USGS
science for a changing world

Streamflow and Erosion Response to Prolonged Intense Rainfall of November 1–2, 2000, Island of Hawaii, Hawaii

U.S. Department of the Interior
U.S. Geological Survey
Water-Resources Investigations Report 02-4117

Streamflow and Erosion Response to Prolonged Intense Rainfall of November 1–2, 2000, Island of Hawaii, Hawaii

By Richard A. Fontaine and Barry R. Hill

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 02-4117

Honolulu, Hawaii
2002

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information write to:

District Chief
U.S. Geological Survey
677 Ala Moana Blvd., Suite 415
Honolulu, HI 96813

Copies of this report can be purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286
Denver, CO 80225-0286

CONTENTS

FIGURES

TABLES

Streamflow and Erosion Response to Prolonged Intense Rainfall of November 1–2, 2000, Island of Hawaii, Hawaii

By Richard A. Fontaine and Barry R. Hill

Abstract

A combination of several meteorologic and topographic factors produced extreme rainfall over the eastern part of the island of Hawaii on November 1–2, 2000. Storm rainfall was concentrated in two distinct areas, the Waiakea and Kapapala areas, where maximum rainfall totals of 32.47 and 38.97 inches were recorded. Resultant flooding caused damages in excess of 70 million dollars, among the highest totals associated with flooding in the State's history. Storm rainfall had recurrence intervals that ranged from 10 years or less for maximum 1-hour totals to 100 years or more for maximum 24-hour totals.

As part of this study, peak flow and/or erosion data were collected at 41 sites. Analyses of these data indicated that peak discharges of record occurred at 6 of 12 sites where historic data were available. Peak flows with estimated recurrence intervals from 50 to over 100 years were recorded at 4 of 11 sites. Peak flows were poorly correlated with total storm rainfall. Critical rainfall durations associated with peak flows ranged from 1 to 12 hours and were about 3 hours at most sites. Rainfall-runoff computations and field observations indicated that infiltration-excess overland flow alone was not sufficient to have caused the observed flood peaks and therefore saturation-excess overland flow and subsurface flow probably contributed to peak flows at most sites.

Most hillslope erosion associated with the storm took place along or near the Kaoiki Pali in the Kapapala area. Hillslope erosion was predominately caused by overland flow.

INTRODUCTION

During November 1–2, 2000, prolonged and intense rain fell in two separate areas of the island of Hawaii: the Waiakea area and the Kapapala area (fig. 1). Storm rainfall totals exceeded 30 in. within both high-rainfall areas, and ranged from 5 to 25 in. within a larger surrounding area encompassing most of the eastern half of the island (Paul Haraguchi, consulting meteorologist, written commun., 2001). The resultant flooding caused millions of dollars in damages to roads, bridges, homes, businesses, and farms. No human fatalities resulted from the storm, and only one injury was reported. This study was done by the U.S. Geological Survey (USGS), as part of the USGS Office of Surface Water's national program to document the effects of extreme floods in the United States.

Purpose and Scope

This report describes the streamflow response to the storm of November 1–2, 2000, and documents the geomorphic effects of the storm and flood. These descriptions are based on (1) determinations or estimates of peak streamflows at selected locations within the Waiakea and Kapapala high-rainfall areas, (2) determinations of the recurrence intervals of the flood peaks at gaging stations with adequate data, (3) comparisons of peak streamflows at different locations on the basis of area-weighted rainfall and drainage area, and (4) descriptions of hillslope erosional features related to the storm and flood in the Kapapala area. Detailed descriptions of storm meteorology, rainfall distribution and intensity, and geomorphic effects in the Waiakea high-rainfall area are provided by Haraguchi (Paul Haraguchi, consulting meteorologist, written commun., 2001), and are not included in this report. Large-scale mass movement on the Kilauea Volcano that may have occurred during the storm (Cervelli and others, 2002) also is not described here.

During the period October 28–29, 2000, strong thunderstorms brought rainfall, estimated to be as great as 24 to 27 in., to localized areas of eastern Maui (Kevin Kodama, National Weather Service, written commun., 2000). Runoff from this storm overflowed bridges, prompting the closure of several roads. Numerous tourists and local residents were temporarily stranded as a result of the storm although no fatalities occurred. Although flooding was significant, analysis of the October 28–29, 2000 storm on Maui was not included in the scope of this report.

Acknowledgements

The assistance of Kevin Kodama, National Weather Service, Paul Haraguchi consulting meteorologist, and Sterling Yong, State of Hawaii Flood Coordinator, in obtaining information is gratefully acknowledged. Mr. and Mrs. Gordon Cran of the Kapapala Ranch were kind enough to allow us access to ranch lands for fieldwork and provided directions to sites of interest. Saku Nakamura of the Natural Resources Conservation Service provided data on soil properties and Michael Lisowski of the U.S. Geological Survey provided valuable insights regarding geomorphic processes associated with the storm.

STUDY AREA

The high-rainfall areas of Waiakea and Kapapala (fig. 1) are located on the windward (eastern) slopes of the island of Hawaii. The study area includes parts of the volcanoes of Mauna Kea, Mauna Loa, and Kilauea. These volcanoes are of Pleistocene or Recent age; Mauna Loa and Kilauea are active volcanoes (Stearns and Macdonald, 1946). Surface and subsurface rocks include basaltic and andesitic aa and pahoehoe lava flows and the Pahala Ash (Stearns and Macdonald, 1946). The climate is generally warm and humid. Prevailing winds are northeast trades, and orographic effects imposed by the high, broad, volcanic mountains of the island have a major effect on annual and storm rainfall distribution (Paul Haraguchi, consulting meteorologist, written commun., 2001). Historically, sugar plantations have dominated land use at altitudes below 3,000 ft. Diversified agriculture, cattle ranching, and forestry expanded after the closure of the plantations in the 1990's but much of the former sugar lands remain fallow. At altitudes above 3,000 ft, most of the land is forest, park, military reservations, or hunting areas.

Waiakea High-Rainfall Area

The Waiakea high-rainfall area (figs. 1 and 2) includes the city of Hilo and extends from about Papaikou on the north to Glenwood on the south, and from sea level to an altitude of approximately 4,000 ft (Paul Haraguchi, consulting meteorologist, written commun., 2001). Mean annual rainfall in this area ranges from 118 in. along the coast to 236 in. at altitudes near 3,000 ft (Giambelluca and others, 1986). Except for the urban areas near the ocean, land cover is generally dense, tropical, native, and introduced forest vegetation, with some agricultural activity on extensive former sugarcane lands.

The Waiakea high-rainfall area includes the lower windward slopes of both Mauna Kea and Mauna Loa. Mauna Kea lies to the north of the Wailuku River (fig. 2), and its slopes are formed of moderate to highly permeable aa and pahoehoe basaltic and andesitic lava flows of the Hamakua Volcanics capped with Pahala Ash (Stearns and Macdonald, 1946) (updated geologic names used are from Langenheim and Clague, 1987). South of the Wailuku River, the area includes historic and prehistoric basaltic aa and pahoehoe lava flows of the Kau Basalt and basaltic flows of the Kahuku Basalt capped by Pahala Ash (Stearns and Macdonald, 1946).

Although all of the surficial geologic materials are highly permeable, the differing permeabilities of aa lava flows, pahoehoe lava flows, and ash are likely to affect infiltration and runoff during rainfall. Stearns and Macdonald (1946 p. 159) considered the Pahala Ash to be generally less permeable than the lava flows of the Hamakua Volcanics, and suggested that the ash may increase runoff during storms. Sato and others (1973, p. 27) considered pahoehoe lavas to have low permeability in comparison to surrounding soils, although they noted that aa lava flows act as ground-water recharge areas (Sato and others, 1973, p. 34) and

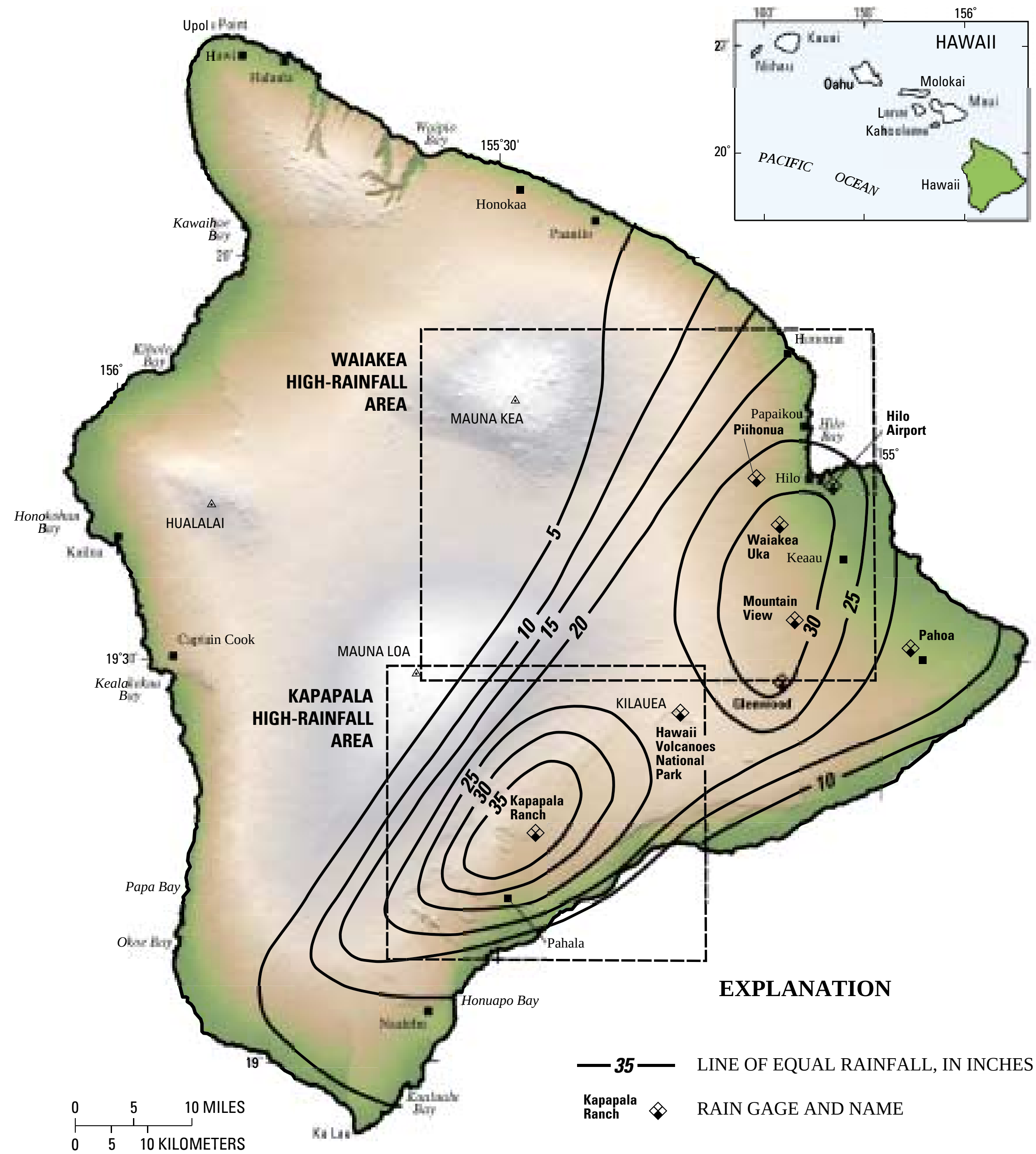
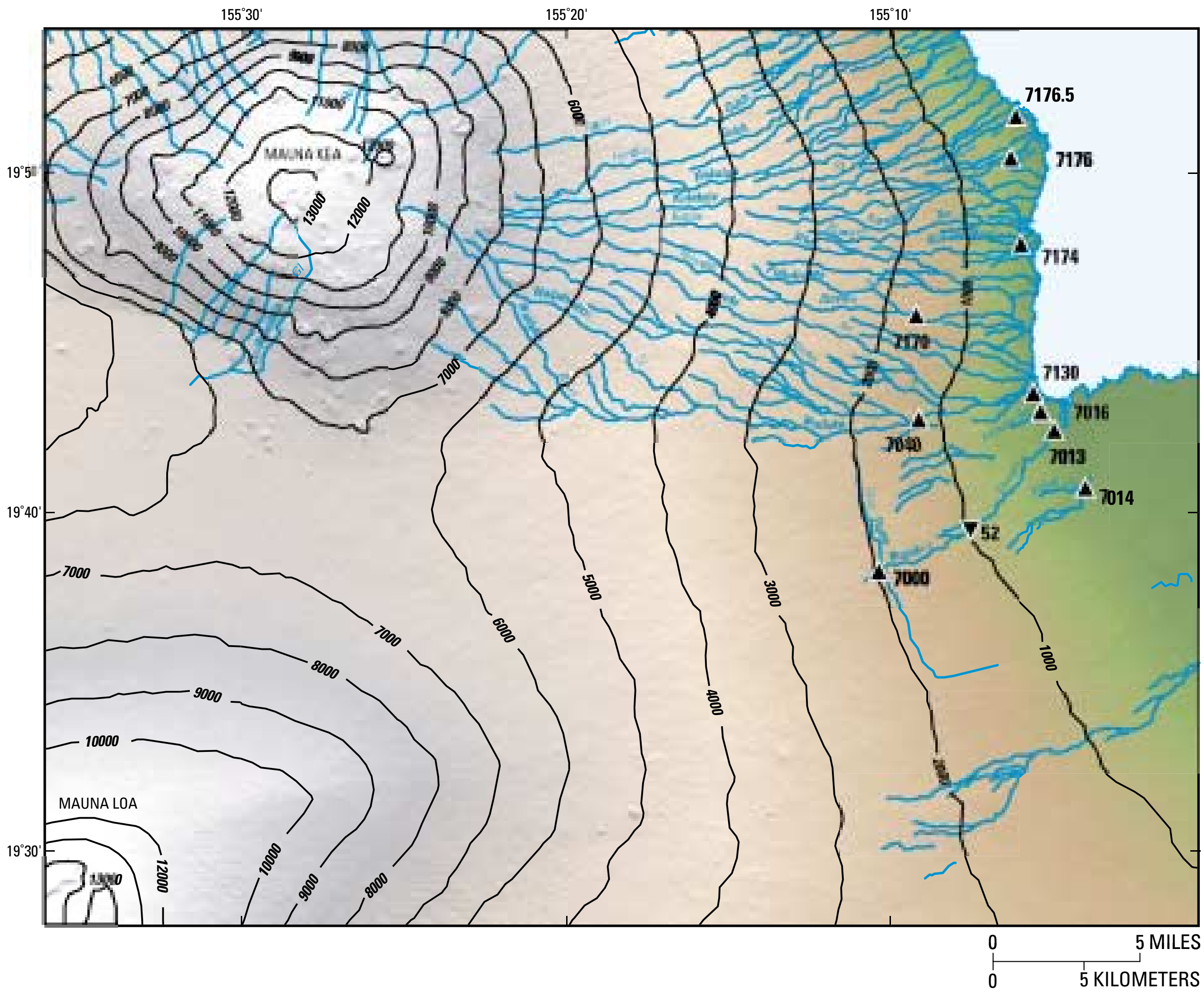


Figure 1. Study areas and total rainfall, November 1–2, 2000 flood, island of Hawaii, Hawaii (rainfall lines from consulting meteorologist, Paul Haraguchi, written commun., 2001).



