ESTIMATION OF MAGNITUDE AND FREQUENCY OF FLOODS FOR STREAMS ON THE ISLAND OF OAHU, HAWAII

By Michael F. Wong

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Conversion Factors

Multiply	By	To obtain
acre	4,047	square meter
foot (ft)	0.3048	meter
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
inch (in.)	25.4	millimeter
inch per year (in/yr)	2.54	centimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Temperature is given in degrees Fahrenheit (°F) , which can be converted to degrees Celsius (°C) by using the equation:

$$°C = (°F - 32)/1.8$$

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ABSTRACT

This report describes techniques for estimating the magnitude and frequency of floods for the island of Oahu. The log-Pearson Type III distribution and methodology recommended by the Interagency Committee on Water Data was used to determine the magnitude and frequency of floods at 79 gaging stations that had 11 to 72 years of record. Multiple regression analysis was used to construct regression equations to transfer the magnitude and frequency information from gaged sites to ungaged sites. Oahu was divided into three hydrologic regions to define relations between peak discharge and drainage-basin and climatic characteristics. Regression equations are provided to estimate the 2-, 5-, 10-, 25-, 50-, and 100-year peak discharges at ungaged sites. Significant basin and climatic characteristics included in the regression equations are drainage area, median annual rainfall, and the 2-year, 24-hour rainfall intensity. Drainage areas for sites used in this study ranged from 0.03 to 45.7 square miles. Standard error of prediction for the regression equations ranged from 34 to 62 percent.

Peak-discharge data collected through water year 1988, geographic information system (GIS) technology, and generalized least-squares regression were used in the analyses. The use of GIS seems to be a more flexible and consistent means of defining and calculating basin and climatic characteristics than using manual methods. Standard errors of estimate for the regression equations in this report are an average of 8 percent less than those published in previous studies.

INTRODUCTION

Available peak-discharge data are used in flood-frequency studies to estimate the magnitude and frequency of floods that can occur at gaged sites. Estimates of magnitude and frequency of floods are used when planning and designing structures such as dams, bridges, culverts, highways, and buildings. These estimates are also needed at ungaged sites. Estimates at ungaged sites may be computed by regression of flood magnitude and frequency information at gaged sites with drainage-basin and climatic characteristics. Because of the need for assessing existing storm-drainage design standards, and for preparing new standards, the Department of Public Works, City and County of Honolulu, entered into a cooperative study with the U.S. Geological Survey (USGS) to develop estimates of the magnitude and frequency of floods for the island of Oahu.

PURPOSE AND SCOPE

The purpose of this report is to present, for unregulated streams on the island of Oahu, estimates of the magnitude and frequency of floods at gaged sites and techniques that can be used to estimate the magnitude and frequency of floods at ungaged sites. In addition, this report compares the results of applying regression equations to observed peak discharges, the log-Pearson Type III estimates, estimates from the design curves in the 1988 City and County of Honolulu storm drainage standards, and estimates from regression equations by Nakahara (1980).

This report uses peak-discharge data collected through water year 1988 at 79 gaging stations on the island of Oahu, Bulletin 17B guidelines (Interagency Advisory Committee on Water Data, 1982) for flood-frequency analysis, multiple regression techniques, generalized least-squares regression analysis designed for use with peak-discharge data, and geographic information system (GIS) technology for computing drainage-basin and climatic characteristics.

DESCRIPTION OF STUDY AREA

For this flood-frequency study, information on the physiographic and climatic characteristics related to flood hydrology is used to select drainage-basin and climatic characteristics that can influence the magnitude of floods. This information is also used to delineate regional hydrologic boundaries.

PHYSIOGRAPHY

The island of Oahu is located in the Pacific Ocean at about latitude 21°30'N and longitude 158°W (fig. 1). Oahu, with an area of 608 mi^2, is the third largest island of the Hawaiian island chain. Like the other Hawaiian islands, Oahu was created by volcanic activity and shaped by erosional forces. The current topography is dominated by two mountain ranges, the Koolau and the Waianae, both of which are eroded remnants of great elongated shield volcanoes (Macdonald and others, 1983). The two ranges are approximately parallel and trend northwest to southeast (fig. 1). The Koolau Range ranges in altitude from sea level to 3,150 ft, with most of the crest at altitudes of 2,000 to 2,700 ft. The Koolau Range is characterized by steep cliffs on the northeastern (windward) face and slopes incised by large, deep valleys on the southwestern (leeward) side (Armstrong, 1983). The Waianae Range is similar, but has its steep cliffs on the southwestern side and slopes incised by large, deep valleys on the northeastern face (Armstrong, 1983). Altitudes range from sea level to 4,025 ft on the Waianae Range, but most of the crest is between 2,000 and 3,000 ft. Most drainage basins, regardless of shape, are characterized by amphitheater-shaped valley heads, steep walls, and gently sloping floors. Two basin shapes are predominant: the long, narrow valleys with V-shaped cross-sections and the short, broader valleys (fig. 2). Most short, broad valleys are along the windward side of the Koolau Range. Similar shapes are found along the southwestern side of the Waianae Range. Long, V-shaped basins are found on the leeward side and northern part of the Koolau Range and along the northeastern side of the Waianae Range.

CLIMATE

Oahu has a warm, humid climate and two seasons per year: a wet winter season from October through April and a dry summer season from May through September (Blumenstock and Price, 1967). Temperature is fairly uniform, both spatially and temporally, usually ranging between 60 and 80°F. Rainfall varies seasonally, and most precipitation falls during the wet season. The median annual rainfall of 20 to 275 in/yr varies spatially (Division of Water and Land Development, 1982). The wide spatial distribution of rainfall is caused by the prevailing northeasterly trade winds and the topography of the island. Orographic lifting and cooling of the trade winds produces heavier and more frequent rainfall on the windward side and near the crest of the Koolau Range. The Waianae Range, lying in the rain shadow of the Koolau Range, receives significantly less rainfall.

FLOOD HYDROLOGY

Floods on Oahu, other than those generated by high ocean waves, are caused by high-intensity rainfall. Because the predominant northeasterly trade winds do not usually bring flood-producing rainfall, most major rainstorms are caused by the non-trade wind or Kona-wind condition. The Kona-wind condition frequently occurs from October through April and can bring intense local showers affecting a small area, sometimes with thunder and lighting, or it can blanket the entire island with rain. A review of 2,317 recorded annual peak discharges with known dates shows that 89 percent of the peaks occurred between October and May (fig. 3). This distribution of peak discharges follows the general seasonality of Kona-wind storms. Hurricanes and tropical storms can also bring heavy rains as well as high waves. Unrelated to the above conditions are rare storms caused by low pressure areas in the upper atmosphere (Blumenstock and Price, 1967). When this condition exists, trade-wind conditions are capable of producing heavy downpours (Ekern and others, 1971). In fact, some of Oahu's heaviest rains, such as the New Year's Eve Storm of 1987–88 (Division of Water and Land Development, 1988), have been caused by upper-level low pressure areas above trade winds.

High-intensity rainfall, small drainage-basin size, steep basin and stream slopes, and little channel storage, produce floods that are flashy. Most drainage basins have rapid runoff response to rainfall characterized by a steep triangular shaped hydrograph and usually with a time to peak of less than 1 hour (Ekern and others, 1971). Most drainage basins are not homogeneous, and have different characteristics in upstream and downstream areas. In general, the upstream ends of basins are steep mountain slopes, which cause rapid rates of runoff, and the downstream ends are flat coastal plains, which result in slower rates of runoff. Extreme floods also transport large volumes of sediment, including large boulders, which can scour, damage, and inhibit flood control works and other hydraulic structures located downstream. Damaging floods, at

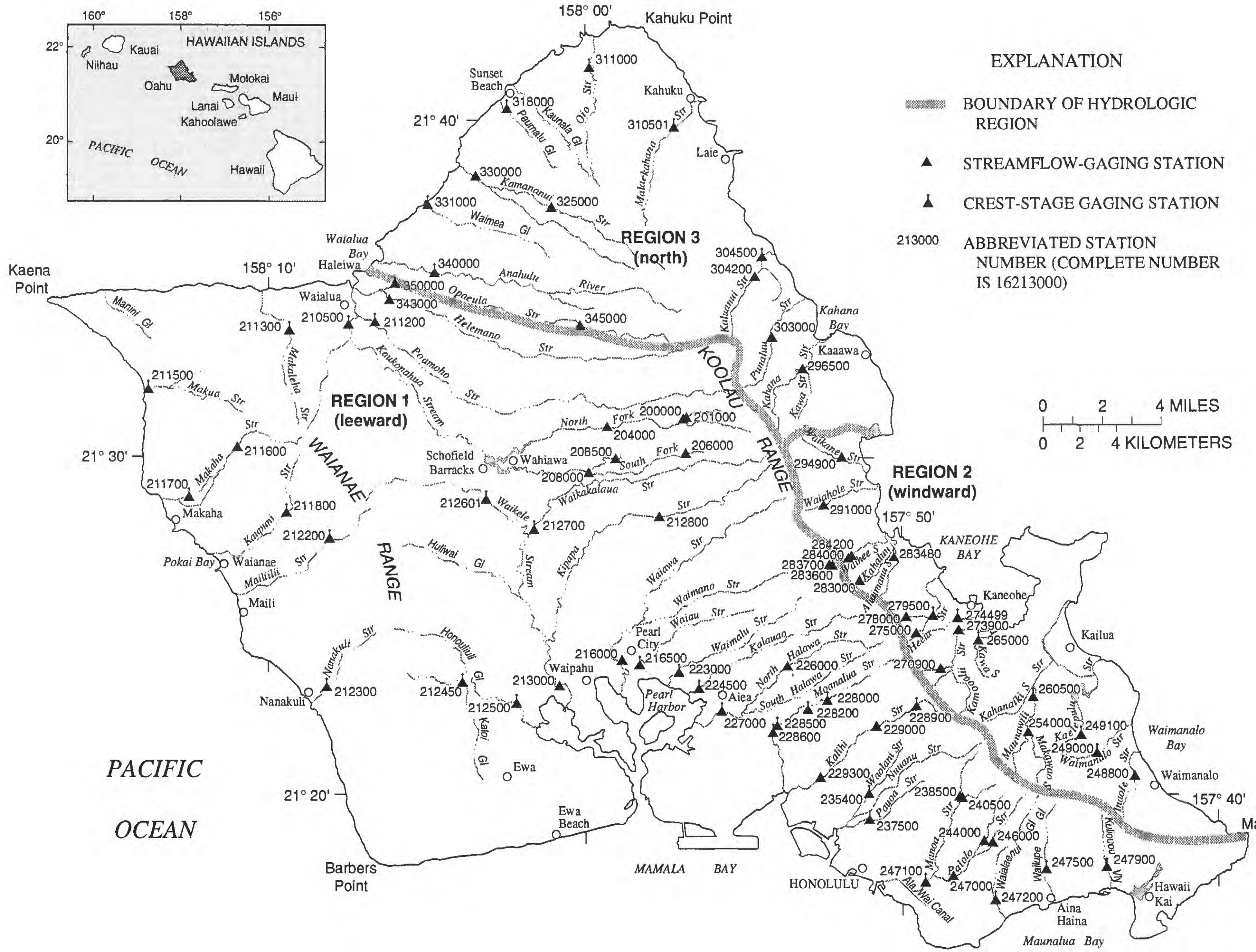


Figure 1. Hydrologic regions used in the study and locations of streamflow- and crest-stage gaging stations, Oahu, Hawaii.

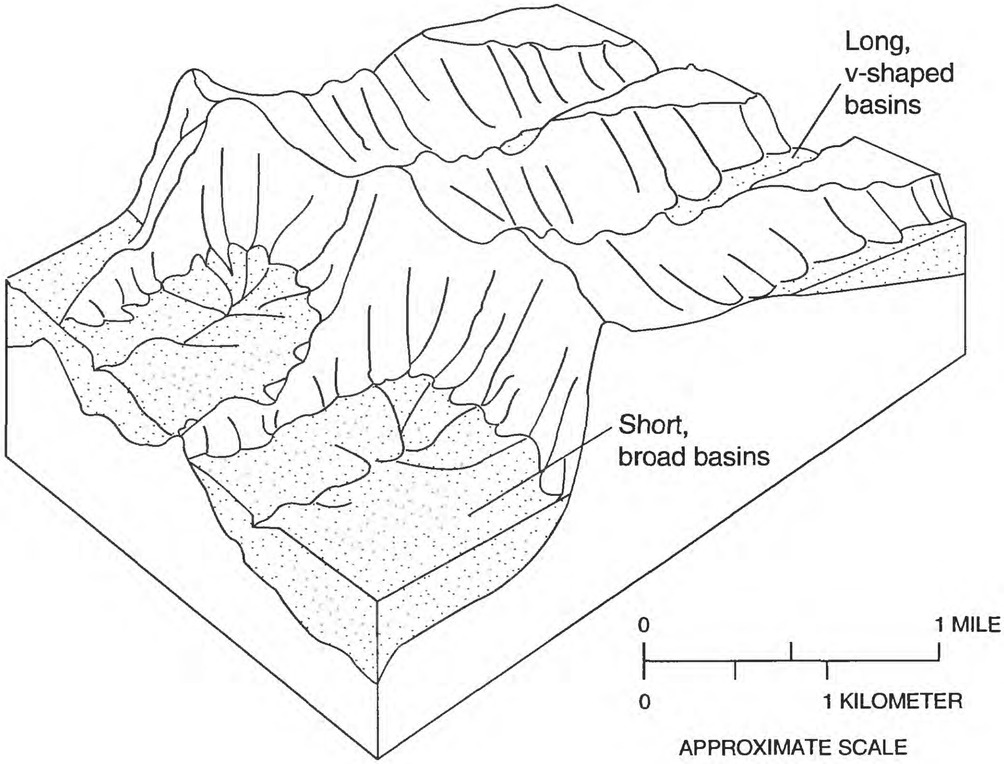


Figure 2. Block diagram showing typical drainage-basin shapes for Oahu, Hawaii (by S.K. Izuka, U.S. Geological Survey).

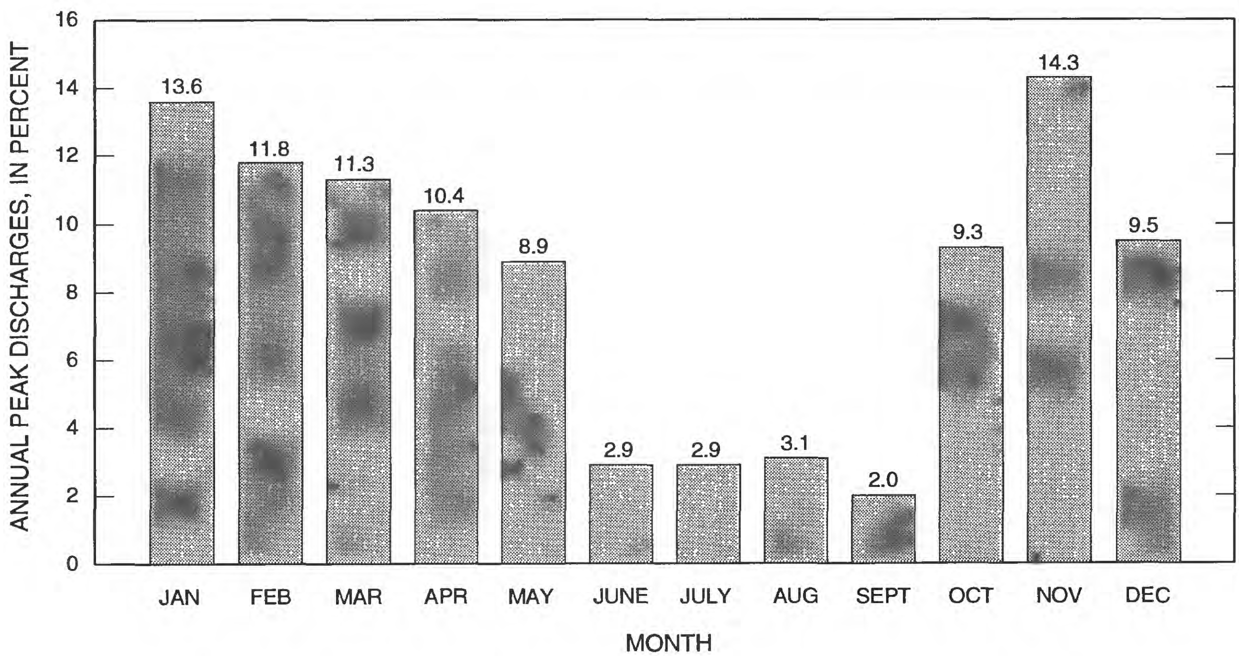


Figure 3. Monthly occurrence of 2,317 annual peak discharges for 79 stream-gaging stations, Oahu, Hawaii, 1913-88.

one time or another, have occurred in most inhabited areas of Oahu (Wu, 1967; Division of Water and Land Development, 1983).

