ESTIMATION OF MEDIAN STREAMFLOWS AT PERENNIAL STREAM SITES IN HAWAII

By Richard A. Fontaine, Michael F. Wong, and Iwao Matsuoka

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Multiply	By	To obtain
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
mile, statute (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

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ABSTRACT

The most accurate estimates of median streamflows at perennial stream sites in Hawaii are those made at streamflow-gaging stations. Two alternative methods for estimating median streamflows at ungaged sites are described in this report. Multiple-regression equations were developed for estimating median streamflows at ungaged, unregulated, perennial stream sites. The equations relate combinations of drainage area, mean altitude of the main stream channel, and mean annual precipitation to median streamflow. Streamflow data from 56 long-term continuous-record gaging stations were used in the analysis. Median-streamflow data for all 56 sites were adjusted using record-extension techniques to reflect base period (1912 through 1986) conditions.

Hawaii was subdivided into two geographic groups and multiple-regression equations were developed for each. The standard error of prediction for the equation developed for the first group, the islands of Oahu, Molokai, and Hawaii, is 41 percent. The standard error of prediction for the equation developed for the second group, the islands of Kauai and Maui, is 54 percent.

A method for estimating median-streamflow, based on discharge measurements and data from nearby streamflow-gaging stations, was also developed for 27 regulated, perennial windward Oahu sites. Standard errors of prediction for 23 of the sites range from 5 to 34 percent. Median-streamflow estimates for the four remaining sites were considered poor and no measures of accuracy are provided. Discharge measurements can be used to make estimates of median streamflows at ungaged, regulated sites where the regression equations developed in this report are not applicable. Discharge measurements can also be used to make estimates of median streamflows at ungaged, unregulated sites. Estimates of median streamflows based on discharge measurements have greater standard errors than estimates based on continuous streamflow records and in general have smaller standard errors than estimates based on regression equations.

INTRODUCTION

Background

In Hawaii serious concerns exist over possible water shortages and uncertainty over ownership of water. In an attempt to deal with these problems, the Hawaii State Constitutional Convention of 1978 opted for a State Water Code. In 1982, the State legislature created the Advisory Study Commission on Water Resources to develop a State Water Code "to recognize, clarify, and systematize legal concepts relating to water resources" (Lee and Valenciano, 1986, p. 201). In 1987 the State Water Code was passed by the Hawaii State Legislature. General administration of the Code was assigned to the Commission on Water Resources Management.

Part VI of the State Water Code of 1987 calls for the protection of instream uses of water. To protect instream uses, the Commission needed to specify minimum streamflows or depths of water required in a stream to protect fishery, wildlife, recreational, aesthetic, scenic, and other beneficial uses (Yuen, 1990, p. V-37). According to the Code, beneficial instream uses include, but are not limited to (1) maintenance of fish and wildlife habitats, (2) outdoor recreational activities, (3) maintenance of ecosystems such as estuaries, wetlands, and stream vegetation, (4) aesthetic values such as waterfalls and scenic waterways, (5) navigation, (6) instream hydropower generation, (7) maintenance of water quality, (8) the conveyance of irrigation and domestic water supplies to downstream points of diversion, and (9) the protection of traditional and customary Hawaiian Rights (Yuen, 1990, p. V-37).

The Commission on Water Resource Management, Department of Land and Natural Resources selected median streamflow as the quantitative basis for establishing standards. Median streamflow is defined as a rate of flow that is equaled or exceeded 50 percent of the time at a particular location. In 1987, the Department of Land and Natural Resources entered into a cooperative study with the U.S. Geological Survey to estimate median streamflows at perennial stream sites in Hawaii.

Purpose and Scope

This report describes techniques for estimating the median streamflow for ungaged, perennial stream sites in Hawaii that are either unregulated or regulated. The report also provides median-streamflow estimates at selected partial-record, regulated stream sites in windward Oahu.

To provide a methodology for estimating median streamflow for ungaged, perennial stream sites, daily streamflow data collected in Hawaii since 1909 at a total of 664 sites were reviewed. A total of 56 stations were selected from the data base representing sites where flows were both perennial and unregulated. Multiple regression analyses relating median streamflow at the 56 stations to selected basin characteristics were conducted. The regression equations developed can be used to estimate median streamflow for ungaged, unregulated, perennial streams on the islands of Kauai, Oahu, Molokai, Maui, and Hawaii.

To provide median-streamflow estimates at 27 partial-record, regulated, perennial stream sites located in windward Oahu, about 12 discharge measurements per site were made over a 3-year period. In addition, historic data files were reviewed to locate any existing data for the sites. Discharge measurements at each site were correlated with data available at nearby, hydrologically similar, continuous-record stations. Median streamflow at the continuous-record stations and the relations established between the partial-record and continuous-record stations were used to estimate median streamflow for the partial-record stations. The techniques applied at the 27 windward Oahu sites can be used to provide median-streamflow estimates at both unregulated and regulated perennial stream sites in Hawaii.

ESTIMATION OF MEDIAN STREAMFLOWS AT UNGAGED, UNREGULATED, PERENNIAL SITES

Median streamflow can be reliably determined from long-term continuous records, but data cannot be collected at all sites where information might be needed. Other methods that are based on existing data can be used to estimate median streamflows at ungaged sites. Thomas and Benson (1970) demonstrated that a practical estimation method is to relate streamflow characteristics at gaged sites to basin characteristics by multiple-regression analysis. Results of the regression analyses then can be extended to estimate streamflow characteristics at the ungaged sites based on easily determined basin characteristics. Characteristics used in the multiple-regression analyses, the resulting equations, and the accuracy and limitations of the equations are discussed in the following sections.

Selection of Data for Analyses

To apply multiple-regression techniques a data set composed of streamflow and basin characteristics for gaged sites was compiled. To develop this data set it was necessary to screen all sites where data were available to determine which were appropriate for inclusion. Once sites were selected, the streamflow characteristics of interest (in this case median streamflow) and the significant basin characteristics for each of the selected gaged basins were determined.

Site Selection

Estimates of median streamflows at ungaged, unregulated, perennial stream sites were based on data from unregulated and perennial continuous-record stations. Unregulated streamflow stations are defined as those having no identified diversions upstream from the gage. An exception to this rule is where the diverted flows upstream from the streamflow station are gaged. Here it is possible to add diverted flows to data from the gage and, therefore, reconstruct what unregulated flows at the gage would have been. Perennial streamflow stations are defined as those that have a minimum of 10 years of record and have no zero-flow days.

Available surface-water data for the period 1910-1979 in Hawaii have been summarized by Matsuoka (1981 and 1983). In addition the U.S. Geological Survey (USGS) (1980-87) has published data collected since 1979 in a series of annual data reports. In these reports, data-collection stations are listed and information including the period of record, the existence of upstream diversions or regulation, and if zero-flow days have occurred are provided. A total of 664 stations have been gaged for some period of time between 1910 and

1986, and 112 of these can be considered unregulated. Included in the 112 stations is one, Punaluu Stream near Punaluu, Oahu (station 16303000) where the upstream diversions were gaged and therefore unregulated flows can be accurately reconstructed.

The 112 unregulated stations were then screened to determine those that also met the perennial-flow criteria. Only 56 of the stations had at least 10 years of record and no zero-flow days. The 56 stations considered unregulated, perennial gages that were be used in this study and their periods of record are listed in table 1. Locations of the 56 streamflow-gaging stations are shown in figures 1 through 5.

Median-Streamflow Data

A flow-duration curve is a cumulative frequency curve that indicates the percentage of time specified discharges were equaled or exceeded during a set time period (Searcy, 1959, p.1). In this study the flow-duration statistic of interest is the median or the streamflow that is equaled or exceeded 50 percent of the time.

Median streamflows computed for the 56 gaging stations listed in table 1 were compared with each other as part of the regression analyses and will also be used as estimates of future streamflow conditions. Accurate comparison of median streamflows assumes that data are based on concurrent periods of record. Dissimilarities between median streamflows at gages will then be due to differences in climatic or drainage-basin characteristics and not because the records cover different periods of time (Searcy, 1959, p. 12). Median streamflow computed for the period of record at a gaging station has no time-sampling error because the median statistic was based on the entire population of daily mean discharges for the period. When median-streamflow estimates are used as predictors of future streamflow conditions, time-sampling errors may become significant. To minimize the time-sampling errors, records from long-term stations should be used. Calculated median streamflow for short-term stations can be improved by adjusting the flow to represent longer periods (Searcy, 1959, p. 12).

The problem becomes one of selecting a long-term or base period during which physical conditions have remained essentially the same and is of a sufficient length to be used to represent future streamflow conditions without significant error. The base period needs to be selected such that an adequate number of the 56 selected gages have the equivalent of complete record for the entire base period. Gages with complete, long-term records for the base period will be considered as index stations and their records will be used to adjust records from the remaining stations. Index stations therefore need to have common or concurrent periods of record with all short-term stations with which they are to be correlated.

Table 1.--*Unregulated, perennial streamflow-gaging stations used in the regression analyses*

[p, station in operation as of end of water year 1986; ft, feet]

Station number	Latitude	Longitude	Station name	Period of record
			Island of Kauai	
16010000	22°08'09"	159°37'22"	Kawaikoi Stream near Waimea	1909-1916; 1919-p
16013000	22°07'13"	159°36'14"	Mohihi Stream at altitude 3,420 ft, near Waimea	1920-1926; 1936-1971
16017000	22°06'57"	159°33'53"	Koaie Stream at altitude 3,770 ft, near Waimea	1919-1932; 1954-1968
16019000	22°05'20"	159°34'18"	Waialae Stream at altitude 3,820 ft, near Waimea	1920-1932; 1952-p
16068000	22°04'19"	159°25'05"	East Branch of North Fork Wailua River near Lihue	1912-p
16071500	22°04'44"	159°23'55"	Left Branch Opaekaa Stream near Kapaa	1960-p
16097500	22°10'54"	159°25'17"	Halaulani Stream at altitude 400 ft, near Kilauea	1957-p
16105000	22°10'15"	159°29'53"	Waioli Stream near Hanalei	1914-1932
16106000	22°09'05"	159°31'40"	Lumahai River near Hanalei	1914-1917; 1920-1933
16108000	22°08'20"	159°33'38"	Wainiha River near Hanalei	1952-1956; 1957-p
16115000	22°11'20"	159°35'50"	Hanakapiai Stream near Hanalei	1931-1952
16116000	22°11'00"	159°37'35"	Hanakoa Stream near Hanalei	1931-1952
16117000	22°09'50"	159°38'15"	Kalalau Stream near Hanalei	1931-1955
			Island of Oahu	
16200000	21°31'09"	157°56'53"	North Fork Kaukonahua Stream above Right Branch, near Wahiawa	1913-1953; 1960-p
16201000	21°31'10"	157°56'55"	Left Branch of North Fork Kaukonahua Stream near Wahiawa	1913-1953
16206000	21°30'05"	157°56'50"	South Fork Kaukonahua Stream near Wahiawa	1913-1917; 1944-1957
16303003	21°33'33"	157°54'06"	Combined records of stations 16302000, Punaluu Ditch, and 16303000, Punaluu Stream near Punaluu	1953-p
			Island of Molokai	
16400000	21°09'31"	156°45'53"	Halawa Stream near Halawa	1917-1932; 1937-p
16402000	21°07'35"	156°49'50"	Pulena Stream near Wailau	1919-1928; 1937-1957
16403000	21°07'25"	156°49'45"	Waiakeakua Stream near Wailau	1919-1929; 1937-1957
16403900	21°07'59"	156°52'38"	Kawainui Stream near Pelekunu	1968-1980

