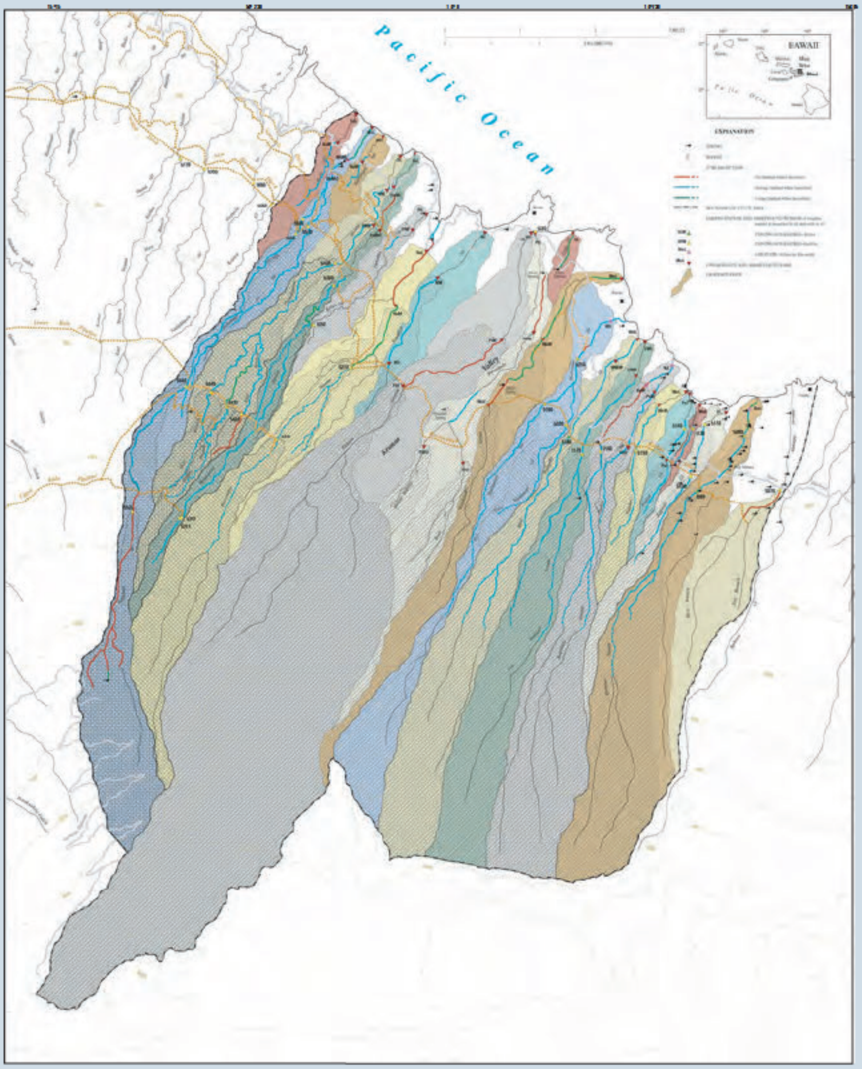
Prepared in cooperation with the
State of Hawaii Commission on Water Resource Management

Median and Low-Flow Characteristics for Streams under Natural and Diverted Conditions, Northeast Maui, Hawaii



Scientific Investigations Report 2004-5262

U.S. Department of the Interior
U.S. Geological Survey

EXHIBIT S-4

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By Stephen B. Gingerich

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U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
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Multiply	**By**	**To obtain**
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

Vertical coordinate information is referenced relative to local mean sea level.

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Median and Low-Flow Characteristics for Streams under Natural and Diverted Conditions, Northeast Maui, Hawaii

By Stephen B. Gingerich

Abstract

Flow-duration statistics under natural (undiverted) and diverted flow conditions were estimated for gaged and ungaged sites on 21 streams in northeast Maui, Hawaii. The estimates were made using the optimal combination of continuous-record gaging-station data, low-flow measurements, and values determined from regression equations developed as part of this study. Estimated 50- and 95-percent flow duration statistics for streams are presented and the analyses done to develop and evaluate the methods used in estimating the statistics are described. Estimated streamflow statistics are presented for sites where various amounts of streamflow data are available as well as for locations where no data are available.

Daily mean flows were used to determine flow-duration statistics for continuous-record stream-gaging stations in the study area following U.S. Geological Survey established standard methods. Duration discharges of 50- and 95-percent were determined from total flow and base flow for each continuous-record station. The index-station method was used to adjust all of the streamflow records to a common, long-term period. The gaging station on West Wailuaiki Stream (16518000) was chosen as the index station because of its record length (1914–2003) and favorable geographic location. Adjustments based on the index-station method resulted in decreases to the 50-percent duration total flow, 50-percent duration base flow, 95-percent duration total flow, and 95-percent duration base flow computed on the basis of short-term records that averaged 7, 3, 4, and 1 percent, respectively.

For the drainage basin of each continuous-record gaged site and selected ungaged sites, morphometric, geologic, soil, and rainfall characteristics were quantified using Geographic Information System techniques. Regression equations relating the non-diverted streamflow statistics to basin characteristics of the gaged basins were developed using ordinary-least-squares regression analyses. Rainfall rate, maximum basin elevation, and the elongation ratio of the basin were the basin characteristics used in the final regression equations for 50-percent duration total flow and base flow. Rainfall rate and maximum basin elevation were used in the final regression equations for the 95-percent duration total flow and base flow. The relative errors between observed and estimated flows ranged from 10 to 20 percent for the 50-percent duration total flow and base flow, and from 29 to 56 percent for the 95-percent duration total flow and base flow.

The regression equations developed for this study were used to determine the 50-percent duration total flow, 50-percent duration base flow, 95-percent duration total flow, and 95-percent duration base flow at selected ungaged diverted and undiverted sites. Estimated streamflow, prediction intervals, and standard errors were determined for 48 ungaged sites in the study area and for three gaged sites west of the study area. Relative errors were determined for sites where measured values of 95-percent duration discharge of total flow were available. East of Keanae Valley, the 95-percent duration discharge equation generally underestimated flow, and within and west of Keanae Valley, the equation generally overestimated flow. Reduction in 50- and 95-percent flow-duration values in stream reaches affected by diversions throughout the study area average 58 to 60 percent.

Introduction

For more than a century, surface-water diversion systems have transported water from the wet, northeastern part of Maui, Hawaii, to the drier, central part of the island, mainly for large-scale sugarcane cultivation. Since the 1930’s, the Territory and then the State issued water permits to Alexander and Baldwin, Inc., Hawaiian Commercial and Sugar Co., and East Maui Irrigation Co., Ltd. (EMI), for the diversion of water from streams in northeast Maui. The collection system consists of 388 separate intakes, 24 miles of ditches, and 50 miles of tunnels, as well as numerous small dams, intakes, pipes, and flumes (Wilcox, 1996). With few exceptions, the diversions capture all of the base flow, which represents the ground-water contribution to total streamflow, and an unknown percentage of total streamflow at each stream crossing. During 1925–97, total flow for the diversion systems measured at Honopou Stream, to the west of the study area where records of total diversion-system flow are most complete, averaged about 163 Mgal/d (million gallons per day) (Gingerich, 1999). The highest average flow for an individual ditch system was measured in the Koolau/Wailoa Ditch system, where total flow crossing Honopou Stream averaged 110 Mgal/d for 1924–87. The source of diverted water is a watershed with an area of about 56,000 acres, about two-thirds of which is owned by the State (Wilcox, 1996) and managed by the State Department of Land and Natural Resources.

The Hawaii State Water Code mandates that the Commission on Water Resource Management (CWRM) establish a statewide instream-use protection program (Chapter 174C-71, Hawaii Revised Statutes). The principal mechanism that CWRM has for the protection of instream uses is establishing instream flow standards. "Each instream flow standard shall describe the flows necessary to protect the public interest in the particular stream. Flows shall be expressed in terms of variable flows of water necessary to protect adequately fishery, wildlife, recreational, aesthetic, scenic, or other beneficial instream uses in the stream in light of existing and potential water developments including the economic impact of restriction of such use" (Chapter 174C-71, Hawaii Revised Statutes). CWRM has recognized certain instream uses as beneficial, including: (1) maintenance of fish and wildlife habitat, (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) maintenance of water quality, (6) conveyance of irrigation and domestic water supplies to downstream points of diversion, and (7) protection of traditional and customary Hawaiian rights.

The U.S. Geological Survey, in cooperation with CWRM and in collaboration with the Maui Department of Water Supply, the Hawaii State Board of Land and Natural Resources, and East Maui Irrigation Co., Ltd., undertook an investigation to assist in determining equitable, reasonable, and beneficial instream and off-stream uses of the surface-water resources of northeast Maui. The overall objectives of the 3-year study are to (1) assess the effects of existing surface-water diversions on flow characteristics for perennial streams in northeast Maui, (2) characterize the effects of diversions on instream temperature variations, and (3) estimate the effects that streamflow restoration (full or partial) will have on habitat availability for native stream fauna (fish, shrimp, and snails) in northeast Maui. Scientific information generated by the overall study will allow CWRM to complete its work on documenting water rights and uses associated with northeast Maui streams and analyzing the economic effects of curtailing existing uses on the streams, and to then establish technically defensible instream flow standards for those streams.

Purpose and Scope

This report addresses objective 1 described above. This report presents selected estimated flow-duration statistics for streams in northeast Maui, Hawaii, and describes the analyses done to develop and evaluate the methods used in estimating the statistics. Estimated streamflow statistics are presented for sites where various amounts of streamflow data are available and for locations where no data are available. Morphometric, hydrologic, and geologic basin characteristics are provided for each stream basin in the study area. Equations used to estimate the 50- and 95-percent duration flows of total streamflow and stream base flow at ungaged locations are presented. An evaluation of the accuracy of the equations and limitations for their use is also provided. Most-reliable estimates of streamflow statistics for natural (undiverted) and unnatural (diverted) sites on 21 streams and the basis for these estimates are provided. The statistics for undiverted and diverted flow were compared to assess the effects of existing surface-water diversions on flow characteristics for perennial streams in northeast Maui.

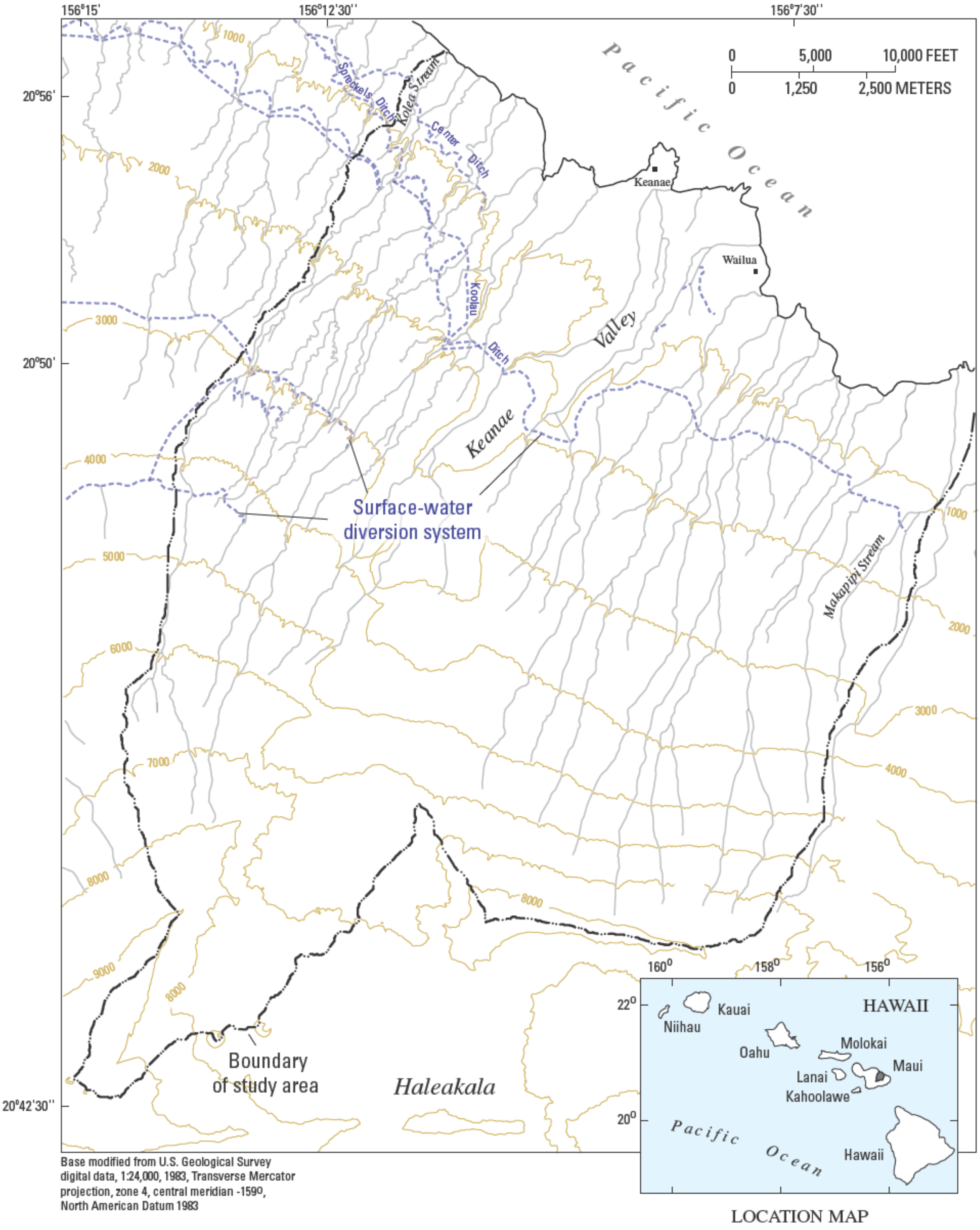
Description of Study Area

The study area lies on the northern flank of the East Maui Volcano (Haleakala), which forms the eastern part of the island of Maui, the second-largest island in the Hawaiian archipelago. The study area, covering about 67 mi2, is bounded to the north by about 11 mi of coastline and lies between (and includes) the drainage basins of Kolea Stream to the west and Makapipi Stream to the east (fig. 1). Land-surface altitudes range from sea level to 10,000 ft at the summit of Haleakala. The topography is gently sloping except for the steep sides of gulches and valleys that were eroded by the numerous streams. The largest valley is Keanae Valley, which extends from the coast to Haleakala Crater where the valley walls are nearly 1,000 ft high. Most of the study area is made up of forest reserves; at intermediate altitudes, rain forests densely cover the slopes up to about 7,000 ft. Grasses and shrubs cover the upper slopes to the north wall of Haleakala Crater. Two small villages (Keanae and Wailua) are at low altitudes along the coast at the mouth of Keanae Valley. Land use around the villages is mainly small-scale agriculture, including wetland taro cultivation.

Streams flow generally south to north from the high altitude flank of Haleakala to the coast. Twenty-two named streams reach the coast in the study area. Access to streams is made difficult by the steep rugged terrain of the incised stream valleys and dense native and non-native vegetation. Rainfall is highly orographic and rates average between about 45 in/yr at the summit of Haleakala to greater than 350 in/yr at about 2,500-ft altitude. Rainfall at the coast ranges from 120 to 160 in/yr (Giambelluca and others, 1986).

Previous Studies

Low-flow duration statistics have not previously been estimated specifically for ungaged streams in the study area of northeast Maui. Fontaine and others (1992) developed regression equations (one for Oahu, Molokai, and Hawaii, and one for Maui and Kauai) to estimate median flows at ungaged, unregulated, perennial streams in the State. Data from gaging stations on ten streams in the northeast Maui study area were used in developing the median-flow equations. Hirashima (1965) and Matsuoka (1983) computed flow statistics for gaging stations throughout the State of Hawaii, including some stations in the study area. Yamanaga (1972) developed regression equations for low-flow frequency to describe annual minimum 7-day and 30-day mean flows at 2- and 20-year recurrence intervals using data from selected windward and leeward gaged basins across the State, including 14 stations in the current study area. The equations and flow-duration statistics presented in this report supersede any previously reported equations or flow-duration statistics. Gingerich (1999)



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Transverse Mercator projection, zone 4, central meridian -159°, North American Datum 1983

Figure 1. Northeast Maui study area, island of Maui, Hawaii.

described the ground-water occurrence and contribution to streamflow for northeast Maui covering an area encompassing the current study area. That report detailed the amount of streamflow, base flow, and surface-water diversions in streams and gave detailed descriptions of low-flow measurements made in many of the streams in the current study area.

Numbering System for Surface-Water Gaging Stations

The surface-water gaging stations mentioned in this report are numbered according to the USGS "downstream order" numbering system. Station numbers increase in a downstream direction along the main stream. All stations on a tributary entering upstream from a mainstream station have lower station numbers. A station on a tributary that enters between two mainstream stations is given a number between those two station numbers. In this report, the complete 8-digit downstream-order number for each gaging station has been abbreviated to the middle four digits, for example, 16518000 becomes 5180.

Acknowledgments

The author would like to thank Chiu Yeung and Chien-Hwa Chen for delineating drainage basins and determining the basin characteristics, and Richard Fontaine and Michael Wong for assistance with the statistical analysis used in this report. Layout work on this report was done by Luis Menoyo. East Maui Irrigation Co., Ltd. provided cooperation and assistance in accessing the study area.

Streamflow Characteristics at Continuous-Record Stream-Gaging Stations

Values of daily mean flow are used to determine total streamflow and base flow flow-duration statistics for continuous-record stream-gaging stations. The USGS has operated 16 continuous-record stream-gaging stations for various periods at unregulated sites in or near the northeast Maui study area since 1910 (Fontaine, 1996), although only two of these stations (station 5080 on Hanawi Stream near Nahiku and station 5180 on West Wailuaiki Stream near Keanae) are currently active (Plate 1, table 1). In addition, records from 17 continuous-record stream-gaging stations on regulated sites are available for analysis.

The USGS established standard methods for estimating flow-duration statistics for stream-gaging stations (Searcy, 1959). A flow-duration curve is a graphical representation of the percentage of time streamflows for a given time interval (usually daily) are equaled or exceeded over a specified period at a stream site (fig. 2). Flow-duration curves are constructed by first ranking all of the daily mean discharge values for the period of record at a gaging station, next computing the probability of each value being equaled or exceeded, and then plotting the discharges against their associated exceedance probabilities. Flow-duration statistics are points along the flow-duration curve. For example, the 50-percent duration streamflow (or median streamflow; Q_{50}) has been exceeded 50 percent of the time during the specified period. Flow-duration statistics reflect streamflow conditions only for the period of record for which they were calculated. If the period of record analyzed is sufficiently long, the flow-duration statistics can be considered an indicator of probable future conditions (Searcy, 1959). In an analysis of the data from five long-term stream gages on Oahu, the median discharge determined from a 10-yr streamflow record had a standard error of 15 percent, whereas the standard error for the median discharge determined from a 50-yr record improved to 6 percent (Fontaine, 1996).

At three regulated gaging stations (5090, 5110, and 5210), total unregulated streamflow was calculated by adding the daily flows for the gaging station of interest to the corresponding daily flows for an upstream gaging station on the same stream but above the 1,300-ft (Koolau Ditch) diversion (the flows at stations 5080, 5100, and 5190 plus 5200, respectively). Flow-duration statistics were then calculated using the combined record. This technique is appropriate for estimating the low flows of interest in this study because the diversion captures all low flows much greater than the value of the median total flow, TFQ_{50}, so that the downstream gaging station on each stream measures only that flow gained below the diversion. Combined flows at the downstream gaging station estimated from this technique are incorrect only when the diversion is overtopped, which is generally 20 to 30 percent of the time.

The assumption that the diversion systems within the 1,700- to 1,200-ft altitude interval intercept all low streamflows up to at least the TFQ_{50} is based on measurements made at four stream diversions in the study area. The overtopping discharges in the four monitored streams were significantly greater than the TFQ_{50} discharge for each stream. These sites are separated into two categories: (1) sites on West Wailuaiki and Hanawi Streams where water levels at the diversion structures and streamflow were measured concurrently at active continuous-record gaging stations, and (2) sites on Waikamoi and Honomanu Streams, where water levels at the diversion structures were measured concurrently with water levels at staff plates from former continuous-record gaging stations (fig. 3). At all four sites, submersible transducers were used to monitor the water level in the stream every 15 minutes relative to the crests of the diversion dams preventing water from flowing further downstream. When a transducer indicated that the water level was higher than the crest of the diversion dam, it was assumed that water was flowing downstream past the diversion dam. When the transducer indicated that the water level was lower than the crest of the diversion dam, it was assumed that all flow in the stream was captured by the diver-

Table 1. Continuous-record surface-water gaging stations operated by the U.S. Geological Survey, northeast Maui, Hawaii.

[Abbreviated station numbers are highlighted in **bold**; active station locations are shown in ***bold italics***]

Gaging-station number	Station location	Period of record	Station altitude (feet)	Low flow regulated during period of record
16**5070**00	Makapipi Stream	1932-45	920	Yes
16**5080**00	***Hanawi Stream***	1914-15, 1921-Present	1,318	No
16**5090**00	Hanawi Stream	1932-47, 1992-95	500	Yes
16**5100**00	Kapaula Gulch	1921-63	1,346	No
16**5110**00	Kapaula Gulch	1932-47	540	Yes
16**5130**00	Waiaaka Stream	1932-47	650	Yes
16**5140**00	Paakea Gulch	1932-47	650	Yes
16**5150**00	Waiohue Gulch	1921-63	1,316	No
16**5160**00	Kopiliula Stream	1914-17, 1921-1958	1,292	No
16**5170**00	East Wailuaiki Stream	1914-17, 1922-58	1,329	No
16**5180**00	***West Wailuaiki Stream***	1914-17, 1921-Present	1,343	No
16**5190**00	West Wailuanui Stream	1914-17, 1921-58	1,268	No
16**5200**00	East Wailuanui Stream	1914-17, 1921-58	1,287	No
16**5210**00	Wailuanui Stream	1932-36, 1938-47	620	Yes
16**5220**00	Palauhulu diversion ditch to Keanae[a]	1934-68	51	Yes
16**5240**00	Honomanu Stream	1921-27, 1932-34, 1962-68	2,900	No
16**5270**00	Honomanu Stream	1914-17, 1921-64	1,733	No
16**5310**00	Kula diversion from Haipuaena Stream	1946-68	4,320	Yes
16**5311**00	Haipuaena Stream	1946-68	4,320	Yes
16**5350**00	Haipuaena diversion ditch to Kolea Stream	1938-60	1,866	Yes
16**5360**00	Haipuaena Stream	1946-60	1,512	Yes
16**5420**00	East Branch Puohokamoa Stream	1921-27, 1931-33	2,800	No
16**5430**00	Middle Branch Puohokamoa Stream	1921-27, 1932-34, 1962-69	2,900	Yes
16**5440**00	West Branch Puohokamoa Stream	1921-28, 1932-34	2,800	Yes
16**5450**00	Puohokamoa Stream	1914-17, 1921-71	1,322	Yes
16**5528**00	Waikamoi Stream	1953-68	4,487	Yes
16**5540**00	Waikamoi Stream	1921-28, 1932-34	3,000	Yes
16**5545**00	East Branch Waikamoi Stream	1921-28, 1932-33	3,020	Yes
16**5550**00	Waikamoi Stream	1922-57	1,294	Yes
16**5560**00	Waikamoi Stream	1914-17, 1921-22	1,150	Yes
16**5570**00	Alo Stream	1914-17, 1921-57	1,248	No
16**5650**00[b]	Kaaiea Gulch	1921-62	1,310	No
16**5660**00[b]	Oopuola Stream	1930-57	1,205	No
16**5700**00[b]	Nailiihaele Stream	1910-11, 1913-75	1,205	No
16**5770**00[b]	Kailua Stream	1910-11, 1913-58	1,253	No

[a] USGS station previously published as "Taro patch feeder ditch at Keanae, Maui"

[b] located west of current study area

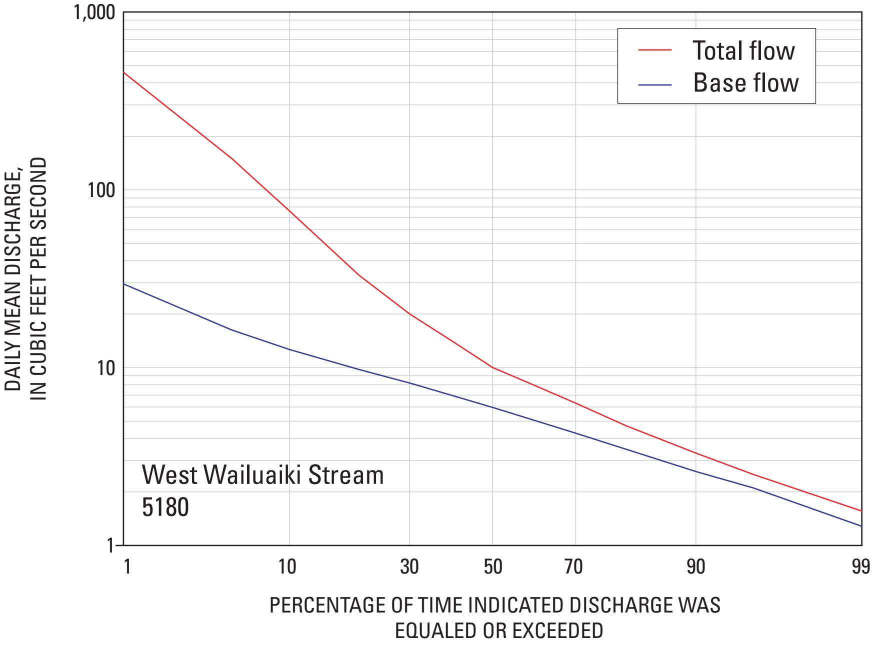


Figure 2. Flow-duration curves of total streamflow and base flow at gaging station 5180 on West Wailuaiki Stream, northeast Maui, Hawaii, for period 1914-2002.

sion and the stream was dry immediately downstream of the diversion.

At West Wailuaiki and Hanawi Streams, the water levels were compared with discharge determined from stage measurements made every 15 minutes at the active continuous-record gaging stations upstream (stations 5180 and 5080, respectively). Relation plots of water level and stream discharge show the range of discharges at which the diversion dam is overtopped and flow continues downstream. For West Wailuaiki Stream, the overtopping is initiated at discharge ranging from 20 to 30 ft^3/s (TFQ$_{30}$ to TFQ$_{20}$ on the basis of the flow-duration plot in fig. 2). In other words, streamflow does not pass the diversion dam at 1,300 ft on West Wailuaiki Stream roughly 70 to 80 percent of the time. On Hanawi Stream, the overtopping discharge ranges from 15 to 30 ft^3/s (TFQ$_{25}$ to TFQ$_{15}$ on the basis of the flow-duration plot for station 5080 discussed later in fig. 7). Streamflow does not pass the dam at 1,300 ft on Hanawi Stream roughly 75 to 85 percent of the time.

At Honomanu and Waikamoi Streams, the water levels relative to the crests of the diversion dams were compared to water levels collected every 15 minutes at staff plates bolted into the bedrock in former gaging station pools upstream from the dams. Ratings for these staff plates are available from the U.S. Geological Survey archives for the time when the stations were discontinued in 1957. Although some erosion on the bedrock and concrete controls at these former gaging stations was observed, the assumption was made that the ratings for staff plates would still provide a reasonable range of flow estimates in the stream to estimate the overtopping discharge. At Honomanu Stream, the overtopping discharge ranges from 15 to 18 ft^3/s (TFQ$_{25}$ to TFQ$_{22}$ on the basis of the flow-duration plot for station 5270 discussed later in fig. 7). Therefore, streamflow does not pass the diversion dam at 1,720 ft on Honomanu Stream roughly 75 to 78 percent of the time. On Waikamoi Stream, where the water level-discharge relation recorded is more variable, the overtopping discharge is at least 25 ft^3/s (TFQ$_{20}$ on the basis of the flow-duration plot for station 5550 discussed later in fig. 7). Streamflow does not pass the diversion dam at 1,200 ft on Waikamoi Stream roughly 80 percent of the time.

The technique used to determine the combined median and low-flow statistics for a gaging station downstream of the major diversion can be illustrated by using data from Hanawi Stream. From gaging station 5080, upstream of the Koolau diversion, TFQ$_{50}$ is 7.1 ft^3/s (table 2) and from gaging station 5090, downstream of the Koolau diversion and several spring inflows, TFQ$_{50}$ is 22 ft^3/s. Because the Koolau Ditch captures at least 15-30 ft^3/s at Hanawi Stream near 1,300 ft altitude, the median flows measured at gaging station 5090 are only those flows gained downstream of the Koolau diversion. The combined TFQ$_{50}$ at gaging station 5090 is estimated to be 29 ft^3/s (7.1 + 22 ft^3/s). Median and low-flow statistics for 5090 were generated in two ways, from combined daily flows at the two stations and by adding the statistics calculated from each station's daily flows individually (Table 3). The results of each calculation compare favorably, indicating that, for the study area, flow statistics for sites on gaining streams above and below the major diversion can be estimated by adding the statistics for each site. For the three stations in the study area (5090, 5110, and 5210), the value determined from adding the flow statistics was always less than the value determined

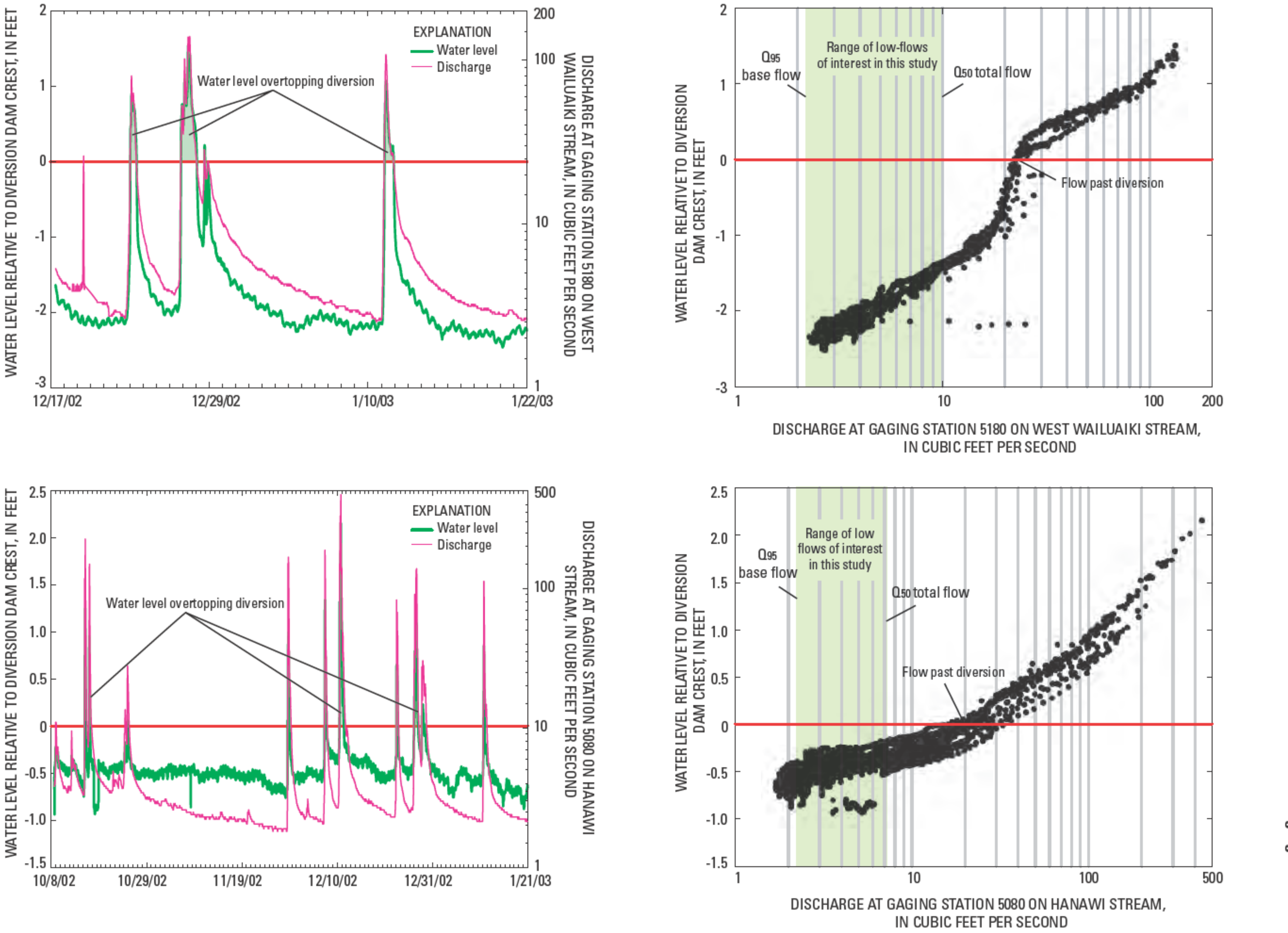


Figure 3. Relation between water level and stream discharge at diversions on selected streams within the 1,700- to 1,200-ft altitude interval, northeast Maui, Hawaii.

