of the City and County of Honolulu (City and County of Honolulu, Dept. Public Works, 1969), an estimate of the design peak discharge is about 6,000 cfs for the drainage area gaged by station 2280. A recent study to evaluate the streamflow-data program in Hawaii (Yamanaga, 1972) used regression techniques to relate streamflow characteristics to drainage-basin characteristics. An estimate of the 50-year recurrence-interval flood for station 2280 computed on the basis of relationships developed in this study is 5,560 cfs.

The storm-runoff data discussed previously indicate a significant inflow and increase of the flood peak between stations 2280 and 2282, most notably for the February 1, 1969 and July 25, 1970 storms. A discharge of 4,580 cfs (maximum peak, 46 years of record, table 6) at station 2280 would yield a peak discharge of 6,000 cfs at station 2282 using the weighted curve (B) in figure 5.

Rainfall-Runoff Model

A parametric rainfall-runoff simulation model developed by the research program of the U.S. Geological Survey has been used to analyze data from the two upstream gages, 2275 and 2277.

The model attempts to approximate the physical laws governing the components of the rainfall-runoff system by using sets of equations to represent rates of infiltration, soil-moisture storage, percolation, evapotranspiration, and surface-flow routing. This model was developed especially for simulating flood hydrographs for small drainage areas. Principal input data are point rainfall and daily potential evapotranspiration.

The structure of the model deals with three components of the hydrologic cycle, namely: antecent moisture, infiltration, and surface runoff.

The antecedent moisture component is essentially an accounting mechanism, which was designed to simulate the distribution of moisture in, and the evapotranspiration from, the soil. Four parameters are contained in this component: a pan coefficient, which converts a measured pan evaporation record into an estimate of potential evapotranspiration; a coefficient, which proportions the amounts of infiltration and surface runoff for those periods with daily rainfall; a value, which represents the maximum effective amount of base-moisture storage at field capacity; and a coefficient, which represents the rate of drainage of infiltrated soil moisture. Input into the moisture-accounting component consists of the daily records of rainfall and evaporation. The output is the calculated amounts of base-moisture storage and infiltrated surface-moisture storage. The moisture-accounting component is essentially a more complex version of the antecedent-precipitation index, (API) which was developed to estimate an initial infiltration rate for a storm period.

The infiltration component is constructed about an approximation to the Philip equation for unsaturated flow (Philip, 1954). In order to carry out this process, three parameters are needed: a measure of the capillary potential (soil suction) at the wetting front for soils at field-capacity moisture conditions; a parameter, which is a function of the variable base-moisture storage used to vary the capillary potential over a range; and the computed saturated-soil conductivity. Storm-rainfall data, and the values of base-moisture storage and the surface-moisture content are the inputs into this component. The output consists of the generated rainfall excess.

Surface runoff, the third component, converts the rainfall excess into a flood hydrograph by use of the Clark flood-routing method (Clark, 1945). This component needs only a single parameter, which is a linear reservoir-routing coefficient. The input to this component is the excess rainfall generated by the infiltration component. A flood hydrograph is the output.

The optimum parameter values for each component are determined by use of an optimization technique built into the model. In using this technique, all parameters must be bounded, and, thus, can be constrained to a "reasonable" value range.

An optimization or calibration phase is the first step in using the model. The parameters are assigned initial values and the input data, consisting of daily rainfall and evaporation records, storm rainfall and hydrographs are entered into the computer. Using these data and the initial parameter values, the simulated flood-hydrograph response for each storm period is computed. The optimization technique then revises the parameter values and recomputes a new set of responses. Essentially, this is a fitting process, which terminates when arbitrary criteria are met. The final parameter values are considered to be the "optimum" values based on the input data.

The second step in the use of the model is an analysis of the errors in the simulated results. Errors of prediction result from errors in data input and the approximations used in the model structure to imitate the physical system.

The final phase of the modeling work is to determine the extent of transferability of the simulation results. This depends primarily on the derived parameters. The parameters must either be constant or be related to physical variables, which can be measured in other basins of interest.

The foregoing is a very brief summary of the U.S. Geological Survey's rainfall-runoff simulation model. For a more detailed description and a presentation of case studies, the reader is referred to Dawdy and others (1972).

Application of the Model - Moanalua Valley

Preliminary work has been conducted to test the utility of the U.S. Geological Survey's model with some of the available data in Moanalua Valley. As an initial step, the two upstream tributary basins were selected for testing. Ten storms for stations 2275 and 2277 were selected based on coverage of the storm by the instrumentation. The data used were the storm rainfall and hydrographs defined at 5-minute intervals, the daily rainfall totals for an arbitrary time prior to the storm, and the daily evaporation.

Because of difficulties with the rainfall definition for station 2277.01, the test results for the 2277 basin were not available at the time of this report. The results for the 2275 basin, however, are encouraging. For the optimization or calibration phase using 10 storms, the model was tested using three storm-rainfall inputs, the first run used the rainfall measured at station 2275.01, the second used data from 2275.02, and the third used a weighted combination of the rainfall from stations 2275.01 and 2275.02. The best overall results in flood-peak simulation was achieved using the combination rainfall.

Use of the rainfall data from 2275.01 only yielded simulated peaks that were higher than the observed peaks for eight of 10 storms, and the restriction to 2275.02 data caused considerable scatter with the largest peak being grossly underestimated.

Figure 6 shows the scatter diagram of observed and simulated peaks for station 2275.0 using the weighted rainfall data from 2275.01 and 2275.02.

These results represent only a preliminary investigation using somewhat limited data. It is expected that data on future storms, especially major storm events, and experimentation with various rainfall-distribution schemes and subsequent recalibration of the model will yield significantly better results.

Significance of Model Results

An error analysis based on the results achieved after the final calibration will be carried out. Also, a study of parameter sensitivity will be initiated to determine the degree to which the simulation results are dependent upon individual parameters. The results of this sensitivity study should be of particular importance in the assessment of transfer value.

One aim of the modeling aspect of the project is to develop a stream-system model for Moanalua Valley. The type of model envisioned will combine the Geological Survey's rainfall-runoff model for hydrograph simulation for the two upland tributaries with a channel-routing component and lateral-inflow component to reproduce storm hydrographs at stations 2280 and 2282 on the main channel. In pursuit of this objective, a preliminary investigation has been made into the use of the Corps of Engineers' HEC-1 Flood Hydrograph package (Hydrologic Engineering Center, Corps of Engineers, 1970).

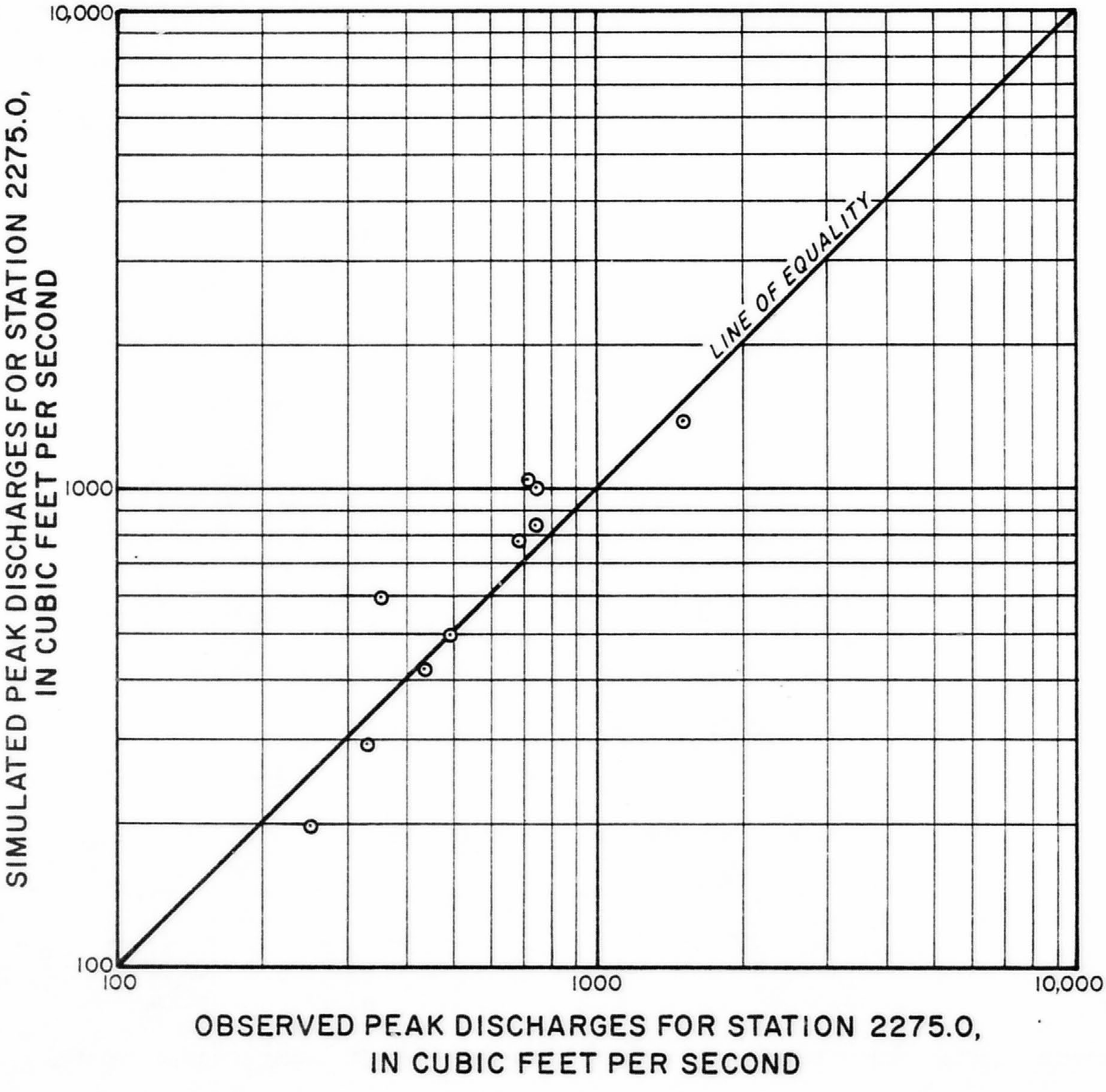

Figure 6. Relationship of observed and simulated instantaneous peak discharges for station 2275.

This package is essentially a stream-system model composed of various computer routines such as unit-hydrograph computation, loss-rate function (storm-rainfall loss), channel routing, combining of tributary inflows, and optimization. Components of the model can be used separately or in various combinations.

Data for the 10 storms used in the Geological Survey's rainfall-runoff model for the two upstream-tributary basins were used as input for the HEC-1 program. The program components used were the computation of the loss-rate function and unit-hydrograph optimization.

The output consists of a tabular summary of rainfall and rainfall excess, observed and computed discharges at 5-minute intervals, an optimized unit-hydrograph (Clark method) for each storm, and the parameters needed to define the rainfall loss-rate function. Because of the great bulk of the data, the output was not included as part of this report. It is, however, available at the Hawaii District office, U.S. Geological Survey.

It is hoped that the modeling will aid the establishment of the natural-basin flood response of the Moanalua Stream system, prior to construction of the H-3 highway.

A comparison of this natural-basin response to the post-construction response will be of value in an assessment of the effects of the highway construction on the Moanalua Basin.

Channel Morphology

The stream channel proper is a rubble-strewn swath of roughly trapezoidal cross section, between steep-cut banks. The banks are composed of moderately- to poorly-sorted fine to very coarse materials, and the flood plain supports dense vegetal growth. The stream is ephemeral.

Stream width between cut banks increases fairly regularly from about 20 feet in the headwaters to about 35 feet at the debris basin near the urban boundary (fig. 7).

Channel depth between cut banks varies from about 3 feet to about 6.5 feet, but not with any particular regularity.

Slope of the channel is variable and unstable, because large boulders tend to form temporary natural dams and the fill behind these dams often has a slope of less than 0.01. Below these dams, slopes may exceed 0.10, until another dam-and-pool sequence is encountered. Average slope of the main channel for the first 20,000 feet upstream from the debris basin is 0.027 (fig. 8).

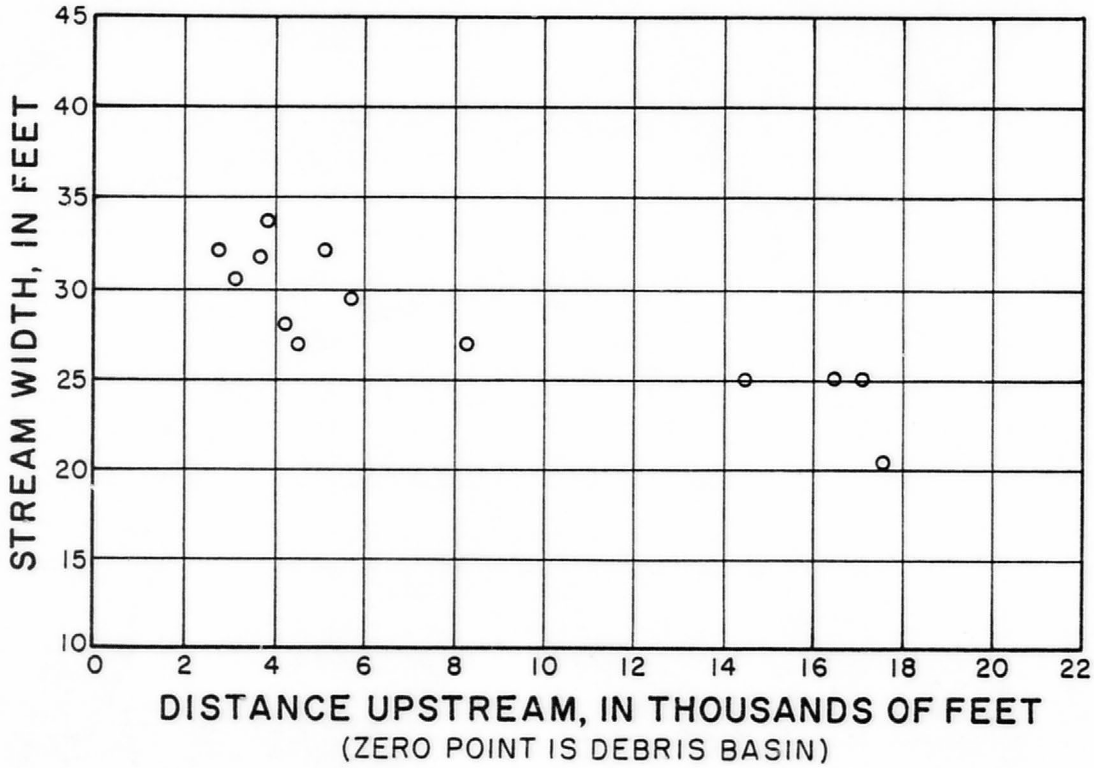

Figure 7. Relation between channel width and distance upstream from debris basin, Moanalua Stream.