EXPLANATION

—— 9000 ——	TOPOGRAPHIC CONTOUR, IN FEET ABOVE MEAN SEA LEVEL
▲ 7000	STREAMFLOW-GAGING STATION AND ABBREVIATED NUMBER
▼ 52	MISCELLANEOUS DISCHARGE MEASUREMENT SITE AND NUMBER

Figure 2. Waiakea high-rainfall area and data-collection sites, island of Hawaii, Hawaii.

presumably contribute little or no surface runoff. For most soils, surface permeability is 2.0 to 20 in/hr (Sato and others, 1973; Saku Nakamura, Natural Resources Conservation Service, written commun., 2001). Most soils overlying ash or pahoehoe lavas have decreases of two orders of magnitude in permeability at depths ranging from 8 to 72 in. below land surface (Saku Nakamura, Natural Resources Conservation Service, written commun., 2001). Soils overlying aa lavas have increases in permeability with depth (Saku Nakamura, Natural Resources Conservation Service, written commun., 2001). The parts of the study area underlain by ash or pahoehoe lavas therefore are more likely to generate shallow subsurface flow during heavy rainfall, owing to their decreases in permeability at shallow depths on steep slopes (Freeze, 1974), than are parts of the area underlain by aa lavas, which have increases in permeability at depth.

Kapapala High-Rainfall Area

The Kapapala high-rainfall area (figs. 1 and 3) includes the Kapapala Ranch, the community of Wood Valley, and the town of Pahala, and extends approximately from altitudes of 1,000 to 7,000 ft (Paul Haraguchi, consulting meteorologist, written commun., 2001). Mean annual rainfall ranges from about 39 in. near the 7,000-ft elevation to 118 in. at the 3,000-ft elevation (Giambelluca and others, 1986). From 3,000 ft to sea level, annual rainfall decreases to about 40 in. (Giambelluca and others, 1986). Until the end of plantation agriculture in 1995, much of the area below an altitude of 3,000 ft to the southwest of the Kapapala Ranch was used for sugar cultivation. Most of the former sugarcane lands now are used for macadamia nut orchards, pasture, or are left fallow. The land to the northeast of the Kapapala Ranch has been used for pasture for many years. Forests cover most of the area above an altitude of about 3,500 ft.

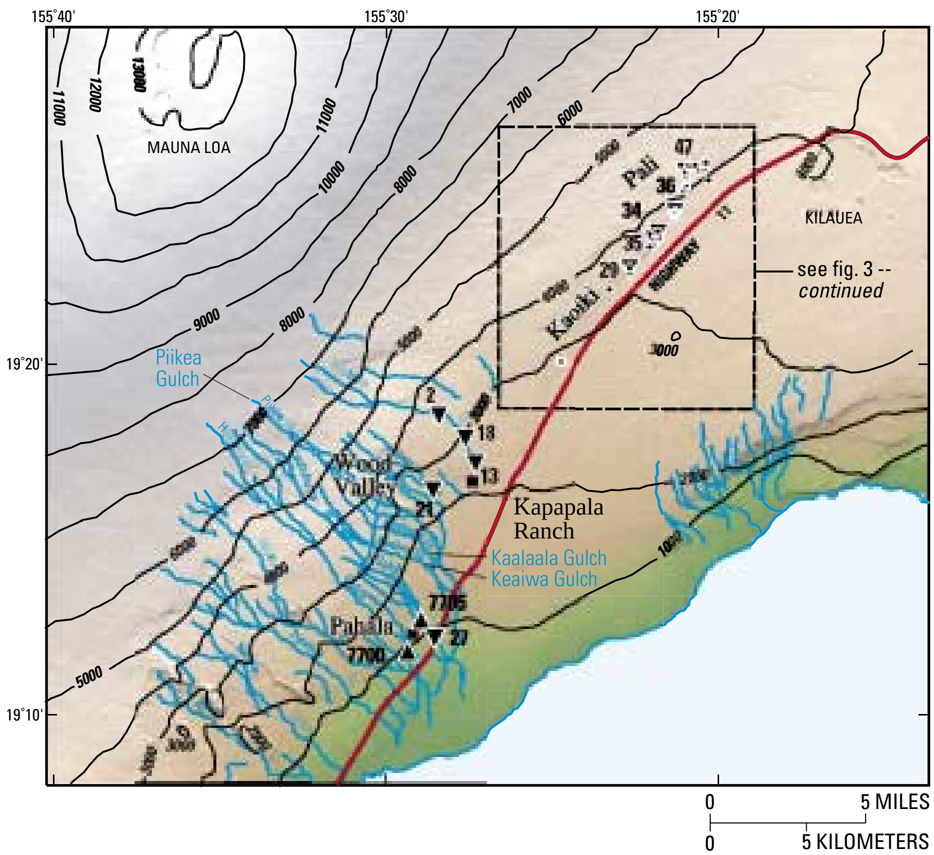
The Kapapala high-rainfall area is located mostly on the slopes of Mauna Loa, but extends onto the southwestern slopes of Kilauea as well. Surficial geology on Mauna Loa include primarily basaltic lava flows of the Kau Basalt, with smaller exposures of ash-capped basaltic lava flows of the Kahuku Basalt and a large landslide deposit in the Wood Valley area (Stearns and Clark, 1930; Stearns and Macdonald, 1946). On Kilauea, the surficial geology consists of historic and prehistoric basaltic lava flows (Stearns and Macdonald, 1946). Several major landforms related to structural deformation or large-scale mass movement on both Mauna Loa and Kilauea are within the Kapapala high-rainfall area, including fault scarps called pali in Hawaii and numerous fissures and extensional cracks (Stearns and Macdonald, 1946).

As in the Waiakea high-rainfall area, differences in the permeabilities of surficial geologic materials may affect rates and process of storm runoff in the Kapapala high-rainfall area. Stearns and Clark (1930, p. 177) and Stearns and Macdonald (1946, p. 76–77) considered the Pahala Ash exposed on the Kahuku Basalt to be less permeable than the surrounding Kau Basalt. Soils developed on ash have permeabilities ranging from 2.0 to 6.0 in/hr, whereas soils developed on lava have surface permeabilities ranging from 6.0 to 20 in/hr (Sato and others, 1973; Saku Nakamura, Natural Resources Conservation Service, written commun., 2001). Infiltration-excess overland flow therefore will occur at rainfall intensities of 2.0 to 20 in/hr. Soils developed on both types of parent material have decreases of one to two orders of magnitude in permeability at depths ranging from 4 in. below land surface for soils developed on lavas to 48 in. below land surface for ash soils (Saku Nakamura, Natural Resources Conservation Service, written commun., 2001). Such significant decreases in permeability at shallow depths on steep hillslopes are likely to result in shallow subsurface storm flow during intense rainfall (Freeze, 1974).

STORM CHARACTERISTICS

Haraguchi (Paul Haraguchi, consulting meteorologist, written commun., 2001) identified four primary conditions whose simultaneous convergence during November 1–2, 2000 contributed to the extreme nature of the storm. The conditions included (1) the upslope topography of eastern Hawaii, (2) the location of a large upper level trough 500 mi southwest of Kauai, (3) the pattern of southeasterly trade winds in the area, and (4) the location of the remnants from tropical storm Paul.

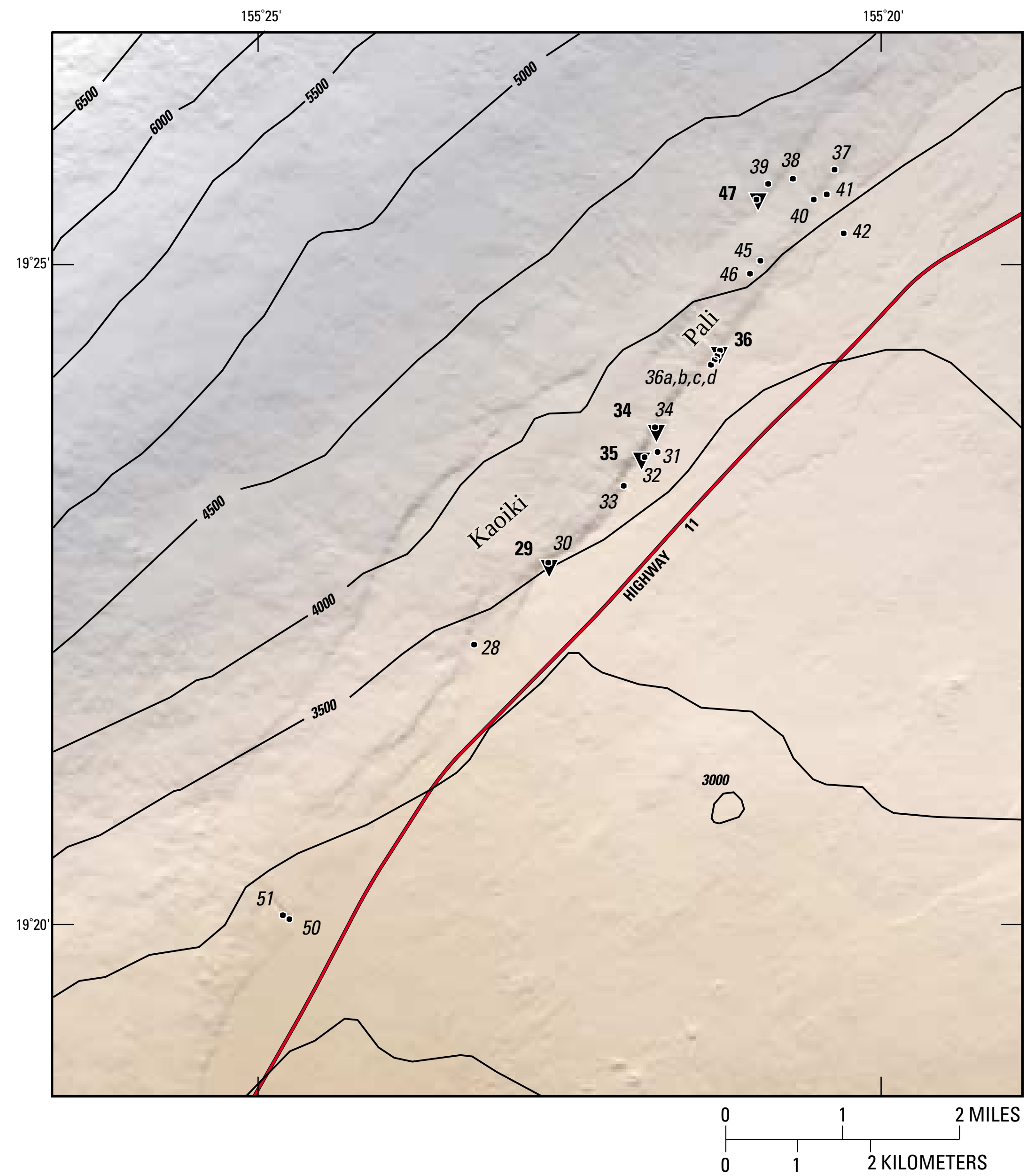
Total rainfall amounts for the storm of November 1–2, 2000 were historical maximums at many locations, and exceeded 30 in. at some gages (Paul Haraguchi, consulting meteorologist, written commun., 2001). However, in some parts of eastern Hawaii, the maximum rainfall totals from the November 1–2, 2000 storm were not significantly greater than those recorded



EXPLANATION

3000	TOPOGRAPHIC CONTOUR, IN FEET ABOVE MEAN SEA LEVEL
▲ 7000	STREAMFLOW-GAGING STATION AND ABBREVIATED NUMBER
▼ 27	MISCELLANEOUS DISCHARGE MEASUREMENT SITE AND NUMBER
• 50	EROSIONAL FEATURE SITE AND NUMBER

Figure 3. Kapapala high-rainfall area and data-collection sites, island of Hawaii, Hawaii.



EXPLANATION

6500 — TOPOGRAPHIC CONTOUR, IN FEET ABOVE MEAN SEA LEVEL

▼ 29 — MISCELLANEOUS DISCHARGE MEASUREMENT SITE AND NUMBER

• 50 — EROSIONAL FEATURE SITE AND NUMBER

Figure 3. Kapapala high-rainfall area and data-collection sites, island of Hawaii, Hawaii--*Continued*.

during other storms. Several previous 24-hour rainfall totals recorded on the island of Hawaii have been in excess of 25 in. (Stearns and Clark, 1930; Paul Haraguchi, consulting meteorologist, written commun., 2001). Storms with rainfall equal to or greater than the storm of November 1–2, 2000 probably occurred before the historical period of record in Hawaii and are likely to occur periodically in the future.

Rainfall Amounts

According to provisional data from the National Weather Service (NWS) hydronet network (internet site http://www.prh.noaa.gov/hnl/pages/hydrology.html), the mean rainfall during October 2000 at six rain gages in the Waiakea high-rainfall area was 182 percent of normal, whereas year-to-date (January through October 2000) totals averaged 92 percent of normal. In the Kapapala high-rainfall area, rainfall during October 2000 averaged 63 percent of normal at two rain gages. January through October 2000 rainfall totals at the two gages averaged 51 percent of normal. Thus, antecedent soil moisture was probably higher in the Waiakea high-rainfall area than in the Kapapala high-rainfall area.

During the November 1–2, 2000 storm, rainfall totals of as much as 38.97 in. in the Kapapala high-rainfall area and 32.47 in. in the Waiakea high-rainfall area were recorded (Kapapala Ranch and Mountain View NWS gages). Lines of equal rainfall shown in figure 1 (Paul Haraguchi, consulting meteorologist, written commun., 2001) depict the spatial distribution of total rainfall for the November 1–2, 2000 storm. Haraguchi (consulting meteorologist, written commun., 2001) summarized daily rainfall totals at 39 gages and hourly rainfall totals at 11 gages that were used to develop the rainfall map. Two distinct storm centers with greater than 30 in. of rainfall can be seen in figure 1. The Waiakea high-rainfall area 30-in. rainfall line extends southwest from near Hilo Airport to Glenwood. The Kapapala high-rainfall area 30-in. rainfall line is centered near Kapapala Ranch.