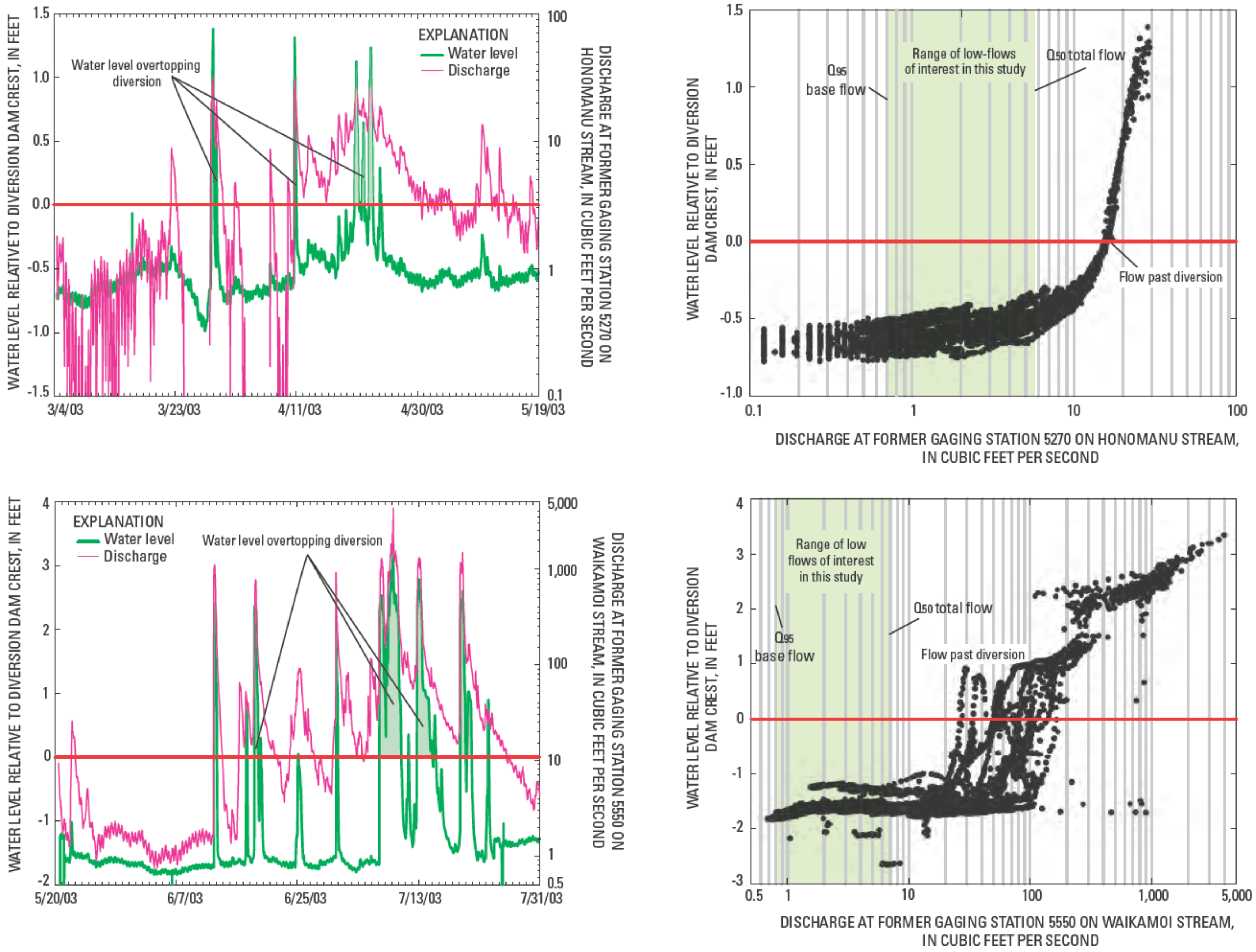


Figure 3. Relation between water level and stream discharge at diversions on selected streams within the 1,700- to 1,200-ft altitude interval, northeast Maui, Hawaii—Continued.

Table 2. Selected estimated median and low-flow characteristics for continuous-record sites, northeast Maui, Hawaii.

[Qxx is the xx-percent flow duration of streamflow; ft³/s, cubic feet per second; base period is 1914-17, 1921-2001; active stations are shown in ***bold italics***; +, combined with record from indicated station; index station is station 5180; --, no adjustment; NA, not applicable]

Gaging-station number	Length of concurrent record (years)	Q_{50} total flow		Q_{50} base flow		Q_{95} total flow		Q_{95} base flow	
		during concurrent period (ft³/s)	adjusted to index station (ft³/s)	during concurrent period (ft³/s)	adjusted to index station (ft³/s)	during concurrent period (ft³/s)	adjusted to index station (ft³/s)	during concurrent period (ft³/s)	adjusted to index station (ft³/s)
5070	13	2.9	2.2	1.6	1.3	0.00	0.00	0.00	0.00
5080	82	7.1	--	4.6	--	2.4	--	2.2	--
5090+5080	18	29	28	25	24	19	19	19	19
5100	42	5.2	4.9	2.9	2.8	1.3	1.1	1.0	0.90
5110+5100	15	8.1	7.5	5.3	5.1	3.4	3.3	3.1	3.0
5130	15	0.90	0.86	0.79	0.77	0.54	0.54	0.54	0.53
5140	15	4.2	4.0	3.9	3.8	3.1	3.0	3.1	3.0
5150	42	6.5	6.2	5.0	5.0	3.1	3.0	2.9	2.8
5160	40	9.1	8.0	5.4	5.0	2.6	2.3	2.1	2.0
5170	39	10	9.1	6.1	5.7	3.1	2.8	2.6	2.5
5180	83	10	--	6.0	--	2.5	--	2.1	--
5190	40	5.1	4.4	2.7	2.4	1.1	1.0	0.93	0.85
5200	40	3.7	3.2	2.2	2.0	1.0	0.90	0.82	0.80
5210+5190+5200	13	9.8	10	5.6	6.1	2.4	2.5	2.1	2.0
5220[a]	34	3.4	--	NA	NA	2.4	--	NA	NA
5240	14	2.0	2.2	0.88	0.93	0.31	0.37	0.28	0.30
5270	46	6.2	5.7	3.0	2.8	1.2	1.0	0.82	0.74
5311+5310[a]	22	0.46	0.50	0.15	0.17	0.05	0.03	0.03	0.03
5360+5310[a]+5350	14	6.8	6.8	3.5	3.5	2.1	1.7	1.6	1.3
5420	8	0.93	0.88	0.58	0.53	0.31	0.29	0.19	0.27
5430	15	1.3	1.4	0.62	0.67	0.18	0.21	0.12	0.15
5440	9	1.9	1.9	1.1	1.0	0.46	0.55	0.37	0.44
5450	53	13	12	6.8	6.4	2.8	2.5	2.2	2.1
5528	15	0.12	0.14	0.05	0.06	0.02	0.02	0.02	0.01
5540	7	2.5	2.5	1.3	1.2	0.62	0.69	0.32	0.46
5545	8	1.5	1.3	0.80	0.72	0.46	0.47	0.37	0.43
5550	35	7.9	7.0	3.8	3.5	1.3	1.1	0.89	0.80
5560	4	15	7.1	5.1	3.6	2.0	1.5	1.6	1.0
5570	39	3.1	2.7	1.6	1.4	0.77	0.70	0.62	0.58

[a] gaging station on diversion ditch

Table 3. Comparison of flow statistics computed for stream sites where natural flows are estimated, using data from multiple continuous-record gaging stations, northeast Maui, Hawaii.

[All flows are in cubic feet per second; relative error is (column 4 – column 5)/column 4 x 100]

Flow statistic	Downstream gaging station	Upstream gaging station		Sum of upstream and downstream flow statistic	Flow statistic based on combined up-stream and down-stream daily flows	Relative error, in percent
	5090	**5080**				
TFQ_{50}	19	7.1		26	28	-7
BFQ_{50}	19	4.6		24	24	0
TFQ_{95}	16	2.4		18	19	-5
BFQ_{95}	16	2.2		18	19	-5
	5110	**5100**				
TFQ_{50}	4.7	2.4		7.1	7.5	-5
BFQ_{50}	2.8	2.2		5.0	5.1	-2
TFQ_{95}	1.1	1.9		3.0	3.3	-9
BFQ_{95}	0.90	1.9		2.8	3.0	-7
	5210	**5190**	**5200**			
TFQ_{50}	1.6	4.4	3.2	9.2	10	-8
BFQ_{50}	1.0	2.4	2.0	5.4	6.1	-11
TFQ_{95}	0.39	1.0	0.90	2.3	2.5	-8
BFQ_{95}	0.32	0.85	0.80	2.0	2.0	0

by first combining the concurrent daily flows, but the relative error in the value determined from adding the flow statistics was less than or equal to 10 percent in each case.

On Haipuaena Stream (plate 1), gaging station 5310 recorded diverted flow into the Upper Kula Pipeline near 4,300 ft altitude, and gaging station 5311 recorded streamflow past the diversion (Fontaine, 1996). These two records were added together to obtain the total streamflow at this altitude. Further downstream, flow diverted in Kolea Stream was measured at gaging station 5350. This flow was added to that at gaging station 5360 (1,512 ft altitude) upstream of Spreckels Ditch and gaging station 5310 to obtain a value for total streamflow at 1,512 ft altitude.

Gingerich (1999) used a computerized base-flow separation method described by Wahl and Wahl (1995) to estimate the base-flow component of streamflow for northeast Maui streams. Two variables, N (number of days) and f (turning-point test factor) must be assigned values in the method. The method divides the daily streamflow record into non-overlapping N-day periods and determines the minimum flow within each N-day window. If the minimum flow within a given N-day window is less than f times the minimums in the adjacent N-day windows, then the central window minimum is made a turning point on the base-flow hydrograph. Wahl and Wahl (1995) recommend a value of 0.9 for the turning-point test factor for most applications. The value of N determined for each stream is shown in table 2 of Gingerich (1999). A base-flow-duration curve can than be constructed using the daily base-flow data (fig. 2).

Streamflow records generally are adjusted to a common base period for comparison so that differences in flow among stations reflect spatial differences in climate and drainage-basin characteristics and not simply temporal differences in rainfall. Flow-duration curves based on short records are unreliable for predicting the future flow pattern, but they can be made more reliable by adjusting them to represent longer periods. The index-station method described in Searcy (1959) was used to adjust all of the streamflow records used in this analysis to a common period (called the base period).

Index station selection

The two currently active continuous-record gaging stations (5180 on West Wailuaiki Stream and 5080 on Hanawi Stream) are the obvious candidates for index stations in this study. Both have been operated nearly continuously from 1914 to the present (2004), with a break during 1918–1920. The median total (TFQ_{50}) and median base flow (BFQ_{50}) for gaging station 5180 are 10 ft^3/s and 6.0 ft^3/s, respectively, and the TFQ_{50} and BFQ_{50} for gaging station 5080 are 7.1 ft^3/s and 4.6 ft^3/s, respectively (fig. 4 and table 2).

The records for gaging-stations 5180 and 5080 appear to have long-term downward trends in annual median total flow and base flow during the period 1914–present (fig. 4) and a Kendall's Tau trend test (Helsel and Hirsch, 1992) on those flow statistics confirms such a trend (table 4). Rather than decreasing monotonically, the flow might actually have decreased in a stepwise manner, and examination of figure 4 indicates that such a stepwise decrease may have occurred about 1941–42. The median total flow at gaging station 5180 during 1914–42 was 14 ft^3/s, and after 1942 was 9.6 ft^3/s. Analysis of a subset of the data, for the period 1942–2001, shows no statistical trend in median streamflow after the indicated earlier stepped decrease in flow (table 4). No obviously apparent reason exists for such a stepped decrease in median total flow and base flow about 1941–42. Such stepped changes in flow trends are typically caused by changes in a watershed such as reforestation or by the addition of a streamflow diversion but there is little evidence that these factors caused the changes in flow at stations 5180 (on West Wailuaiki Stream) and 5080 (on Hanawi Stream). Helsel and Hirsch (1992) strongly caution against performing step-trend analysis without prior knowledge of an event that would contribute to such a change in streamflow. Additionally, rainfall records for this area do not cover the entire period of streamflow record so it is not possible to determine if rainfall patterns have changed similarly to the flow. Therefore, flow statistics for these stations were calculated on the basis of the entire period of record with no adjustments made for monotonic or step-wise trends in the data.

Gaging station 5180 on West Wailuaiki Stream is favorably located geographically as an index station, because it is near the center of the study area, whereas gaging station 5080, on Hanawi Stream, is at the eastern end of the study area. Therefore, all adjustments of streamflow characteristics to a common base period for the continuous-record stations were made using only gaging station 5180 as the index station. The record for gaging station 5080 was not adjusted because the record was the same length as the index-station base period.

Adjustments to streamflow characteristics for a common period using the index-station method

Relations between the index station and each shorter-term record at the other gaging stations were developed using the following steps (Searcy, 1959):

1. Flow-duration curves were developed for the station with a short-term record and the index-station record for concurrent periods of record.

2. Discharges for 13 flow-duration points, ranging from 1 to 99 percent, at the short-term station were plotted on logarithmic scales against the same flow-duration points at the index station.

3. A line or smooth curve was drawn through the points. The upper part of the line is typically a 45-degree line parallel (assuming 1 log cycle on x-axis is same length as 1 log cycle on y-axis) to lines of equal yield (drainage-area ratio) and equal flow (rainfall ratio) if the

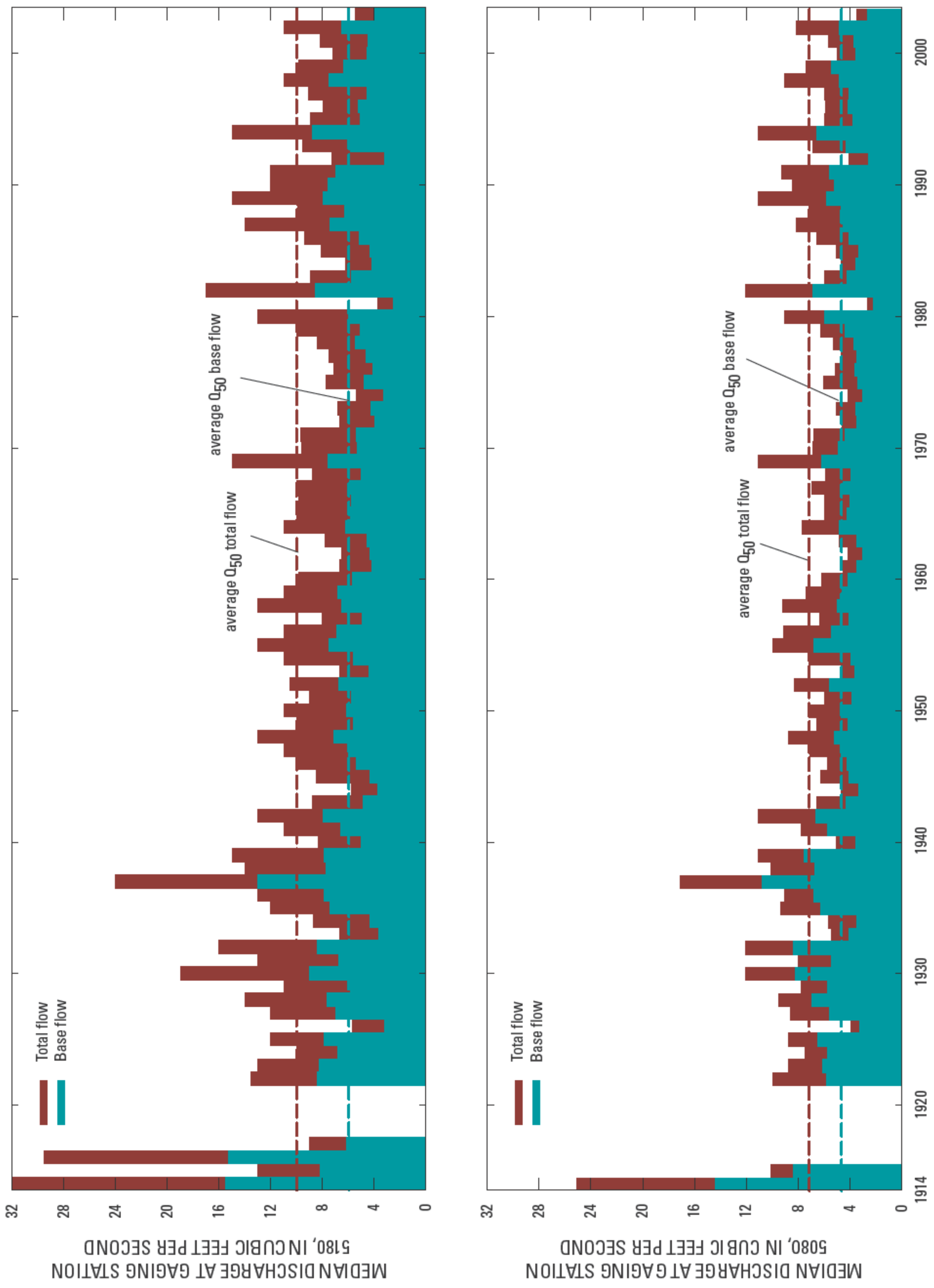


Figure 4. Annual median streamflow and base flow for 1914-2002 at gaging stations 5180 on West Wailuaiki Stream and 5080 on Hanawi Stream, northeast Maui, Hawaii.

Table 4. Trend analysis of annual median flow at active gaging station records for West Wailuaiki (5180) and Hanawi (5080) Streams, northeast Maui, Hawaii.

[Statistically significant trends shown in **bold**]

Gaging station number	Annual median streamflow	Period of record	Kendall's Tau	P-level	Slope of trend
5180	Total flow	1914-17, 1921-2001	-0.171	0.022	**-0.039**
5180	Base flow	1914-17, 1921-2001	-0.210	0.005	**-0.025**
5080	Total flow	1914-15, 1921-2001	-0.194	0.010	**-0.030**
5080	Base flow	1914-15, 1921-2001	-0.296	0.000	**-0.025**
5180	Total flow	1942-2001	0.012	0.893	0.000
5180	Base flow	1942-2001	0.005	0.964	0.001
5080	Total flow	1942-2001	-0.010	0.919	0.000
5080	Base flow	1942-2001	-0.069	0.440	-0.005

streams have similar high flow characteristics. Deviation from the line at the lower points is commonly an indication of different geologic characteristics that effect low flows between the stream basins.

4. The adjusted discharges at the various flow-duration points for the short-term station are graphically determined from the plot using the corresponding flow-duration points from the index station for the entire period of record (base period) of the index station.

For example, selected flow-duration points for total flow and base flow at gaging station 5170 on East Wailuaiki Stream, which was operated during 1914–17 and 1922–58, are plotted against the flow-duration points for the index station (5180) during the same period on logarithmic axes (fig. 5) and smooth fitting lines are drawn through the points. Matching base period flow-duration points are determined from the relation plot (e.g. base period TFQ_{50} at station 5180 = 10 ft^3/s and adjusted TFQ_{50} at station 5170 = 9.0 ft^3/s; base period TFQ_{95} at station 5180 = 2.5 ft^3/s and adjusted TFQ_{95} at station 5170 = 2.8 ft^3/s) and then plotted to determine the adjusted flow-duration curve for station 5170 (fig. 6). Similar relation plots and adjusted flow-duration curves were computed for 26 continuous-record gaging stations for streams in the study area (fig. 7).

The adjusted Q_{50} and Q_{95} statistics for total flow and base flow for the 26 stations are listed in table 2. Adjustments to TFQ_{50} ranged from a 17-percent increase (station 5528) to a 53-percent decrease (station 5560), and averaged a 6-percent decrease. Adjustments to TFQ_{95} ranged from a 20-percent increase (station 5440) to a 40-percent decrease (stations 5310 + 5311) and averaged a 5-percent decrease. Adjustments to BFQ50 ranged from a 20-percent increase (station 5528) to a 29-percent decrease (station 5560) and averaged a 4-percent decrease. Adjustments to BFQ_{95} ranged from a 44-percent increase (station 5540) to a 50-percent decrease (station 5528) and averaged a 1-percent decrease. In general, the largest adjustments were needed for stations with the shortest record lengths.

The point on the total flow-duration curve at which streamflow is equivalent to median base flow provides added information about the ground-water contribution to streamflow. BFQ_{50} ranges from 56 percent to 78 percent on the total flow-duration curve for the gaged basins and averages 70 percent (table 5). BFQ_{95} ranges from 95 percent to 98 percent on the total flow duration curve for the gaged basins and averages 96 percent. Gaging stations east of the index station on West Wailuaiki Stream all have the same or higher rainfall-normalized low flow relative to the index station, indicating a higher ground-water contribution to these streams. The mapped springs that contribute to the low flows in these streams are listed in the “Comments” column in table 5. Gaging stations west of the index station generally have the same or lower rainfall-normalized low flows relative to the index station, indicating that the ground-water contribution to streamflow is relatively less to the west. The effects of minor upstream diversions in this area also are apparent from the relatively lower low-flows measured at the gaging stations.

Estimation of Flow Characteristics of Ungaged Streams

Multiple linear-regression analysis is a standard technique used to develop equations for estimating streamflow statistics for ungaged sites (Koltun and Schwartz, 1986; Vogel and Kroll, 1990; Ludwig and Tasker, 1993; Ries and Friesz, 2000). In this study, a selected streamflow statistic (the duration discharges TFQ_{50}, TFQ_{95}, BFQ_{50}, or BFQ_{95}) at unregulated, gaged sites was the dependent variable and the quantified basin characteristics, rainfall rates, and surficial geologic units were the independent variables used as input in the regression analysis. The regression analysis statistically relates the dependent variable to the independent variables and results in an equation that can be used to estimate the selected streamflow statistic for a site where no streamflow data are available. The goal of the regression algorithm is to minimize the differences between the values of the dependent variable used in the analysis (observed values) and the corresponding values provided by the regression equations (estimated or fitted values).

Drainage-Basin Characteristics

For the drainage basin of each continuous-record gaged site and selected ungaged sites, the morphometric, geologic, and rainfall characteristics were quantified using Geographic Information System (GIS) techniques.

Morphometric characteristics

Drainage basins were delineated on the basis of 10-meter digital elevation model (DEM) data and the GIS program GISWeasel (U.S. Geological Survey, 2004). The drainage basins thus delineated (plate 1) were checked against existing manually determined drainage-basin boundaries for gaged sites to ensure the reliability of the computerized delineation routine. Minor adjustments were made to the boundaries of those drainage basin for which the computer-delineated drainage area differed from the manually determined drainage area by more than 5 percent (Chiu Yeung, U.S. Geological Survey, written commun., 2003). The GIS program Basinsoft (Harvey and Eash, 1996) was used to quantify basin characteristics considered in the regional regression analysis. Basinsoft uses GIS data layers of drainage divides, hydrography, and a digital elevation model to automatically and efficiently quantify 22 morphometric characteristics for each drainage basin selected. These characteristics are described in Appendix A. Computed basin characteristics for the gaged basins are listed in Table 6 and those for selected ungaged basins are listed in table 7.

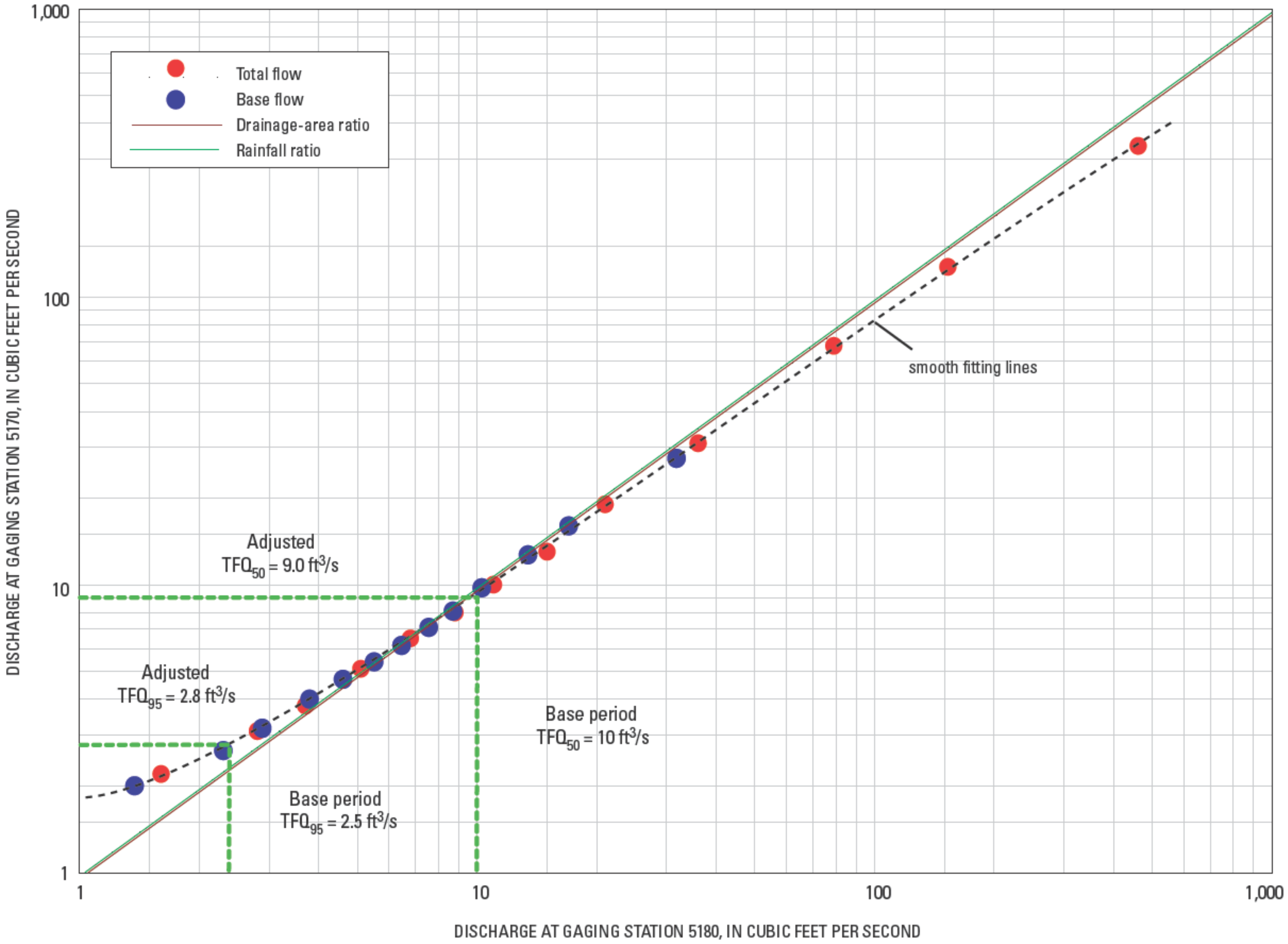


Figure 5. Correlation between flows at gaging stations 5170 (East Wailuaiki Stream) and 5180 (West Wailuaiki Stream), based on discharge of equal percentage duration for period of concurrent record 1914-17 and 1922-58, northeast Maui, Hawaii.

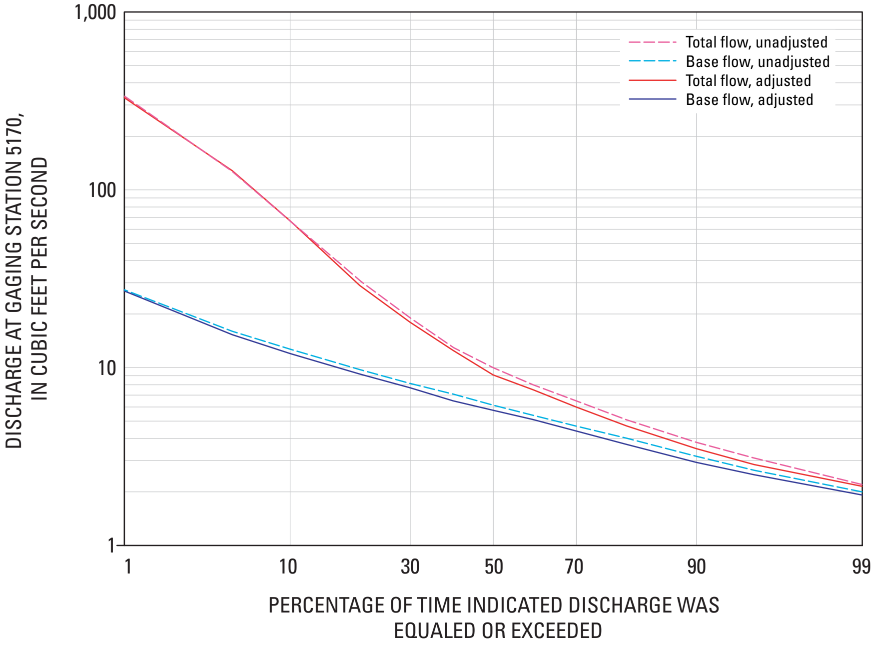


Figure 6. Unadjusted and adjusted flow-duration curves of total streamflow and base flow at gaging station 5170 on East Wailuaiki Stream, northeast Maui, Hawaii.

The ungaged basins are denoted by an abbreviation for the stream name followed by a U, M, or L for upper, middle, or lower locations on the stream (plate 1). These three locations on each stream roughly correspond to the following settings: (U) upstream of the main diversion ditch at around 1,700- to 1,200-ft altitude; (M) roughly 600- to 500-ft altitude; and (L) near the stream mouth. These locations were chosen to help meet the goals of objective 3 of this study regarding the habitat available in the stream for native species.

Hydrologic and geologic characteristics

Average yearly total rainfall rates for each drainage basin were determined using GIS techniques by overlaying the drainage-basin boundaries on a map of mean annual rainfall isohyets from Giambelluca and others (1986) (fig. 8). The overlying GIS layers created polygons that were assigned rainfall rates, in inches per year, equal to the average of the two bounding isohyets of each polygon. Each polygon area, in square feet, was multiplied by the assigned rainfall rate, after converting the rainfall rate to feet per second, to determine a volume rainfall rate, in cubic feet per second, for each polygon. Final rainfall rates were then determined by summing the rainfall volumes in a basin. In areas of equal rainfall rates, larger drainage basins would have larger total rainfall volumes and smaller drainage basins would have smaller total rainfall volumes. Average annual rainfall rates in the gaged basins ranged from 1.3 to 76 ft^3/s (table 6). Average annual rainfall rates in the ungaged basins ranged from 1.9 to 192 ft^3/s (table 7).

Distributions of surficial geologic units in each gaged drainage basin were determined from a digital geology map by Sherrod and others (2003) (fig. 9). Three geologic units were considered, the Honomanu Basalt, the Kula Volcanics, and the Hana Volcanics (table 6). The percentage of each unit in the basin was determined by dividing the area of each unit in the basin by the total basin area and multiplying the result by 100. Only two gaged basins contained surficial exposures of Honomanu Basalt, both having less than 1 percent of the total area of each basin, so only Kula and Hana Volcanics were included in the following analysis.

Development of regression equations

Linear equations generated by use of regression analysis have the general form

$$Y_i = b_0 + b_1 X_1 + b_2 X_2 + \ldots + b_n X_n + \varepsilon_i \qquad (1)$$

where Y_i is the estimate of the dependent variable for site i, X_1 to X_n are the *n* independent variables, b_0 to b_n are the *n*+1 regression model coefficients, and e_i is the residual error (difference between the observed and estimated value of the dependent variable for site *i*). Regression analysis results must be evaluated to make sure that the following assumptions are met: (1) equation 1 adequately describes the relation between the dependent and independent variables, (2) the mean of e_i is zero, (3) the variance of e_i is constant and independent of the value of X_n, (4) values of e_i are normally distributed, (5) values of e_i are independent of each other, (6) all independent variables selected are statistically significant at the 5-percent level, (7) independent variables are not correlated, and (8) the

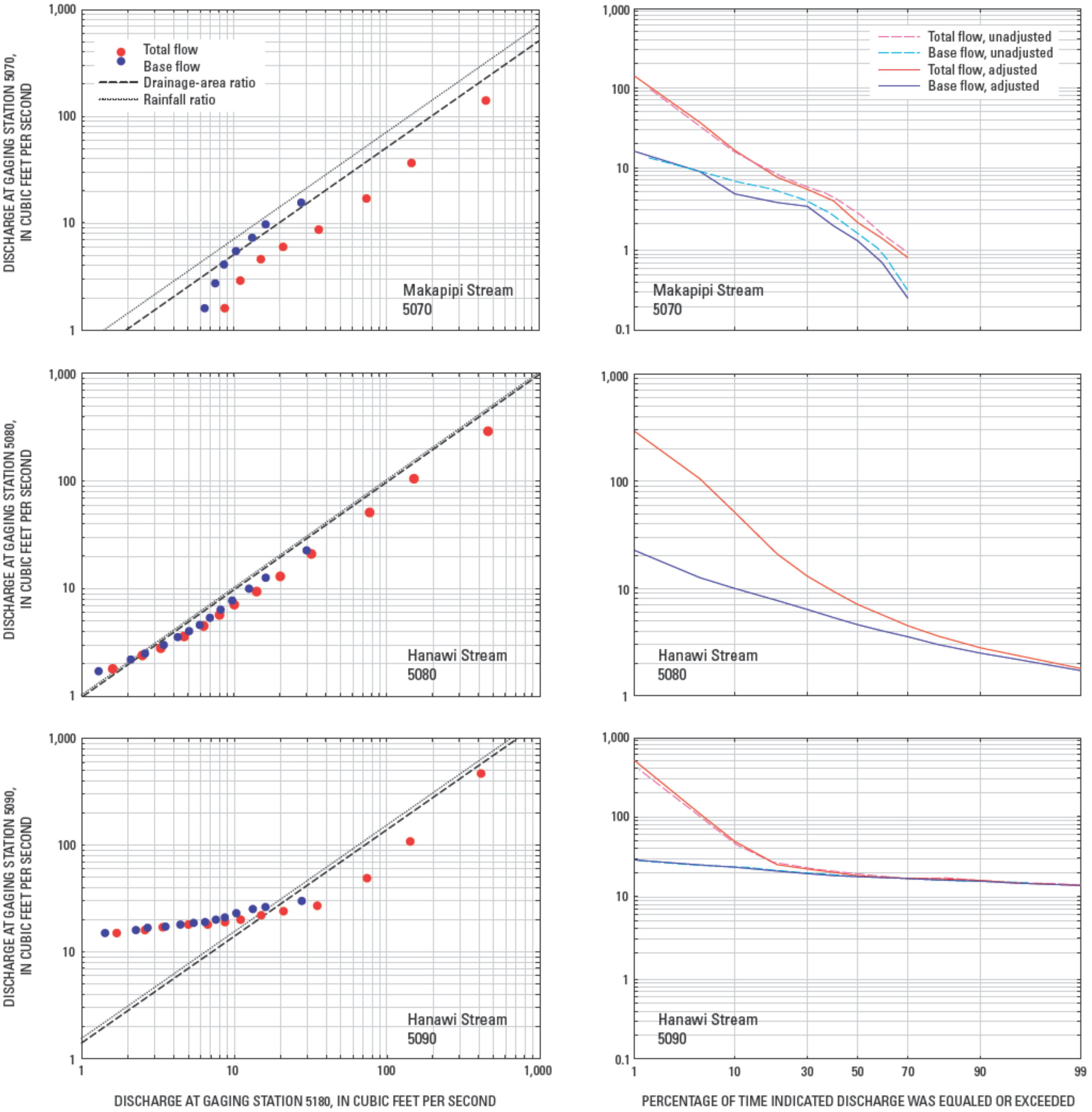


Figure 7. Correlation of flows at selected gaging stations in northeast Maui, Hawaii with flow at index station 5180 (West Wailuaiki Stream) based on discharge of equal percentage duration and unadjusted and adjusted duration curves of total streamflow and base flow.