PREVIOUS STUDIES

In 1957, the USGS, in cooperation with the Division of Water and Land Development, Department of Land and Natural Resources, State of Hawaii; and the Department of Public Works, City and County of Honolulu, created a program to collect peak-discharge data for the investigation of the magnitude and frequency of floods on Oahu. The ultimate goal of this program was to define the magnitude and frequency of floods on a regional as well as an island basis. To accomplish this, a crest-stage gage network for measuring peak discharges was created. By the following year, 1958, the number of streamflow-gaging stations on Oahu increased from 24 to 28 and 22 crest-stage gages were installed (Lee, 1978).

From 1958 to 1974, a series of annual reports on the peak-discharge data-collection program was published by the USGS under the title "An Investigation of Floods in Hawaii." This series listed annual peak discharges at gaged sites. Only reports number 5 (Vaudrey, 1963) and number 15 (Nakahara, 1973) gave flood-frequency curves for selected streams. Vaudrey (1963) used the distribution-free graphical method (Dalrymple, 1960) and Nakahara (1973) followed the U.S. Water Resources Council Bulletin 15 guidelines (U.S. Water Resources Council, 1967).

In 1957, T. Mitsuda and J. Tanaka developed the first storm drainage-design criteria published by the City and County of Honolulu (1957). This manual presented flood-frequency curves for 12 streams fitted by the (Type I extremal) Gumbel distribution. Dodo and Ling (1958) reproduced the Mitsuda and Tanaka flood-frequency curves in their storm-drainage report for the City and County of Honolulu, City Planning Commission. For ungaged drainage areas, both reports recommended the use of the rational method and correlation with gaged basins of similar physiographic conditions. An earlier effort by Carson (1939) presented flood-intensity frequency curves for three streams on Oahu.

A review by Chow (1966) of the above drainage-design criteria made no mention of frequency curves but did present two envelope curves based on maximum recorded peak discharges. These two curves regionalized Oahu into windward and leeward (including Honolulu) areas (Chow, 1966). This division was based on drainage-area size, location of the streamflow gages, and the probable maximum precipitation values. The 1969 City and County of Honolulu storm drainage standards (1969) adopted Chow's envelope curves. The recurrence intervals for these envelope curves were determined by Wu (1967) to be between 50 and 100 years. As a continuing development, the 1988 storm-drainage standards (City and County of Honolulu, 1988) modified the envelope curves into design curves approximating the 100-year flood and regionalized Oahu geographically into three regions.

To provide for a uniform technique for determining flood frequencies, the U.S. Water Resources Council published Bulletin 15 (U.S. Water Resources Council, 1967). Bulletin 15 guidelines endorsed the log-Pearson Type III distribution for determining flood-frequency curves to be adopted by all federal agencies. In 1970, the State of Hawaii adopted the Bulletin 15 guidelines (Division of Water and Land Development, 1970). The log-Pearson Type III methodology has been updated and currently Bulletin 17B guidelines (Interagency Advisory Committee on Water Data, 1982) are used.

A study of flood hydrology of drainage basins with areas of less than 10 mi^2 on the island of Oahu by Wu (1967) gave flood-frequency curves for selected streams using the Gumbel distribution. Wu was the first to apply multiple-regression methods on Oahu to estimate the magnitudes of 100-year floods. Wu (1967) gave two regional flood formulas for the 100-year flood using data from 23 drainage basins. These equations related the 100-year peak to four basin and climatic characteristics: drainage area, watershed length, watershed height, and the 100-year, 24-hour rainfall. The island was divided into four geographic regions; one equation was applicable for the windward region, and the other equation for Honolulu and central Oahu regions. The last region, Waianae, had insufficient data for analysis. No standard error of estimate for the regression equations was given.

The last flood-frequency study on Oahu to use the Gumbel distribution was done by Cheng and Lau

(1973). Cheng and Lau used the Gumbel distribution to develop flood-frequency curves for gaged streams and the index-flood method (Dalrymple, 1960) to provide regionalized flood-frequency estimates. Results from the index-flood method regionalized Oahu into four contiguous and one non-contiguous region.

An analysis of the stream-gaging network in Hawaii by Yamanaga (1972) derived regression equations for peak flow, mean flow, flow variability, flood volume, and low flow for the entire State of Hawaii. The peak-flow equations were for the 2-, 5-, 10-, 25-, and 50-year recurrence intervals and were geographically regionalized into two regions, the windward and leeward sides of each island in the State. These equations related the estimates computed by the log-Pearson Type III distribution to various combinations of drainage-basin and climatic characteristics. Among the characteristics used were drainage area, main channel length, mean basin altitude, mean annual precipitation, percentage of gentle slope, and range in basin altitude. Standard errors of estimates for the regression equations ranged from 42 to 63 percent.

In 1975 the USGS (Lee, 1978) derived regional flood-frequency regression equations for Oahu. This study "regionalized" Oahu by drainage-basin size but not geographically. However, the study remained unpublished because of some doubt regarding the "uniformity" of flood-flow frequencies at that time (Reuben Lee, written commun., 1978). Nakahara in 1980 applied multiple regression analysis for regional analysis and divided Oahu into three regions using the method of residuals (Nakahara, 1980). Flood estimates for the 2-, 5-, 10-, 25-, 50-, and 100-year recurrence intervals using guidelines from Bulletin 17A (U.S. Water Resources Council, 1977) were related to drainage area, forest cover, and the 2-year, 24-hour rainfall. Standard errors of estimates for the regression equations ranged from 33 to 67 percent.

Wong (1991) compared the index-flood method, cluster analysis, and method of residuals for the regionalization of drainage basins on Oahu. Results showed that all three methods gave comparable regression standard errors of estimates. The method of residuals was used to regionalize Oahu into four regions. Standard errors of prediction for the generalized least-squares regression equations ranged from 18 to 57 percent.

The present study improves on the work by Wong (1991) and differs from other previous flood-frequency studies for Oahu by using additional gaging stations, longer periods of record, updated guidelines (Bulletin 17B), GIS procedures for computing drainage-basin and climatic characteristics, and generalized least-squares regression techniques.

DATA BASE FOR REGRESSION EQUATIONS

Flood-frequency estimates at gaged sites can be transferred to ungaged sites by regression analysis. For regression analysis, both the dependent and independent variables must be available in quantitative form. The applicability of the derived regression equations depends on reliable and consistent information derived from records of peak discharge at gaging stations, a method to estimate magnitude and frequency of floods, and procedures to estimate drainage-basin and climatic characteristics.

ANNUAL PEAK-DISCHARGE DATA

The most fundamental part of a flood-frequency study is the collection and analysis of annual peak-discharge data. The annual peak discharge is the largest instantaneous discharge recorded each year at gaged sites. As of water year 1988, there were 70 active gaging stations on Oahu, of which 28 were (continuous recording) streamflow-gaging stations and 42 were crest-stage gaging stations (Nakahara and others, 1989). A continuous-recording gage collects data on the entire range of streamflows, whereas a crest-stage gage collects only peak-discharge data. In addition, peak-discharge data have been collected at gaging stations that have subsequently been discontinued.

Bulletin 17B guidelines (Interagency Advisory Committee on Water Data, 1982) recommend a minimum of 10 years of data for flood-frequency studies. The use of the 10-year data minimum allows for a good representative sample of the type of flood data involved. Because of climatic changes, a small sample may not be representative of all flow possibilities. Wu (1967) determined that for Oahu, wet and dry years alternated in cycles of 3 to 4 years and recommended a 12-year data minimum. A review of the current annual peak-discharge data show that this 3 to 4 year cycle was more apparent in the annual peak-discharge data for windward Oahu drainage basins than for the basins on the leeward side. The annual peak-discharge data for stations on the leeward side generally showed a greater variability in year-to-year magnitudes.

There were 82 gaging stations on Oahu with 10 or more years of record available for flood-frequency analysis. Three stations were eliminated because their annual peak discharges were affected by significant diversion or regulation. Diversions were considered significant at stations where the measured diversions exceeded 30 percent of the mean daily discharge on the day that the annual peak discharge occurred. Significant regulation was defined as a flood-control reservoir controlling more than 50 percent of the drainage basin. No stations were eliminated because of urbanization within the basin boundaries. Annual peak discharge series for drainage basins with some urbanization showed no significant trends or differences in the peak discharges when compared to nearby non-urban basins. The final 79 stations used in this study are listed in table 1 and shown in figure 1. For this report, the prefix 16 of the eight-digit station number has been dropped. For example, the abbreviated station number 211500 is used rather than the complete number 16211500.

Annual peak-discharge records for the 79 gaging stations, as of water year 1988, had record lengths ranging from 11 to 72 years (table 1) and a mean of 29.6 years. Of the 79 stations, 65 had record lengths longer than 20 years and the total years of record for all 79 stations is 2,335 station-years. Of these 79 stations, 42 are crest-stage gages and 37 are continuous-recording streamflow-gaging stations (table 1).

FLOOD-FREQUENCY DATA

A flood-frequency analysis uses available annual peak-discharge data to estimate the frequency and magnitude of floods that can occur. In a frequency analysis, a theoretical frequency distribution is assumed for the population of floods and the statistical parameters of this distribution are computed from the peak-discharge sample data (Kite, 1977).

Following the Bulletin 17B (Interagency Advisory Committee on Water Data, 1982) guidelines, flood-frequency curves were developed for each gaging station by using the log-Pearson Type III distribution. The log-Pearson Type III distribution is characterized by three statistics: the mean, standard deviation, and skew coefficient. These three statistics are computed from the logarithmic transformation of annual peak discharges. The skew is the numerical measurement of the lack of symmetry. If the skew coefficient is zero, then the log-Pearson becomes identical to the log-normal distribution (Cudworth, 1989). Bulletin 17B gives a generalized skew map for determination of skew. A generalized skew of –0.05 for Hawaii, from the skew map, was used for all frequency computations in this report. Lee (1984) computed a generalized skew of –0.14 for the State of Hawaii. However, this skew value was reported as not being significantly different from –0.05 (Lee, 1984) so use of the –0.05 value was considered satisfactory.

Program J407 in WATSTORE (Kirby, 1979), which has been updated to Bulletin 17B guidelines, was used to generate the station frequency curves. As part of this analysis, the annual peak-discharge series were tested for outliers. Outliers are data points which depart significantly from the remaining data and can significantly affect the statistics used to compute the flood frequency curve (Interagency Advisory Committee on Water Data, 1982, p.17). Results for the five stations that had high outliers detected were not adjusted because the required historic information was not available. The 18 stations that had low outliers deleted (table 2) were adjusted using the conditional probability adjustment given in Bulletin 17B. The three statistics used to characterize the annual peak discharge series for each station are listed in table 2. Final frequency curves were determined by making adjustments as recommended by Bulletin 17B guidelines.

From the flood-frequency analysis, values of peak discharge were obtained for the 2-, 5-, 10-, 25-, 50-, and 100-year recurrence intervals. The estimated peak discharges for these recurrence intervals and the maximum known floods of record are given in table 3 (at end of report). The accuracy of these flood estimates can be computed in terms of standard error in log units by methods given by Hardison (1969, 1971). The accuracy of the flood estimate is a function of record length, standard deviation of the annual peak discharges, correlation between the mean and standard deviation of the annual peak discharges, skew coefficient, and the recurrence interval.

Table 1. Stream-gaging stations on Oahu, Hawaii, used in the study

[Station locations shown in figure 1; p, gage is in operation as of water year 1988; rec, recording gage, either digital or graphic or both; csg, crest-stage gage]

Station number	Station name	Years of record	Period of record	Type of gage
200000	North Fork Kaukonahua Stream above Right Branch near Wahiawa	64	1913–53; 1960–p	rec
201000	Right Branch of North Fork Kaukonahua Stream near Wahiawa	34	1914–53	rec
204000	North Fork Kaukonahua Stream near Wahiawa	22	1947–68	rec
206000	South Fork Kaukonahua Stream near Wahiawa	13	1945–57	rec
208000	South Fork Kaukonahua Stream at East Pump Reservoir near Wahiawa	31	1958–p	rec
208500	Right Branch of South Fork Kaukonahua Stream near Wahiawa	15	1958–72	rec
210500	Kaukonahua Stream at Waialua	22	1963–p	csg
211200	Poamoho Stream near Waialua	22	1967–p	csg
211300	Makaleha Stream near Waialua	31	1958–p	csg
211500	Makua Stream at Makua	30	1958–p	csg
211600	Makaha Stream near Makaha	29	1960–p	rec
211700	Makaha Stream at Makaha	23	1966–p	csg
211800	Kaupuni Stream at altitude 374 feet near Waianae	28	1961–p	csg
212200	Mailiilii Stream near Waianae	31	1958–p	csg
212300	Nanakuli Stream at Nanakuli	21	1968–p	csg
212450	Kaloi Gulch tributary near Honouliuli	21	1968–p	csg
212500	Honouliuli Stream near Waipahu	29	1956–p	csg
212601	Waikele Stream at Wheeler Field	30	1958–p	csg
212700	Waikakalaua Stream near Wahiawa	31	1958–p	csg
212800	Kipapa Stream near Wahiawa	32	1957–p	rec
213000	Waikele Stream at Waipahu	36	1952–p	rec
216000	Waiawa Stream near Pearl City	36	1953–p	rec
216500	Waimano flood channel at Pearl City	15	1955–69	csg
223000	Waimalu Stream near Aiea	34	1952–p	csg
224500	Kalauao Stream at Moanalua Road at Aiea	34	1954–p	csg
226000	North Halawa Stream near Aiea	39	1930–33; 1954–p	rec
227000	Halawa Stream at Aiea	20	1954–79	csg
228000	Moanalua Stream near Honolulu	61	1927–p	csg
228200	Moanalua Stream near Aiea	20	1969–p	csg
228500	Moanalua Stream at altitude 100 feet near Honolulu	11	1958–70	csg
228600	Moanalua Stream near Tripler Hospital	18	1971–p	csg
228900	Kalihi Stream near Kaneohe	21	1968–p	csg
229000	Kalihi Stream near Honolulu	72	1917–p	rec
229300	Kalihi Stream at Kalihi	28	1960–p	rec
235400	Waolani Stream at Honolulu	30	1959–p	csg
237500	Pauoa Stream at Honolulu	31	1958–p	csg
238500	Waihi Stream at Honolulu	63	1915–83	rec
240500	Waiakeakua Stream at Honolulu	70	1914–p	rec
244000	Pukele Stream near Honolulu	56	1927–82	rec
246000	Waiomao Stream near Honolulu	45	1927–71	rec
247000	Palolo Stream near Honolulu	27	1953–79	rec
247100	Manoa–Palolo drainage canal at Moiliili	21	1968–p	csg

