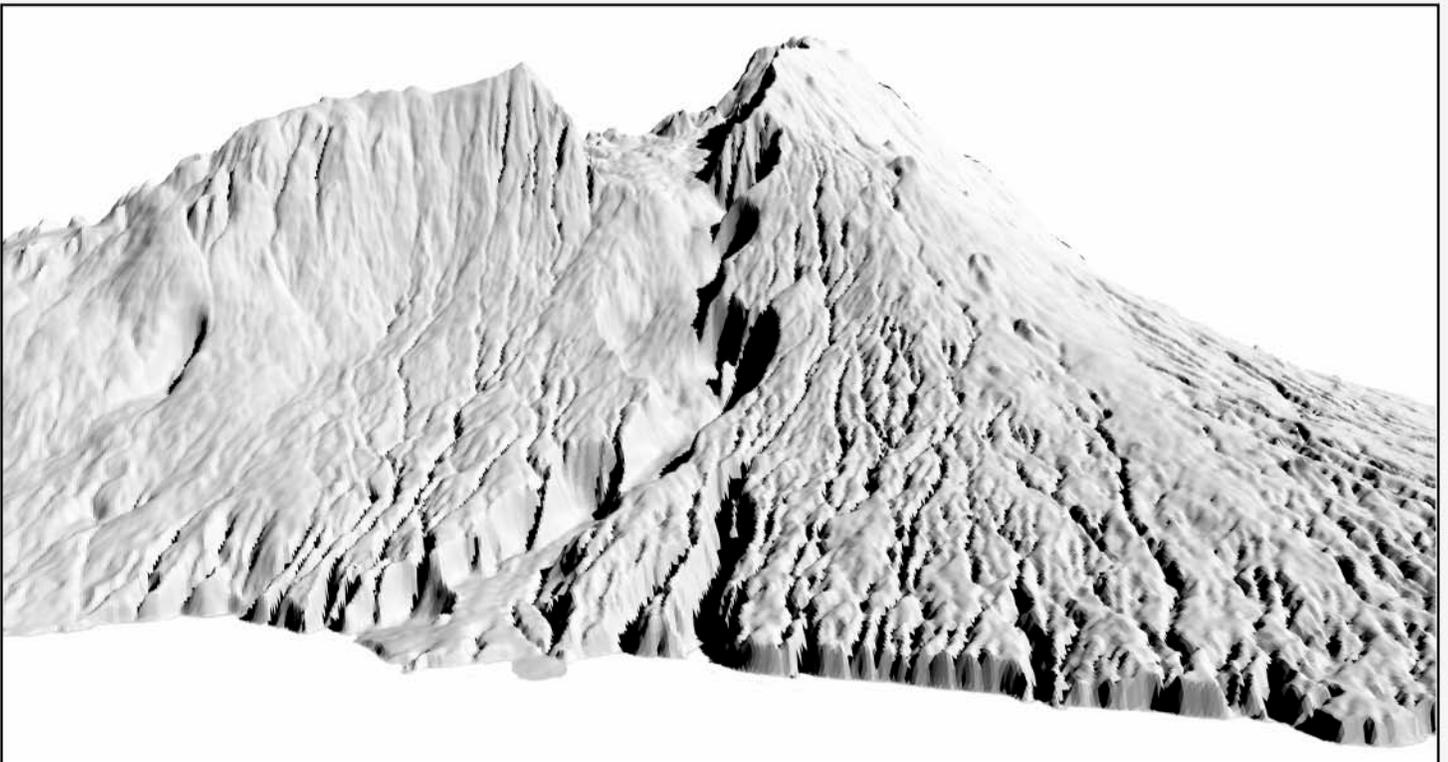


U.S. Department of the Interior

Ground-Water Occurrence and Contribution to Streamflow, Northeast Maui, Hawaii

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 99-4090



Prepared in cooperation with the
COUNTY OF MAUI DEPARTMENT OF WATER SUPPLY
STATE OF HAWAII COMMISSION ON WATER RESOURCE MANAGEMENT

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1999

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary



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

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Ground-Water Occurrence and Contribution to Streamflow, Northeast Maui, Hawaii

By Stephen B. Gingerich

Abstract

The study area lies on the northern flank of the East Maui Volcano (Haleakala) and covers about 129 square miles between the drainage basins of Maliko Gulch to the west and Makapipi Stream to the east. About 989 million gallons per day of rainfall and 176 million gallons per day of fog drip reaches the study area and about 529 million gallons per day enters the ground-water system as recharge. Average annual ground-water withdrawal from wells totals only about 3 million gallons per day; proposed (as of 1998) additional withdrawals total about 18 million gallons per day. Additionally, tunnels and ditches of an extensive irrigation network directly intercept at least 10 million gallons per day of ground water.