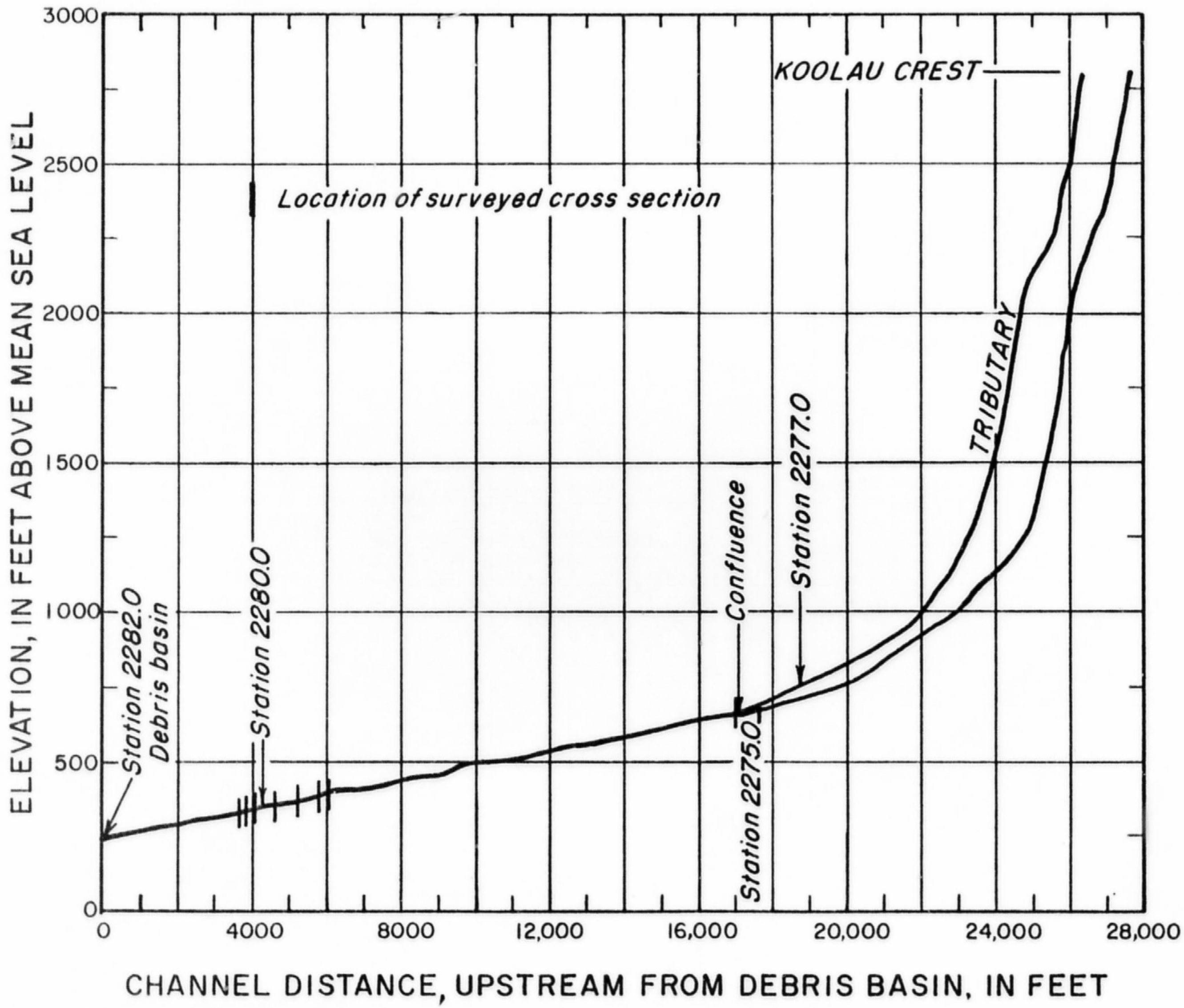

Figure 8. Longitudinal profile of Moanalua Stream with stations and cross-section locations indicated.

The impact of these relatively steep slopes is apparent in the sharp flood peaks and in the size of material transported by streamflow. The stream gradient is, of course, a reflection of the original steep gradient of land surface from ocean to the Koolau Mountain crest. Entrenchment has been extremely rapid since the cessation of volcanic activity, and many landslides have resulted from the development of unstable slopes on either side of Moanalua Valley. Many of the entrenched "meanders" in Moanalua Stream are actually the result of massive landslides, which forced the stream to cut new channels against an opposite valley wall. A few of these slides are easily recognized, but much more remains to be done to determine the relative ages, extent and volume of material, and particularly the stability of existing slide deposits.

Shallow, frequent, soil avalanches also occur in the high-rainfall part of Moanalua Valley. Scott (1969), in a study of the soil-avalanching process in Manoa Valley, Oahu, concluded that soil avalanches are an important factor in denudation near the Koolau crest, accounting for about 1 foot of lowering in 800 years.

Recognition of landsliding as an important process in the basin morphology is necessary to an understanding of the channel development. Landslide debris is always poorly sorted, so at each point of contribution to the channel, the stream begins the sorting process. In many cases, blocks too large for the stream to move have diverted the channel. Past landslides may have formed temporary dams, resulting in deposition of lacustrine deposits. Most of the ancient taro patches in the middle part of the basin were in boggy flats immediately upstream from large slides.

In cross section, the stream channel is a narrow steep-sided trapezoid. Plots of surveys at the nine study sections are shown in figure 9. In the time between the two surveys, the channels changed only slightly, and even where changes occurred, scouring at one point of the channel tended to be balanced by filling at another point, so that the cross-sectional area tended to remain about the same at a point. The exception is section 4220, about 160 feet downstream from gage 2280, where the predominant tendency was scouring. This is possibly the result of cyclic storage and release of coarse material in the gage pool.

Bank material is a 1- to 3-foot depth of fine soil with roots and weed growth, underlain by either poorly-sorted slide debris, or old alluvium with particle-size distribution similar to that in the present channel (fig. 10).

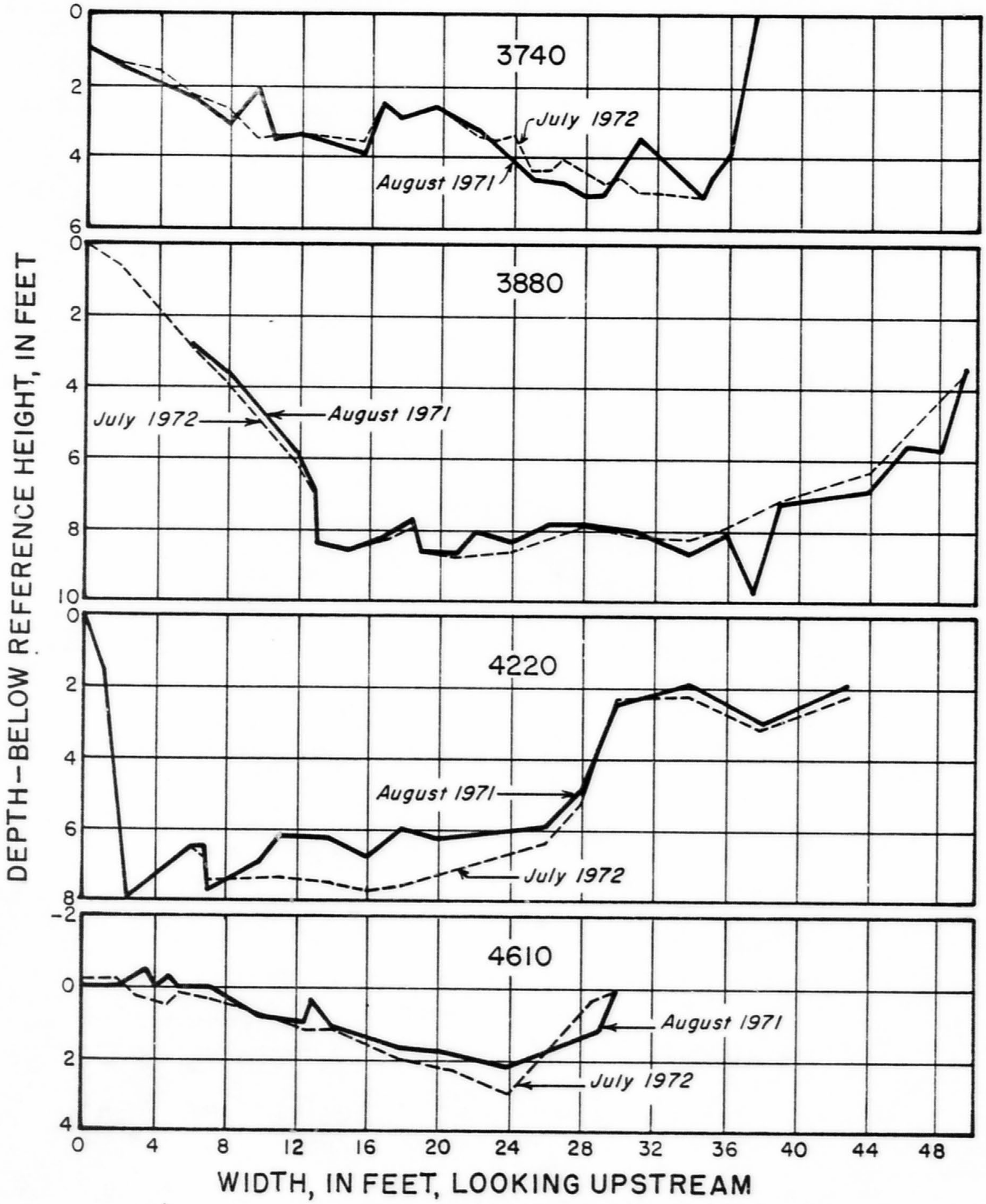

Figure 9a. Cross-section profiles at selected locations, Moanalua Stream.

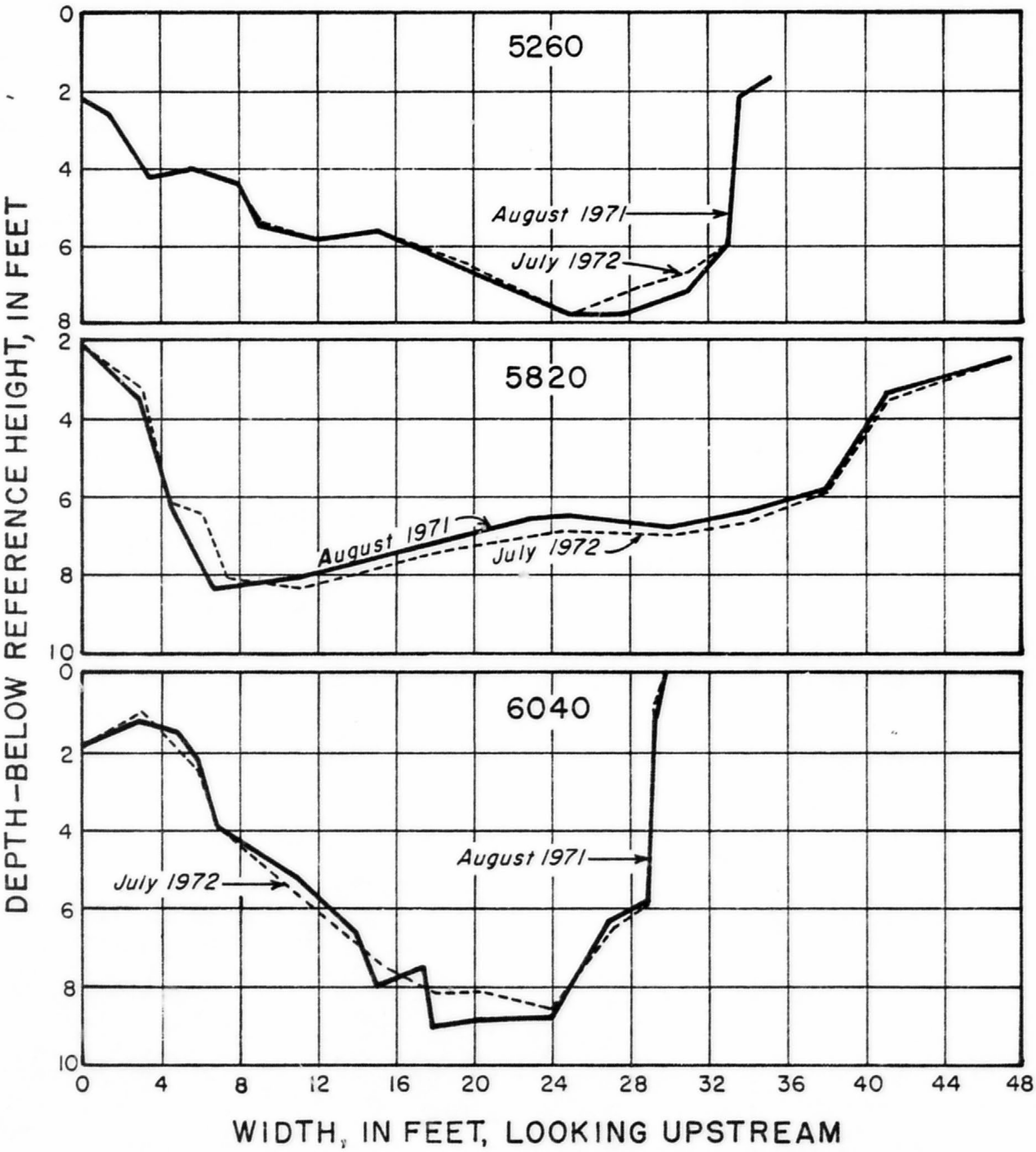

Figure 9b. Cross-section profiles at selected locations, Moanalua Stream.

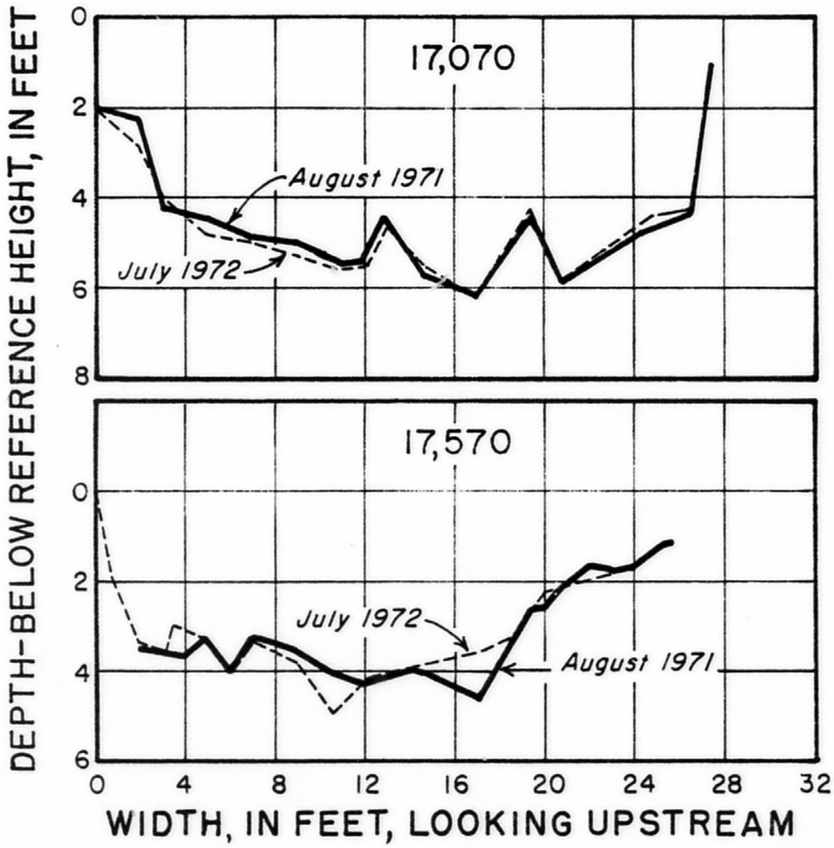

Figure 9c. Cross-section profiles at selected locations, Moanalua Stream.

Figure 10. Photograph of bank material. Colluvial material (top) typical of slide areas. Stream channel alluvium in foreground.

Sediment Transport

Sediment is transported by a stream in two basic modes: (1) Bedload is that part of the sediment load that moves by rolling, slipping, or sliding, and remains very close to the streambed. (2) Suspended-sediment load consists of particles that are suspended in the flow by the upward components of turbulence (or by colloidal suspension in the case of very fine particles).

Particles may move in suspension at one flow rate, and as bedload at a lower flow. Although observations of bed material are often used to deduce the rate of bedload discharge, bed-material samples collected at low flows may contain appreciable amounts of material that would be in suspension at higher flows.

The original source of all fluvial sediment is the land surface surrounding the stream, but in a more immediate sense, bedload is largely composed of material already available in the channel or banks. Suspended sediment is largely fine material derived from upland erosion, gullies, banks, and flood plains, as well as from some residue left in the channel by previous flow events.

Rate of bedload discharge is largely a function of the size, shape, specific gravity of sediment and the flow hydraulics. A stream transports as much coarse sediment as is possible under a given flow condition.

Rate of suspended-sediment discharge is largely a function of the availability of sediment for transport. Most streams are never loaded to their full capacity to transport fine sediment.

For a more complete discussion of sediment-transport processes, the reader is referred to Colby (1963).

Suspended-Sediment Discharge

Figure 11 shows discharge and concentration curves and the computed suspended-sediment load for January 22-24, 1972, the most significant storm period for which samples are available. This figure illustrates the considerable quantity of sediment that may be transported in suspension. Although only limited comparison with bedload is possible at this time, it is worth noting that during the storm of January 22, the stream transported a suspended-sediment load (348 tons), equivalent to 45 percent of the load of coarse material accumulated in the debris basin during the 1970-71 water year. Return interval of a storm of the January 22 magnitude is about 2 years (State of Hawaii, 1970).