Table 1.--*Unregulated, perennial streamflow-gaging stations used in the regression analyses*--Continued

[p, station in operation as of end of water year 1986; ft, feet]

Station number	Latitude	Longitude	Station name	Period of record
			Island of Molokai--continued	
16404000	21°08'11"	156°52'43"	Pelekunu Stream near Pelekunu	1919-1929; 1937-1957; 1971-1982
16404200	21°08'08"	156°53'09"	Pilipililau Stream near Pelekunu	1968-p
16405000	21°08'38"	156°52'26"	Lanipuni Stream near Pelekunu	1919-1929; 1937-1957
16416000	21°05'50"	156°48'48"	Punaula Gulch near Pukoo	1947-1972
			Island of Maui	
16502000	20°40'55"	156°02'50"	Hahalawe Gulch near Kipahulu	1927-1969
16508000	20°48'37"	156°07'00"	Hanawi Stream near Nahiku	1914-1916; 1921-p
16510000	20°48'46"	156°07'05"	Kapaula Gulch near Nahiku	1921-1963
16515000	20°49'05"	156°07'45"	Waiohue Gulch near Nahiku	1921-1963
16516000	20°49'05"	156°08'12"	Kopiliula Stream near Keanae	1914-1917; 1921-1958
16517000	20°49'03"	156°08'26"	East Wailuaiki Stream near Keanae	1913-1917; 1922-1958
16518000	20°49'16"	156°08'37"	West Wailuaiki Stream near Keanae	1914-1917; 1921-p
16519000	20°49'40"	156°08'53"	West Wailuaiki Stream near Keanae	1913-1917; 1922-1958
16520000	20°49'24"	156°08'37"	East Wailuaiki Stream near Keanae	1914-1917; 1921-1958
16524000	20°49'17"	156°12'14"	Homomanu Stream at Haiku-uka boundary near Kailiili	1919-1927; 1932-1934; 1962-1968
16527000	20°50'07"	156°11'18"	Homomanu Stream near Keanae	1913-1964
16557000	20°51'46"	156°11'49"	Alo Stream near Huelo	1910-1957
16565000	20°52'02"	156°12'17"	Kaaiea Gulch near Huelo	1921-1962
16566000	20°52'17"	156°12'29"	Oopuola Stream near Huelo	1930-1957
16577000	20°52'35"	156°13'25"	Kailua Stream near Huelo	1910-1911; 1913-1918; 1919-1958
16585000	20°53'14"	156°14'52"	Hoolawanui Stream near Huelo	1910-1971
16586000	20°53'17"	156°14'35"	Hoolawaliilii Stream near Huelo	1912-1957
16587000	20°53'20"	156°15'20"	Honopou Stream near Huelo	1910-p
16618000	20°58'54"	156°33'26"	Kahakuloa Stream near Honokohau	1939-1943; 1947-1970; 1974-p
16620000	20°57'48"	156°35'22"	Honokohau Stream near Honokohau	1913-1920; 1922-1988
16636000	20°53'45"	156°38'40"	Kanaha Stream above pipeline intake, near Lahaina	1916-1925; 1926-1932

Table 1.--*Unregulated, perennial streamflow-gaging stations used in the regression analyses*--Continued

[p, station in operation as of end of water year 1986; ft, feet]

Station number	Latitude	Longitude	Station name	Period of record
			Island of Hawaii	
16717000	19°46'00"	155°09'16"	Honolii Stream near Papaikou	1911-1913; 1967-p
16717800	19°57'20"	155°11'20"	Pohakupuka Stream near Papaaloa	1962-1979
16720000	20°05'18"	155°40'58"	Kawainui Stream near Kamuela	1964-p
16720300	20°05'13"	155°40'59"	Kawaiki Stream near Kamuela	1968-p
16737000	20°07'46"	155°39'51"	Waiilikahi Stream near Waimanu	1939-1960
16739000	20°08'50"	155°39'46"	Punalulu Stream near Waimanu	1939-1952
16740000	20°09'05"	155°39'58"	Waiaalala Stream near Waimanu	1939-1952
16741000	20°09'05"	155°40'09"	Paopao Stream near Waimanu	1939-1952
16742000	20°09'15"	155°40'15"	Kukui Stream near Waimanu	1939-1952; 1959-1966
16757000	20°03'17"	155°40'01"	Waikoloa Stream near Kamuela	1947-1971

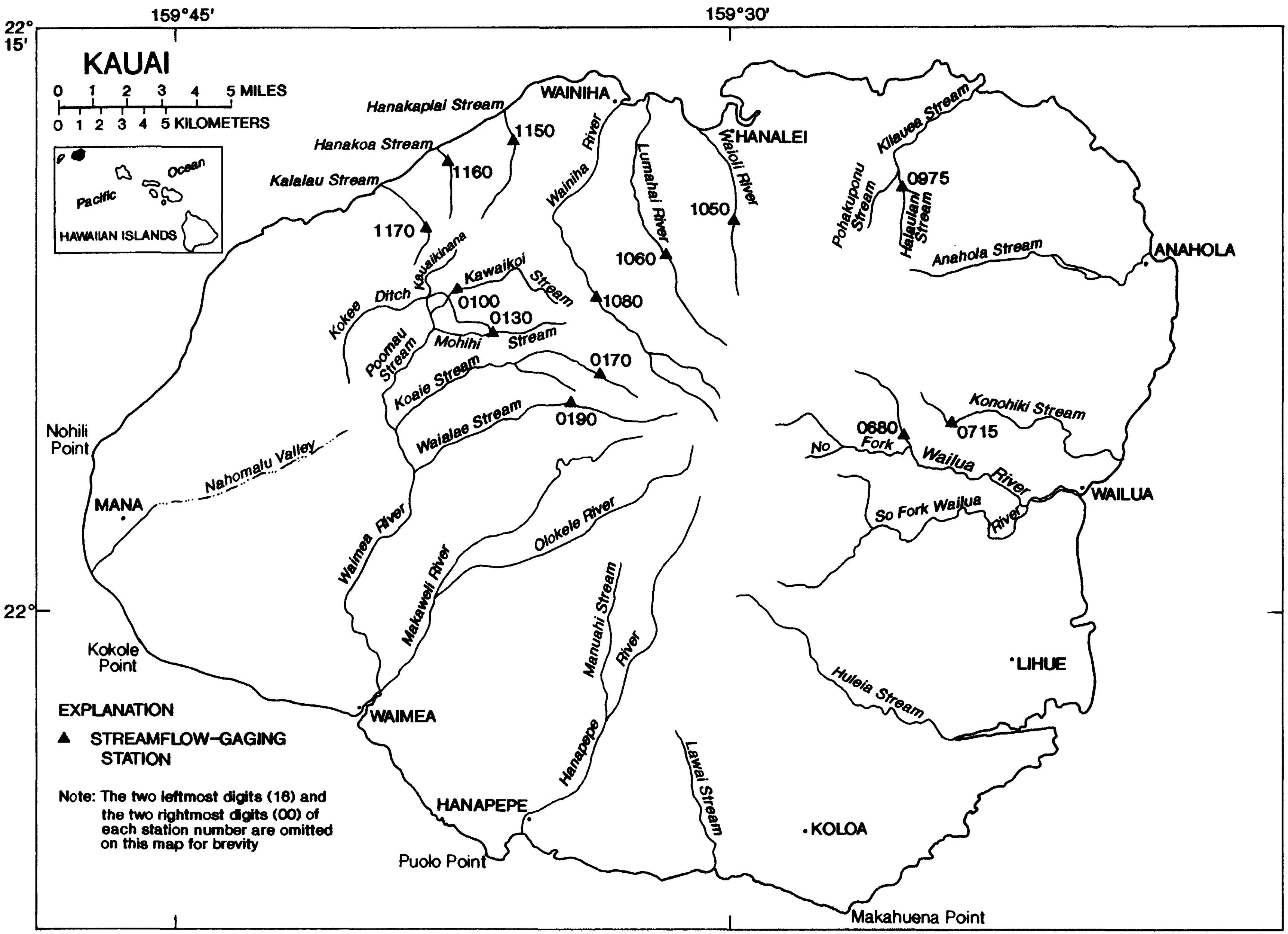

Figure 1. Locations of unregulated, perennial streamflow-gaging stations used in the regression analyses, island of Kauai.