The total amount of average annual streamflow in gaged stream subbasins upstream of 1,300 feet altitude is about 255 million gallons per day and the total amount of average annual base flow is about 62 million gallons per day. Six major surface-water diversion systems in the study area have diverted an average of 163 million gallons per day of streamflow (including nearly all base flow of diverted streams) for irrigation and domestic supply in central Maui during 1925–97.

Fresh ground water is found in two main forms. West of Keanae Valley, ground-water flow appears to be dominated by a variably saturated system. A saturated zone in the uppermost rock unit, the Kula Volcanics, is separated from a freshwater lens near sea level by an unsaturated zone in the underlying Honomanu Basalt. East of Keanae Valley, the ground-water system appears to be fully saturated above sea level to altitudes greater than 2,000 feet.

The total average annual streamflow of gaged streams west of Keanae Valley is about 140 million gallons per day at 1,200 feet to 1,300 feet altitude. It is not possible to estimate the total average annual streamflow at the coast. All of the base flow measured in the study area west of Keanae Valley represents ground-water discharge from the high-elevation saturated zone. Total average daily ground-water discharge from the high-elevation saturated zone upstream of 1,200 feet altitude is greater than 38 million gallons per day, all of which is eventually removed from the streams by surface-water diversion systems. Perennial streamflow has been measured at altitudes greater than 3,000 feet in several of the streams. Discharge from the high-elevation saturated zone is persistent even during periods of little rainfall.

The total average annual streamflow of the gaged streams east of Keanae Valley is about 109 million gallons per day at about 1,300 feet altitude. It is not possible to estimate the total average annual streamflow at the coast nor at higher altitudes. All of the base flow measured east of Keanae Valley represents ground-water discharge from the vertically extensive freshwater-lens system. Total average daily ground-water discharge to gaged streams upstream of 1,200 feet altitude is about 27 million gallons per day. About 19 million gallons per day of ground water discharges through the Kula and Hana Volcanics between about 500 feet and 1,300 feet altitude in the gaged stream subbasins. About 13 million gallons per day of this discharge is in Hanawi Stream. The total ground-water discharge above 500 feet altitude in this part of the study area is greater than 56 million gallons per day.

INTRODUCTION

A growing population and new agricultural users have increased demand on the existing water-supply systems in many areas of the island of Maui. A potential source of additional water development is ground water in northeast Maui. The County of Maui Department of Water Supply has proposed drilling new wells and using existing wells to ultimately withdraw 16.5 Mgal/d (million gallons per day) of ground water from the Haiku area between Maliko and Kakipi Gulches (County of Maui Department of Water Supply, 1992) (fig. 1). There is concern that withdrawing ground water for domestic and agricultural uses could reduce ground-water discharge into streams. The State of Hawaii Water Resources Protection Plan (State of Hawaii, 1990) emphasizes the importance of instream uses of water and the natural relations between ground-water and surface-water resources. Sustained streamflow is necessary for several endangered and threatened native animal species. Current knowledge of the relation between surface and ground water in northeast Maui is limited and a better understanding of the ground-water flow system is needed for water-resource management purposes.

In cooperation with the State of Hawaii Commission on Water Resource Management and the County of Maui Department of Water Supply, the U.S. Geological Survey (USGS) investigated the interaction between ground water and surface water on the north flank of East Maui Volcano. Historic and new streamflow and ground-water data were collected and analyzed to determine streamflow gains and losses in selected areas, and a conceptual model of the ground-water system in the study area was formulated.

Purpose and Scope

The purpose of this report is to (1) quantify the ground-water contribution to streams, (2) evaluate the effects of geologic controls on ground-water/surface-water interaction, and (3) describe the conceptual model of ground-water occurrence in northeast Maui. Existing streamflow data were analyzed to estimate ground-water discharge into streams. Reconnaissance-level observations of geologic features and their relation to ground-water discharge were made throughout much of

the study area. Streamflow measurements were made along selected streams in the study area to characterize the gains and losses along each stream.