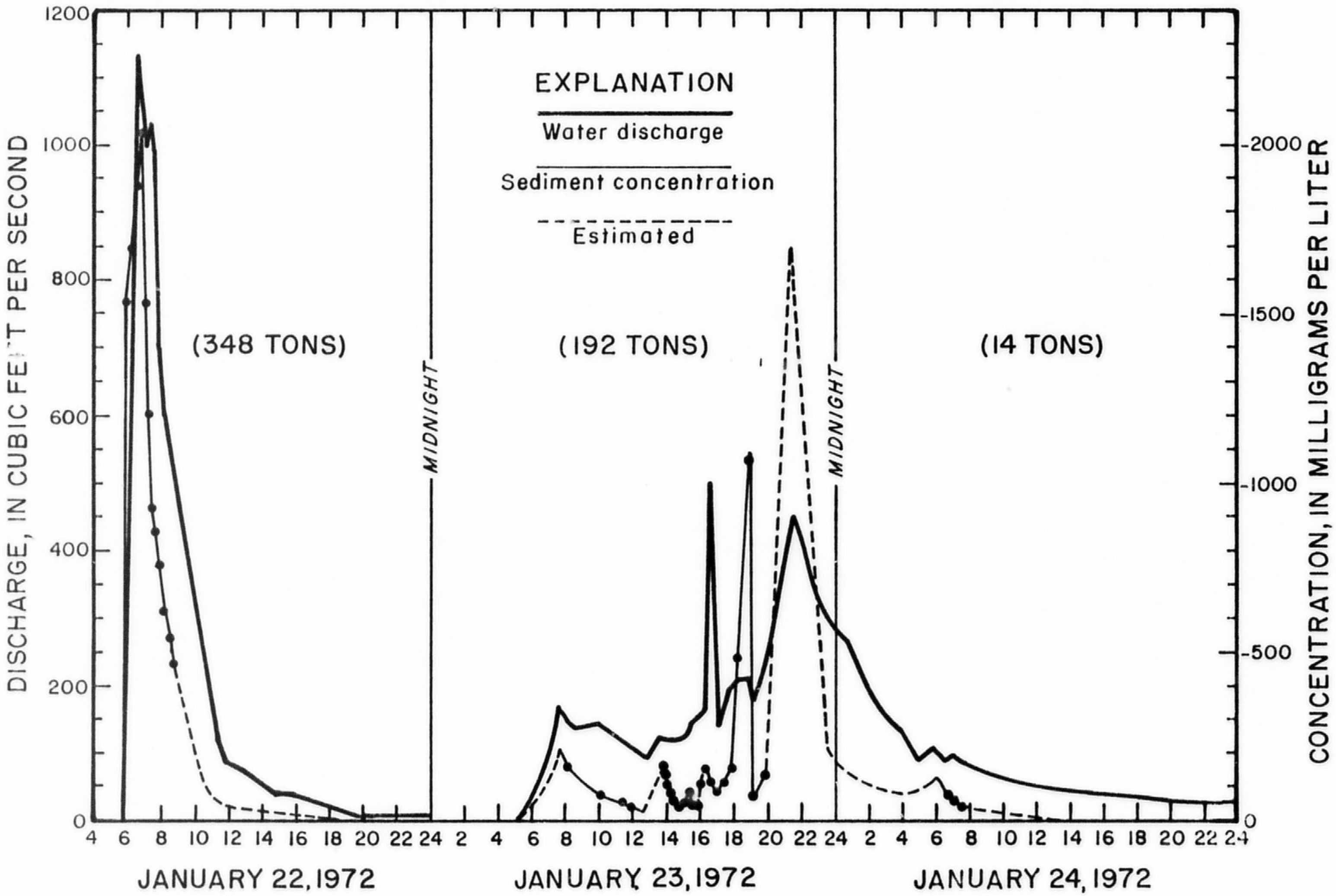

Figure 11. Streamflow and suspended-sediment concentration graphs, Moanalua Stream near Aiea (2282). Value in parentheses is the sediment load for the day shown.

A tool often used for extending suspended-sediment data is the sediment-transport curve, a graph representing the average relation between water discharge, the independent variable, and sediment discharge, taken as the dependent variable. Sediment-transport curves can represent concomitant values of discharge and sediment discharge for instantaneous, daily, monthly, annual, or storm periods. Adjustments can be made to the curves to compensate for the relative impact of such variables as rainfall intensity and vegetative cover (Colby, 1956). The basic relation represents a simple sediment-transport model, very useful for the continuing analysis of sediment data. Figure 12 shows preliminary plots of data from two of the mainstem gages, 2275 and 2282. These plots show the expected general relation between water and sediment discharge. Also apparent is the greater scatter in points representing the smaller drainage area (2275). This scatter probably is the result of more frequent flows and more rapid response of the streamflow to rainfall. The downstream gage, in contrast, represents the combined runoff from all parts of the watershed, probably further modified by mixing as the flow passes through the debris basin. An average curve has not been drawn through the scatter of points, because the data represent a fairly narrow range of conditions. However, some rough calculations of sediment discharge from the data at gage 2282 resulted in a suspended-sediment load of about 12,000 tons for an event similar to the 50-year design flood (Parsons,Brinckerhoff-Hirota Associates, 1967, fig. 4A). For a complete explanation of the method and a comparison to bedload, see the later section on bedload-discharge computations.

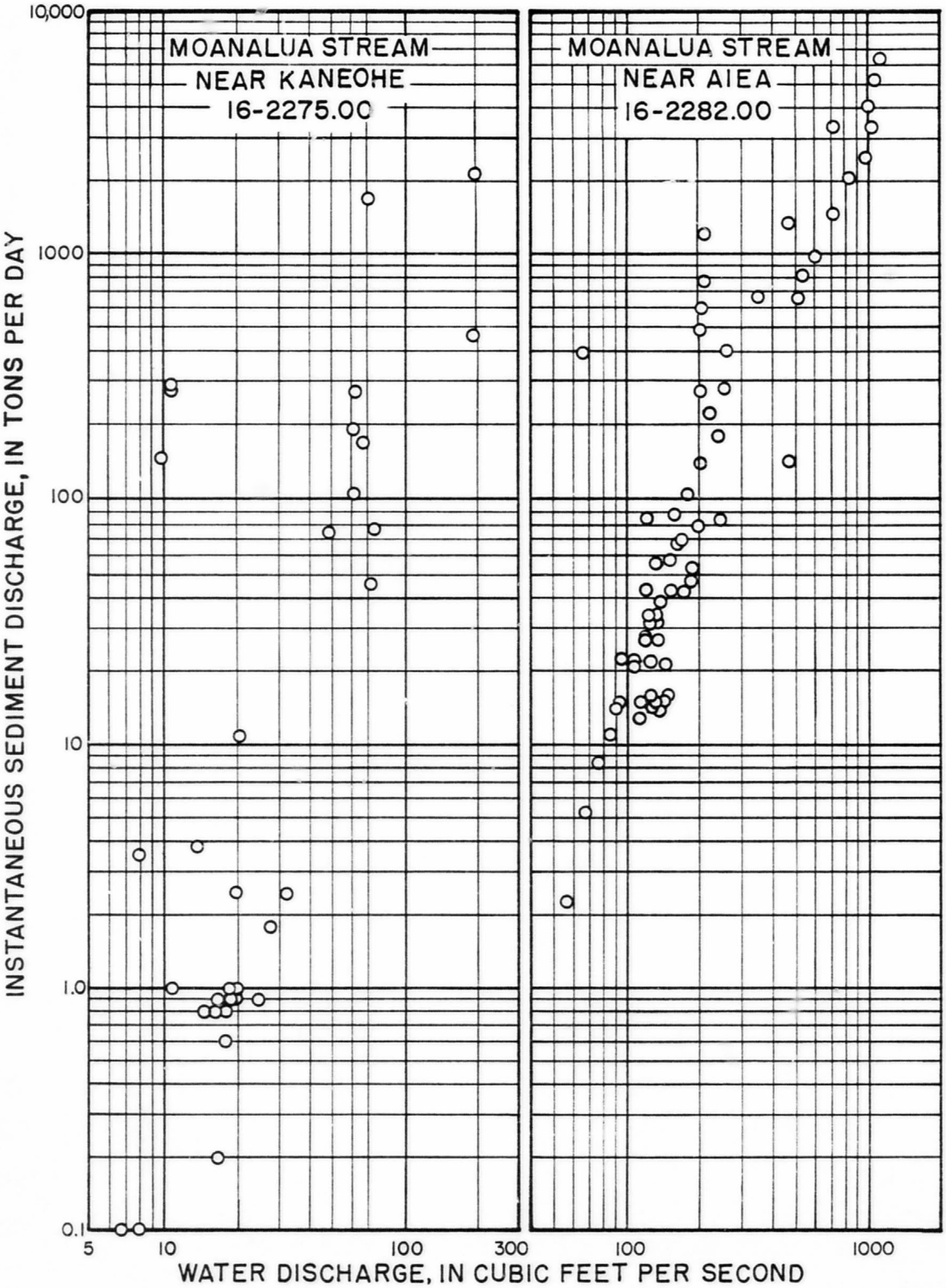

Figure 12. Instantaneous water discharge versus suspended-sediment discharge at the two mainstream sampling sites.

Available particle-size information is meager; but on the basis of similarity with other streams on Oahu, some observations can be made: (1) Only 10 percent or less of the suspended load is in the sand (0.062-2.0 mm) size range. Field observations indicate that most particles in this size range are actually soft aggregates representing the final weathering products of basalt. (2) The high proportion of clay (< 0.004) creates high turbidity even at relatively low concentration; because of the great particle surface area per unit of weight. (3) There is a paucity of material in the coarse sand and fine gravel range, indicating the peculiarities of the weathering process. The result is a quite distinct break between suspended load and bedload transport. (4) Most suspended sediment is derived from sources outside the channel and, because it consists mostly of fine material, moves completely out of the system with each flood. Exceptions may occur when tributary flow caused by local showers is completely absorbed by the dry mainstream channel, leaving residual fine material to be transported by the next large storm.

Bedload

Critical Diameter of Particles

The diameter of the largest particle moved under various combinations of channel width, slope, and water discharge can be predicted roughly, using available bedload-discharge equations. For the present theoretical analysis the Schoklitsch (1934) equations were chosen. The equations are simple in form, require only the hydraulic data available from past records, allow analysis for a particular grain size, and relate bedload movement directly to discharge. Other equations were considered that relate particle movement to a shear force operating parallel to the bed, and to the mean particle size, but it is questionable whether the forces causing movement of large particles in fully-developed turbulence can be represented by a pure shear vector; and it is even more questionable whether the wide range of bed-material sizes in Moanalua Stream can be characterized by a single diameter.

The Schoklitsch equation used for predicting the critical diameter of particles was the critical-flow equation:

$$Q_c = \frac{0.0638D}{S^{4/3}} \qquad (1)$$

where Q_c is the critical discharge capable of moving a particle, in cfs per foot of channel width; D is the effective diameter of the particle, in feet, and S is the slope in feet/feet. (In this and subsequent calculations, the specific gravity of sediment is taken as being 2.65.)[3]

Transformation of equation (1) to:

$$D_c = Q_o \left(\frac{S^{4/3}}{0.0638} \right) \qquad (2)$$

yields an expression for the critical diameter of a particle, D_c, for any given combination of discharge, Q_o, and slope, with units the same as in equation (1). By implication, since $Q_o = Q/B$, or total discharge (Q) divided by width (B), D_c also can be shown as a function of channel width. In figure 13, such relations are presented, using the design-discharge for the 50-year flood (about 4,700 cfs). The family of curves representing various slopes all show the increase in critical diameter with decreasing width, (or increasing Q_o). These curves can be used as guides in selecting a stable-channel width for a given diameter of bed material, or in selecting stream training materials.

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[3] This is the abbreviated form of equations used in first approximation engineering calculations. The more general form of equation (1) is: $Q_c = K \left(\frac{\gamma_s - \gamma}{\gamma} \right)^a \frac{d}{S^{4/3}}$, where K and a are constants, γ_s is the specific gravity of the sediment and γ is the specific gravity of water, and other symbols are as defined above.

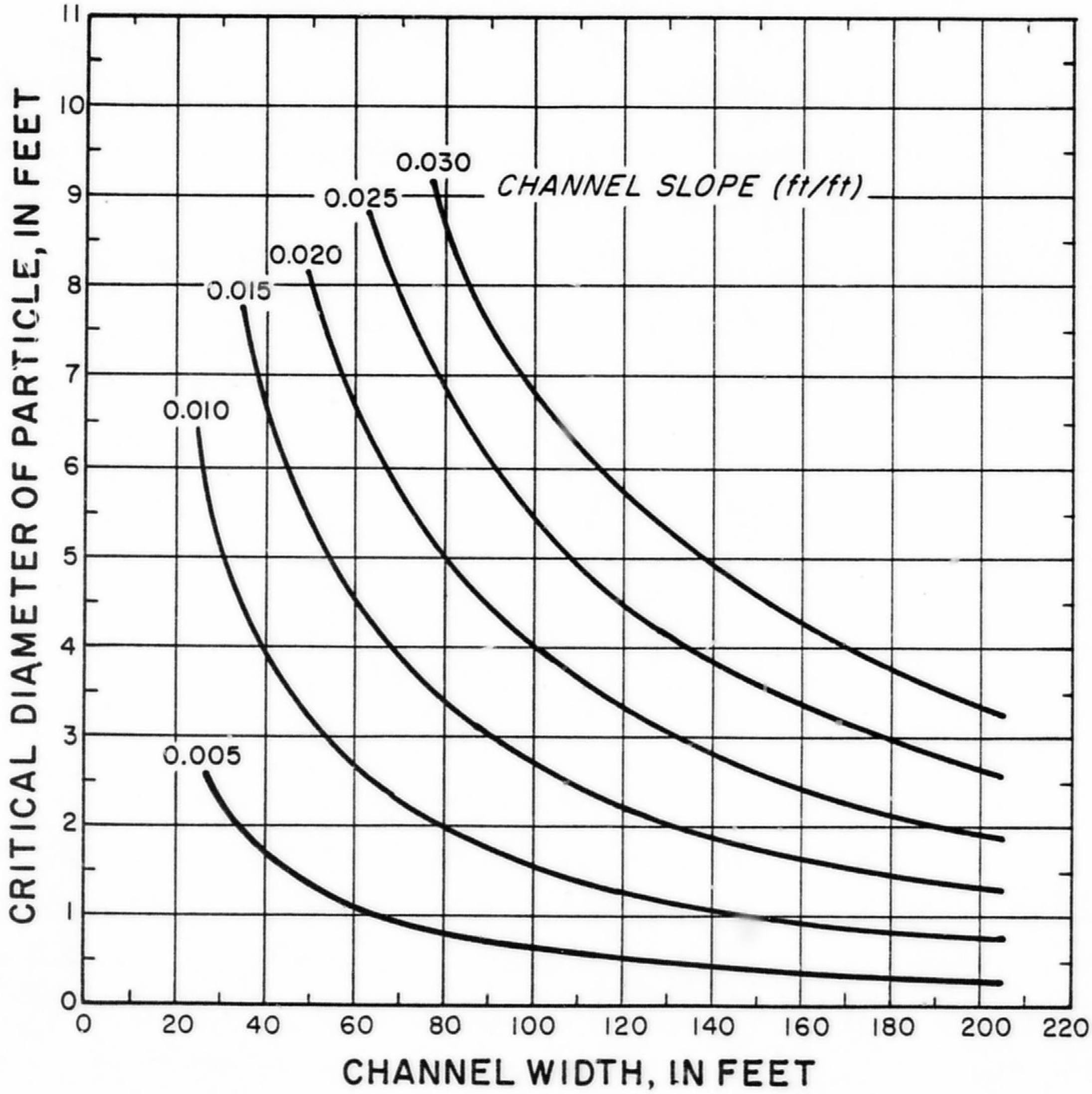

Figure 13. Critical particle diameter for a flow of 4,700 cfs, for various combinations of slope and channel width, according to the Schoklitsch relationship at an assumed specific gravity of sediment of 2.65.

It must be emphasized that the curves in figure 13 are derived by extension of the Schoklitsch equation to particle sizes far greater than those used to develop the equation--in fact, no generally-accepted procedure has been developed for predicting the movement of particles larger than about 60 mm (0.2 ft). Therefore, such extensions must be considered only as aids to engineering judgment until verified by actual observations. However, if the curves only indicate the order of magnitude, very large particles may be moved by flood flows in a channel as steep and narrow as Moanalua Stream, a conclusion borne out by observation. From figure 13, if the full 4,700-cfs flow were contained in a 30-foot width on a slope of 0.01, particles as much as 5 feet in diameter might be transported.

Anderson and others (1970) show tentative design curves for riprap (p. 19-21). Although the procedure used is not directly comparable, their curves indicate that for a slope of 0.01 and for flows and velocities likely to be encountered in Moanalua Stream, stable riprap would require an average diameter considerably in excess of 600 mm (about 2 ft).

Bedload-Discharge Computations

Although a complete rating of bedload for the entire range of water discharge cannot yet be made, theoretical ratings were developed, using the Schoklitsch equation:

$$G_o = 25 \frac{S^{3/2}}{D^{1/2}} (Q_o - Q_c) \qquad (3)$$

where G_o is bedload discharge, in lb/sec/ft width, and other symbols and units are as shown in equation (1).