Table 1. Stream-gaging stations on Oahu, Hawaii, used in the study--*Continued*

Station number	Station name	Years of record	Period of record	Type of gage
247200	Waialaenui Gulch at Honolulu	11	1958–68	csg
247500	Wailupe Gulch at Aina Haina	31	1958–p	csg
247900	Kuliouou valley at Kuliouou	19	1970–p	csg
248800	Inoaole Stream at Waimanalo	31	1958–p	csg
249000	Waimanalo Stream at Waimanalo	24	1963; 66–p	csg
249100	Kaelepulu Stream tributary at Kailua	26	1966–p	csg
254000	Makawao Stream near Kailua	31	1958–p	rec
260500	Maunawili Stream at Highway 61 near Kailua	31	1958–p	csg
265000	Kawa Stream at Kanehoe	20	1965; 68–p	csg
270900	Luluku Stream at altitude 220 feet near Kaneohe	20	1967–87	rec
273900	Kamooalii Stream at Kaneohe	23	1958–80	rec
274499	Keaahala Stream at Kamehameha Highway at Kaneohe	30	1959–p	csg
275000	Haiku Stream near Heeia	49	1915–19, 39–77, 83–p	rec
278000	Iolekaa Stream near Heeia	27	1940–70	rec
279500	Heeia Stream at Kaneohe	22	1965–p	csg
283000	Kahaluu Stream near Heeia	34	1937–71	rec
283480	Ahuimanu Stream near Kahaluu	26	1963–p	csg
283600	South Fork Waihee Stream near Heeia	26	1963–p	rec
283700	North Fork Waihee Stream near Heeia	26	1963–p	rec
284000	Waihee Stream near Heeia	45	1938–82	rec
284200	Waihee Stream near Kahaluu	14	1975–p	rec
291000	Waiahole Stream at altitude 250 feet near Waiahole	13	1956–68	rec
294900	Waikane Stream at altitude 75 feet at Waikane	29	1960–p	rec
296500	Kahana Stream at altitude 30 feet near Kahana	29	1960–p	rec
303000	Punaluu Stream near Punaluu	35	1954–p	rec
304200	Kaluanui Stream near Punaluu	22	1967–p	rec
304500	Kaluanui Stream at Hauula	31	1958–p	csg
310501	Malaekahana Stream at altitude 30 feet near Kahuku	30	1959–p	csg
311000	Oio Stream near Kahuku	31	1958–p	csg
318000	Paumalu Gulch at Sunset Beach	21	1968–p	csg
325000	Kamananui Stream at Pupukea Military Road near Maunawai	25	1964–p	rec
330000	Kamananui Stream at Maunawai	31	1958–p	rec
331000	Waimea Gulch near Kawailoa Camp	21	1968–p	csg
340000	Anahulu River near Haleiwa	31	1958–p	csg
343000	Helemano Stream at Haleiwa	15	1968–82	rec
345000	Opaeula Stream near Wahiawa	29	1960–p	rec
350000	Opaeula Stream near Haleiwa	33	1956–p	csg

Table 2. Peak-discharge statistics at stream-gaging stations on Oahu, Hawaii

[Bulletin 17B weighted statistics based on guidelines in Interagency Committee on Water Data (1982); Std. dev., one standard deviation]

Station number	Peak-discharge statistics from logarithms of annual floods					
	Gaged record			Bulletin 17B weighted		
	Mean	Std. dev.	Skew	Mean	Std. dev.	Skew
200000	3.382	0.218	–0.572	3.382	0.218	–0.424
201000	3.010	0.180	–0.015	3.010	0.180	–0.027
204000	3.401	0.120	0.547	3.401	0.120	0.262
[1]206000	2.956	0.243	–0.655	2.979	0.203	–0.021
208000	3.239	0.278	–0.091	3.239	0.278	–0.076
[1]208500	2.703	0.551	–1.100	2.742	0.487	–0.436
210500	3.301	0.498	–0.016	3.301	0.498	–0.030
211200	3.049	0.541	–0.527	3.049	0.541	–0.301
211300	2.704	0.411	–0.043	2.704	0.411	–0.045
211500	2.354	0.588	–0.059	2.354	0.588	–0.056
211600	2.478	0.386	–0.132	2.478	0.386	–0.101
211700	2.708	0.483	0.045	2.708	0.483	0.005
211800	2.440	0.588	–0.250	2.440	0.588	–0.170
212200	2.424	0.662	–0.693	2.424	0.662	–0.419
212300	2.760	0.545	–0.891	2.760	0.545	–0.455
[1]212450	2.229	0.499	–0.822	2.259	0.444	–0.297
212500	2.732	0.573	–0.713	2.732	0.573	–0.420
[1]212601	2.590	0.490	–1.065	2.645	0.377	–0.107
[1]212700	2.907	0.405	–0.532	2.928	0.361	–0.004
212800	3.275	0.227	0.508	3.275	0.227	0.285
213000	3.492	0.392	–0.163	3.492	0.392	–0.125
216000	3.908	0.321	–0.625	3.908	0.321	–0.400
[2]216500	2.422	0.402	1.614	2.422	0.402	0.393
223000	3.244	0.370	–0.051	3.244	0.370	–0.051
[1]224500	2.925	0.306	–0.807	2.940	0.274	–0.253
226000	3.102	0.373	–0.057	3.102	0.373	–0.055
227000	3.296	0.264	–0.195	3.296	0.264	–0.128
228000	3.005	0.323	–0.632	3.005	0.323	–0.458
228200	3.056	0.333	–0.586	3.056	0.333	–0.318
[1]228500	3.271	0.329	–1.252	3.302	0.279	–0.425
228600	3.144	0.331	0.215	3.144	0.331	0.085
228900	2.586	0.451	–0.782	2.586	0.451	–0.410
229000	3.148	0.403	–0.355	3.148	0.403	–0.283
[1]229300	3.365	0.366	–0.813	3.384	0.331	–0.325
235400	2.732	0.377	–0.348	2.732	0.377	–0.231
237500	2.556	0.327	0.281	2.556	0.327	0.156
238500	2.827	0.322	0.106	2.827	0.322	0.070
240500	2.719	0.283	0.569	2.719	0.283	0.403
244000	2.620	0.349	–0.017	2.620	0.349	–0.025
246000	2.565	0.356	–0.545	2.565	0.356	–0.377

Table 2. Peak-discharge statistics at stream-gaging stations on Oahu, Hawaii--*Continued*

Station number	Peak-discharge statistics from logarithms of annual floods: Gaged record: Mean	Gaged record: Std. dev.	Gaged record: Skew	Bulletin 17B weighted: Mean	Bulletin 17B weighted: Std. dev.	Bulletin 17B weighted: Skew
247000	3.128	0.272	-0.145	3.128	0.272	-0.107
247100	3.445	0.329	-0.583	3.445	0.329	-0.322
[1]247200	2.908	0.330	-1.381	2.952	0.242	-0.289
[1]247500	2.737	0.364	-0.187	2.754	0.330	0.186
[2]247900	2.603	0.376	1.352	2.603	0.376	0.461
248800	2.485	0.518	-0.784	2.485	0.518	-0.463
249000	3.106	0.372	-0.176	3.106	0.372	-0.123
[1]249100	2.043	0.501	-0.809	2.071	0.444	-0.251
[1]254000	2.912	0.472	-0.555	2.938	0.415	0.054
260500	3.248	0.360	-0.141	3.248	0.360	-0.108
[1]265000	2.832	0.518	-0.952	2.886	0.395	0.316
[1]270900	2.213	0.453	-1.551	2.265	0.324	0.038
273900	3.226	0.463	-0.071	3.226	0.463	-0.062
[1]274499	2.658	0.466	-0.762	2.685	0.408	-0.122
275000	2.801	0.486	-0.728	2.801	0.486	-0.491
[2]278000	1.647	0.481	0.431	1.647	0.481	0.227
279500	2.952	0.574	-0.217	2.952	0.574	-0.143
283000	2.142	0.333	1.087	2.142	0.333	0.534
[2]283480	3.078	0.421	-0.153	3.078	0.421	-0.110
[1]283600	1.991	0.320	-0.686	2.015	0.267	0.179
[1]283700	1.898	0.329	-0.770	1.923	0.273	0.161
[2]284000	2.613	0.387	0.046	2.613	0.387	0.020
284200	2.669	0.255	-0.040	2.669	0.255	-0.045
291000	2.786	0.333	0.411	2.786	0.333	0.147
294900	3.330	0.384	-0.839	3.330	0.384	-0.479
296500	3.499	0.172	-1.015	3.499	0.172	-0.537
303000	3.254	0.240	-0.564	3.254	0.240	-0.364
304200	2.923	0.270	-0.439	2.923	0.270	-0.257
304500	3.122	0.300	-0.531	3.122	0.300	-0.335
310501	2.806	0.621	-0.335	2.806	0.621	-0.223
311000	2.330	0.487	-0.091	2.330	0.487	-0.076
[1]318000	2.203	0.460	-0.868	2.235	0.395	-0.209
325000	3.086	0.233	-0.164	3.086	0.233	-0.117
330000	3.398	0.277	-0.261	3.398	0.277	-0.181
331000	1.858	0.667	0.405	1.858	0.667	0.190
340000	3.454	0.312	0.515	3.454	0.312	0.286
343000	3.581	0.465	-0.529	3.581	0.465	-0.265
345000	3.292	0.203	0.517	3.292	0.203	0.279
350000	3.214	0.328	0.157	3.214	0.328	0.084

[1]stations with low outliers deleted, conditional probability adjustment applied (18 stations)
[2]stations with high outliers detected, no adjustment applied (5 stations)

DRAINAGE-BASIN AND CLIMATIC CHARACTERISTICS COMPUTED BY A GEOGRAPHIC INFORMATION SYSTEM (GIS)

To perform a regional regression analysis, drainage-basin and climatic characteristics that can be related to peak discharges must be quantified in a consistent manner. GIS software was used to compute values for 13 of the 15 characteristics described in this section. The main-channel slope and drainage-basin area were computed by the manual methods of Nakahara (1980). The 13 remaining characteristics were determined using seven digitized coverages that contained drainage-basin outlines, stream-channel lengths, area of forest cover, area of urban cover, topographic contours, lines of equal median annual rainfall, and lines of equal 24-hour rainfall intensities that have a 2-year recurrence interval. All coverages except topographic contours were digitized from the relevant data on the 1983, 1:24,000 topographic quadrangle maps of Oahu. The lines depicting median annual rainfall and the 2-year, 24-hour rainfall intensity were first transferred to the topographic maps and then digitized. The topographic contour map was created by using the digital elevation model for the island of Oahu (U.S. Geological Survey, 1987). The digital elevation model was converted by GIS software to a topographic contour map coverage with contours at 40-meter intervals. Basin and climatic characteristics for each of the gaged drainage basins used in this study are listed in table 4 (at end of report). A statistical summary for each of the characteristics is given in table 5. Descriptions of the drainage-basin and climatic characteristics along with the methods for their computation are given below.

BW: The average drainage-basin width, in miles, determined as a ratio of drainage-basin area (DAG) to main-channel length (CL): BW = DAG / CL. BW is computed after both drainage area and channel length have been determined.

CL: The main-channel length, in miles, is the distance along a stream from the gaging station to the drainage-basin divide. Channel length was determined by GIS from digitized 1:24,000-scale topographic maps. If a stream flowed through many smaller basins (a major basin stream), the longest possible route was determined and the lengths of stream segments flowing through the sub-basins were added together.

CLD: A shape factor of a drainage basin computed by calculating the ratio of main-channel length (CL) to the diameter of a circle having the same drainage area as the basin (CLD = CL/diameter). The inverse of this factor, diameter divided by channel length, is known as the elongation ratio (Chow, 1964, p.4-51). This shape factor often is used to relate time of flow concentration to basin shape (Davis, 1974). Large CLD values characterize long, narrow basins whereas small values denote short, wide basins.

CS: The main-channel slope of a drainage basin, in feet per mile. This value is computed by dividing the altitude difference between points located at the 10-percent and 85-percent distances of the main-channel length (CL) measured upstream from the gaging station, by the distance between these points (Benson, 1962). This characteristic was not computed by GIS.

DA: Area of a drainage basin, in square miles. Determined by planimeter following standard USGS guidelines on 1:24,000 topographic maps. These values have been previously published for each gaging station in the annual data reports (Nakahara and others, 1989).

DAG: Area of a drainage basin, in square miles. Determined by GIS from digitized basin outlines on 1:24,000 topographic maps. For basins that consist of more than one drainage basin (major basins), the areas of the smaller basins (sub-basins) were added together.

E: The mean drainage-basin altitude, in feet above mean sea level, measured by overlaying a GIS coverage of drainage basins on a 40-meter contour coverage created from a digital elevation model and then calculating the area-weighted average to obtain a mean altitude in that basin. An area-weighted average is computed by multiplying the average altitude between two contours by the area between the same two contours and then summing up all these products and dividing by the total basin area. The value in meters was converted to feet.

FC: Forest/vegetative cover of a drainage basin, in percent. This variable is the ratio of the drainage area covered by forests and/or vegetation, as shown in green on the 1:24,000 topographic maps, to its total drainage area. Computed from a GIS coverage, which differentiated the green areas within each drainage basin.

MR: The meander ratio, a dimensionless measurement computed as the ratio of the main-channel length (CL) to the length of the valley. (MR = CL/length of valley), where the length of the valley was determined by measuring a straight line or series of straight lines not exceeding five line segments, that linearize the stream's path in the drainage basin, between the gaging station and the basin divide. High values signify high meandering whereas values close to one indicate nearly straight streams.

P: The median annual rainfall, in inches, determined by overlaying a GIS coverage of lines of equal median annual rainfall on the drainage-basin coverage and then computing the area-weighted average of rainfall in each basin. Lines of median rainfall were from the Division of Water and Land Development (1982).

P224: The 2-year recurrence interval 24-hour rainfall intensity, in inches, was computed by overlaying a GIS coverage of the 2-year, 24-hour rainfall on a drainage-basin coverage and computing the area-weighted average of rainfall in each basin. Lines of equal rainfall intensity were from Giambelluca and others (1984).

PA: The convexity ratio, which is a measure of boundary regularity. It is computed by dividing the perimeter of a basin by its area (PA = PER / DAG).

PER: The perimeter of the drainage basin, in miles. Determined by GIS from the digitized drainage-basin coverage. For major basins, the perimeter was determined by summing all line segments that outlined that basin.

RF: A shape factor determined by dividing the drainage area by the square of the main channel length ($RF = DAG/CL^2$). This factor can also be considered as the basin width divided by channel length ($RF = BW/CL = DAG/CL^2$).

UC: Urban cover of a drainage basin, in percent. This variable is the ratio of the drainage area covered by the urban development, as shown in pink on the 1:24,000 topographic maps, to its total drainage area. Determined from a GIS coverage, which differentiated the pink areas within each drainage basin.

Table 5. Statistical summary of drainage-basin and climatic characteristics for gaged basins on Oahu, Hawaii

Characteristic symbol	Description	Range of values: Minimum	Range of values: Maximum	Median	Mean	Standard deviation
BW	Average basin width, in miles	0.086	2.16	0.616	0.688	0.390
CL	Main channel (stream) length, in miles	0.338	26.4	4.15	5.90	5.72
CLD	Shape factor, dimensionless	0.991	8.41	2.21	2.56	1.33
CS	Main channel slope, in feet/mile	55.0	4980	265	593	882
DA[1]	Area of a drainage basin, in square miles	0.03	45.7	2.59	4.62	7.32
DAG	Area of a drainage basin, in square miles, computed by a geographic information system (GIS)	0.03	46.2	2.57	4.62	7.33
E	Mean basin altitude, in feet	200	2110	1160	1150	399
FC	Forest/vegetative cover, in percent	33	100	91	84	18
MR	Meander ratio, dimensionless	1.02	3.32	1.19	1.34	0.380
P	Mean annual precipitation in inches	29	239	99	105	48
P224	2-year recurrence interval, 24-hour rainfall intensity, in inches	4.72	9.10	6.75	6.85	1.13
PA	Shape factor, in 1/miles	0.893	27.8	3.26	4.19	4.17
PER	Perimeter of a drainage basin, in miles	0.802	41.3	7.86	10.2	7.76
RF	Form factor, dimensionless	0.011	0.800	0.160	0.211	0.172
UC	Urban cover, in percent	0	36	0	4	9

[1]the standard drainage area used in the regression analysis

The convenience and precision in determining the drainage-basin characteristics were greatly improved by using the GIS. The use of GIS therefore allowed for a larger number of characteristics to be considered in the regression analysis. Among these characteristics were a number of different basin-shape factors (CLD, PA, and RF). However, the drainage areas computed from GIS (DAG) compared with the previously determined drainage areas (DA) had an mean absolute difference of 0.09 mi^2. Ideally, there should be no difference. A further review of the drainage areas showed that only two DA's had differences greater than 10 percent, when compared with the DAG's. These two stations, 211200 and 247100, accounted for 43 percent of the differences in drainage area. For these two stations, the original computations were found in error. Drainage areas for the two stations were revised to the DAG values. After these corrections, the mean absolute difference between the DA's and DAG's was 0.05 mi^2. Because of this difference, a hypothesis test was done to see if there were any differences in the mean values between the DA's and DAG's. For this test, the null hypothesis was that no differences exist. Using the nonparametric Wilcoxon signed-ranks tests (Iman and Conover, 1983) with a significance level of 1 percent (0.01), the null hypothesis was accepted with a p-value of 0.79. The p-value being the smallest significance level that would allow the null hypothesis to be rejected (Iman and Conover, 1983). Therefore, the use of the GIS-derived characteristics is acceptable. However, because all the DA values are previously published, the DA's were used except for the two stations where corrections were made in the regression analysis.