One of the distinguishing characteristics of the November 1–2, 2000 storm was that most of the rain fell in periods of only 24 hours in duration. Plots of provisional, hourly rainfall data from the NWS Kapapala Ranch and Waiakea Uka stations depict the temporal pattern of rain during this storm (fig. 4). The most intense rainfall at the Kapapala Ranch station (in the Kapapala high-rainfall area) was during a 6-hour period that extended from 0600 to 1200 hours on November 2. During this 6-hour period, hourly rainfall totals ranged from 3.02 to 4.15 in. The most intense rainfall at the Waiakea Uka station (in the Waiakea high-rainfall area) was during a 4-hour period from 2200 hours on November 1 to 0200 hours on November 2. During this 4-hour period, hourly rainfall totals ranged from 2.57 to 3.24 in.

The temporal distribution of storm rainfall was distinctly different in the Waiakea and Kapapala high-rainfall areas. Peak-rainfall intensities occurred much later in the Kapapala high-rainfall area. As a result, the amount of rain that fell prior to the period of maximum intensity was much greater there. In the Waiakea high-rainfall area, as represented by the data for the Waiakea Uka station (fig. 4), the 4-hour period of most intense rainfall occurred 14 hours after the beginning of the storm. A total of 6.65 in., or 21 percent of the total-storm rainfall of 30.89 in., fell prior to the period of most intense rainfall. A total of 12.83 in., or 42 percent of the total-storm rainfall, fell after the period of most intense rainfall. In the Kapapala high-rainfall area, as represented by the data for the Kapapala Ranch station (fig. 4), the 6-hour period of most intense rainfall occurred 22 hours after the storm began. A total of 13.73 in., or 35 percent of the total-storm rainfall of 38.97 in., fell prior to the period of most intense rainfall. A total of 2.99 in., or 8 percent of the total-storm rainfall, fell after the period of most intense rainfall.

Maximum rainfall totals and recurrence intervals for selected durations for the November 1–2, 2000 storm are summarized in table 1. Rainfall frequency data are discussed in the next section. The maximum rainfall totals shown in table 1 can be used to further contrast the Waiakea and Kapapala high-rainfall areas. The only rain gage in table 1 that is located in the Kapapala high-rainfall area is the Kapapala Ranch gage. Maximum rainfall totals for durations of 1, 3, 6, 12, and 24-hours at the Kapapala Ranch gage were higher than all but one value recorded at each of the other gages in table 1, the exception being the maximum 1-hour rainfall total of 4.56 in. at Hilo Airport. The maximum 3- and 6-hour rainfall totals of 12.25 and 22.25 in. at Kapapala Ranch were 25 and 48 percent greater than maximum totals for those durations at any of the other gages. These data indicate that, for the most part, maximum rainfall intensities were greater in the Kapapala high-

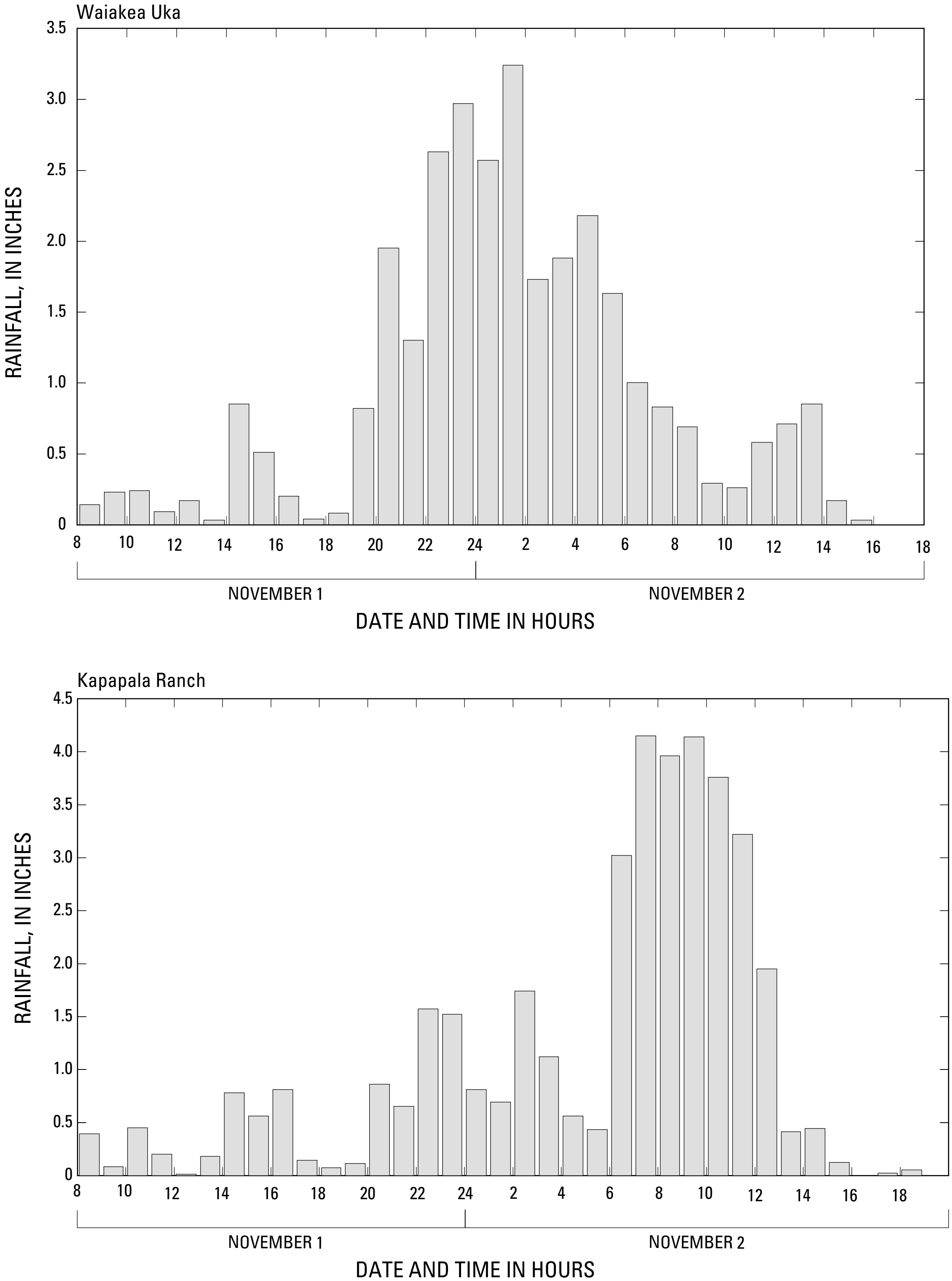


Figure 4. Graph showing hourly rainfall totals for November 1–2, 2000 at Waiakea Uka and Kapapala Ranch, island of Hawaii, Hawaii. (Provisional data from the National Weather Service)

Table 1. Maximum rainfall totals and recurrence intervals for selected durations, November 1–2, 2000 flood, island of Hawaii, Hawaii

[Provisional data from the National Weather Service, Honolulu, Hawaii; >, greater than; rain gage locations are shown in figure 1]

National Weather Service rain gage	Depth (inches)/Recurrence interval (years)				
	1 hour	3 hours	6 hours	12 hours	24 hours
Piihonua	3.35/1	8.67/10	14.15/25–50	20.44/50–100	24.73/50–100
Hilo Airport	4.56/5–10	9.78/50–100	13.21/50–100	22.55/>100	26.89/>100
Waiakea Uka	3.24/1	8.78/10–25	15.02/50–100	23.90/>100	29.11/>100
Mountain View	3.31/2	8.56/25–50	13.24/50–100	19.28/>100	29.75/>100
Glenwood	2.32/1	6.24/5–10	10.78/25	17.51/100	26.60/>100
Pahoa	2.76/1	5.73/2–5	9.90/25	14.33/50	16.03/25
Hawaii Volcanoes National Park	2.10/1	5.40/5	7.00/5	13.80/25–50	20.80/100
Kapapala Ranch	4.15/10	12.25/>100	22.25/>100	28.73/>100	37.02/>100

rainfall area than they were in the Waiakea high-rainfall area.

Rainfall Frequency

The severity of rainfall events, both in terms of total rainfall and intensity, can be quantified through the use of rainfall-frequency data. Frequency data are commonly expressed in terms of recurrence intervals in years. The recurrence interval is approximately the average period of time between events that are greater than or equal to a specified value. For example, an event with a recurrence interval of 50 years is one that has a rainfall total expected to be equaled or exceeded, over the long term, an average of once every 50 years. Recurrence intervals are computed for rainfall totals that fall within specified durations or time intervals.

Recurrence intervals associated with maximum rainfall totals for selected durations of time for the November 1–2, 2000 storm are summarized in table 1. Recurrence interval data in table 1 were based on analyses contained in Technical Paper 43 published by the U.S. Weather Bureau (1962).

Recurrence interval data summarized in table 1 indicate that for durations of 1-hour, the maximum rainfall intensities recorded during the November 1–2, 2000 flood were not extreme. With the exception of the Kapapala Ranch and Hilo Airport data, where 5 to 10 year recurrence intervals were found, maximum 1-hour rainfall totals were of a magnitude that would be expected to occur every 1 to 2 years on average. The severity of the November 1–2, 2000 storm, as measured by rainfall recurrence interval, increased as the duration of the time interval increased. Twenty-four hour rainfall totals had recurrence intervals greater than or equal to 100 years at six of the eight rain gages included in table 1.

DESCRIPTION OF FLOOD

Rainfall intensities of greater than 10 in/day can be expected at least once a year somewhere in the State of Hawaii (Lee and Valenciano, 1986, p. 201). Flooding is therefore common throughout the State, particularly in areas such as the Waiakea and Kapapala high-rainfall areas (Harris and Nakahara, 1980; Haraguchi, 1980a; and Haraguchi, 1980b). In these areas, intense rainfall is common and most streams have small watersheds (less than 50 mi^2) with very steep slopes. In combination, these factors produce significant volumes of runoff and short response times.

Total flood damages associated with the November 1–2, 2000 storm were estimated to be in excess of 70 million dollars (Paul Haraguchi, consulting meteorologist, written commun., 2001). Travel in and around the Waiakea and Kapapala high-rainfall areas was brought to a standstill as numerous bridges and stream crossings were destroyed. Most notable among the damaged crossings were the four bridges along Highway 11 near Pahala and the Komohana Street Bridge over Alenaio Stream. Figure 5 is a picture taken at the site of the former Highway 11 Bridge over Keaiwa Stream, just north of Pahala, on November 3, 2000.

Figure 5. Photograph showing site of destroyed Highway 11 bridge over Keaiwa Stream near Pahala, Hawaii, November 3, 2000, island of Hawaii, Hawaii. Note person (circled) for scale.

In response to the extreme flooding and level of damage, the Governor of Hawaii declared the island of Hawaii a disaster area on November 4, 2000. Within a week the island was declared a federal disaster area. In the sections that follow are summaries of the peak-flow discharge and frequency, and rainfall-runoff data for the November 1–2, 2000 storm in the Waiakea and Kapapala high-rainfall areas.

Peak Flows

As part of this study, the U.S. Geological Survey collected peak flow and/or erosion data at 41 sites to aid in the description of the flood. These 41 sites are listed in table 2 and their locations are shown in figures 2 and 3.

Waiakea High-Rainfall Area

Peak flow and/or peak stage data were collected at 11 sites in the Waiakea high-rainfall area. These sites are listed in table 2 and their locations are shown in figure 6. Included among the 11 sites are 8 active stream-gaging stations, 2 discontinued stream-gaging stations, and 1 miscellaneous site. Of the eight active gaging stations, only two are continuous record sites where stage and discharge data are collected at 15-minute increments, and of the two, only one operated during the flood. The six remaining active stations are crest-stage gages where only measurements of peak stage and peak discharge are available for the storm. Data collection activities at the one miscellaneous and two discontinued sites were undertaken specifically for the study of this flood.

Peak flow and stage data for the November 1–2, 2000 flood in the Waiakea high-rainfall area are summarized in table 3. Also included in table 3 are the periods of record at the gaging stations and the dates and magnitudes of the previous peak flows of record. Recurrence interval data in table 3 is discussed in the following section of the report.

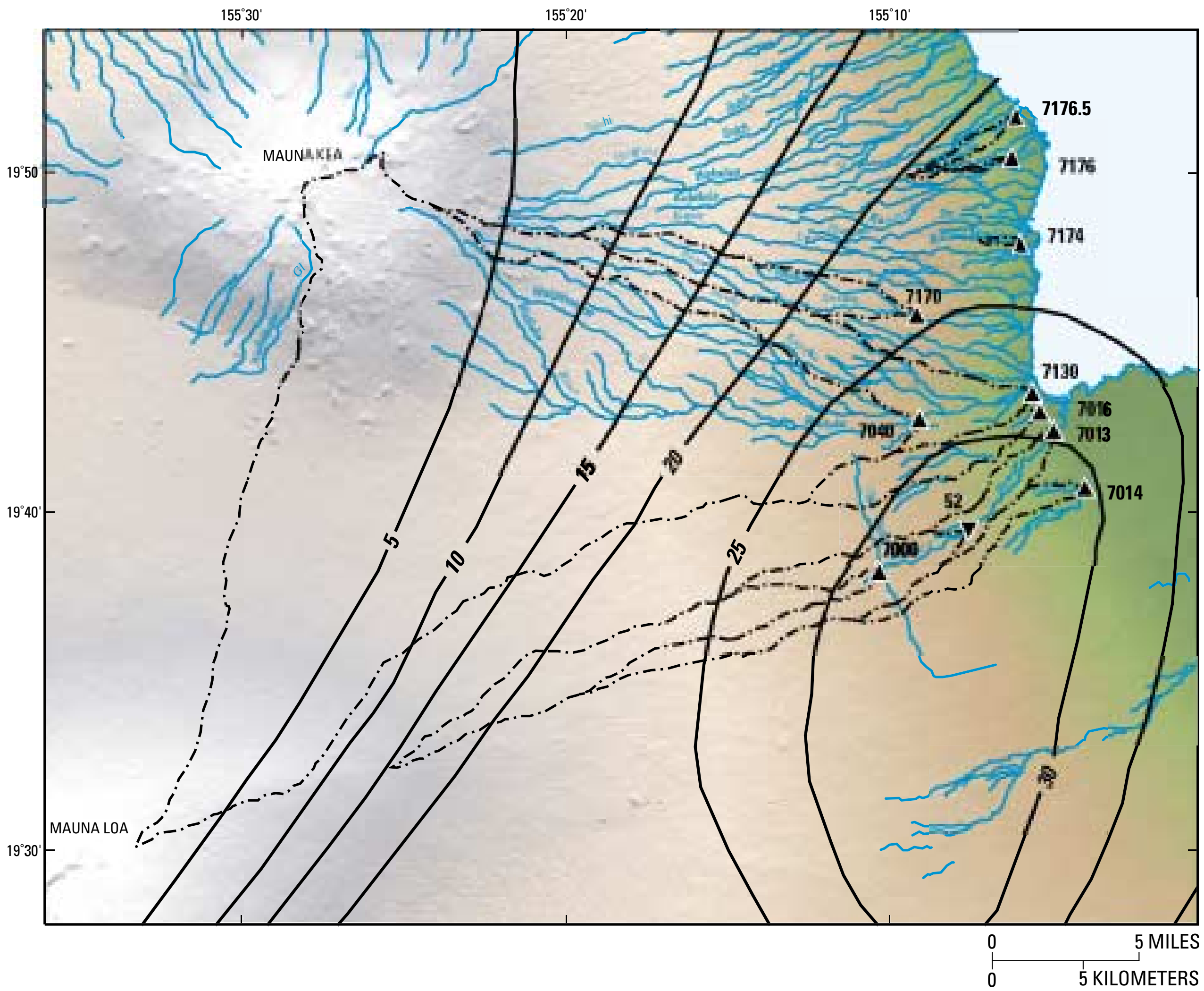
A variety of hydraulic models and hydrologic techniques were utilized to compute peak stages and flows at the 11 sites in the Waiakea high-rainfall area. The peak stage at site 7000 was determined by using