Size distribution of bed material was assumed to be that shown in the composite sample (table 4). Available hydraulic data are given in table 7. A bedload-transport curve, (fig. 14), was developed by drawing a smooth curve through the computed-bedload discharge at the tabulated flows. This curve was then applied to the design-flow hydrograph at $\frac{1}{4}$-hour intervals to produce a table of equivalent bedload-discharges (table 8). Computed bedload for the 50-year design flood was 2,600 tons. Equivalent volume of deposited sediment would be about 47,000 cubic feet (110 lb/cu ft dry weight). Bedload during an actual 50-year flood would probably be greater, because high-flow conditions would persist longer than the $5\frac{1}{4}$-hour period, and bank erosion and landslides might make available a large supply of debris.

Table 7. Hydraulic characteristics of flows measured at gage 16-2280, Moanalua Stream near Honolulu

Measurement number	Date	Discharge (cfs)	Width (ft)	Mean depth (ft)	Slope (ft/ft)	Mean velocity (fps)	Computed [1] bedload discharge (tons/day)
3	Nov. 19, 1927	84	33.0	1.76	0.024[2]	1.44	0
98d	Dec. 21, 1955	97	20.5	1.71	.024	2.78	309
99d	Dec. 21, 1955	86	20.5	1.61	.024	2.56	25
115	Oct. 23, 1958	123	26.0	2.10	.024	2.24	392
143	Nov. 15, 1965	119	23.8	2.25	.024	2.23	411
152	Jan. 27, 1968	81	29.5	1.63	.024	1.68	0
Indirect (slope-area)	May 14, 1963	3,400[3]	109 [3]	--	.024	--	20,400

1/ Computed from Schoklitsch equation.

2/ Measured slope, from indirect measurement of 5/14/63; used as slope for computations at other flows.

3/ Effective width for bedload computation was 35 feet. Effective water discharge for main channel width was 2,640 cfs (from section no. 3).

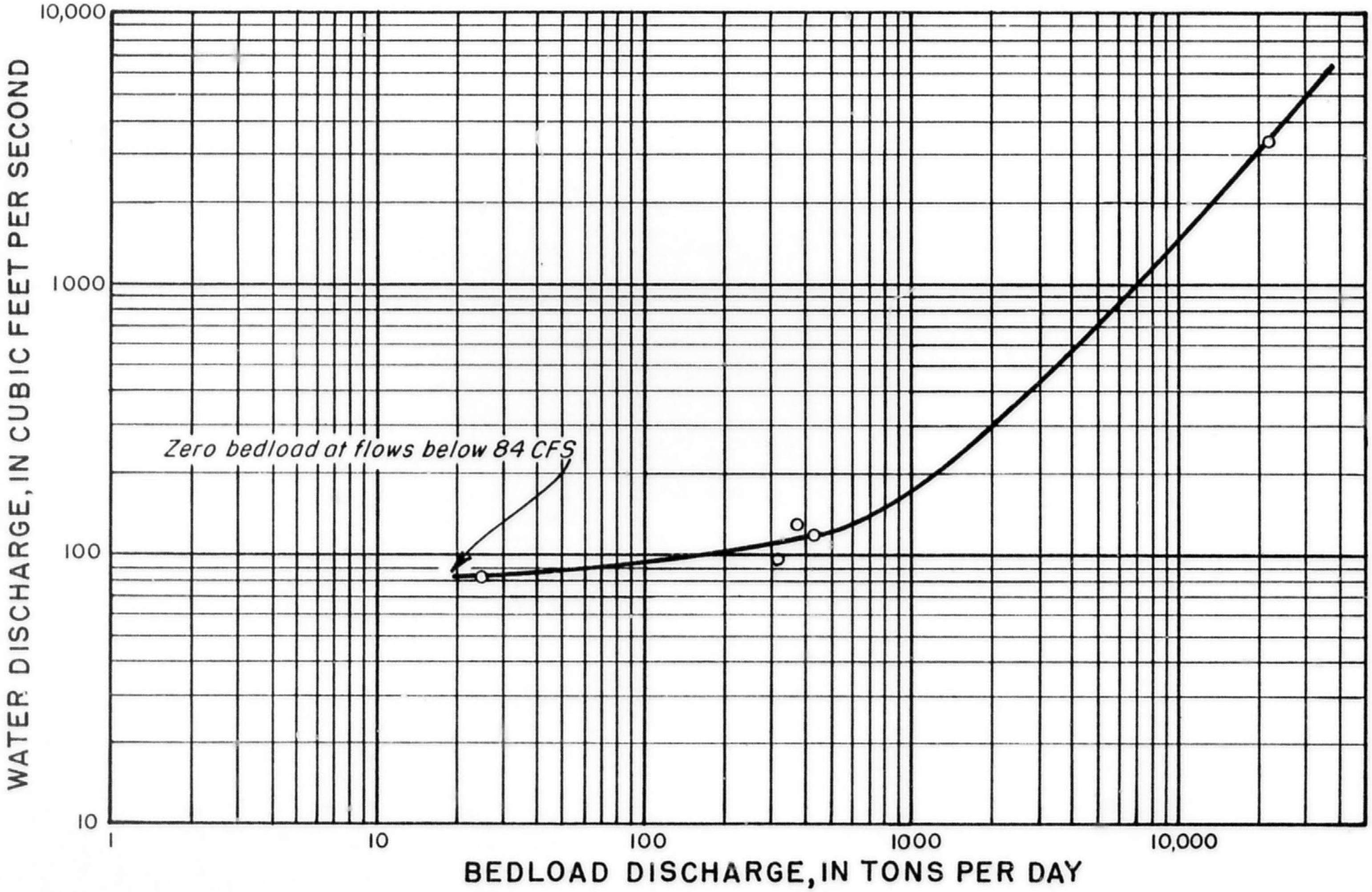

Figure 14. Bedload-transport curve, computed from discharge measurements, Moanalua Stream near Honolulu (2280). Computations by Schoklitsch (1934) equation.

Table 8. Computation of bedload discharge for the design flow[1] hydrograph, existing conditions (peak = 4,650 cfs)

Flow for ¼-hour periods (cfs)	Equivalent bedload discharge (tons/day)	Flow for ¼-hour periods (cfs)	Equivalent bedload discharge (tons/day)
700	5,000	1,400	10,500
3,500	21,000	1,200	8,500
4,400	28,000	1,000	7,000
4,650	29,500	800	5,700
4,300	25,000	600	4,100
3,800	22,500	500	3,400
3,300	20,500	400	2,600
2,800	18,000	300	2,000
2,400	16,000	200	1,200
2,000	13,000	100	140
1,700	12,000		

Total by ¼-hour interval ------------------------------ 255,640

$$\text{Total for storm} = \frac{255{,}640}{4 \times 24} \approx 2{,}600 \text{ tons}$$

[1]From Parsons, Brinckerhoff-Hirota Assoc., 1967, fig. 4A.

Observations of Coarse-Material Movement

About 50 fragments of the old bridges or road-crossing pavement have been located and keyed to reference points in the downstream mile of channel below their origins. The largest of these is an irregular block of bridge material more than 3 feet in its greatest dimension. Unfortunately, this particular block is only 10 yards downstream from the first crossing, so the possibility exists that its present location is the result of bulldozing for crossing construction. However, two other particles of dimensions 2.9 x 1.5 x 0.8 feet and 2.4 x 1.7 x 1.4 feet are in the channel fill 100-300 feet downstream, in a reach showing no evidence of channel rectification. These and other particles show a progressive rounding and smoothing in the downstream direction, indicating bedload transport. Well-rounded fragments of mortar and concrete as much as 1 foot in diameter also were found in the most recent debris-basin deposits.

The evidence confirms that large particles are transported quite frequently by flows in Moanalua Stream. Using equation (1) and a stream width of 35 feet, the flow required to move a 2.9-foot diameter particle with an energy slope of 0.024 is 940 cfs, a flow with a return interval of approximately 1.5 years at gage 2280.

Accumulation in the Debris Basin

The debris basin at the downstream limit of the study area serves as a trap for most of the coarse sediment transported from the watershed. Successive level surveys have been performed by U.S. Geological Survey personnel to determine the accumulation. Filling between surveys was as follows:

Period	Net volume of fill (cu ft)	Net weight of fill (tons)[1]
Oct. 2, 1969 - Aug. 7, 1970	34,000	1,900
Aug. 8, 1970 - July 26, 1971	14,000	770

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[1] Assuming deposited unit weight of 110 pounds per cubic feet.

Comparison with Computed Bedload

The bedload-transport curve (fig. 14) was used along with storm hydrographs to compute bedload discharge for the same periods covered by the debris-basin surveys. Results are:

Period	Computed bedload (tons)
Oct. 2, 1969 - Aug. 7, 1970	1,800
Aug. 8, 1970 - July 26, 1971	1,800

It is, of course, coincidental that the computed bedload is the same for both periods. Comparison between measured (2,670 tons) and computed bedload (3,600 tons) for the entire period indicates that the Schoklitsch equation yields results in the proper order of magnitude. Perfect short-term agreement between measured accumulations and computed loads cannot be expected for several reasons:

1) The trap-efficiency of the debris basin is not known. Planned measurements at the downstream end of the lined channel after significant storm events will serve to estimate trap efficiency. Observations indicate the trap efficiency of the debris basin is quite low. Slots in the dam allow material smaller than about one foot in diameter to pass through, although decreased velocities cause most particles this size to settle in the upper part of the debris basin. Since its construction in 1969, the basin has been filled to only a fraction of its capacity. Plans call for periodic removal of material, as required for efficient operation.

2) It is well known that coarse material moves intermittently during the short-duration storm typical of Moanalua. Rapid accumulation during a particular storm may be the result of deposition near the basin during previous storm periods. Observed accumulation over a long period, coupled with cross-section surveys in the reach above the debris basin should help reconcile differences in computed and measured bedload discharge.

3) Initial accumulations in the debris basin may have been partly a result of channel changes made during debris basin construction.

4) Flows used for computing bedload are from the long-term gage (2280), becuse sufficient hydraulic data for developing a sediment-transport curve are available only at that site. Actual flow at the debris basin (and thus the computed bedload) would undoubtedly be greater for a given storm. Further adjustments will be possible when sufficient hydraulic measurements are available near the downstream gage (2282).

SUMMARY

Variations in rainfall within Moanalua Valley can be pronounced for storms. With the exception of the storm of July 25, 1970, and the estimates made for rain gage 2275.01 for the storm of April 5-6, 1971, storm rainfall decreased with decreasing elevation. The rain-gage network (density and recording interval) gives adequate coverage to storm events.

The storm hydrographs are of a steep-sided, triangular shape, very similar to other small Hawaiian watersheds. Time to peak is short, especially for the two upstream subregions (stations 2275 and 2277). For the five storms covered in the report, the hydrograph shape is essentially translated downstream from the confluence of the two main tributaries. There appears to be significant inflow between stations 2280 and 2282 for storms in which there is a significant amount of rainfall in the mid and lower parts of the valley. For periods of essentially equal rainfall, some differences in runoff volume attributable to basin characteristics can be noted for the two upper subregions. Data indicate that the basin upstream from station 2275 generates a larger volume of runoff.

The February 1, 1969 storm produced the maximum peak discharge at station 2282 (2,950 cfs) for the period covered by this report.

A fairly good correlation exists between the flood peaks observed at station 2280 and those for station 2282. Preliminary estimates indicate that the 50-year flood at gage 2282 would probably be in the range of 5,500 to 6,000 cfs.

Preliminary results from the limited use of the U.S. Geological Survey's rainfall-runoff model have been encouraging. The calibration phase based on 10 storms for the basin upstream from station 2275 produced a reasonable correlation between simulated and observed peaks. Because of the variations in rainfall, the weighted combination of two rainfall inputs produced the best results. It is expected that data on future storms, especially major storms, and experimentation with various rainfall-distribution schemes and subsequent recalibration of the model will yield significantly better results.

Some preliminary work using the Corps of Engineer's HEC-1 flood hydrograph package has been accomplished, and the results are available at the Hawaii District office of the U.S. Geological Survey.

Data collected through July 1972 indicate that Moanalua Stream has a considerable capability of transporting sediment, both as bedload and as suspended sediment. Observations and calculations by the Schoklitsch formulae indicate the stream often moves material in excess of 2 feet in diameter. One mortar-covered particle 2.9 x 1.5 x 0.8 feet has been observed in the bed material, and is assumed to have been transported by the stream from an old bridge several hundred feet upstream. Calculations indicate that a particle this size would be moved by a flow of about 940 cfs, a flow likely to occur at the 2280 gage about once every 1.5 years.

Between October 2, 1969 and July 26, 1971, about 48,000 cubic feet, or 2,700 tons of coarse material has accumulated in the debris basin. Computed bedload for the same period, by the Schoklitsch equation was 3,600 tons. Similar computations, using the design hydrograph for a 50-year flood with a peak of 4,650 cfs resulted in a bedload of 2,600 tons, although such a storm would probably result in a much greater bedload because of up-stream occurrences such as landslides and bank erosion.

Suspended-sediment samples collected at gage 2282 were used to compute the suspended-sediment load for the storm period January 22-24, 1972. During the 3-day period, the suspended-sediment load was 554 tons. Of this amount 348 tons were trans-ported by the flood of January 22, a flood with a probable return interval of about 2 years.

Rough calculations of suspended-sediment load, using the instantaneous relation of water and sediment discharge at gage 2282, resulted in a storm load of 12,000 tons for a flood similar to the design flood; or a load equivalent to 4.6 times the com-puted bedload discharge.

PLANS FOR FUTURE STUDY

A detailed outline of future study effort in Moanalua Valley is shown in table 1. In general, future plans are:

1. To continue the collection of data on hydrology and sedimentation.

2. To document watershed conditions, especially changes, during the course of the study.

3. To relate the runoff and sediment data to the rainfall and watershed factors in such a way as to produce usable mathematical models of the interrelations of all relevant factors.

4. To optimize and generalize model designs for maximum transfer value to other Hawaiian-type watersheds.

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APPENDIX 1

SUMMARY OF SUSPENDED-SEDIMENT CONCENTRATION INFORMATION, MOANALUA STREAM

Appendix 1. Summary of suspended-sediment concentration information, Moanalua Stream. (Data collected after September 30, 1970 are provisional, and are subject to revision.)

Station No. 16-2275: Moanalua Stream near Kaneohe, Oahu

Date	Time	Discharge (cfs)	Sediment concentration (mg/l)	Instantaneous sediment discharge (t/dy)
Nov. 14, 1969	1420	19	23	1.2
Nov. 20, 1970	1505	9.7	212	5.6
Jan. 28, 1971	1115	2.1	6	0
Feb. 1, 1971	1130	1.8	3	0
Feb. 1, 1971	1145	2.0	4	0
Dec. 19, 1971	0630*	14	83	3.1
Dec. 19, 1971	0645*	30	38	3.1
Dec. 19, 1971	0700*	28	24	1.8
Dec. 19, 1971	0715*	25	14	.9
Dec. 19, 1971	0730*	20	16	.9
Dec. 19, 1971	0745*	18	12	.6
Dec. 20, 1971	1500	1.3	3	0
Jan. 25, 1972	1100*	1.4	7	0
Feb. 18, 1972	0840*	20	46	2.5
Feb. 22, 1972	1330	1.3	2	0
Feb. 22, 1972	1445	.99	0	0
Feb. 23, 1972	1025	17	5	.2
Feb. 27, 1972	1705	.79	1	0

Appendix 1. Summary of suspended-sediment concentration information, Moanalua Stream (continued)

Station No. 16-2275: Moanalua Stream near Kaneohe, Oahu (continued)

Date	Time	Discharge (cfs)	Sediment concentration (mg/l)	Instantaneous sediment discharge (t/dy)
Mar. 3, 1972	0215*	11	33	1.0
Mar. 7, 1972	1530	.83	1	0
Mar. 9, 1972	1115	.55	0	0
Apr. 4, 1972	1030*	19	18	.9
Apr. 4, 1972	1040*	20	19	1.0
Apr. 4, 1972	1100*	20	18	1.0
Apr. 4, 1972	1115*	19	19	1.0
Apr. 4, 1972	1130*	18	21	1.0
Apr. 4, 1972	1140*	17	20	.9
Apr. 4, 1972	1200*	16	19	.8
Apr. 4, 1972	1215*	15	19	.8
Apr. 6, 1972	1740*	72	243	47
Apr. 6, 1972	1755*	77	377	78
Apr. 6, 1972	1810*	64	1580	273
Apr. 6, 1972	1830*	72	5490	1070
Apr. 6, 1972	1855*	62	1150	193
Apr. 6, 1972	1910*	69	925	172
Apr. 6, 1972	1925*	63	617	105
Apr. 14, 1972	2145*	49	554	73
Apr. 14, 1972	2205*	106	1080	309

Appendix 1. Summary of suspended-sediment concentration information, Moanalua Stream (continued)

Station No. 16-2275: Moanalua Stream near Kaneohe, Oahu (continued)

Date	Time	Discharge (cfs)	concentration (mg/l)	Instantaneous sediment discharge (t/dy)
Apr. 14, 1972	2320*	194	4060	2130
Apr. 17, 1972	0945	22	177	11
Apr. 17, 1972	1000	17	245	11
Apr. 17, 1972	1100	12	994	32
Apr. 17, 1972	1110*	12	985	32
Apr. 17, 1972	1110	12	914	30
Apr. 17, 1972	1115*	11	978	29
Apr. 17, 1972	1115	11	775	23
Apr. 17, 1972	1140*	10	546	15
Apr. 17, 1972	1140	10	492	13
Apr. 17, 1972	1230*	8.0	167	3.6
Apr. 17, 1972	1235	8.0	138	3.0
Apr. 17, 1972	1415	6.1	29	.5
Apr. 17, 1972	1430*	6.1	37	.6
Apr. 17, 1972	1810*	48	399	52
Apr. 17, 1972	1820*	47	490	62

* Sample obtained with automatic pumping sampler USPS-67.