REGRESSION ANALYSIS

The ordinary least-squares estimator used in traditional regression analysis assumes that the errors or residuals are random, uncorrelated, normally distributed, and have equal standard deviations (Draper and Smith, 1981). Therefore, all stations used in the regression analysis are given equal weight. However, these conditions are not always met with hydrologic data, because streamflow records at gaged sites used in the regression analysis are of different record lengths. In addition, cross-correlation of concurrent flows among nearby gaged sites can exist (Stedinger and Tasker, 1985). To solve these problems, Tasker (1980) used a weighted least-squares estimator to correct for unequal record length. Later, Stedinger and Tasker (1985) developed a generalized least-squares estimator that accounts for cross-correlation among sites as well as for unequal record length. Both the weighted least-squares and generalized least-squares estimators assign each station a different regression weight to improve model accuracy. Where the ordinary least-squares assumptions were violated it has been shown that weighted least-squares and generalized least-squares estimators are appropriate and provide reduced standard errors of estimate for the regression equations (Stedinger and Tasker, 1985).

For the regression analysis, the peak discharges for specified recurrence intervals were the dependent variables and the drainage-basin and climatic characteristics were the independent variables. The multiple regression technique requires that dependent and independent variables be linearly related. Examination of the flood peaks and the basin and climatic characteristics along with previous studies (Thomas and Benson, 1970), has shown that the logarithmically transformed characteristics are linearly related. Therefore, the variables in this study were transformed by using the common (base 10) logarithm.

After transforming the variables, the first step of the regression analysis was to determine the significant independent variables for each peak-discharge characteristic. This was done by using correlation and stepwise regression procedures. Correlation measures the degree of linear relation between two variables. In addition to calculating the degree of correlation between the dependent and independent variables, correlations between all pairs of independent variables were also determined. Because high correlation between two independent variables tends to reduce the statistical significance of each variable involved in regression analysis, only the more significant and reliable one should be retained.

The stepwise regression procedure was used to determine the most statistically significant predictor variables. In this procedure, variables are added or deleted one by one into the regression model according to their level of significance for entry and retention (Draper and Smith, 1981). In this study, an entry and retention significance level of 0.05 (5 percent) was used in the stepwise regression F-test to limit the number of variables. Also, the use of the 5-percent significance level generally limited the final regression equations to two or three variables. The stepwise procedure was run for each recurrence interval (2-, 5-, 10-, 25-, 50-, 100-year) for the whole island and all the individual regions that were identified.

In choosing variables and regions, a study of the standard error of estimate in percent (%SE) and the coefficient of determination, R^2, was done on the stepwise regression results. The %SE is the measure of model error and lack of fit of the regression equation, while the R^2 is the fraction of the total variability of the observed dependent variables explained by the independent variables. In general, use of statistically significant predictor variables minimized the %SE and maximized R^2. The chosen variables were then used to develop the regression equations. The resulting regression equations have the form:

$$Q_t = a(X_1^{b1})(X_2^{b2})\ldots(X_n^{bn})(\mathrm{BCF}) \qquad (1)$$

where:

Q_t = a flood of t (years) recurrence interval,

$X_1, X_2, \ldots, X_n$ = basin and/or climatic characteristics,

a = the regression constant,

$b1, b2, \ldots, bn$ = the regression coefficients or exponents of the basin and/or climatic characteristics, and

BCF = the bias-correction factor.

The bias-correction factor is used to correct for retransformation bias that results when the logarithmic transformation is used. The use of the bias-correction factor will give the mean value of predicted discharge, while not using the bias-correction factor will provide the median value. Because peak discharge is log-normally distributed about the regression curve (Choquette, 1988), the use of the bias-correction factor will result in a more conservative estimate of peak discharge. In this study the bias-correction factor was determined by the "smearing estimate" (Duan, 1983).

The generalized least-squares estimator in the GLSNET program in ANNIE (Lumb and others, 1990; G.D. Tasker, written commun., 1990) was then used to compute the final regression equations. The final models were checked to ensure that all independent variables were statistically significant, the coefficients of the independent variables were hydrologically reasonable, correlation between independent variables was not significant, the standard error was minimized, the coefficient of determination was maximized, overly influential observations were not present, and that residual variances were constant.

REGIONALIZATION OF FLOOD-FREQUENCY ESTIMATES

Regional analysis is a procedure of extending streamflow records in space (Riggs, 1973). Because streamflow records are collected at only a few of the many sites where information is needed, streamflow characteristics are commonly estimated at ungaged sites using information obtained from gaged sites. Regional analysis may also produce improved estimates of the flow characteristics at the gaged sites (Riggs, 1973).

For regional analysis, basins with similar flood response or characteristics are grouped into homogeneous regions. Homogeneity of the region's flood characteristics can reduce errors in estimates of peak flood discharge for gaged and ungaged sites, whereas heterogeneity can increase the estimation error in these flood estimates (Lettenmaier and others, 1987). The simplest method of regionalization has been to group basins geographically. However, continuous geographical regions are not a guarantee of homogeneity since adjacent basins can be physically very different (Wiltshire, 1985).

A regression analysis with all 79 stations was conducted with the peak flood estimates as the dependent variables. The significant independent variables were drainage area, 2-year, 24-hour rainfall intensity, and mean basin altitude for the 25-, 50-, and 100-years floods. The equations for the 2-, 5-, and 10-years floods differed by having median annual precipitation instead of the 2-year, 24-hour rainfall intensity as an independent variable.

The residuals in log units from the 50-year recurrence interval equation were chosen to be used for regionalization. Drainage basins were grouped together in this study by using the method of residuals. The method of residuals involves classifying basins into regions using the sign and magnitude of the residuals (differences in predicted and observed peak discharges), basin and climatic conditions, and hydrologic judgment. The method of residuals assumes that the general trends in the residuals reflect inherent variations in the flood response of various regions (Bhaskar and O'Conner, 1989). Thus, residuals with similar sign and magnitude are assumed to represent regions with similar flood characteristics and are grouped together (Choquette, 1988). In practice, regions commonly follow geographical or political boundaries. Because of the subjective nature of this method, Tasker (1982) proposed the use of the Wilcoxon signed-ranks test to provide some objectivity. This non-parametric test is used to compare residuals between regions to determine if the apparent grouping of the residuals represent consistent differences in the residuals and flood response (Choquette, 1988). The Wilcoxon signed-ranks test does not statistically verify the regions but provides a quantitative index as a guide for defining "homogeneous" regions (Choquette, 1988; Tasker, 1982). In addition to the Wilcoxon signed-ranks test, the regression equations for all regions were tested to insure that they met the regression requirements stated above.

The residuals in log units from the 50-year recurrence interval equation, were plotted on a map of Oahu. On the basis of this residual plot, a number of geographically continuous regions were determined. These regions were then checked by the Wilcoxon signed-ranks test and by regression analysis. For the Wilcoxon signed-ranks test, all the various groupings failed at the 0.10 (10 percent) significance level. Failure of the Wilcoxon signed-ranks test indicates that the residuals for the individual regions are not statistically different from those of the island as a whole. In other words, based only on the Wilcoxon signed-ranks test, failure indicates that subdivision of the island into regions is not called for. Groupings based on previous studies (Yamanaga, 1972; Nakahara, 1980; Wong, 1991) were also tested by the Wilcoxon signed-ranks test and regression analysis. Using the current data, all of these previous groupings also failed the Wilcoxon signed-ranks test. Data from some of the previous and current groupings, including the island as a whole, when checked by regression analysis, resulted in poor equations with high standard errors or violated the regression assumptions. A grouping was found however, that while not passing the Wilcoxon signed-ranks test, did provide regression equations with smaller uncertainties than the equations for the island as a whole. The improvement in regression equations justifies this grouping, dividing Oahu into three regions, each region with regression equations that met the regression requirements stated above. These three regions are leeward Oahu, including stations 200000 through 247900 and 343000; windward Oahu, including stations 248800 through 294900; and north Oahu, including stations 296500 through 350000. The divides between the delineated regions were extended to the coast as shown in figure 1.

REGIONAL REGRESSION EQUATIONS

For the three regions, regression equations, bias-correction factors, standard errors of estimate and prediction, and equivalent years of record are given in tables 6 through 8. The standard errors of estimate for all the regression equations range from 27 to 58 percent. The average standard error for these equations was 39 percent.

LIMITATIONS AND ACCURACY OF REGRESSION EQUATIONS

The regression equations in tables 6 through 8 apply only to streams where peak discharge is not significantly affected by diversions, regulations, or urbanization. As mentioned, diversions were considered significant at stations where the measured diversions exceeded 30 percent of the mean daily discharge on the day of the annual peak discharge, significant regulation was defined as having a flood-control reservoir controlling more than 50 percent of the drainage-basin area, and urbanization was measured as the percentage of urban cover. Most streams on Oahu flow through unaltered channels in their upper reaches and then through residential or urban areas in the lower reaches before discharging into the Pacific Ocean. Most gaging stations are located near these residential and urban areas, so that some effects of these alterations are present in the gaged record. For ungaged basins where streamflow is affected by significant urbanization, peak discharges can be estimated according to the methods of Sauer and others (1983). Significant urbanization in this study is defined as any basin having an urban cover of greater than 36%. As part of this study, flood-peaks for basins with urban cover were compared with nearby non-urban basins. No significant trends or differences in the peak discharges were noted. Thirty-six percent was the highest value of urban cover (table 5) measured for any of the basins used in this study.

The standard error of estimate, expressed as a percentage (%SE), is an approximate measure of the reliability of the regression equation. The standard error of estimate is a measure of the model error, whereas the

Table 6. Regression equations for estimating peak discharges for streams in leeward Oahu (region 1), Hawaii

[DA, drainage area; P, median annual rainfall]

Regression equation	Bias-correction factor	R^2	Standard error (percent) of estimate	Standard error (percent) of prediction	Equivalent years of record
$Q = 3.26\ (DA^{0.634})\ (P^{1.08})$	(1.115)	0.74	40	43	4.2
$Q_5 = 25.8\ (DA^{0.642})\ (P^{0.773})$	(1.069)	0.73	38	40	5.8
$Q_{10} = 73.5\ (DA^{0.646})\ (P^{0.621})$	(1.052)	0.72	36	39	8.2
$Q_{25} = 217\ (DA^{0.646})\ (P^{0.464})$	(1.040)	0.71	35	38	11.4
$Q_{50} = 425\ (DA^{0.645})(P^{0.368})$	(1.037)	0.70	35	38	13.7
$Q_{100} = 758\ (DA^{0.643})\ (P^{0.286})$	(1.040)	0.69	35	39	15.8

Table 7. Regression equations for estimating peak discharge for streams in windward Oahu (region 2), Hawaii

[DA, drainage area]

Regression equation	Bias-correction factor	R^2	Standard error (percent) of estimate	Standard error (percent) of prediction	Equivalent years of record
$Q_2 = 525\ (DA^{0.704})$	(1.165)	0.75	58	62	2.5
$Q_5 = 1140\ (DA^{0.748})$	(1.138)	0.80	53	58	3.9
$Q_{10} = 1700\ (DA^{0.763})$	(1.129)	0.82	50	54	5.7
$Q_{25} = 2580\ (DA^{0.773})$	(1.124)	0.83	46	52	8.6
$Q_{50} = 3360\ (DA^{0.776})$	(1.125)	0.83	45	51	11.0
$Q_{100} = 4250\ (DA^{0.777})$	(1.133)	0.83	44	50	13.6

Table 8. Regression equations for estimating peak discharge for streams in north Oahu (region 3), Hawaii

[DA, drainage area; P224, 2-year, 24-hour rainfall intensity]

Regression equation	Bias-correction factor	R^2	Standard error (percent) of estimate	Standard error (percent) of prediction	Equivalent years of record
$Q_2 = 0.00356\ (DA^{0.870})\ (P224^{5.85})$	(1.036)	0.90	38	45	3.6
$Q_5 = 0.151\ (DA^{0.836})\ (P224^{4.30})$	(1.000)	0.90	27	34	8.3
$Q_{10} = 1.76\ (DA^{0.805})\ (P224^{3.24})$	(1.000)	0.86	27	34	10.2
$Q_{25} = 24.8\ (DA^{0.777})\ (P224^{2.10})$	(1.000)	0.78	31	38	10.7
$Q_{50} = 125\ (DA^{0.765})\ (P224^{1.39})$	(1.000)	0.70	34	43	10.5
$Q_{100} = 500\ (DA^{0.758})\ (P224^{0.792})$	(1.011)	0.61	39	48	10.1

standard error of prediction (%SP) is a measure of the model error and the sampling error of the data used in the regression analysis (G.D. Tasker, oral commun., 1990). The standard error of prediction was determined by the GLSNET program in ANNIE (Lumb and others, 1990; G.D. Tasker, written commun., 1990). The standard error can also be expressed as the number of equivalent years of record (*EQ*) needed at the ungaged site to achieve the reliability of the regression equation (Hardison, 1971). The equivalent years of record, *EQ*, is calculated by the equation in Hardison (1971) as applied by the GLSNET program (G.D. Tasker, written commun., 1990). This equation is:

$$EQ = K^2 \, [SD/SE_p]^2, \qquad (2)$$

where:

EQ = the equivalent years of record associated with the regression equation;

K^2 = a factor based on the mean skewness of the logarithms of the annual series of flood peaks at all stations in a hydrologic region and based on the recurrence interval, which relates the standard error associated with a given recurrence interval to the mean standard deviation of the logarithms of the annual peaks in a region and the number of annual peaks;

SD = the mean standard deviation of the logarithms of the annual peaks at all stations in a hydrologic region; and

SE_p = the standard error of prediction, in log units, associated with a regression equation.

The standard errors of the regression models apply only to streamflow estimates for basins that have values of the independent variable(s) within the range of those values used to derive that equation. For the equations in tables 6 through 8, statistical characteristics of the independent variables are shown in table 9. The use of the regression equations that have values outside the range shown in table 9 can result in potentially large extrapolation errors.

DISCUSSION OF EQUATIONS AND REGIONS

The regression equations for the leeward Oahu region (table 6) have two significant variables, drainage area and median annual rainfall. The drainage basins in the leeward region generally are similar to the long, V-shaped basin shape, however, drainage basins along the Waianae Coast are similar to the short, broad basins in shape, but are larger in area. The leeward region has the highest average drainage areas of all the regions (table 9) because the region includes the two largest drainage basins on Oahu (gaged by stations 213000 and 210500), which cover most of the central area of Oahu.

In the windward Oahu region (table 7), drainage area is the only significant variable in all the regression equations. The windward region contains essentially the same area as the windward regions determined by Wu (1967), Yamanaga (1972), Nakahara (1980), and Wong (1991). All of these windward regions differ only by the assignment of a few gaging stations. The drainage basins in the windward region are the smallest in average drainage area (table 9) of the three regions. Drainage basins in this region generally are short, broad basins. The headwaters of these basins all start along the steep cliffs of the Koolau Range (fig. 1).

The equations for the north Oahu region (table 8) contain two variables, drainage area and the 2-year, 24-hour rainfall intensity. The drainage basins in the north Oahu region generally are long, V-shaped basins and are similar to those in the leeward Oahu region. The equations also are similar to those for the leeward Oahu region, except that 2-year, 24-hour rainfall intensity replaces median annual rainfall.