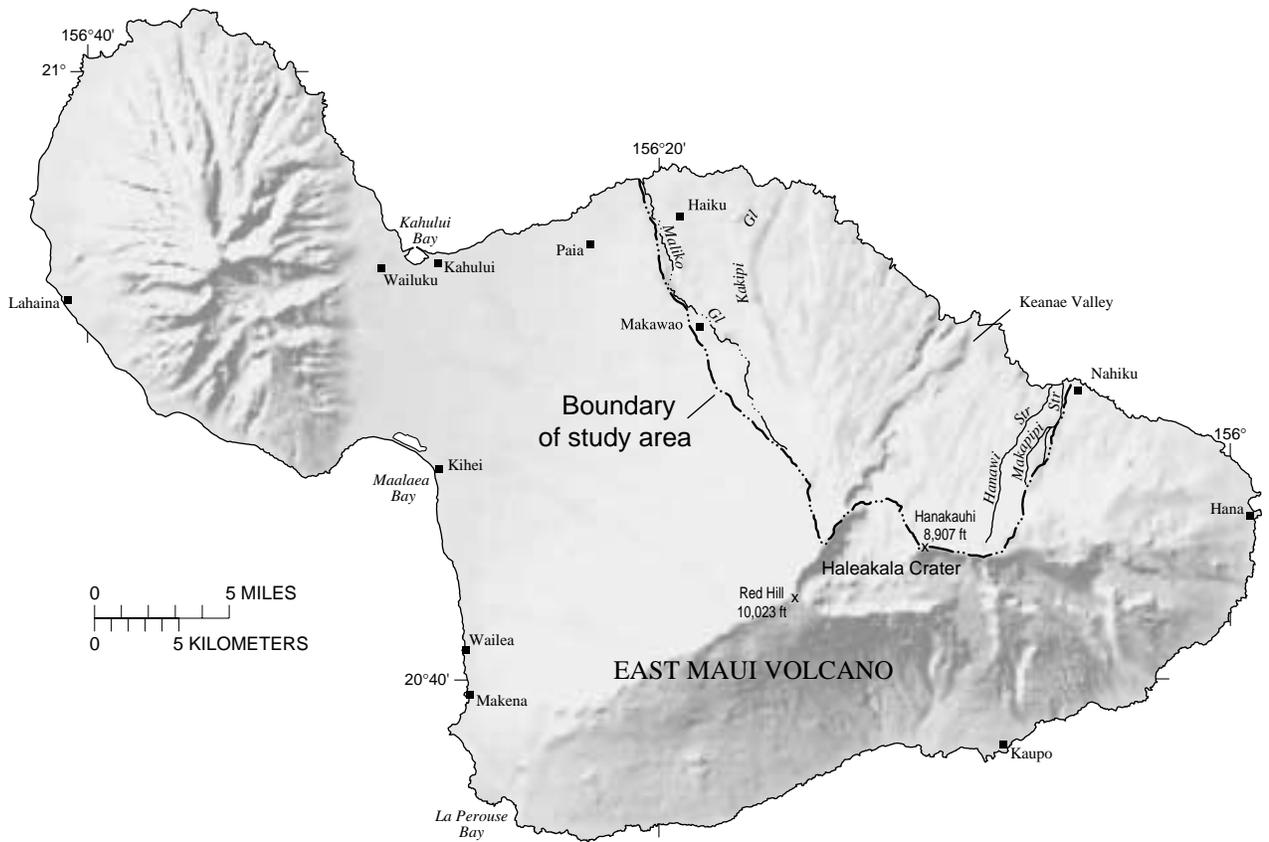
Numbering System for Surface-Water Gaging Stations

The surface-water gaging stations mentioned in this report are numbered according to the USGS “downstream order” numbering system. Stations 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 number for each station has been abbreviated to the middle four digits, for example 16587000 becomes 5870.