Appendix 1. Summary of suspended-sediment concentration information, Moanalua Stream, Oahu (continued)

Station No. 16-2277: Moanalua Stream tributary near Kaneohe

Date	Time	Discharge (cfs)	Sediment concentration (mg/l)	Instantaneous sediment discharge (t/dy)
Nov. 14, 1969	1315	30	367	30
Nov. 14, 1969	1335	28	197	15
Nov. 20, 1970	1505	9.7	212	5.6
Jan. 28, 1971	1115	2.1	6	0
Feb. 1, 1971		1.8	3	0
Feb. 1, 1971		2.0	4	0
Apr. 17, 1972	1500	1.1	2	0

Station No. 16-2280: Moanalua Stream near Honolulu

Date	Time	Discharge (cfs)	Sediment concentration (mg/l)	Instantaneous sediment discharge (t/dy)
Jan. 14, 1970	1030	45	23	2.8
Feb. 1, 1971	0845	35	26	2.5
Feb. 1, 1971	0930	26	18	1.3
Feb. 1, 1971	1415	14	6	.2
Apr. 20, 1971	1310	133	77	28
Apr. 17, 1972	1530	10	97	2.6

Appendix 1. Summary of suspended-sediment concentration information, Moanalua Stream, Oahu (continued)

Station No. 16-2282: Moanalua Stream near Aiea

Date	Time	Discharge (cfs)	Sediment concentration (mg/l)	Instantaneous sediment discharge (t/dy)
Jan. 3, 1969	1030	113	44	13
Jan. 3, 1969	1405	71	17	3.3
Nov. 14, 1969	1325	30	2020	153
Nov. 14, 1969	1335	28	1750	118
Nov. 27, 1970	1720	223	1720	1040
Nov. 27, 1970	1730	227	1240	760
Nov. 27, 1970	1750	208	887	498
Apr. 20, 1971	0845	246	271	180
Apr. 20, 1971	1105	122	258	85
Apr. 20, 1971	1325	156	132	56
Dec. 20, 1971	1300	6	7	.1
Jan. 22, 1972	0555*	163	1540	678
Jan. 22, 1972	0610*	708	1690	3230
Jan. 22, 1972	0625*	1080	1770	5160
Jan. 22, 1972	0640*	1110	2130	6380
Jan. 22, 1972	0655*	1000	1520	4100
Jan. 22, 1972	0710*	1030	1200	3340
Jan. 22, 1972	0725*	990	953	2550
Jan. 22, 1972	0740*	857	867	2010
Jan. 22, 1972	0750*	702	768	1460

Appendix 1. Summary of suspended-sediment concentration information, Moanalua Stream, Oahu (continued)

Station No. 16-2282: Moanalua Stream near Aiea (continued)

Date	Time	Discharge (cfs)	Sediment concentration (mg/l)	Instantaneous sediment discharge t/dy)
Jan. 22, 1972	0810*	594	617	990
Jan. 22, 1972	0825*	552	541	806
Jan. 22, 1972	0840*	528	460	656
Jan. 23, 1972	0830*	131	94	33
Jan. 23, 1972	0840	131	156	55
Jan. 23, 1972	1015	137	72	27
Jan. 23, 1972	1145*	116	48	15
Jan. 23, 1972	1200*	113	43	13
Jan. 23, 1972	1350	125	129	44
Jan. 23, 1972	1415*	125	65	22
Jan. 23, 1972	1425*	128	47	16
Jan. 23, 1972	1440*	128	44	15
Jan. 23, 1972	1455*	131	42	15
Jan. 23, 1972	1510*	137	41	15
Jan. 23, 1972	1525*	146	68	27
Jan. 23, 1972	1540*	143	39	15
Jan. 23, 1972	1555*	146	41	16
Jan. 23, 1972	1610*	153	104	43
Jan. 23, 1972	1625*	169	150	68
Jan. 23, 1972	1640*	486	107	140

Appendix 1. Summary of suspended-sediment concentration information, Moanalua Stream, Oahu (continued)

Station No. 16-2282: Moanalua Stream near Aiea (continued)

Date	Time	Discharge (cfs)	Sediment concentration (mg/l)	Instantaneous sediment discharge (t/dy)
Jan. 23, 1972	1655*	173	91	43
Jan. 23, 1972	1725*	183	105	52
Jan. 23, 1972	1740*	198	148	79
Jan. 23, 1972	1810*	205	490	271
Jan. 23, 1972	1840*	205	1080	598
Jan. 23, 1972	1910*	183	93	46
Jan. 23, 1972	1940*	242	125	82
Jan. 24, 1972	0640*	94	58	15
Jan. 24, 1972	0655*	91	55	14
Jan. 24, 1972	0725*	86	48	11
Jan. 27, 1972	1120	e 2	1	0
Feb. 22, 1972	1510	e 2	10	.1
Feb. 23, 1972	0845	116	134	42
Feb. 23, 1972	0850*	116	82	26
Feb. 23, 1972	0850	119	85	27
Feb. 23, 1972	0900*	108	72	21
Feb. 23, 1972	0900	108	76	22
Feb. 23, 1972	0925	91	88	22
Feb. 23, 1972	1035	79	40	8.5
Feb. 23, 1972	1100	69	29	5.4

Appendix 1. Summary of suspended-sediment concentration information, Moanalua Stream, Oahu (continued)

Station No. 16-2282: Moanalua Stream near Aiea (continued)

Date	Time	Discharge (cfs)	Sediment concentration (mg/l)	Instantaneous sediment discharge (t/dy)
Feb. 27, 1972	1405	4	3	0
Mar. 3, 1972	0305*	67	2170	393
Mar. 3, 1972	0320*	470	1030	1310
Mar. 3, 1972	0335*	358	698	675
Mar. 3, 1972	0350*	262	568	402
Mar. 3, 1972	0405*	258	408	284
Mar. 3, 1972	0420*	223	374	225
Mar. 3, 1972	0435*	205	250	138
Mar. 3, 1972	0450*	180	208	101
Mar. 3, 1972	0505*	166	175	78
Mar. 3, 1972	0520*	150	140	57
Mar. 3, 1972	0535*	134	106	38
Mar. 3, 1972	0550*	131	97	34
Mar. 3, 1972	0605*	125	96	32
Mar. 3, 1972	1255*	58	15	2.3
Apr. 15, 1972	0010*	246	764	507
Apr. 15, 1972	0025*	274	680	503
Apr. 15, 1972	0040*	262	763	540
Apr. 15, 1972	0055*	208	698	393
Apr. 15, 1972	0110*	173	548	256

Appendix 1. Summary of suspended-sediment concentration information, Moanalua Stream, Oahu (continued)

Station No. 16-2282: Moanalua Stream near Aiea (continued)

Date	Time	Discharge (cfs)	Sediment concentration (mg/l)	Instantaneous sediment discharge (t/dy)
Apr. 15, 1972	0125*	160	570	246
Apr. 15, 1972	0140*	153	622	257
Apr. 15, 1972	0155*	143	620	240
Apr. 15, 1972	0210*	137	780	289
Apr. 15, 1972	0225*	131	1020	361
Apr. 15, 1972	0255*	119	879	282
Apr. 15, 1972	0310*	113	636	194
Apr. 15, 1972	0325*	108	443	129

* Sample obtained with automatic pumping sampler USPS-67.

e Discharge estimated from flow at gage 16-2280.

APPENDIX 2

MASS RAINFALL CURVES, STORM HYDROGRAPHS, AND STORM SUMMARIES FOR SELECTED PERIODS

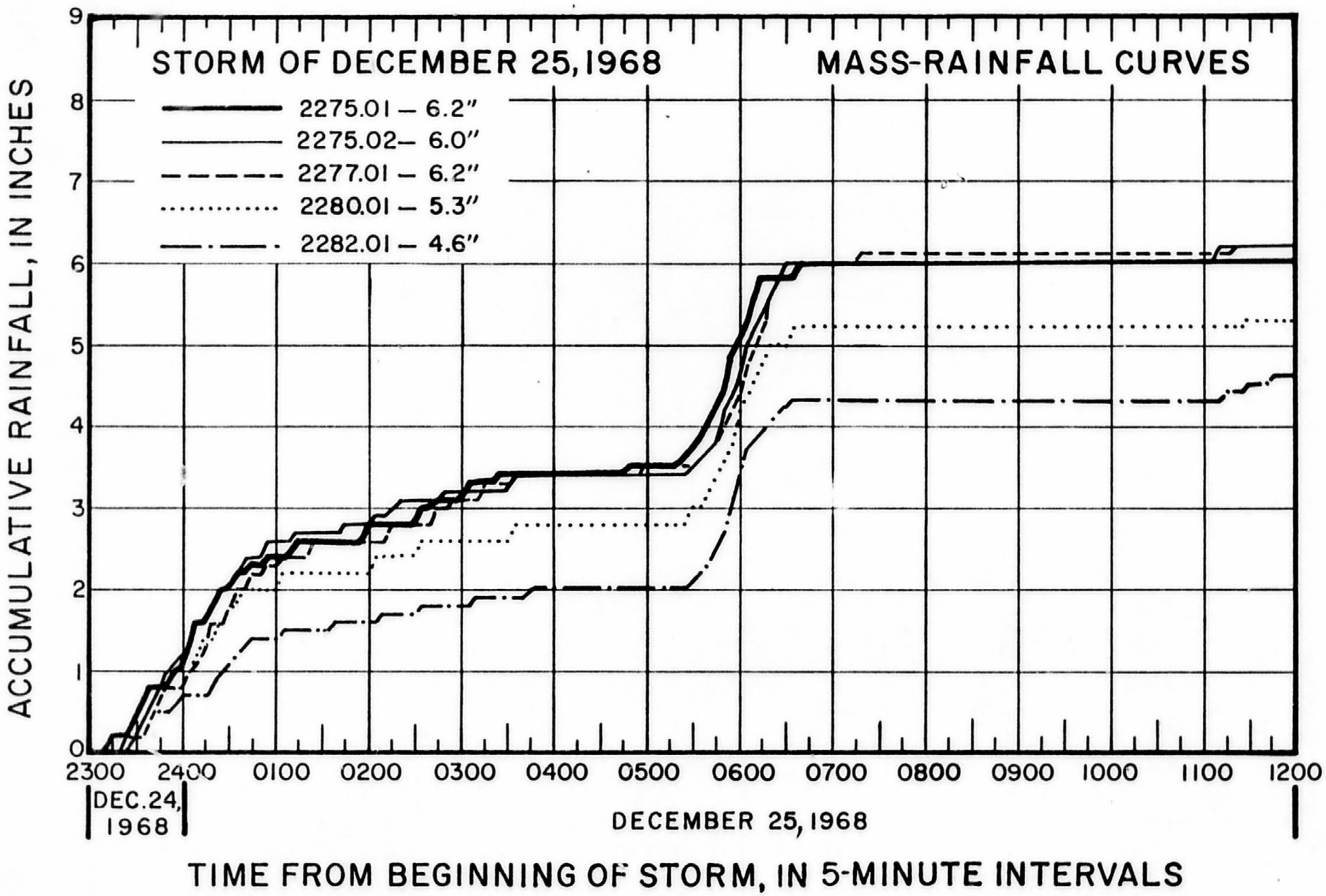

Plate 1. Mass rainfall curves for storm of December 25, 1968, Moanalua Valley.

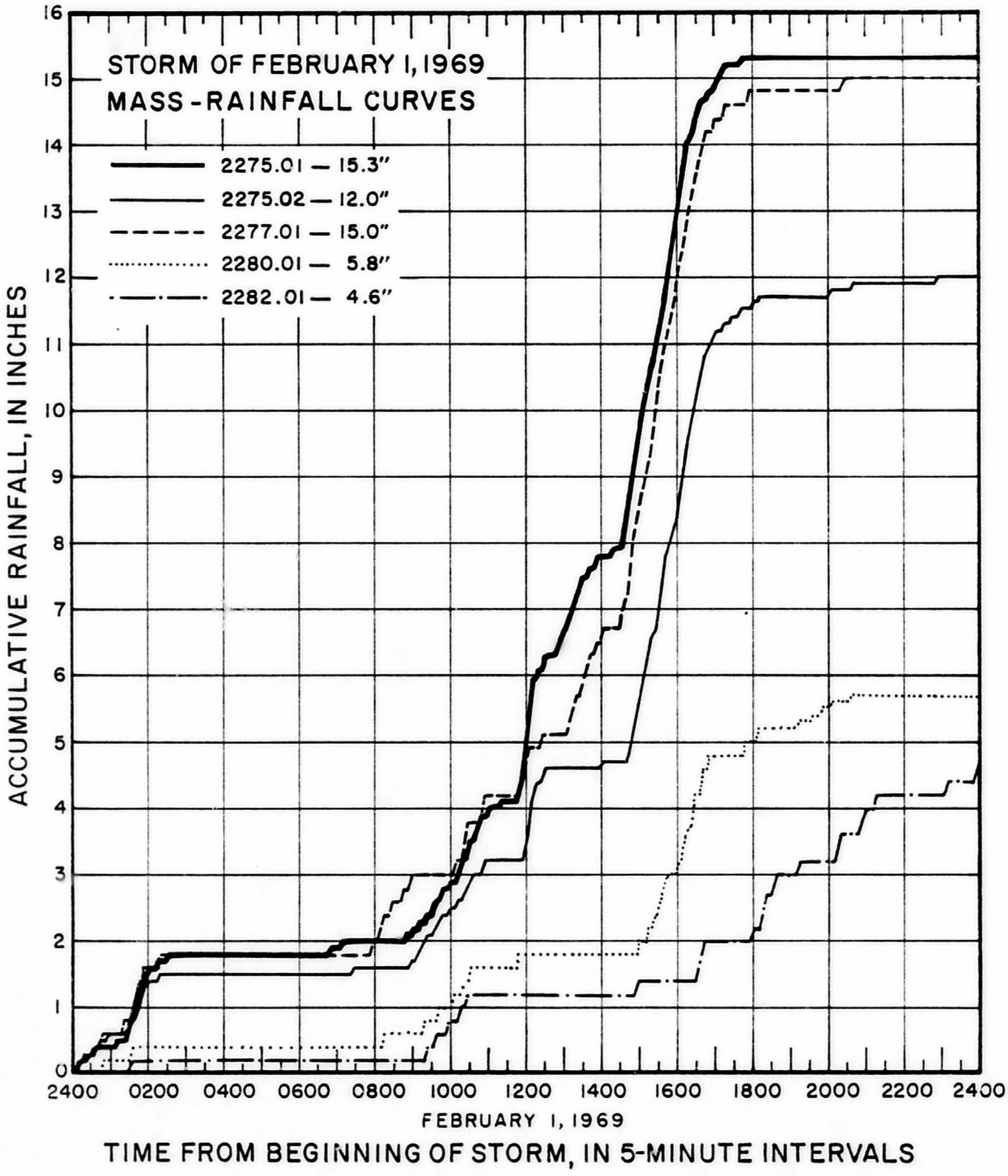

Plate 2. Mass rainfall curves for storm of February 1, 1969, Moanalua Valley.