Table 2. Peak-flow and erosion measurement sites for November 1–2, 2000 flood, island of Hawaii, Hawaii

Site number (figs. 2 and 3)	USGS station number	Station name	Peak flow data	Erosion data	Station type	Remarks
7000	16700000	Waiakea Stream near Mountain View	No	No	abandoned continuous-record streamgage	peak stage measurement
7013	16701300	Waiakea Stream at Hilo	Yes	No	crest-stage gage	peak discharge from slope-area measurement
7014	16701400	Palai Stream at Hilo	Yes	No	crest-stage gage	peak discharge from slope-area measurement
7016	16701600	Alenaio Stream at Hilo	Yes	No	crest-stage gage	bank erosion near gage; peak discharge from slope-area measurement
7040	16704000	Wailuku River at Piihonua	Yes	No	active continuous-record streamgage	peak discharge from rating
7130	16713000	Wailuku River at Hilo	Yes	No	abandoned continuous-record streamgage	peak discharge from rating; streambank landslide near gage
7170	16717000	Honolii Stream near Papaikou	Yes	No	active continuous-record streamgage	peak discharge from rating
7174	16717400	Kalaoa Mauka Stream near Hilo	Yes	No	crest-stage gage	peak discharge from flow through culvert measurement
7176	16717600	Alia Stream near Hilo	Yes	No	crest-stage gage	peak discharge from rating
7176.5	16717650	Kapehu Stream near Pepeekeo	Yes	No	crest-stage gage	peak discharge from flow through culvert measurement
7700	16770000	Hionamoa Gulch at Pahala	Yes	No	abandoned crest-stage gage	peak discharge from critical-depth measurement
7705	16770500	Paauau Gulch at Pahala	Yes	No	active continuous-record streamgage	bank erosion at gage; peak discharge from flow through culvert measurement
2	191822155281601	Waihaka Stream at altitude 3,230 feet near Pahala	Yes	No	miscellaneous	bank erosion upstream; peak discharge from critical-depth measurement
13	191702155271301	Waihaka Stream at altitude 2,290 feet near Pahala	Yes	No	miscellaneous	above channel headcut; peak discharge from critical-depth measurement
18	191744155273001	Waihaka Stream at altitude 2,740 feet near Pahala	Yes	No	miscellaneous	peak discharge from critical-depth measurement
21	191616155282601	Waiakaloa Gulch at Wood Valley Camp	Yes	No	miscellaneous	peak discharge from critical-depth measurement
27	191209155282301	Paauau Stream below Highway 11 at Pahala	Yes	No	miscellaneous	peak discharge from critical-depth measurement
28	none	none	No	Yes	miscellaneous	
29	192228155224201	Unnamed Gulch above Peter Lee Road near Wood Valley	Yes	No	miscellaneous	upstream of site 30; peak discharge from critical-depth measurement
30	none	none	No	Yes	miscellaneous	downstream of site 29
31	none	none	No	Yes	miscellaneous	downstream of site 35
32	none	none	No	Yes	miscellaneous	
33	none	none	No	Yes	miscellaneous	

Table 2. Peak-flow and erosion measurement sites for November 1–2, 2000 flood, island of Hawaii, Hawaii--Continued

Site number (figs. 2 and 3)	USGS station number	Station name	Peak flow data	Erosion data	Station type	Remarks
34	192326155215101	Unnamed gulch at altitude 3,530 feet Kaoiki Pali near Volcano	Yes	Yes	miscellaneous	peak discharge from critical-depth measurement
35	192314155215901	Unnamed gulch at altitude 3,470 feet Kaoiki Pali near Volcano	Yes	No	miscellaneous	upstream of site 31; peak discharge from critical-depth measurement
36a	none	none	No	Yes	miscellaneous	
36b	none	none	No	Yes	miscellaneous	
36c	none	none	No	Yes	miscellaneous	
36d	192400155212101	Unnamed gulch at altitude 3,460 feet Kaoiki Pali near Volcano	Yes	Yes	miscellaneous	peak discharge from critical-depth measurement
37	none	none	No	Yes	miscellaneous	
38	none	none	No	Yes	miscellaneous	
39	none	none	No	Yes	miscellaneous	
40	none	none	No	Yes	miscellaneous	
41	none	none	No	Yes	miscellaneous	
42	none	none	No	Yes	miscellaneous	
45	none	none	No	Yes	miscellaneous	
46	none	none	No	Yes	miscellaneous	
47	192507155210401	Unnamed gulch at altitude 4,000 feet near Volcano	Yes	Yes	miscellaneous	peak discharge from critical-depth measurement
50	none	none	No	Yes	miscellaneous	
51	none	none	No	Yes	miscellaneous	
52	193940155073901	Waiakea Stream above Hoaka Stream at Waiakea	Yes	No	miscellaneous	peak discharge from critical-depth measurement



EXPLANATION

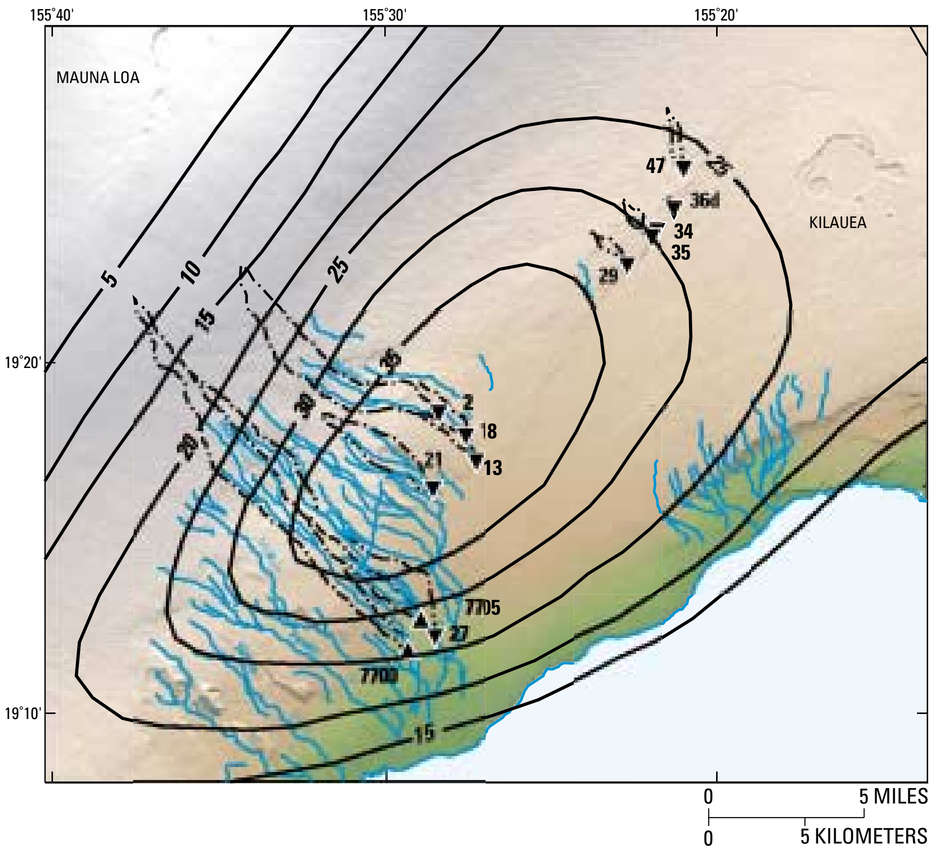
— 10 — LINE OF EQUAL RAINFALL, IN INCHES

▲ 7000 STREAMFLOW-GAGING STATION AND ABBREVIATED NUMBER

▼ 52 MISCELLANEOUS DISCHARGE MEASUREMENT SITE AND NUMBER

–·–·–·– WATERSHED BOUNDARY

Figure 6. Total rainfall in the Waiakea high-rainfall area, November 1–2, 2000 flood, island of Hawaii, Hawaii (rainfall lines from consulting meteorologist, Paul Haraguchi, written commun., 2001).



EXPLANATION

—— 15 —— LINE OF EQUAL RAINFALL, IN INCHES

▲ 7705 STREAMFLOW-GAGING STATION AND ABBREVIATED NUMBER

▼ 27 MISCELLANEOUS DISCHARGE MEASUREMENT SITE AND NUMBER

–·–·–·–·– WATERSHED BOUNDARY

Figure 7. Total rainfall in the Kapapala high-rainfall area, November 1–2, 2000 flood, island of Hawaii, Hawaii (rainfall lines from consulting meteorologist, Paul Haraguchi, written commun., 2001).

differential leveling techniques to refer a flagged high-water mark to the stage datum used at the gage. Critical-depth techniques (Barnes and Davidian, 1978, p. 189) were used to compute the peak flow at site 52. Use of the critical-depth technique to compute peak flows was validated by Jarrett and England (2002). Slope-area techniques (Fulford, 1994) were used to compute peak flows at sites 7013, 7014, and 7016. A calibrated stage-discharge rating curve (Rantz and others, 1982) was used to compute peak flows at sites 7040, 7130, 7170, and 7176. Flow-through culvert computations (Fulford, 1998) were used to compute peak flows at sites 7174 and 7176.5.

Record peak flows and/or stages were recorded at 4 of the 11 sites including Waiakea Stream near Mountain View (site 7000), Waiakea Stream at Hilo (site 7013), Palai Stream at Hilo (site 7014), and Alenaio Stream at Hilo (site 7016). The four sites with new peaks of record are all located in or close to the area enclosed by the 30-in. rainfall line shown in figure 6. At the Waiakea Stream near Mountain View gage, the peak

Table 3. Peak flows and associated recurrence intervals for November 1–2, 2000 flood, and previous record peak flows, island of Hawaii, Hawaii

[ft^3/s, cubic feet per second; --, not available; >, greater than; P, operational as of 2002]

Site number[a]	Previous record peak flow (ft^3/s)	Date of previous peak	Period of peak-flow record	November 1–2, 2000 Peak flow (ft^3/s)	November 1–2, 2000 Recurrence interval (years)
7000	310[b]	08/26/70	1930-95	--[c]	>100
7013	3,670	08/12/94	1968-75, 1979, 1993-P	5,760	70
7014	1,260	02/20/79	1965-71, 1979-80, 1994, 2001-P	1,580	50
7016	1,010	07/30/97	1997-P	6,300	--
7040	80,200	08/11/40	1928-40, 1940-1947, 1948-P	40,700	10
7130	79,800	12/13/87	1977-79, 1980-95	75,000	10
7170	22,600	05/23/78	1911-13, 1967-P	14,300	5
7174	400	02/20/79	1963-67, 1973-76, 1978-79, 1985, 2001-P	228	15
7176	2,850	02/20/79	1962-72, 1979, 1986, 1994-P	1,520	80
7176.5	3,320	02/20/79	1963-68, 1975, 1979, 1985-86, 1994-P	1,900	30
7700	10,400	02/20/79	1963-80, 1985-86, 1994	11,400	25
7705	3,600	01/05/69 01/08/75	1963-79, 1994-98, 2001-P	4,480	15
2	--	--	none	7,150	--
13	--	--	none	11,600	--
18	--	--	none	8,920	--
21	--	--	none	5,500	--
27	--	--	none	7,180	--
29	--	--	none	530	--
34	--	--	none	54	--
35	--	--	none	229	--
36d	--	--	none	145	--
47	--	--	none	262	--
52	--	--	none	6,420	--

[a] Site number refers to the site numbers from table 2
[b] Peak stage associated with the peak flow was 4.47 feet
[c] Peak stage during the November 1-2, 2000 flood was 6.44 feet

discharge was not determined; however, the peak stage from this flood (6.44 ft) was 1.97 ft higher than the peak stage for the period of record (1930 to 1995). Peak flow at the Waiakea Stream at Hilo gage (site 7013) was 57 percent higher than any peak there since 1968. Peak flow at the Palai Stream gage (site 7014) was 25 percent higher than any peak there since 1965. These findings were based on both published and unpublished USGS data collected at the gages.

The peak flow for the Alenaio Stream at Hilo gage (site 7016) was significantly higher than the previous peak of record; however, records have been collected at this site for only 5 years. Peak flows during the November 1–2, 2000 storm at three sites north of Hilo (sites 7174, 7176, and 7176.5) were on average 44 percent lower than their previous peak flows of record (February 20, 1979 flood; Harris and Nakahara, 1980).

Kapapala High-Rainfall Area

Peak flow data were collected at 12 sites in the Kapapala high-rainfall area. These sites are listed in table 2 and shown in figure 7. The 12 sites include 1 active stream-gaging station, 1 discontinued crest-stage gage, and 10 miscellaneous sites. No continuous records of discharge are available in the area because site 7705 (Paauau Gulch at Pahala) was inoperable during the November 1–2, 2000 flood. Data collection activities at the one discontinued site and the 10 miscellaneous sites were undertaken specifically for the study of this flood.

Peak-flow data for the November 1–2, 2000 flood in the Kapapala high-rainfall area are summarized in table 3. Also included in table 3 are the periods of record at the gaging stations and the dates and magnitudes of the previous peak flows of record. Recurrence interval data in table 3 is discussed in the following section. Note that for the 10 miscellaneous sites in table 3, only peak flow data for the November 1–2, 2000 flood are included because there are no historical data for these sites.

Several hydraulic models were used to compute peak flows at the 12 sites in the Kapapala high-rainfall area. The peak flow at site 7705 was determined using a combination of culvert and road overflow analyses (Fulford, 1998). Critical-depth techniques (Barnes and Davidian, 1978. p. 189) were used to compute peak flows for the remaining 11 sites.