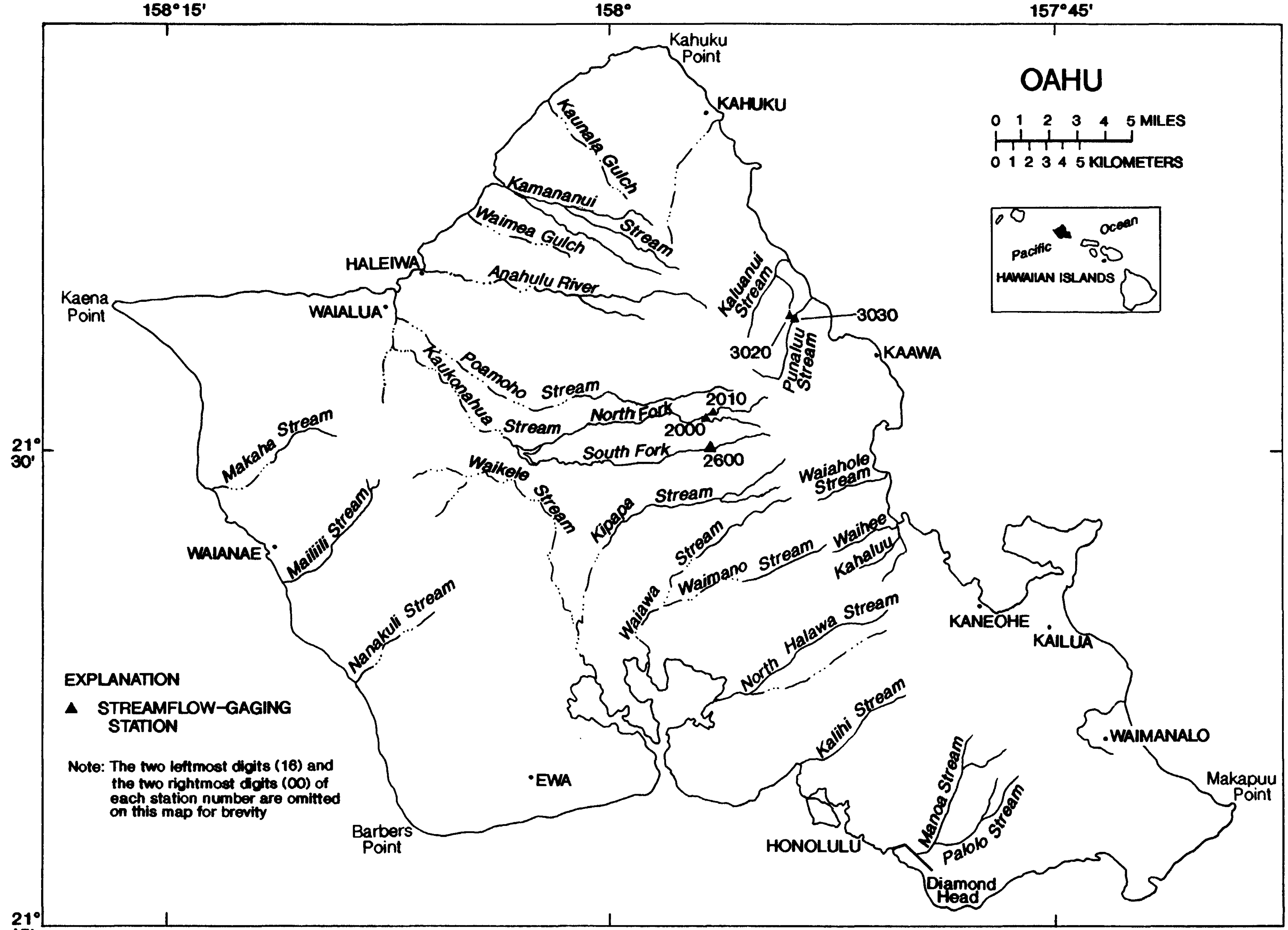

Figure 2. Locations of unregulated, perennial streamflow-gaging stations used in the regression analyses, island of Oahu.

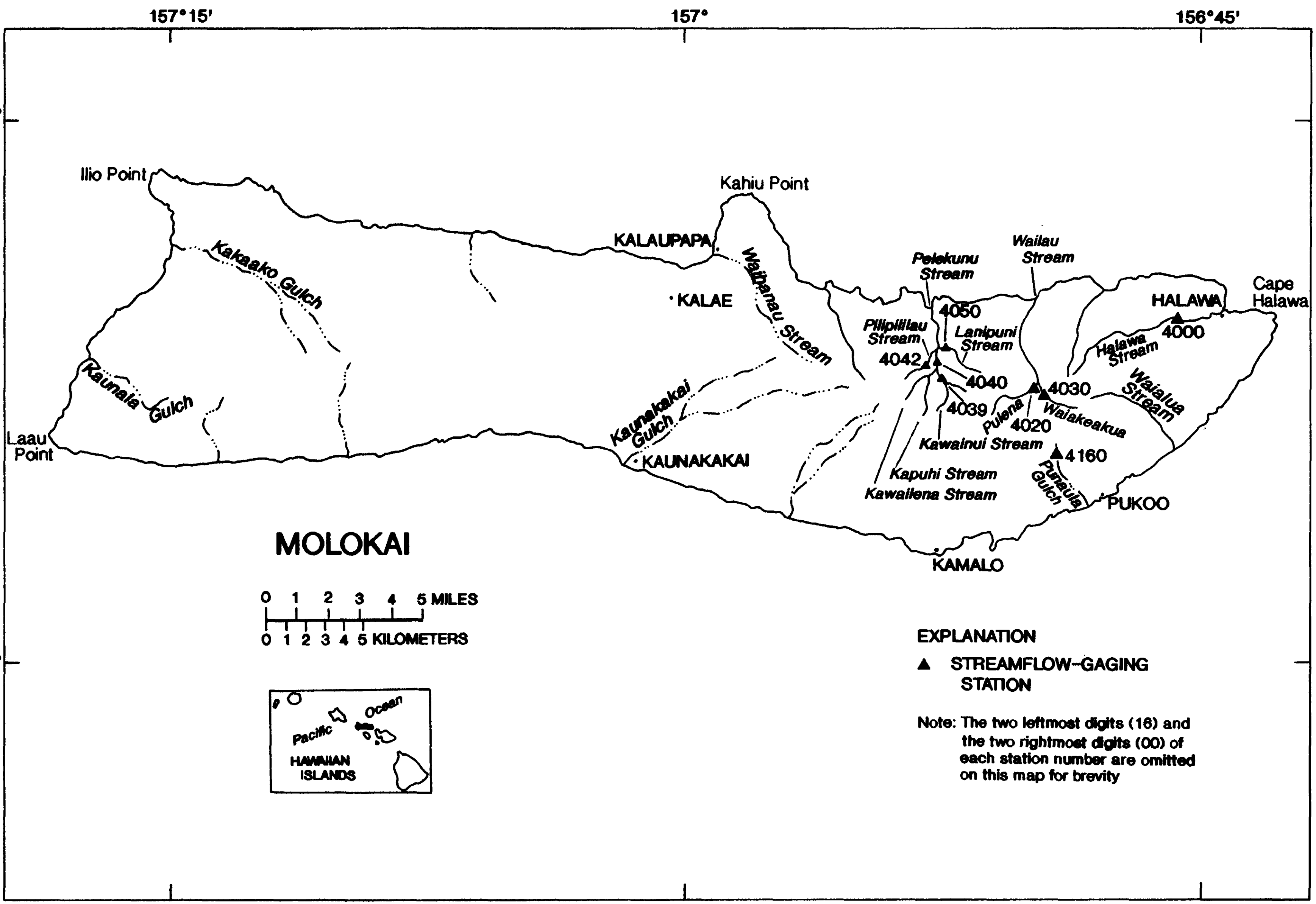

Figure 3. Locations of unregulated, perennial streamflow-gaging stations used in the regression analyses, island of Molokai.

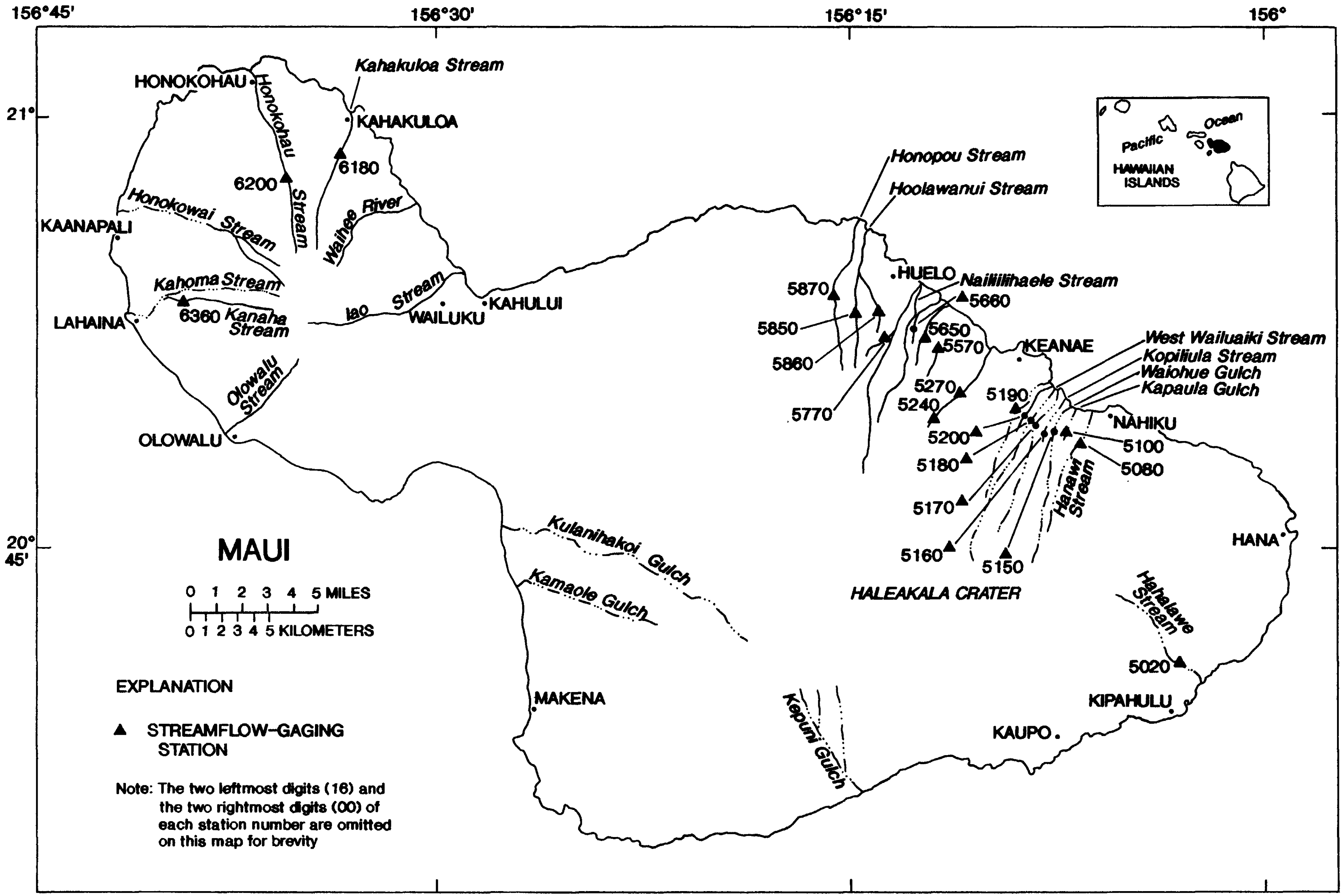

Figure 4. Locations of unregulated, perennial streamflow-gaging stations used in the regression analyses, island of Maui.