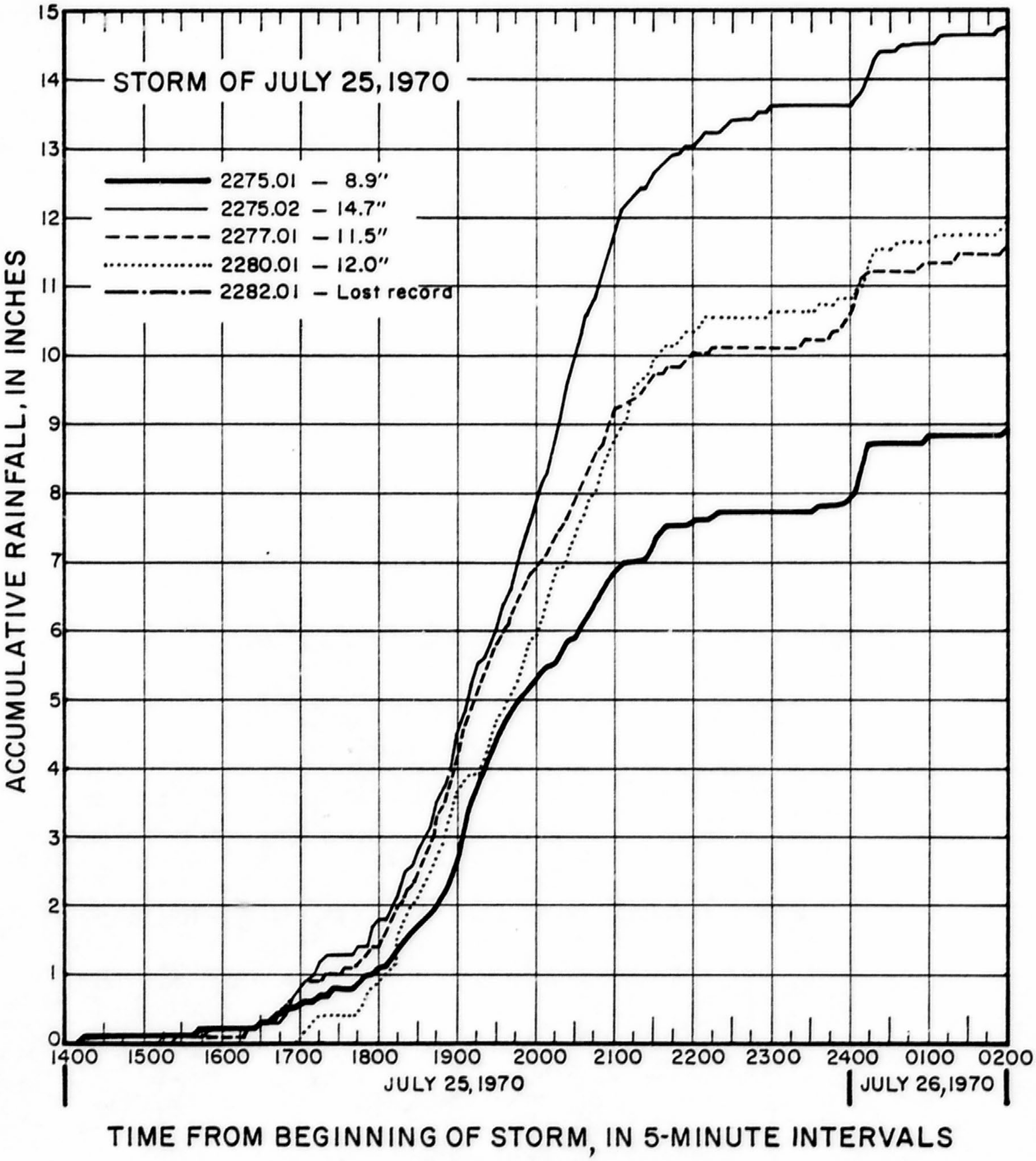

Plate 3. Mass rainfall curves for storm of July 25, 1970, Moanalua Valley.

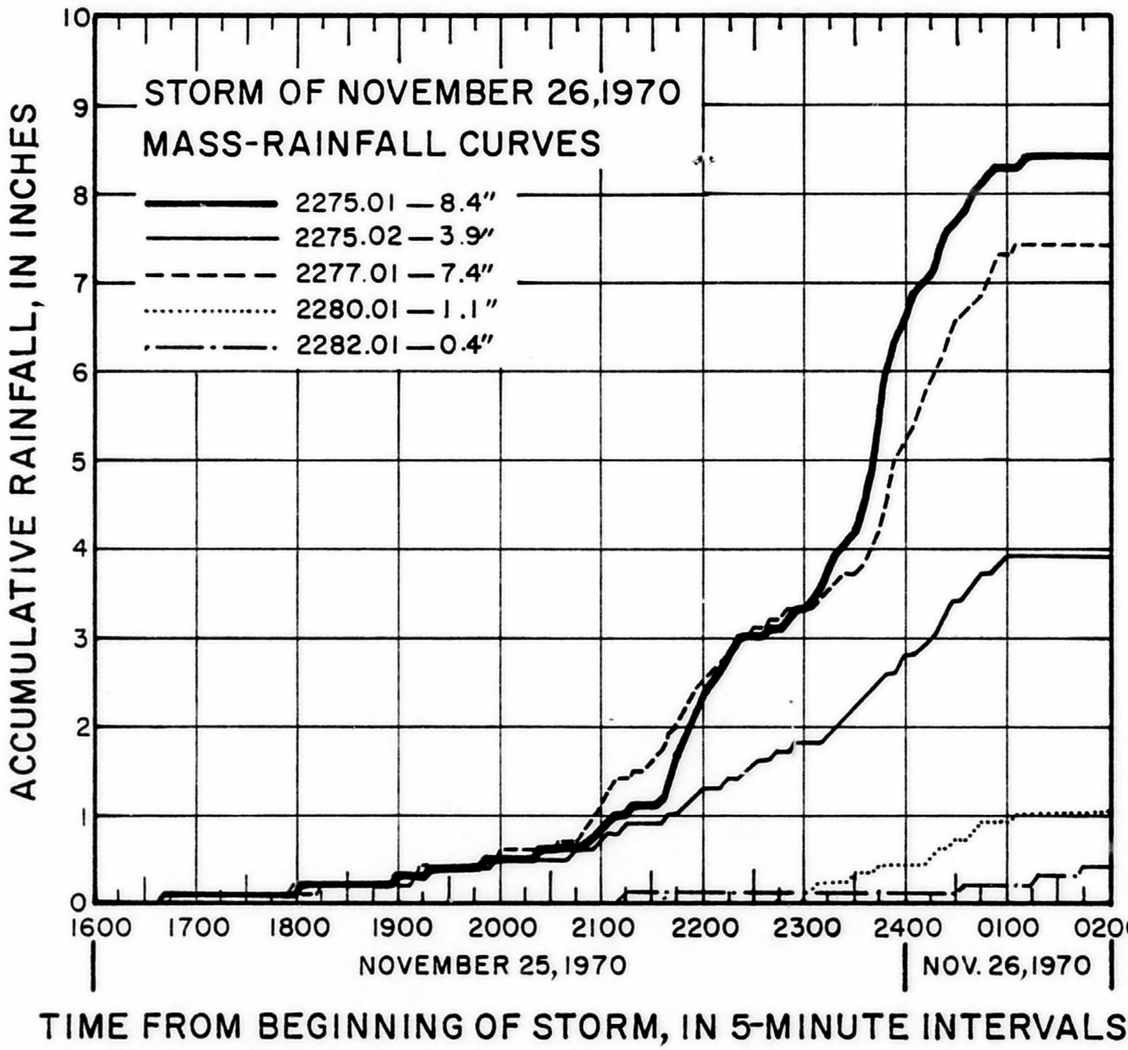

Plate 4. Mass rainfall curves for storm of November 25-26, 1970, Moanalua Valley.

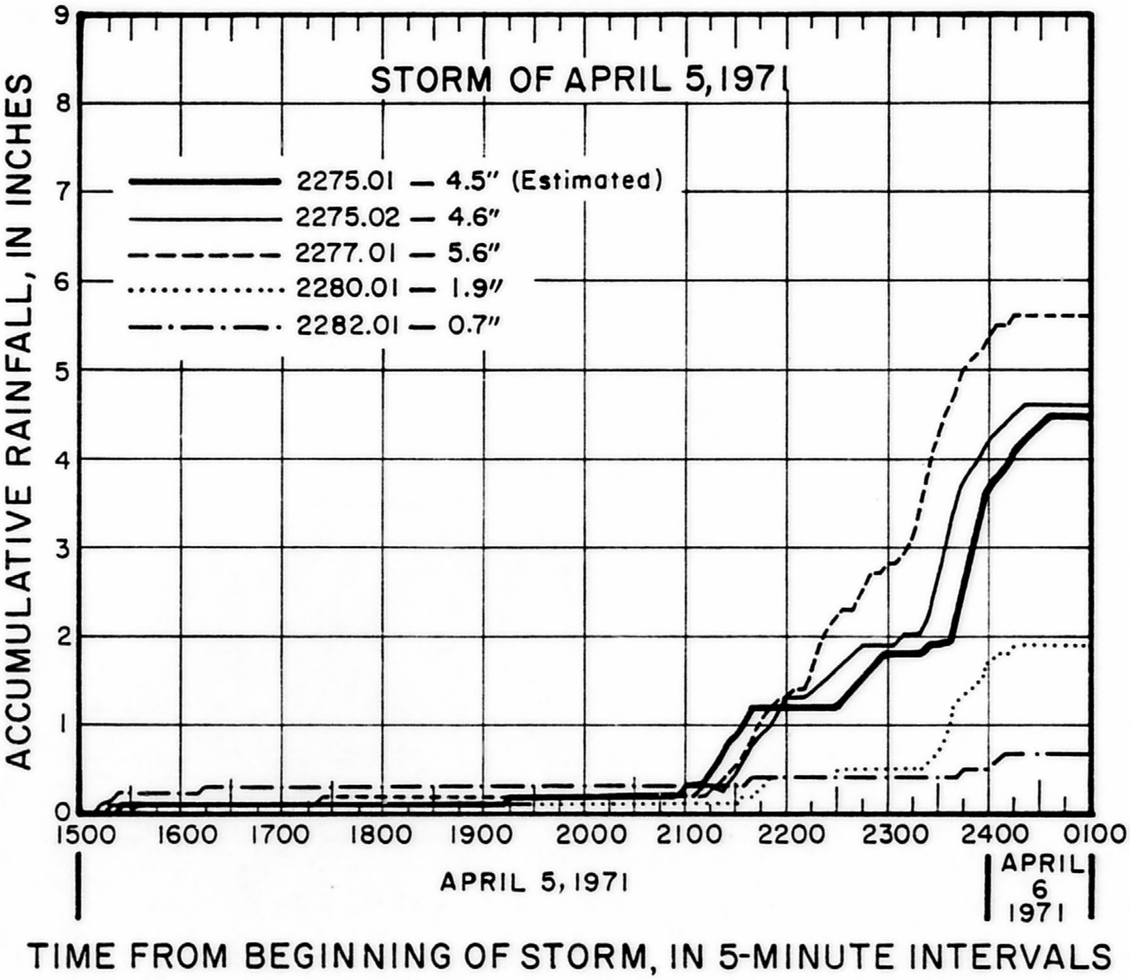

Plate 5. Mass rainfall curves for storm of April 5-6, 1971, Moanalua Valley.

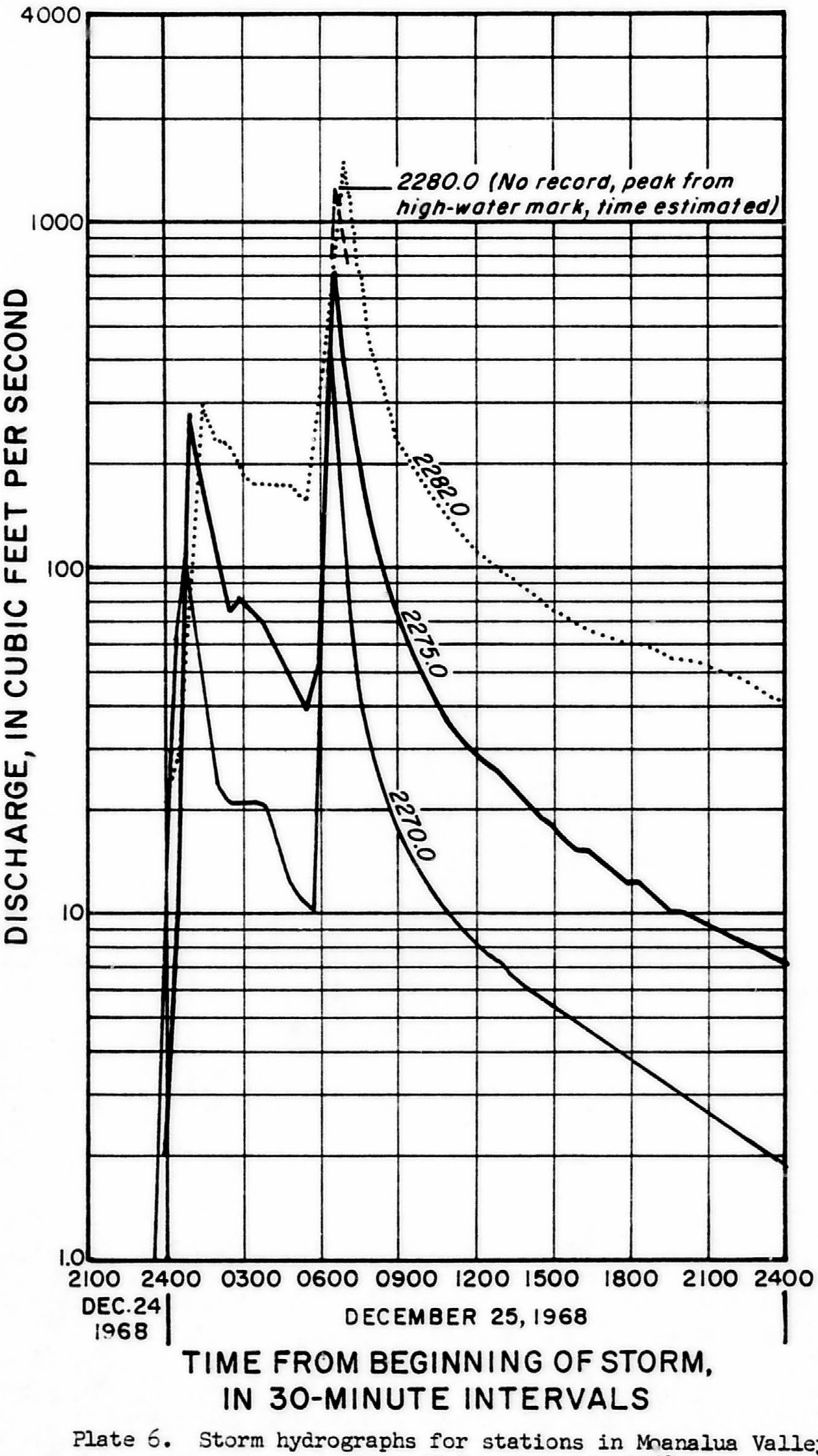

Plate 6. Storm hydrographs for stations in Moanalua Valley, storm of December 25, 1968.