SENSITIVITY ANALYSIS

Because the drainage-basin and climatic characteristics used in the regression equations must be computed from maps or other data sources, possibilities exist for error in measurement and judgment. To determine how much error can be introduced by computation error, a sensitivity analysis was done as described by Lumia (1991). The 50-year peak discharge was computed by the regression equation using the mean values (table 9) of the relevant basin and climatic characteristics for that region. This value represents the "base" 50-year flood. The mean values of the basin characteristics were then changed by increasing and decreasing each value by 10, 20, and 30 percent. The resulting percentage of change in the 50-year peak-discharge estimates are shown in table 10. For the two-variable equations, one basin characteristic was held constant at the mean value while the other varied.

Table 9. Statistical summary of selected drainage-basin, climatic, and flood-frequency characteristics by regions for Oahu, Hawaii

[Min-Max, range of minimum to maximum values; Std.dev., one standard deviation; A, draiange area; P, median annual rainfall; P224, 2-year, 24-hour rainfall intensity; UC, urban cover]

Characteristic		Region 1 (Leeward)	Region 2 (Windward)	Region 3 (North)
Number of stations		46	20	13
Mean interstation cross-correlation[1]		0.41	0.50	0.45
Mean gaged record skew		-0.282	-0.363	-0.206
DA (square miles)	Min–Max	0.60–45.7	0.03–5.34	1.11–13.5
	Median	3.52	0.98	2.98
	Mean	6.11	1.41	4.32
	Std.dev.	9.05	1.38	3.54
P (inches)	Min–Max	29–239	52–146	66–197
	Median	95	98	140
	Mean	98	99	135
	Std.dev.	52	28	48
P224 (inches)	Min–Max	4.72–8.78	5.62–9.10	5.21–9.04
	Median	6.34	7.70	7.05
	Mean	6.50	7.49	7.11
	Std.dev.	1.12	0.883	1.10
UC (percent)	Min–Max	0–32	0–36	0–0
	Median	0	0	0
	Mean	5	5	0
	Std.dev.	9	10	0
Years of record	Min–Max	11–72	13–49	21–35
	Median	30	26	30
	Mean	31	27	28
	Std.dev.	15	9	5

[1]computed from the cross-correlation matrix in the GLSNET program

Table 10. Results of sensitivity analysis showing percentage of change in computed 50-year peak discharges within each of the three hydrologic regions on Oahu, Hawaii

[DA, drainage area; P, median annual rainfall; P224, 2-year, 24-hour rainfall intensity]

	Change in computed 50-year peak discharge (percent)						
	Error in explanatory variable (percent)						
Explanatory variable	-30	-20	-10	0	+10	+20	+30
Region 1 (Leeward)							
DA	-20.5	-13.4	-6.5	0.0	6.4	12.5	18.5
P	-12.3	-7.8	-3.8	0.0	3.6	7.0	10.2
Region 2 (Windward)							
DA	-24.2	-16.0	-7.9	0.0	7.6	15.1	22.5
Region 3 (North)							
DA	-23.9	-15.7	-7.7	0.0	7.6	15.0	22.3
P224	-39.0	-26.7	-13.6	0.0	14.2	28.8	44.0

Results from table 10 show that for the north Oahu region, the 50-year peak-discharge equation is about twice as sensitive to possible 2-year, 24-hour rainfall-intensity error than to drainage-area error. The opposite is true in the leeward Oahu region where the percentage of change in the computed 50-year flood is about twice as large with possible drainage-area error than with possible errors in median annual rainfall. The windward Oahu region, with drainage area as the only variable, had equations as sensitive to variations in drainage area as did the other two regions. In general, likely errors in measurement would not be greater than plus or minus 10 percent.

COMPARISON OF WEIGHTED AVERAGE 100-YEAR DISCHARGE ESTIMATES WITH OTHER METHODS

Because new regression equations were derived to estimate peak discharges, a graphical comparison was made to see how these equations compare with other methods of estimating peak discharge. This comparison could help to determine which method is best for a particular application. The graphical comparisons were made by plotting the weighted average 100-year peak-discharge estimates, which were determined by equation 3 below, against the maximum known discharge (table 3) and the peak-discharge estimates determined by Bulletin 17B methods (Interagency Advisory Committee on Water Data, 1982), the 1988 storm drainage standards (City and County of Honolulu, 1988), and the 100-year peak-discharge regression equations of Nakahara (1980). The data used in these comparisons can be found in tables 3 and 11. The plotted data and lines of equal value are shown in figure 4.

Figure 4A shows the weighted average 100-year peak-discharge estimates compared with the maximum known discharges. Most of the discharges fall above the line of equal value showing that most of the weighted 100-year estimates are greater than the maximum known discharges. Only 9 of the 79 gaging stations have maximum observed discharges greater than the weighted average 100-year estimates. These are for stations 229000, 240500, 247900, 275000, 283000, 283600, 283700, 284000, and 303000 (table 3). The lengths of record for these 9 stations range from 19 to 72 years, and have an average of 42 years (table 1).

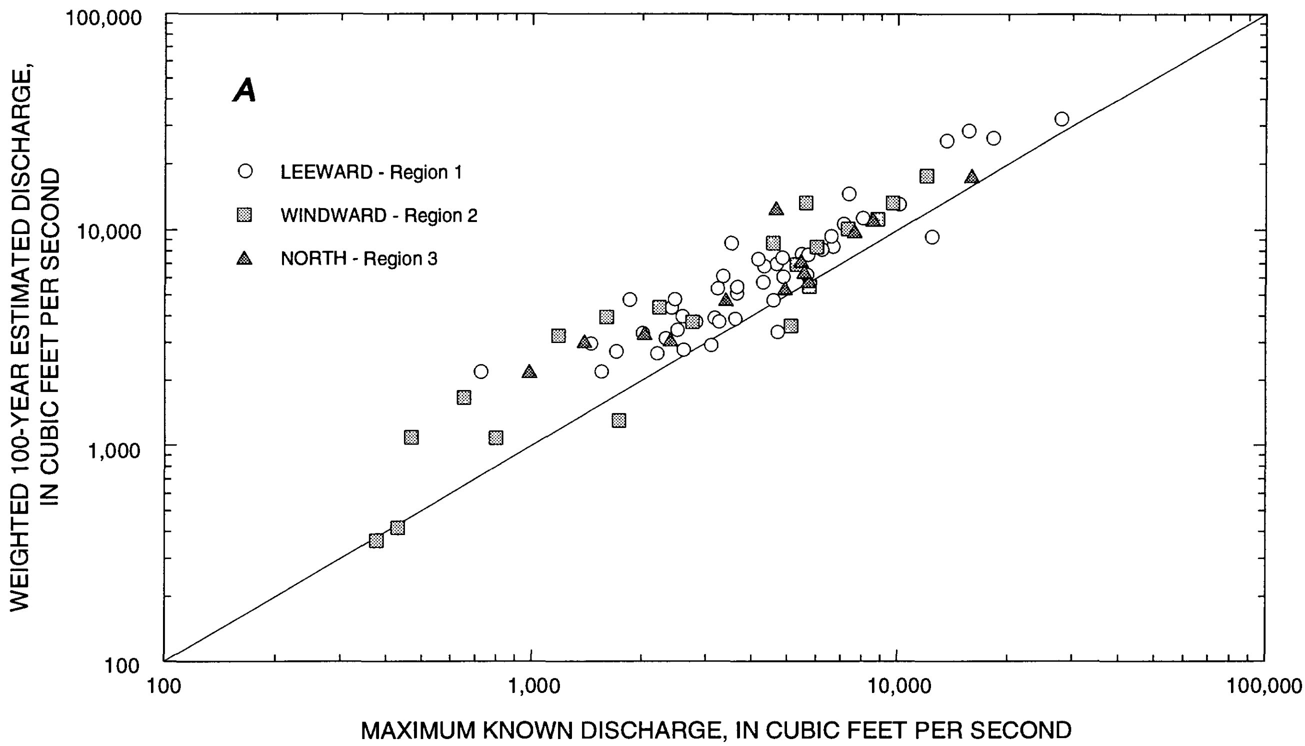
In figure 4B, the weighted average 100-year peak-discharge estimates are plotted against the 100-year peak discharges determined by Bulletin 17B methods (Interagency Advisory Committee on Water Data, 1982). As can be seen, most of the points fall along the line of equal value. This was expected because the Bulletin 17B 100-year discharge estimates are the observed data used to develop the 100-year peak-discharge regression equations in tables 6 through 8. The weighted average estimates are higher, however, in the region around 1,000 ft^3/s (figure 4B).

Figure 4C shows the weighted average 100-year peak-discharge estimates plotted against the discharge estimates determined from plate 6 in the 1988 storm drainage standards (City and County of Honolulu, 1988). The estimates from plate 6 are listed in table 11. Most of the 77 discharge estimates fall below the line of equal value in figure 4C. This shows that most of the City and County discharge estimates are greater than the weighted average 100-year peak-discharge estimates. Of the 23 discharge estimates that fall above the line of equal value, 12 are from sites located in leeward Oahu and 11 from windward Oahu.

Figure 4D shows the weighted average 100-year peak-discharge estimates plotted against the 100-year peak-discharge estimates from the regression equations of Nakahara (1980). This figure shows that the equations of Nakahara (1980) provide estimates that generally are larger than the weighted average 100-year peak-discharge estimates from this study. Only 27 of the 72 estimates fell above the line of equal value. In comparing the regression equations between these two studies, in Nakahara's (1980) report, the %SE varied from 33 to 67 percent, and averaged 48 percent. The regression equations from this study had an average %SE of 39 percent. This results in a difference between the averages of about 9 percent in the %SE. Thus, the addition of 10 years of data along with improved computational techniques has improved in %SE of the regression equations.

ESTIMATION OF PEAK DISCHARGE USING REGRESSION EQUATIONS

This section provides methods and examples for computing a peak discharge for a selected recurrence interval at a specific site. Two methods are provided for use depending on if the site is gaged or ungaged. Both methods use the regression equations in tables 6 through 8 for estimating peak discharges on Oahu. The



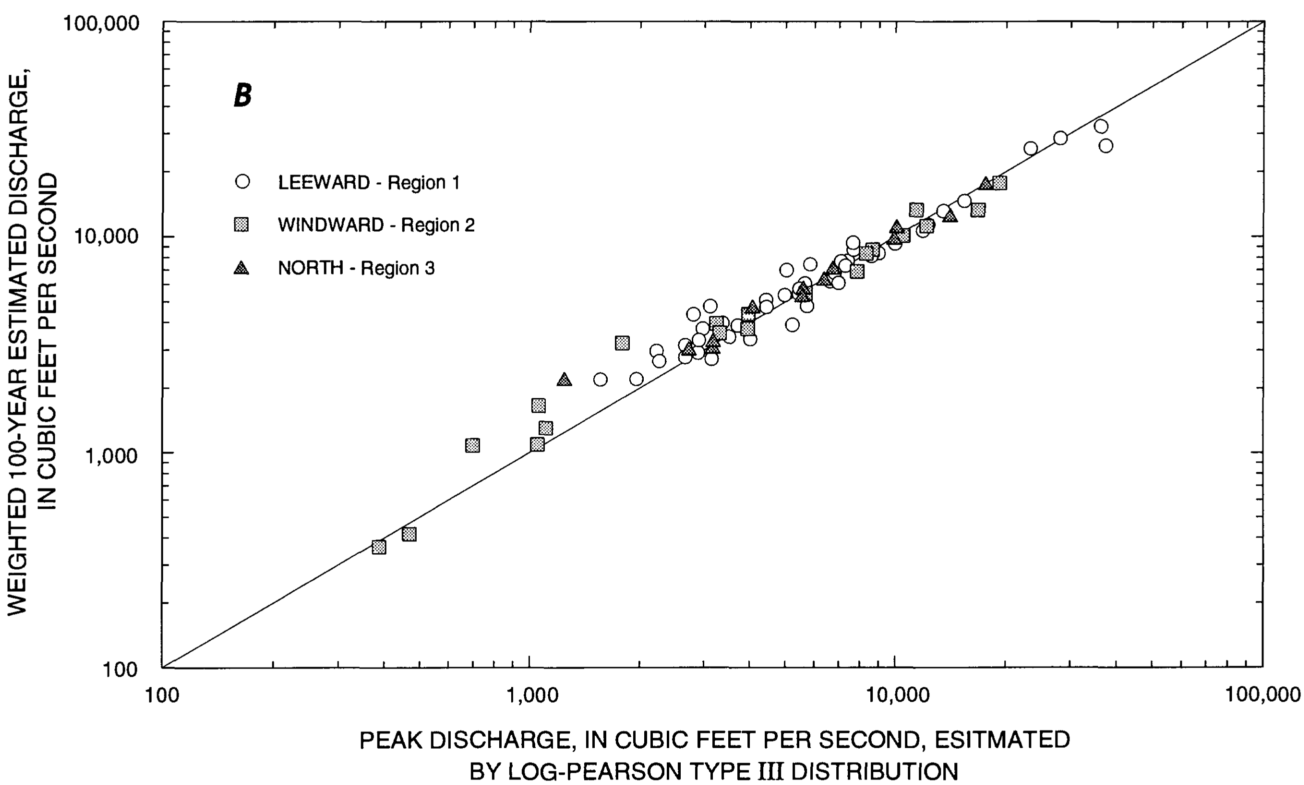
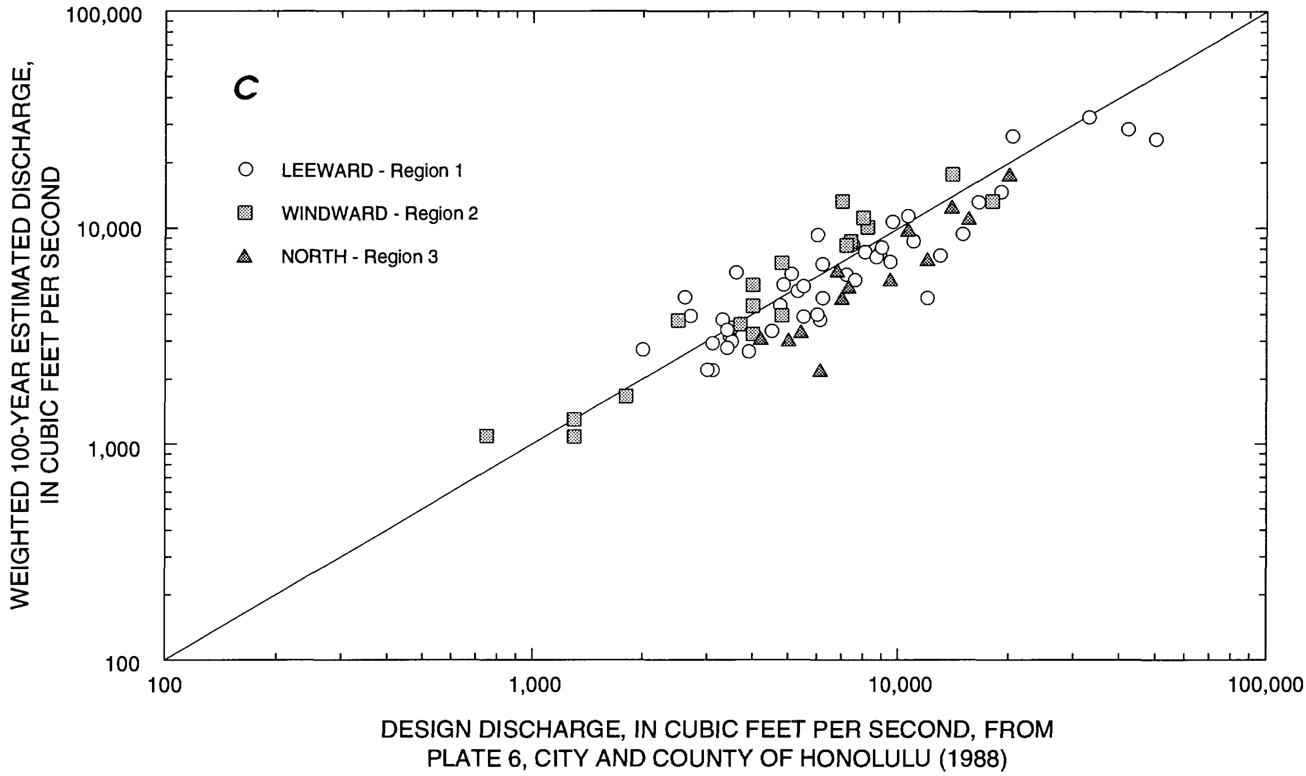


Figure 4. Relation of weighted average 100-year discharge estimates to; ***A***, maximum known discharge; ***B***, peak discharge; ***C***, design discharge; and ***D***, 100-year estimated discharge, Oahu, Hawaii.