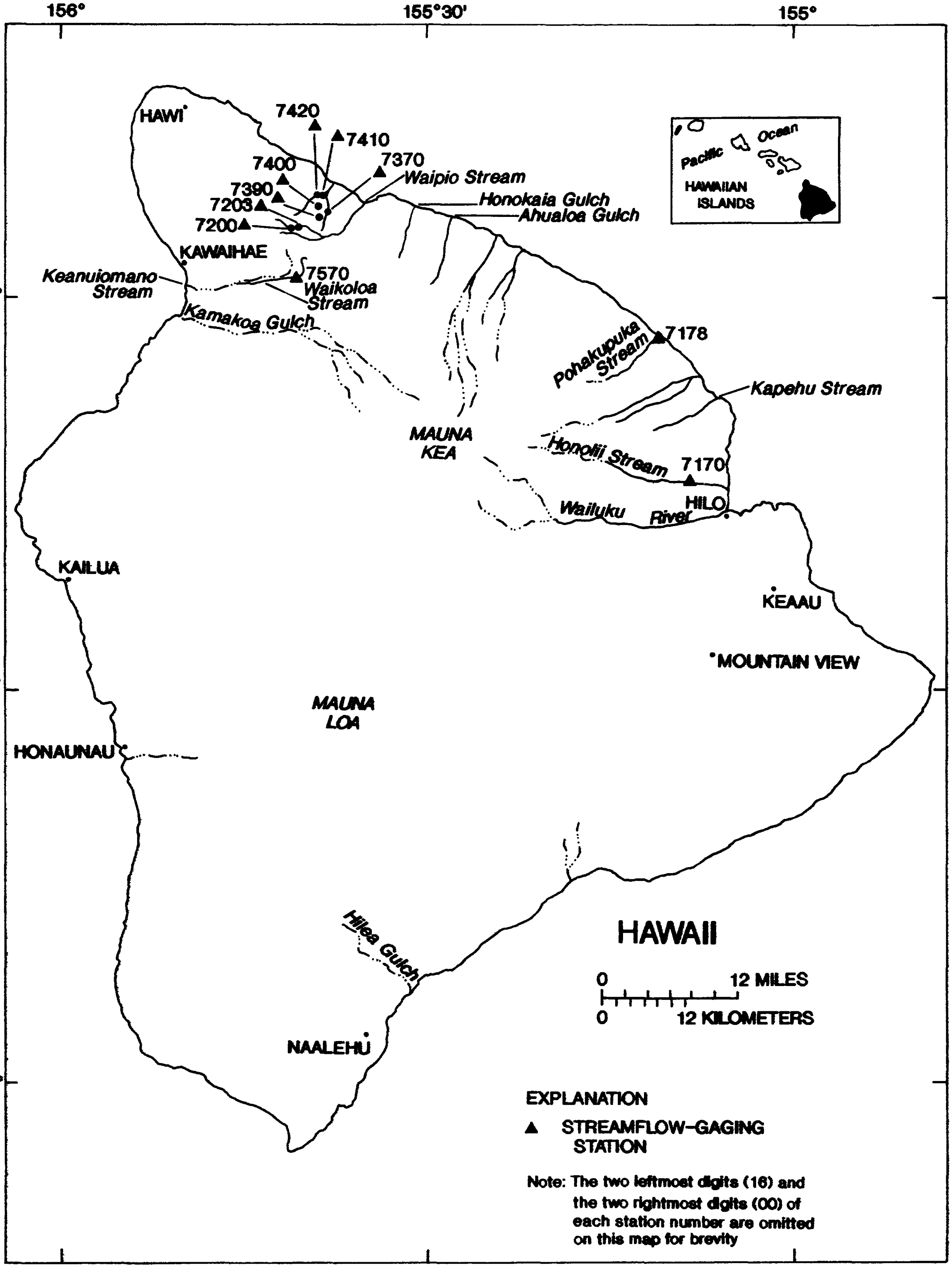

Figure 5. Locations of unregulated, perennial streamflow-gaging stations used in the regression analyses, island of Hawaii.

Periods of record for the 56 stations listed in table 1 vary considerably, making the process of selecting a base period difficult. To facilitate the analysis, water years with complete records during the period 1910 through 1986, for each of the 56 stations were compared graphically (fig. 6). Water years are the 12-month periods that run from October 1 through September 30. Data shown in figure 6 indicate that, to avoid eliminating any of the 56 stations, the base period should span as much of the period from 1910 through 1986 as possible. For example, if the base period did not include at least part of the period 1940 through 1986, none of the 10 stations on the island of Hawaii would have concurrent record and would therefore be eliminated from the analyses.

Station 16587000 has the longest, complete period of record (75 years) of the 56 stations shown in figure 6. Data from station 16587000 were analyzed to determine how much of the station's period of record would be used as the base period and which of the remaining stations qualified as index stations. Median streamflows were computed for the entire period of record at station 16587000 and for numerous combinations of a variety of short-term periods. The range of median streamflows computed and the standard errors of median base period or long-term estimates based on the variety of short-term periods evaluated are shown in table 2. Data in table 2 clearly demonstrate how

Table 2.--*Comparison of long-term median streamflow for the period 1912 through 1986 at station 16587000, Honopou Stream near Huelo, Maui, to that computed for a variety of short-term periods*

[ft^3/s, cubic feet per second]

Length of period (years)	Number of periods evaluated	Range of median streamflow estimates (ft^3/s)	Standard error (percent)
75	1	2.5	0.0
70	3	2.4 - 2.5	2.8
65	3	2.4 - 2.5	4.0
60	4	2.4 - 2.6	4.6
50	6	2.3 - 2.7	6.4
40	6	2.2 - 2.7	7.8
30	6	2.2 - 2.8	10.1
20	7	2.0 - 2.8	12.0
10	8	1.9 - 3.0	15.4
5	15	1.7 - 4.0	24.2
1	16	0.9 - 7.7	69.7

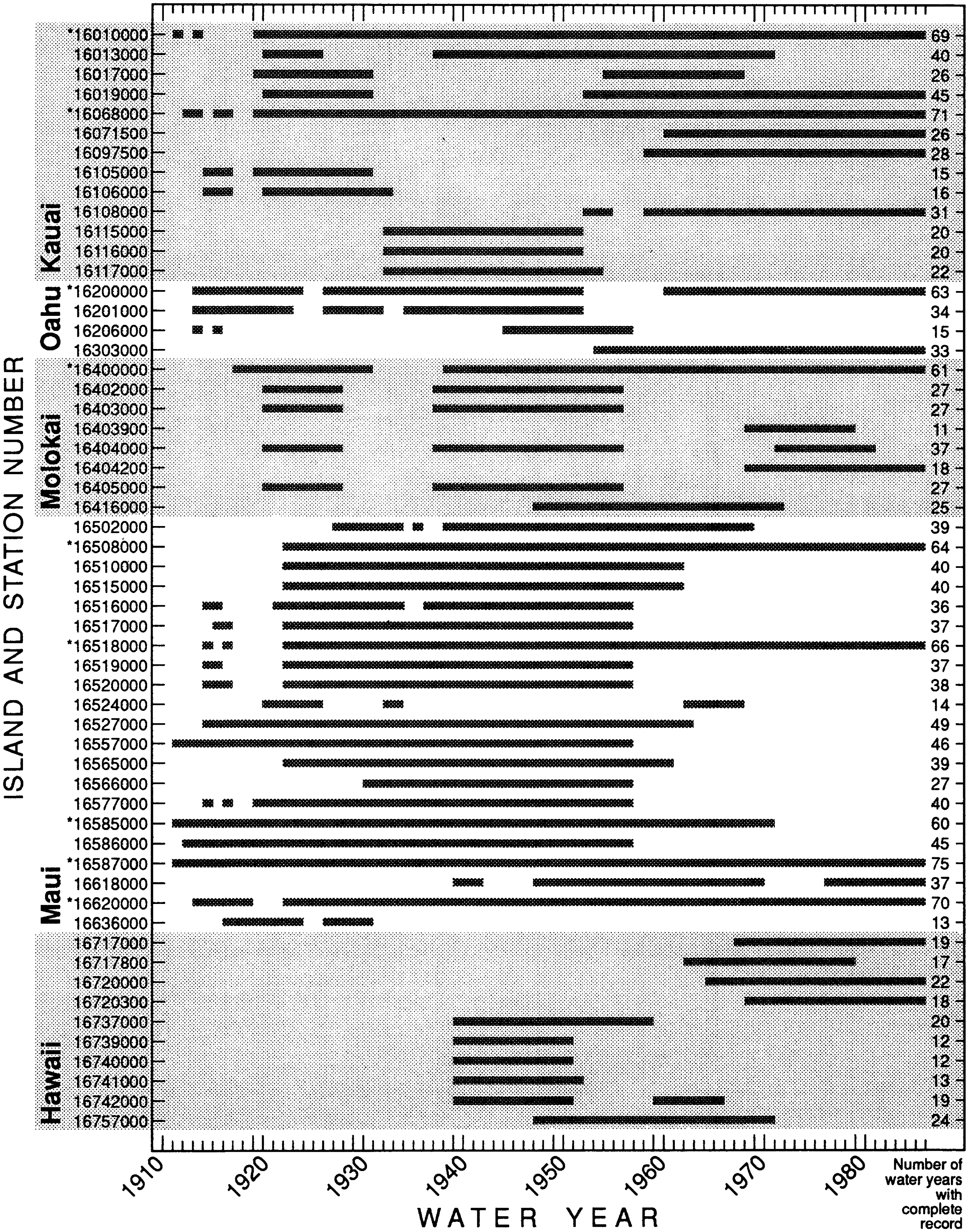

Figure 6. Water years with complete record for the streamflow-gaging stations used in the regression analyses, 1910 through 1986. Stations marked with an asterisk (*) were used as index stations in the analyses.

estimates of long-term medians are improved with increased length of record. Errors in estimates of long-term median-streamflow for tested combinations with at least 60 years of record were less than 5 percent. On the basis of these results, the base period for this study was the entire length of record at station 16587000, or the period 1912 through 1986 water years. It was assumed that any station with at least 60 years of record provides an acceptable estimate of the median streamflow for this entire base period and therefore long-term conditions. Nine of the 56 stations with at least 60 years of record are indicated in figure 6 and were used as index stations. None of the index stations are located on the island of Hawaii.

To include more of the 56 stations as index stations would require that the base period be shortened. None of the 56 stations have between 50 and 60 years of record. There are four stations that have between 45 and 50 years of record. The reduction in the length of base period required to include these four stations as index stations would eliminate several stations from the analysis entirely. The stations would be eliminated because their periods of record would now fall outside the base period. This was not considered an acceptable tradeoff.

To compute long-term estimates of median streamflows for the 47 stations with less than 60 years of record, the index-station method was used (Searcy, 1959, p. 12). To apply the index-station method, each of the short-term stations needs to be correlated with at least one of the index stations. Flow-duration curves were computed for the period of common or concurrent record at the stations. Corresponding flow-duration points for the two stations were plotted on logarithmic paper, thus establishing a curve or relation between the two stations. A basic assumption underlying the index-station method is that the short-term relation represents the relation between the stations for the long-term, or base, period. Given this assumption, the median streamflow for the base period at the index station can be used with the curve to obtain the base-period median streamflow for the short-term station. Estimated base-period (1912-1986) or long-term median streamflows for the 56 stations used in the regression analyses are listed in table 3.