Record peak flows took place at both of the stations in the Kapapala high-rainfall area with historic information, Hionamoa Gulch at Pahala (site 7700) and Paauau Gulch at Pahala (site 7705). Peak flows at the Hionamoa and Paauau gages were 10 and 24 percent higher than the previous peaks of record at the gages since 1963. These findings were based on both published and unpublished USGS data collected at the gages. The two sites with new peaks of record are close to the area enclosed by the 30-in. rainfall line shown in figure 7.

Attempts were made to determine peak flows for Keaiwa, Kaalaala, and Piikea Gulches near Highway 11 (fig. 3). At each of these locations, bridges were heavily damaged or destroyed during the flood. Unfortunately no suitable sites were found where flood hydraulic models could be applied. At each of these locations the flow broke into multiple channels and in many places created new ones. Peak flow determinations of 7,360 cubic feet per second (ft^3/s), 6,460 ft^3/s, and 6,920 ft^3/s were made at Keaiwa, Kaalaala, and Piikea Gulches, respectively, after the February 20, 1979 flood (Harris and Nakahara, 1980, p.12). Given that (1) maximum storm total rainfall in this area during the 1979 flood was 26.80 in. (Harris and Nakahara, 1980, p. 8) while the maximum recorded during the November 1–2, 2000 flood was 38.97 in. and (2) peak flows at the two historic stream gages in the area (sites 7700 and 7705) had significantly higher flows in 2000 compared with 1979, it is probably reasonable to assume that peak flows at these sites during the November 2000 flood were higher than those determined for the February 20, 1979 flood.

Peak-Flow Frequency

As explained in the section on rainfall frequency, the recurrence interval of a given peak flow is a measure of the average number of years between floods with flows that equal or exceed it. For example, the 100-year peak flow is one that would be equaled or exceeded, over the long term, an average of once every 100 years. This does not imply that floods will take place at regular intervals: two 100-year floods could take place within the same year, or 100 years could pass without a single 100-year flood. Another way to view the recurrence interval is to take its reciprocal (for example 100 year becomes 1/100 or 0.01), which yields the annual exceedance probability. In this case, a 100-year flood has an annual exceedance probability of 0.01, or a 1 percent chance of occurring or being exceeded in any given year.

In this study, Log Pearson type III procedures, as described by the Interagency Advisory Committee on Water Data in Bulletin 17B (1982) were used to compute frequency curves for each of the data collection sites (table 3) that have a minimum of 10 years of record. These frequency curves were then used to estimate recurrence intervals for the November 1–2, 2000 flood. When computing frequency curves, the station skew was weighted with a generalized skew coefficient of –0.05 (Interagency Committee on Water Data, 1982, p. 12) and where available, historic information was used to extend the effective length of record (Interagency Committee on Water Data, 1982, app. 6). Historic record lengths were based on published and unpublished USGS records available for the sites as well as those for adjacent sites. When available, the November 1–2, 2000 peak discharge was included in the frequency analyses. None of the sites where frequency analyses were run have peak discharges affected by reservoirs. No trends were detected in any of the annual peak flow series; therefore, all were treated as being homogeneous. In general, the higher a given peak flow is relative to the historic peak flows at a site, the higher the recurrence interval. In this respect, recurrence intervals computed for the November 1–2, 2000 flood are also a reflection of the past flooding history at a site.

Waiakea High-Rainfall Area

Sufficient historic records were available for 9 of the 11 data sites in the Waiakea high-rainfall area to compute recurrence intervals for the November 1–2, 2000 flood. The recurrence interval data are shown in table 3. The recurrence interval for the November 1–2, 2000 flood on Waiakea and Palai Streams (sites 7000, 7013, and 7014) ranged from 50 to greater than 100 years. An exact recurrence interval was not shown for site 7000 because the peak flow for the November 1–2, 2000 storm could not be determined. The peak flow was known to be significantly greater than that associated with the highest point on the stage-discharge rating curve in effect when the station was last in operation (5.00 ft gage height is equivalent to 473 ft^3/s) because the peak stage for the November 1–2, 2000 flood was 6.44 ft and the stage-discharge rating was unlikely to have changed significantly since 1995. The peak-flow frequency curve computed for site 7000 indicated that a 100-year flood has a discharge of about 440 ft^3/s, thus a greater-than-100-year recurrence interval shown in table 3. No recurrence interval was shown for site 52 because this is a miscellaneous site with no historic data. No recurrence interval was shown for site 7016 because there are only 5 years of historic data available. On the basis of the locations of sites 52 and 7016 and the recurrence interval computed for adjacent sites, the November 1–2, 2000 flood probably had a recurrence interval between 50 and 100 years at those locations.

At sites on the Wailuku River and Honolii Stream (sites 7040, 7130, and 7170) the recurrence intervals were 5 to 10 years. At each of these sites there were several historic peak flows that were greater than the November 1–2, 2000 flood. For example, in 73 years of record at site 7040, the November 1–2, 2000 peak flow of 40,700 ft^3/s was exceeded by five annual peak flows, with the highest being 80,200 ft^3/s in August 1940.

At sites on three small streams north of Hilo, (sites 7174, 7176, and 7176.5) the recurrence intervals were 15, 80, and 30 years, respectively. The recurrence interval of 80 years for Alia Stream (site 7176) appears to be somewhat of an outlier; however, given the data collected over the 40-year historic period of record at the site, the computation is reasonable. At Alia Stream the two highest peaks of record are 2,850 ft^3/s and 1,520 ft^3/s (February 1979 and November 2000 floods) while the third highest peak was only 560 ft^3/s (April 1986 flood). The 1979 and 2000 peak flows are 5.1 and 2.7 times greater than any previous peak flow recorded at Alia Stream in 40 years. As noted earlier, the higher a given peak flow is relative to the historical peak flows, the higher the recurrence interval. At Alia Stream, both the 1979 and 2000 floods are significantly higher than the other historic peak flows, therefore the statistical frequency analyses show them to have high recurrence intervals.

Kapapala High-Rainfall Area

Only 2 of the 12 sites in the Kapapala high-rainfall area had sufficient historic data to compute recurrence intervals for the November 1–2 flood. These were site 7700 on Hionamoa Gulch at Pahala and site 7705 on Paauau Gulch at Pahala. Recurrence intervals were reasonably consistent and were 25 years for site 7700 and 15 years for site 7705 (table 3). The remaining 10 sites were miscellaneous sites with no historic data.

Rainfall-Runoff Relations

The relations between the rainfall that fell during the storm of November 1-2, 2000, and the runoff responses of streams in the Waiakea and Kapapala high-rainfall areas are examined in this section of the report. Improving our understanding of flooding processes in these areas is important for those living nearby and for county, state, and federal officials who must plan for the recurrence of damaging floods.

The process of flood generation or production involves a complex interaction of atmospheric inputs, geology and geomorphology, vegetation and soils, and human influences (Pilgrim and Cordery, 1992, p. 9.1). The relatively young and evolving nature of the bedrock (Stearns and Macdonald, 1946) and the extreme spatial variation of rainfall (figure 1) in the study area further complicate the process.

A simplistic, yet useful way to consider rainfall-runoff relationships can be found in the structure of the rational method formula (Pilgrim and Cordery, 1992, p. 9.15),

$$q = F\,C\,i\,A, \qquad (1)$$

where:

q is the flood peak flow,
F is a unit's conversion factor, which in English units equals 1.008 and is generally omitted from the formula,

Table 4. Rainfall and runoff data for November 1–2, 2000 flood, island of Hawaii, Hawaii
[mi^2, square mile; $ft^3/s/mi^2$, cubic feet per second per square mile]

Site number[a]	Drainage area (mi^2)	Peak unit runoff ($ft^3/s/mi^2$)	Peak hourly rainfall (inches)	Rain gage used for peak rainfall	Peak-runoff ratio (peak unit runoff as percentage of peak hourly rainfall)	Area-weighted storm rainfall (inches)
7000	17.4	--	--	--	--	23.1
7013	35.8	161	3.24	Waiakea	8	25.8
7014	5.08	311	3.24	Waiakea	15	30.0
7016	8.62	731	3.24	Waiakea	35	28.2
7040	230	168	3.35	Piihonua	8	8.9
7130	256	293	3.35	Piihonua	14	10.0
7170	11.6	1,230	3.35	Piihonua	57	17.1
7174	0.24	950	3.35	Piihonua	44	22.5
7176	0.58	2,620	3.35	Piihonua	[b]121	22.5
7176.5	1.09	1,740	3.35	Piihonua	81	22.5
7700	9.31	1,220	4.15	Kapapala	46	26.9
7705	1.74	2,780	4.15	Kapapala	96	33.4
2	6.54	1,090	4.15	Kapapala	40	28.1
13	7.97	1,460	4.15	Kapapala	54	29.4
18	7.45	1,200	4.15	Kapapala	45	29.0
21	2.50	2,200	4.15	Kapapala	82	34.8
27	7.41	969	4.15	Kapapala	36	31.6
29	0.30	1,770	3.12	[c]average	91	32.5
34	[d]0.01	[e]5,400	3.12	[c]average	[b]277	27.5
35	0.37	619	3.12	[c]average	32	29.3
36d	[d]0.05	[e]2,900	3.12	[c]average	[b]149	27.5
47	0.43	609	3.12	[c]average	31	26.0
52	31.3	205	3.24	Waiakea	10	25.2

[a] Site numbers correspond to sites listed in table 2 and shown in figures 2 and 3
[b] Values greater than 100 are considered unreasonable and likely result from errors in drainage area, rainfall intensities, or peak flow estimates
[c] Averages were computed from peak hourly rainfall at the Kapapala Ranch and Hawaii Volcanoes National Park gages
[d] Computed drainage area has a high degree of uncertainty owing to poorly defined drainage area boundaries
[e] Peak unit runoff is subject to error owing to the uncertainty in the computed drainage area

C is a dimensionless term that relates runoff to rainfall,
i is the rainfall intensity, and
A is the drainage area of the basin.

The rational formula is widely used to estimate flood flows in small basins and can be considered “an approximate deterministic model representing the flood peak” (Pilgrim and Cordery, 1992, p. 9.15). In this simplistic model, the *C* term incorporates most of the complexities referred to above. However, flood peak flow in this model is directly correlated to drainage area of the basin and rainfall intensity. The rainfall intensity term has a time frame, which is considered to be the time of concentration for the basin or the time it takes water to travel from the most remote point in the basin to the point of interest. The rational method is not used for computations in this report. The implication for this study, derived from the rational method formula, is that while total rainfall for a storm is an important factor affecting total storm runoff, peak flows are more influenced by rainfall that fell over shorter periods of time.

To evaluate rainfall-runoff relations in the study area, peak-flow and recurrence-interval data from table 3 along with rainfall-runoff data shown in table 4 were used. Table 4 includes the drainage area, peak unit runoff, area-weighted storm rainfall, the most proximate NWS hourly rain gage and the maximum hourly rainfall recorded at the gage during the November 1–2, 2000 storm, and peak runoff ratios for each of the 22 sites where peak-flow data were collected. Watershed boundaries were digitized and geographic information system (GIS) techniques were used to compute

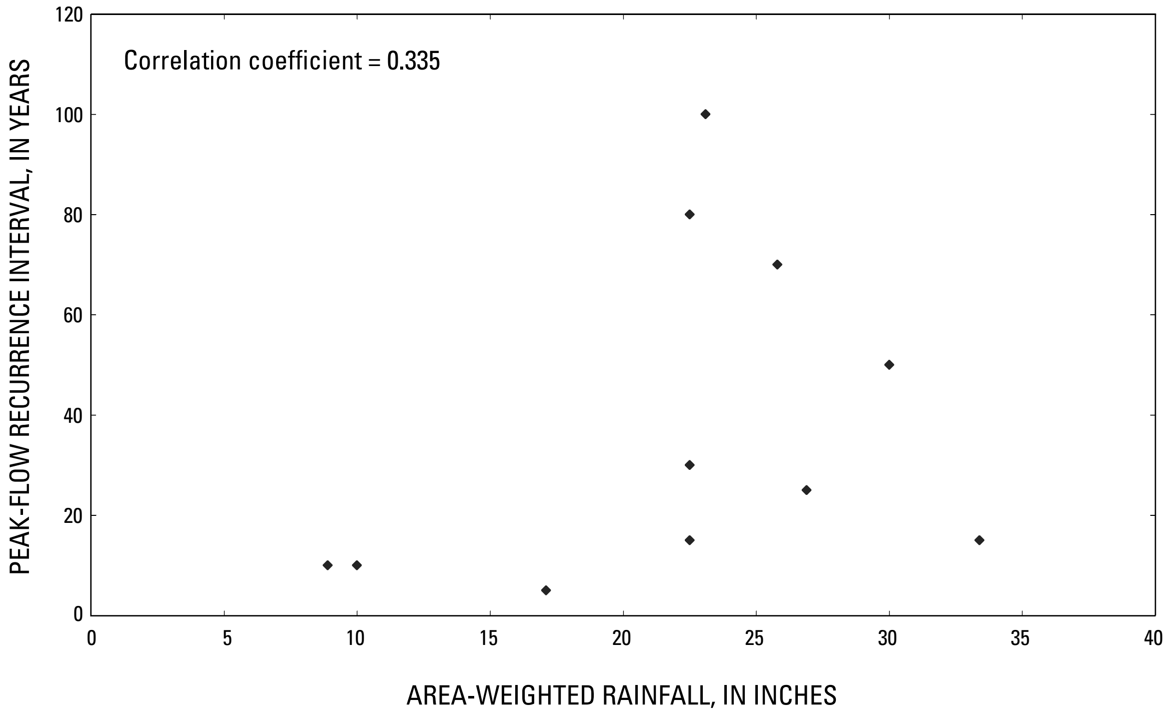


Figure 8. Scatterplot of peak-flow recurrence interval and area-weighted storm rainfall, November 1–2, 2000 flood, island of Hawaii, Hawaii.

watershed drainage areas in square miles. The watershed boundaries are shown in figures 6 and 7. Peak unit runoff is simply the peak flow rate at a location divided by the drainage area upstream from it.

Area-weighted storm rainfall values were based on the application of the isohyetal method (Linsley and others, 1982, p. 71). Lines of equal storm precipitation were overlain on a map showing watershed boundaries (figs. 6 and 7). The area-weighted rainfall was then computed for each site in table 4 by weighting the average precipitation between successive rainfall lines by the area between them, adding these values, and dividing the total by the total watershed drainage area (Fontaine and Nielsen, 1994, p. 28). Average precipitation within the innermost rainfall lines was assigned the value of rainfall associated with the highest line.