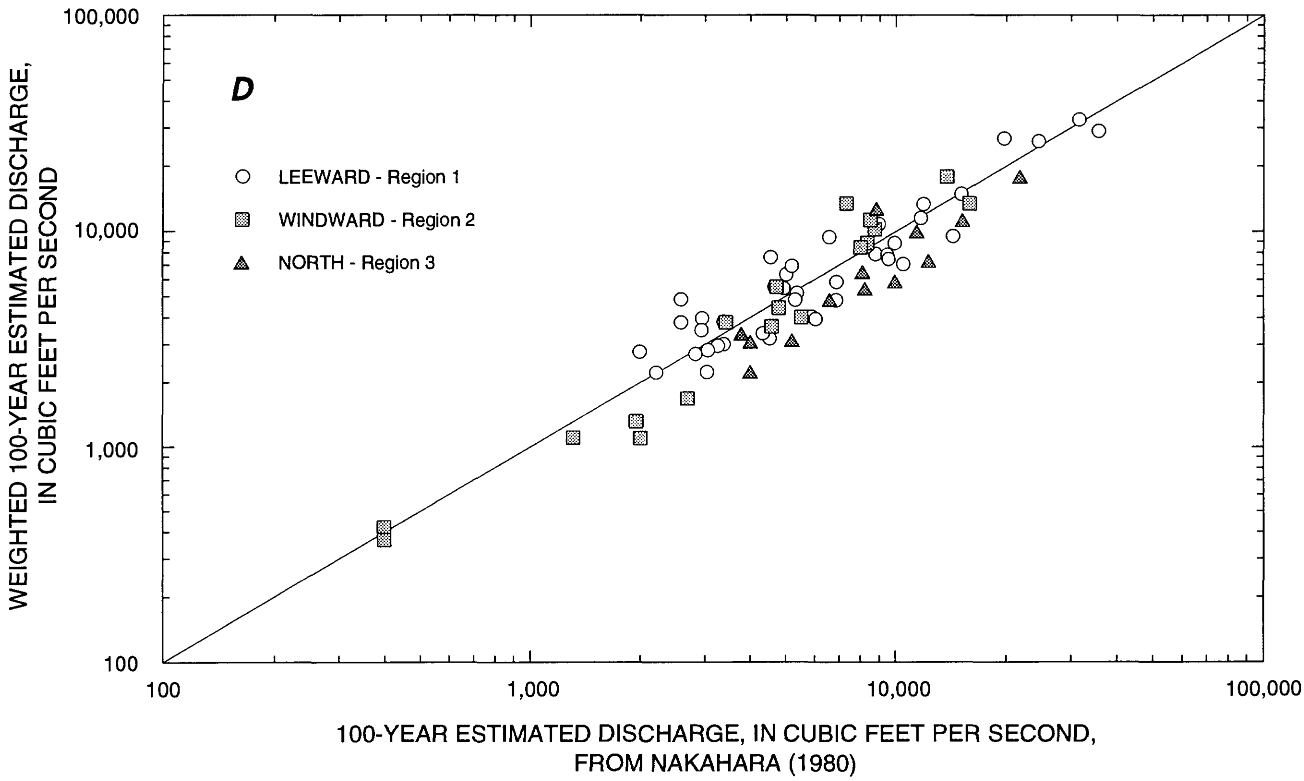


Figure 4. Relation of weighted average 100-year discharge estimates to; ***A***, maximum known discharge; ***B***, peak discharge; ***C***, design discharge; and ***D***, 100-year estimated discharge, Oahu, Hawaii--Continued.

Table 11. Additional data used in comparing the weighted 100-year peak discharge estimates with other methods for Oahu, Hawaii

[Hydrologic regions shown in fig. 1: 1, leeward Oahu; 2, windward Oahu; 3, north Oahu; Plate 6 curves and discharge from Storm Drainage Standards (City and County of Honolulu, 1988); ft^3/s, cubic feet per second; previous 100-year peak discharge from Nakahara (1980);. --, no data]

Station number	Hydrologic region	Area in 100 acres	Plate 6 curve used	Plate 6 discharge (ft^3/s)	Previous 100-year peak discharge (ft^3/s)
200000	1	8.8	B	3,600	5,020
201000	1	7.7	B	3,450	4,520
204000	1	31.1	B	9,500	10,500
206000	1	12.4	B	4,750	-
208000	1	25.8	B	8,100	8,810
208500	1	5.5	B	2,700	2,950
210500	1	248	B	42,000	35,700
211200	1	81.2	B	19,000	15,100
211300	1	26.6	C	5,300	5,370
211500	1	27.1	C	5,500	4,940
211600	1	14.8	C	3,500	3,380
211700	1	33.6	C	6,200	5,200
211800	1	22.9	C	4,850	4,660
212200	1	9.7	C	2,600	2,580
212300	1	25.5	C	5,100	-
212450	1	10.9	C	3,100	2,210
212500	1	70.4	C	11,000	9,930
212601	1	40.6	B	12,000	5,310
212700	1	47.9	B	13,000	4,550
212800	1	27.4	B	8,900	9,490
213000	1	292	B	50,000	24,500
216000	1	169	B	33,000	31,600
216500	1	16.8	B	6,100	2,580
223000	1	38.2	B	10,600	11,700
224500	1	16.6	B	6,000	5,890
226000	1	22.1	B	7,500	8,340
227000	1	56.2	B	14,900	14,300
228000	1	17.5	B	6,200	6,870
228200	1	21.4	B	7,200	-
228500	1	26.6	B	8,700	9,570
228600	1	28.4	B	9,000	-
228900	1	3.8	B	2,000	1,990
229000	1	16.7	B	6,000	6,560
229300	1	33.2	B	9,600	8,980
235400	1	8.2	B	3,500	2,940
237500	1	9.2	B	3,900	2,830
238500	1	7.3	B	3,300	3,380
240500	1	6.8	B	3,100	3,260
244000	1	7.6	B	3,400	3,060
246000	1	6.6	B	3,000	3,040
247000	1	23.2	B	7,600	6,880
247100	1	67.8	B	16,500	11,900
247200	1	11.2	B	4,500	4,330
247500	1	15.0	B	5,500	6,040
247900	1	7.6	B	3,400	-

Table 11. Additional data used in comparing the weighted 100-year peak discharge estimates with other methods for Oahu, Hawaii--*Continued*

Station number	Hydrologic region	Area in 100 acres	Plate 6 curve used	Plate 6 discharge (ft^3/s)	Previous 100-year peak discharge (ft^3/s)
248800	2	7.7	A	4,800	5,520
249000	2	13.8	A	7,400	8,340
249100	2	1.0	A	750	1,310
254000	2	13.0	A	7,200	8,010
260500	2	34.2	A	18,000	15,900
265000	2	7.6	A	4,800	–
270900	2	2.8	A	1,800	2,690
273900	2	27.0	A	14,000	13,800
274499	2	4.0	A	2,500	3,430
275000	2	6.2	A	4,000	4,720
278000	2	1.8	A	1,300	2,000
279500	2	11.5	A	7,000	7,320
283000	2	1.8	A	1,300	1,950
283480	2	14.8	A	8,200	8,750
283600	2	0.19	A	–	398
283700	2	0.20	A	–	398
284000	2	6.0	A	3,700	4,580
284200	2	6.2	A	4,000	–
291000	2	6.3	A	4000	4,790
294900	2	14.2	A	8,000	8,500
296500	3	23.9	A	12,000	12,300
303000	3	17.8	A	9,500	9,980
304200	3	7.1	A	4,200	5,190
304500	3	13.6	A	7,300	8,230
310501	3	25.9	A	13,900	8,830
311000	3	13.6	B	5,000	4,000
318000	3	16.6	B	6,100	3,990
325000	3	20.0	B	7,000	6,590
330000	3	62.7	B	15,500	15,200
331000	3	14.3	B	5,400	3,780
340000	3	86.4	B	20,000	21,700
343000	1	90.9	B	20,400	19,700
345000	3	19.1	B	6,800	8,090
350000	3	38.1	B	10,600	11,400

use of the regression equations apply only under the conditions described in the accuracy and limitations section.

GAGED SITES

The regression equation for each region was applied to the gaged sites in that region and the resulting peak-discharge estimates are listed in table 3. At gaged sites, two peak-discharge estimates are available, one from the frequency curves based on gaged record and the other from the regression equations. Another estimate would be to combine them. Combining the estimates provides a regional adjustment to the gaged record. To combined estimates, a weighted average of the peak discharges was used. The equation outlined in Choquette (1988) and described below weighs the two peak estimates by record length in years. By combining the regression and gaged record peak-discharge estimates, time-sampling errors at sites with short record lengths are reduced, providing an improved estimate of peak discharge. Weighted average peak-discharge values have been computed by equation 3 below for all 79 gaged sites used in this study and are shown in table 3. The weighting equation for peak discharges at gaged stations is:

$$Q_{t_w} = \left[Q_{t_g}(N) + Q_{t_r}(EQ)\right] / (N + EQ), \qquad (3)$$

where: Q_{t_w} = the weighted average peak discharge, in cubic feet per second, for the t-year recurrence interval;

Q_{t_g} = the t-year peak discharge, in cubic feet per second, computed from the gaged record;

Q_{t_r} = the regional regression estimate, in cubic feet per second, from the equation for the t-year peak discharge;

N = the number of years of gaged record at the station (table 1); and

EQ = the equivalent years of record associated with the regression equation (tables 8-10).

UNGAGED SITES

The purpose of regional analysis is to transfer flood-frequency data spatially. This is done by using the derived regression equations for ungaged basins. Flood estimates for ungaged sites are determined from the regression equations in tables 8 through 10 depending on the region in which the ungaged basin lies. If an ungaged site is near a gaged site on the same stream, Thomas (1987) provides four equations that use both the regression equation estimate and the discharges from the flood-frequency analysis of the gaged record. A criterion for using these equations requires that the drainage area of the ungaged site be within 50 to 150 percent of the drainage area of the gaged site. These equations were evaluated for applicability to streams on Oahu by using four pairs of gaged sites that met the drainage-area size criterion. The equation providing the best results was that originally presented by Sauer (1973). This equation is:

$$Q_{t_u} = C_u\left(Q_{r_u}\right), \qquad (4)$$

where:

Q_{t_u} = the final t-year peak discharge, in cubic feet per second, for the ungaged site;

C_u = an adjustment factor defined as:

$$C_u = R - [2\left(\left|DA_g - DA_u\right|\right) / DA_g](R - 1.0), \qquad (5)$$

where:

R = the ratio of the weighted discharge estimate of Q_{t_w} for the gaged site to the regression estimate of Q_{t_r} for the gaged site;

DA_g = the drainage area, in square miles, of the gaged site;

DA_u = the drainage area, in square miles, of the ungaged site;

$\left|DA_g - DA_u\right|$ = the absolute value of the difference between the gaged and ungaged drainage areas;

Q_{r_u} = the regression estimate of Q_t, in cubic feet per second, at the ungaged site.

A note in using equation 5: The ratio C_u approaches 1.0 when the drainage area of the ungaged site approaches either 50 or 150 percent of the drainage area of the gaged site. When the drainage area of the ungaged site is more than 50 percent smaller or larger than that of the gaged site, no adjustment is applied to the regression estimate to account for the data at the gaged site.

SAMPLE COMPUTATIONS

The following examples illustrate the use of the methods described in this report for estimating peak discharges at gaged and ungaged sites.

Example 1. Gaged site: Estimate the 50-year peak discharge at Moanalua Stream near Honolulu (station 228000).

First, check to see if site is affected by significant diversions, regulations, or urbanization. Next, determine in which region the station is located.Station 228000 is in the leeward Oahu region (fig. 1) and is not affected by significant diversions, regulations, or urbanization. Table 6 gives the equation for the 50-year peak flood as:

$$Q_{50_r} = 425\,(DA^{0.645})(P^{0.368})(1.037), \qquad (6)$$

with an equivalent years of record (EQ) of 13.7. The basin characteristics needed are drainage area (DA) and median annual precipitation (P), which for station 228000 are 2.73 mi^2 and 124 in., respectively (table 4). These values fall within the ranges of values for each characteristic (table 9), so equation 6 is applicable for this site. Substituting the respective values in equation (6) gives the regression estimate:

$$Q_{50_r} = 425(2.73^{0.645})(124^{0.368})(1.037),$$
$$= 425(1.911)(5.894)(1.037),$$
$$= 4{,}964 \text{ ft}^3/\text{s or } 4{,}960 \text{ ft}^3/\text{s, (table 3).}$$

From table 3, the 50-year peak discharge based on the gaged record (Q_{50_g}) is 3,870 ft^3/s. The number of years of record (N) for the gaged record estimate is 61 years (table 1). The weighted average estimate of the 50-year peak can now be determined from equation 3.

$$Q_{50_w} = [(3{,}870)(61) + (4{,}960)(13.7)] / (61 + 13.7),$$
$$= (236{,}070 + 67{,}952) / 74.7,$$
$$= 304{,}022 / 74.7 = 4{,}070 \text{ ft}^3/\text{s (table 3).}$$

Therefore, the weighted average estimate of the 50-year peak discharge at Moanalua Stream (station 228000) is 4,070 ft^3/s.

Example 2. Ungaged site near a gaged site on the same stream: Estimate the 10-year peak discharge at an ungaged site upstream of station 294900, Waikane Stream.

First, check to see if this site is affected by significant diversions, regulation, or urbanization. Next, determine in which region the ungaged site is located. This site is in the windward Oahu region and there are no significant diversions, regulation, or urbanization present. The equation to estimate the 10-year flood is found in table 9:

$$Q_{10_r} = 1{,}700\,(DA^{0.763})(1.129). \qquad (7)$$

For this ungaged site the drainage area is 1.57 mi^2, which falls within the range of drainage area values given in table 13, so that equation 7 can be used. To use equation 4, the drainage area of the ungaged site must fall within the 50- to 150-percent limits of drainage area at the gaged site and be on the same stream. The drainage area of station 294900 is 2.22 mi^2 (table 4) and the 50- to 150-percent lower and upper limits of drainage area are 1.11 to 3.33 mi^2. Because the drainage area of the ungaged site falls within these limits, equation 4 can be used. The regression estimate is:

$$Q_{10_r} = 1{,}700(1.57^{0.763})(1.129) = 1{,}700(1.411)(1.129)$$
$$= 2{,}710 \text{ ft}^3/\text{s.}$$

If the drainage area were less than 1.11 or greater than 3.33 mi^2, then the final estimate for this ungaged site would be 2,710 ft^3/s. The weighted average estimate at the gaged site, station 294900, is 5,830 ft^3/s and the regression estimate is 3,530 ft^3/s (table 3). Applying equation 4 gives:

$$R = 5{,}830/3{,}530 = 1.652, \text{ and}$$
$$C_u = 1.652 - [2(|2.22 - 1.57|)/2.22](1.652 - 1.0),$$
$$= 1.652 - (0.5856)(0.652),$$
$$= 1.652 - (0.3818) = 1.270.$$

Therefore, the final 10-year peak discharge for the ungaged site, Q_{10_u}, is

$$Q_{10_u} = C_u\,(Q_{10_r}) = (1.270)(2{,}710) = 3{,}440 \text{ ft}^3/\text{s.}$$

SUMMARY

To adequately design bridges, flood control structures, and buildings located in or adjacent to flood plains, a reasonable estimate of flood magnitude and frequency is necessary. Flood-frequency and regression analyses were used to develop equations for estimating the 2-, 5-, 10-, 25-, 50-, and 100-year peak discharges for gaged and ungaged streams on Oahu. Flood-frequency analysis using the log-Pearson Type III distribution was done on 79 gaging stations with 11 to 72 years of record. Regression analysis techniques were used to improve estimates for gaged sites and to transfer gaged-site estimates to ungaged sites. This study differs from past studies by using peak-discharge data collected to water year 1988, additional gaging stations, geographic information systems (GIS) technology, generalized least-squares regression analysis, and updated flood frequency guidelines.