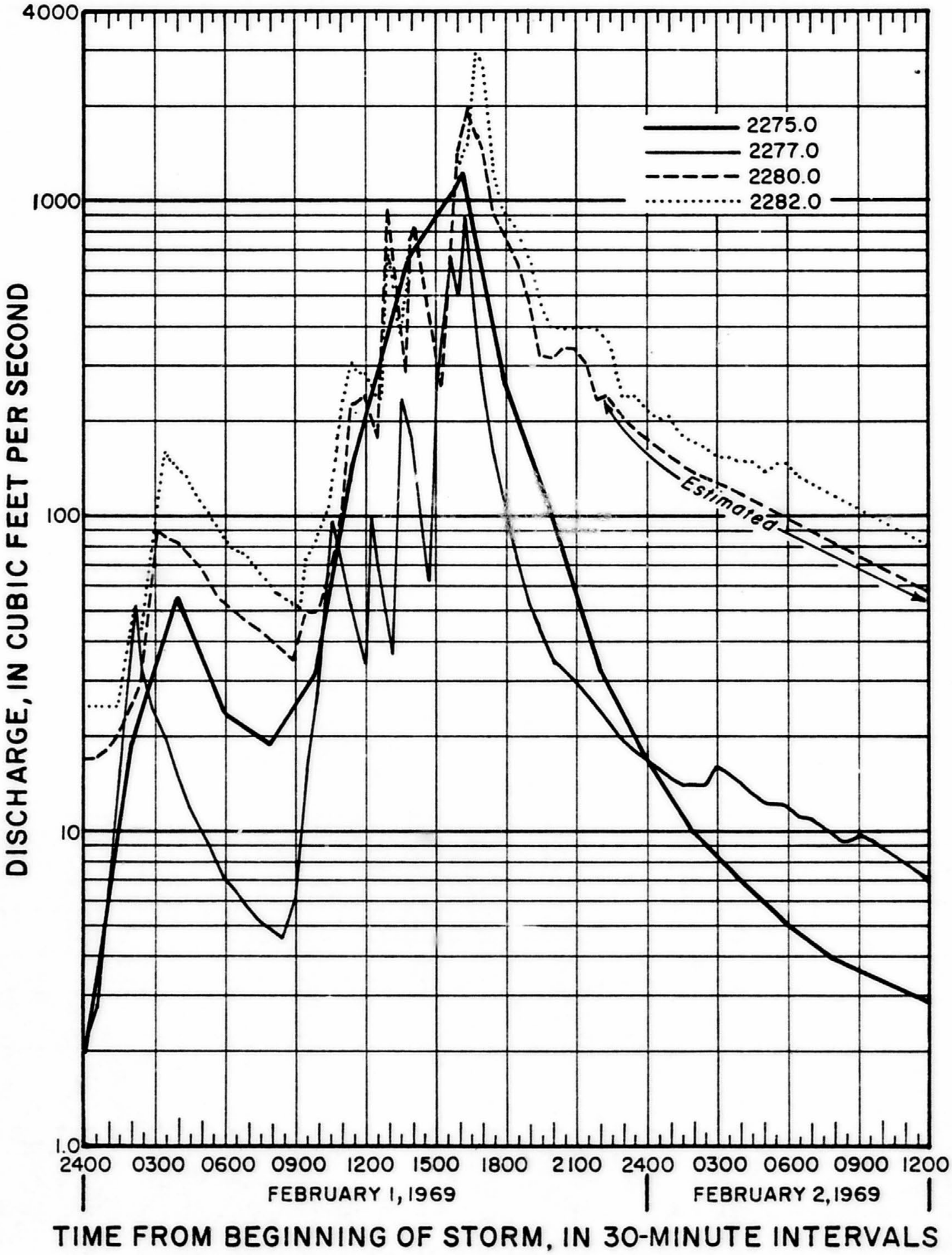

Plate 7. Storm hydrographs for stations in Moanalua Valley, storm of February 1, 1969.

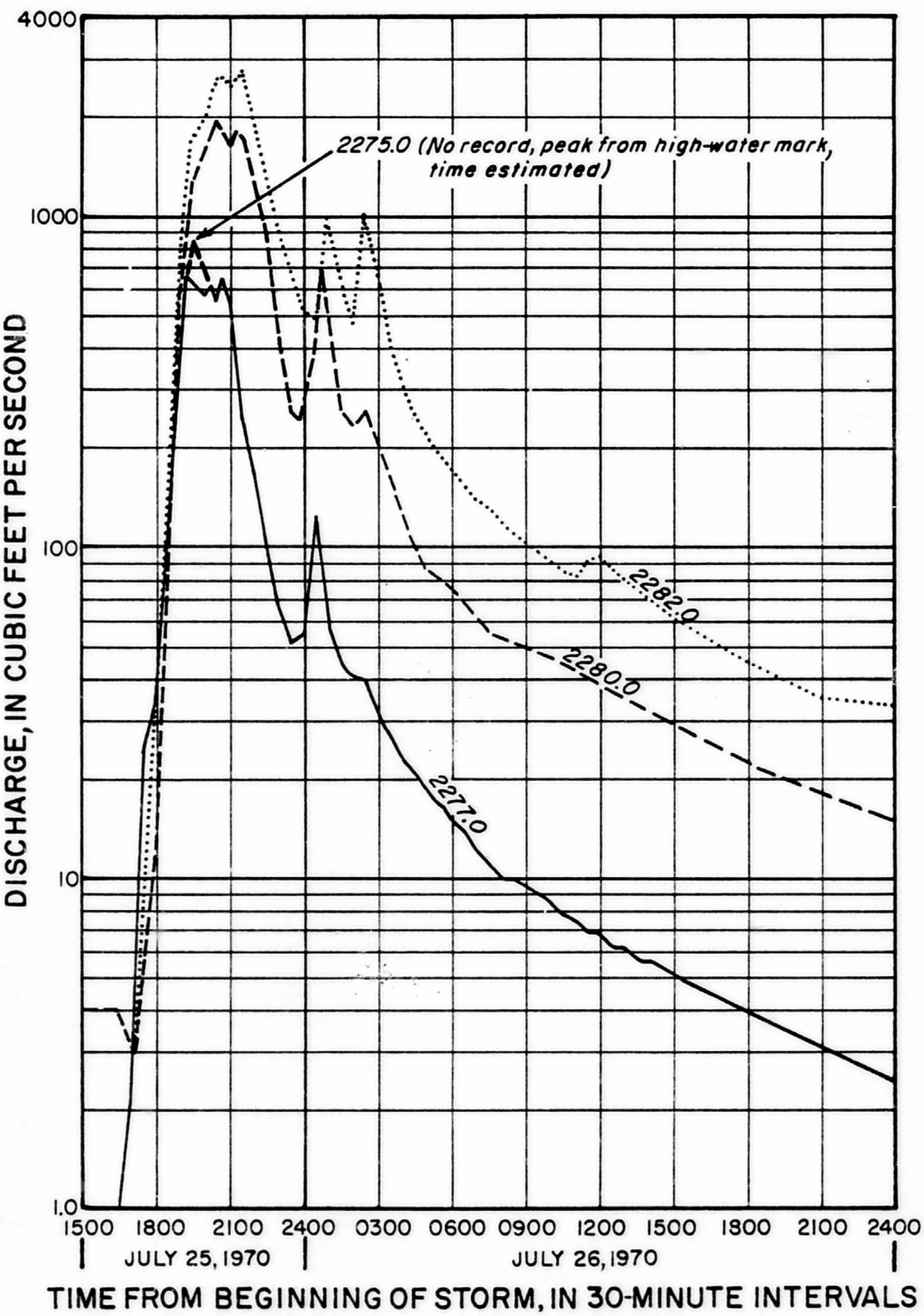

Plate 8. Storm hydrographs for stations in Moanalua Valley, storm of July 25, 1970.

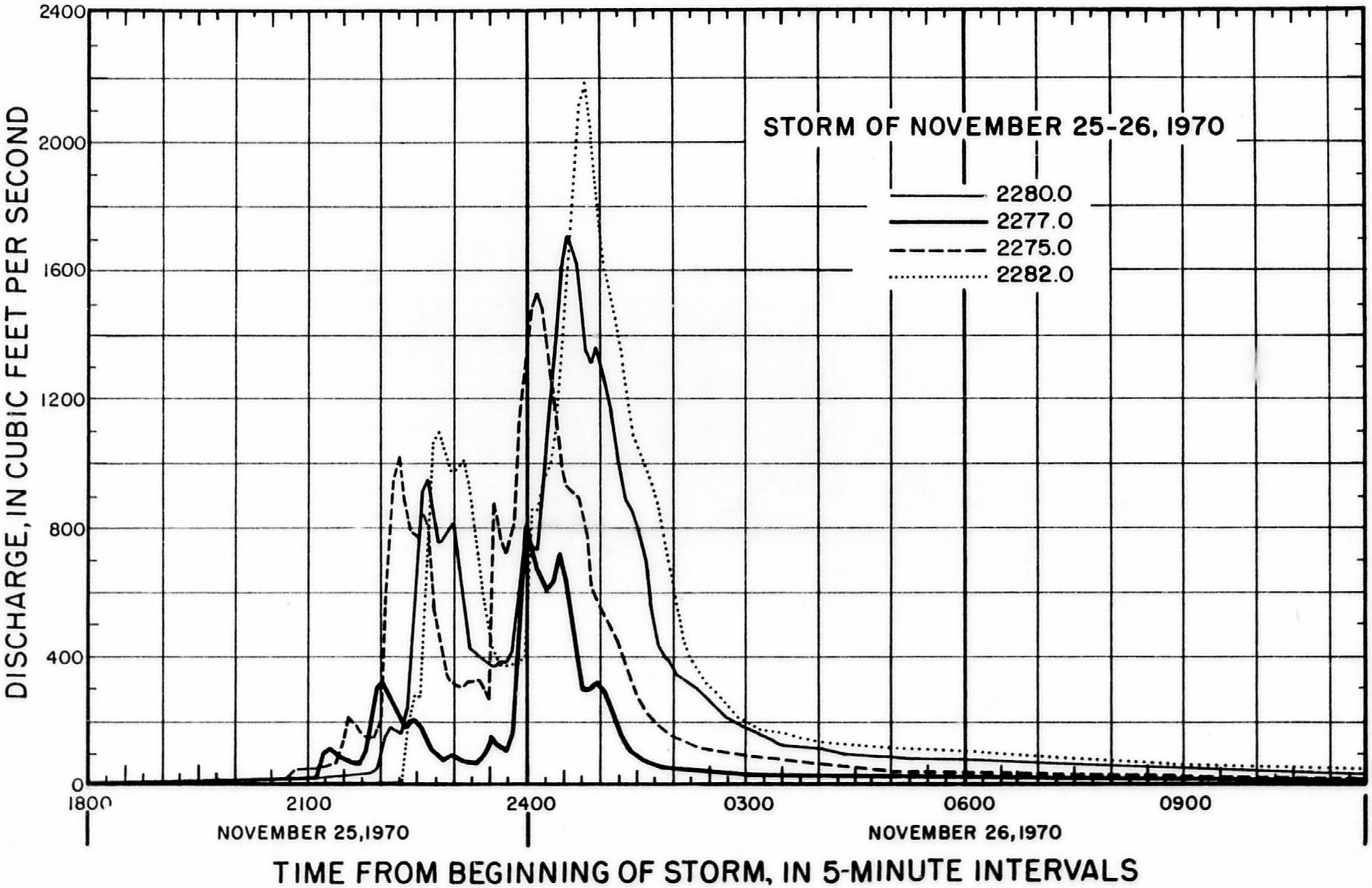

Plate 9. Storm hydrographs for stations in Moanalua Valley, storm of November 25-26, 1970.

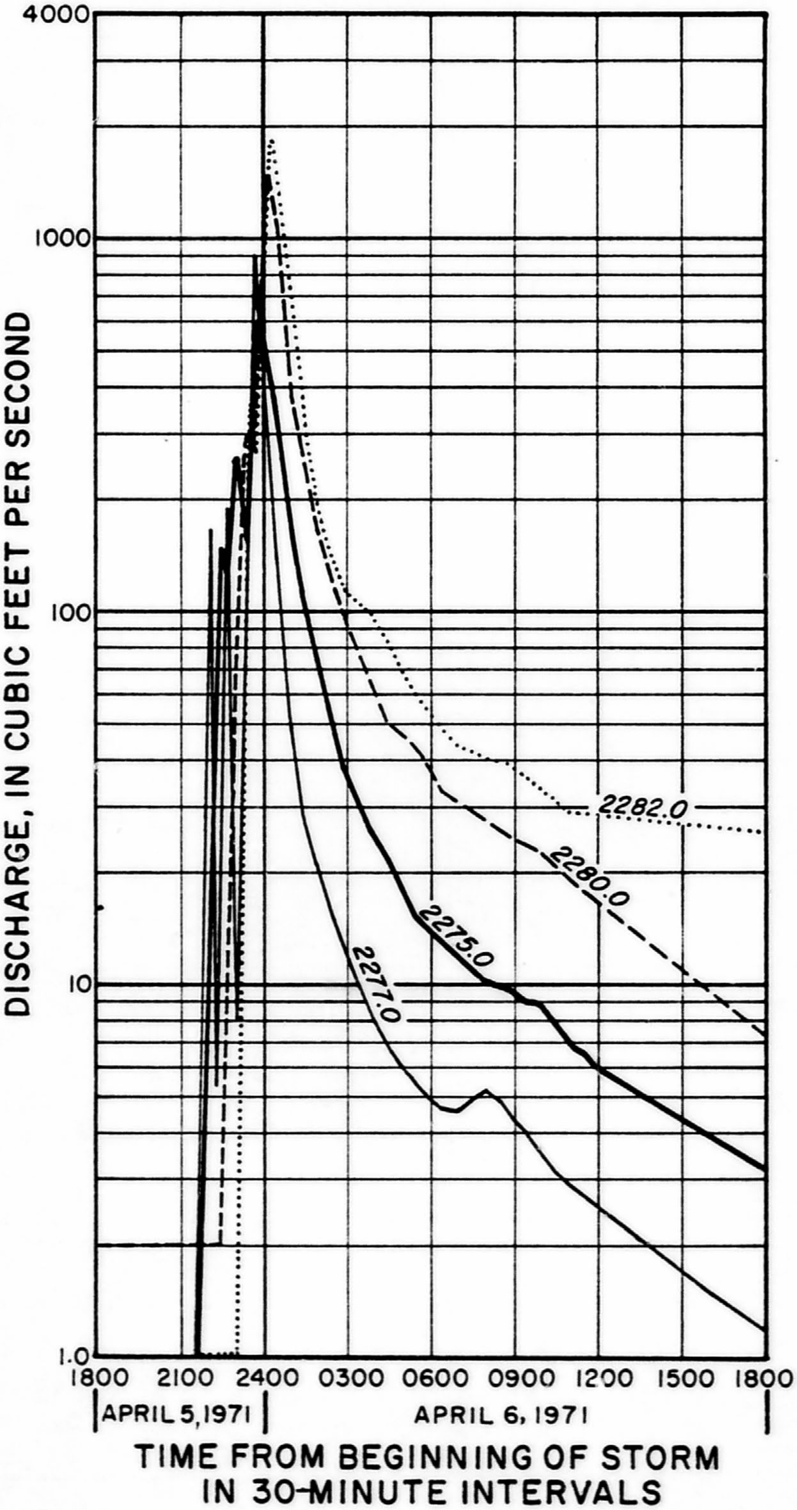

Plate 10. Storm hydrographs for stations in Moanalua Valley, storm of April 5-6, 1971.

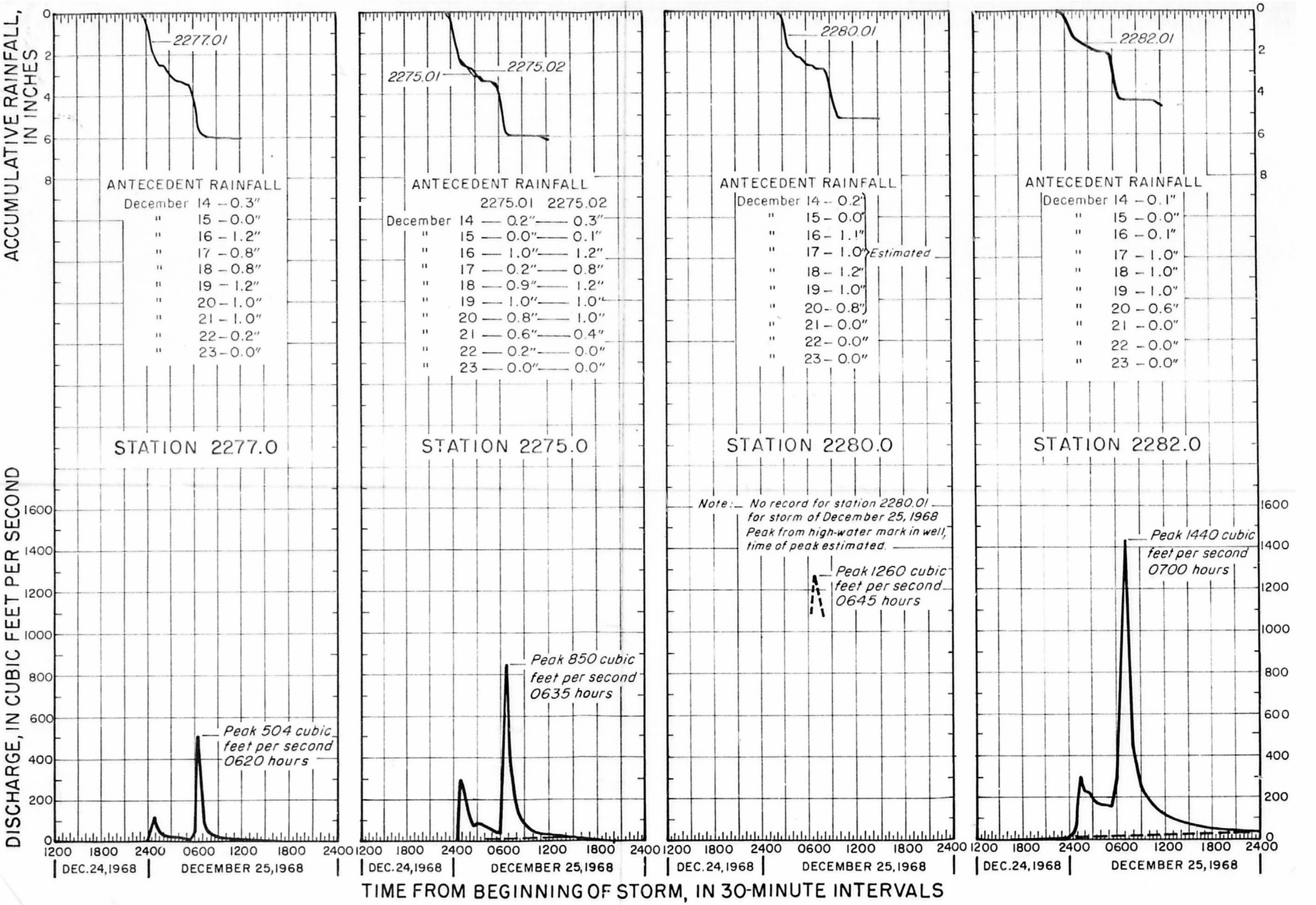

Plate 11. Hydrograph, rainfall mass curve, and 10-day antecedent rainfall for Moanalua Valley hydrologic network, storm of December 25, 1968.