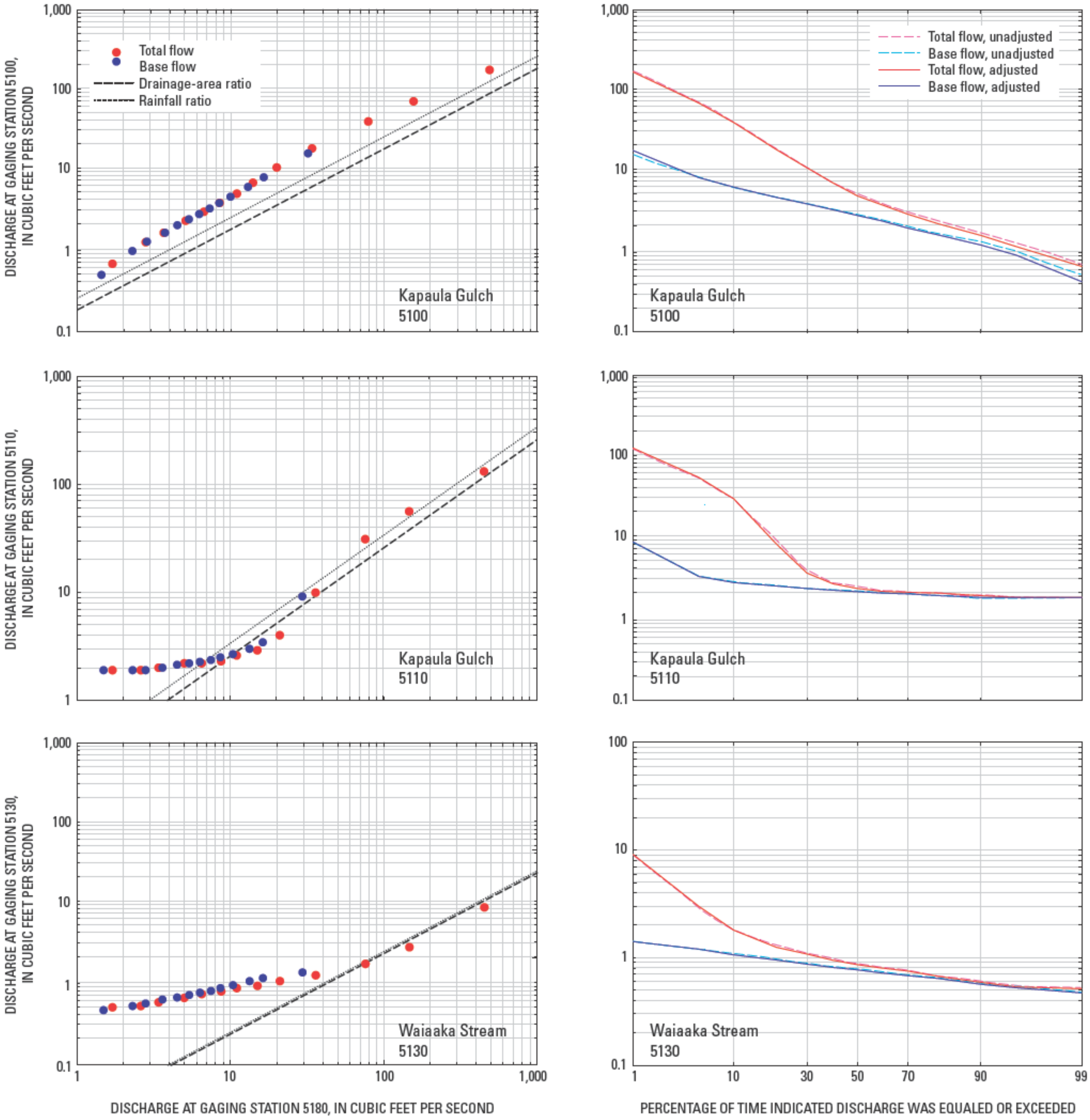


Figure 7. Correlation of flows at selected gaging stations in northeast Maui, Hawaii with flow at index station 5180 (West Wailuaiki Stream) based on discharge of equal percentage duration and unadjusted and adjusted duration curves of total streamflow and base flow–Continued.

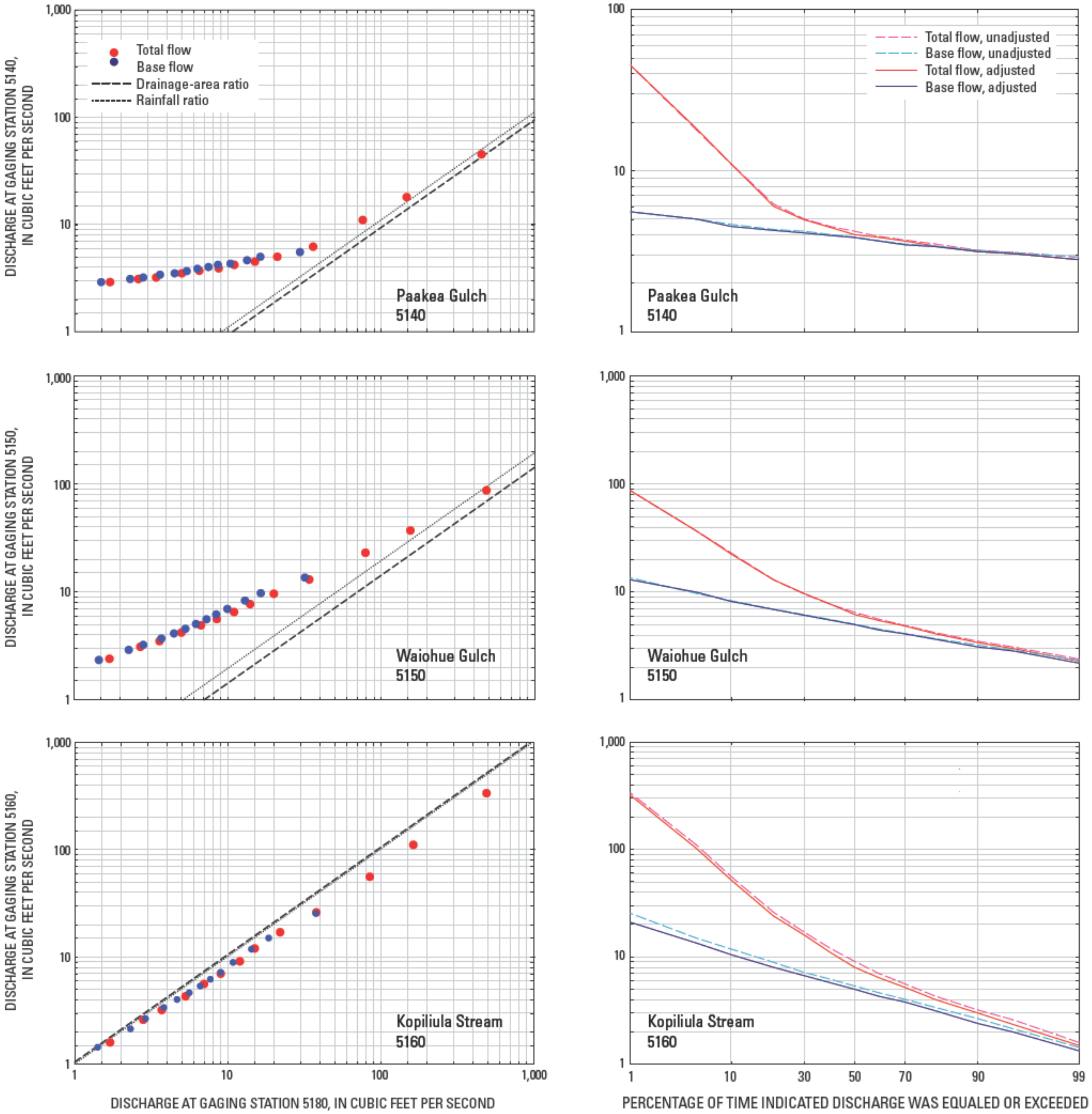


Figure 7. Correlation of flows at selected gaging stations in northeast Maui, Hawaii with flow at index station 5180 (West Wailuaiki Stream) based on discharge of equal percentage duration and unadjusted and adjusted duration curves of total streamflow and base flow–Continued.

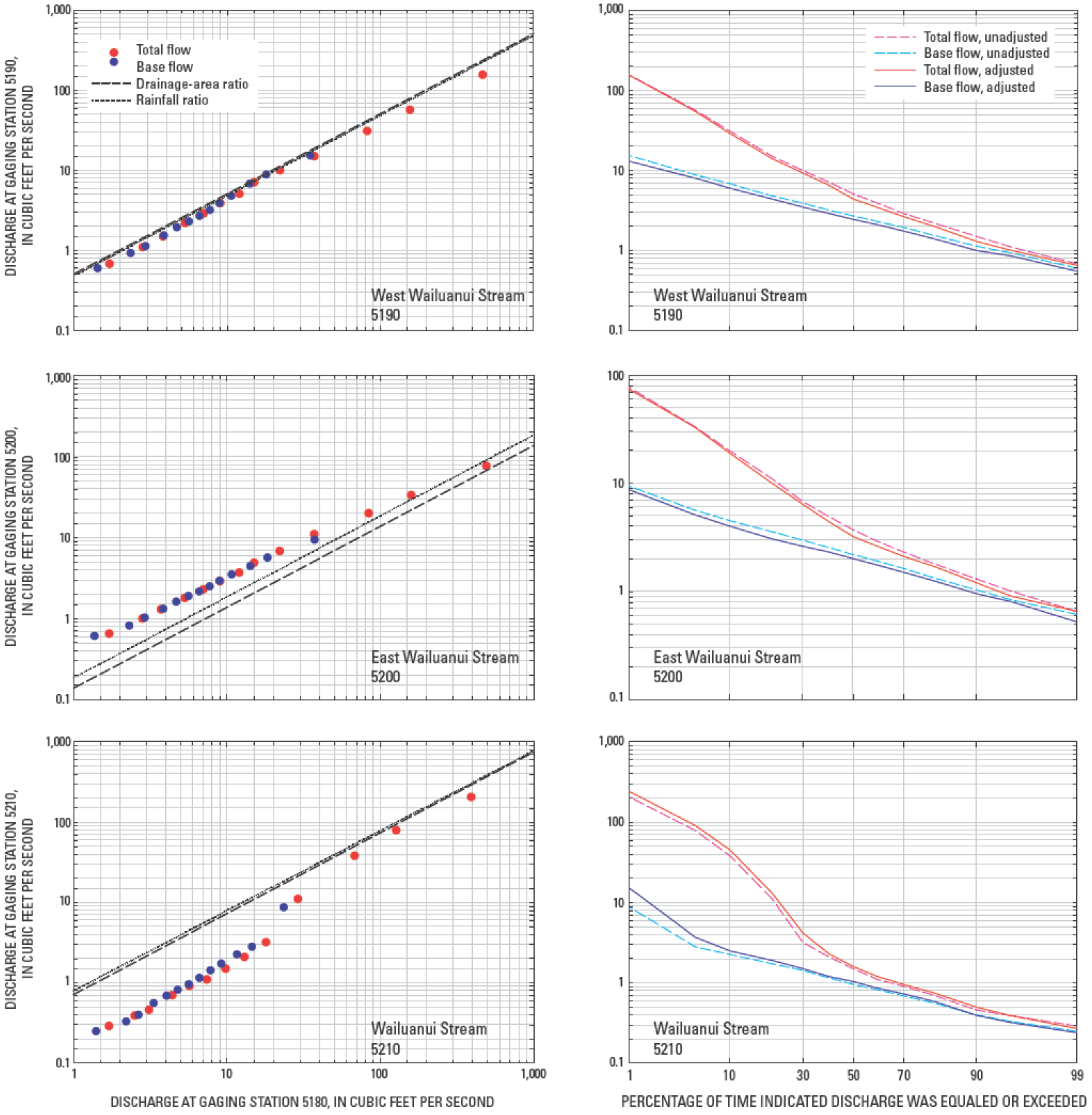


Figure 7. Correlation of flows at selected gaging stations in northeast Maui, Hawaii with flow at index station 5180 (West Wailuaiki Stream) based on discharge of equal percentage duration and unadjusted and adjusted duration curves of total streamflow and base flow—Continued.

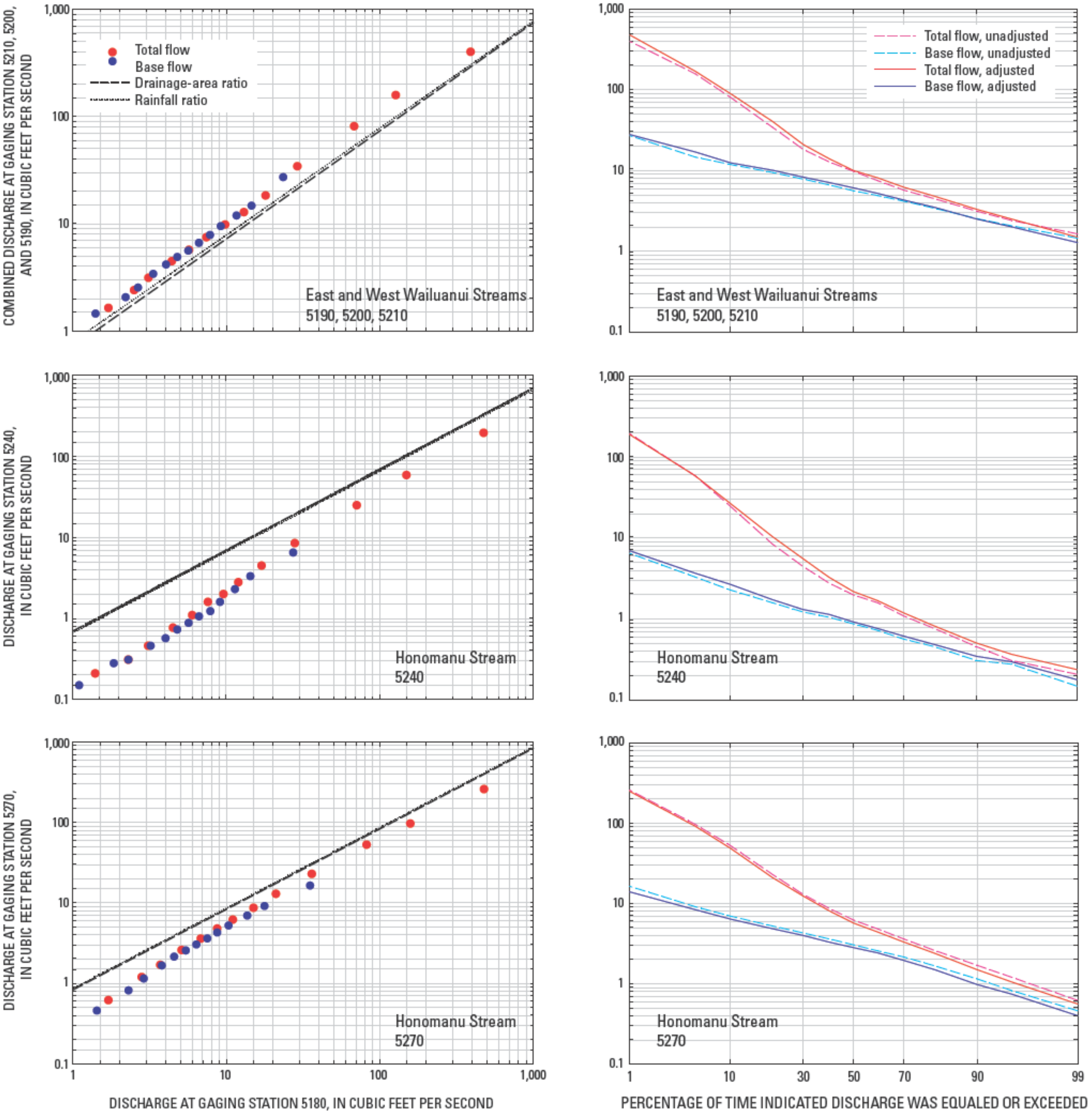
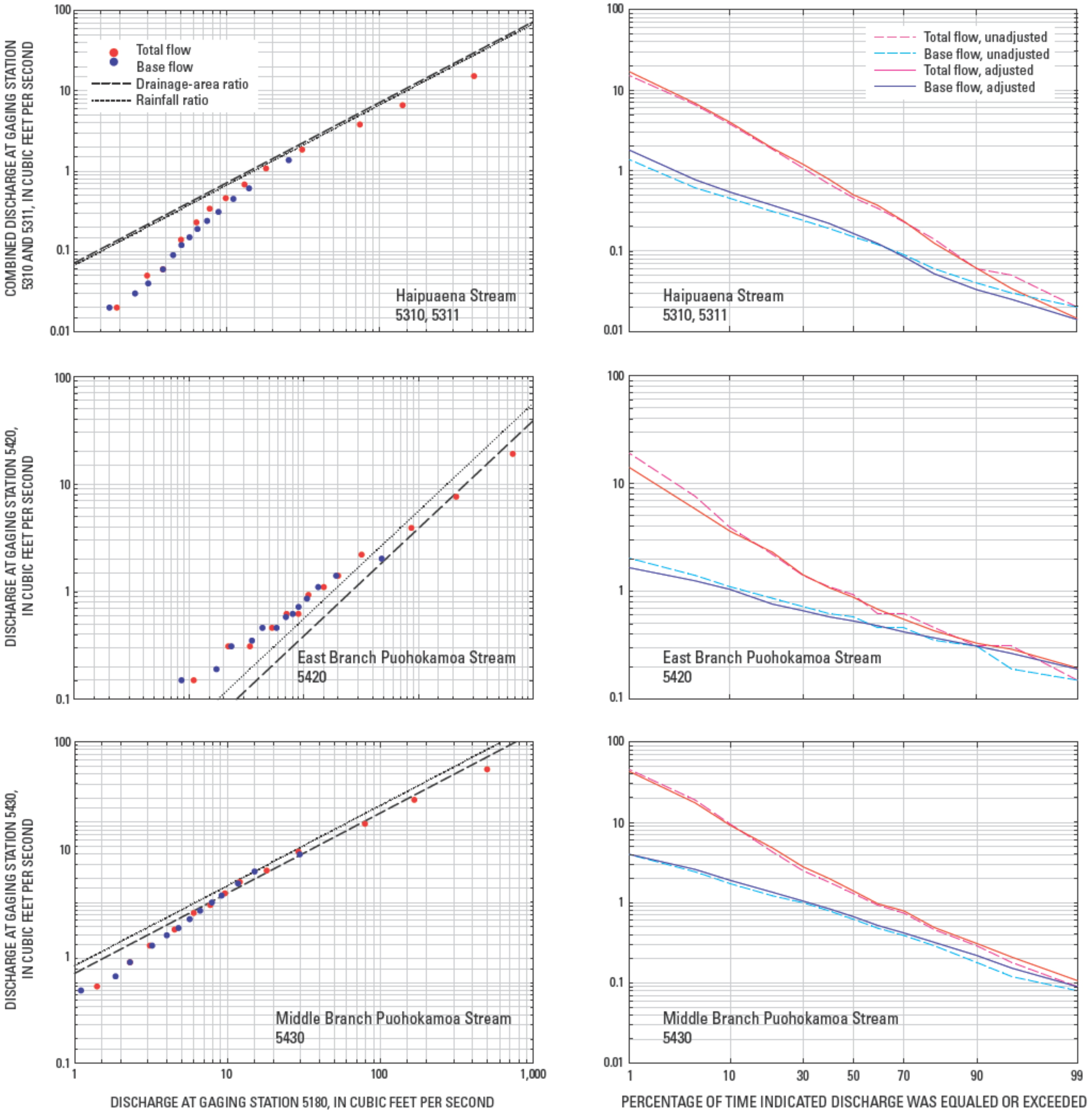


Figure 7. Correlation of flows at selected gaging stations in northeast Maui, Hawaii with flow at index station 5180 (West Wailuaiki Stream) based on discharge of equal percentage duration and unadjusted and adjusted duration curves of total streamflow and base flow–Continued.



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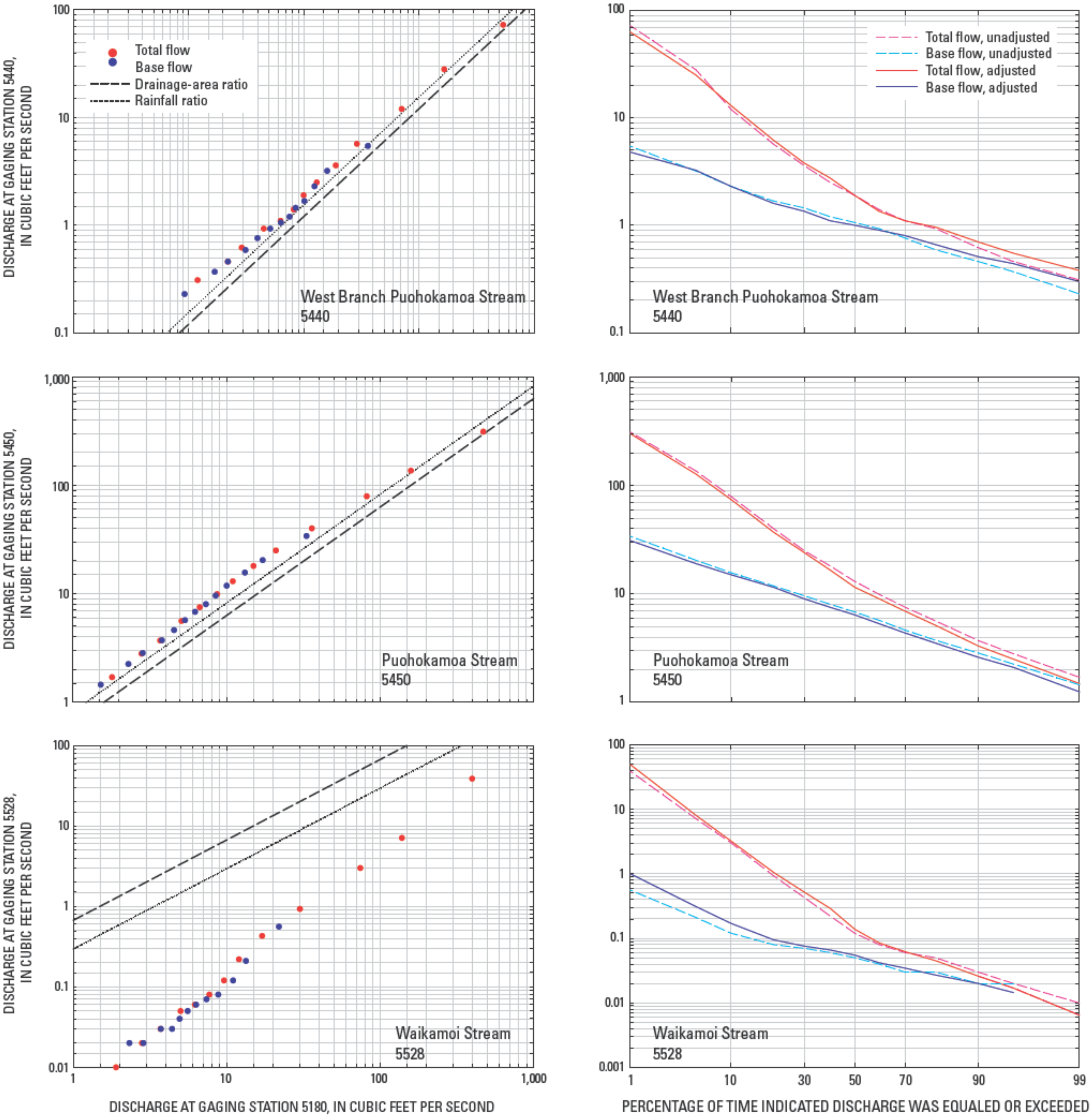


Figure 7. Correlation of flows at selected gaging stations in northeast Maui, Hawaii with flow at index station 5180 (West Wailuaiki Stream) based on discharge of equal percentage duration and unadjusted and adjusted duration curves of total streamflow and base flow–Continued.

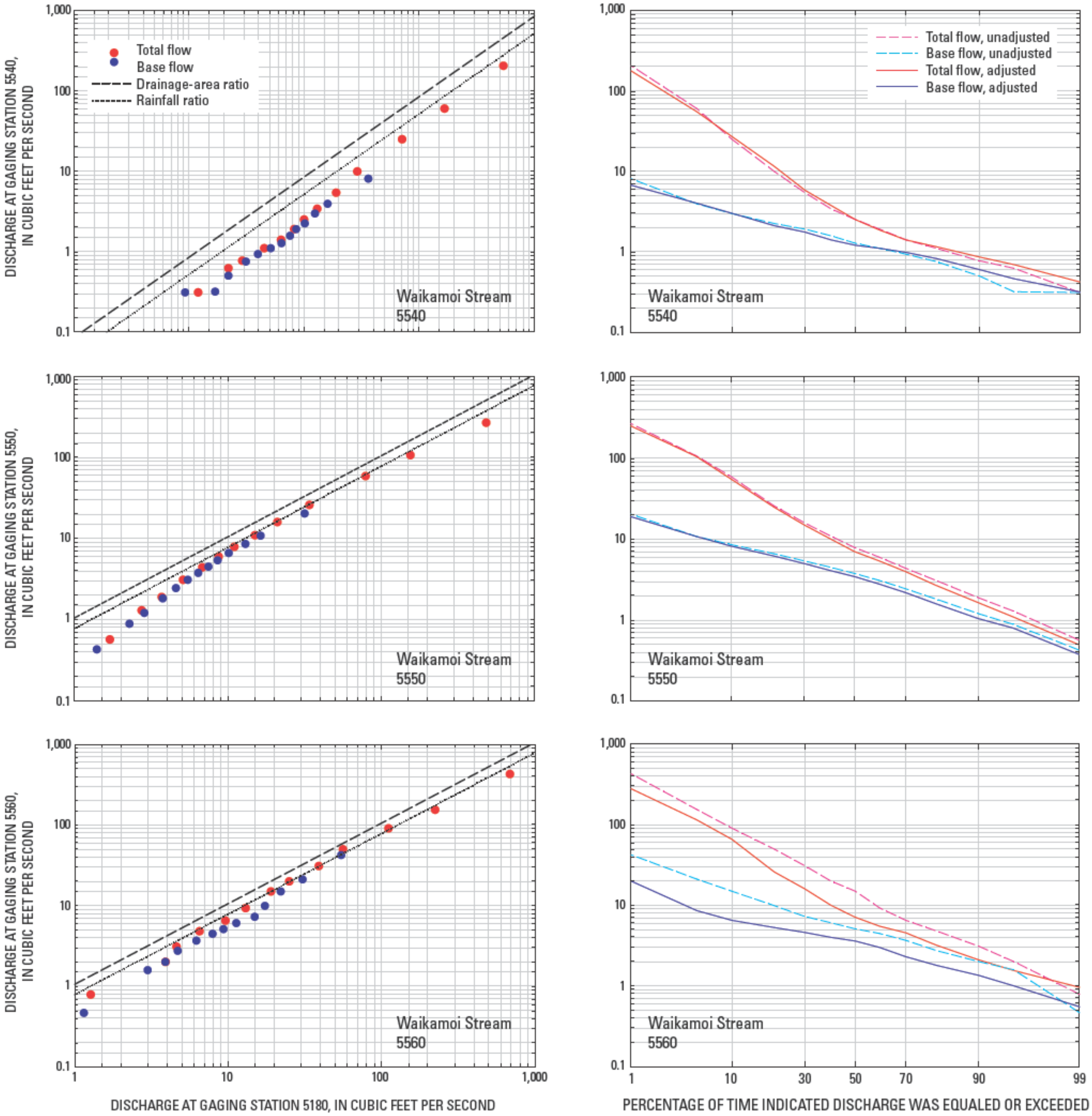


Figure 7. Correlation of flows at selected gaging stations in northeast Maui, Hawaii with flow at index station 5180 (West Wailuaiki Stream) based on discharge of equal percentage duration and unadjusted and adjusted duration curves of total streamflow and base flow—Continued.

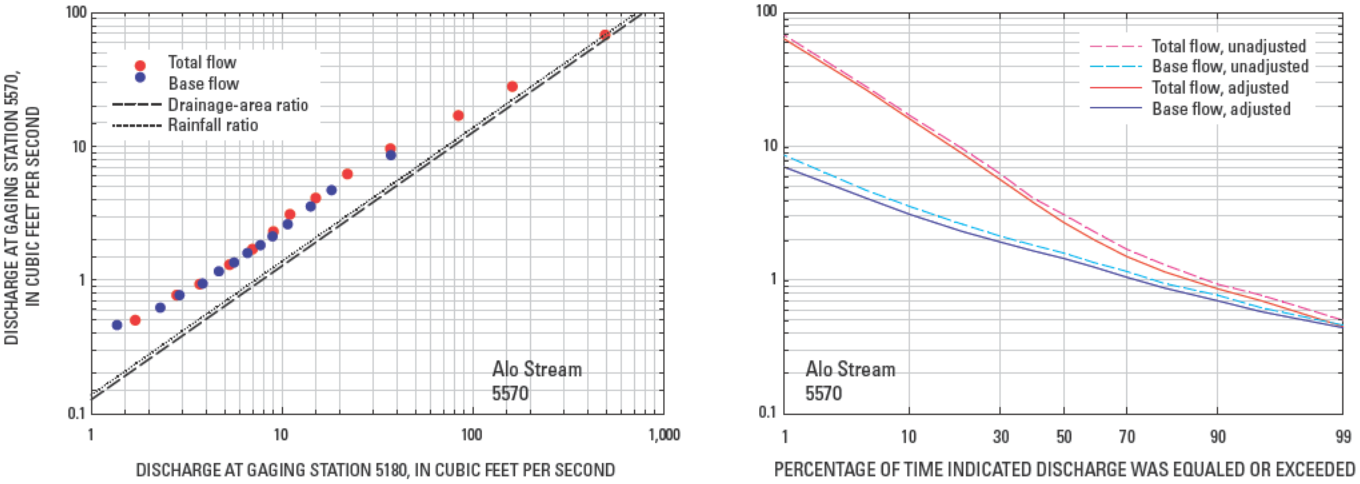


Figure 7. Correlation of flows at selected gaging stations in northeast Maui, Hawaii with flow at index station 5180 (West Wailuaiki Stream) based on discharge of equal percentage duration and unadjusted and adjusted duration curves of total streamflow and base flow–Continued.