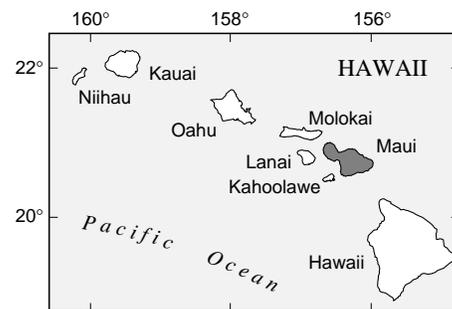
Description of Study Area

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 129 mi², is bounded to the north by about 19 mi of coastline and lies between the drainage basins of Maliko Gulch to the west and Makapipi Stream to the east (fig. 1). Land-surface altitudes range from sea level to nearly 9,000 ft at Hanakauhi on the north wall of Haleakala Crater. The topography is gently sloping except for the steep sides of gulches and valleys that have been 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 to about 7,000 ft. Grasses and shrubs cover the upper slopes to the north wall of Haleakala Crater. Small towns and farms can be found at low altitudes along the coast. West of Kakipi Gulch (fig. 1), land use at lower altitudes (below 4,000 ft) changed from primarily livestock grazing prior to the 1920's to pineapple cultivation in the 1920's and 1930's and then



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". Shaded relief from U.S. Geological Survey digital elevation models, 1:250,000



LOCATION MAP

Figure 1. Island of Maui and northeast Maui study area, Hawaii.

to pineapple cultivation mixed with livestock grazing and some residential areas from the 1940's to the present (1999) (Territorial Planning Board, 1939; Economic Planning and Coordination Authority, 1957; Soil Conservation Service, 1982). At higher altitudes, much of the land is forested State conservation land or used for livestock grazing.

Acknowledgments

Garret Hew of East Maui Irrigation Co., Inc. and many private land owners in the study area provided cooperation and assistance.

GEOLOGIC SETTING

East Maui Volcano is formed primarily by extrusive shield- and post-shield-stage lavas and secondarily by rejuvenated-stage volcanic rocks that cover the summit and southern and eastern regions (fig. 2). Intrusive volcanic rocks in the form of dikes associated with rift zones and volcanic vents are oriented along three axes.

Extrusive Volcanic Rocks

Extrusive volcanic rocks consist mainly of lava flows that effused from fissures and vents. Most lava flows emerge from fissures as pahoehoe, characterized by smooth, ropy surfaces, and can change to aa as they advance downslope. Pahoehoe flows generally dominate near the rift zones of volcanoes, whereas aa flows dominate farther down the flanks. Pahoehoe flows contain numerous ellipsoidal voids (lava tubes) whereas aa flows contain massive central cores typically sandwiched between rubbly clinker layers.

The East Maui Volcano was built by eruptions principally from three rift zones and a presumed central vent (Stearns and Macdonald, 1942). Rocks formed from the main shield-building stage of the volcano are known as the Honomanu Basalt (fig. 2) and consist of tholeiitic basalt found as thick accumulations of thin lava flows and associated intrusive rocks and rare pyroclastic deposits (Langenheim and Clague, 1987). The end of the shield-building stage of the volcano has been estimated to be between 0.93 and 0.97 million years ago on the basis of potassium-argon age dating (Chen and others, 1991). The lavas of the Honomanu Basalt have

typical dips of 2 to 22 degrees with the flatter dips near the isthmus where lava flows approached the West Maui Volcano. The basalts were laid down as vesicular pahoehoe and aa flows averaging about 15 ft thick (Stearns and Macdonald, 1942, p. 61). Contrary to typical observations of shield-stage lava flows in which aa is found in greater abundance than pahoehoe away from the volcanic vents, pahoehoe flows are abundant throughout the Honomanu Basalt, even at the periphery of the volcano. In the Nahiku area, the Honomanu Basalt is petrographically more similar in nature to the Kula Volcanics (Stearns and Macdonald, 1942). Individual lava flows range from 15 to 75 ft thick; few exceed 40 ft thick and most are less than 30 ft thick.

In the study area, Honomanu Basalt exposures are found in many of the more deeply incised gulches and along the coast between the gulches (Stearns and Macdonald, 1942). The most extensive field exposures are found in Honomanu Stream valley where the type section for this unit is located.