Table 3.--*Estimated base-period (1912-1986) median streamflows for the unregulated, perennial streamflow-gaging stations used in the regression analyses*

[ft^3/s, cubic feet per second; --, indicates the station is an index-station]

Station number	Correlated index-station	Concurrent years of record	Median streamflow for period of record (ft^3/s)	Base-period median streamflow (ft^3/s)
		Island of Kauai		
16010000	--	--	13.4	13.4
16013000	16010000	34	3.0	3.0
16017000	16010000	14	8.2	7.9
16019000	16010000	34	6.8	6.8
16068000	--	--	31.6	31.6
16071500	16068000	26	1.8	1.8
16097500	16068000	28	7.5	7.6
16105000	16010000	12	20.0	19.3
16106000	16010000	13	66.6	60.3
16108000	16010000	28	79.3	80.4
16115000	16010000	20	8.4	8.7
16116000	16010000	20	1.8	1.9
16117000	16010000	22	5.2	5.4
		Island of Oahu		
16200000	--	--	7.3	7.3
16201000	16200000	18	4.9	4.7
16206000	16200000	8	5.8	6.0
16303003	16200000	26	19.8	19.1
		Island of Molokai		
16400000	--	--	14.2	14.2
16402000	16400000	18	20.1	19.1
16403000	16400000	18	7.6	7.1
16403900	16400000	11	4.9	5.9
16404000	16400000	18	9.3	8.8
16404200	16400000	18	1.0	1.1
16405000	16400000	18	8.3	7.6
16416000	16400000	25	0.36	0.36
		Island of Maui		
16502000	16508000	31	3.2	3.2
16508000	--	--	7.1	7.1
16510000	16508000	40	5.3	4.6
16515000	16508000	40	6.7	6.2
16516000	16518000	21	9.1	8.2

Table 3.--*Estimated base-period (1912-1986) median streamflows for the unregulated, perennial streamflow-gaging stations used in the regression analyses*--Continued

[ft^3/s, cubic feet per second; --, indicates the station is an index-station]

Station number	Correlated index-station	Concurrent years of record	Median streamflow for period of record (ft^3/s)	Base-period median streamflow (ft^3/s)
		Island of Maui--continued		
16517000	16518000	35	10.3	8.5
16518000	--	--	10.4	10.4
16519000	16518000	35	5.2	4.5
16520000	16518000	35	3.8	3.3
16524000	16518000	11	2.1	2.5
16527000	16518000	41	6.2	6.0
16557000	16587000	46	3.1	2.9
16565000	16587000	39	2.9	2.8
16566000	16587000	27	1.2	1.1
16577000	16587000	38	9.8	9.1
16585000	--	--	5.6	5.6
16586000	16587000	45	4.4	4.4
16587000	--	--	2.5	2.5
16618000	16620000	23	8.8	9.1
16620000	--	--	24.3	24.3
16636000	16620000	5	5.0	4.9
		Island of Hawaii		
16717000	16518000	19	38.0	45.0
16717800	16518000	17	7.7	9.1
16720000	16518000	22	4.2	5.6
16720300	16518000	18	1.7	2.2
16737000	16518000	20	4.3	4.3
16739000	16518000	12	2.4	2.5
16740000	16518000	12	0.59	0.60
16741000	16518000	13	1.1	1.1
16742000	16518000	12	0.91	0.94
16757000	16518000	24	4.0	4.0

Basin-Characteristic Data

To do regression analyses, basin characteristics that might be related to median streamflow need to be determined in a quantitative form. Basin characteristics considered in this study can be placed in one of three basic categories: basin morphology, land use, and climate. The seven characteristics considered are: drainage area, channel length, mean basin altitude, mean altitude of the main stream channel, forest cover, swamp cover, and mean annual precipitation. The seven characteristics are described below:

Drainage area (DA)--in mi^2; determined by planimetering the area enclosed by basin divides drawn on 1:24,000-scale USGS topographic maps. Previous studies have consistently shown that drainage area is an important factor in determining streamflow characteristics for a basin (Thomas and Benson, 1970).

Channel length (CL)--in mi; is the longest distance measured along a stream from the site of interest to the basin divide. The stream channel was defined by the blue line on 1:24,000-scale USGS topographic maps and measured using a map wheel.

Mean basin altitude (BE)--in ft; determined by placing a uniform grid over the basin outline as identified on 1:24,000-scale USGS topographic maps. The altitude at a minimum of 25 grid intersections in the basin were estimated from the topographic maps. Mean basin altitude was calculated as the average of the altitudes at the grid intersections. Mean basin altitude acts as a surrogate index for factors such as temperature, wind, and solar radiation, which are difficult to evaluate and may cause streamflow variations (Thomas and Benson, 1970).

Mean altitude of the main stream channel (CE)--in ft; determined by averaging channel altitudes determined at points located 10 percent and 85 percent of the channel length upstream from the gaging station.

Forest cover (FC)--in percent; is the percentage of the drainage area covered by forest and vegetation. Forest cover was determined to be the area shown in green on the 1:24,000-scale USGS topographic maps and was measured with a planimeter. Percent forest cover serves to represent variations in evapotranspiration and rainfall interception caused by various degrees of vegetation.

Swamp cover (SC)--in percent; is the percentage of the drainage area covered by swamps. Swamp cover was determined to be the area shown on the 1:24,000-scale USGS topographic maps that was identified as swamp or marsh. Area of swamp cover was measured with a planimeter. A constant of 0.1 percent was added to all sites where the percent of swamp cover was determined to be zero. Use of the constant avoids problems caused when using logarithms with a data set that includes zero values. Swamps and wetlands can affect streamflows as a result of their ability to store water, provide ground-water recharge, and cause increased evapotranspiration (Carter, 1986).

Mean annual precipitation (P)--in in.; determined by placing a uniform grid over maps showing lines of equal mean annual precipitation as prepared by Giambelluca and other (1986). Mean annual precipitation was determined at a minimum of 20 to 25 grid intersections located within the drainage-basin boundary. Mean annual precipitation for the basin was calculated as the average of the values determined at each of the grid intersections.

Basin characteristics described above are summarized for each of the 56 unregulated, perennial, streamflow-gaging stations used in the regression analyses in table 4. Each of the 56 gaging stations were also classified as being located on either the windward or leeward regions of their respective island. The divisions between windward and leeward were based on work by Yamanaga (1972).

Development of Multiple-Regression Equations

For the regression analysis, the adjusted base-period median-streamflow values were the dependent variables and the independent variables were the basin characteristics. The multiple-regression technique requires that independent and dependent variables be linearly related. An examination of the median-streamflow values and the basin characteristics, along with previous studies (Thomas and Benson, 1970), have shown that the logarithmic transformation creates the required linear relation. The natural log (base e) transformation was used for transformation of all variables in this study. A problem with logarithmic transformations is the bias introduced when regression results are back-transformed from logarithms to the original units of measurement. This problem can be corrected by using a bias-correction factor. The smearing estimate (Duan, 1983) was used to estimate this bias-correction factor.

After transforming all variables, the significant independent variables for median streamflow were determined by correlation and stepwise regression. Correlation measures the degree of the linear relation between two variables. This degree of relation is indicated by the Pearson correlation coefficient, which ranges from -1 to 1. Values close to -1 or 1 represent high correlation among variables. In regression analysis, high correlation among independent variables tends to reduce the significance of each variable involved and can lead to unstable regression models. To avoid this problem, only the more significant and reliable variable should be retained in the regression model.

Table 4.--*Basin characteristics for the unregulated, perennial streamflow-gaging stations used in the regression analyses*

[mi^2, square miles; mi, miles; ft, feet; %, percent; in., inches; L, leeward; W, windward]

Station number	Region	Drainage area (mi^2)	Channel length (mi)	Basin altitude (ft)	Channel altitude (ft)	Forest cover (%)	Swamp cover (%)	Mean annual rainfall (in.)
				Island of Kauai				
16010000	L	3.95	6.41	3,840	3,720	58	42	132
16013000	L	1.68	4.42	3,920	3,750	72	28	135
16017000	L	1.68	4.69	4,250	4,080	18	82	180
16019000	L	1.79	4.35	4,360	4,240	31	69	146
16068000	W	6.27	4.30	1,390	860	100	0.1	147
16071500	W	0.65	1.90	790	720	100	0.1	105
16097500	W	1.90	2.41	1,110	2,500	82	8.0	139
16105000	W	1.81	2.88	2,220	2,500	100	0.1	180
16106000	W	6.95	3.81	2,280	1,260	100	0.1	262
16108000	W	10.2	6.95	3,210	1,620	73	27	274
16115000	W	2.73	3.51	2,990	2,060	100	0.1	123
16116000	W	0.50	1.50	3,440	2,020	100	0.1	95
16117000	W	1.55	1.40	2,890	1,460	99	0.1	90
				Island of Oahu				
16200000	L	1.38	4.84	1,750	1,520	100	0.1	255
16201000	L	1.17	3.00	1,700	1,550	100	0.1	250
16206000	L	1.93	5.84	1,650	1,490	100	0.1	243
16303003	W	2.78	3.02	1,160	745	100	0.1	200
				Island of Molokai				
16400000	W	4.62	5.26	2,210	1,980	100	0.1	86
16402000	W	4.38	3.69	2,200	1,620	100	0.1	130
16403000	W	1.41	1.60	1,960	1,930	100	0.1	128
16403900	W	1.18	1.80	2,370	2,190	100	0.1	132
16404000	W	2.59	2.16	2,330	1,730	100	0.1	131
16404200	W	0.49	1.06	2,340	2,160	100	0.1	123
16405000	W	1.09	1.56	2,270	1,540	100	0.1	95
16416000	L	0.24	1.10	2,430	2,170	100	0.1	119
				Island of Maui				
16502000	L	0.43	2.50	2,470	2,360	95	2.0	153
16508000	W	3.49	6.20	4,630	4,070	85	0.1	257
16510000	W	0.69	0.54	2,100	3,420	100	0.1	257
16515000	W	0.32	2.40	2,490	2,000	100	0.1	250
16516000	W	4.31	6.60	4,600	4,150	100	0.1	223
16517000	W	3.11	6.50	4,340	4,000	100	0.1	226
16518000	W	3.66	6.80	4,800	4,000	100	0.1	207
16519000	W	1.93	6.80	4,650	3,910	100	0.1	190
16520000	W	0.51	2.50	2,115	1,980	100	0.1	241
16524000	W	2.54	5.60	5,425	5,280	100	0.1	164

Table 4.--*Basin characteristics for the unregulated, perennial streamflow-gaging stations used in the regression analyses*--Continued

[mi², square miles; mi, miles; ft, feet; %, percent; in., inches; L, leeward; W, windward]

Station number	Region	Drainage area (mi²)	Channel length (mi)	Basin altitude (ft)	Channel altitude (ft)	Forest cover (%)	Swamp cover (%)	Mean annual rainfall (in.)
				Island of Maui--continued				
16527000	W	3.17	7.10	4,810	4,670	100	0.1	180
16557000	W	0.47	2.30	1,900	1,790	100	0.1	204
16565000	W	0.58	3.80	2,125	2,130	100	0.1	201
16566000	W	0.20	1.70	1,665	1,590	100	0.1	180
16577000	W	2.41	6.10	3,170	2,840	100	0.1	193
16585000	W	1.34	4.90	2,350	2,190	100	0.1	165
16586000	W	0.55	2.70	1,815	1,750	100	0.1	150
16587000	W	0.64	3.00	1,790	1,830	100	0.1	175
16618000	W	3.47	5.70	2,285	1,870	92	8.0	154
16620000	W	4.11	6.20	3,190	2,690	99	0.1	236
16636000	L	1.51	3.70	3,350	2,660	100	0.1	124
				Island of Hawaii				
16717000	L	11.6	13.4	3,720	3,590	100	0.1	190
16717800	W	2.76	9.30	2,330	2,330	85	0.1	191
16720000	W	1.58	2.50	4,620	4,330	100	0.1	108
16720300	W	0.45	1.70	4,410	4,470	100	0.1	148
16737000	W	0.76	3.30	3,760	3,610	100	0.1	166
16739000	W	0.66	3.70	3,220	3,100	100	0.1	159
16740000	W	0.12	0.47	2,340	2,170	100	0.1	137
16741000	W	0.32	2.00	2,780	2,680	100	0.1	152
16742000	W	0.22	1.60	2,580	2,550	100	0.1	144
16757000	W	0.78	2.00	3,860	3,870	100	0.1	103

The stepwise regression procedure adds or deletes variables 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 chosen for the F-test used in stepwise regression to measure significance. Previous regression analyses between streamflow characteristics and basin characteristics in Hawaii have shown that a 5 percent significance value usually limits regression models to no more than 3 independent variables (Yamanaga, 1972; Nakahara, 1980; Wong, 1991). The final regression model when back-transformed has the form,

$$Q_{50} = a(X^b)(Y^c)(Z^d)(BCF),$$

where: Q_{50} is the median streamflow in ft^3/s,
X,Y, and Z are basin characteristics,
a is the regression constant,
b, c, and d are the regression coefficients, or exponents of the basin characteristics, and
BCF is the bias-correction factor.