Table 5. Comparisons of base-flow to total-flow duration statistics and streamflow characteristics at selected stations to those at index gaging station 5180 on West Wailuaiki Stream, northeast Maui, Hawaii

[Qxx is the xx-percent flow duration of streamflow; +, combined with record from indicated station]

Gaging-station number	Equivalent total flow duration-discharge, in percent		Rainfall-normalized flow relative to index station		Comments
	Q_{50} base flow	Q_{95} base flow	Low flow relative to index station	High flow relative to index station	
5070	62	--	Lower	Same	Intermittent flow; dry 30 percent of time; Q_{95} not comparable
5080	69	97	Higher	Same	
5090+5080	66	96	Higher	Same	Includes Big and Hanawi Springs
5100	72	98	Same	Lower	
5110+5100	71	97	Higher	Same	Includes Pali Spring
5130	56	95	Higher	Same	Includes unnamed springs
5140	60	95	Higher	Same	Includes numerous unnamed springs
5150	67	97	Higher	Same	
5160	71	98	Higher	Same	
5170	73	97	Higher	Same	
5180	72	97	--	--	Index station
5190	73	98	Same	Same	
5200	72	97	Higher	Same	
5210+5200+5190	71	97	Same	Same	Combination of several gages
5240	78	97	Lower	Same	Lower low flows due to minor diversion at 3,000 ft altitude
5270	75	98	Lower	Same	Lower low flows due to minor diversion at 3,000 ft altitude
5311+5310	76	97	Lower	Same	Combination of two gages
5360+5311+5310+5350	75	98	Same	Lower	Combination of several gages
5420	75	98	Same	Lower	
5430	72	98	Lower	Same	Lower low flows due to diversions at 3,000 ft and 4,300 ft altitude
5440	74	97	Same	Same	Diversion effects not apparent
5450	77	96	Same	Lower	Lower low flows due to diversions at 3,000 ft and 4,300 ft altitude
5528	74	97	Lower	Same	4,487 ft altitude; intermittent flow; dry 1 percent of time
5540	74	95	Same	Same	
5550	78	96	Lower	Same	Lower low flows due to diversions at 3,000 ft and 4,300 ft altitude
5560	74	98	Same	Same	Gage operated before minor upstream diversions were active
5570	76	97	Same	Lower	
Average	70	96			

Table 6. Watershed characteristics for selected gaged stream drainage basins, northeast Maui, Hawaii

[Abbreviation definitions and units are described in appendix A; gaging stations in ***bold italics*** were used to develop the final regression equations for estimating flow-duration statistics; precipitation data modified from Giambelluca and others (1986); ft^3/s, cubic feet per second; geology data from Sherrod and others (2003); ND, not determined]

Gaging-station number	BL	BP	BR	BS	BW	CCM	CR	DA	ER	MAXELEV	MCL	MCS	MCSP	MCSR	MINELEV	RB	RN
5070	4.92	10.94	4283	1038	0.39	0.17	2.24	1.89	0.32	5219	4.6	887	0.16	0.94	936	10	25400
5080	6.34	14.90	6775	1557	0.57	0.18	2.21	3.62	0.34	8093	6.0	1036	0.19	0.95	1318	9	38798
5090	7.01	17.86	7587	1433	0.74	0.17	2.22	5.15	0.37	8093	7.0	971	0.23	1.00	506	7	45008
5100	5.40	9.19	2968	854	0.13	0.12	3.12	0.69	0.17	4325	4.1	690	0.16	0.76	1357	33	24894
5110	5.44	11.55	3787	1099	0.17	0.14	3.35	0.95	0.20	4325	4.9	745	0.18	0.90	538	25	27527
5130	1.66	2.42	881	1008	0.05	0.09	2.27	0.09	0.21	1587	1.1	922	0.04	0.63	706	24	10264
5140	3.15	4.39	1741	1023	0.11	0.11	2.10	0.35	0.21	2373	2.2	808	0.08	0.69	632	22	15330
5150	3.54	4.70	1413	885	0.15	0.16	1.83	0.53	0.23	2771	2.4	567	0.10	0.69	1358	19	8973
5160	7.37	15.83	6993	1652	0.53	0.15	2.27	3.88	0.30	8372	6.4	956	0.21	0.86	1379	11	46589
5170	7.58	16.02	7186	1527	0.46	0.16	2.41	3.51	0.28	8527	6.2	946	0.20	0.81	1341	13	44113
5180	8.33	17.08	7518	1761	0.44	0.16	2.51	3.69	0.26	8857	6.5	941	0.21	0.78	1339	15	47174
5190	7.14	17.19	6706	1797	0.26	0.17	3.54	1.88	0.22	8055	6.1	741	0.22	0.85	1349	21	38688
5200	2.67	5.92	1424	1162	0.19	0.17	2.34	0.51	0.30	2733	2.5	595	0.10	0.92	1309	11	8531
5210	9.18	19.51	7467	1736	0.30	0.18	3.32	2.75	0.20	8055	7.3	749	0.27	0.80	588	24	41635
5240	5.81	14.47	5420	1619	0.44	0.18	2.55	2.57	0.31	8331	5.4	965	0.18	0.94	2911	10	30319
5270	7.44	18.48	6594	1670	0.41	0.18	2.97	3.07	0.27	8331	6.9	915	0.23	0.93	1737	14	36338
5311	1.99	4.47	1645	1073	0.13	0.15	2.45	0.27	0.29	5979	1.7	952	0.06	0.87	4334	12	10986
5360	7.14	15.14	4468	1577	0.17	0.15	3.90	1.20	0.17	5979	6.0	714	0.22	0.84	1511	33	29733
5420	0.78	2.44	773	1793	0.18	0.16	1.82	0.14	0.55	3645	0.8	802	0.03	1.07	2872	3	4835
5430	3.50	7.98	2705	1639	0.14	0.13	3.24	0.48	0.22	5613	3.5	754	0.13	0.99	2908	20	21675
5440	2.41	5.23	1610	1779	0.18	0.17	2.22	0.44	0.31	4470	2.1	844	0.07	0.85	2860	10	9756
5450	6.74	14.99	4304	1795	0.34	0.17	2.78	2.31	0.26	5620	6.4	625	0.26	0.95	1316	15	25914
5528	5.42	12.49	4864	1422	0.46	0.18	2.24	2.48	0.33	9329	5.0	849	0.17	0.93	4465	9	27800
5540	6.77	17.39	6340	1399	0.46	0.17	2.77	3.13	0.30	9329	7.1	794	0.25	1.04	2989	12	37028
5550	10.11	24.81	8034	1516	0.38	0.17	3.56	3.87	0.22	9329	9.9	722	0.37	0.98	1295	21	48426
5560	10.34	25.29	8195	1525	0.38	0.17	3.61	3.90	0.22	9329	10.2	717	0.38	0.99	1134	22	49689
5570	2.34	5.38	1270	1551	0.20	0.16	2.22	0.47	0.33	2505	2.2	491	0.10	0.92	1235	9	7836
5650	3.44	7.65	1835	1572	0.19	0.15	2.70	0.64	0.26	3140	3.1	542	0.13	0.91	1305	15	12224
5660	1.62	3.74	784	1451	0.15	0.12	2.16	0.24	0.34	2014	1.5	555	0.06	0.93	1230	9	6313
5700	9.43	16.92	5469	1185	0.38	0.16	2.51	3.61	0.23	6686	7.8	658	0.30	0.82	1217	19	34724
5770	6.12	11.95	3712	1165	0.39	0.20	2.18	2.39	0.29	4975	5.9	571	0.25	0.97	1263	12	18981

Table 6. Watershed characteristics for selected gaged stream drainage basins, northeast Maui, Hawaii—Continued

[Abbreviation definitions and units are described in appendix A; gaging stations in ***bold italics*** were used to develop the final regression equations for estimating flow-duration statistics; precipitation data modified from Giambelluca and others (1986); ft^3/s, cubic feet per second; geology data from Sherrod and others (2003); ND, not determined]

Gaging-station number	RR	SD	SF	SR	TSL	Annual basin rainfall (ft^3/s)	Ratio of gage to index station annual basin rainfall	Percent coverage by surficial geologic unit		
								Honomanu Basalt	Kula Volcanics	Hana Volcanics
5070	392	5.93	12.8	0.85	11.2	35	0.71	0	0	100
5080	455	5.73	11.1	0.67	20.7	51	1.03	0	11	89
5090	425	5.93	9.5	0.68	30.6	76	1.55	0	7	92
5100	323	8.39	42.2	0.81	5.8	13	0.26	0	0	100
5110	328	7.27	31.2	0.68	6.9	17	0.34	1	0	99
5130	365	11.65	30.5	0.91	1.1	1.3	0.03	0	0	100
5140	397	8.81	28.5	0.79	3.1	5.5	0.11	0	0	100
5150	301	6.35	23.8	0.64	3.3	9.7	0.20	0	9	91
5160	442	6.66	14.0	0.58	25.9	50	1.01	0	58	42
5170	449	6.14	16.4	0.62	21.6	48	0.97	0	100	0
5180	440	6.28	18.8	0.53	23.1	49	1.00	0	93	7
5190	390	5.77	27	0.41	10.8	24	0.81	0	63	37
5200	241	5.99	14.0	0.51	3.0	9.1	0.19	0	98	2
5210	383	5.58	30.6	0.43	15.3	38	0.77	0	74	26
5240	375	5.59	13.1	0.60	14.4	33	0.66	0	100	0
5270	357	5.51	18.0	0.55	16.9	43	0.86	0	100	0
5311	368	6.68	14.9	0.89	1.8	3.3	0.07	0	100	0
5360	295	6.65	42.5	0.45	8.0	20	0.41	0	100	0
5420	317	6.25	4.2	0.45	0.9	2.8	0.06	0	100	0
5430	339	8.01	25.4	0.46	3.9	8.0	0.16	0	100	0
5440	308	6.06	13.1	0.47	2.7	7.6	0.15	0	100	0
5450	287	6.02	19.6	0.35	13.9	40	0.82	0	100	0
5528	389	5.72	11.9	0.60	14.1	15	0.30	0	100	0
5540	365	5.84	14.7	0.57	18.3	26	0.52	0	100	0
5550	324	6.03	26.4	0.48	23.4	38	0.78	0	100	0
5560	324	6.06	27.4	0.47	23.7	39	0.79	0	100	0
5570	236	6.17	11.7	0.32	2.9	6.8	0.14	0	100	0
5650	240	6.66	18.6	0.35	4.2	9.8	ND	ND	ND	ND
5660	210	8.05	11.0	0.38	1.9	3.1	ND	ND	ND	ND
5700	323	6.35	24.7	0.56	22.9	50	ND	ND	ND	ND
5770	311	5.11	15.7	0.49	12.2	37	ND	ND	ND	ND

Table 7. Watershed characteristics for selected ungaged stream drainage basins, northeast Maui, Hawaii

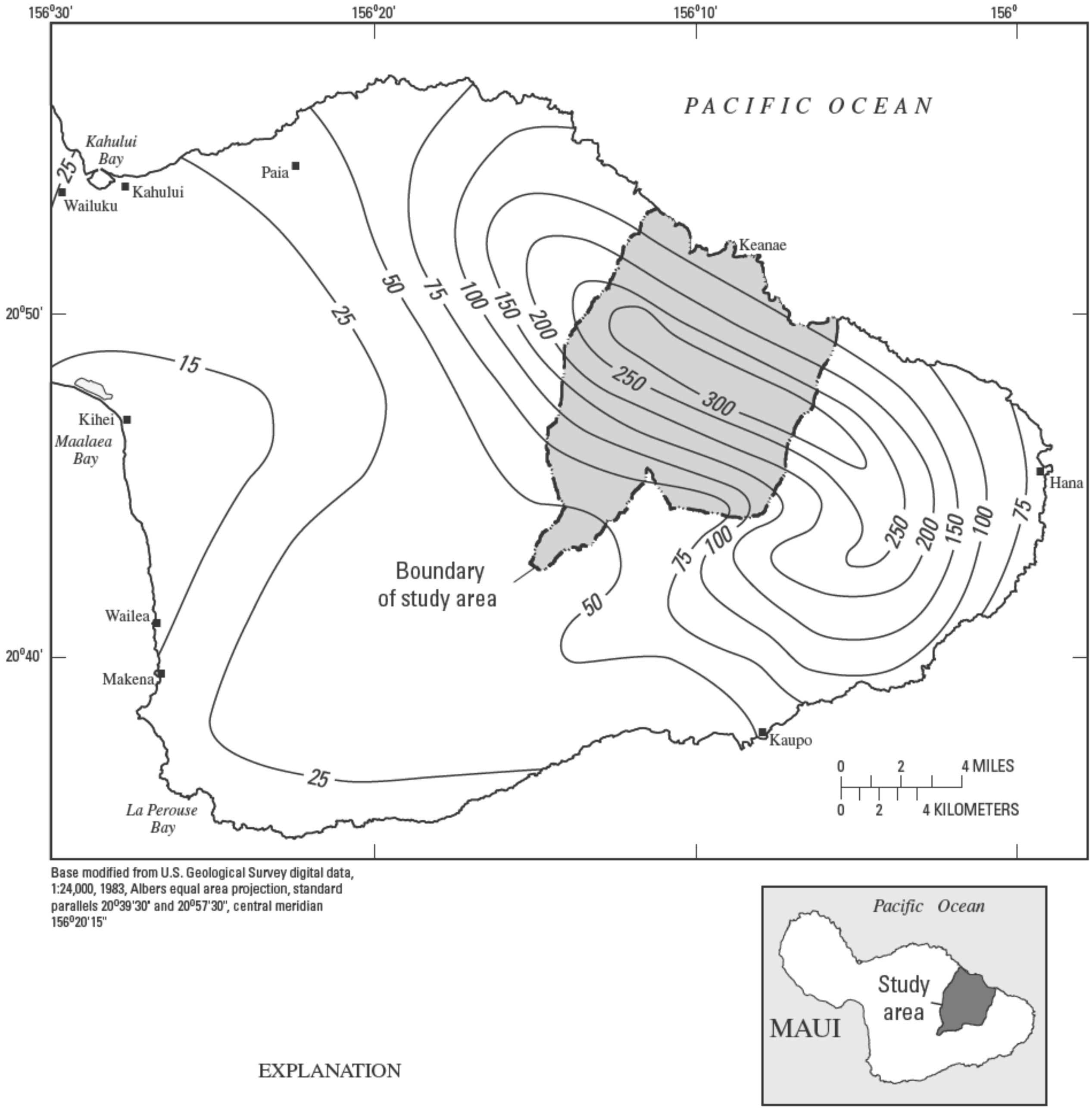
[Basins and abbreviations listed from east to west; L, lower; M, middle; U, upper; watershed characteristic abbreviation definitions and units are described in appendix A; precipitation data modified from Giambelluca and others (1986); ft^3/s, cubic feet per second; values in **bold** fall outside the range shown in table 8 used to develop the regression equations]

Stream location	BL	BP	BR	BS	BW	CCM	CR	DA	ER	MAXELEV	MCL	MCS	MCSP
Hanawi lower (HwL)	9.02	19.24	8040	1488	0.59	0.17	2.34	5.36	0.29	8093	7.6	947	0.25
Kapaula lower (KL)	5.79	12.46	4151	1186	0.19	0.14	3.40	1.07	0.20	4325	5.3	732	0.20
Waiaaka lower (WaL)	1.85	3.62	1482	1485	0.08	0.10	2.71	0.14	0.23	**1546**	1.44	1119	0.04
Paakea lower (PaL)	3.10	0.03	2296	1303	0.17	0.14	2.43	0.53	0.27	**2372**	2.74	866	0.09
Paakea upper (PaU)	1.90	3.61	1059	801	0.12	0.10	2.14	0.23	0.28	**2372**	1.63	642	0.06
Waiohue lower (WeL)	3.84	7.78	2738	1270	0.24	0.18	2.30	0.91	0.28	2766	3.63	791	0.13
Waiohue middle (WeM)	3.49	6.70	2269	1078	0.21	0.17	2.19	0.75	0.28	2766	3.23	671	0.13
Puakaa middle (PuM)	3.15	6.80	1889	1338	0.13	0.12	3.06	0.39	0.23	**2491**	3.00	655	0.12
Puakaa upper (PuU)	2.06	4.65	1177	1113	0.13	0.12	2.52	0.27	0.29	**2491**	2.08	602	0.09
Kopiliula lower (KpL)	8.29	19.80	8343	1699	0.57	0.16	2.58	4.70	0.30	8372	8.0	837	0.28
Kopiliula middle (KpM)	8.95	18.88	7800	1688	0.47	0.15	2.60	4.19	0.26	8372	7.5	855	0.26
East Wailuaiki lower (EWL)	8.92	20.94	8498	1630	0.44	0.17	2.98	3.94	0.25	8527	8.0	812	0.28
East Wailuaiki middle (EWM)	8.35	19.77	8096	1582	0.46	0.17	2.86	3.80	0.26	8527	7.5	843	0.26
West Wailuaiki lower (WWL)	9.46	21.77	8822	1833	0.43	0.16	3.04	4.07	0.24	8857	8.3	819	0.29
West Wailuaiki middle (WWM)	8.97	20.58	8385	1796	0.44	0.16	2.92	3.97	0.25	8857	7.8	839	0.27
Wailuanui lower (WL)	9.17	22.69	8017	1772	0.35	0.19	3.56	3.24	0.22	8055	8.2	777	0.29
Waiokomilo lower (WoL)	10.44	23.09	6459	1405	0.25	0.18	4.01	2.63	0.18	6483	9.2	686	0.35
Waiokomilo middle (WoM)	8.41	18.94	5977	1478	0.25	0.17	3.68	2.11	0.20	6483	7.5	828	0.26
Waiokomilo upper (WoU)	7.42	15.75	5108	1314	0.20	0.16	3.66	1.48	0.19	6483	6.2	828	0.22
Ohia lower (OL)	2.10	2.92	388	821	0.11	0.15	1.75	0.22	0.25	**413**	1.2	358	0.06
Palauhulu lower (PhL)	8.62	20.48	5745	1510	0.32	0.17	3.49	2.74	0.22	5816	8.2	666	0.32
Palauhulu middle (PhM)	7.43	16.57	5299	1587	0.33	0.17	3.01	2.41	0.24	5816	6.7	772	0.24
Kano upper (KoU)	4.99	11.09	3792	1251	0.20	0.13	3.17	0.97	0.22	5816	4.3	827	0.15
Hauoli Wahine upper (HWU)	1.34	3.94	1052	1280	0.27	0.15	1.85	0.36	**0.51**	3049	1.4	749	0.05
Piinaau lower (PiL)	16.45	36.91	9976	1984	1.07	0.22	2.48	17.58	0.29	**10011**	14.9	620	0.60
Piinaau middle (PiM)	11.92	33.25	9536	1993	1.40	0.21	2.30	16.63	**0.39**	**10011**	13.3	652	0.52
Piinaau upper (PiU)	10.47	29.95	8689	2019	1.43	0.21	2.19	14.96	**0.42**	**10011**	11.7	664	0.45
Nuaailua lower (NL)	4.25	9.18	2389	1967	0.28	0.23	2.38	1.19	0.29	**2409**	3.5	698	0.13
Nuaailua middle (NM)	3.07	6.51	1891	1726	0.16	0.17	2.66	0.48	0.25	**2409**	2.6	710	0.10
Nuaailua upper (NU)	1.18	2.80	653	1036	0.10	0.11	2.30	0.12	0.33	**2409**	1.0	609	0.04
Honomanu lower (HnL)	9.86	23.91	8304	2115	0.52	0.19	2.99	5.09	0.26	8331	8.9	946	0.29
Honomanu middle (HnM)	8.81	21.63	7654	1867	0.49	0.18	2.93	4.34	0.27	8331	8.0	960	0.26
Punalau lower (PlL)	3.89	8.75	2531	1947	0.22	0.16	2.70	0.84	0.27	2566	3.5	648	0.14
Punalau middle (PlM)	3.56	7.89	2053	1748	0.22	0.16	2.52	0.78	0.28	2566	3.2	604	0.13
Haipuaena lower (HaL)	9.44	21.05	5709	1758	0.17	0.15	4.70	1.60	**0.15**	5979	8.4	652	0.33
Haipuaena middle lower (HaML)	8.80	19.65	5509	1771	0.17	0.15	4.59	1.46	**0.16**	5979	7.8	647	0.31
Haipuaena middle upper (HaMU)	8.04	17.87	5042	1744	0.17	0.15	4.31	1.37	**0.16**	5979	7.2	675	0.28
Puohokamoa lower (PL)	8.78	19.69	5599	1801	0.36	0.17	3.14	3.12	0.23	5613	8.5	594	0.35
Puohokamoa middle lower (PML)	8.20	18.44	5100	1752	0.36	0.17	3.02	2.97	0.24	5613	7.9	592	0.33
Puohokamoa middle upper (PMU)	7.56	17.01	4700	1799	0.35	0.17	2.95	2.65	0.24	5613	7.3	617	0.30
Wahinepee lower (WpL)	1.56	4.46	1247	1642	0.26	0.19	1.98	0.40	**0.46**	**1320**	1.7	679	0.07
Wahinepee middle (WpM)	1.06	3.14	746	1353	0.26	0.17	1.69	0.28	**0.56**	**1320**	1.2	603	0.05
Waikamoi lower (WiL)	12.23	29.77	9205	1650	0.39	0.17	3.86	4.74	0.20	9329	12.0	686	0.46
Waikamoi middle lower (WiML)	11.60	28.29	8834	1623	0.40	0.17	3.69	4.67	0.21	9329	11.4	701	0.43
Waikamoi middle upper (WiMU)	11.22	27.54	8594	1609	0.41	0.17	3.62	4.61	0.22	9329	11.1	703	0.42
Kolea lower (KaL)	3.08	7.02	1808	1833	0.20	0.15	2.51	0.62	0.29	**1846**	2.7	627	0.11
Kolea middle (KaM)	2.53	5.83	1321	1688	0.20	0.15	2.30	0.51	0.32	**1846**	2.2	603	0.09

Table 7. Watershed characteristics for selected ungaged stream drainage basins, northeast Maui, Hawaii—Continued

[Basins and abbreviations listed from east to west; L, lower; M, middle; U, upper; watershed characteristic abbreviation definitions and units are described in appendix A; precipitation data modified from Giambelluca and others (1986); ft³/s, cubic feet per second; values in **bold** fall outside the range shown in table 8 used to develop the regression equations]

Stream location	MCSR	MINELEV	RB	RN	RR	SD	SF	SR	TSL	Annual basin rainfall (ft³/s)
Hanawi lower (HwL)	0.84	53	12	47070	418	5.85	15.20	0.64	31.4	79
Kapaula lower (KL)	0.91	174	25	28937	333	6.97	31.30	0.62	7.5	18
Waiaaka lower (WaL)	0.78	64	19	15036	410	10.15	24.16	0.75	1.44	**1.9**
Paakea lower (PaL)	0.89	76	14	16286	366	7.09	18.12	0.67	3.76	7.9
Paakea upper (PaU)	0.86	1313	12	11139	293	10.52	15.84	0.80	2.39	**3.8**
Waiohue lower (WeL)	0.94	28	13	15317	352	5.59	16.21	0.62	5.10	15
Waiohue middle (WeM)	0.93	497	13	13356	339	5.89	16.26	0.62	4.40	13
Puakaa middle (PuM)	0.95	602	20	15238	278	8.07	25.28	0.49	3.17	**6.4**
Puakaa upper (PuU)	1.01	1314	12	9734	253	8.27	15.71	0.54	2.24	**4.7**
Kopiliula lower (KL)	0.97	29	11	54003	421	6.47	14.61	0.49	30.4	**62**
Kopiliula middle (KM)	0.84	572	15	50530	413	6.48	19.11	0.51	27.1	**54**
East Wailuaiki lower (EWL)	0.89	29	16	50650	406	5.96	20.21	0.50	23.5	**54**
East Wailuaiki middle (EWM)	0.90	431	14	48633	409	6.01	18.35	0.53	22.8	**52**
West Wailuaiki lower (WWL)	0.87	35	17	53722	405	6.09	21.98	0.45	24.8	**54**
West Wailuaiki middle (WWM)	0.87	472	16	51549	407	6.15	20.29	0.47	24.4	**53**
Wailuanui lower (WL)	0.89	38	20	41455	353	5.17	25.96	0.44	16.8	44
Waiokomilo lower (WoL)	0.88	24	33	36511	280	5.65	41.42	0.49	14.9	40
Waiokomilo middle (WoM)	0.89	506	26	34370	316	5.75	33.53	0.56	12.1	34
Waiokomilo upper (WoU)	0.83	1375	29	31821	324	6.23	37.28	0.63	9.2	24
Ohia lower (OL)	0.57	25	16	2582	133	6.66	19.85	0.44	1.5	**2.2**
Palauhulu lower (PhL)	0.95	71	21	33102	280	5.76	27.11	0.44	15.8	48
Palauhulu middle (PhM)	0.90	517	18	31149	320	5.88	22.89	0.49	14.2	44
Kano upper (KoU)	0.87	2024	20	28683	342	7.56	25.61	0.66	7.3	18
Hauoli Wahine upper (HWU)	1.05	1997	4	6995	267	6.65	4.93	0.59	2.4	7.5
Piinaau lower (PiL)	0.91	35	12	46178	270	4.63	15.38	0.31	81.4	**192**
Piinaau middle (PiM)	1.12	475	7	44633	287	4.68	8.55	0.33	77.9	**181**
Piinaau upper (PiU)	1.12	1322	6	41236	290	4.75	7.32	0.33	71.0	**152**
Nuaailua lower (NL)	0.83	20	12	10462	260	4.38	15.22	0.36	5.2	16
Nuaailua middle (NM)	0.84	518	16	10927	290	5.78	19.86	0.41	2.8	7.1
Nuaailua upper (NU)	0.88	1756	9	5752	234	8.81	11.81	0.59	1.0	**2.0**
Honomanu lower (HnL)	0.91	27	15	44236	347	5.33	19.09	0.45	27.1	**76**
Honomanu middle (HnM)	0.91	677	14	42645	354	5.57	17.90	0.51	24.2	**65**
Punalau lower (PlL)	0.89	35	14	15897	289	6.28	18.06	0.33	5.3	12
Punalau middle (PlM)	0.89	513	13	13070	260	6.37	16.26	0.35	5.0	12
Haipuaena lower (HaL)	0.90	270	44	37942	271	6.65	55.84	0.37	10.6	25
Haipuaena middle lower (HaML)	0.89	470	42	36866	280	6.69	52.98	0.37	9.8	24
Haipuaena middle upper (HaMU)	0.89	937	37	33587	282	6.66	47.31	0.39	9.1	23
Puohokamoa lower (PL)	0.96	14	19	33088	284	5.91	24.66	0.33	18.5	50
Puohokamoa middle lower (PML)	0.97	513	18	30273	277	5.94	22.64	0.34	17.6	49
Puohokamoa middle upper (PMU)	0.97	913	17	28077	276	5.97	21.55	0.34	15.8	45
Wahinepee lower (WeL)	1.09	73	5	6702	280	5.37	6.07	0.41	2.2	**4.1**
Wahinepee middle (WeM)	1.09	574	3	4335	237	5.81	4.06	0.45	1.6	**3.0**
Waikamoi lower (WiL)	0.98	124	25	55302	309	6.01	31.55	0.42	28.5	50
Waikamoi middle lower (WiML)	0.98	495	23	52895	312	5.99	28.83	0.43	27.9	49
Waikamoi middle upper (WiMU)	0.99	735	21	51440	312	5.99	27.26	0.44	27.6	49
Kolea lower (KaL)	0.89	38	12	11996	257	6.64	15.26	0.34	4.1	7.0
Kolea middle (KaM)	0.87	525	10	8924	227	6.76	12.52	0.36	3.4	**6.1**

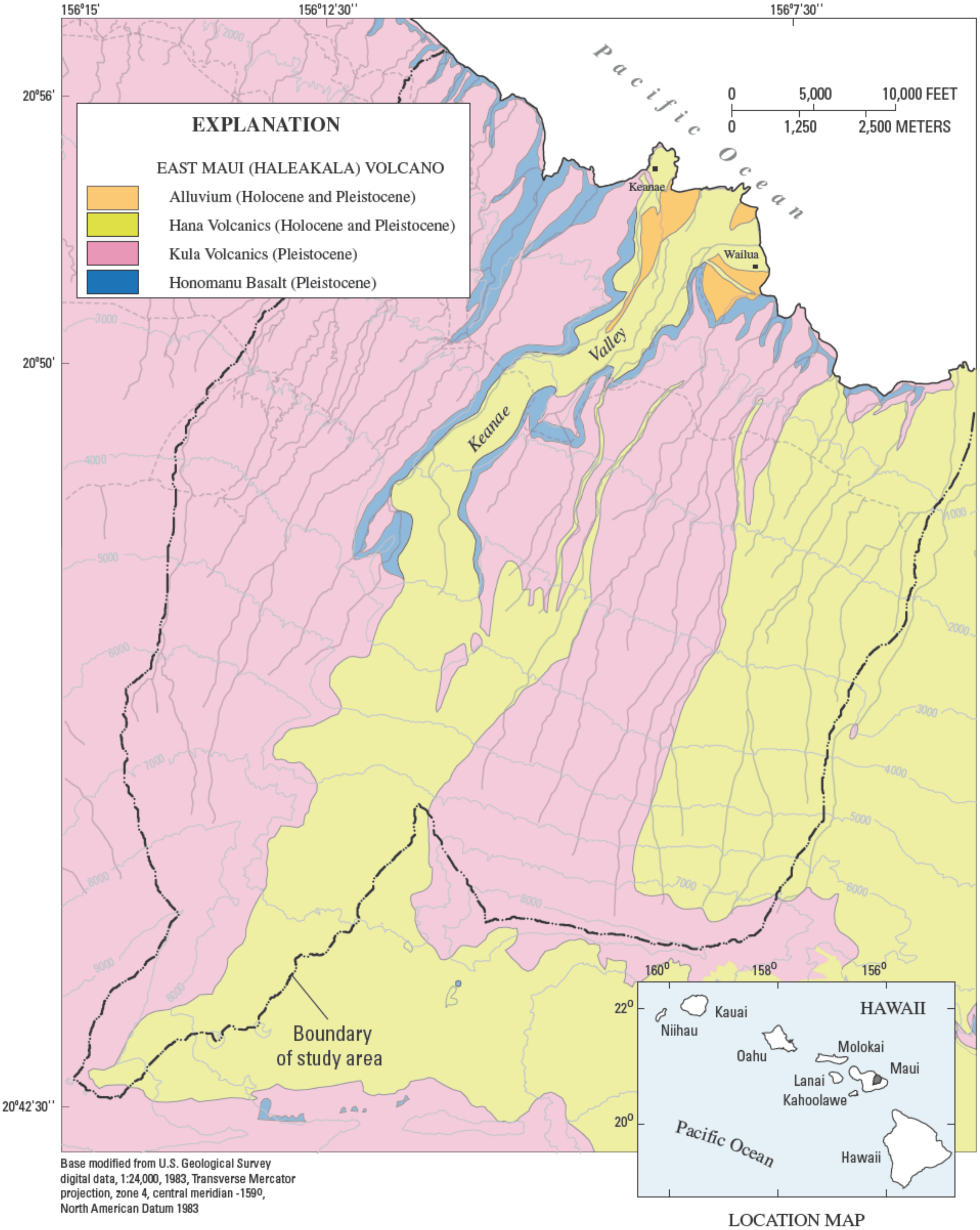


Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 20°39'30" and 20°57'30", central meridian 156°20'15"

EXPLANATION

— 25 — MEAN ANNUAL RAINFALL--Interval, in inches, is variable. (to convert rate in inches/year to feet/second, multiply by 2.65×10^{-9})

Figure 8. Mean annual rainfall, east Maui, Hawaii (modified from Giambelluca and others, 1986).



Base modified from U.S. Geological Survey
digital data, 1:24,000, 1983, Transverse Mercator
projection, zone 4, central meridian -159°,
North American Datum 1983

Figure 9. Generalized surficial geology, northeast Maui, Hawaii (modified from Sherrod and others, 2003).

signs and magnitudes of the coefficients determined for the significant, independent variables are hydrologically reasonable (Fontaine and others, 1992; Iman and Conover, 1983, p. 367).

Streamflow and basin characteristics used in hydrologic regression usually are log-normally distributed; therefore, the variables must be transformed to logarithms to satisfy regression assumption 2. The dependent and independent variables were transformed using log-base 10 units. Where values of percent coverage of Kula Volcanics were 0 percent, they were set to 1 percent before log transformation.

Ordinary-Least-Squares (OLS) regression analysis was used to develop the equations presented in this report. Because streamflow data are correlated spatially and in time, assumption 5 for use of regression is not strictly satisfied. A theoretically more appropriate method, Generalized-Least Squares (GLS) regression, was developed by Tasker and Stedinger (1989) to allow weighting to compensate for length-of-record and spatial correlations. However, Vogel and Kroll (1990) found that the equation parameters (b_0 to b_n) were nearly identical when either OLS or GLS was used to develop the equation, even though OLS does not correct for length-of-record or spatial differences. Ries and Friesz (2000) used Weighted-Least-Squares (WLS) regression analysis to predict duration flows because WLS can compensate for length-of-record differences. They found that equations developed using WLS and GLS methods were nearly identical. Because the streamflow statistics used in the development of the equations in this report were adjusted to equivalent lengths of record, and the spatial correlations between gaged basins in the study area are relatively insignificant, OLS regression analysis was determined to be the most appropriate for this study.

Regression assumption 7 was addressed by removing independent variables having high correlation (> 90 percent) with several other independent variables in the analysis. For example, Drainage Area (DA) was highly correlated with Total Stream Length (98 percent), Basin Relief (94 percent), Rainfall (93 percent), and Basin Width (91 percent), and therefore DA was removed from further analysis. Other basin characteristics removed from further consideration because of high correlations were Basin Perimeter (BP), Rotundity of Basin (RB), and Main Channel Length (MCL).

A variable-selection algorithm was applied to the remaining independent variables to aid in determining which combination of independent variables provides the best estimates of the dependent variables. The algorithm used was a leaps-and-bounds implementation with Mallow's *Cp* as the selection criterion (Insightful Corporation, 2002). Subsets of the independent variables were evaluated and ranked according to the lowest value of Mallow's *Cp* for each subset of 1, 2, 3 … n independent variables. The subsets of 1, 2, 3, and 4 independent variables having the lowest Mallow's *Cp* were then further analyzed using OLS regression to select a final model for each statistic.

During equation development, several gaging stations were eliminated from the analysis because (1) the sites were known outliers on the basis of observed hydrologic differences or (2) plots of Cook's distance (Draper and Smith, 1998) indicated that the flow statistics for a particular gaging station were statistically biasing the results. Gaging stations eliminated for hydrologic reasons prior to the Mallow's *Cp* analysis were stations 5070, 5311, and 5528 (intermittent streams); station 5090 (has anomalous spring input); and stations 5110, 5130, 5140, and 5210 (regulated streams). Gaging stations 5240 and 5420 were eliminated because of high Cook's distance values determined during the analyses. The final number of gaging stations from which data were used to develop the equations was 17 (n = 17).

The final models were selected on the basis of the following parameters: (1) Mallow's *Cp* statistic; (2) R^2, the proportion of total variation about the mean explained by the regression; (3) SE_r, the average standard error of the estimates; and (4) Pr ($>|t|$), the probability of significance for an independent variable in the regression. Pr ($>|t|$) had to be lower than 5 percent for each independent variable used in the regression model for that independent variable to be included.

The retransformed regression equations are biased because they predict the median rather than the mean response of the dependent variable. In the case of streamflow data, the median tends to be lower than the mean. Duan's (1983) "smearing estimate", the mean error of the retransformed residuals, was used as the bias-correction factor (BCF) to adjust the retransformed b_0 coefficient. This BCF is advantageous in that it does not require normally distributed regression residuals and is simple to calculate (Ries and Friesz, 2000).