The peak-runoff ratio was computed as the peak runoff rate (in cubic feet per second converted to inches of runoff per second) divided by the peak rainfall rate (in inches per second) and is expressed as a percent. The peak rainfall rate was taken to be the maximum hourly rainfall from the closest NWS rain gage (provisional data from the NWS). The selected rain gages and their peak hourly rainfall intensities are shown in table 4. The peak rainfall rate used in these computations should optimally correspond to the time of concentration for the watershed in question. In small (less than about 1 mi^2), intermediate (about 1–10 mi^2), and large (greater than about 10 mi^2) watersheds, the optimum peak rainfall rates would be less than 1 hour, 1 to 3 hours, and 3 hours or more, respectively. In this analysis, the 1-hour peak rainfall rate was used for all sites, without any significant loss of accuracy because rainfall during the November 1–2, 2000 storm was characterized by extended periods of uniform, high intensity rainfall. For example, rainfall intensities for the maximum 3-hour durations, at the four index stations used in the table 4 computations, averaged 90 percent of the intensities for the maximum 1-hour durations. In addition, rainfall intensities for durations of less than 1 hour were not available.

To explore the relationship between peak flows and rainfall data, a scatterplot of peak-flow recurrence interval (table 3) compared with area-weighted storm rainfall (table 4) was prepared (fig. 8). As can be seen in figure 8, peak-flow recurrence intervals show little correlation with storm-total area-weighted rainfall (correlation coefficient is 0.335). For example, the four sites with area-weighted storm rainfall totals of between 20

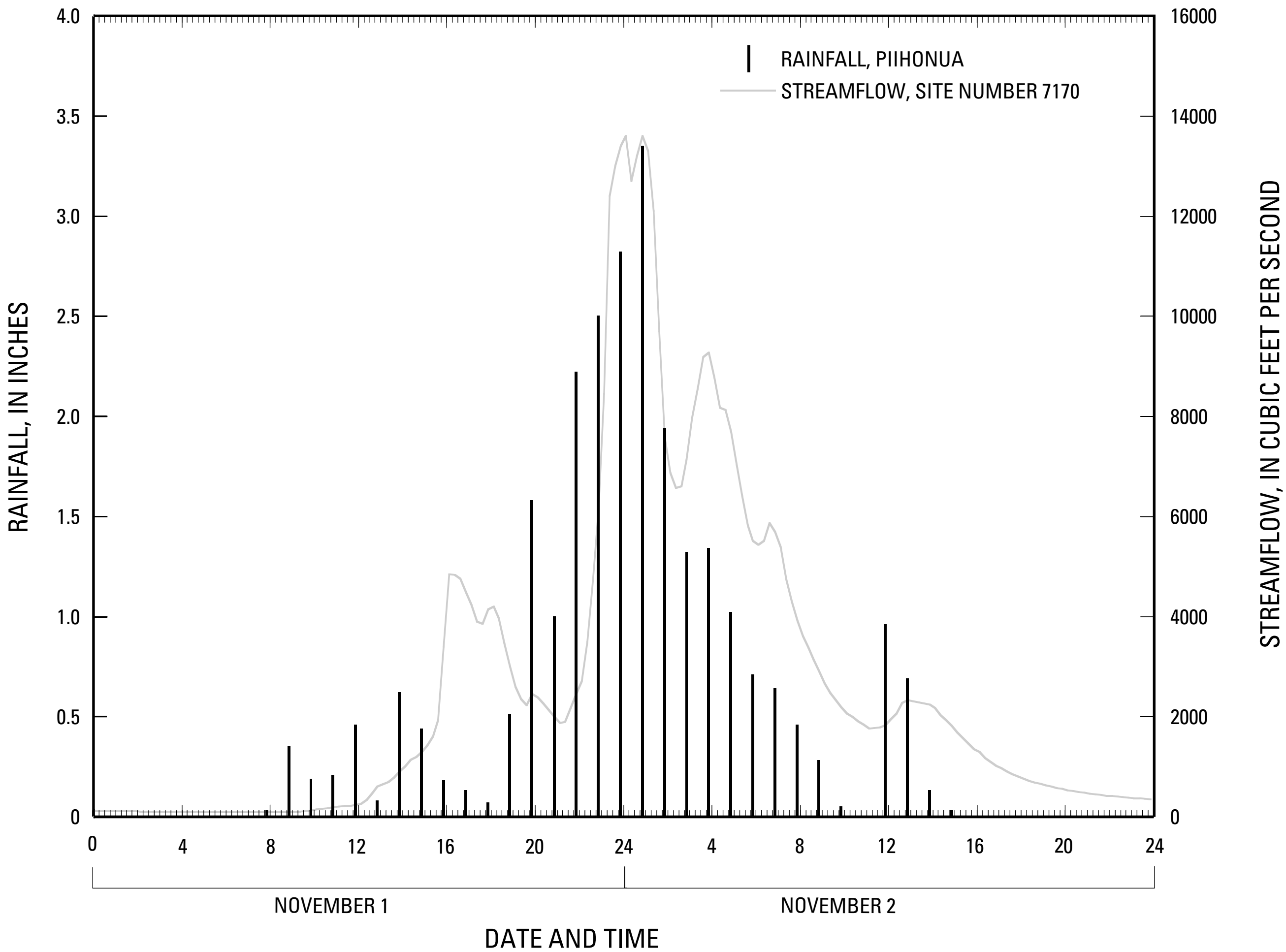


Figure 9. Piihonua hourly rainfall totals and Honolii streamflow data, November 1–2, 2000 flood, island of Hawaii, Hawaii.

and 25 in. have recurrence intervals that range between 15 and greater than 100 years. The lack of a correlation between peak-flow recurrence intervals and storm-total rainfall indicates that peak flows are more strongly influenced by shorter-duration rainfall totals.

Perhaps the best way to evaluate the relations between peak flows and short-duration rainfall totals is to compare streamflow hydrographs with short-duration rainfall that fell on the watershed area upstream from the streamflow recording station. Unfortunately, during the November 1–2, 2000 flood, only one USGS continuous-record gaging station was in operation and hourly rainfall data are currently only available for selected rain gages in the study area. Watershed-wide rainfall intensity data from the NWS are not available for the November 1–2, 2000 flood at this time. Streamflow data collected at 15-minute increments for Honolii Stream (site 7170) are compared with the most proximate NWS hourly rain-gage data (Piihonua) in figure 9. The data in figure 9 indicate that initially there was little streamflow response to rainfall. Between 1300 and 1500 hours on November 1, 1.06 in. of rain fell, resulting in the initial rise in the flow hydrograph which peaked between 1 and 2 hours later. The next rainfall peak was the 1.58 in. of rain, which fell between 1900, and 2000 hours on November 1. Again the flow hydrograph started to rise about 2 hours later. At this point rainfall intensity and streamflow continued to increase with both the rainfall and flow rates peaking between 2400 hours on November 1 and 0100 hours on November 2. After 0100 hours, both the rainfall and streamflow rates fell significantly. The rainfall between 0100 and 0200 hours on November 2 was 1.94 in.; however, this rate was not sufficient to continue to increase streamflow. This implies that the peak flow and response time at site 7170 was associated with the 4-hour period of time that rainfall rates were greater than 1.94 in/hr (between 2100 hours on November 1 and 0100 hours on November 2). The earlier response times of 1 to 2 hours and this 4-hour duration of intense rainfall prior to a drop in the flow hydrograph implies that the time of concentration or critical rainfall duration, for the November 1–2, 2000 storm, is somewhere between 1 to 2 and 4 hours for this watershed. Again, given the limitations in the rainfall data, this is only an approximation.

According to Benson's (1962, p. 32) study of the correlation of peak flows and rainfall intensities, the best results come from using rainfall intensities having the same recurrence intervals as the peak flows. Therefore, it could be assumed that another measure of time of concentration or critical rainfall duration would be provided by comparing the peak flow and maximum rainfall recurrence intervals from tables 1 and 3. For each site with a peak-flow recurrence interval in table 3, the most proximate rain gage was selected (table 4). The minimum rainfall duration with a recurrence interval (table 1) that most closely matches the peak-flow recurrence interval was then determined and summarized in table 5. For example, for site 7170, the critical rainfall duration is 1 to 3 hours while the analysis of the hydrograph (fig. 9) indicates the critical rainfall duration was between 1 to 4 hours.

Table 5. Critical rainfall durations associated with peak flows for November 1–2, 2000 flood, island of Hawaii, Hawaii

Site number[a]	Critical rainfall duration (hours)[b]
7000	12
7013	6
7014	3–6
7040	3
7130	3
7170	1–3
7174	3
7176	12
7176.5	6
7700	1–3
7705	1–3

[a] Site numbers are listed in table 2 and shown in figures 2 and 3.
[b] Minimum rainfall duration with a recurrence interval matching the peak flow recurrence interval.

To compare peak-flow rates at a variety of sites with differing drainage areas, it is best to use the peak unit-runoff rate (the peak flow rate divided by the drainage area, table 4). A scatterplot of peak unit-runoff rate compared with drainage area is shown in figure 10. Data for sites 34 and 36 were not included in figure 10 because of uncertainties in their computed drainage areas. Data for sites 7040 and 7130, although consistent with the generalized trend line shown, were not included in figure 10 because their drainage areas were an order of magnitude greater than those for the remaining sites. Data in figure 10 indicate that the peak unit-runoff rates generally decline with increasing drainage area. High-intensity rainfall is more likely to extend over entire watersheds when those watersheds are small. In larger drainages, the timing and spatial distribution of high rainfall intensities are more likely to vary throughout the watersheds, therefore leading to peak runoff rates that are not synchronized. Although the trend of declining peak unit-runoff rates is clear, the relation is not strong enough (correlation coefficient is -0.444) to allow use of the data in figure 10 to make estimates of peak unit-runoff rates at sites where peak-flow calculations were not made for the November 1–2, 2000 flood.

Peak runoff ratios (table 4), in conjunction with soil permeability data (Sato and others, 1973; Saku Nakamura, Natural Resources Conservation Service, written commun., 2001), indicate that infiltration-excess (Horton) overland flow did not account for large proportions of the peak flows. Peak streamflows represented between 8 and 96 percent of peak rainfall for the 19 sites where reasonable comparisons could be made, that is, at sites where peak-runoff rates were less than 100 percent of peak-rainfall rates (table 4). The average peak-runoff ratio for the 19 sites was 43 percent. Peak streamflow was more than 50 percent of peak rainfall at 6 sites and more than 80 percent of peak rainfall at 4 sites (table 4). These peak-runoff ratios are high in view of the high infiltration rates in the study area. Permeability data for soils in the study area indicate that rainfall intensities of at least 2.0 and up to 20.0 in/hr are necessary to exceed infiltration rates and cause any Horton overland flow. For many of the soils in the study area, permeability data indicate that rainfall intensities of 6.0 in/hr are required to generate Horton overland flow. Actual maximum hourly rainfall intensities ranged from 2.10 to 4.56 in. (table 1), so some Horton overland flow probably was generated during the storm

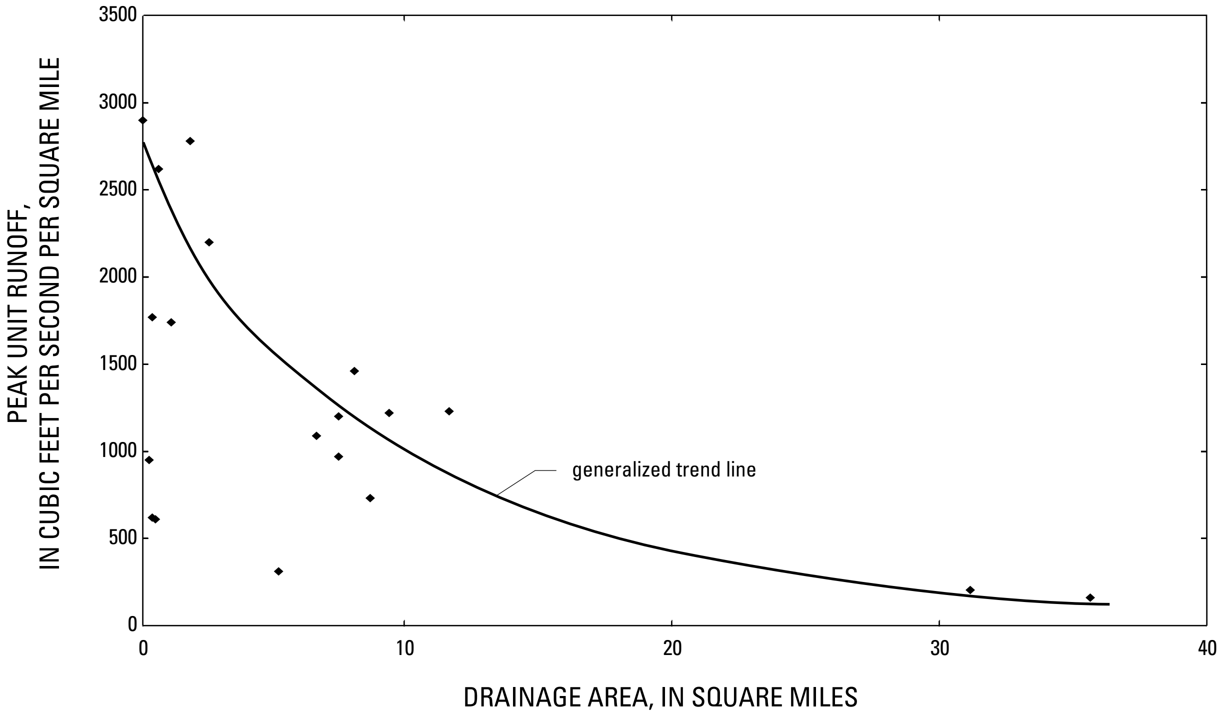


Figure 10. Relation between peak unit runoff and drainage area, November 1–2, 2000 flood, island of Hawaii, Hawaii.

on soils with permeabilities between 2.0 and 6.0 in/hr. However, the large areas with permeabilities greater than 6.0 in/hr probably contributed no Horton overland flow because rainfall intensities were less than infiltration rates. Therefore, the generally high peak-runoff ratios (table 4) for watersheds with highly permeable soils indicate that saturation overland flow and subsurface stormflow probably contributed to peak flows. This conclusion is supported by field evidence of restricted areas of overland flow, and by subsurface permeability data that indicate sharp decreases in permeability at shallow depths.

Waiakea High-Rainfall Area

In the description of the study area it was noted that the watersheds north of the Wailuku River lie on the slopes of Mauna Kea with its older, Hamakua Volcanics lava flows and the remaining sections of the Waiakea high-rainfall area lie on the slopes of Mauna Loa with its younger and often historic Kau Basalt lava flows. This geologic distinction is readily apparent when viewing the rainfall-runoff data in table 4. Sites located on the slopes of Mauna Kea have peak unit-runoff rates and peak-runoff ratios that are four to five times higher than those for sites located on the slopes of Mauna Loa.

Six sites have rainfall-runoff data for watersheds on the slopes of Mauna Loa (sites 52, 7013, 7014, 7016, 7040, and 7130). Peak unit-runoff values for the six sites range from 161 to 731 cubic feet per second per square mile ($ft^3/s/mi^2$) and average 311 $ft^3/s/mi^2$. Peak-runoff ratios range from 8 to 35 percent and average 15 percent.