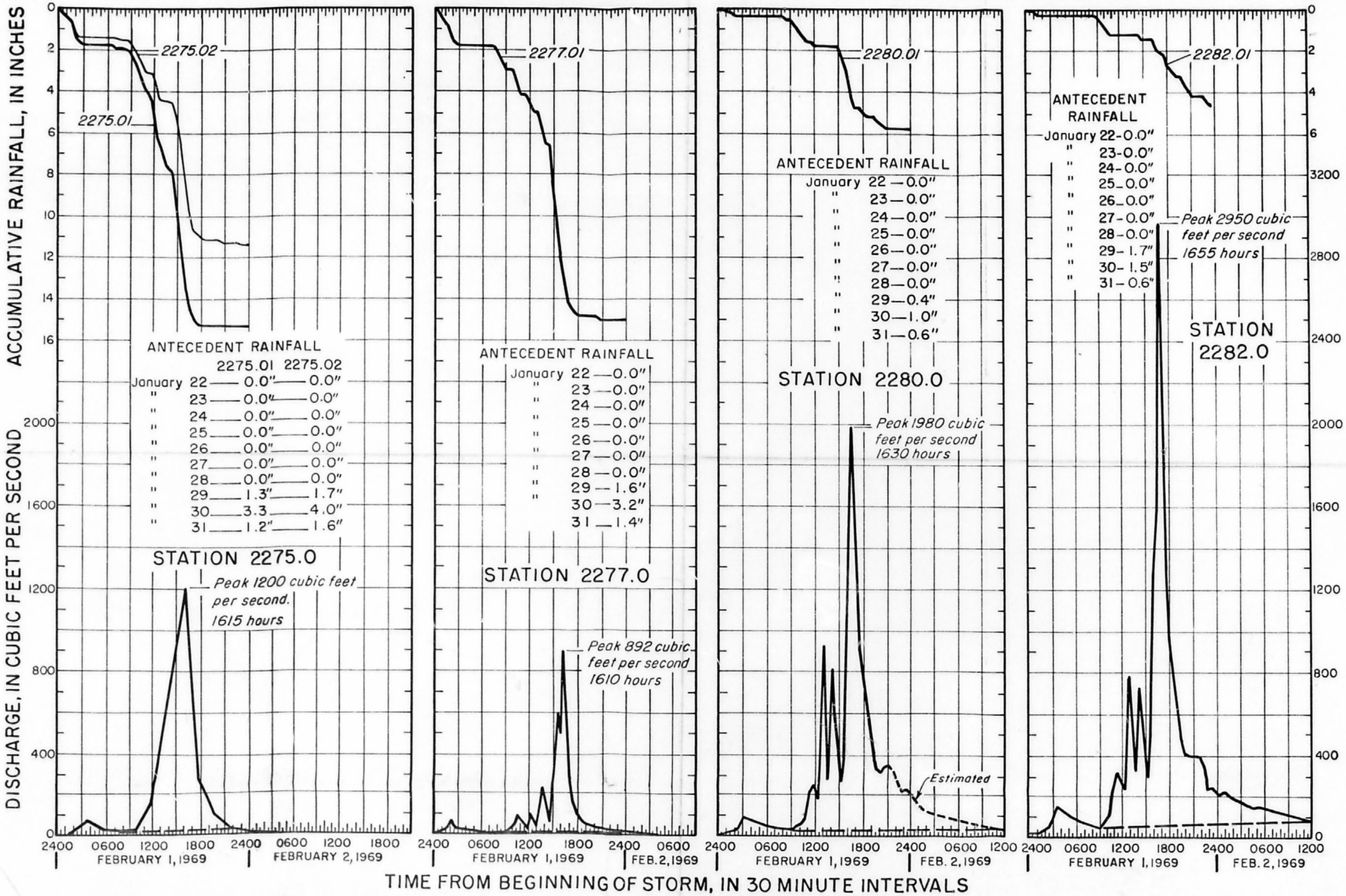

Plate 12. Hydrograph, rainfall mass curve, and 10-day antecedent rainfall for Moanalua Valley hydrologic network, storm of February 1, 1969.

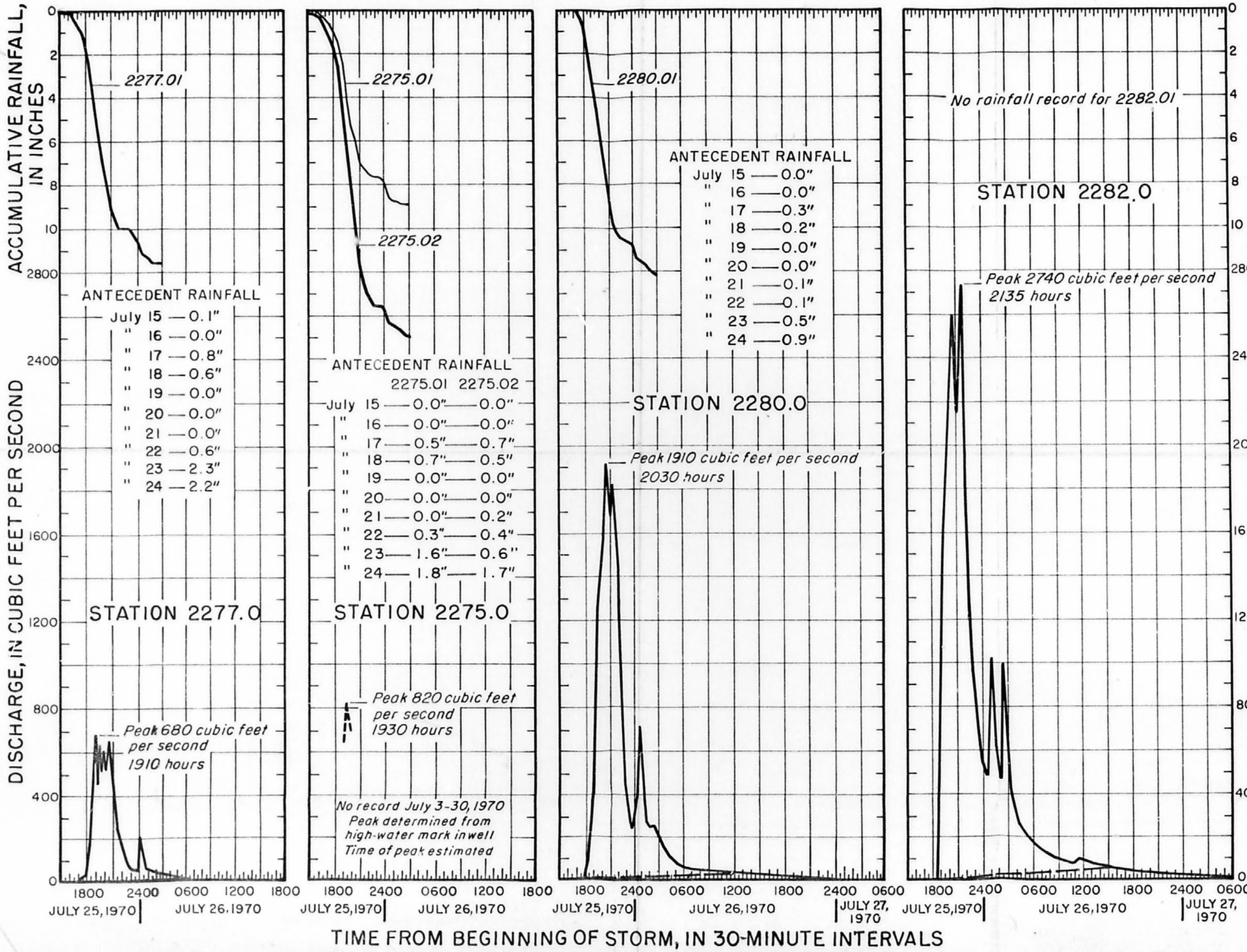

Plate 13. Hydrograph, rainfall mass curve, and 10-day antecedent rainfall for Moanalua Valley hydrologic network, storm of July 25, 1970.

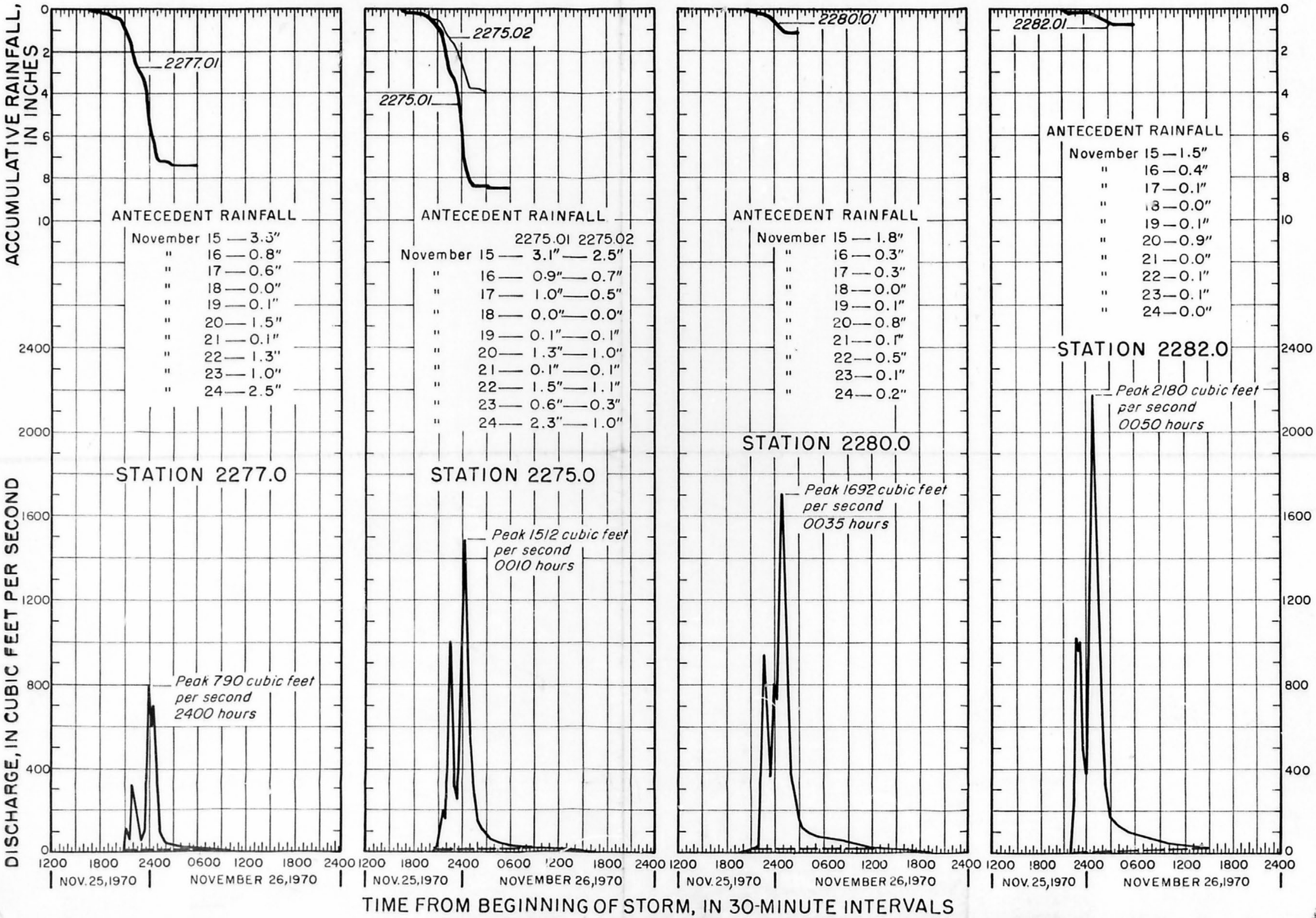

Plate 14. Hydrograph, rainfall mass curve, and 10-day antecedent rainfall for Moanalua Valley hydrologic network, storm of November 25-26, 1970.

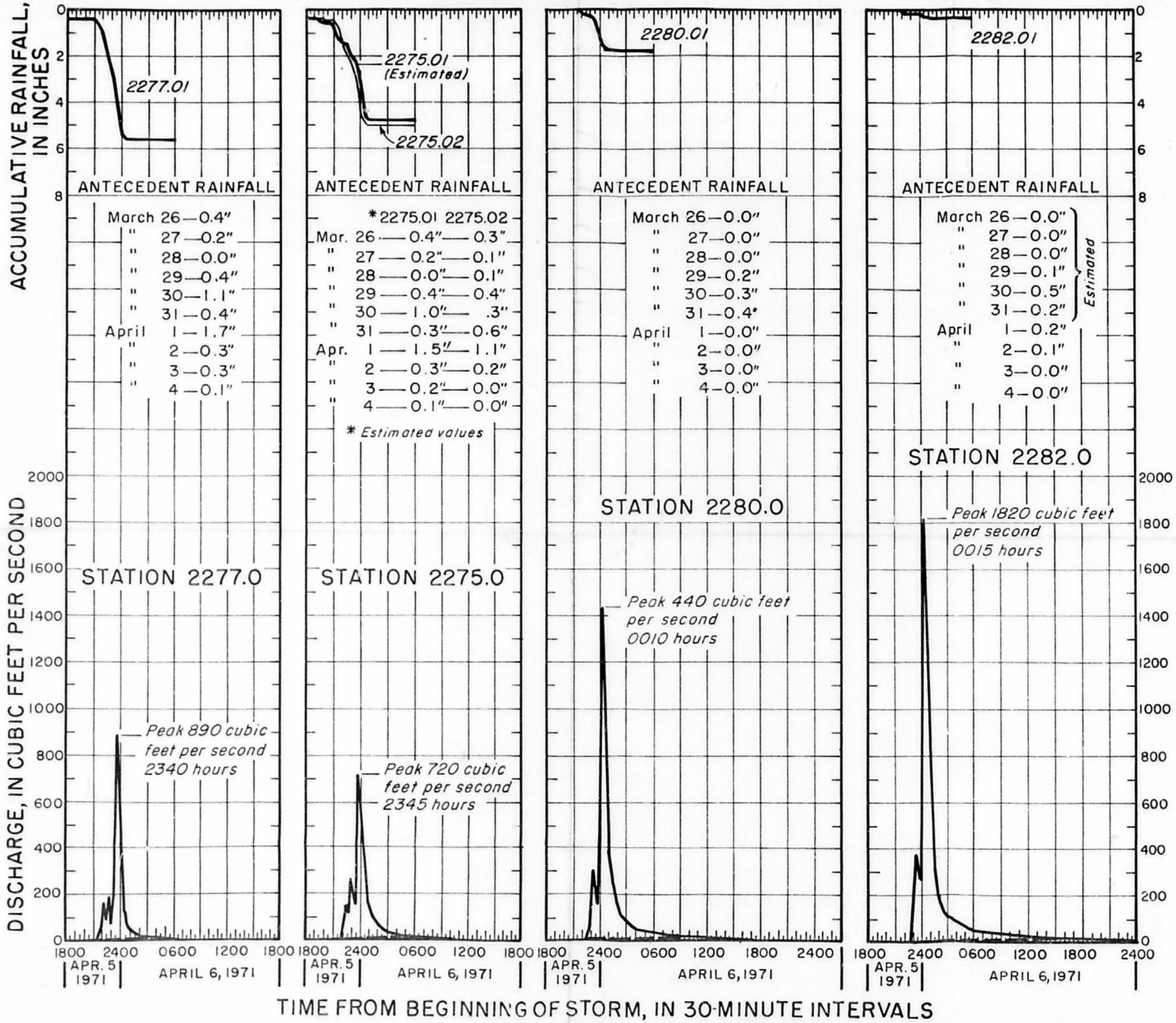

Plate 15. Hydrograph, rainfall mass curve, and 10-day antecedent rainfall for Moanalua Valley hydrologic network, storm of April 5-6, 1971.