Accuracy and limitations of the regression equations

Regression equations for predicting duration discharges TFQ_{50}, TFQ_{95}, BFQ_{50}, and BFQ_{95} at unregulated sites were developed using OLS regression as described above. The equations, along with several measures of model adequacy and the BCF for each equation, are presented in table 8. The measures of model adequacy include (1) the coefficient of determination (R^2); (2) the average standard error of estimate (SE_r), in percent; (3) the average standard error of prediction (SE_p), in percent; and (4) the median absolute deviation (MAD), in percent. The R^2 is a measure of the proportion of the variation in the dependent variable that is explained by the independent variables. The SE_r is a measure of the average precision with which the regression equations estimate the streamflow statistics for stations used in the analyses, whereas the SE_p indicates the average precision with which the equation can be used to estimate streamflow statistics for ungaged sites with basin characteristics similar to those for the stations used in the regression analyses. About 68 percent of streamflows estimated using the regression equations would have errors within the noted average standard errors. Half of the regression-equation estimates for stations used in the analyses had absolute

Table 8. Summary of regression equations developed for estimating selected flow-duration statistics of northeast Maui streams, Hawaii.

[**Statistic**: TF is total flow; BF is base flow, Q_{xx} is the xx-percent duration flow; **Statistic estimator**: Rainfall is area-weighted rainfall rate (cubic feet per second); MAXELEV is maximum drainage-basin elevation (feet); ER is elongation ratio (dimensionless); **R^2**: Coefficient of determination (percent); **SE_r** and **SE_p**: Average standard error of estimate and prediction (percent); **MAD**: Median absolute deviation (percent); **BCF**: Bias correction factor; n = 17 for all equations]

Statistic	Statistic estimator	R^2	SE_r	SE_p	MAD	BCF
TFQ_{50}	$3{,}184(\text{Rainfall})^{1.338}(\text{MAXELEV})^{-1.366}(\text{ER})^{-0.946}$	94.9	15.3	20.9	12	1.009
BFQ_{50}	$25{,}384(\text{Rainfall})^{1.525}(\text{MAXELEV})^{-1.735}(\text{ER})^{-0.937}$	91.0	22.5	30.5	17	1.019
TFQ_{95}	$56{,}267(\text{Rainfall})^{1.478}(\text{MAXELEV})^{-1.750}$	76.6	38.1	50.3	21	1.059
BFQ_{95}	$409{,}732(\text{Rainfall})^{1.620}(\text{MAXELEV})^{-2.054}$	75.3	43.0	56.5	28	1.073

Range used in analysis

	Minimum	Mean	Maximum
Rainfall	6.8	28	51
MAXELEV......	2,505	6,602	9,329
ER	0.17	0.26	0.34

errors, in percent, that were greater than the MAD, and half of them were less than the MAD. Scatter plots comparing observed and estimated flow-duration statistics show the fit of the regression equations for sites used in determining the equations (fig. 10).

The rainfall rates for stations used in developing the regression equations ranged from 51 to 6.8 ft³/s and averaged 28 ft³/s (table 8). For all four equations, rainfall has a positive coefficient, thus higher rainfall rates lead to higher estimated flows. The value of MAXELEV ranged from 9,329 to 2,505 ft and averaged 6,602. For all four equations, MAXELEV has a negative coefficient, thus higher elevations lead to lower estimated flows. The value of ER ranged from 0.34 to 0.17 and averaged 0.26. Only the median flow equations included ER, which has a negative coefficient in both equations. Therefore, short and wide drainage basins (higher ER), will have lower median flows. Estimates of flow-duration statistics derived by using the regression equations for drainage basins with characteristics outside the ranges (table 8) used in equation development could be subject to substantial errors.

Values of estimated streamflow statistics and several measures of estimation error for each continuous-record gaging station in the study area and at four gaged stations (5650, 5660, 5700, and 5770) west of the study area can be compared to the observed statistics to evaluate the performance of the equations (table 9). Statistics were generated for the gaged stations west of the study area to provide an additional indication of the accuracy of the equations for sites where measured streamflows are available. Estimated streamflow, in cubic feet per second, is the value determined by applying the regression equation. Prediction intervals (90 percent lower confidence limit [90% LCL], 90 percent upper confidence limit [90% UCL]), in cubic feet per second, indicate the uncertainty inherent in the use of the regression equations. Assurance is 90 percent that the true value of the streamflow statistic will be within the prediction interval. Standard error, in percent, is a measure of the precision with which the equation estimates the streamflow statistic. Measured flow, in cubic feet per second, is the observed streamflow statistic determined from the continuous record and adjusted to the long-term index station. Relative error, in percent, is calculated from [100(estimated flow – measured flow)/measured flow], and where available, indicates how well the estimated value matches the measured value. The value of MAD for each equation (table 8) is the average of relative errors for all stations used in the development of the regression equations.

At the stations used in the development of the equations, the equations tend to predict more accurately the higher flow statistics, TFQ_{50} and BFQ_{50}, than the lower flow statistics, TFQ_{95} and BFQ_{95}. At the outlier stations eliminated from the regression analysis, the accuracy of the equation estimates generally is poor, indicating that a factor not considered in the regression analysis is probably affecting the streamflow statistics at these stations (fig. 11). The most likely factor is variable subsurface geology that can control where streams are intermittent and where springs discharge high flow to streams. At the stations on intermittent streams (stations 5070 and 5528), the equations overestimate the flow-duration statistics. At stations on streams with notable springs (stations 5090, 5110, 5130, 5140), the equations underestimate the flow-duration statistics, especially at lower flows. At two (stations 5110 and 5210) of the three regulated stations where streamflow statistics were determined on the basis of combined records of the upstream and downstream gaging stations, the equations provide a reasonably accurate estimate of the flow statistics at the downstream stations. At stations 5110 and 5210, the rela-

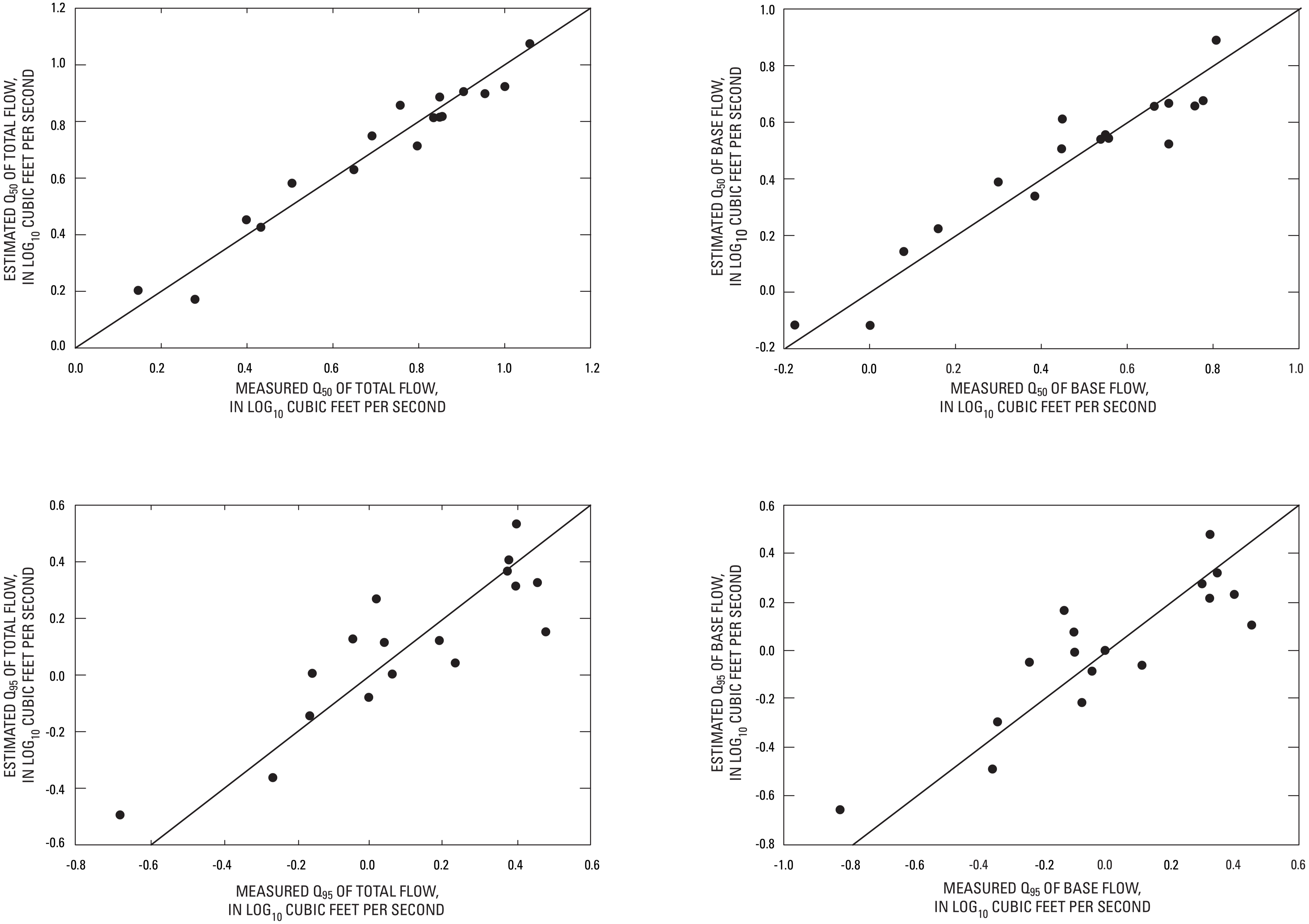


Figure 10. Relation between measured and estimated flow statistics (in log10 cubic feet per second) for selected gaged basins used in determining the regression equations, northeast Maui, Hawaii. Equations are listed in table 8.

Table 9. Streamflow statistics estimated using regression equations, lower and upper confidence intervals, standard errors, measured flows, and relative errors for continuous-record sites, northeast Maui, Hawaii.

[Gaging stations in **bold** were used to develop the final regression equations for estimating low-flow statistics; TFQ_{xx} is the xx-percent flow duration of total streamflow; BFQ_{xx} is the xx-percent flow duration of base flow; estimated and measured flow and confidence intervals are in cubic feet per second; 90% LCL and 90% UCL is 90-percent lower and upper confidence level; Standard error is in percent; Relative error is the percent difference between the measured statistic and the estimated statistic; measured flows in ***bold italics*** are within the 90-percent confidence interval of the computed estimate; NA, not applicable]

Gaging-station number	Statistic	TFQ_{50}	BFQ_{50}	TFQ_{95}	BFQ_{95}
5070	Estimated flow	9.1	6.0	3.4	3.0
	90% LCL	8.0	4.9	2.4	2.2
	90% UCL	10	7.3	4.6	4.3
	Standard error	7.8	11.4	17.6	19.7
	Measured flow	2.2	1.3	0.00	0.00
	Relative error	310	360	NA	NA
5080	Estimated flow	7.7	4.6	2.7	2.2
	90% LCL	6.8	3.8	2.1	1.7
	90% UCL	8.8	5.6	3.5	3.0
	Standard error	7.5	11.1	14.2	15.9
	Measured flow	***7.1***	***4.6***	***2.4***	***2.2***
	Relative error	8	0	13	0
5090 + 5080	Estimated flow	12	7.9	4.9	4.3
	90% LCL	10	6.1	3.4	2.8
	90% UCL	15	10	7.1	6.6
	Standard error	10.3	15.2	21.5	24.1
	Measured flow	28	24	19	19
	Relative error	-57	-67	-74	-77
5100	Estimated flow	5.7	3.3	1.1	0.89
	90% LCL	4.8	2.6	0.88	0.71
	90% UCL	6.6	4.1	1.3	1.1
	Standard error	8.9	13.0	11.3	12.7
	Measured flow	***4.9***	***2.8***	***1.1***	***0.90***
	Relative error	16	18	0	-1
5110 + 5100	Estimated flow	6.7	4.1	1.5	1.3
	90% LCL	5.9	3.4	1.2	1.0
	90% UCL	7.6	4.9	1.9	1.7
	Standard error	6.9	10.2	11.8	13.2
	Measured flow	***7.5***	5.1	3.3	3.0
	Relative error	-11	-20	-55	-57
5130	Estimated flow	0.81	0.44	0.20	0.16
	90% LCL	0.62	0.29	0.10	0.08
	90% UCL	1.0	0.65	0.37	0.33
	Standard error	15.2	22.4	37.4	42.1
	Measured flow	***0.86***	0.77	0.54	0.53
	Relative error	-6	-43	-63	-70

Table 9. Streamflow statistics estimated using regression equations, lower and upper confidence intervals, standard errors, measured flows, and relative errors for continuous-record sites, northeast Maui, Hawaii—Continued

[Gaging stations in **bold** were used to develop the final regression equations for estimating low-flow statistics; TFQ_{xx} is the xx-percent flow duration of total streamflow; BFQ_{xx} is the xx-percent flow duration of base flow; estimated and measured flow and confidence intervals are in cubic feet per second; 90% LCL and 90% UCL is 90-percent lower and upper confidence level; Standard error is in percent; Relative error is the percent difference between the measured statistic and the estimated statistic; measured flows in ***bold italics*** are within the 90-percent confidence interval of the computed estimate; NA, not applicable]

Gaging-station number	Statistic	TFQ_{50}	BFQ_{50}	TFQ_{95}	BFQ_{95}
5140	Estimated flow	3.3	2.0	0.86	0.76
	90% LCL	2.8	1.6	0.60	0.50
	90% UCL	3.9	2.6	1.2	1.1
	Standard error	9.4	13.8	21.0	23.5
	Measured flow	4.0	3.8	3.0	3.0
	Relative error	-18	-45	-71	-75
5150	Estimated flow	5.2	3.4	1.5	1.4
	90% LCL	4.5	2.7	1.1	0.9
	90% UCL	6.1	4.2	2.1	2.0
	Standard error	8.2	12.1	18.9	21.2
	Measured flow	6.2	5.0	3.0	2.8
	Relative error	-15	-32	-50	-52
5160	Estimated flow	8.1	4.8	2.5	2.0
	90% LCL	7.3	4.1	1.9	1.5
	90% UCL	9.0	5.6	3.1	2.6
	Standard error	6.1	9.0	13.6	15.2
	Measured flow	***8.0***	***5.0***	***2.3***	***2.0***
	Relative error	1	-4	4	0
5170	Estimated flow	8.0	4.6	2.3	1.8
	90% LCL	7.3	4.0	1.8	1.4
	90% UCL	8.8	5.3	2.8	2.4
	Standard error	5.5	8.1	13.0	14.5
	Measured flow	9.1	5.7	***2.8***	2.5
	Relative error	-12	-21	-21	-28
5180	Estimated flow	8.5	4.8	2.2	1.8
	90% LCL	7.7	4.2	1.7	1.4
	90% UCL	9.3	5.6	2.8	2.3
	Standard error	5.4	8.0	13.1	14.7
	Measured flow	10	6.0	***2.5***	***2.1***
	Relative error	-15	-20	-12	-14

Table 9. Streamflow statistics estimated using regression equations, lower and upper confidence intervals, standard errors, measured flows, and relative errors for continuous-record sites, northeast Maui, Hawaii—Continued

[Gaging stations in **bold** were used to develop the final regression equations for estimating low-flow statistics; TFQ_{xx} is the xx-percent flow duration of total streamflow; BFQ_{xx} is the xx-percent flow duration of base flow; estimated and measured flow and confidence intervals are in cubic feet per second; 90% LCL and 90% UCL is 90-percent lower and upper confidence level; Standard error is in percent; Relative error is the percent difference between the measured statistic and the estimated statistic; measured flows in ***bold italics*** are within the 90-percent confidence interval of the computed estimate; NA, not applicable]

Gaging-station number	Statistic	TFQ_{50}	BFQ_{50}	TFQ_{95}	BFQ_{95}
5190	Estimated flow	4.3	2.2	0.89	0.66
	90% LCL	3.9	1.9	0.70	0.51
	90% UCL	4.8	2.6	1.1	0.86
	Standard error	5.7	8.5	13.1	14.6
	Measured flow	***4.4***	***2.4***	***1.0***	***0.85***
	Relative error	-2	-12	-11	-22
5200	Estimated flow	3.9	2.5	1.4	1.3
	90% LCL	3.3	2.0	1.0	0.89
	90% UCL	4.4	3.1	2.0	1.9
	Standard error	8.1	11.9	18.9	21.2
	Measured flow	3.2	***2.0***	0.90	0.80
	Relative error	22	25	56	63
5210 + 5200 + 5190	Estimated flow	8.6	4.9	1.8	1.4
	90% LCL	7.7	4.1	1.5	1.1
	90% UCL	9.6	5.7	2.2	1.8
	Standard error	6.2	9.1	11.1	12.4
	Measured flow	10	6.1	2.5	2.0
	Relative error	-14	-20	-28	-30
5240	Estimated flow	4.5	2.4	1.3	1.0
	90% LCL	4.0	2.1	1.1	0.83
	90% UCL	5.0	2.9	1.6	1.3
	Standard error	6.1	9.0	11.1	12.4
	Measured flow	2.2	0.93	0.37	0.30
	Relative error	100	160	250	230
5270	Estimated flow	7.3	4.2	2.0	1.6
	90% LCL	6.9	3.6	1.6	1.2
	90% UCL	8.0	4.7	2.4	2.0
	Standard error	5.0	7.3	11.9	13.3
	Measured flow	5.7	2.8	1.0	0.74
	Relative error	28	50	82	120

Table 9. Streamflow statistics estimated using regression equations, lower and upper confidence intervals, standard errors, measured flows, and relative errors for continuous-record sites, northeast Maui, Hawaii—Continued

[Gaging stations in **bold** were used to develop the final regression equations for estimating low-flow statistics; TFQ_{xx} is the xx-percent flow duration of total streamflow; BFQ_{xx} is the xx-percent flow duration of base flow; estimated and measured flow and confidence intervals are in cubic feet per second; 90% LCL and 90% UCL is 90-percent lower and upper confidence level; Standard error is in percent; Relative error is the percent difference between the measured statistic and the estimated statistic; measured flows in ***bold italics*** are within the 90-percent confidence interval of the computed estimate; NA, not applicable]

Gaging-station number	Statistic	TFQ_{50}	BFQ_{50}	TFQ_{95}	BFQ_{95}
5311 + 5310	Estimated flow	0.35	0.14	0.08	0.05
	90% LCL	0.25	0.09	0.04	0.02
	90% UCL	0.49	0.23	0.17	0.12
	Standard error	19.3	28.7	45.6	51.6
	Measured flow	0.50	***0.17***	0.03	***0.03***
	Relative error	-30	-18	170	67
5360 + 5310 + 5350	Estimated flow	6.6	3.7	1.2	0.94
	90% LCL	5.7	3.0	1.0	0.79
	90% UCL	7.6	4.6	1.4	1.1
	Standard error	8.2	12.1	9.2	10.2
	Measured flow	***6.8***	***3.5***	1.7	1.3
	Relative error	-3	6	-29	-28
5420	Estimated flow	0.30	0.14	0.15	0.10
	90% LCL	0.20	0.08	0.08	0.05
	90% UCL	0.45	0.25	0.27	0.20
	Standard error	22.5	33.5	34.9	39.4
	Measured flow	0.88	0.53	0.29	0.27
	Relative error	-66	-74	-48	-63
5430	Estimated flow	1.6	0.78	0.33	0.24
	90% LCL	1.4	0.61	0.22	0.15
	90% UCL	1.9	1.0	0.50	0.37
	Standard error	9.4	13.8	22.9	25.7
	Measured flow	***1.4***	***0.67***	0.21	***0.15***
	Relative error	14	16	57	60
5440	Estimated flow	1.5	0.78	0.46	0.35
	90% LCL	1.3	0.62	0.33	0.24
	90% UCL	1.8	0.99	0.63	0.50
	Standard error	9.1	13.4	18.4	20.7
	Measured flow	1.9	1.0	***0.55***	***0.44***
	Relative error	-21	-22	-16	-20

Table 9. Streamflow statistics estimated using regression equations, lower and upper confidence intervals, standard errors, measured flows, and relative errors for continuous-record sites, northeast Maui, Hawaii—Continued

[Gaging stations in **bold** were used to develop the final regression equations for estimating low-flow statistics; TFQ_{xx} is the xx-percent flow duration of total streamflow; BFQ_{xx} is the xx-percent flow duration of base flow; estimated and measured flow and confidence intervals are in cubic feet per second; 90% LCL and 90% UCL is 90-percent lower and upper confidence level; Standard error is in percent; Relative error is the percent difference between the measured statistic and the estimated statistic; measured flows in ***bold italics*** are within the 90-percent confidence interval of the computed estimate; NA, not applicable]

Gaging-station number	Statistic	TFQ_{50}	BFQ_{50}	TFQ_{95}	BFQ_{95}
5450	Estimated flow	12	7.9	3.6	3.3
	90% LCL	11	6.5	2.6	2.3
	90% UCL	14	9.6	5.0	4.6
	Standard error	7.5	11.0	18.1	20.3
	Measured flow	***12***	6.4	2.5	2.1
	Relative error	0	23	44	57
5528	Estimated flow	1.2	0.55	0.33	0.22
	90% LCL	0.98	0.39	0.21	0.13
	90% UCL	1.5	0.78	0.53	0.37
	Standard error	13.2	19.5	26.8	30.1
	Measured flow	0.14	0.06	0.02	0.01
	Relative error	760	820	1600	2100
5540	Estimated flow	2.9	1.4	0.76	0.55
	90% LCL	2.5	1.1	0.57	0.40
	90% UCL	3.3	1.7	1.0	0.76
	Standard error	8.0	11.9	16.4	18.4
	Measured flow	***2.5***	***1.2***	***0.69***	***0.46***
	Relative error	16	17	10	20
5550	Estimated flow	6.6	3.5	1.4	1.1
	90% LCL	6.0	3.1	1.1	0.83
	90% UCL	7.3	4.1	1.7	1.4
	Standard error	5.6	8.3	12.6	14.0
	Measured flow	***7.0***	***3.5***	***1.1***	0.80
	Relative error	-6	0	27	38
5560	Estimated flow	6.7	3.6	1.4	1.1
	90% LCL	6.1	3.1	1.1	0.84
	90% UCL	7.4	4.2	1.7	1.4
	Standard error	5.6	8.3	12.5	14.0
	Measured flow	7.1	***3.6***	***1.5***	***1.0***
	Relative error	-6	0	-13	10

Table 9. Streamflow statistics estimated using regression equations, lower and upper confidence intervals, standard errors, measured flows, and relative errors for continuous-record sites, northeast Maui, Hawaii—Continued

[Gaging stations in **bold** were used to develop the final regression equations for estimating low-flow statistics; TFQ_{xx} is the xx-percent flow duration of total streamflow; BFQ_{xx} is the xx-percent flow duration of base flow; estimated and measured flow and confidence intervals are in cubic feet per second; 90% LCL and 90% UCL is 90-percent lower and upper confidence level; Standard error is in percent; Relative error is the percent difference between the measured statistic and the estimated statistic; measured flows in ***bold italics*** are within the 90-percent confidence interval of the computed estimate; NA, not applicable]

Gaging-station number	Statistic	TFQ_{50}	BFQ_{50}	TFQ_{95}	BFQ_{95}
5570	Estimated flow	2.7	1.7	1.1	0.96
	90% LCL	2.3	1.3	0.76	0.65
	90% UCL	3.2	2.2	1.5	1.4
	Standard error	9.3	13.7	19.9	22.3
	Measured flow	***2.7***	***1.4***	0.70	0.58
	Relative error	0	13	57	66
5650[a]	Estimated flow	4.0	2.5	1.2	1.1
	90% LCL	3.5	2.1	0.94	0.80
	90% UCL	4.5	2.9	1.6	1.5
	Standard error	6.6	9.7	16.0	17.9
	Measured flow	2.6	1.4	0.71	0.61
	Relative error	54	79	69	80
5660[a]	Estimated flow	1.2	0.73	0.50	0.42
	90% LCL	1.0	0.53	0.32	0.26
	90% UCL	1.5	1.0	0.78	0.70
	Standard error	12.2	18.0	26.0	29.2
	Measured flow	***1.0***	0.42	0.25	0.21
	Relative error	9	74	100	100
5700[a]	Estimated flow	15	9.3	3.7	3.3
	90% LCL	13	7.5	2.7	2.3
	90% UCL	17	11	5.1	4.6
	Standard error	8.1	11.9	17.8	19.9
	Measured flow	***16***	***9.5***	***4.5***	***4.0***
	Relative error	-6	-2	-18	-18
5770[a]	Estimated flow	12	7.9	4.0	3.7
	90% LCL	10	6.4	2.8	2.5
	90% UCL	14	9.8	5.7	5.5
	Standard error	8.3	12.2	20.3	22.7
	Measured flow	8.9	5.0	2.1	1.7
	Relative error	35	58	99	110

[a] located west of current study area

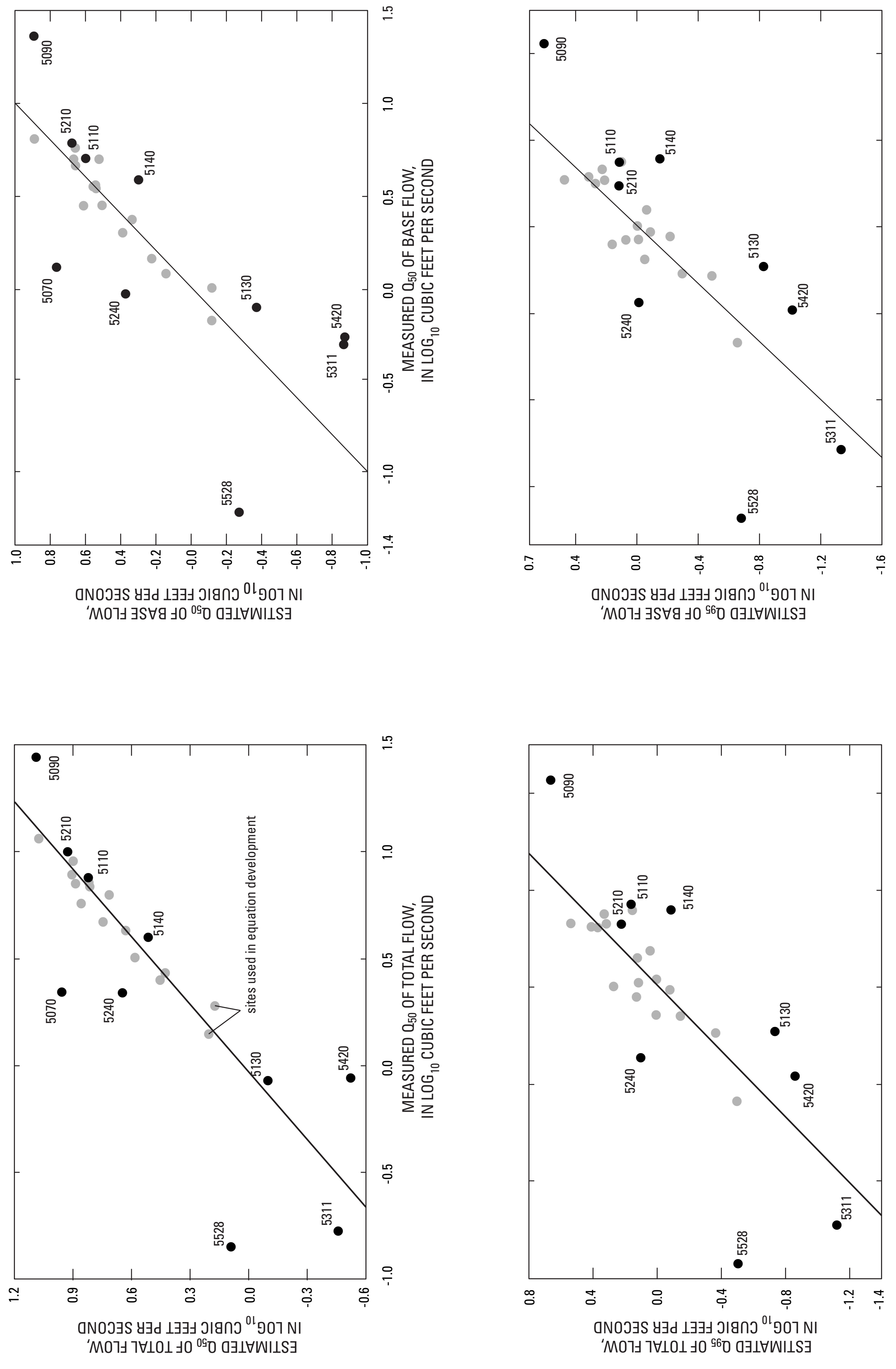


Figure 11. Relation between measured and estimated flow statistics (in log10 cubic feet per second) for gaged basins not used (outliers) in determining regression equations, northeast Maui, Hawaii. Equations are listed in table 8.

tive errors for TFQ_{50} and BFQ_{50}, range from -10 to -20 percent and for TFQ_{95} and BFQ_{95}, the relative errors range from -28 to -57 percent. At the third regulated station (station 5090) where streamflow statistics were determined on the basis of combined records, the estimates have relative errors ranging from -57 to -77 percent, indicating that the anomalous input from springs to Hanawi Stream is not accounted for by the equations.

The regression equation for TFQ_{50} estimates that statistic within a relative error of ±25 percent at 20 of the continuous-record gaging stations. Flow at 15 stations is underestimated and flow at 12 stations is the same as the measured statistic or overestimated. All but one of the TFQ_{50} flows at stations east of Keanae Valley and downstream of the Koolau ditch are underestimated, indicating the influence of springs with high discharge volume in this area (fig. 12). The only overestimate east of Keanae Valley is at gaging station 5070 on an intermittent reach of Makapipi Stream. The regression equation for BFQ_{50} estimates that statistic within a relative error of ±25 percent at 18 of the continuous-record gaging stations. Flow at 13 stations is underestimated and flow at 14 stations is the same as measured or overestimated. Most of the flow at stations east of Keanae Valley is underestimated with the stations downstream of the Koolau ditch having the greatest errors (fig. 13). The regression equation for TFQ_{95} estimates that statistic within a relative error of ±50 percent at 15 of the continuous-record gaging stations. The errors are higher for lower flows because, for the same absolute error in flow, the relative error, in percent, increases as the actual flow decreases. For example, at station 5180, an absolute error of 1.0 ft^3/s is 10 percent of TFQ_{50} (10 ft^3/s) but 17 percent of BFQ_{50} (6.0 ft^3/s). Flow at 13 stations is underestimated and flow at 14 stations is the same as the measured statistic or overestimated. The cluster of underestimated stations east of Keanae Valley and downstream from the Koolau ditch is apparent at lower flows (fig. 14). The regression equation for BFQ_{95} estimates that statistic within a relative error of ±50 percent at 12 of the continuous-record gaging stations. Flow at 12 stations is underestimated and flow at 15 stations is the same as the measured statistic or overestimated. The cluster of underestimated stations east of Keanae Valley and below the ditch is persistent at this lowest flow statistic (fig. 15).

The results of applying the equation for TFQ_{50} developed in this study can be compared with results using an equation for TFQ_{50} developed by Fontaine and others (1992) for streams on Maui and Kauai:

$$\mathrm{TFQ}_{50} = 4.49(\mathrm{DA})^{0.808}(\mathrm{CE})^{-0.641}(\mathrm{P})^{0.985} \quad , \qquad (2)$$

where: TFQ_{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, and

P is mean annual precipitation, in inches.

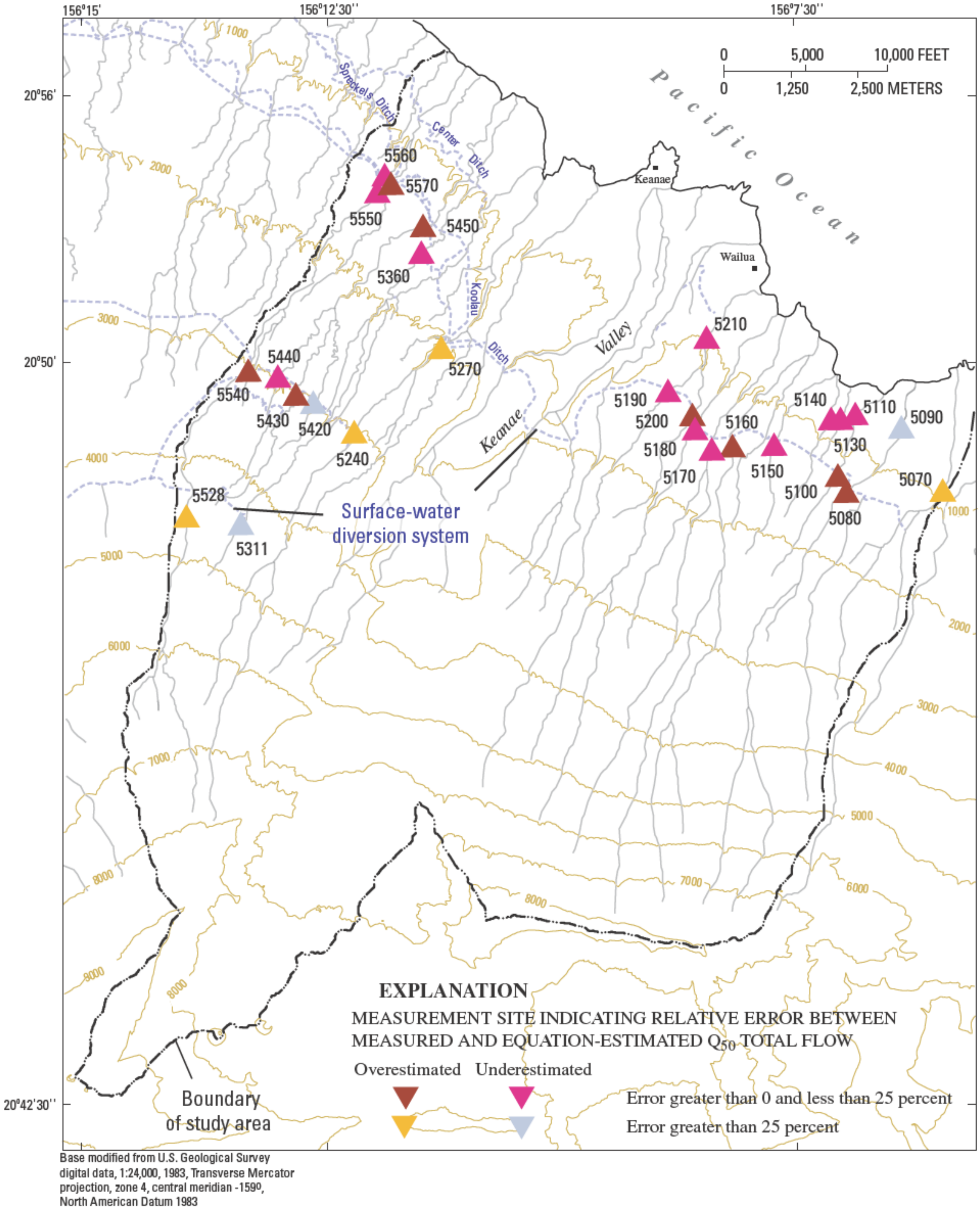
For this comparison, *CE* was calculated using the relation 0.5[MAXELEV+MINELEV], and *P* was calculated using the relation 13.53719[Rainfall/DA] for each drainage basin from the data in table 5, because the original values from Fontaine and others (1992) were not available. For the 17 stations from which data were used to develop the regression equations for this study, equation 2 (1992 study) provides a MAD of 20 percent compared with 12 percent determined using the equation for TFQ_{50} (table 8) developed in this study. The SE_r and SE_p for the newly developed equation are also lower (15.3 and 20.9 percent, respectively) than for the previous equation (46.2 and 54.3 percent, respectively). Therefore, the newly developed equation for TFQ_{50} is an improvement over the equation determined by Fontaine and others (1992).