Four sites have rainfall-runoff data for watersheds on the slopes of Mauna Kea (sites 7170, 7174, 7176, and 7176.5). Peak unit-runoff values for the four sites range from 950 to 2,620 $ft^3/s/mi^2$ and average 1,635 $ft^3/s/mi^2$. The peak-runoff ratio for site number 7176 (Alia Stream near Hilo) was computed to be greater than 100 percent, which implies that the maximum runoff rate from the watershed was greater than the maximum rainfall rate that fell on it. With the exception of unusual circumstances, such as dam failures, this is not a physical possibility and implies that one or more of the computations for this watershed were in error. The Piihonua hourly rain gage, while located a significant distance from the Alia Stream watershed, was still the closest site with hourly rainfall data for use in computing the peak-runoff ratio. It is likely that differences in rainfall between that recorded at the Piihonua rain gage and that falling on the Alia Stream watershed exist which would therefore render computations using the Piihonua rain gage data incorrect. Another possibility is that there were errors in the computation of the peak-flow rate for the Alia Stream site. Excluding data for site 7176, peak-runoff ratios for the three remaining sites range from 44 to 81 percent and average 61 percent.

The estimates of critical rainfall durations (table 5) for sites in the Waiakea high-rainfall area do not show any clear patterns. Critical durations for five of the nine sites located in the Waiakea high-rainfall area are approximately 3 hours. The values of 12 and 6 hours computed for sites 7176 and 7176.5 do not appear reasonable and this could be attributed to the lack of a proximate hourly rain gage for these watersheds. Values of 12 and 6 hours computed for sites 7000 and 7013 in the Waiakea Stream watershed could be a function of the lower rates of runoff from that area. Watershed response time will be slower when higher percentages of rainfall infiltrate into the ground.

Kapapala High-Rainfall Area

Rainfall-runoff data were computed for 12 sites in the Kapapala high-rainfall area (table 4). Peak unit-runoff and peak-runoff ratios determined for sites 34 and 36d were found to be unreasonable. As noted above, peak-runoff ratios greater than 100 percent are not probable in this area. Watersheds in the vicinity of sites 34 and 36d are extremely poorly defined and errors in the measurement of drainage areas for these sites are likely. Sites 34 and 36d were determined to have very small drainage areas (0.01 and 0.05 mi^2) and therefore any measurement errors would lead to large percentage differences in the computations of areas and therefore peak unit-runoff and peak-runoff ratios. Rainfall-runoff data for these sites are not used in the summary provided below.

Unlike the Waiakea high-rainfall area, no clear trends were apparent in the rainfall-runoff data computed for the 10 sites in Kapapala high-rainfall area (table 4). Peak unit-runoff values range from 609 to 2,780 $ft^3/s/mi^2$ and average 1,390 $ft^3/s/mi^2$. Peak-runoff ratios range from 31 to 96 percent and average 55 percent. Peak unit-runoff and peak-runoff ratios computed for the Kapapala high-rainfall area are similar to but slightly lower than those computed for the area north of the Wailuku River in the Waiakea high-rainfall area.

Estimates of critical rainfall durations (table 5) were computed for only two sites in the Kapapala high-rainfall area (sites 7700 and 7705). For both sites, computed durations were 1 to 3 hours indicating the rapid response of peak-flow rates in these streams to periods of peak-rainfall intensities. One factor that might have contributed to this rapid response, noted in an earlier section of this report, is that the periods of maximum rainfall intensities in the Kapapala high-rainfall area took place much later in the storm and after significant amounts of antecedent rainfall had already fallen (fig. 2). This fact coupled with the higher rainfall intensities recorded in the Kapapala high-rainfall area (table 1) could have contributed to faster response times.

An interesting pattern in computed peak unit runoff was noted for sites 2, 18, and 13 along Waihaka Stream near Kapapala Ranch. As can be seen from the data for these sites in table 4, proceeding downstream from site 2, with a drainage area of 6.54 mi^2, to site 18, with a drainage area of 7.45 mi^2, to site 13, with a drainage area of 7.97 mi^2, peak unit runoff increased from 1,090 to 1,460 $ft^3/s/mi^2$. This trend contrasts with the normal pattern of declining peak unit runoff rates with increasing drainage area (fig. 10). At these sites on Waihaka Stream, the increasing peak unit-runoff rates are directly correlated to the fact that the area of maximum storm rainfall, and most likely intensity, was closer to site 13 and Kapapala Ranch. Another factor is likely to be land use in the area. As noted in the description of the study area, most of the land above an altitude of about 3,500 ft is forested. Site 2 on Waihaka Stream is at an altitude of 3,230 ft and therefore downstream from that altitude the percentage of non-forested land area in the watershed increases. Runoff from the non-forested lands would be higher because infiltration rates there would be lower (Dunne and Leopold, 1978, p. 167).

EROSIONAL FEATURES IN THE KAPAPALA HIGH-RAINFALL AREA

Erosional features attributed to the storm of November 1–2, 2000 included both channel and hillslope features. This report focuses on the hillslope features because of their relation to surface runoff generation processes (overland flow).

Hillslope erosional features included mass-wasting and fluvial (caused by flowing water) features, and some features that showed evidence of both mass-movement and fluvial erosion (table 6). Hillslope features were observed along the Kaoiki Pali, between the Kapapala Ranch and Kilauea Volcano (fig. 3). A few small features also were noted above Wood Valley. No hillslope features were observed southwest of Wood Valley or northeast of site 47 (fig. 7) in Hawaii Volcanoes National Park.

Field visits were made to all hillslope features along the Kaoiki Pali to collect information on the processes and materials contributing to the hillslope failures and to measure representative dimensions of the failures. These features had a variety of forms, but in general, the features had well-defined headscarps below the top of the pali, steep sides, or banks, highly irregular scar surfaces, and deposits on the gentle slope at the foot of the pali. Erosional features on ash deposits typically had lobe-shaped lateral scarps along their banks that appeared to be the result of mass wasting following undercutting by fluvial erosion (fig. 11). Locations were determined by altimeter, compass bearings to mapped features, and from examination of topographic maps. Except where precluded by steep slopes or unstable landslide deposits, the headscarp of each failure was examined for signs of overland flow, including debris deposits, rill or channel cutting, and flattened leaves of grass oriented in the presumed direction of flow. Deposits were examined to infer the extent to which they were transported after the initial failures by flowing water. Failure scars were also examined for evidence of subsurface flow, including macropore openings, deposits of fine sediment at ash-basalt contacts, persistent moisture, or moss growth at headscarps. Topographic slopes were measured with an Abney level. Dimensions were measured with a range finder or fiberglass tape.

Hillslope erosional features included debris slides, debris flows, slumps, gullies, and features having characteristics of both gullies and landslides (table 6). Altitudes at the tops of the erosional features ranged from 2,640 to 4,020 ft. Topographic slopes at the tops of the features ranged from 11 to 100 percent. Measured lengths ranged from 20 to 668 ft, average widths ranges from 2.3 to 157 ft, and average depths ranged from 2.3 to 9 ft (table 7). Measured volumes ranged from 51 to 12,400 cubic yards (table 7). Of the 21 features visited in the field, 8 occurred in ash deposits, 11 involved basalt interlayered with ash, and only two failures occurred in basalt without interlayered ash. Five of the features did not have discernible evidence of overland flow at their upslope ends. Evidence of overland flow was found for the other 16 features.

Shear stresses computed for peak flows at or near hillslope erosional features ranged from 2.47 to 42.6 pounds per square foot (lb/ft^2) and are summarized in table 8. Shear stress was computed as:

$$T = \gamma ds \qquad (2)$$

Where T is shear stress, in pounds per square foot,
γ is the specific weight of water, in pounds per cubic foot,
d is maximum flow depth, in feet, and
s is the topographic slope of the channel bed, in feet per foot (Leopold and others, 1964, p. 157).

Depths were determined from cross-section surveys. Slopes were determined from cross-section surveys and measurements of distances between cross sections (sites 36 and 47), or were calculated from values of discharge (Q), in ft^3/s, and conveyance (K), in ft^3/s, computed for critical-depth flow measurements (sites 29, 34, and 35):

$$S = \left(\frac{Q}{K}\right)^2 . \qquad (3)$$

Slopes (S) computed using (3) are energy slopes, and underestimate the bed slopes to an unknown degree.

The computed shear stresses are at or above the critical shear stresses required to initiate channels on ungrazed grass-covered valley floors (Prosser and Slade, 1994; Prosser and Dietrich, 1995; Prosser and Abernathy, 1996) and are substantially higher than the critical shear stresses required to erode grassy valley floors under simulated grazing that would be more representative of actual field conditions along the Kaoiki

Table 6. Hillslope erosional features along the Kaoiki Pali resulting from the November 1–2, 2000 flood, island of Hawaii, Hawaii
[--, not determined]

Site number[a]	Type of feature	Altitude at headscarp (feet)	Hillslope gradient (percent)	Geologic materials	Evidence for overland flow
28	debris flow	3,030	40	basalt/ash	Yes
30	debris flow/gully	3,250	29	basalt/ash	Yes
31	debris slide	3,350	12	basalt	Yes
32	debris slide	3,440	50	basalt/ash	No
33	debris slide	3,410	80	basalt/ash	No
34	debris flow/gully	3,530	75	basalt/ash	Yes
36a	slump/gully	3,360	25	ash	Yes
36b	gully	3,420	33	ash	Yes
36c	slump	3,430	33	ash	Yes
36d	gully	3,460	17	basalt/ash	Yes
37	slump/gully	3,880	33	ash	Yes
38	gully	3,890	11	ash	Yes
39	gully	4,020	18	basalt/ash	Yes
40	gully	3,740	14	basalt/ash	Yes
41	slump/gully	3,720	20	basalt/ash	Yes
42	debris slide	3,590	--	basalt	No
45	debris flow/gully	3,810	17	ash	Yes
46	debris flow	3,810	18	basalt/ash	No
47	gully	4,000	27	basalt/ash	Yes
50	debris slide	2,640	100	ash	No
51	gully	2,640	100	ash	Yes

[a] Site numbers are listed in table 2 and shown in figure 4.

Pali (Prosser and Slade, 1994; Prosser and Dietrich, 1995; Prosser and Abernathy, 1996). The peak flows along the Kaoiki Pali, therefore, appear to have exerted sufficient shear stresses to initiate the observed hillslope erosional features.

Previous studies (Prosser and Slade, 1994; Prosser and Dietrich, 1995; Prosser and Abernathy, 1996) have shown that a shear stress of about 0.52 lb/ft^2 is sufficient to erode a grazed grass-covered valley floor. Substituting a value of 0.52 lb/ft^2 in (2) and rearranging to solve for *d* at the sites listed in table 8 gives a range of 0.04 to 0.76 ft of depth corresponding to the critical shear stress. Flow depths less than this range would not be likely to initiate erosion. Thus, the maximum flow depths at locations where erosion did not occur were likely less than 0.76 ft, even in swales and other topographic depressions that would tend to concentrate flow. Substantial amounts of overland flow therefore were probably restricted to locations where erosion was observed. Widespread overland flow with depths of greater than a few tenths of a foot probably did not occur. This observation supports the peak runoff ratio analysis presented earlier, which indicated the possibility of major contributions of subsurface storm flow to peak flows.

Collapse features above lava tubes were noted in several locations at the foot of the pali. Field evidence indicates that many of these features intercepted surface runoff. No evidence of discharge of subsurface flow from lava tubes was found.

Evidence of previous erosional episodes along the Kaoiki Pali was found in a few locations. Near site 34 (fig. 3), previously unmapped alluvium was found exposed at one of the collapse features described above, indicating possibly two earlier periods of fluvial erosion and deposition in the unchanneled area. A tree exposed in the landslide scar at site 36 (fig. 3), had two distinct sets of roots, one about 4 ft higher than the other, indicating burial in an earlier erosional episode and subsequent exhumation in the storm of November 1–2, 2000.

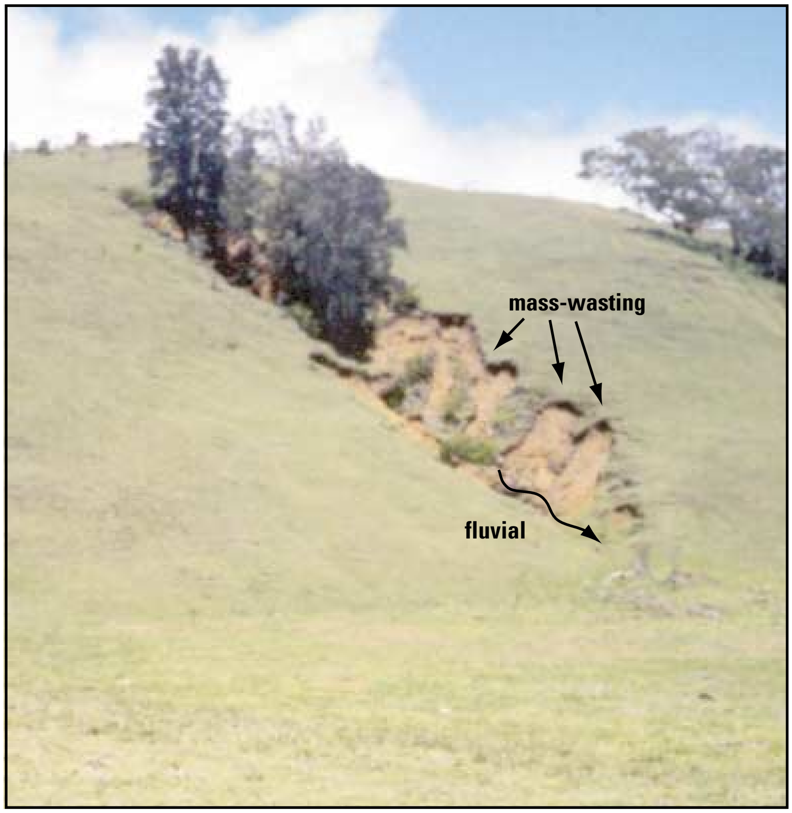


Figure 11. Hillslope erosional feature at site 47 along Kaoiki Pali, showing evidence of both fluvial and mass-wasting erosion, island of Hawaii, Hawaii.