The Kula Volcanics, which overlies the Honomanu Basalt, consists of post-shield-stage lava flows of hawaiite with some ankaramite and alkalic basalt and associated intrusive rocks and pyroclastic and sedimentary deposits (Langenheim and Clague, 1987). The Kula Volcanics is estimated to be 0.36 to 0.93 million years old with many of the oldest rocks having chemical compositions transitional from the shield- to post-shield-stage lava (Chen and others, 1991). Exposures from this transitional phase are 50 to 100 ft thick and are commonly difficult to characterize as belonging to either the Honomanu Basalt or the Kula Volcanics. In some places the two units are separated by a thin red soil layer that has been altered by the weight and heat of the overlying flows. The Kula Volcanics almost completely covers the underlying Honomanu Basalt and exposures range from 2,500 ft thick near the summit to 50 to 200 ft thick near the coast. Individual lava flows average about 20 ft in thickness near the summit and 50 ft near the periphery, but flows as much as 200 ft thick are not rare (Stearns and Macdonald, 1942, p. 75). The usual dip of the flows is about 10 degrees. The flows are thicker and narrower than the Honomanu Basalt and have more lenticular bedding because they filled swales and valleys eroded into the underlying Honomanu Basalt. Flows of the Kula Volcanics are exposed throughout most of the study area with the exception of the Keanae Valley floor, along the coast, and the area

EXPLANATION

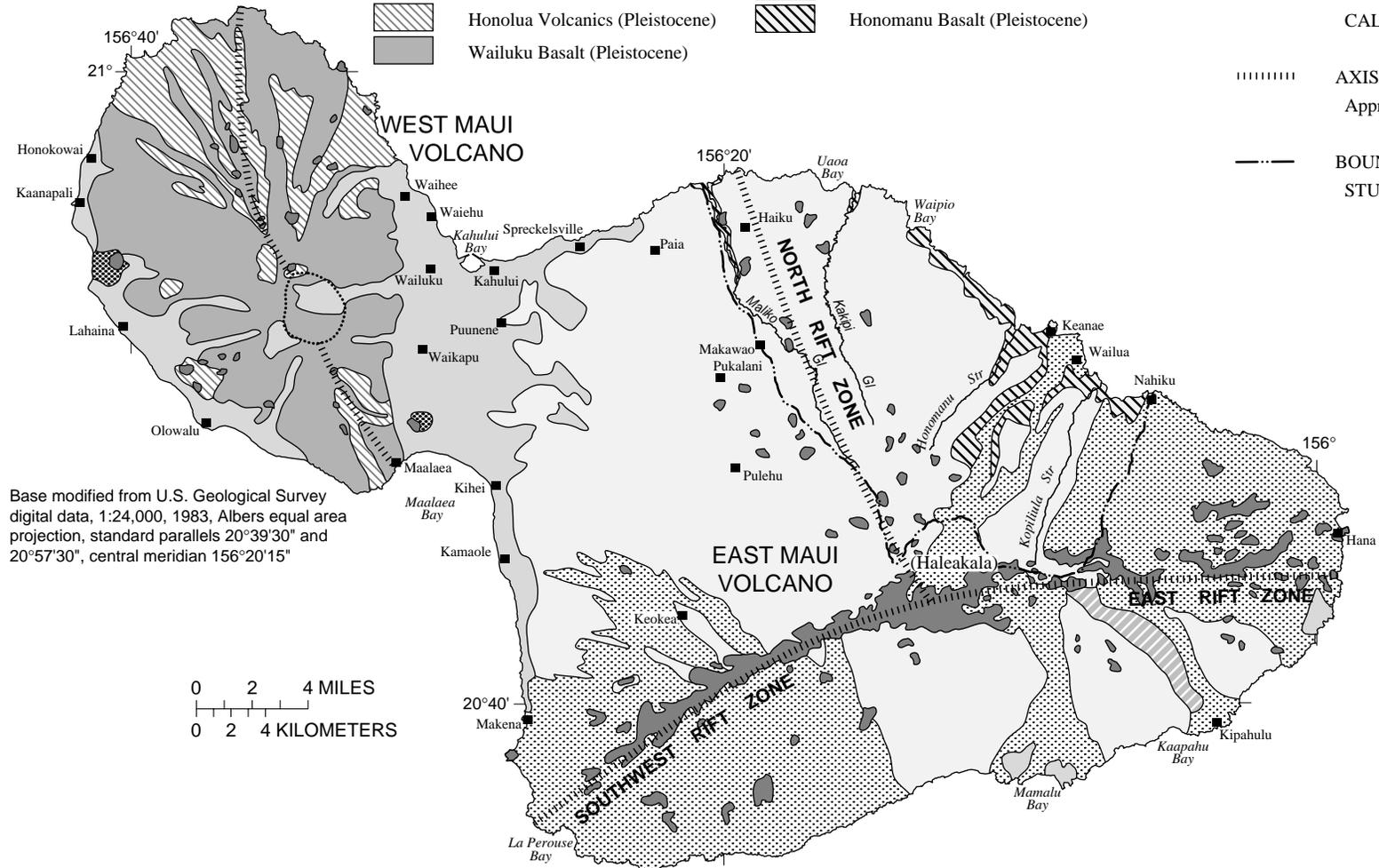
SEDIMENTARY DEPOSITS
(Holocene and Pleistocene)