Application of the regression equations to ungaged sites

The regression equations developed for this study from the flow statistics in table 2 and the basin characteristics listed in tables 5 and 6 were used to estimate the TFQ_{50}, TFQ_{95}, BFQ_{50}, and BFQ_{95} duration discharges at selected ungaged sites in the study area (plate 1). Estimated streamflow, prediction intervals, standard error, measured flow, and relative error for 47 ungaged sites are listed in Table 10. Where possible, measured flow values were determined using a combination of flow-duration statistics for an upstream gaging-station and low-flow measurements at ungaged sites downstream of the diversions to provide additional basis for evaluating the equation-based estimates.

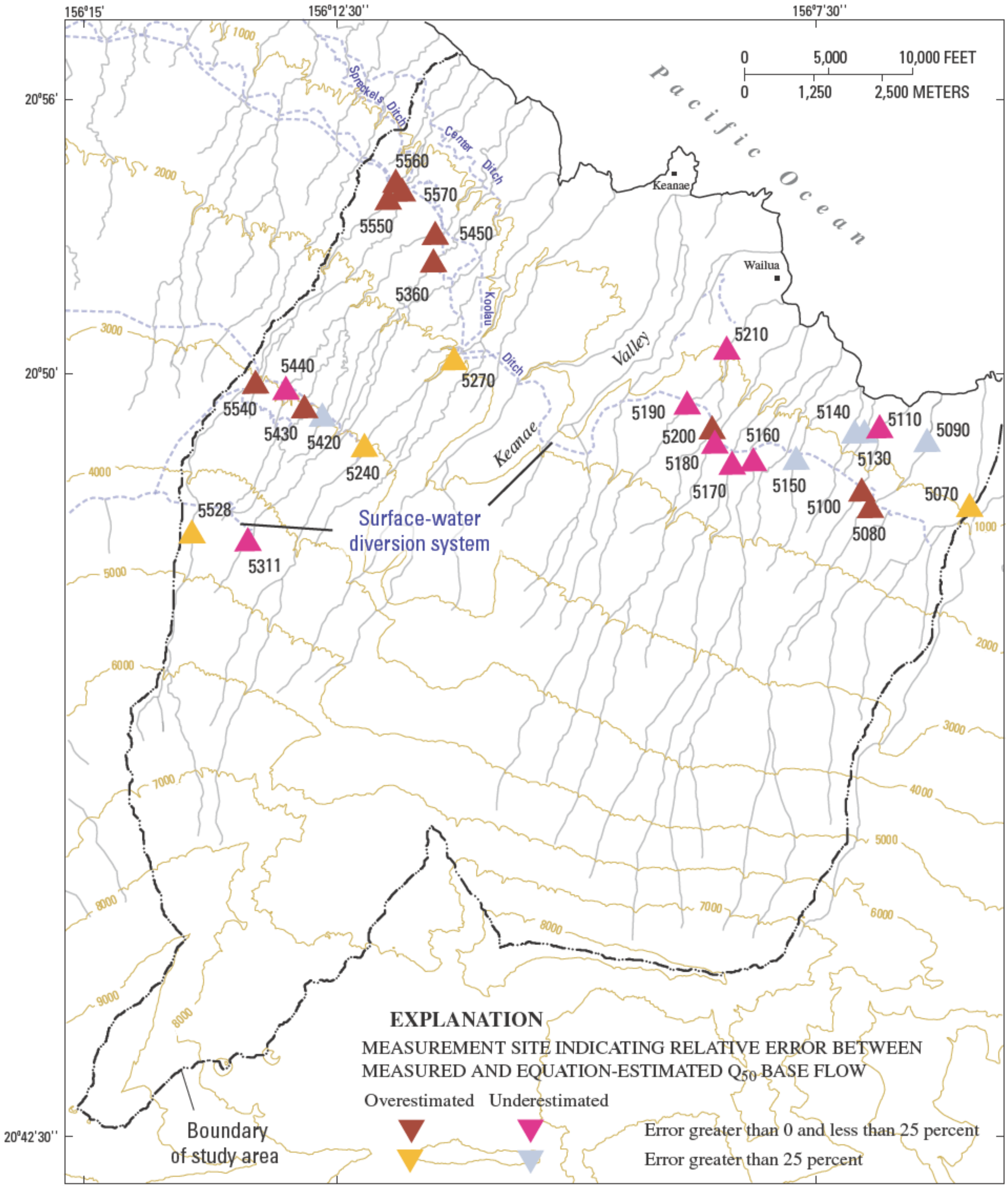
Generally, an estimate of flow at an ungaged site made on the basis of a flow-duration discharge at an upstream gaging station and a single measurement of flow at the ungaged site results in a large uncertainty in the estimate. For most ungaged sites in the study area, however, these values are all the information that is available. This technique is considered applicable in the study area because the streams are dry immediately downstream of the diversions at least 50 percent of the time, and measured low flow further downstream represents only those gains to the stream downstream of the diversions. Inflow downstream of the diversions from minor tributaries is insignificant.

Low-flow estimates listed in table 10 were derived from low-flow measurements from three sources: (1) measurements made as part of this study in 2002 and 2003; (2) measurements made as part of a previous USGS study in the area during 1995 to 1999 (Gingerich, 1999); and (3) measurements made by EMI in 1928 (reported in Gingerich, 1999). The average of all these low-flow measurements were assumed roughly equal to TFQ_{95} flow duration. This is because the flow at the index station (5180) during all the USGS measurements (1995–99 and 2002–03) ranged from TFQ_{94} to TFQ_{97} and the flow was at TFQ_{90} during the 1928 EMI measurements. The difference in flow between TFQ_{90} (3.3 ft^3/s) and TFQ_{95} (2.5 ft^3/s) at 5180 is 0.8 ft^3/s, or a relative difference of 32 percent. However, because the low-flow measurements were all made downstream of the diversion ditches during base-flow periods, there is little variation between low flows even as flow at the



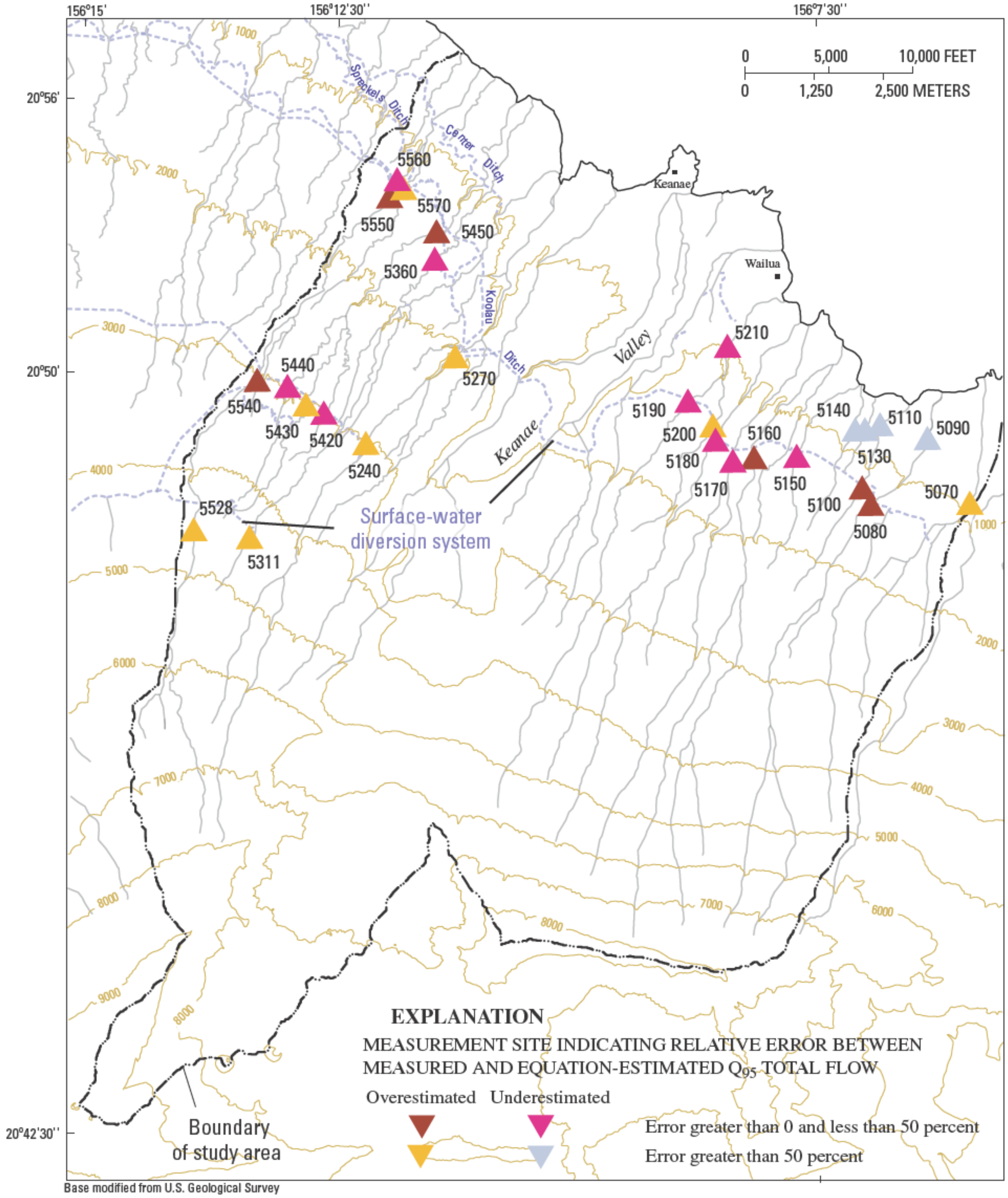
Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Transverse Mercator projection, zone 4, central meridian -159°, North American Datum 1983

Figure 12. Distribution of relative error between measured and equation-estimated median total flow (TFQ_{50}) at gaging-stations, northeast Maui, Hawaii.



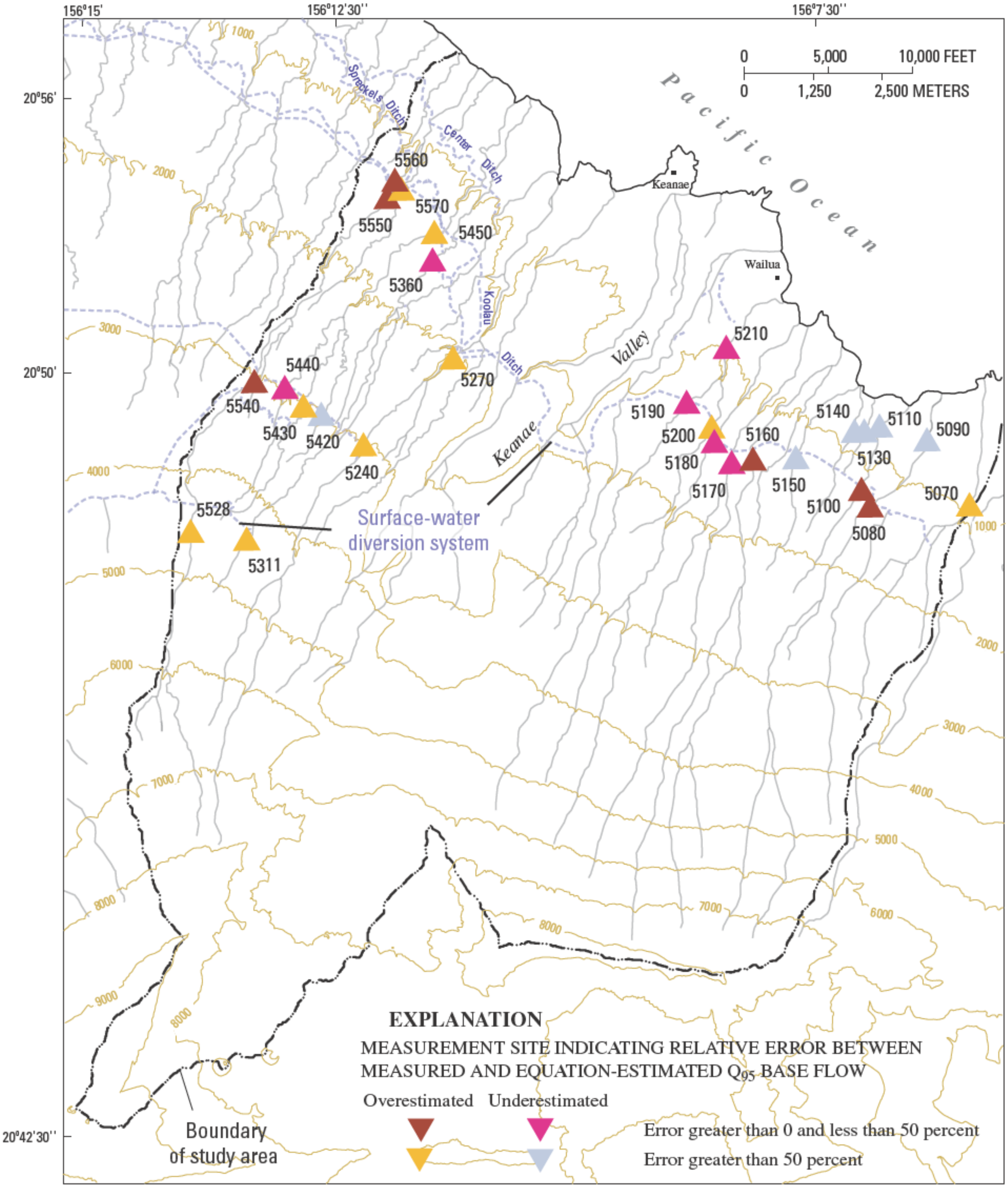
Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Transverse Mercator projection, zone 4, central meridian -159º, North American Datum 1983

Figure 13. Distribution of relative error between measured and equation-estimated median base flow (BFQ_{50}) at gaging-stations, northeast Maui, Hawaii.



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Transverse Mercator projection, zone 4, central meridian -159o, North American Datum 1983

Figure 14. Distribution of relative error between measured and equation-estimated Q_{95} total flow (TFQ_{95}) at gaging-station, northeast Maui, Hawaii.



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Transverse Mercator projection, zone 4, central meridian -159°, North American Datum 1983

Figure 15. Distribution of relative error between measured and equation-estimated Q_{95} base flow (BFQ_{95}) at gaging-station, northeast Maui, Hawaii.

Table 10. Streamflow statistics estimated using regression equations, lower and upper confidence intervals, standard errors, measured flow, and relative errors for ungaged basins, northeast Maui, Hawaii.

[TFQxx is the xx-percent flow duration of total streamflow; BFQxx is the xx-percent flow duration of base flow; estimated and measured flow and confidence intervals are in cubic feet per second; 90% LCL and UCL is 90-percent lower and upper confidence level; Standard error is in percent; Relative error is ([estimated flow – measured flow]/measured flow x 100), in percent; L, lower; M, middle; U, upper; Measured flows in ***bold italic*** fall within the lower and upper 90-percent confidence interval; East Maui Irrigation Co., Ltd (EMI) 1928 measurements from March 16-20 when index station had a Q_{90} flow (reported in Gingerich, 1999); >, likely greater than; <, likely less than; --, not available]

Stream location	Statistic	TFQ_{50}	BFQ_{50}	TFQ_{95}	BFQ_{95}	Source of measured flow estimates
Hanawi lower (HwL)	Estimated flow	16	10	5.1	4.6	**TFQ_{50}, BFQ_{50}, BFQ_{95}**: combined flow statistics from 5080 and 5090 upstream; **TFQ_{95}**: Average of flow on entire stream Feb. 22, 1995 [**Q_{97}**] (Gingerich, 1999) and combined **Q_{95}** flows from 5080 and 5090 upstream plus flow Nov. 7, 2003 [**Q_{94}**]
	90% LCL	14	8.3	3.5	3.0	
	90% UCL	19	13	7.6	7.0	
	Standard error	9.1	13.4	22.1	24.8	
	Measured flow	> 28	> 24	25	> 19	
	Relative error	< -43	< -58	-79	< -76	
Kapaula lower (KL)	Estimated flow	7.5	4.6	1.8	1.5	Combined flow statistic from 5100 and 5110 upstream
	90% LCL	6.6	3.9	1.4	1.2	
	90% UCL	8.7	5.6	2.2	2.0	
	Standard error	7.2	10.6	12.6	14.1	
	Measured flow	> 7.5	> 5.1	> 3.3	> 3.0	
	Relative error	0	< -8	< -45	< -50	
Waiaaka lower (WaL)	Estimated flow	1.3	0.80	0.39	0.34	Flow statistics from 5130 upstream; unknown amount of upstream diversion at Koolau Ditch
	90% LCL	1.1	0.57	0.22	0.18	
	90% UCL	1.8	1.1	0.67	0.62	
	Standard error	13.0	19.2	31.9	35.9	
	Measured flow	> 0.86	> 0.77	> 0.54	> 0.53	
	Relative error	< 63	< 4	< -28	< -36	
Paakea lower (PaL)	Estimated flow	4.3	2.8	1.5	1.4	Flow statistics from 5140 upstream; unknown amount of upstream diversion at Koolau Ditch
	90% LCL	3.7	2.3	1.0	0.89	
	90% UCL	5.1	3.6	2.1	2.1	
	Standard error	8.9	13.1	21.7	24.3	
	Measured flow	> 4.0	> 3.8	> 3.0	> 3.0	
	Relative error	< 8	< -24	< -50	< -53	
Paakea upper (PaU)	Estimated flow	1.5	0.88	0.50	0.42	No data available
	90% LCL	1.3	0.68	0.33	0.27	
	90% UCL	1.8	1.1	0.75	0.66	
	Standard error	10.0	14.7	23.5	26.4	
	Measured flow	--	--	--	--	
	Relative error	--	--	--	--	
Waiohue lower (WeL)	Estimated flow	7.8	5.5	2.9	2.8	Flow statistics from 5150 upstream plus EMI 1928 measurement
	90% LCL	6.6	4.3	1.9	1.8	
	90% UCL	9.3	7.1	4.4	4.5	
	Standard error	9.8	14.4	24.0	26.9	
	Measured flow	> 6.8	> 5.6	> 3.6	> 3.5	
	Relative error	< 16	< -2	< -19	< -20	

Table 10. Streamflow statistics estimated using regression equations, lower and upper confidence intervals, standard errors, measured flow, and relative errors for ungaged basins, northeast Maui, Hawaii—Continued

[TFQxx is the xx-percent flow duration of total streamflow; BFQxx is the xx-percent flow duration of base flow; estimated and measured flow and confidence intervals are in cubic feet per second; 90% LCL and UCL is 90-percent lower and upper confidence level; Standard error is in percent; Relative error is ([estimated flow – measured flow]/measured flow x 100), in percent; L, lower; M, middle; U, upper; Measured flows in ***bold italic*** fall within the lower and upper 90-percent confidence interval; East Maui Irrigation Co., Ltd (EMI) 1928 measurements from March 16-20 when index station had a Q_{90} flow (reported in Gingerich, 1999); >, likely greater than; <, likely less than; --, not available]

Stream location	Statistic	TFQ_{50}	BFQ_{50}	TFQ_{95}	BFQ_{95}	Source of measured flow estimates
Waiohue middle (WeM)	Estimated flow	6.5	4.4	2.3	2.2	Flow statistics from 5150 upstream plus EMI 1928 measurement
	90% LCL	5.5	3.5	1.6	1.4	
	90% UCL	7.6	5.6	3.4	3.4	
	Standard error	9.0	13.2	21.9	24.6	
	Measured flow	> 6.8	> 5.6	3.6	> 3.5	
	Relative error	< -4	< -21	-36	< -37	
Puakaa middle (PuM)	Estimated flow	3.6	2.2	1.0	0.88	**TFQ_{95}**: EMI 1928 measurement; unknown amount of upstream diversion at Koolau Ditch
	90% LCL	3.1	1.8	0.70	0.60	
	90% UCL	4.2	2.8	1.4	1.3	
	Standard error	8.6	12.7	20.0	22.4	
	Measured flow	--	--	> 0.62	--	
	Relative error	--	--	< 61	--	
Puakaa upper (PuU)	Estimated flow	1.9	1.1	0.63	0.54	No data available
	90% LCL	1.6	0.89	0.44	0.35	
	90% UCL	2.2	1.4	0.92	0.81	
	Standard error	9.1	13.3	21.3	23.9	
	Measured flow	--	--	--	--	
	Relative error	--	--	--	--	
Kopiliula lower (KpL)	Estimated flow	11	6.7	3.4	2.9	Flow statistics from 5160 upstream plus average of 6 USGS low-flow measurements in 2002-03
	90% LCL	9.7	5.6	2.5	2.1	
	90% UCL	13	8.1	4.6	4.0	
	Standard error	7.2	10.6	16.9	19.0	
	Measured flow	> 11	> 8.1	5.4	5.1	
	Relative error	0	< -17	-38	-43	
Kopiliula middle (KpM)	Estimated flow	10	6.2	2.8	2.3	Flow statistics from 5160 upstream plus average of 7 USGS low-flow measurements in 2002-03
	90% LCL	9.4	5.3	2.2	1.7	
	90% UCL	12	7.3	3.6	3.1	
	Standard error	6.1	9.0	14.8	16.5	
	Measured flow	> 9.0	6.0	3.3	3.0	
	Relative error	< 11	< 3	-18	-23	

Table 10. Streamflow statistics estimated using regression equations, lower and upper confidence intervals, standard errors, measured flow, and relative errors for ungaged basins, northeast Maui, Hawaii—Continued

[TFQxx is the xx-percent flow duration of total streamflow; BFQxx is the xx-percent flow duration of base flow; estimated and measured flow and confidence intervals are in cubic feet per second; 90% LCL and UCL is 90-percent lower and upper confidence level; Standard error is in percent; Relative error is ([estimated flow – measured flow]/measured flow x 100), in percent; L, lower; M, middle; U, upper; Measured flows in ***bold italic*** fall within the lower and upper 90-percent confidence interval; East Maui Irrigation Co., Ltd (EMI) 1928 measurements from March 16-20 when index station had a Q_{90} flow (reported in Gingerich, 1999); >, likely greater than; <, likely less than; --, not available]

Stream location	Statistic	TFQ_{50}	BFQ_{50}	TFQ_{95}	BFQ_{95}	Source of measured flow estimates
East Wailuaiki lower (EWL)	Estimated flow	10	6.1	2.7	2.2	Flow statistics from 5170 upstream plus EMI 1928 measurement
	90% LCL	9.3	5.2	2.1	1.7	
	90% UCL	12	7.1	3.4	2.9	
	Standard error	6.0	8.8	14.4	16.2	
	Measured flow	***> 9.4***	***> 6.1***	***> 3.2***	***> 2.8***	
	Relative error	< 6	0	< -16	< -21	
East Wailuaiki middle (EWM)	Estimated flow	9.5	5.6	2.5	2.1	Flow statistics from 5170 upstream plus EMI 1928 measurement
	90% LCL	8.5	4.8	2.0	1.6	
	90% UCL	10	6.4	3.3	2.8	
	Standard error	5.8	8.8	14.0	15.7	
	Measured flow	***> 9.4***	***> 6.1***	***3.2***	***2.8***	
	Relative error	< 1	< -8	-22	< -25	
West Wailuaiki lower (WWL)	Estimated flow	10	6.0	2.5	2.1	Flow statistics from 5180 upstream plus EMI 1928 measurement
	90% LCL	9.3	5.2	2.0	1.6	
	90% UCL	12	7.1	3.3	2.7	
	Standard error	6.0	8.9	14.2	15.9	
	Measured flow	***> 11***	***> 6.7***	***> 3.3***	> 2.9	
	Relative error	< -9	< -10	< -24	< -28	
West Wailuaiki middle (WWM)	Estimated flow	9.7	5.6	2.4	2.0	Flow statistics from 5180 upstream plus EMI 1928 measurement
	90% LCL	8.7	4.8	1.9	1.5	
	90% UCL	11	6.5	3.1	2.6	
	Standard error	5.8	8.5	13.9	15.6	
	Measured flow	***> 11***	> 6.7	3.3	2.9	
	Relative error	< -12	< -16	-27	-31	
Wailuanui lower (WL)	Estimated flow	9.5	5.5	2.2	1.8	Combined flow statistics from 5190, 5200, and 5210 upstream plus average of 2 USGS low-flow measurements in 2002-03; unknown amount of taro diversion and return flow
	90% LCL	8.6	4.7	1.7	1.4	
	90% UCL	10.5	6.4	2.7	2.2	
	Standard error	5.8	8.5	12.2	13.7	
	Measured flow	***> 9.5***	***> 5.8***	***2.7***	***> 2.4***	
	Relative error	< -5	< -17	-27	< -28	

Table 10. Streamflow statistics estimated using regression equations, lower and upper confidence intervals, standard errors, measured flow, and relative errors for ungaged basins, northeast Maui, Hawaii—Continued

[TFQxx is the xx-percent flow duration of total streamflow; BFQxx is the xx-percent flow duration of base flow; estimated and measured flow and confidence intervals are in cubic feet per second; 90% LCL and UCL is 90-percent lower and upper confidence level; Standard error is in percent; Relative error is ([estimated flow – measured flow]/measured flow x 100), in percent; L, lower; M, middle; U, upper; Measured flows in ***bold italic*** fall within the lower and upper 90-percent confidence interval; East Maui Irrigation Co., Ltd (EMI) 1928 measurements from March 16-20 when index station had a Q_{90} flow (reported in Gingerich, 1999); >, likely greater than; <, likely less than; --, not available]

Stream location	Statistic	TFQ_{50}	BFQ_{50}	TFQ_{95}	BFQ_{95}	Source of measured flow estimates
Waiokomilo lower (WoL)	Estimated flow	14	8.7	2.8	2.4	**TFQ_{95}**: 1999 USGS low-flow measurement (Gingerich, 1999)
	90% LCL	12	6.8	2.2	1.8	
	90% UCL	17	11	3.6	3.2	
	Standard error	9.8	14.4	14.2	15.9	
	Measured flow	--	--	5.7	--	
	Relative error	--	--	-51	--	
Waiokomilo middle (WoM)	Estimated flow	10	6.1	2.2	1.8	**TFQ_{95}**: Average of EMI 1928 measurement and 1999 USGS low-flow measurement (Gingerich, 1999)
	90% LCL	9.0	5.0	1.8	1.4	
	90% UCL	12	7.4	2.6	2.3	
	Standard error	7.3	10.7	11.4	12.8	
	Measured flow	--	--	4.9	--	
	Relative error	--	--	-55	--	
Waiokomilo upper (WoU)	Estimated flow	7.0	3.9	1.3	1.1	No data available
	90% LCL	6.1	3.3	1.1	0.90	
	90% UCL	7.8	4.7	1.6	1.3	
	Standard error	6.9	10.2	9.1	10.1	
	Measured flow	--	--	--	--	
	Relative error	--	--	--	--	
Ohia lower (OL)	Estimated flow	8.7	8.6	4.6	6.1	Ohia Spring average flow is 4.7 cubic feet per second (Stearns and Macdonald, 1942) but little flow reaches the ocean due to infiltration and agricultural evapotranspiration losses
	90% LCL	5.5	4.3	1.5	1.8	
	90% UCL	14	17	14	21	
	Standard error	26.6	40.0	69.1	79.3	
	Measured flow	--	--	--	--	
	Relative error	--	--	--	--	
Palauhulu lower (PhL)	Estimated flow	17	11	4.4	4.0	**TFQ_{95}**: TFQ_{95} flow at 5220, measuring taro diversion from stream; losing stream therefore effects of natural flow addition are unknown
	90% LCL	14	8.9	3.1	2.7	
	90% UCL	20	15	6.3	6.0	
	Standard error	9.6	14.2	20.5	23.0	
	Measured flow	--	--	> 2.4	--	
	Relative error	--	--	< 83	--	

Table 10. Streamflow statistics estimated using regression equations, lower and upper confidence intervals, standard errors, measured flow, and relative errors for ungaged basins, northeast Maui, Hawaii—Continued

[TFQxx is the xx-percent flow duration of total streamflow; BFQxx is the xx-percent flow duration of base flow; estimated and measured flow and confidence intervals are in cubic feet per second; 90% LCL and UCL is 90-percent lower and upper confidence level; Standard error is in percent; Relative error is ([estimated flow – measured flow]/measured flow x 100), in percent; L, lower; M, middle; U, upper; Measured flows in ***bold italic*** fall within the lower and upper 90-percent confidence interval; East Maui Irrigation Co., Ltd (EMI) 1928 measurements from March 16-20 when index station had a Q_{90} flow (reported in Gingerich, 1999); >, likely greater than; <, likely less than; --, not available]

Stream location	Statistic	TFQ_{50}	BFQ_{50}	TFQ_{95}	BFQ_{95}	Source of measured flow estimates
Palauhulu middle (PhM)	Estimated flow	14	9.3	3.9	3.5	Plunkett Spring average flow is 2.7 cubic feet per second (Stearns and Macdonald, 1942) but stream goes dry due to infiltration losses so effects of natural flow addition are unknown
	90% LCL	12	7.5	2.8	2.4	
	90% UCL	16	12	5.4	5.1	
	Standard error	8.3	12.2	18.9	21.1	
	Measured flow	--	--	--	--	
	Relative error	--	--	--	--	
Kano upper (KoU)	Estimated flow	4.5	2.5	1.0	0.82	No data available
	90% LCL	4.2	2.2	0.87	0.68	
	90% UCL	4.9	2.8	1.2	0.99	
	Standard error	4.5	6.6	9.7	10.9	
	Measured flow	--	--	--	--	
	Relative error	--	--	--	--	
Hauoli Wahine upper (HWU)	Estimated flow	1.5	0.93	0.88	0.75	No data available
	90% LCL	1.2	0.64	0.66	0.54	
	90% UCL	2.0	1.4	1.2	1.0	
	Standard error	14.7	21.8	16.7	18.7	
	Measured flow	--	--	--	--	
	Relative error	--	--	--	--	
Piinaau lower (PiL)	Estimated flow	40	28	13	13	**TFQ_{95}**: EMI 1928 measurement, unknown amount of upstream diversion at Koolau Ditch
	90% LCL	31	19	7.1	6.3	
	90% UCL	52	41	25	25	
	Standard error	14.6	21.6	36.3	40.9	
	Measured flow	--	--	> 0.47	--	
	Relative error	--	--	< 2700	--	
Piinaau middle (PiM)	Estimated flow	28	20	12	11	**TFQ_{95}**: EMI 1928 measurement, unknown amount of upstream diversion at Koolau Ditch
	90% LCL	22	13	6.7	5.8	
	90% UCL	36	29	22	22	
	Standard error	15.0	22.2	34.9	39.3	
	Measured flow	--	--	> 0.47	--	
	Relative error	--	--	< 2500	--	

Table 10. Streamflow statistics estimated using regression equations, lower and upper confidence intervals, standard errors, measured flow, and relative errors for ungaged basins, northeast Maui, Hawaii—Continued

[TFQxx is the xx-percent flow duration of total streamflow; BFQxx is the xx-percent flow duration of base flow; estimated and measured flow and confidence intervals are in cubic feet per second; 90% LCL and UCL is 90-percent lower and upper confidence level; Standard error is in percent; Relative error is ([estimated flow – measured flow]/measured flow x 100), in percent; L, lower; M, middle; U, upper; Measured flows in ***bold italic*** fall within the lower and upper 90-percent confidence interval; East Maui Irrigation Co., Ltd (EMI) 1928 measurements from March 16-20 when index station had a Q_{90} flow (reported in Gingerich, 1999); >, likely greater than; <, likely less than; --, not available]