Residuals from the regression analysis of the entire State (56 stations) were plotted geographically and analyzed visually for possible regional grouping. The use of groupings into homogeneous regions can improve regression estimates (Lettenmaier and others, 1987). Possible groupings of islands were determined from the residual plots and from existing knowledge of the geology and hydrology of the area. These groupings were then tested for significance at the 10-percent level by using the Wilcoxon Signed Ranks Test (Tasker, 1982) on the regression residuals. The Wilcoxon Signed Ranks Test does not statistically verify regions but provides a quantitative index as a guide for defining homogeneous regions (Choquette, 1988; Tasker, 1982). In addition to the Wilcoxon test, the percent standard error of estimate from regression analyses of the various groupings were also used to judge the groupings. The results of the Wilcoxon test showed that none of the groupings chosen were significantly different from the State as a whole at the 10-percent significance level. The regression analysis of the groupings did indicate that lumping data for Oahu, Molokai, and Hawaii together and data for Kauai and Maui together did provide improved standard errors.

Ordinary-least-squares regression procedures were used to develop the final regression models to estimate median streamflows for the Oahu, Molokai, and Hawaii grouping and the Kauai and Maui grouping. Final models were tested to ensure that (1) all independent variables selected were statistically significant at the 5-percent level, (2) the standard error was minimized, (3) the coefficient of determination adjusted for degrees of freedom was maximized, (4) multicolinearity or correlation between selected variables was not a problem, (5) overly influential observations were not present, and (6) residual variances were constant. In addition to the statistical measures of acceptability, the signs and magnitudes of the coefficients determined for the significant, independent variables were reviewed to ensure that they were hydrologically reasonable.

The independent variable that gave the best estimates for median streamflow for the Oahu, Molokai, and Hawaii grouping was drainage area. No additional independent variable qualified under the 5-percent significance-level criteria. The independent variables that gave the best estimates for median streamflow for the Kauai and Maui grouping were drainage area, mean altitude of the main stream channel, and mean annual precipitation. Regression equations, used to estimate median streamflow for the two groupings, their respective coefficients of determination, and standard errors of regression and prediction are shown in table 5. The regression statistics, as well as the accuracy and limitations of the equations, are described in the next section of the report. Smearing adjustments or bias correction factors of 1.055 and 1.090 were incorporated into the regression constants for the Oahu, Molokai, and Hawaii and for the Kauai and Maui equations.

Accuracy and Limitations of the Equations

The coefficient of determination, standard error of the regression, and standard error of prediction associated with the regression equations are shown in table 5. The coefficient of determination provides a measure of the proportion of total variation of median streamflow accounted for by the regression equations. Standard error of the regression is a measure of the average deviation of observed median streamflows from those predicted by the regression equations. Standard error of prediction is a measure of average deviation to be expected when applying the regression equations at ungaged sites. About 68 percent of median-streamflow estimates, using the regression equation, should be within the given standard errors of prediction of their true values. Standard errors determined from the regression equations are comparable to standard errors associated with estimates of long-term median streamflow made for station 16587000 (table 2) in which between 1 and 5 years of continuous-data are used. To provide a graphical representation of the accuracy of the regression equation computed for the Oahu, Molokai, and Hawaii geographic group, observed median streamflow is plotted against drainage area in figure 7. Drainage area is the only independent variable included in the regression equation for the group. The difference between observed and predicted median-streamflow data for each of the stations is represented by the vertical distance (measured in cubic feet per second) between the circles and the regression equation, which is plotted as the straight line in figure 7.

Limitations on the use of the equations in table 5 also need to be considered. The equations should not be used for sites that are subjected to the effects of regulation. The equations are only applicable for perennial stream sites on the islands for which they were developed. Within each island grouping the equations should be applied only at sites having basin

Table 5.--*Summary of regression equations used to estimate median streamflows for the base period at ungaged, unregulated, perennial stream sites in Hawaii*

Geographic grouping	Number of stations	Regression equation	R^2	SE_r	SE_p
Oahu, Molokai and Hawaii	22	$Q_{50} = 4.25\ (DA)^{1.04}$	0.91	37.2	41.4
Kauai and Maui	34	$Q_{50} = 4.49\ (DA)^{0.808}(CE)^{-0.641}(P)^{0.985}$	0.78	46.2	54.3

Where: Q_{50} is median streamflow, in cubic feet per second

DA is drainage area, in square miles

CE is mean altitude of the main stream channel, in feet

P is mean annual precipitation, in inches

R^2 is the coefficient of determination, adjusted for lost degrees of freedom

SE_r is the standard error of the regression, in percent, from units of natural logarithms

SE_p is the standard error of prediction, in percent, from units of natural logarithms

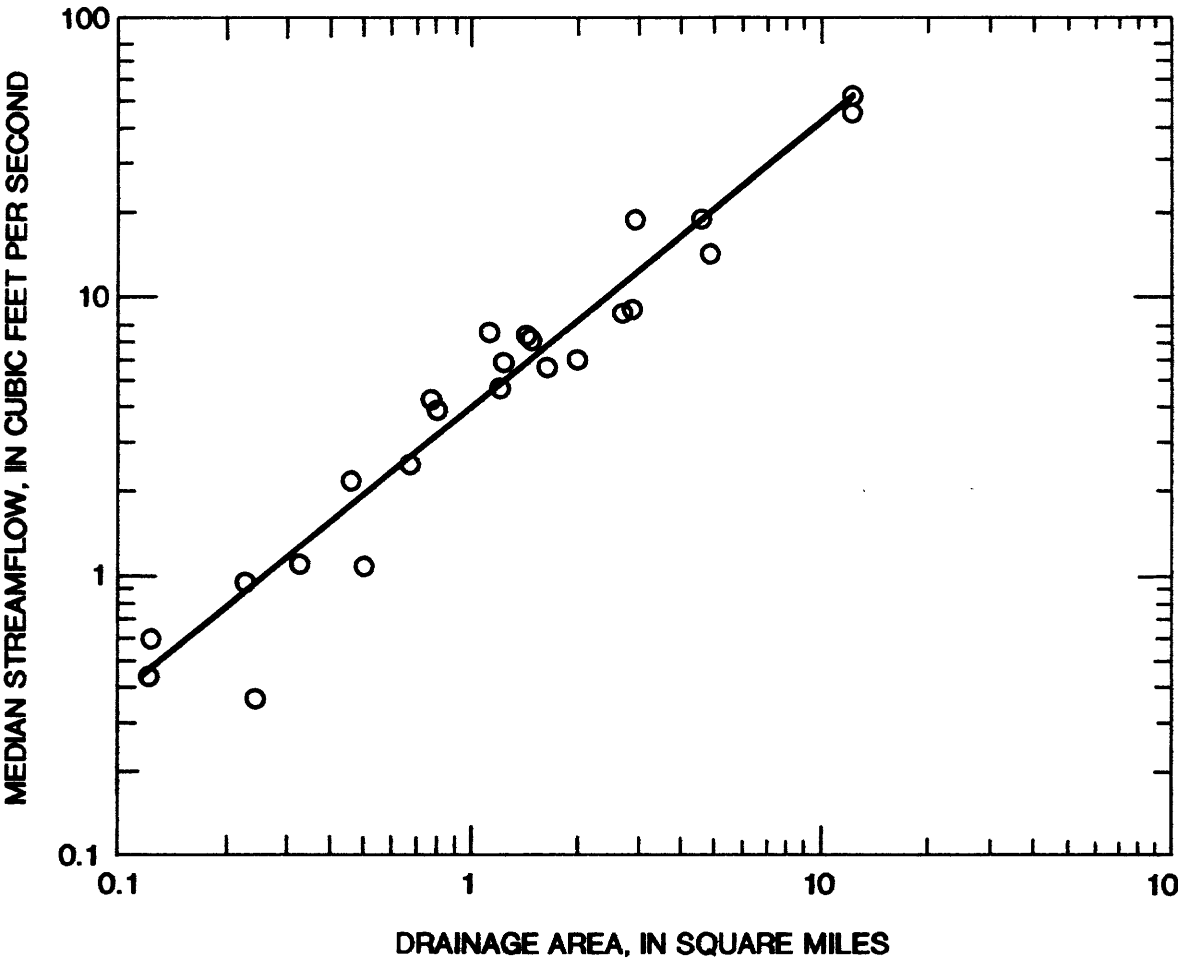

Figure 7. Plot of observed median streamflow as a function of drainage area with the calibrated regression line for the Oahu, Molokai, and Hawaii geographic grouping.

characteristics within the range of values at the gaged sites used to develop the equations. Ranges for the basin characteristics used in each of the regression equations are summarized in table 6. Application of the regression equations at sites with basin characteristics outside the appropriate ranges, as indicated in table 6, will provide median-streamflow estimates with unknown levels of accuracy.

Table 6.--*Ranges of basin-characteristic values at stations used to develop regression equations*

Geographic grouping	DA minimum	DA maximum	CE minimum	CE maximum	P minimum	P maximum
Oahu, Molokai and Hawaii	0.12	11.6	n.a.	n.a.	n.a.	n.a.
Kauai and Maui	0.20	10.2	720	5,280	90	274

Where: n.a. indicates not applicable
DA is drainage area, in square miles
CE is mean altitude of the main stream channel, in feet
P is mean annual precipitation, in inches

ESTIMATION OF MEDIAN STREAMFLOWS AT REGULATED, PERENNIAL WINDWARD OAHU SITES

A significant number of perennial stream sites in Hawaii are subject to regulation and the equations developed in the preceding section of this report are not applicable at regulated sites. As previously noted, in the section "Site Selection," only 112 of the 664 streamflow-gaging stations that have been operated in Hawaii for some period of time between 1910 and 1986 can be considered unregulated. Accurate median streamflows can be computed at gaged, regulated stations. To be representative of future conditions, the median streamflows should be based on long-term data collected over a period of uniform regulation similar to what is expected in the future. Because median-streamflow estimates are required at ungaged, regulated sites, a different technique is required. In this section of the report, specific regulated sites located on the windward side of Oahu were selected. Additional hydrologic data collected at selected sites and concurrent data available at nearby continuous-record index stations were analyzed by correlation and ordinary-least-squares regression to provide estimates of median streamflows. Associated accuracies and limitations of the results are also discussed.