WEST MAUI VOLCANO
Lahaina Volcanics (Pleistocene)
Honolua Volcanics (Pleistocene)
Wailuku Basalt (Pleistocene)

EAST MAUI (HALEAKALA)
VOLCANO

Hana Volcanics (Holocene and Pleistocene?)
Kipahulu Member (Pleistocene?)
Kula Volcanics (Pleistocene)
Honomanu Basalt (Pleistocene)

CINDER, SPATTER,
AND PUMICE CONES
CONTACT
APPROXIMATE
CALDERA BOUNDARY
AXIS OF RIFT ZONE--
Approximately located
BOUNDARY OF
STUDY AREA



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"

Figure 2. Generalized surficial geology, Maui, Hawaii (modified from Langenheim and Clague, 1987).

east of Kopiliula Gulch (fig. 2). This latter area is covered with flows of the Hana Volcanics.

The Hana Volcanics is rejuvenated-stage lava flows of alkalic basalt, basanite, rare occurrences of ankaramite and hawaiiite and associated intrusive rocks and pyroclastic and sedimentary deposits (Langenheim and Clague, 1987). The Hana Volcanics is unique among Hawaiian rejuvenated-stage eruptions because of the presence of ankaramite and hawaiiite, because its vents are aligned along preexisting rift zones and the erosional period preceding these eruptions was rather short. A 300,000-year period of quiescence occurred between the last Kula Volcanics flows and the onset of Hana-stage volcanism about 45,000 to 75,000 years ago (Eric Bergmanis, Univ. of Hawaii, oral commun., 1998). The most recent eruption of Hana Volcanics was about 200 years ago on the southwest rift zone of the East Maui Volcano (fig. 2). No eruptions of Hana Volcanics have been mapped along the north rift zone; the flows of Hana Volcanics in the study area all appear to have their source at the summit or along the east rift zone of the East Maui Volcano.

The Hana Volcanics is mostly aa and ranges from a few feet thick to several hundred feet thick where it was confined by valley walls during emplacement (Stearns and Macdonald, 1942). In a detailed mapping study of the Hana Volcanics on the southwest rift zone, 90 percent of the flows were found to be aa flows or flows transitional between aa and pahoehoe. The flows ranged from 0.05 to 16 mi² in area, 0.6 to 8 mi in length, and 7.2×10^{-4} to 1×10^{-1} mi³ in volume (Eric Bergmanis, Univ. of Hawaii, oral commun., 1998). Flows of the Hana Volcanics in the study area are expected to exhibit similar characteristics. Flows of the Kipahulu Member of the Hana Volcanics are not found in the study area (fig. 2).

Intrusive Volcanic Rocks

Intrusive volcanic rocks include those rocks, such as dikes, that formed when magma cooled below the ground surface. Dikes associated with rift zones are the dominant intrusive rocks in Hawaiian volcanoes. The East Maui Volcano has three primary rift zones (Stearns and Macdonald, 1942; Langenheim and Clague, 1987) and the study area includes one of these, the north rift zone (fig. 2). Because of the relative youth of East Maui Volcano, dike exposures are scarce and limited to the

summit walls and the larger valleys (Stearns and Macdonald, 1942). However, positive gravity anomalies extending from the summit to the northwest, southwest, and east, indicate the presence of dense, intrusive dikes beneath the ground surface (Kinoshita and Okamura, 1965). These gravity anomalies correspond to the locations of typical rift-zone surface features such as cinder, spatter, and pumice cones.