For regression analysis, peak-discharge estimates for selected frequencies determined by applying the log-Pearson Type III distribution to the peaks of record were related to basin and climatic characteristics. Most characteristics were computed by GIS. The use of GIS was found to be a more convenient and consistent means of defining and calculating basin and climatic characteristics than the manual methods.

To improve the standard errors of the regression equations, Oahu was divided into three hydrologically similar regions. These regions are leeward, windward and north Oahu. Drainage-basin and climatic characteristics included in the regression equations are drainage area and median annual rainfall for the leeward Oahu region, drainage area for the windward Oahu

region, and drainage area and the 2-year, 24-hour rainfall intensity for the north Oahu region. Drainage areas for sites used in this study ranged from 0.03 to 45.7 mi^2. Final regression equations were derived using generalized least-squares regression techniques. The use of generalized least-squares regression provided improvements in the regression estimates by accounting for cross-correlation and different record lengths in a set of data for gaging stations in a region. The standard error of estimate for the regression equations given ranged from 27 to 58 percent. Standard error of prediction ranged from 34 to 62 percent. The use of generalized least-squares regression, and other improvements incorporated in this study, reduced the standard error of estimate for the regression equations by an average of 8 percent compared with previously published regression equations. A full discussion on the accuracy and limitations of the regression equations and a sensitivity analysis and sample calculations are given to help apply the derived regression equations.

The results using the derived regression equations were compared graphically with other methods used to estimate peak discharges. The graphical comparisons were made by plotting the weighted average 100-year peak-discharge estimates from the regression equations compared with the maximum observed discharge and estimates of the 100-year peak discharge determined in this study and in two previous studies. The comparison showed that most of the estimates from the regression equations in this study are lower than the peak-discharge estimates based on equations from the other studies.

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Table 3. Estimated peak discharges for selected recurrence intervals and maximum known discharges at stream-gaging stations on Oahu, Hawaii

[ft^3/s, cubic foot per second. Estimated peak discharge is Q_t, where t = 2, 5, 10, 25, 50, and 100 years. **Upper row**, values are from individual frequency curves. **Middle row**, values were computed by using the regression equations. **Lower row**, values are the weighted average of the station Q_t (upper row) and regression Q_t (middle row), see equation 3 on page 25. All regression estimates include the retransformation bias-correction factor]

Station number	Q_2	Q_5	Q_{10} (ft^3/s)	Q_{25}	Q_{50}	Q_{100}	Maximum known discharge: Water year	Maximum known discharge: Discharge (ft^3/s)
200000	2,500	3,710	4,470	5,380	6,020	6,630	1982	5,640
	1,650	2,340	2,850	3,530	4,070	4,640		
	2,450	3,600	4,290	5,100	5,680	6,240		
201000	1,020	1,450	1,740	2,100	2,380	2,660	1940	2,320
	1,500	2,120	2,590	3,210	3,710	4,230		
	1,070	1,550	1,900	2,380	2,760	3,160		
204000	2,490	3,160	3,610	4,180	4,610	5,040	1963	4,660
	2,840	4,380	5,560	7,140	8,420	9,750		
	2,550	3,410	4,140	5,190	6,070	7,010		
206000	953	1,410	1,730	2,150	2,470	2,800	1955	2,410
	1,970	2,830	3,470	4,320	4,990	5,700		
	1,200	1,850	2,400	3,160	3,760	4,390		
208000	1,750	2,980	3,920	5,220	6,280	7,410	1963	5,460
	2,340	3,680	4,720	6,130	7,280	8,480		
	1,820	3,090	4,090	5,460	6,590	7,770		
208500	598	1,440	2,180	3,290	4,220	5,220	1968	3,160
	503	915	1,260	1,780	2,220	2,710		
	577	1,290	1,850	2,640	3,260	3,930		
210500	2,010	5,260	8,660	14,700	20,700	28,100	1963	15,600
	4,300	8,700	12,700	18,500	23,600	29,200		
	2,380	5,980	9,760	16,000	21,800	28,600		
211200	1,190	3,240	5,280	8,660	11,800	15,400	1974	7,340
	1,900	3,930	5,780	8,600	11,100	13,800		
	1,300	3,380	5,420	8,640	11,500	14,700		
211300	509	1,120	1,690	2,610	3,450	4,430	1966	3,640
	799	1,710	2,560	3,900	5,100	6,460		
	544	1,210	1,870	2,960	3,960	5,120		
211500	229	708	1,270	2,350	3,500	4,980	1976	3,220
	647	1,480	2,290	3,590	4,790	6,180		
	280	833	1,490	2,690	3,900	5,390		
211600	306	638	929	1,380	1,780	2,220	1982	1,450
	523	1,130	1,710	2,610	3,440	4,380		
	333	720	1,100	1,730	2,310	2,980		
211700	510	1,300	2,120	3,590	5,030	6,820	1976	4,310
	664	1,570	2,460	3,940	5,300	6,880		
	534	1,350	2,210	3,710	5,130	6,840		
211800	286	871	1,520	2,720	3,930	5,440	1982	3,640
	581	1,330	2,050	3,220	4,300	5,540		
	324	950	1,640	2,860	4,050	5,480		

Table 3. Estimated peak discharges for selected recurrence intervals and maximum known discharges at stream-gaging stations on Oahu, Hawaii--*Continued*

Station number	Q_2 (ft³/s)	Q_5 (ft³/s)	Q_{10} (ft³/s)	Q_{25} (ft³/s)	Q_{50} (ft³/s)	Q_{100} (ft³/s)	Maximum known discharge: Water year	Maximum known discharge: Discharge (ft³/s)
212200	295 267 292	978 646 926	1,730 1,030 1,580	3,040 1,670 2,670	4,280 2,280 3,670	5,730 2,990 4,800	1982	2,460
212300	632 331 582	1,680 905 1,510	2,670 1,530 2,350	4,210 2,630 3,650	5,530 3,710 4,810	6,990 5,020 6,140	1976	3,320
212450	191 236 199	434 606 471	649 991 745	976 1,660 1,220	1,260 2,300 1,670	1,560 3,060 2,200	1980	724
212500	592 890 630	1,670 2,230 1,760	2,730 3,600 2,920	4,440 5,890 4,850	5,970 8,050 6,640	7,690 10,600 8,720	1982	3,500
212601	448 801 491	920 1,860 1,070	1,330 2,900 1,670	1,950 4,580 2,670	2,500 6,130 3,640	3,110 7,920 4,770	1982	1,850
212700	849 1,880 972	1,710 3,530 2,000	2,460 4,960 2,980	3,630 7,030 4,540	4,670 8,800 5,940	5,850 10,700 7,490	1963	4,830
212800	1,840 2,600 1,930	2,900 4,010 3,070	3,740 5,100 4,020	4,950 6,560 5,370	5,970 7,730 6,500	7,100 8,970 7,720	1963	5,680
213000	3,160 4,090 3,260	6,660 8,660 6,940	9,730 12,900 10,300	14,500 19,300 15,600	18,600 24,900 20,300	23,300 31,100 25,700	1955	13,600
216000	8,500 4,040 8,030	15,200 7,750 14,200	20,100 11,000 18,400	26,500 15,600 23,900	31,300 19,600 28,100	36,200 23,900 32,400	1982	27,900
216500	249 468 297	564 1,070 705	895 1,660 1,160	1,510 2,620 1,990	2,140 3,500 2,790	2,970 4,520 3,770	1955	2,810
223000	1,770 1,820 1,780	3,600 3,310 3,560	5,200 4,570 5,080	7,670 6,370 7,340	9,840 8,000 9,310	12,300 9,560 11,400	1968	8,020
224500	895 928 898	1,490 1,740 1,530	1,920 2,450 2,020	2,480 3,490 2,730	2,920 4,390 3,340	3,360 5,380 4,000	1963	2,580
226000	1,280 1,490 1,300	2,610 2,580 2,610	3,780 3,480 3,730	5,600 4,760 5,410	7,190 5,830 6,840	9,000 6,980 8,420	1932	6,650
227000	2,000 1,900 1,980	3,300 3,670 3,380	4,260 5,210 4,540	5,560 7,500 6,260	6,590 9,460 7,760	7,660 11,600 9,400	1966	6,570
228000	1,070 1,250 1,080	1,910 2,180 1,930	2,510 2,950 2,560	3,290 4,050 3,410	3,870 4,960 4,070	4,440 5,970 4,750	1931	4,580

Table 3. Estimated peak discharges for selected recurrence intervals and maximum known discharges at stream-gaging stations on Oahu, Hawaii--*Continued*

Station number	Q_2	Q_5	Q_{10} (ft³/s)	Q_{25}	Q_{50}	Q_{100}	Maximum known discharge: Water year	Maximum known discharge: Discharge (ft³/s)
228200	1,180	2,190	2,950	3,990	4,810	5,660	1980	4,860
	1,340	2,380	3,240	4,490	5,540	6,680		
	1,210	2,230	3,030	4,170	5,110	6,110		
228500	2,100	3,470	4,410	5,590	6,450	7,300	1968	4,150
	1,340	2,500	3,450	4,880	6,090	7,420		
	1,890	3,140	4,000	5,230	6,250	7,370		
228600	1,380	2,640	3,720	5,410	6,900	8,600	1980	6,200
	1,340	2,510	3,510	4,990	6,260	7,650		
	1,370	2,610	3,650	5,250	6,620	8,160		
228900	414	937	1,380	2,030	2,570	3,140	1980	1,700
	458	800	1,080	1,490	1,840	2,220		
	421	907	1,300	1,840	2,280	2,740		
229000	1,470	3,100	4,470	6,490	8,180	10,000	1931	12,400
	1,170	2,070	2,810	3,870	4,770	5,740		
	1,450	3,020	4,300	6,130	7,630	9,230		
229300	2,520	4,640	6,240	8,410	10,100	11,900	1974	7,110
	1,490	2,790	3,910	5,540	6,940	8,470		
	2,390	4,320	5,710	7,580	9,060	10,700		
235400	558	1,130	1,600	2,300	2,880	3,510	1963	2,500
	567	1,080	1,510	2,170	2,740	3,380		
	559	1,120	1,580	2,260	2,840	3,460		
237500	353	674	956	1,400	1,800	2,260	1963	2,200
	538	1,060	1,510	2,210	2,820	3,510		
	375	735	1,070	1,620	2,110	2,680		
238500	666	1,250	1,740	2,500	3,160	3,900	1921	3,250
	657	1,170	1,590	2,210	2,740	3,320		
	665	1,240	1,720	2,460	3,080	3,780		
240500	501	891	1,230	1,780	2,290	2,880	1921	3,090
	609	1,090	1,500	2,090	2,590	3,150		
	507	906	1,260	1,820	2,340	2,930		
244000	418	821	1,160	1,690	2,150	2,660	1930	2,600
	570	1,060	1,480	2,110	2,650	3,250		
	429	843	1,200	1,760	2,250	2,790		
246000	387	740	1,010	1,380	1,670	1,960	1930	1,550
	492	933	1,310	1,890	2,390	2,940		
	396	762	1,060	1,480	1,840	2,210		
247000	1,360	2,280	2,970	3,920	4,680	5,470	1968	4,270
	908	1,830	2,660	3,920	5,030	6,280		
	1,300	2,200	2,900	3,920	4,800	5,770		
247100	2,900	5,320	7,140	9,610	11,500	13,500	1968	10,100
	1,890	3,790	5,480	8,020	10,200	12,700		
	2,730	4,990	6,670	9,050	11,000	13,200		
247200	919	1,440	1,790	2,240	2,570	2,900	1958	2,010
	431	936	1,410	2,170	2,860	3,640		
	784	1,270	1,630	2,200	2,730	3,340		

Table 3. Estimated peak discharges for selected recurrence intervals and maximum known discharges at stream-gaging stations on Oahu, Hawaii--*Continued*

Station number	Q_2	Q_5	Q_{10}	Q_{25}	Q_{50}	Q_{100}	Maximum known discharge: Water year	Maximum known discharge: Discharge (ft^3/s)
	(ft^3/s)							
247500	554	1,070	1,530	2,260	2,920	3,700	1968	3,600
	473	1,060	1,620	2,520	3,340	4,290		
	544	1,070	1,550	2,330	3,050	3,900		
247900	375	809	1,260	2,080	2,920	4,010	1988	4,700
	252	592	927	1,490	2,010	2,620		
	353	758	1,160	1,860	2,540	3,380		
248800	335	847	1,310	2,010	2,600	3,240	1981	1,600
	700	1,500	2,220	3,360	4,380	5,590		
	362	920	1,450	2,300	3,070	3,960		
249000	1,300	2,640	3,780	5,520	7,010	8,680	1963	4,560
	1,050	2,310	3,460	5,260	6,870	8,770		
	1,280	2,590	3,720	5,450	6,970	8,710		
249100	123	281	423	643	835	1,050	1988	467
	168	330	474	703	912	1,160		
	127	287	432	658	858	1,090		
254000	859	1,930	2,970	4,700	6,350	8,320	1965	6,000
	1,010	2,220	3,310	5,030	6,570	8,390		
	870	1,960	3,020	4,770	6,410	8,340		
260500	1,790	3,560	5,060	7,300	9,220	11,400	1965	9,690
	1,990	4,550	6,890	10,600	13,700	17,700		
	1,800	3,670	5,340	8,020	10,400	13,300		
265000	733	1,620	2,530	4,150	5,780	7,860	1969	5,290
	692	1,480	2,190	3,320	4,330	5,520		
	728	1,600	2,450	3,900	5,270	6,910		
270900	183	344	480	686	864	1,060	1971	651
	343	703	1,030	1,540	2,000	2,550		
	201	403	602	943	1,270	1,660		
273900	1,700	4,140	6,560	10,600	14,500	19,200	1969	12,000
	1,730	3,920	5,930	9,080	11,200	15,200		
	1,700	4,110	6,430	10,200	13,400	17,700		
274499	493	1,070	1,590	2,410	3,130	3,950	1965	2,750
	437	909	1,330	2,000	2,610	3,320		
	489	1,050	1,550	2,320	2,990	3,750		
275000	693	1,650	2,470	3,670	4,650	5,680	1965	5,740
	599	1,270	1,880	2,830	3,690	4,710		
	688	1,620	2,410	3,540	4,470	5,470		
278000	43	111	188	335	492	700	1965	797
	256	515	747	1,110	1,450	1,840		
	61	162	285	522	770	1,080		
279500	924	2,740	4,760	8,470	12,200	16,800	1965	5,600
	926	2,020	3,010	4,570	5,960	7,610		
	924	2,630	4,400	7,070	10,100	13,300		
283000	130	258	384	606	828	1,110	1965	1,730
	250	502	727	1,080	1,410	1,790		
	138	283	433	702	970	1,300		

Table 3. Estimated peak discharges for selected recurrence intervals and maximum known discharges at stream-gaging stations on Oahu, Hawaii--*Continued*