Stream location	Statistic	TFQ_{50}	BFQ_{50}	TFQ_{95}	BFQ_{95}	Source of measured flow estimates
Piinaau upper (PiU)	Estimated flow	21	14	9.4	8.5	No data available
	90% LCL	16	9.7	5.5	4.7	
	90% UCL	27	20	16	16	
	Standard error	14.4	21.3	31.1	34.9	
	Measured flow	--	--	--	--	
	Relative error	--	--	--	--	
Nuaailua lower (NL)	Estimated flow	9.9	7.4	4.0	4.1	**TFQ_{95}**: EMI 1928 measurement; unknown amount of upstream diversion at Spreckels Ditch; effects of natural flow addition are unknown because stream may be gaining or losing
	90% LCL	8.0	5.4	2.4	2.3	
	90% UCL	12	10	6.7	7.2	
	Standard error	12.1	17.8	29.8	33.5	
	Measured flow	--	--	> 0.31	--	
	Relative error	--	--	< 1200	--	
Nuaailua middle (NM)	Estimated flow	3.9	2.5	1.2	1.1	**TFQ_{95}**: EMI 1928 measurement; unknown amount of upstream diversion at Spreckels Ditch; effects of natural flow addition are unknown because stream may be gaining or losing
	90% LCL	3.3	2.0	0.86	0.75	
	90% UCL	4.5	3.1	1.8	1.7	
	Standard error	8.6	12.6	20.8	23.3	
	Measured flow	--	--	> 0.31	--	
	Relative error	--	--	< 290	--	
Nuaailua upper (NU)	Estimated flow	0.56	0.28	0.19	0.15	No data available
	90% LCL	0.43	0.19	0.11	0.08	
	90% UCL	0.73	0.42	0.34	0.27	
	Standard error	15.1	22.4	33.3	37.5	
	Measured flow	--	--	--	--	
	Relative error	--	--	--	--	
Honomanu lower (HnL)	Estimated flow	16	10	4.6	4.0	Values are maximum estimates using flow statistics from 5270 upstream because stream infiltration losses are unknown; stream goes dry at low flow
	90% LCL	14	8.3	3.2	2.7	
	90% UCL	19	13	6.6	6.0	
	Standard error	8.5	12.6	20.7	23.2	
	Measured flow	< 5.7	< 2.8	< 1.0	< 0.74	
	Relative error	> 180	> 260	> 320	> 440	

Table 10. Streamflow statistics estimated using regression equations, lower and upper confidence intervals, standard errors, measured flow, and relative errors for ungaged basins, northeast Maui, Hawaii—Continued

[TFQxx is the xx-percent flow duration of total streamflow; BFQxx is the xx-percent flow duration of base flow; estimated and measured flow and confidence intervals are in cubic feet per second; 90% LCL and UCL is 90-percent lower and upper confidence level; Standard error is in percent; Relative error is ([estimated flow – measured flow]/measured flow x 100), in percent; L, lower; M, middle; U, upper; Measured flows in ***bold italic*** fall within the lower and upper 90-percent confidence interval; East Maui Irrigation Co., Ltd (EMI) 1928 measurements from March 16-20 when index station had a Q_{90} flow (reported in Gingerich, 1999); >, likely greater than; <, likely less than; --, not available]

Stream location	Statistic	TFQ_{50}	BFQ_{50}	TFQ_{95}	BFQ_{95}	Source of measured flow estimates
Honomanu middle (HnM)	Estimated flow	13	8.0	3.7	3.1	Values are maximum estimates using flow statistics from 5270 upstream because stream infiltration losses are unknown; stream goes dry at low flow
	90% LCL	11	6.6	2.7	2.2	
	90% UCL	15	9.7	5.0	4.4	
	Standard error	7.3	10.8	17.8	19.9	
	Measured flow	< 5.7	< 2.8	< 1.0	< 0.74	
	Relative error	> 130	> 190	> 240	> 320	
Punalau lower (PlL)	Estimated flow	6.5	4.5	2.2	2.1	No data available
	90% LCL	5.5	3.5	1.5	1.4	
	90% UCL	7.6	5.7	3.4	3.4	
	Standard error	9.4	13.8	22.9	25.7	
	Measured flow	--	--	--	--	
	Relative error	--	--	--	--	
Punalau middle (PlM)	Estimated flow	5.8	3.9	2.1	2.0	**TFQ_{95}**: EMI 1928 measurement; unknown amount of upstream diversion at Spreckels Ditch; effects of natural flow addition are unknown because stream may be gaining or losing; stream goes dry at low flow
	90% LCL	4.9	3.1	1.4	1.3	
	90% UCL	6.8	5.0	3.1	3.1	
	Standard error	9.1	13.5	22.3	25.0	
	Measured flow	--	--	0.00	0.00	
	Relative error	--	--	NA	NA	
Haipuaena lower (HaL)	Estimated flow	9.7	5.6	1.6	1.3	Flow statistics from 5360 upstream plus EMI 1928 measurement; effects of natural flow addition are unknown because stream is losing; stream goes dry at low flow
	90% LCL	8.0	4.2	1.3	1.1	
	90% UCL	12	7.4	1.9	1.6	
	Standard error	10.7	15.7	9.3	10.4	
	Measured flow	6.8	3.5	***1.7***	***1.3***	
	Relative error	43	60	6	0	
Haipuaena middle lower (HaML)	Estimated flow	8.8	5.0	1.5	1.2	Flow statistics from 5360 upstream plus EMI 1928 measurement; effects of natural flow addition are unknown because stream is losing; stream goes dry at low flow
	90% LCL	7.3	3.9	1.2	1.0	
	90% UCL	10	6.5	1.7	1.4	
	Standard error	10.1	14.8	9.1	10.2	
	Measured flow	6.8	3.5	***1.7***	***1.3***	
	Relative error	29	43	-12	-8	

Table 10. Streamflow statistics estimated using regression equations, lower and upper confidence intervals, standard errors, measured flow, and relative errors for ungaged basins, northeast Maui, Hawaii—Continued

[TFQxx is the xx-percent flow duration of total streamflow; BFQxx is the xx-percent flow duration of base flow; estimated and measured flow and confidence intervals are in cubic feet per second; 90% LCL and UCL is 90-percent lower and upper confidence level; Standard error is in percent; Relative error is ([estimated flow – measured flow]/measured flow x 100), in percent; L, lower; M, middle; U, upper; Measured flows in ***bold italic*** fall within the lower and upper 90-percent confidence interval; East Maui Irrigation Co., Ltd (EMI) 1928 measurements from March 16-20 when index station had a Q_{90} flow (reported in Gingerich, 1999); >, likely greater than; <, likely less than; --, not available]

Stream location	Statistic	TFQ_{50}	BFQ_{50}	TFQ_{95}	BFQ_{95}	Source of measured flow estimates
Haipuaena middle upper (HaMU)	Estimated flow	7.8	4.5	1.4	1.1	Flow statistics from 5360 upstream; effects of natural flow addition are unknown because stream may be gaining or losing
	90% LCL	6.7	3.5	1.2	0.93	
	90% UCL	9.2	5.6	1.6	1.3	
	Standard error	9.0	13.2	9.0	10.0	
	Measured flow	***6.8***	***3.5***	1.7	***1.3***	
	Relative error	15	29	-18	-15	
Puohokamoa lower (PL)	Estimated flow	18	12	5.0	4.7	Flow statistics from 5450 upstream plus EMI 1928 measurement; effects of natural flow addition are unknown because stream may be gaining or losing
	90% LCL	15	9.6	3.4	3.0	
	90% UCL	22	16	7.5	7.3	
	Standard error	10.1	14.9	22.7	25.4	
	Measured flow	> 12	> 6.6	> 2.7	> 2.3	
	Relative error	< 50	< 82	< 85	< 100	
Puohokamoa middle lower (PML)	Estimated flow	17	11	4.8	4.4	Flow statistics from 5450 upstream plus EMI 1928 measurement; effects of natural flow addition are unknown because stream may be gaining or losing
	90% LCL	14	9.0	3.3	2.9	
	90% UCL	20	15	7.0	6.8	
	Standard error	9.6	14.1	22.0	24.7	
	Measured flow	> 12	> 6.6	2.7	> 2.3	
	Relative error	< 42	< 67	78	< 91	
Puohokamoa middle upper (PMU)	Estimated flow	15	9.9	4.3	3.9	Flow statistics from 5450 upstream; effects of natural flow addition are unknown because stream may be gaining or losing
	90% LCL	13	7.9	3.0	2.6	
	90% UCL	17	12.4	6.1	5.8	
	Standard error	8.7	12.8	20.3	22.8	
	Measured flow	> 11	> 6.4	> 2.5	> 2.1	
	Relative error	< 25	< 55	< 72	< 86	
Wahinepee lower (WeL)	Estimated flow	2.4	1.8	1.6	1.6	**TFQ_{95}**: EMI 1928 measurement; unknown amount of upstream diversion at Wailoa Ditch; effects of natural flow addition are unknown because stream may be gaining or losing
	90% LCL	1.8	1.1	0.88	0.83	
	90% UCL	3.2	2.7	2.8	3.0	
	Standard error	16.6	24.6	33.9	38.1	
	Measured flow	--	--	> 0.46	--	
	Relative error	--	--	< 250	--	

Table 10. Streamflow statistics estimated using regression equations, lower and upper confidence intervals, standard errors, measured flow, and relative errors for ungaged basins, northeast Maui, Hawaii—Continued

[TFQxx is the xx-percent flow duration of total streamflow; BFQxx is the xx-percent flow duration of base flow; estimated and measured flow and confidence intervals are in cubic feet per second; 90% LCL and UCL is 90-percent lower and upper confidence level; Standard error is in percent; Relative error is ([estimated flow – measured flow]/measured flow x 100), in percent; L, lower; M, middle; U, upper; Measured flows in ***bold italic*** fall within the lower and upper 90-percent confidence interval; East Maui Irrigation Co., Ltd (EMI) 1928 measurements from March 16-20 when index station had a Q_{90} flow (reported in Gingerich, 1999); >, likely greater than; <, likely less than; --, not available]

Stream location	Statistic	TFQ_{50}	BFQ_{50}	TFQ_{95}	BFQ_{95}	Source of measured flow estimates
Wahinepee middle (WeM)	Estimated flow	1.3	0.89	0.97	0.94	**TFQ_{95}**: EMI 1928 measurement; unknown amount of upstream diversion at Wailoa Ditch; effects of natural flow addition are unknown because stream may be gaining or losing
	90% LCL	0.92	0.54	0.56	0.50	
	90% UCL	1.8	1.4	1.7	1.7	
	Standard error	19.2	28.5	32.4	36.5	
	Measured flow	--	--	0.46	--	
	Relative error	--	--	110	--	
Waikamoi lower (WiL)	Estimated flow	10	5.7	2.0	1.6	Flow statistics from 5550 and 5570 upstream plus Waikamoi middle upper and middle lower sites; effects of natural flow addition are unknown because stream is losing; stream goes dry at low flow
	90% LCL	9.0	4.8	1.6	1.2	
	90% UCL	12	6.9	2.6	2.1	
	Standard error	7.1	10.4	13.2	14.8	
	Measured flow	***< 11***	***< 5.9***	< 2.8	< 2.4	
	Relative error	> -9	> -3	> -29	> -33	
Waikamoi middle lower (WiML)	Estimated flow	9.6	5.4	2.0	1.6	Flow statistics from 5550 and 5570 upstream plus Waikamoi middle upper plus average of 9 USGS low-flow measurements in 2002-03
	90% LCL	8.6	4.5	1.6	1.2	
	90% UCL	11	6.4	2.5	2.0	
	Standard error	6.6	9.6	13.1	14.7	
	Measured flow	***> 11***	***> 5.9***	2.8	2.4	
	Relative error	-13	-8	-29	-33	
Waikamoi middle upper (WiMU)	Estimated flow	9.2	5.2	2.0	1.6	Flow statistics from 5550 and 5570 upstream plus average of 10 USGS low-flow measurements in 2002-03
	90% LCL	8.3	4.4	1.6	1.2	
	90% UCL	10	6.1	2.5	2.0	
	Standard error	6.2	9.2	13.1	14.6	
	Measured flow	> 10.5	***> 5.7***	2.6	> 2.2	
	Relative error	< -16	< -9	-23	< -27	
Kolea lower (KaL)	Estimated flow	4.8	3.4	1.9	1.9	**TFQ_{95}**: EMI 1928 measurement; unknown amount of upstream diversion at Wailoa Ditch; effects of natural flow addition are unknown because stream may be gaining or losing
	90% LCL	3.9	2.5	1.2	1.1	
	90% UCL	5.9	4.6	3.1	3.2	
	Standard error	11.4	16.9	28.1	31.5	
	Measured flow	--	--	> 0.2	--	
	Relative error	--	--	< 1100	--	

Table 10. Streamflow statistics estimated using regression equations, lower and upper confidence intervals, standard errors, measured flow, and relative errors for ungaged basins, northeast Maui, Hawaii—Continued

[TFQxx is the xx-percent flow duration of total streamflow; BFQxx is the xx-percent flow duration of base flow; estimated and measured flow and confidence intervals are in cubic feet per second; 90% LCL and UCL is 90-percent lower and upper confidence level; Standard error is in percent; Relative error is ([estimated flow – measured flow]/measured flow x 100), in percent; L, lower; M, middle; U, upper; Measured flows in ***bold italic*** fall within the lower and upper 90-percent confidence interval; East Maui Irrigation Co., Ltd (EMI) 1928 measurements from March 16-20 when index station had a Q_{90} flow (reported in Gingerich, 1999); >, likely greater than; <, likely less than; --, not available]

Stream location	Statistic	TFQ_{50}	BFQ_{50}	TFQ_{95}	BFQ_{95}	Source of measured flow estimates
Kolea middle (KaM)	Estimated flow	3.6	2.5	1.6	1.5	**TFQ_{95}**: EMI 1928 measurement; unknown amount of upstream diversion at Wailoa Ditch; effects of natural flow addition are unknown because stream may be gaining or losing
	90% LCL	3.0	1.9	0.98	0.89	
	90% UCL	4.4	3.4	2.5	2.5	
	Standard error	11.3	16.7	26.9	30.2	
	Measured flow	--	--	> 0.16	--	
	Relative error	--	--	< 900	--	

index station varied between TFQ_{90} and TFQ_{95}. Flow-duration values for five gaging stations (5090, 5110, 5130, 5140, and 5210) operated downstream of the Koolau Diversion indicate an average relative difference between TFQ_{90} and TFQ_{95} of 11 percent, and absolute differences ranging from 0.05 ft^3/s at station 5130 to 1.0 ft^3/s at station 5090. In general, base flows sustained by springs downstream from the diversion ditch exhibit less variability. Where measured TFQ_{50} and BFQ_{50} flow durations are listed in table 10, they are based on a combination of upstream flow statistics and the measured TFQ_{95} low flows, but are preceded by a greater than symbol (>) indicating that the TFQ_{95} flow is a minimum value and the actual flow is higher by an unknown amount.

Application of the regression equations to estimate flow at some of the sites shown in table 10 violates the assumptions of the regression analysis because they are intermittent-flow sites or have basin characteristics that are outside the range used to develop the equations. Some of the poor results shown in table 10 can be explained by these violations. A plot of the spatial distribution of relative-error values for TFQ_{95}, the only duration discharge for which some measured flow values are available, shows two distinct groupings of results. East of Keanae Valley, the TFQ_{95} equation generally underestimates flow, and within and west of Keanae Valley, the equation generally overestimates flow (fig. 16). This grouping reflects the pattern for ground-water occurrence east and west of Keanae Valley described by Gingerich (1999). West of Keanae Valley, ground water occurs at high elevations in the low-permeability Kula Volcanics and at low elevations in the higher permeability Honomanu Basalt. Streams at high elevations gain base flow from the upper perched zone and lose water to the underlying unsaturated zone nearer the coast. Where streams lose water at lower elevations, the regression equations generally overestimate the amount of water in the stream. East of Keanae Valley, the discharge of ground water from a vertically extensive freshwater lens causes streams to gain flow all the way to the coast. The regression equations generally underestimate the additional streamflow gained from springs. Within Keanae Valley, streamflow gain from the freshwater lens is lost to the veneering lava flows of the Hana Volcanics; hence, the equations overestimate streamflow here as well.

Ordinarily, regression equations would be developed for each distinct hydrologic regime (east or west of Keanae Valley) to better account for the basin characteristics controlling streamflow. However, dividing the gaging stations used to generate the regression equations (n =17) into two groups would result in the number of stations in each group (n = 8 and n = 9) being too small for significant statistical analyses.

At sites where flow is underestimated by the regression equation, the relative errors range from 7 to 79 percent and average 30 percent. At sites where flow is overestimated, the relative errors are not always meaningful because many of the streams are dry. Therefore, any flow estimate greater than zero means that relative error for that site cannot be calculated.

Most-reliable Estimates of Natural Flow-Duration Statistics

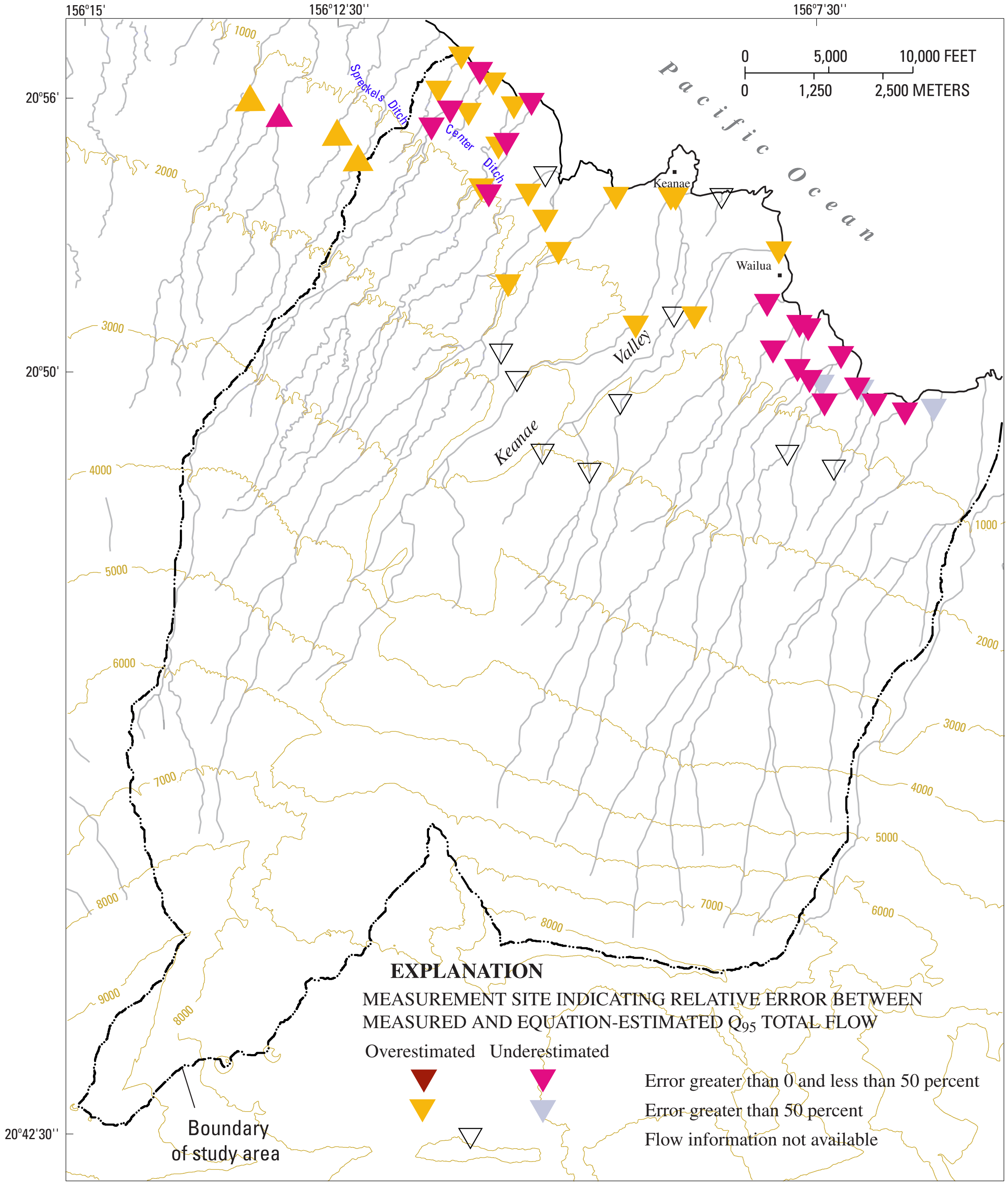
Most-reliable estimates of flow-duration statistics for natural (undiverted) streamflow at ungaged sites on 21 streams in the study area were made using a combination of continuous record gaging-station data, low-flow measurements, and values determined from the regression equations developed as part of this study (Table 11). No estimates were made for Piinaau Stream because no flow data were available and the regression equations were not applicable to this intermittent stream. Furthermore, all three of the basin characteristics for Piinaau Stream that are used in the regression equations fall outside the range of values used to develop the equations (table 8). The reliability of the estimates depends on the combination of data used to develop the estimates. Estimates of flow statistics developed on the basis of data from continuous-record gaging stations are deemed the most reliable; those estimates developed from the regression equations alone are considered the least reliable. Estimates that are developed for sites downstream from gaging stations and adjusted on the basis of low-flow measurements or the regression equations are considered to be of intermediate reliability.

The various data combinations used to develop the most-reliable estimates can be described using Hanawi Stream as an example. At the Hanawi upper site, the TFQ_{50}, TFQ_{95}, BFQ_{50}, and BFQ_{95} duration discharges were estimated on the basis of data available from gaging station 5080. At the Hanawi middle site, which is downstream from the Koolau ditch, duration discharges were estimated from a combination of daily flows at gaging stations 5090 at the middle site and 5080 at the upper site. At the Hanawi lower site, TFQ_{95} was developed using the estimated TFQ_{95} at the middle site (19 ft^3/s), plus the average of gains in streamflow downstream from the middle site, which was determined from two pairs of low-flow measurements [2.8 ft^3/s (TFQ_{97} at index site); and 3.4 ft^3/s (TFQ_{94} at index site)]. TFQ_{50} at the Hanawi lower site was estimated using the estimated TFQ_{50} from the middle site (28 ft^3/s), plus the estimated gain between the lower and middle sites, using the TFQ_{50} regression equation (16 ft^3/s – 12 ft^3/s = 4.0 ft^3/s). BFQ_{50} and BFQ_{95} were estimated in a similar manner to TFQ_{50}.

Discussion of results for selected streams

For some streams, the decisions made in developing the most-reliable estimates of flow-duration statistics require further discussion. Estimates for middle and lower sites on Makapipi Stream were not attempted due to lack of flow data at these sites and the inapplicability of the regression equations to this intermittent/losing stream.

The TFQ_{95} estimate at the middle site on Waiokomilo Stream was based on flow measurements upstream that demonstrated net gains of about 4.1 ft^3/s (Gingerich, 1999)



Base modified from U.S. Geological Survey
digital data, 1:24,000, 1983, Transverse Mercator
projection, zone 4, central meridian -159°,
North American Datum 1983

Figure 16. Distribution of relative error between measured and equation-estimated Q_{95} total flow (TFQ_{95}) at ungaged sites in the study area and at selected gages west of the study area, northeast Maui, Hawaii.

Table 11. Estimates of natural (undiverted) streamflow statistics for gaged and ungaged basins, northeast Maui, Hawaii.

[TFQxx is the xx-percent flow duration of total streamflow; BFQxx is the xx-percent flow duration of base flow; all flows are in cubic feet per second; numbers in ***bold italic*** are considered maximums at sites downstream of unquantified but known losing reaches; g.s., gaging station; adj., adjustment]

Stream location	TFQ_{50}	BFQ_{50}	TFQ_{95}	BFQ_{95}	Source of estimate
Makapipi					
upper (5070)	2.2	1.3	0.0	0.0	Continuous record gaging station
Hanawi					
lower (HwL)	32	26	22	19	Middle site estimate plus equation adj.; **TFQ**$_{95}$: Middle site estimate plus low-flow measurements
middle (5090)	28	24	19	19	Continuous record gaging station plus upper site estimate
upper (5080)	7.1	4.6	2.4	2.2	Continuous record gaging station
Kapaula					
lower (KL)	8.3	5.7	3.5	3.2	Middle site estimate plus regression equation adj.
middle (5110)	7.5	5.1	3.3	3.0	Continuous record gaging station plus upper site estimate
upper (5100)	4.9	2.8	1.2	1.1	Continuous record gaging station
Waiaaka					
lower (WaL)	1.4	1.1	0.73	0.70	Middle site estimate plus regression equation adj.
middle (5130)	0.86	0.77	0.54	0.52	Continuous record gaging station
Paakea					
lower (PaL)	6.5	5.5	4.1	4.0	Middle site estimate plus regression equation adj.
middle (5140)	5.5	4.7	3.5	3.4	Continuous record gaging station plus upper site estimate
upper (PaU)	1.5	0.90	0.50	0.40	Regression equation
Waiohue					
lower (WeL)	8.8	7.5	4.5	3.6	Middle site estimate plus measurement plus regression equation adj.
middle (WeM)	7.4	6.0	3.9	3.0	Upper site estimate plus equation adj.; **TFQ**$_{95}$: Upper site estimate plus low-flow measurement
upper (5150)	6.2	5.0	3.0	2.9	Continuous record gaging station
Kopiliula					
lower (KpL)	15	9.5	5.5	3.8	Middle sites estimates plus equation adj.; **TFQ**$_{95}$: Middle sites estimates plus low-flow measurements
Middle (KpM)	10	6.5	3.4	2.3	Upper site estimate plus equation adj.; **TFQ**$_{95}$: Upper site estimate plus low-flow measurements
middle (PuM)	3.6	2.2	1.1	0.90	Regression equation; **TFQ**$_{95}$: Upper site estimate plus low-flow measurement
upper (5160)	8.0	5.0	2.4	2.0	Continuous record gaging station
upper (PuU)	1.9	1.1	0.60	0.50	Regression equation
East Wailuaiki					
lower (EWL)	11	7.2	3.4	2.9	Middle site estimate plus equation adj.; **TFQ**$_{95}$: Middle site estimate plus low-flow measurement
middle (EWM)	11	6.8	3.2	2.8	Upper site estimate plus equation adj.; **TFQ**$_{95}$: Upper site estimate plus low-flow measurement
upper (5170)	9.1	5.8	2.9	2.5	Continuous record gaging station
West Wailuaiki					
lower (WWL)	12	7.2	3.5	2.4	Middle site estimate plus equation adj.; **TFQ**$_{95}$: Middle site estimate plus low-flow measurement
middle (WWM)	11	6.8	3.3	2.3	Upper site estimate plus equation adj.; **TFQ**$_{95}$: Upper site estimate plus low-flow measurement
upper (5180)	10	6.0	2.5	2.1	Continuous record gaging station
Wailuanui					
lower (WL)	11	6.7	2.7	2.3	Middle site estimate plus equation adj.; **TFQ**$_{95}$: Middle site estimate plus low-flow measurements
middle (5210)	10	6.1	2.5	2.0	Continuous record gaging station plus upper sites estimates
upper (5200)	4.4	2.5	1.0	0.90	Continuous record gaging station
upper (5190)	3.2	2.0	0.90	0.80	Continuous record gaging station

Table 11. Estimates of natural (undiverted) streamflow statistics for gaged and ungaged basins, northeast Maui, Hawaii—Continued

[TFQxx is the xx-percent flow duration of total streamflow; BFQxx is the xx-percent flow duration of base flow; all flows are in cubic feet per second; numbers in ***bold italic*** are considered maximums at sites downstream of unquantified but known losing reaches; g.s., gaging station; adj., adjustment]

Stream location	TFQ$_{50}$	BFQ$_{50}$	TFQ$_{95}$	BFQ$_{95}$	Source of estimate
Waiokomilo					
lower (WoL)	14	8.7	6.8	6.8	Regression equation; **TFQ$_{95}$**:measurement plus upper site estimate
middle (WoM)	10	6.1	5.4	5.4	Regression equation; **TFQ$_{95}$**:measurement plus upper site estimate
upper (WoU)	7.0	3.9	1.3	1.1	Regression equation
Ohia					
lower (OL)	4.7	4.7	4.7	4.7	Spring measurements
Palauhulu					
lower (5220)	***17***	***11***	4.3	4.0	Regression equation; **TFQ$_{95}$**, **BFQ$_{95}$**: measurements at gaging station plus upper sites estimates
middle (PhM)	***14***	***9.3***	***1.9***	***1.6***	Regression equation; **TFQ$_{95}$**, **BFQ$_{95}$**: measurements plus upper sites estimates
upper (KoU)	4.5	2.5	1.0	0.82	Regression equation
upper (HWU)	1.6	0.93	0.88	0.75	Regression equation
Piinaau					
lower (PiL)					
middle (PiM)	No estimates available due to lack of data				
upper (PiU)					
Nuaailua					
lower (NL)	9.9	7.4	3.3	3.3	Regression equation; **TFQ$_{95}$**, **BFQ$_{95}$**: middle site estimate plus equation adj.
middle (NM)	3.9	2.5	0.50	0.40	Regression equation; TFQ$_{95}$, **BFQ$_{95}$**: upper site estimate plus low-flow measurement
upper (NU)	0.56	0.28	0.19	0.15	Regression equation
Honomanu					
lower (HnL)	***15***	***9.0***	***1.1***	***0.70***	Middle site estimate plus equation adj.; **TFQ$_{95}$**, **BFQ$_{95}$**: Middle site estimate plus low-flow measurement
Middle (HnM)	***11***	***6.7***	***1.1***	***0.70***	Upper site estimate plus equation adj.; **TFQ$_{95}$**, **BFQ$_{95}$**: Upper site estimate plus low-flow measurement
upper (5270)	5.7	2.8	1.1	0.70	Continuous record gaging station
Punalau					
lower (PlL)	6.5	4.5	2.3	2.2	Regression equation
middle (PlM)	5.8	3.9	2.1	2.0	Regression equation; **TFQ$_{95}$**,**BFQ$_{95}$**: low-flow measurement
Haipuaena					
lower (HaL)	9.9	5.5	2.0	1.6	Middle-lower site estimate plus equation adj.; **TFQ$_{95}$**, **BFQ$_{95}$**: Middle-lower site estimate plus low-flow measurement
middle lower (HaML)	8.9	4.9	2.0	1.6	Middle-upper site estimate plus equation adj.; **TFQ$_{95}$**, **BFQ$_{95}$**: Middle-upper site estimate plus low-flow measurement
middle upper (HaMU)	8.0	4.3	1.9	1.5	Upper site estimate plus equation adj.
upper (5360)	6.8	3.6	1.7	1.3	Continuous record gaging station plus upstream gaging station
Puohokamoa					
lower (PL)	17	11	3.6	3.1	Middle-lower site estimate plus equation adj.; **TFQ$_{95}$**, **BFQ$_{95}$**: Middle-lower site estimate plus low-flow measurement
middle lower (PML)	16	10	3.6	3.1	Middle-upper site estimate plus equation adj.; **TFQ$_{95}$**, **BFQ$_{95}$**: Middle-upper site estimate plus low-flow measurement
middle upper (PMU)	14	8.4	3.1	2.7	Upper site estimate plus equation adj.
upper (5450)	12	6.4	2.5	2.1	Continuous record gaging station
Wahinepee					
lower (WpL)	2.4	1.8	1.1	1.1	Middle site estimate plus equation adj.
middle (WpM)	1.3	0.90	0.50	0.50	Regression equation; **TFQ$_{95}$**, **BFQ$_{95}$**: low-flow measurement

Table 11. Estimates of natural (undiverted) streamflow statistics for gaged and ungaged basins, northeast Maui, Hawaii—Continued

[TFQxx is the xx-percent flow duration of total streamflow; BFQxx is the xx-percent flow duration of base flow; all flows are in cubic feet per second; numbers in ***bold italic*** are considered maximums at sites downstream of unquantified but known losing reaches; g.s., gaging station; adj., adjustment]

Stream location	TFQ$_{50}$	BFQ$_{50}$	TFQ$_{95}$	BFQ$_{95}$	Source of estimate
Waikamoi					
lower (WiL)	13	7.0	***2.8***	***2.0***	Middle-lower site estimate plus equation adj.; **TFQ$_{95}$**, **BFQ$_{95}$**: Middle-lower site estimate plus low-flow measurements
middle lower (WiML)	13	6.7	***2.8***	***1.9***	Middle-upper site estimate plus equation adj.; **TFQ$_{95}$**: Middle-upper site estimate plus low-flow measurements
middle upper (WiMU)	12	6.6	2.6	1.9	Upper sites estimates plus low-flow measurements
upper (5570)	2.7	1.5	0.70	0.60	Continuous record gaging station
upper (5550)	7.0	3.5	1.1	0.80	Continuous record gaging station
Kolea					
lower (KaL)	4.8	3.4	0.60	0.60	Regression equation; **TFQ$_{95}$**, **BFQ$_{95}$**: Middle site estimate plus equation adj.
middle (KaM)	3.6	2.5	0.20	0.20	Regression equation; **TFQ$_{95}$**,**BFQ$_{95}$**: low-flow measurement

combined with the estimate developed from the regression equation at the upper site (1.3 + 5.9 – 1.8 = 5.4 ft^3/s). At the lower site, additional gains (0.12 ft^3/s) and a tributary inflow (1.3 ft^3/s) increase the undiverted flow estimate to 6.8 ft^3/s [5.2 ft^3/s were diverted from the stream for taro at the time of the measurements (Gingerich, 1999)]. The estimate for TFQ_{95} at the upper site appears high on the basis of reconnaissance observations on March 5, 2003, when the stream at the upper site was observed to be nearly dry, yet the average daily flow at the index station was 5.8 ft^3/s (about BFQ_{50}). However, because no other measurements are available to support this observation, the estimate from the regression equation was not adjusted.

Ohia Stream is fed almost entirely by Ohia Spring, which discharges about 4.7 ft^3/s (Stearns and Macdonald, 1942), yet during reconnaissance on March 12, 2003 (about TFQ_{85} at index station), the stream was nearly dry at the mouth. Streamflow is lost to evapotranspiration through watercress agriculture and through infiltration to the subsurface where stream channel modifications have filled the natural channel with soil and vegetation. The regression-equation-derived estimates for this stream basin are not reliable because rainfall (2.2 ft^3/s) and MAXELEV (413 ft) values for this basin are outside the ranges used to develop the equations (table 8). Therefore, the most-reliable estimates are based on the average spring discharge, and are considered maximum values because of the unquantified streamflow losses between the spring and the coast.

Palauhulu Stream also has sections of losing channel and was dry between 800 and 300 ft altitude during reconnaissance on March 12–13, 2003 (about TFQ_{85} at index station). Therefore, estimates of TFQ_{95} and BFQ_{95} at the middle site (about 500 ft altitude) are maximum values, assuming all flow at the upper sites reaches the middle site. Estimates of TFQ_{95} and BFQ_{95} at the lower site are based on a continuous record gaging station (5220), which measured diversions from the stream, plus flow from the middle and upper sites assuming that all flow from those sites would reach the lower site.