Table 7. Dimensions of selected hillslope erosional features along the Kaoiki Pali resulting from the November 1–2, 2000 flood, island of Hawaii, Hawaii
[--, not determined; (e), estimated; max., maximum width reported in place of average width]

Site number[a]	Horizontal length (feet)	Average width (feet)	Average depth (feet)	Volume (cubic yards)
28	306	72	9	7,340
30	668	--	--	--
30.1	262	2.3	2.3	51
31	163	105	8	5,070
32	355	157	6(e)	12,400
33	180	40	--	--
34	420	20	5(e)	1,560
36a	131	72 (max.)	--	--
36b	--	--	--	--
36c	91	66 (max.)	--	--
36d	142	75 (max.)	--	--
37	253	--	--	--
50	20	35	--	--
51	--	8	--	--

[a] Site numbers are listed in table 2 and shown in figure 4

Table 8. Shear stresses exerted by peak flows upstream of hillslope erosional features along the Kaoiki Pali, November 1–2, 2000 flood, island of Hawaii, Hawaii

Site number[a]	Depth (feet)	Channel bed slope (feet per foot)	Shear stress (pounds per square foot)
29	3.6	[b]0.011	2.47
34	3.9	[b]0.015	3.64
35	5.1	[b]0.012	3.81
36	2.6	[c]0.125	20.5
47	3.1	[c]0.220	42.6

[a] Site numbers are listed in tables 1 and 2 and shown in figure 3; site 29 is upstream of site 30

[b] Channel bed slope estimated from hydraulic model computations

[c] Channel bed slope measured in the field

Several fissures or cracks were observed near site 35 along the top of the Kaoiki Pali. These cracks are not necessarily related to the storm of November 1–2, 2000, but they appear to be recent based on “bridges” of live grasses that span the cracks. These cracks indicate the possibility of future large and rapid mass-movement failures along the Kaoiki Pali. Hummocky deposits near site 36 (fig. 3) may have resulted from earlier such failures.

In addition to the hillslope failures associated with the storm, major channel widening and deepening occurred on many streams in the Kapapala high-rainfall area, and many completely new channels were cut where existing channels lacked the capacity to convey the storm runoff owing to low channel conveyance or blockage by debris or engineered structures. One such channel, Waihaka Stream at the Kapapala Ranch, was eroded to a depth of about 40 ft. Channel deepening and widening followed a pattern similar to that of the discontinuous gullies described in the southwest U.S. by Leopold and others (1964); headcuts and plunge pools were created where resistant lava prevented downcutting upstream but easily-eroded ash allowed downcutting downstream (fig. 12). Downstream from headcuts, channel depth and bank height decreased until peak flows were able to overtop banks, leading to cutting of more new channels on previously unchanneled hillslopes. Channel cutting was apparently enhanced both by the low resistance of the Pahala Ash to erosion by surface water and the youthful age of the landscape, which has poorly developed drainage and only minor topographic divides between stream basins.

A detailed investigation of the extent and magnitude of channel erosion related to the storm of November 1–2, 2000, is beyond the scope of this report. However, near site 2 (fig. 3), an attempt was made to estimate the amount of channel widening by measuring the maximum lengths of the roots of ohia trees exposed along the channel banks. These measurements indicated about 20 ft of erosion on each bank. This estimate is consistent with anecdotal information on the widening of the channel at the nearby ranch pipeline crossing, which was destroyed during the storm and rebuilt in December 2000 (Gordon Cran, Kapapala Ranch, oral commun., 2001).

Channel erosion appeared to be much more extensive during the storm of November 1–2, 2000, than in other recent storms that were of only slightly smaller magnitude. The extensive channel erosion during the storm of November 1–2, 2000, may have been a result of the long duration of intense rainfall and high streamflow (fig. 9), as suggested by Costa and O’Connor (1995) for study sites on the U.S. mainland.

Fewer erosional features were documented in the Waiakea high-rainfall area (Paul Haraguchi, consulting meteorologist, written commun., 2001). These features included several landslides on coastal cliffs and streambanks. Hillslope erosional features and channel erosion did not occur to the same degree as in the Kapapala high-rainfall area possibly because the thick ash deposits that are easily eroded by surface water do not occur in the Waiakea area.

SUMMARY AND CONCLUSIONS

The unique convergence of the upslope topography of eastern Hawaii, the location of a large upper level trough and remnants from tropical storm Paul, and the pattern of tradewinds in the area combined to produce extreme rainfall over parts of the island of Hawaii on November 1–2, 2000. Two distinct storm centers received rainfall in excess of 30 inches: the Waiakea and the Kapapala high-rainfall areas. Most of the rain fell in a 24-hour period and maximum-recorded rainfall for the entire storm in the Waiakea and Kapapala areas was 32.47 inches at Mountain View and 38.97 inches at Kapapala Ranch. The severity of the November 1–2, 2000 storm, as measured by the recurrence interval of the rainfall, increased as the duration of the time interval increased. Maximum 1-hour rainfall totals had

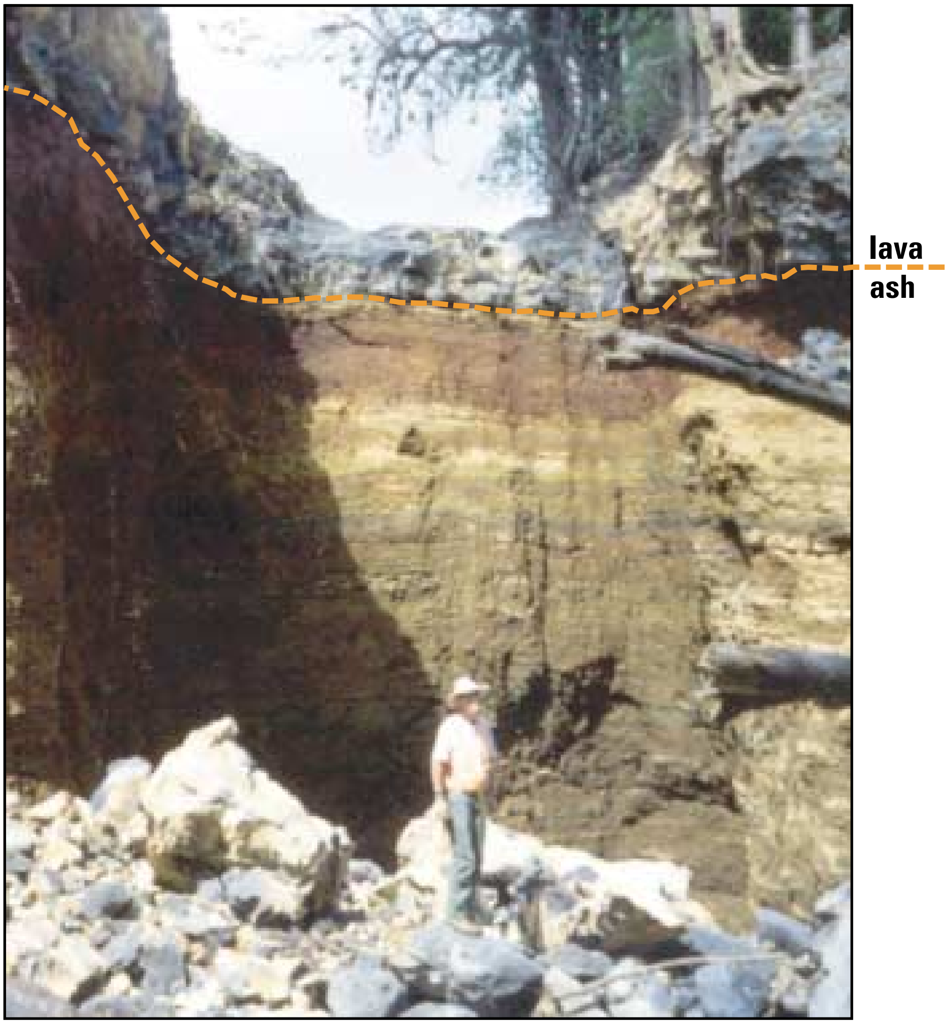


Figure 12. Headcut on Waihaka Stream between Kapapala Ranch and site 13, showing effect of resistant cap of lava above ash deposits, island of Hawaii, Hawaii.

recurrence intervals of 10 years or less while most maximum 24-hour rainfall totals had recurrence intervals equal to or greater than 100 years.

Peak flow and/or erosion data were collected at 41 sites to aid in the description of the flooding associated with the November 1–2, 2000 storm. New peak discharges of record occurred at six of the 12 sites where historic data were available. The recurrence intervals associated with the peak discharges ranged between 50 and 100 years for streams south of the Wailuku River in the Waiakea high-rainfall area. The majority of the remaining streams in the study area had recurrence intervals between 5 and 30 years. Peak unit-runoff rates computed for 22 sites ranged from 161 to 5,400 cubic feet per second per square mile of watershed area. Peak unit-runoff rates averaged 311 cubic feet per second per square mile for the Wailuku River and streams to its south, in the Waiakea high-rainfall area. Peak unit-runoff rates in the remainder of the Waiakea and the Kapapala high-rainfall areas were comparable and averaged 1,635 and 1,390 cubic feet per second per square mile.

Analysis of rainfall-runoff relationships in the study area was complicated by the complex and evolving nature of the geology and the extreme spatial variation of the storm rainfall. Peak flows were found to be poorly correlated to area-weighted storm rainfall and were therefore more strongly influenced by shorter-duration rainfall totals. Comparison of peak streamflow and rainfall recurrence interval data indicated the critical rainfall durations for the generation of peak flows ranged from 1 to 12 hours and were about 3 hours at most sites. Peak-runoff rates divided by peak-rainfall intensities were found to average 43 percent at 19 sites. While maximum hourly rainfall intensities exceeded infiltration rates in parts of the study area, the overland flow generated would not have been sufficient to account for the high peak-runoff rates. This finding indicates the saturation overland flow and subsurface flow probably contributed to peak flows at most sites.

Most hillslope erosion related to the storm occurred along or near the Kaoiki Pali in the Kapapala high-rainfall area. The erosion was mostly caused by overland flow and was associated with thick ash deposits of the Kahuku Basalt.

REFERENCES CITED

Barnes, H.H., Jr., and Davidian, Jacob, 1978, Indirect methods: chap. 5 *in* Hydrometry: Principles and Practices, Herschy, R.W., ed., New York, Wiley, p. 149–191.

Benson, M.A., 1962, Factors influencing the occurrence of floods in a humid region of diverse terrain: U.S. Geological Survey Water-Supply Paper 1580-B, 64 p., 1 pl.

Cervelli, Peter, Segall, Paul, Jonson, Kaj, Lisowski, Michael, and Miklius, Asta, 2002, Sudden seismic fault slip on the south flank of Kilauea volcano, Nature, v. 415, p. 1014–1018.

Costa, J.E., and O’Connor, J.E., 1995, Geomorphically effective floods, *in* Costa, J.E., and others (eds.), Natural and Anthropogenic Influences in Fluvial Geomorphology, Geophysical Monograph 89, American Geophysical Union, p. 45–56.

Dunne, Thomas, and Leopold, L.B., 1978, Water in environmental planning: San Francisco, Calif., W.H. Freeman and Company, 818 p.

Fontaine, R.A., and Nielsen, J.P., 1994, Flood of April 1987 in Maine: U.S. Geological Survey Water-Supply Paper 2424, 50 p.

Freeze, R.A., 1974, Streamflow generation: Reviews of Geophysics and Space Physics, vol. 12, p. 627–647.

Fulford, J.M., 1994, User’s guide to SAC, a computer program for computing discharge by slope-area method: U.S. Geological Survey Open-File Report 94-360, 31 p.

Fulford, J.M., 1998, User’s guide to the U.S. Geological Survey culvert analysis program, version 97-08: U.S. Geological Survey Water-Resources Investigations Report 98-4166, 70 p.

Giambelluca, T.W., Nullet, M.A., and Schroeder, T.A., 1986, Rainfall atlas of Hawaii: Hawaii Department of Land and Natural Resources Report R76, 267 p.

Haraguchi, Paul, 1980a, Storm of November 16–18, 1979, Island of Hawaii: Hawaii Department of Land and Natural Resources Circular C82, 37 p.

Haraguchi, Paul, 1980b, Storms of March 16–19 and 23–24, 1980, Islands of Hawaii and Oahu: Hawaii Department of Land and Natural Resources Circular C84, 24 p.

Harris, D.D., and Nakahara, R.H., 1980, Flood of February 20, 1979 in Hilo, Kau, and Puna Districts, Island of Hawaii: Hawaii Department of Land and Natural Resources Circular C81, 28 p.

Interagency Advisory Committee on Water Data, 1982, Guidelines for determining flood flow frequency: Water Resources Council Bulletin 17B, 28 p., 14 app., 1 pl.

Jarrett, R.D., and England, J.F., Jr., 2002, Reliability of paleostage indicators for paleoflood studies *in* Water science application 5, ancient floods, modern hazards, American Geophysical Union, p. 91–109.

Langenheim, V.A.M., and Clague, D.A., 1987, Chap. 1 *of* Decker, R.W., Wright, T.L., and Stauffer, R.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 55–84.

Lee, Reuben, and Valenciano, Santos, 1986, Hawaii surface-water resources: *in* National Water Summary 1985—hydrologic events and surface-water resources, U.S. Geological Survey Water-Supply Paper 2300, p. 201–206.

Leopold, L.B., Wolman, M.G., and Miller, F.P., 1964, Fluvial processes in Geomorphology: San Francisco, Calif., W.H. Freeman and Company, 522 p.

Linsley, R.K., Jr., Kohler, M.A., and Paulhus, J.L.H., 1982, Hydrology for Engineers: New York, McGraw-Hill, 508 p.

Pilgrim, D.H., and Cordery, Ian, 1992, Flood runoff, chap. 9 *in* Maidment D.R., ed., Handbook of Hydrology: New York, McGraw-Hill, variously paged.

Prosser, I.P., and Abernathy, Bruce, 1996, Predicting the topographic limits to a gully network using a digital terrain model and process thresholds: Water Resources Research, v. 32, p. 2289–2298.

Prosser, I.P., and Dietrich, W.E., 1995, Field experiments on erosion by overland flow and their implication for a digital terrain model of channel initiation: Water Resources Research, v. 31, p. 2867–2876.

Prosser, I.P., and Slade, C.J., 1994, Gully formation and the role of valley-floor vegetation, southeastern Australia: Geology, v. 22, p. 1127–1130.

Rantz, S.E., and others, 1982, Measurement and computation of streamflow, Volume 1 and Volume 2: U.S. Geological Survey Water-Supply Paper 2175, 631 p.

Sato, H.H., Ikeda, Warren, Paeth, Robert, Smythe, Richard, and Takehiro, Minoru, Jr., 1973, Soil Survey of the Island of Hawaii, State of Hawaii: U.S. Department of Agriculture, Soil Conservation Service, 115 p., 195 sheets, 1 pl.

Stearns, H.T., and Clark, W.O., 1930, Geology and water resources of the Kau District, Hawaii: U.S. Geological Survey Water-Supply Paper 616, 194 p., 3 pl.

Stearns, H.T., and Macdonald, G.A., 1946, Geology and ground-water resources of the island of Hawaii: Hawaii Division of Hydrography Bulletin 9, 363 p., 3 pl.

U.S. Weather Bureau, 1962, Rainfall-frequency atlas of the Hawaiian Islands: U.S. Bureau Technical Paper No. 43, Washington D.C., 60 p.