Station number	Q_2	Q_5	Q_{10} (ft³/s)	Q_{25}	Q_{50}	Q_{100}	Maximum known discharge: Water year	Maximum known discharge: Discharge (ft³/s)
283480	1,220	2,720	4,090	6,280	8,250	10,500	1971	7,300
	1,100	2,430	3,640	5,540	7,240	9,240		
	1,210	2,680	4,010	6,100	7,950	10,100		
283600	102	172	230	315	388	469	1982	430
	52	94	132	193	249	316		
	98	162	212	285	347	416		
283700	82	141	189	260	321	388	1965	376
	52	94	132	193	249	316		
	80	135	179	243	300	363		
284000	409	868	1,290	1,960	2,580	3,300	1965	5,110
	581	1,230	1,820	2,740	3,570	4,560		
	418	897	1,350	2,080	2,770	3,590		
284200	469	766	988	1,290	1,540	1,790	1982	1,180
	599	1,270	1,880	2,830	3,690	4,710		
	489	876	1,250	1,880	2,490	3,230		
291000	600	1,160	1,650	2,430	3,140	3,960	1963	2,230
	608	1,290	1,900	2,880	3,750	4,780		
	601	1,190	1,730	2,610	3,420	4,380		
294900	2,290	4,550	6,280	8,600	10,400	12,200	1965	8,800
	1,070	2,360	3,530	5,370	7,020	8,960		
	2,190	4,290	5,830	7,860	9,470	11,200		
296500	3,270	4,420	5,090	5,830	6,310	6,750	1963	5,430
	4,560	5,880	6,380	7,040	7,320	7,860		
	3,410	4,740	5,420	6,150	6,580	7,040		
303000	1,860	2,880	3,560	4,400	5,010	5,600	1974	5,700
	2,540	3,610	4,190	4,970	5,400	6,010		
	1,920	3,020	3,700	4,530	5,100	5,690		
304200	861	1,420	1,820	2,350	2,750	3,160	1982	2,390
	620	1,070	1,430	1,960	2,310	2,760		
	827	1,320	1,700	2,220	2,600	3,030		
304500	1,380	2,390	3,120	4,080	4,820	5,560	1982	4,920
	784	1,440	2,000	2,870	3,510	4,310		
	1,320	2,190	2,840	3,770	4,490	5,250		
310501	675	2,160	3,850	6,980	10,100	14,100	1963	4,640
	1,100	2,090	2,970	4,380	5,450	6,820		
	720	2,140	3,630	6,300	8,900	12,300		
311000	217	552	891	1,480	2,040	2,720	1965	1,390
	274	667	1,120	1,980	2,740	3,750		
	223	576	950	1,610	2,220	2,980		
318000	177	372	539	789	1,000	1,240	1974	982
	199	547	1,000	1,930	2,830	4,070		
	180	422	690	1,170	1,610	2,160		
325000	1,230	1,920	2,410	3,060	3,560	4,070	1975	3,390
	1,690	2,730	3,470	4,530	5,230	6,130		
	1,290	2,120	2,720	3,500	4,050	4,660		

Table 3. Estimated peak discharges for selected recurrence intervals and maximum known discharges at stream-gaging stations on Oahu, Hawaii--*Continued*

Station number	Q_2	Q_5	Q_{10}	Q_{25}	Q_{50}	Q_{100}	Maximum known discharge: Water year	Maximum known discharge: Discharge (ft^3/s)
			(ft^3/s)					
330000	2,540	4,290	5,580	7,320	8,680	10,100	1980	8,540
	2,460	4,510	6,180	8,820	10,800	13,400		
	2,530	4,340	5,730	7,700	9,220	10,900		
331000	69	258	531	1,170	1,970	3,170	1980	2,030
	116	357	705	1,480	2,290	3,430		
	76	286	588	1,270	2,080	3,250		
340000	2,750	5,140	7,280	10,700	13,900	17,600	1974	15,900
	2,520	4,900	6,960	10,300	13,000	16,500		
	2,730	5,090	7,200	10,600	13,700	17,300		
343000	3,990	9,490	14,500	22,500	29,500	37,300	1974	18,200
	2,820	5,330	7,490	10,600	13,300	16,200		
	3,730	8,330	12,000	17,400	21,800	26,500		
345000	1,920	2,880	3,610	4,630	5,470	6,380	1974	5,540
	1,590	2,590	3,310	4,340	5,020	5,900		
	1,880	2,820	3,530	4,550	5,350	6,260		
350000	1,620	3,080	4,340	6,270	7,980	9,940	1974	7,600
	1,060	2,200	3,300	5,170	6,710	8,700		
	1,560	2,900	4,090	6,000	7,670	9,650		

Table 4. Drainage-basin and climatic characteristics for gaged basins on Oahu, Hawaii

[Hydrologic regions shown in fig. 1: 1, leeward; 2, windward; 3, north; BW, basin width; CL, channel length; CLD, shape factor; DA, standard drainage area; DAG, GIS drainage area; E, mean basin elevation; FC, forest cover; MR, meander ratio; P, median annual rainfall; P224, 2-year, 24-hour rainfall intensity; PA, shape factor; PER, basin perimeter; RF, shape factor; UC, urban cover; mi, mile; --, dimensionless; ft/mi, foot per mile; mi^2, square mile; ft, foot; %, percent; in, inch]

Station number	Hydrologic region	BW (mi)	CL (mi)	CLD (--)	CS (ft/mi)	DA (mi^2)	DAG (mi^2)	E (ft)	FC (%)	MR (--)	P (in)	P224 (in)	PA (1/mi)	PER (mi)	RF (--)	UC (%)
200000	1	0.291	4.72	3.57	170	1.38	1.37	1,710	100	1.90	239	8.78	4.57	6.26	0.061	0
201000	1	0.361	3.20	2.64	246	1.20	1.15	1,860	100	1.67	237	8.59	4.30	4.96	0.112	0
204000	1	0.476	10.2	4.10	79	4.86	4.86	1,560	100	1.99	189	7.78	2.54	12.4	0.047	0
206000	1	0.353	5.53	3.51	140	1.93	1.95	1,700	100	1.98	231	8.23	3.50	6.81	0.064	0
208000	1	0.353	11.6	5.07	81	4.04	4.08	1,480	99	3.32	176	7.29	3.44	14.0	0.030	0
208500	1	0.263	3.30	3.14	131	0.86	0.87	1,310	89	1.85	105	6.43	5.13	4.46	0.080	0
210500	1	1.47	26.4	3.76	55	38.7	38.7	1,240	68	1.60	82	6.20	1.05	40.7	0.056	7
211200	1	0.598	21.3	5.29	73	12.7	12.7	1,040	42	1.59	74	6.03	2.29	29.2	0.028	0
211300	1	1.08	3.82	1.67	583	4.15	4.11	1,350	98	1.07	64	6.03	2.32	9.53	0.282	0
211500	1	1.04	4.04	1.75	356	4.24	4.22	1,180	79	1.15	52	4.82	2.53	10.7	0.258	0
211600	1	0.719	3.17	1.86	1,160	2.31	2.28	2,110	91	1.17	61	5.92	3.37	7.68	0.227	0
211700	1	0.895	5.86	2.27	560	5.25	5.24	1,760	91	1.15	47	5.11	2.35	12.3	0.152	0
211800	1	1.41	2.57	1.20	848	3.58	3.62	1,860	95	1.12	52	5.49	2.17	7.86	0.548	0
212200	1	0.671	2.23	1.62	490	1.51	1.50	1,190	93	1.02	42	4.97	3.64	5.44	0.302	0
212300	1	1.14	3.47	1.54	585	3.98	3.98	1,100	82	1.12	29	4.72	2.10	8.38	0.330	0
212450	1	0.503	3.35	2.29	506	1.70	1.68	1,070	34	1.17	35	4.91	3.83	6.44	0.150	0
212500	1	1.410	7.82	2.09	158	11.0	11.0	1,110	43	1.18	40	4.94	1.42	15.7	0.180	0
212601	1	0.872	7.29	2.56	81	6.35	6.35	1,250	64	1.48	50	5.45	2.04	12.9	0.119	3
212700	1	0.432	16.5	5.48	59	7.49	7.14	1,070	52	1.72	100	6.02	2.96	21.1	0.026	4
212800	1	0.484	8.93	3.81	128	4.29	4.32	1,590	100	1.95	187	7.26	2.60	11.2	0.054	0
213000	1	1.93	24.0	3.13	65	45.7	46.2	982	48	1.55	71	5.35	0.893	41.3	0.080	6
216000	1	2.16	11.9	2.08	116	26.4	25.7	929	70	1.40	97	5.69	0.952	24.6	0.181	6
216500	1	0.514	5.16	2.81	202	2.63	2.65	534	57	1.13	51	4.97	3.88	10.3	0.099	32
223000	1	0.616	9.69	3.52	129	5.97	5.97	1,100	96	1.44	111	6.35	2.60	15.5	0.064	2
224500	1	0.346	7.42	4.11	213	2.59	2.57	1,050	89	1.22	97	6.05	5.65	14.5	0.047	6
226000	1	0.652	5.26	2.52	240	3.45	3.43	1,450	100	1.36	127	6.83	2.77	9.48	0.123	0
227000	1	1.020	8.68	2.59	137	8.78	8.81	1,000	82	1.28	92	5.96	1.79	15.8	0.117	7
228000	1	0.580	4.67	2.51	216	2.73	2.71	1,280	100	1.41	124	7.48	2.90	7.85	0.124	0
228200	1	0.590	5.50	2.71	194	3.34	3.24	1,190	100	1.26	117	7.18	2.88	9.33	0.107	0
228500	1	0.609	6.90	2.98	159	4.16	4.20	1,020	93	1.29	103	6.70	2.89	12.1	0.088	4
228600	1	0.612	7.26	3.05	149	4.44	4.44	979	91	1.29	99	6.59	2.94	13.1	0.084	6
228900	1	0.410	1.38	1.63	891	0.60	0.56	1,650	100	1.14	119	8.40	5.95	3.36	0.296	0
229000	1	0.921	2.84	1.56	263	2.61	2.61	1,310	96	1.11	120	7.05	2.65	6.93	0.323	1
229300	1	0.920	5.72	2.21	182	5.18	5.26	1,020	78	1.10	100	6.13	2.18	11.5	0.160	18
235400	1	0.531	2.30	1.84	412	1.28	1.22	1,050	56	1.07	93	5.96	4.46	5.45	0.230	28
237500	1	0.422	3.35	2.50	453	1.43	1.42	765	68	1.14	83	6.51	4.81	6.79	0.127	28
238500	1	0.556	2.06	1.71	1,196	1.14	1.15	1,560	97	1.05	114	8.61	4.58	5.25	0.270	0
240500	1	0.656	1.62	1.39	1,060	1.06	1.06	1,400	97	1.11	111	8.51	4.22	4.47	0.404	0
244000	1	0.486	2.45	1.99	527	1.18	1.19	1,360	89	1.12	98	7.73	4.44	5.31	0.198	4
246000	1	0.422	2.46	2.14	603	1.04	1.04	1,300	97	1.10	92	7.66	5.55	5.76	0.172	2

Table 4. Drainage-basin and climatic characteristics for gaged basins on Oahu, Hawaii--*Continued*

Station number	Hydrologic region	BW (mi)	CL (mi)	CLD (--)	CS (ft/mi)	DA (mi^2)	DAG (mi^2)	E (ft)	FC (%)	MR (--)	P (in)	P224 (in)	PA (1/mi)	PER (mi)	RF (--)	UC (%)
247000	1	0.829	4.38	2.04	280	3.63	3.63	1,060	74	1.09	78	6.61	2.62	9.53	0.189	24
247100	1	1.87	5.65	1.54	323	10.6	10.6	916	68	1.03	82	6.42	1.40	14.8	0.332	30
247200	1	0.387	4.41	2.99	369	1.75	1.71	1,030	83	1.05	60	6.09	5.35	9.12	0.088	15
247500	1	0.894	2.69	1.54	690	2.35	2.40	1,270	91	1.06	55	6.39	2.79	6.69	0.332	4
247900	1	0.545	2.26	1.80	673	1.18	1.23	985	86	1.07	46	6.30	4.16	5.12	0.240	6
248800	2	0.611	1.97	1.59	383	1.21	1.20	397	67	1.13	52	7.00	3.98	4.78	0.309	0
249000	2	0.659	3.25	1.97	172	2.16	2.14	505	68	1.40	71	6.78	3.11	6.65	0.203	0
249100	2	0.179	0.881	1.97	893	0.16	0.16	526	78	1.19	55	5.62	12.9	2.04	0.204	0
254000	2	0.722	2.86	1.77	312	2.04	2.07	526	80	1.22	83	7.03	3.26	6.74	0.253	0
260500	2	1.26	4.37	1.65	173	5.34	5.50	657	84	1.20	84	7.39	1.79	9.85	0.288	3
265000	2	0.630	1.98	1.57	175	1.19	1.25	200	33	1.14	69	5.97	4.08	5.08	0.319	36
270900	2	0.438	1.01	1.34	2,120	0.44	0.44	1,540	96	1.12	108	9.10	6.41	2.83	0.433	0
273900	2	0.632	6.69	2.88	57	4.38	4.22	554	69	1.66	90	8.01	2.79	11.8	0.094	12
274499	2	0.309	1.94	2.22	210	0.62	0.60	236	42	1.11	78	6.74	6.62	3.97	0.159	29
275000	2	0.826	1.19	1.07	1,400	0.97	0.98	1,160	85	1.05	108	8.59	4.07	4.00	0.696	0
278000	2	0.420	0.681	1.13	3,220	0.29	0.29	1,360	100	1.02	99	7.16	7.19	2.06	0.617	0
279500	2	0.839	2.20	1.44	352	1.80	1.85	951	82	1.11	98	7.78	3.09	5.70	0.382	1
283000	2	0.468	0.585	0.991	3,190	0.28	0.27	1,310	100	1.03	116	7.63	8.20	2.24	0.800	0
283480	2	0.885	2.53	1.50	512	2.31	2.24	399	70	1.13	80	6.48	2.84	6.35	0.350	17
283600	2	0.086	0.338	1.76	4,890	0.03	0.03	1,200	100	1.02	137	8.24	27.8	0.802	0.254	0
283700	2	0.094	0.342	1.70	4,370	0.03	0.03	1,700	100	1.05	146	8.31	27.0	0.865	0.274	0
284000	2	0.759	1.13	1.08	1,430	0.93	0.86	1,160	100	1.05	123	7.98	4.63	3.97	0.673	0
284200	2	0.727	1.23	1.15	1,300	0.97	0.89	1,140	100	1.04	123	7.94	4.63	4.12	0.589	0
291000	2	0.749	1.41	1.22	1,010	0.99	1.06	1,240	100	1.13	139	8.03	3.89	4.10	0.533	0
294900	2	0.830	2.71	1.60	483	2.22	2.25	999	99	1.19	126	7.93	2.89	6.49	0.306	0
296500	3	0.883	4.49	2.06	189	3.74	3.74	835	100	1.40	197	9.04	2.36	8.81	0.186	0
303000	3	0.884	3.15	1.67	426	2.78	2.78	1,280	100	1.18	195	8.55	2.60	7.25	0.280	0
304200	3	0.331	3.40	2.84	901	1.11	1.13	1,810	96	1.38	167	7.70	5.29	5.97	0.098	0
304500	3	0.509	4.22	2.55	758	2.12	2.15	1,280	92	1.32	141	7.28	3.51	7.53	0.121	0
310501	3	0.785	5.15	2.27	337	4.05	4.04	794	93	1.40	103	7.00	2.78	11.2	0.152	0
311000	3	0.378	6.01	3.54	265	2.13	2.27	709	85	1.40	67	6.08	4.33	9.81	0.063	0
318000	3	0.627	4.15	2.28	244	2.59	2.60	550	86	1.31	66	5.59	3.13	8.15	0.151	0
325000	3	0.327	9.64	4.82	136	3.13	3.15	1,320	100	2.06	183	7.83	3.31	10.4	0.034	0
330000	3	0.760	12.9	3.65	137	9.79	9.80	1,080	99	1.76	140	7.05	1.69	16.6	0.059	0
331000	3	0.363	6.02	3.61	170	2.23	2.19	708	71	1.29	67	5.21	4.65	10.2	0.060	0
340000	3	0.932	14.6	3.51	121	13.5	13.6	1,330	91	1.57	140	6.75	1.67	22.7	0.064	0
343000	1	0.643	22.0	5.19	93	14.2	14.2	1,210	68	1.80	100	6.33	1.90	27.0	0.029	0
345000	3	0.237	12.7	6.48	79	2.98	3.00	1,900	100	2.38	177	7.81	4.36	13.1	0.019	0
350000	3	0.258	23.2	8.41	87	5.96	5.97	1,340	82	1.97	118	6.57	4.52	27.1	0.011	0