The dikes and the rocks they intrude are commonly referred to as dike complexes. In Hawaiian volcanoes, dike complexes range in width from 1.5 to 3 mi and average about 1.9 mi (Macdonald and others, 1983). The north rift zone of East Maui Volcano appears to be about 3 mi wide near the coast and could be greater than 5 mi wide at 4,000 ft altitude on the basis of the cinder and spatter cones that are in two parallel and roughly linear patterns (fig. 2). On Oahu, the rift zones near the ancient caldera are marked by swarms of closely spaced, nearly vertical, and nearly parallel dikes (Takasaki and Mink, 1985). Dikes in a dike complex average about 100 to 200 per mile of width (Macdonald and others, 1983) and compose 10 percent or more of the rock volume (Takasaki and Mink, 1985). The number of dikes in the dike complex is expected to increase with increasing depth and could average 500 to 600 per mile of width of the complex (Macdonald and others, 1983). The rift zones are hydrologically important because dikes have low permeability and tend to impede the lateral movement of ground water. Ground-water levels in these low-permeability areas can be as high as several thousand feet above sea level.

Hydraulic Conductivity

Hydraulic conductivity is a measure of the capacity of a rock to transmit water. The main elements of lava flows contributing to their hydraulic conductivity are (1) clinker zones associated with aa flows, (2) voids along the contacts between flows, (3) cooling joints normal to flow surfaces, and (4) lava tubes associated with pahoehoe flows. Few published estimates of hydraulic conductivity exist for rocks of the East Maui Volcano.

Stearns and Macdonald (1942) classified the Honomanu Basalt as extremely permeable and considered it hydrologically similar to dike-free shield-building-stage lavas on Oahu, which have reported horizontal hydraulic-conductivity values of 500 to 5,000 ft/d (Hunt, 1996). The horizontal hydraulic

conductivity of the Honomanu Basalt in the western end of the study area was estimated to range from 1,800 to 5,400 ft/d on the basis of aquifer tests and an analytical solution based on recharge (Gingerich, 1999) even though the western end of the study area is in a dike complex. Near the eastern end of the study area near Nahiku, analysis of a single-well aquifer test made at a well that is open to the upper lava flows of the Honomanu Basalt, provided a hydraulic conductivity estimate of about 1 ft/d (unpublished data in USGS Hawaii District aquifer-test files). The rocks of the Honomanu Basalt in the Nahiku area are described as transitional in petrology between Honomanu Basalt and Kula Volcanics and are more similar in nature to rocks of the Kula Volcanics (Stearns and Macdonald, 1942). Therefore, the hydraulic conductivity of the rocks is probably closer to the average hydraulic conductivity of Kula Volcanics.

The specific capacities of wells open to the Honomanu Basalt in or near the Haiku area average about 600 gal/min per ft of drawdown (Gingerich, 1999). The specific-capacity values decrease toward the east and range from 1,400 gal/min per ft of drawdown at the westernmost well to 0.7 gal/min per ft of drawdown at the easternmost well. The specific capacity of well 4801-48 near Nahiku is about 1.5 gal/min per ft of drawdown (unpublished data in USGS Hawaii District aquifer test files).

No estimates of hydraulic conductivity exist from aquifer tests done in wells in the study area open to the Kula or Hana Volcanics. Stearns and Macdonald (1942) classified the Hana Volcanics as very permeable. The specific capacities of four wells open to the Kula Volcanics in the Haiku area range from 0.01 to 0.09 gal/min per ft of drawdown (Gingerich, 1999). The average specific capacity of these four wells is about four orders of magnitude lower than the average specific capacity of the wells that penetrate into the Honomanu Basalt, indicating that the permeability of the Kula Volcanics is significantly lower than permeability of the Honomanu Basalt. This difference in permeability is due to the contrast in thickness of the lava flows and the amount of interflow void spaces able to transmit water. The Honomanu Basalt is composed of many thin lava flows with abundant interflow void space. The Kula Volcanics is composed of thick lava flows with much less interflow pore space.

In general, the average hydraulic conductivity of a dike complex decreases as the number of dike intrusions within the dike complex increases. In addition, hydraulic conductivity is expected to be higher parallel to the strike of the dikes rather than perpendicular to the strike. As mentioned above, the hydraulic conductivity of the rocks in the dike complex along the western end of the study area below about 1,000 ft altitude, was estimated to be several thousand feet per day (Gingerich, 1999). These relatively high values of hydraulic conductivity indicate that this section of the dike complex does not contain abundant dikes and that ground-water flow in the direction parallel to the dikes is relatively unimpeded. Further upslope, dikes may be more abundant, and the hydraulic conductivity of the dike complex may be similar to dike complexes in other volcanic aquifers.