The technique of correlating additional hydrologic data collected at ungaged sites to concurrent data available at gaged stations was applied only at selected regulated windward Oahu sites in this report. However, the technique can be applied to both regulated and unregulated perennial sites in other areas on the islands of Oahu as well as on Kauai, Molokai, Maui, and Hawaii. The obvious limitation of the technique is that the additional hydrologic data must be collected before the estimates of median streamflows can be made.

Site Selection

A total of 27 regulated stream sites located on the windward side of Oahu were selected for analysis. Selected sites are located in six drainage basins: nine sites in the Maunawili basin, five sites each in the Waiahole and Waikane basins, three sites each in the Punaluu and Kaluanui basins, and two sites in the Kahana basin. Locations of the windward Oahu study basins are shown in figure 8. Where possible, sites were selected to coincide with locations where data had previously been collected. The sites selected with associated site numbers, latitude, longitude, description of location, and drainage areas are summarized in table 7. Site numbers are of three types and provide information regarding the data collection history of the location. Eight-digit site numbers are USGS station numbers and indicate that some systematic data collection has previously been done at the location. Two- and three-digit numbers indicate that the location coincides with a site where miscellaneous low-flow data were collected by Takasaki and others (1969, pl. 3). Two- and three-digit site numbers followed by a letter or an underscore and an additional digit are sites where data have not been collected before this study. The leading two or three digits for the third type of site numbers represent the nearest site from the study by Takasaki and others (1969, pl. 3).

Data Collection and Analysis

To determine median streamflows for the 27 sites listed in table 7, about 4 discharge measurements per year were made at each of the 27 sites during water years 1988 through 1990. Measurements were made over a range of discharges that were expected to bracket median streamflows. In addition to these data, previous streamflow measurements available at 19 of the sites were used. Previous measurements were screened and only those that fell within the range of discharges measured at the site during water years 1988 through 1990 were used. This screening was done to prevent potential bias that might be caused by including high- or low-flow measurements in the analysis. An exception was made at site 16260500 where 3 years of record are available and were used in the analysis. All measured discharges for the 27 sites have been published by Takasaki and others (1969), by the USGS in the series of water-resources data reports for Hawaii (1971-91), or in Water-Supply Papers 1937 and 2137 (U.S.Geological Survey, 1971 and 1977).

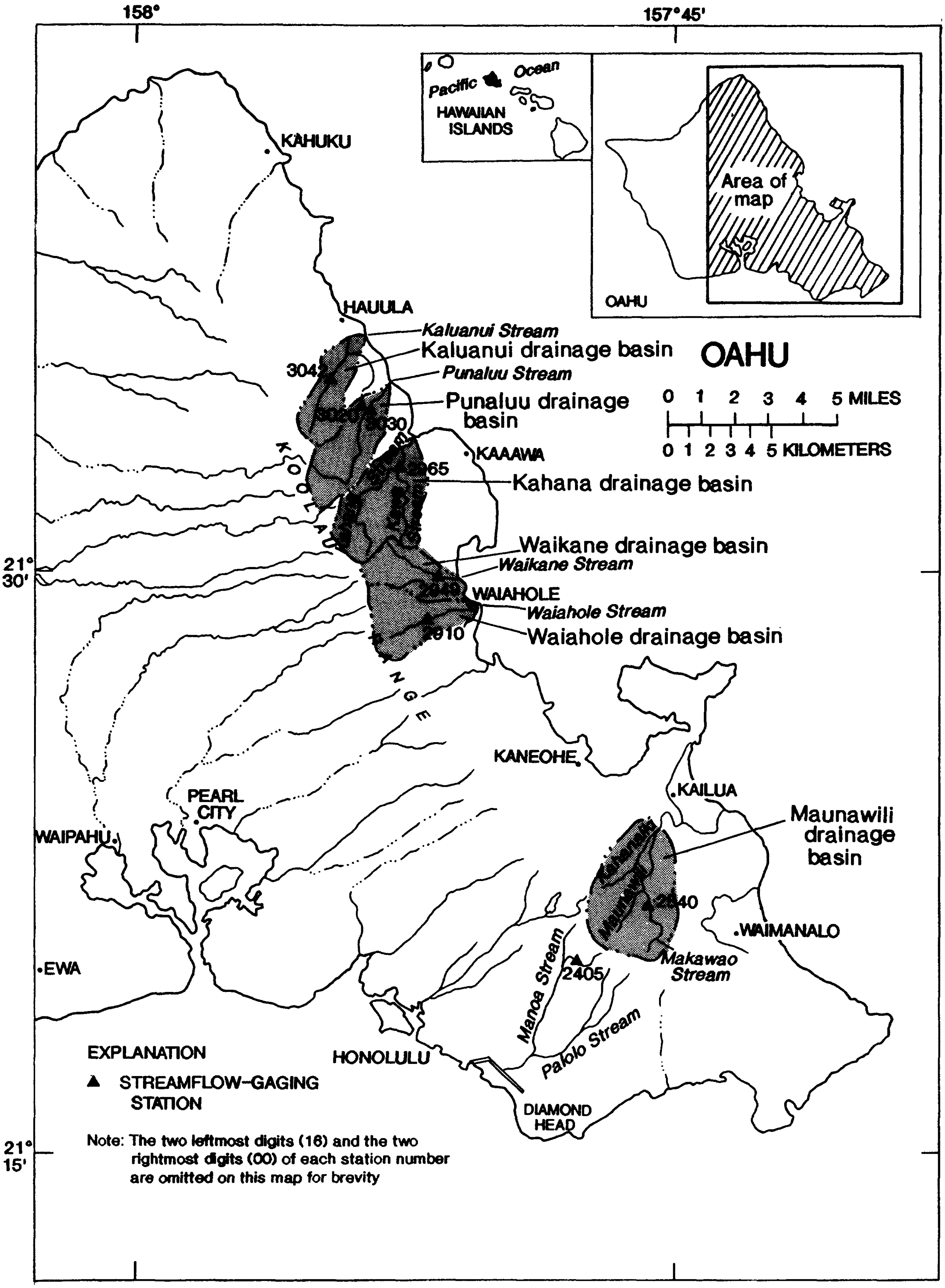

Figure 8. Locations of windward Oahu study basins and regulated, perennial index streamflow-gaging stations.

Table 7.--*Regulated, perennial windward Oahu sites where median-streamflow estimates were made*

[mi², square miles; mi, miles; ft, feet]

Site number	Latitude	Longitude	Location	Drainage area (mi²)
			Maunawili basin	
26	21°21'20"	157°45'52"	Makawao Stream, 1.8 mi southwest of Maunawili School and 2.2 mi southeast of Hawaii Loa College	0.84
28	21°21'26"	157°45'55"	Ainoni Stream, 1.7 mi southwest of Maunawili School and 2.1 mi southeast of Hawaii Loa College	0.60
34_5	21°21'28"	157°46'13"	Maunawili Stream, 1.9 mi southwest of Maunawili School and 1.9 mi southeast of Hawaii Loa College	1.09
35	21°21'51"	157°46'05"	Maunawili Stream, 1.4 mi southwest of Maunawili School and 1.6 mi southeast of Hawaii Loa College	1.19
38	21°21'56"	157°46'46"	Omao Stream, 1.3 mi southwest of Maunawili School and 1.5 mi southeast of Hawaii Loa College	0.94
16260500	21°22'51"	157°45'48"	Maunawili Stream, 0.6 mi west of Maunawili School and 1.6 mi southwest of Kailua Post Office	5.34
45	21°22'22"	157°46'27"	Kahanaiki Stream, 1.4 mi southwest of Maunawili School and 0.9 mi southwest of Hawaii Loa College	0.36
16263000	21°22'20"	157°46'25"	Kahanaiki Stream, 1.3 mi southwest of Maunawili School and 0.9 mi southeast of Hawaii Loa College	0.61
16264100	21°22'49"	157°46'46"	Kahanaiki Stream, 0.9 mi west of Maunawili School and 1.0 mi east of Hawaii Loa College	1.43
			Waiahole basin	
176_5	21°28'29"	157°52'39"	Waiahole Stream, 1.7 mi southwest of Waiahole School and 2.8 mi northwest of Kahaluu	0.92
178	21°28'59"	157°51'39"	Waiahole Stream, 0.6 mi southwest of Waiahole School, 2.2 mi northwest of Kahaluu, and downstream from a diversion ditch	1.65
178T	21°28'59"	157°51'43"	Waiahole Stream, about 100 ft upstream from site 178 and includes flow from diversion ditch	1.65
16293100	21°28'59"	157°51'47"	Waianu Stream, 0.6 mi southwest of Waiahole School and 2.3 mi northwest of Kahaluu	1.64
186_5	21°29'05"	157°50'57"	Waiahole Stream, 0.4 mi southwest Waiahole School and 1.8 mi northwest of Kahaluu	3.76

Table 7.--*Regulated, perennial windward Oahu sites where median-streamflow estimates were made*--Continued

[mi^2, square miles; mi, miles; ft, feet]

Site number	Latitude	Longitude	Location	Drainage area (mi^2)
			Waikane basin	
187_5	21°30'21"	157°52'42	North Fork Waikane Stream, 1.7 mi west of Waikane and 2.0 mi northwest of Waiahole School	0.58
187_8	21°30'17"	157°52'43"	Waikane Stream, 1.7 mi west of Waikane and 1.8 mi northwest of Waiahole School	0.67
190	21°30'07"	157°52'12"	Waikane Stream, 1.1 mi west of Waikane and 1.4 mi west of Waikane School	1.57
191	21°30'02"	157°52'14"	Waikeekee Stream, 1.1 mi west of Waikane and 1.4 mi west of Waikane School	0.43
198	21°29'56"	157°51'15"	Waikane Stream 0.1 mi west of Waikane and 0.7 mi north of Waiahole School	2.50
			Kahana basin	
16295995	21°32'17"	157°53'29"	Kahana Stream, 1.8 mi upstream from main bridge on Kamehameha Highway and 2.8 mi southwest of Kaaawa School	3.20
16297000	21°32'35"	157°53'51"	Kawa Stream, 0.1 mi upstream from mouth and 1.0 mi south of Kahana	2.10
			Punaluu basin	
236	21°33'12"	157°54'05"	Punaluu Stream, 1.4 mi west of Kahana and 2.1 mi southwest of Punaluu	1.80
241	21°33'15"	157°54'06"	Waiaohi Stream, 1.4 mi west of Kahana and 2.1 mi southwest of Punaluu	0.52
251_5	21°34'41"	157°53'21"	Punaluu Stream, 1.4 mi north of Kahana and 0.3 mi south of Punaluu	3.51
			Kaluanui basin	
253	21°34'51"	157°54'59"	Kaluanui Stream, 1.9 mi west of Punaluu Beach Park and 2.3 mi south of cemetery in Hauula	0.85
253_5	21°34'14"	157°54'44"	Kaluanui Stream, 1.5 mi west of of Punaluu Beach Park and 1.6 mi south of cemetery in Hauula	1.96
16304500	21°35'57"	157°54'24"	Kaluanui Stream, 1.2 mi southeast of cemetery in Hauula and 1.4 mi northeast of Sacred Falls	2.12

Relations between discharge measurements for each of the 27 sites and concurrent daily mean discharge at a number of different continuous-record index stations were established using ordinary-least-squares regression. The pairing with highest correlation coefficient was selected as providing the best relation. Index stations considered for the analysis included those with at least 10 years of record that were located near any of the 27 sites. In addition, station 16240500, Waiakeakua Stream at Honolulu, was considered for use as an index station. Takasaki and others (1969) found station 16240500 to be hydrologically similar to windward Oahu basins. Following Searcy (1959), logarithmic transformations were made on all streamflow data before correlation and regression analysis. Index stations used for the analyses and their respective periods of record, drainage areas, and median streamflows are summarized in table 8.