Estimates of flow-duration statistics for Piinaau Stream determined from the regression equations are the highest of any sites in the study area (table 10), yet the flow observations, although scarce, indicate that flows are much lower than estimated. The stream channel was dry between 1,200 ft and 600 ft altitude during reconnaissance on March 14, 2003 (about TFQ_{91} at index station), and only a trickle of flow was observed upstream of the 1,300-ft diversion. A recent (2001) large landslide, which covered the stream at about 1,000 ft altitude and filled most of the stream channel downstream to 600 ft altitude with gravel, cobbles, and boulders, complicates flow in the stream. This basin has the highest rainfall and MAXELEV in the study area and both are above the range of characteristics used to develop the flow-duration regression equations. Because the regression equations are not valid for this stream and reliable flow measurements are lacking, no estimates of stream statistics were made for Piinaau Stream sites.

Information about gaining or losing reaches on Nuaailua or Punalau Streams is not available and therefore estimates were made using the regression equations and single low-flow measurements.

Honomanu Stream is known to lose flow and be mainly dry downstream of the diversion at 1,700 ft altitude (Gingerich, 1999). However, the amount of streamflow lost has not been quantified. Therefore, the estimates of TFQ_{95} and BFQ_{95} at the middle and lower sites (table 11) are maximum values, assuming all natural flow at the upper site (station 5270) reaches the middle and lower sites. The estimates of TFQ_{50} and BFQ_{50} are determined solely from the regression equations and are expected to be overestimates but by an unknown amount.

Losses of flow were observed in the lower reaches of Waikamoi Stream and are expected but have not been quantified in the lower reaches of Haipuaena, Puohokamoa, Wahinepee, and Kolea Streams. Therefore, estimates at ungaged sites in the lower reaches of these streams are expected to be high.

Estimates of Flow-Duration Statistics under Diverted Conditions

Estimates of flow-duration statistics for diverted streams were made for gaged and ungaged sites on 21 streams in the study area downstream from the main diversion systems on the basis of a combination of continuous-record gaging-station data, low-flow measurements, and values determined from the regression equations developed as part of this study (Table 12). It is assumed that the diversion systems remove all flow lower than TFQ_{50} above 1,200 ft altitude in all diverted streams. The flow-duration statistics for the streams can be easily calculated by subtracting the flows above the diversion system from the estimated undiverted flows below the diversion system. For example, TFQ_{50} at the lower site on West Wailuaiki Stream is calculated by subtracting the TFQ_{50} flow (from table 2) at the upper site (station 5180) from the estimated undiverted TFQ_{50} flow (from table 11) at the lower site (12 ft^3/s – 10 ft^3/s = 2 ft^3/s). In this example, it is assumed that all of the 10 ft^3/s median flow at the upper site is removed from the stream by the diversion just downstream from the upper site. Values of BFQ_{50}, TFQ_{95}, and BFQ_{95} are similarly calculated to be 1.2, 1.0, and 0.3 ft^3/s, respectively. West of Keanae Valley, where another diversion ditch at lower altitude (Spreckels) captures additional low flows, the flow statistics for diverted streams are even lower. For example, TFQ_{50} at the lower site on Waikamoi Stream is calculated by subtracting the TFQ_{50} regression-equation estimate at the middle upper site from the estimated TFQ_{50} flow at the lower site (10 ft^3/s – 9.2 ft^3/s = 0.80 ft^3/s) to account for the diversion of 9.2 ft^3/s by Spreckels Ditch. Values of BFQ_{50}, TFQ_{95}, and BFQ_{95} are similarly calculated to be 0.50, 0.20, and 0.00 ft^3/s, respectively. Flow-duration curves of natural and diverted flow for median and lower flows at the lower West Wailuaiki and lower Waikamoi sites illustrate the

Table 12. Estimates of diverted streamflow statistics and percent flow reduction for gaged and ungaged basins, northeast Maui, Hawaii.

[TFQxx is the xx-percent flow duration of total streamflow; BFQxx is the xx-percent flow duration of base flow; percent reduction is relative to undiverted flow at the same location; all flows are in cubic feet per second; numbers in ***bold italic*** are considered maximums at sites downstream of unquantified but known losing reaches]

Stream location	TFQ_{50}		BFQ_{50}		TFQ_{95}		BFQ_{95}		Comments
	Estimate	Percent reduction	Estimate	Percent reduction	Estimate	Percent reduction	Estimate	Percent reduction	
Hanawi									
lower (HwL)	25	22	21	24	20	9	17	11	Diverted at Koolau Ditch
middle (5090)	19	33	19	21	16	16	16	16	Diverted at Koolau Ditch
upper (5080)	7.1	0	4.6	0	2.4	0	2.2	0	Not diverted
Kapaula									
lower (KL)	3.2	61	2.6	54	2.2	37	2.1	34	Diverted at Koolau Ditch
middle (5110)	2.4	68	2.1	59	1.9	42	1.9	37	Diverted at Koolau Ditch
upper (5100)	4.9	0	2.8	0	1.2	0	1.1	0	Not diverted
Waiaaka									
lower (WaL)	1.4	0	1.1	0	0.73	0	0.70	0	Diverted at Koolau Ditch
middle (5130)	0.86	0	0.77	0	0.54	0	0.52	0	Diverted at Koolau Ditch
Paakea									
lower (PaL)	5.0	23	4.6	16	3.6	12	3.6	10	Diverted at Koolau Ditch
middle (5140)	4.0	27	3.8	19	3.0	14	3.0	12	Diverted at Koolau Ditch
upper (PaU)	1.5	0	0.90	0	0.50	0	0.40	0	Not diverted
Waiohue									
lower (WeL)	2.6	70	2.1	72	1.4	69	1.3	64	Diverted at Koolau Ditch
middle (WeM)	1.3	82	1.0	83	0.80	79	0.70	77	Diverted at Koolau Ditch
upper (5150)	6.2	0	5.0	0	3.0	0	2.9	0	Not diverted
Kopiliula									
lower (KpL)	4.7	69	2.8	71	1.7	69	1.3	66	Diverted at Koolau Ditch
middle (KpM)	2.0	80	1.2	82	0.50	85	0.50	78	Diverted at Koolau Ditch
middle (PuM)	1.7	53	1.1	50	0.60	45	0.34	62	Diverted at Koolau Ditch
upper (5160)	8.0	0	5.0	0	2.4	0	2.0	0	Not diverted
upper (PuU)	1.9	0	1.1	0	0.60	0	0.50	0	Not diverted
East Wailuaiki									
lower (EWL)	2.4	78	1.5	79	0.40	88	0.30	90	Diverted at Koolau Ditch
middle (EWM)	1.5	86	1.0	85	0.20	94	0.20	93	Diverted at Koolau Ditch
upper (5170)	9.1	0	5.8	0	2.9	0	2.5	0	Not diverted

Table 12. Estimates of diverted streamflow statistics and percent flow reduction for gaged and ungaged basins, northeast Maui, Hawaii—Continued

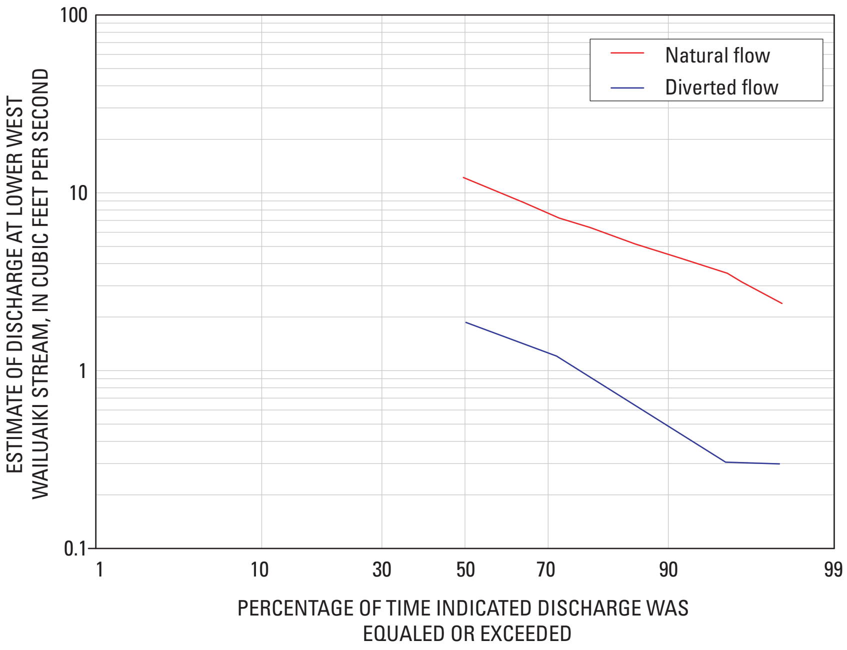
[TFQxx is the xx-percent flow duration of total streamflow; BFQxx is the xx-percent flow duration of base flow; percent reduction is relative to undiverted flow at the same location; all flows are in cubic feet per second; numbers in bold italic are considered maximums at sites downstream of unquantified but known losing reaches]

Stream location	TFQ_{50}		BFQ_{50}		TFQ_{95}		BFQ_{95}		Comments
	Estimate	Percent reduction	Estimate	Percent reduction	Estimate	Percent reduction	Estimate	Percent reduction	
West Wailuaiki									
lower (WWL)	1.9	84	1.2	83	0.30	91	0.30	87	Diverted at Koolau Ditch
middle (WWM)	1.2	89	0.80	88	0.20	94	0.20	91	Diverted at Koolau Ditch
upper (5180)	10	0	6.0	0	2.5	0	2.1	0	Not diverted
Wailuanui									
lower (WL)	1.7	85	1.1	85	0.81	70	0.56	76	Diverted at Koolau Ditch
middle (5210)	1.6	84	1.0	84	0.39	84	0.32	84	Diverted at Koolau Ditch
upper (5200)	4.4	0	2.5	0	1.0	0	0.90	0	Not diverted
upper (5190)	3.2	0	2.0	0	0.90	0	0.80	0	Not diverted
Ohia									
lower (OL)	No estimates available due to lack of data								
Palauhulu									
lower (5220)	7.6	55	4.8	56	1.9	56	1.6	60	Taro diversion
middle (PhM)	***7.9***	44	***5.9***	36	0.0	100	0.0	100	Losing stream
upper (KoU)	4.5	0	2.5	0	1.0	0	0.82	0	Not diverted
upper (HWU)	1.6	0	0.93	0	0.88	0	0.75	0	Not diverted
Piinaau									
lower (PiL)	No estimates available due to lack of data								
middle (PiM)									
upper (PiU)									
Nuaailua									
lower (NL)	9.3	6	7.1	4	3.1	6	3.1	6	Diverted at Spreckels Ditch
middle (NM)	3.3	15	2.2	12	0.30	40	0.25	37	Diverted at Spreckels Ditch
upper (NU)	0.56	0	0.28	0	0.19	0	0.15	0	Not diverted
Honomanu									
lower (HnL)	***8.7***	42	***5.8***	36	0.00	100	0.00	100	Diverted at Spreckels Ditch
middle (HnM)	***5.7***	48	***3.8***	43	0.00	100	0.00	100	Diverted at Spreckels Ditch
upper (5270)	5.7	0	2.8	0	1.1	0	0.70	0	Minor upstream diversion

Table 12. Estimates of diverted streamflow statistics and percent flow reduction for gaged and ungaged basins, northeast Maui, Hawaii—Continued

[TFQxx is the xx-percent flow duration of total streamflow; BFQxx is the xx-percent flow duration of base flow; percent reduction is relative to undiverted flow at the same location; all flows are in cubic feet per second; numbers in bold italic are considered maximums at sites downstream of unquantified but known losing reaches]

Stream location	TFQ_{50}		BFQ_{50}		TFQ_{95}		BFQ_{95}		Comments
	Estimate	Percent reduction	Estimate	Percent reduction	Estimate	Percent reduction	Estimate	Percent reduction	
Punalau									
lower (PlL)	0.80	88	0.60	87	0.20	94	0.20	91	Diverted at Manuel Luis Ditch
middle (PlM)	5.8	0	3.9	0	2.1	0	2.0	0	
Haipuaena									
lower (HaL)	1.9	81	1.1	80	0.10	95	0.10	94	Diverted at Manuel Luis Ditch
middle lower (HaML)	1.0	89	0.50	90	0.10	95	0.10	94	Diverted at Spreckels Ditch
middle upper (HaMU)	1.2	85	0.80	81	0.20	89	0.20	87	Diverted at Wailoa Ditch
upper (5360)	6.8	0	3.6	0	1.7	0	1.3	0	Minor upstream diversion
Puohokamoa									
lower (PL)	3.0	82	2.1	81	0.40	89	0.40	87	Diverted at Manuel Luis Ditch
middle lower (PML)	2.0	87	1.1	89	0.40	88	0.40	87	Diverted at Spreckels Ditch
middle upper (PMU)	3.0	79	2.0	76	0.70	77	0.60	78	Diverted at Wailoa Ditch
upper (5450)	12	0	6.4	0	2.5	0	2.1	0	Minor upstream diversion
Wahinepee									
lower (WpL)	1.1	54	0.90	50	0.60	83	0.60	83	Diverted at Manuel Luis Ditch
middle (WpM)	1.3	0	0.90	0	0.50	0	0.50	0	
Waikamoi									
lower (WiL)	0.8	94	0.5	93	***0.2***	93	***0.00***	100	Diverted at Manuel Luis Ditch
middle lower (WiML)	0.4	97	0.2	97	***0.2***	93	***0.00***	100	Diverted at Manuel Luis Ditch
middle upper (WiMU)	2.3	81	1.6	77	0.80	69	0.50	74	Diverted at Wailoa Ditch
upper (5570)	2.7	0	1.5	0	0.70	0	0.60	0	Not diverted
upper (5550)	7.0	0	3.5	0	1.1	0	0.80	0	Minor upstream diversion
Kolea									
lower (KaL)	1.2	75	0.9	71	0.40	33	0.40	33	Diverted at Manuel Luis Ditch
middle (KaM)	3.6	0	2.5	0	0.20	0	0.20	0	
Average of diverted sites		58		55		60		58	



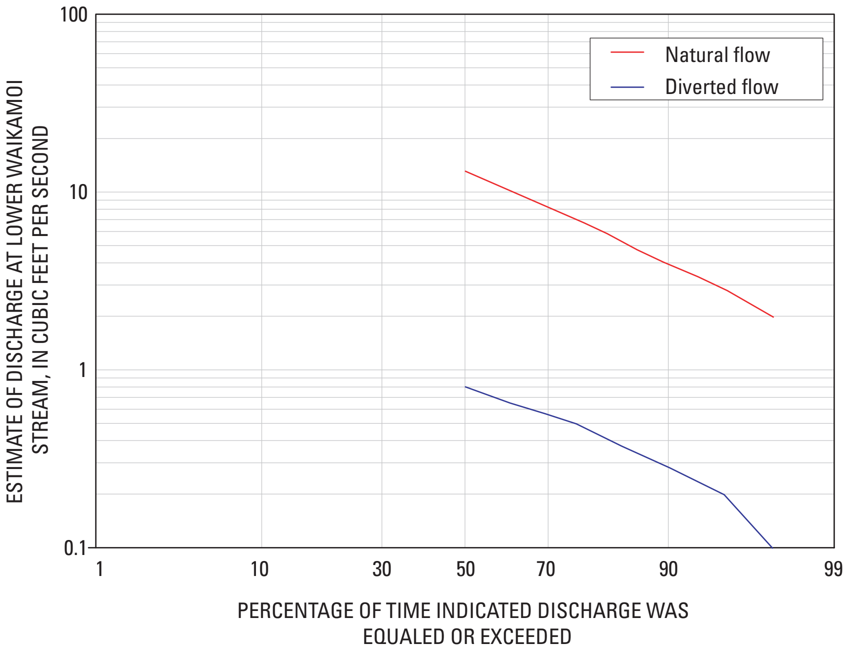


Figure 17. Estimated low-flow duration curves of natural and diverted streamflow at lower West Wailuaiki and Waikamoi Streams, northeast Maui, Hawaii.

significant effects of the diversion on streamflow statistics (fig. 17).

Estimated flow-duration curves are made by connecting the four estimated flow statistics (TFQ_{50}, BFQ_{50}, TFQ_{95}, and BFQ_{95}) with a line assuming a linear relation. The values of BFQ_{50} and BFQ_{95} are plotted at the average equivalent total-flow durations from table 5 (72 and 97 percent, respectively). Inspection of the flow-duration curves in fig. 7 shows that nearly all the curves can be represented by a straight line through TFQ_{50}, BFQ_{50}, TFQ_{95}, and BFQ_{95} so that it is reasonable to synthesize the estimated curves using a straight line to estimate the missing flow-duration points.

In addition to diversions above 1,200 ft altitude, three streams in the study area (Wailuanui, Waiokomilo, and Palauhulu Streams) also are diverted at lower altitudes for taro cultivation. On August 8, 2002, the taro diversion at about 200 ft altitude on Wailuanui Stream was observed to divert all water from the stream and then subsequently allow a significant amount of the diverted water to return to the stream channel downstream. An additional unmeasured amount of flow was observed to enter the Wailuanui stream channel downstream of the taro cultivation. Therefore, the diverted-flow statistics for the lower site at Wailuanui were estimated by assuming 50 percent of the diverted flow at about 200 ft altitude is lost to the stream although measurements to confirm this assumption are not available.

Three taro diversions take water from Waiokomilo Stream downstream of 540 ft altitude including one at 440 ft altitude that takes all low flows (Gingerich, 1999). Flow at the middle Waiokomilo Stream site is affected by one diversion of relatively constant volume of about 0.40 ft^3/s. Additionally, flow at the lower site is reduced by at least 3.7 ft^3/s at the 440-ft altitude diversion, 1.1 ft^3/s at the 220-ft altitude diversion, and an unknown amount of flow is "lost" to individual private water diversions at about 250 ft altitude. These estimates of diverted volumes are determined from a set of low-flow measurements reported in Gingerich (1999). Diverted flow statistics at the lower site were calculated on the assumption that all low flows are removed at 1,300 ft and again at 440 ft altitude (table 12). Because the equations for TFQ_{50} and BFQ_{50} estimate less flow than has been measured for TFQ_{95}, the values for TFQ_{50} and BFQ_{50} were increased to the value of TFQ_{95} and should be considered a minimum estimate.

One taro diversion takes water from Palauhulu Stream at about 50 ft altitude several hundred feet upstream from the stream mouth. A continuous-record gaging station (5220) was operated on the diversion during 1934-68 and during that time, the statistics for flow in the diversion were 3.4, 3.0, 2.4, and 2.3 ft^3/s for TFQ_{50}, BFQ_{50}, TFQ_{95}, and BFQ_{95}, respectively. These values were subtracted from the estimated natural flow statistics at the lower Palauhulu Stream site to obtain estimates of diverted flow statistics.

Estimated total reductions in streamflow due to diversions in the study area average 58 percent for TFQ_{50}, 55 percent for BFQ_{50}, 60 percent for TFQ_{95}, and 60 percent for BFQ_{95}. The streams with the lowest relative reduction in streamflow are mostly those in the eastern side of the study area, where springs discharge below the main diversion (fig. 18 and table 12).

Needs for Additional Data

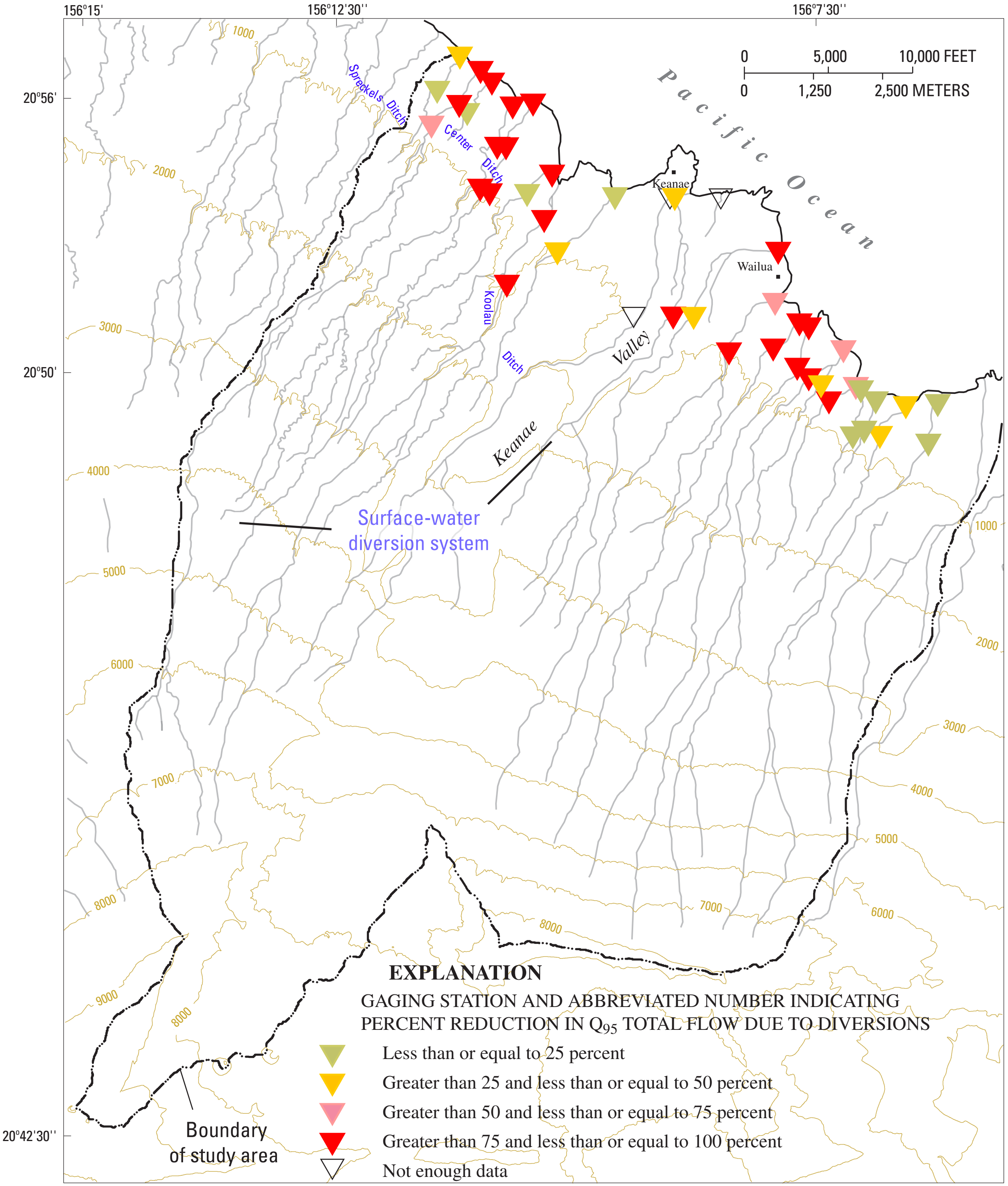
Additional data are needed to improve and confirm the estimates of median and low-flow statistics in the study area. Estimates of flow lost in losing streams would allow better definition of flow statistics in these streams. In reaches where streams go dry, additional water is needed in the reaches to permit accurate measurements of flow losses. Such additional water sources include allowing natural streamflow to bypass the diversions or releasing water from a diversion system into the stream. Streams for which the reliability of flow statistics would be most improved by the data provided by additional measurements include Ohia, Palauhulu, and Piinaau Streams in Keanae Valley; Honomanu Stream; and the lower reaches of streams west of Honomanu.

Summary and Conclusions

Median and low-flow statistics were estimated for streams in northeast Maui, Hawaii, and analyses were made to develop and evaluate the methods used to estimate the statistics. Estimated flow statistics are presented for continuous-record gaging sites and for other sites where various amounts of streamflow data are available, as well as for locations where no data are available.

Records of daily mean flows were used to determine flow-duration, low-flow frequency, and base flow statistics for continuous-record stream-gaging stations in the study area following US Geological Survey established standard methods. Duration discharges of 50- and 95-percent were determined from total-flow and base-flow data for each continuous record. In order to compare streamflow records to each other, records were adjusted to concurrent periods, so that differences between the records were due to differences in climatic or drainage-basin characteristics and not to the fact that the records cover different times. The index-station method was used to adjust all of the streamflow records to a common period with the gaging station on West Wailuaiki Stream (5180), which was chosen as the index station because of its record length (1914–2003) and favorable geographic location near the middle of the study area. Adjusting the record length resulted in average decreases to the 50-percent duration total flow, 50-percent duration base flow, 95-percent duration total flow, and 95-percent duration base flow of 7, 3, 4, and 1 percent, respectively. In general, the largest adjustments were needed for the records with the shortest lengths.

For the drainage basin of each continuous-record gaged site and selected ungaged sites, morphometric, geologic, soil, and rainfall characteristics were quantified using GIS tech-



Base modified from U.S. Geological Survey
digital data, 1:24,000, 1983, Transverse Mercator
projection, zone 4, central meridian -159º,
North American Datum 1983

Figure 18. Reduction in Q_{95} total flow (TFQ_{95}) due to diversions at selected ungaged and gaged sites in the study area, northeast Maui, Hawaii.

niques. Regression equations relating the streamflow statistics to basin characteristics of the gaged basins were developed using ordinary-least-squares regression analyses. Rainfall rate, maximum basin elevation, and the elongation ratio of the basin were the basin characteristics used in the final regression equations for 50-percent duration total flow and base flow. Rainfall rate and maximum basin elevation were used in the final regression equations for the 95-percent duration total flow and base flow. The proportion of the variation in the dependent variable that is explained by the independent variables (R^2) ranged from 94.9 to 75.3 percent, with the highest flows having the highest R^2. Standard errors of prediction ranged from 20.9 to 56.5 percent, with the highest flows having the lowest errors. The relative errors between observed and estimated flows ranged from 11 to 20 percent for the 50-percent duration total flow and from 29 to 56 percent for the 95-percent duration total flow and base flow.

The regression equations developed for this study were used to determine the 50-percent duration total flow, 50-percent duration base flow, 95-percent duration total flow, and 95-percent duration base flow at selected ungaged sites within the study area and at three gaging stations west of the study area using the appropriate basin characteristics. Estimated streamflow, prediction intervals, and standard errors were determined for 47 ungaged sites in the study area and four gaging stations west of the study area. Relative errors were determined for sites for which observed values of 95-percent duration discharge of total flow were available. East of Keanae Valley, the 95-percent duration discharge equation generally underestimated flow, and within and west of Keanae Valley, the equation generally overestimated flow.

Finally, most-reliable estimates of natural (undiverted) and diverted streamflow flow-duration statistics at gaged and ungaged sites on 21 streams in the study area were made using a combination of continuous-record gaging-station data, low-flow measurements, and values determined from the regression equations developed as part of this study. Average reduction in the low flow of streams due to diversions ranges from 55 to 60 percent.

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Appendix A: Selected Drainage-Basin Characteristics Quantified Using Basinsoft

[Descriptions modified from Harvey and Eash (1996) for purposes of regression analyses of streamflow data from northeast Maui, Hawaii]

BL-Basin length, in miles, measured along a line areally centered through the drainage divide from basin outlet to where the main channel extended meets the basin divide.

BP-Basin perimeter, in miles, measured along entire drainage-basin divide.

BR-Basin relief, in feet, measured as the difference between the elevation of the highest grid cell and the elevation of the grid cell at the basin outlet, BR = MAXELEV-MINELEV

BS-Average basin slope, in feet per mile, measured by the "contour-band" method, within the drainage area (DA). BS = (total length of all selected elevation contours) (contour interval) / DA.

BW-Effective basin width, in miles, BW = DA/ BL.

CCM-constant of channel maintenance, in square miles per mile, CCM=DA/TSL=1/SD.

CR-Compactness ratio, dimensionless, the ratio of the perimeter of the basin to the circumference of a circle of equal area, $CR = BP/2\ (\pi\ DA)^{0.5}$.

DA-Drainage area, in square miles.

DF- Drainage frequency, in number of first-order streams per square mile

ER-Elongation ratio, dimensionless, ratio of (1) the diameter of a circle of area equal to that of the basin to (2) the length of the basin, $ER = [4\ DA/\pi\ (BL)^2]^{0.5} = 1.13\ (1/SF)^{0.5}$

MAXELEV- maximum basin elevation, in feet

MCL-Main channel length, in miles, measured along the main channel from the basin outlet to where the main channel, if extended, meets the basin divide.

MCS-Main-channel slope, in feet per mile, an index of the slope of the main channel computed from the difference in streambed elevation at points 10 percent (E_{10}) and 85 percent (E_{85}) of the distances along the main channel from the basin outlet to the basin divide. $MCS = (E_{85} - E_{10}) / (0.75\ MCL)$.

MCSP-Main channel slope proportion, dimensionless, $MCSP=MCL/(MCS)^{0.5}$.

MCSR-Main-channel sinuosity ratio, dimensionless, MCSR = MCL / BL.

MINELEV- minimum basin elevation, in feet

RB-Rotundity of basin, dimensionless, $RB = [\pi\ (BL)^2]/ [4\ DA] = 0.785\ SF$.

RN- Ruggedness number, in feet per mile, RN = (TSL)(BR)/DA

RR-Relative relief, in feet per mile, RR = BR/BP.

RSD- Relative stream density, dimensionless, $RF = DF/(SF)^2$

SD-Stream density, in miles per square mile, SD = TSL / DA.

SF-Shape factor, dimensionless, ratio of basin length to effective basin width, SF = BL/BW.

SR- Slope ratio of main-channel slope to basin slope, dimensionless, SR = MCS/BS

TSL-Total stream length, in miles, computed by summing the length of all stream segments within the DA.

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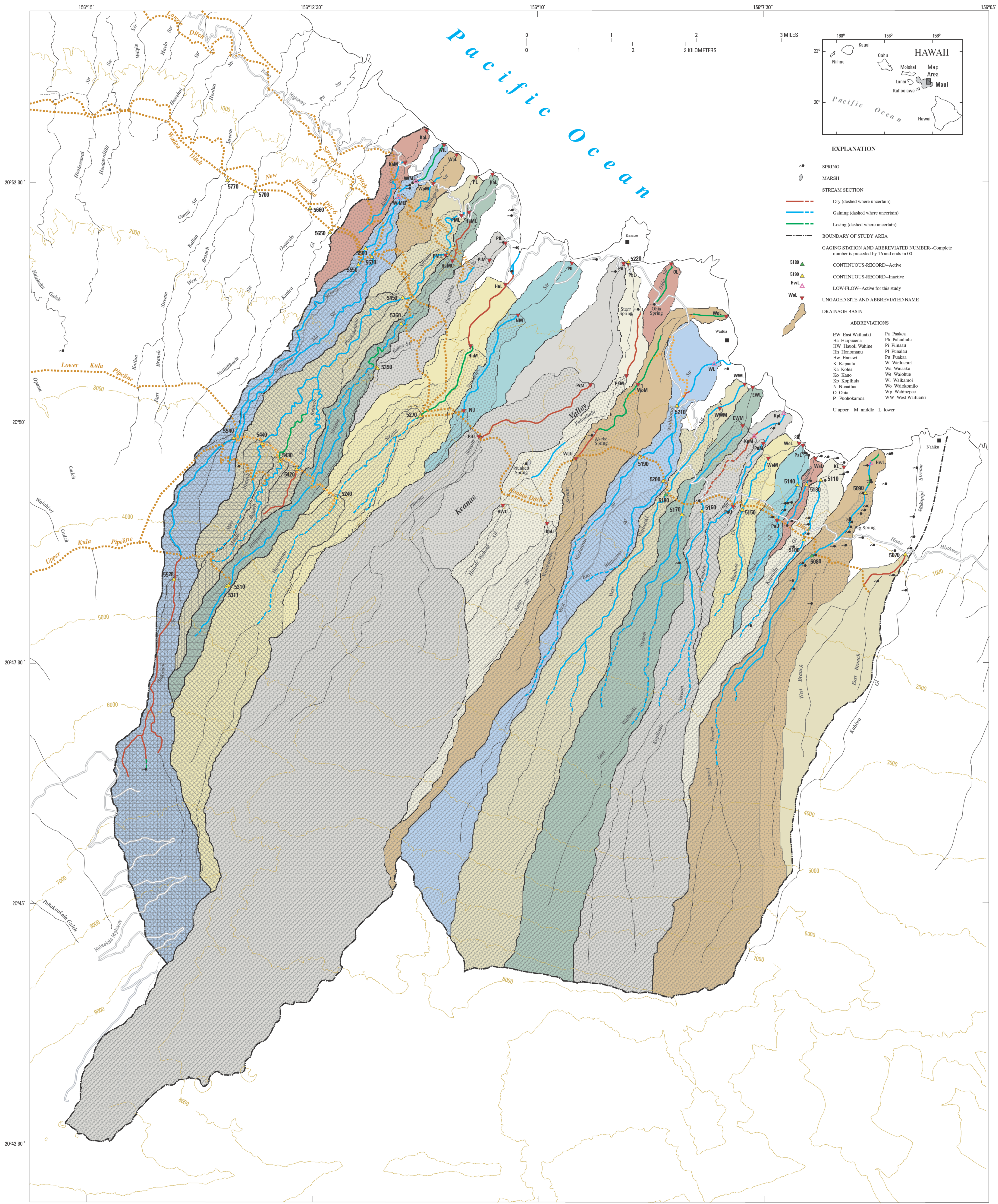

Base modified from U.S. Geological Survey
digital data, 1:24,000, 1983, Transverse Mercator
projection, zone 4, central meridian -159°,
North American Datum 1983

SURFACE-WATER GAGING STATIONS AND DRAINAGE BASINS OF STREAMS, NORTHEAST MAUI, HAWAII

by

Stephen B. Gingerich