Relations developed between discharge at the 27 sites and respective index stations can be used with computed median streamflows at the index stations to estimate median streamflows at the 27 sites. Regression statistics, selected index stations, and estimated median streamflows for the 27 windward Oahu sites are summarized in table 9. Bias-correction factors based on Duan's (1983) smearing estimate were included in the regression estimates.

Stedinger and Thomas (1986) have demonstrated that ordinary-least-squares regression tends to give biased estimates of low-flow frequency statistics when relating base-flow measurements and concurrent daily flows at index stations. Techniques recommended to avoid the bias include graphical correlation (Searcy, 1959), maintenance of variance procedures (Hirsch, 1982), or methods of moments (Gilroy, 1972; Stedinger and Thomas, 1986).

In this study, an estimate for only one value, median streamflow, is required. Regression equations are not provided. Hirsch and Gilroy (1984, p. 708) have demonstrated that when estimating individual values ordinary-least-squares regression procedures are appropriate, assuming other ordinary-least-squares regression assumptions (linear relation and constant variance) are met. Ordinary-least-squares regression statistics provided in table 9 are also appropriate for use especially because the one value estimated, median streamflow, is a measure of central tendency. Measures of central tendency are not subject to the bias that is often evident with data at the extreme ends of fitted regressions.

Table 8.--*Index stations used to estimate median streamflows for windward Oahu sites*

[mi^2, square miles; ft^3/s, cubic feet per second; p, station in operation as of end of water year 1991; ft, feet]

Station number	Latitude	Longitude	Station name	Length of record (years)	Period of record	Drainage area (mi^2)	Median streamflow (ft^3/s)
16240500	21°19'53"	157°48'12"	Waiakeakua Stream at Honolulu	76	1913-21; 1925-p	1.06	3.5
16254000	21°21'49"	157°46'02"	Makawao Stream near Kailua	39	1912-16; 1958-p	2.04	2.6
16291000	21°28'35"	157°52'30"	Waiahole Stream at altitude 250 ft, near Waiahole	14	1955-68; 1970;[1] 1988-90[1]	0.99	5.2
16294900	21°30'00"	157°51'54"	Waikane Stream at altitude 75 ft, at Waikane	33	1959-p	2.22	4.0
16296500	21°32'37"	157°53'07"	Kahana Stream at altitude 30 ft, near Kahana	34	1958-p	3.74	22.6
16303003	21°33'33"	157°54'06"	Combined records of Punaluu Ditch (16302000) with Punaluu Stream (16303000) near Punaluu	38	1953-p	2.78	[2]19.1
16304200	21°35'22"	157°54'38"	Kaluanui Stream near Punaluu	24	1967-p	1.11	1.4

[1]Low-flow partial-record station
[2]Median streamflow extended to represent base period 1912 through 1986 (see table 3)

Table 9.--*Regression-equation statistics and estimated median streamflows for selected regulated, perennial windward Oahu sites*

[ft³/s, cubic feet per second; --, see footnote]

Site number	Number of concurrent measurements	R^2	SE_r	SE_p	Index station number	Estimated median streamflow (ft³/s)
			Maunawili basin			
26	14	0.61	19.3	22.2	16254000	1.2
28	15	0.74	29.4	32.2	16254000	0.98
34_5	12	--	--	--	16254000	[1]1.6
35	16	--	--	--	16254000	[1]1.6
38	14	0.69	21.2	23.4	16254000	1.2
16260500	1,758	0.94	19.6	19.7	16254000	6.7
45	12	0.77	22.2	27.3	16254000	0.52
16263000	12	0.75	21.5	25.6	16254000	0.82
16264100	46	0.65	27.6	28.8	16254000	1.3
			Waiahole basin			
176_5	11	0.72	7.4	9.2	16291000	3.4
178	12	0.75	10.0	13.3	16291000	4.8
178T	9	0.95	4.4	5.3	16291000	6.0
16293100	15	0.72	17.6	20.4	16294900	3.0
186_5	11	0.85	9.1	10.6	16291000	8.5
			Waikane basin			
187_5	12	0.71	23.4	28.1	16294900	1.1
187_8	12	0.97	9.4	11.4	16294900	0.66
190	14	0.74	16.6	20.1	16294900	2.7
191	16	0.83	30.2	33.5	16294900	0.38
198	12	0.94	8.1	9.9	16294900	4.0
			Kahana basin			
16295995	39	0.77	11.6	12.4	16296500	19.2
16297000	31	0.60	27.8	29.9	16294900	3.0
			Punaluu basin			
236	13	0.84	8.1	9.1	16303003	14.7
241	13	0.90	6.6	7.8	16303003	4.4
251_5	12	--	--	--	16303003	[1]16.7
			Kaluanui basin			
253	14	0.97	10.7	13.9	16304200	1.4
253_5	14	0.99	7.2	8.4	16304200	1.4
16304500	6	--	--	--	16304200	[1]0.53

[1]No regression statistics are provided and estimated median streamflow should be used with caution.

Where: R^2 is the coefficient of determination, adjusted for lost degrees of freedom

SE_r is the standard error of the regression, in percent, from units of natural logarithms

SE_p is the standard error of prediction, in percent, from units of natural logarithms

Accuracy and Limitations of Median-Streamflow Estimates

Median-streamflow estimates at ungaged, regulated sites can be no better than the correlation that exists between the site and an index station. The site and index stations, to be highly correlated, need to be reasonably proximate and subject to similar stresses and regulatory effects. As a result all but two of the 27 sites (sites 16293100 and 16297000) in table 9 had the highest correlation with an index station located within the same drainage basin. The coefficient of determination, standard error of the regression, and standard error of prediction are provided as measures of the strengths of the relations and accuracies of the estimates.

No regression statistics are provided for sites 34_5, 35, 251_5, and 16304500. Coefficients of determination for these sites were less than 0.60, or in the case of site 16304500, were based on an inadequate number of concurrent measurements. Although median streamflows are estimated for the four sites, they must be considered poor and of unknown accuracy. Standard errors of prediction for the remaining 23 sites vary between 5 and 34 percent and average 18 percent. The standard errors of prediction in table 9 represent an average error associated with estimated median streamflow at the site and corresponds only to the period of record at the index station. For example, site 187_5 in the Waikane basin was correlated with station 16294900, which has a period of record from 1959 to present (33 years). The estimated median streamflow for site 187_5 of 1.1 ft^3/s is the estimated median for the same period, or 1959 to present, and having a standard error of prediction of 28 percent. Standard errors provided for 23 of the sites in table 9 are comparable only when they are computed for the same period. In this study that means they would have had to be correlated to the same index station. The standard errors of prediction summarized above for regulated windward Oahu sites are likely to be representative of errors to be expected if the correlation techniques were applied to other ungaged, regulated or ungaged, unregulated perennial sites on the islands of Oahu, Kauai, Molokai, Maui, and Hawaii.

Changes in the regulatory patterns currently affecting the windward Oahu basins at the time of this study (1992) can alter flow regimes and therefore invalidate the estimated median streamflows as indicators of future median-streamflow conditions. The overall utility or accuracy of an estimated median as an indicator of future flow conditions is based on the standard errors of prediction provided in table 9 and the length of record at the index station. For example, all other statistics being equal, the site correlated with the index station having the longest period of record provides the best estimates of future conditions. Time-sampling errors introduced by using index stations with short-term records are not included in the standard errors given in table 9. Average time-sampling errors can be estimated by using the mean record length for the index stations used in the analysis (30 years) and data from table 2. As noted in table 2, the standard error when 30 years of record is available to compute the 1912 to 1986 median for station 16587000 is 10 percent.

SUMMARY

The State of Hawaii has selected median streamflow as the quantitative basis for establishing standards to protect instream uses of water. Median streamflow computed for the period of record at a gaging station has no time-sampling error because the median statistic was based on the entire population of daily mean discharges for the period. Estimates of long-term median streamflows at gaged sites with only short-term records have errors that are inversely proportional to the length of record. For example, at station 16587000, estimates of median streamflow for the base period 1912 through 1986 would have a standard error of 24 percent if only 5 years of record were available. The standard error would decrease to 6 percent if 50 years of record were available. Errors in estimates of long-term median streamflows at short-term stations can be reduced when adjusted by correlation with data from long-term stations. To estimate median streamflows at ungaged, unregulated, perennial stream sites in Hawaii, a total of 56 stations with at least 10 years of streamflow record that represent both perennial and unregulated conditions were identified. To allow direct comparison of median streamflows computed for each of the stations, record-extension techniques were used to adjust all data to reflect base-period (1912-1986) conditions. Median streamflows and basin characteristics for the 56 sites were used to develop multiple-regression equations. The equations can be used to estimate median streamflows at ungaged, unregulated, perennial stream sites in Hawaii.

As part of the regression analysis, Hawaii was divided into two groupings and separate equations were developed for each. The basin characteristics selected as providing the best estimates of median streamflow at ungaged, unregulated perennial sites were drainage area for Oahu, Molokai, and Hawaii, and drainage area, mean altitude of the main channel, and mean annual precipitation for Kauai and Maui. Standard errors of prediction for the two groupings were 41 percent (Oahu, Molokai, and Hawaii) and 54 percent (Kauai and Maui).

Median-streamflow estimates were made for 27 regulated, perennial windward Oahu sites. Estimates were based on correlations between discharge measurements made at the 27 sites and data available at proximate, hydrologically similar, continuous-record stations. Median-streamflow estimates provided for four of the sites were considered poor and no measures of accuracy were provided. Standard errors of prediction for the remaining 23 sites vary between 5 percent and 34 percent. These standard errors correspond to a median-streamflow estimate only for the period of record available at the correlated continuous-record stations. Techniques that use discharge measurements at the ungaged, regulated, perennial sites provide reasonable estimates of median streamflows. Discharge measurements can also be used to provide estimates of median streamflows at ungaged, unregulated sites. Estimates of median streamflows based on discharge measurements have greater errors than estimates based on continuous streamflow records and in general have smaller standard errors than estimates based on regression equations.

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