On the basis of a numerical model, Meyer and Souza (1995) estimated that dikes have a hydraulic conductivity of 1×10^{-5} to 1×10^{-2} ft/d and that the dikes reduce the average, effective hydraulic conductivity of the dike complex to about 1×10^{-2} to 1×10^{-1} ft/d. In a summary of aquifer-test analyses for wells on Oahu, Hunt (1996) shows that estimates of hydraulic conductivity for dike-intruded shield-building-stage lava flows are about 10 to 100 times lower than for dike-free, shield-building-stage lava flows.

HYDROLOGIC BUDGET

The water-budget model used for East Maui is an accounting procedure that balances moisture inflow of rainfall and fog drip with moisture outflow of runoff, evapotranspiration, ground-water recharge, and the change in soil-moisture storage (Shade, 1999). The relation of the water budget components is expressed by:

$$G = P + F - R - ET - \Delta SS, \quad (1)$$

where: G = ground-water recharge,
 P = rainfall,
 F = fog drip,
 R = runoff,
 ET = evapotranspiration, and
 ΔSS = change in soil-moisture storage.

The recharge estimates reported by Shade (1999) represent the average of two different monthly water-

budget computation methods that differ in the order in which recharge and evapotranspiration are taken into account. Each water-budget computation method produced a recharge estimate that differed from the average value by about 8 percent.

The water-budget model assumes natural vegetation conditions. Compared with natural vegetation, pineapple cultivation can increase recharge to an area because evapotranspiration from unirrigated pineapple fields is less than evapotranspiration from areas of natural vegetation. Potential evapotranspiration from pineapple fields is estimated to be about 20 percent of measured pan evaporation whereas potential evapotranspiration from sugarcane fields and areas of natural vegetation is equal to pan evaporation (Giambelluca, 1983). During the 1960's, part of the study area west of Kakipi Gulch had as much as 9 mi² in pineapple cultivation (7 percent of the study area) (University of Hawaii Land Study Bureau, 1967). Therefore, the recharge estimate calculated on the basis of natural vegetation conditions is probably slightly underestimated in this area when the effects of pineapple cultivation are considered. Also, a significant amount of water probably recharges the aquifer by infiltration from surface-water diversion ditches and tunnels and from associated surface-water reservoirs, but this amount has not been estimated.

Water budgets were estimated for 14 stream subbasins (table 1 and fig. 3) with USGS surface-water gaging stations upstream of any surface-water diversions. Ground-water discharge is not included in the water-budget determinations for each subbasin because a significant volume of ground water discharges downstream of the gaging stations, either to streams or through springs and diffuse seepage near sea level.

Rainfall and Fog Drip

Rainfall distribution in the area is primarily governed by the orographic effect (fig. 4). Precipitation is heaviest where the prevailing northeasterly trade winds encounter the windward flank of East Maui Volcano, forcing warm, moist air into the cool, higher altitudes. Mean annual rainfall increases from about 50 in/yr at the coast on the western end of the study area to more than 300 in/yr at middle altitudes in the central part of the study area and then decreases to about 50 in/yr at the volcano summit (Giambelluca and others, 1986).

Annual rainfall at 7,030 ft altitude (Haleakala Ranger Station, rain gage 338, fig. 4) ranged from about 18 to 111 in. during 1939–96 (fig. 5). Downslope at 6,150 ft altitude (Honomanu Gulch, rain gage 341, fig. 4), annual rainfall ranged from about 56 to 167 in. during 1935–80 and at 1,280 ft altitude (Paakea, rain gage 350, fig. 4) annual rainfall ranged from about 131 to 287 in. during 1919–81 (fig. 5). Nearer the coast at 700 ft altitude (Kailua, rain gage 446, fig. 4), rainfall ranged from about 75 to 162 in. annually during 1919–85.

Mean monthly rainfall maps of Giambelluca and others (1986) were digitized and used as an input data set for a water-budget model of East Maui (Shade, 1999). The total average annual rainfall in the study area is estimated to be 989 Mgal/d, or 160 in/yr based on data from Shade (1999). Rainfall estimates for individual gaged stream subbasins within the study area (fig. 3) range from 5.18 to 34.79 Mgal/d (table 1, fig. 6).

Studies on the islands of Hawaii, Lanai, and Oahu (Juvik and Nullet, 1995; Giambelluca and Nullet, 1991; Ekern, 1964 and 1983) have shown that, in addition to measured rainfall, water reaches the ground surface through cloud-water interception (fog drip). The fog zone on the windward side of East Maui Volcano extends from about 1,970 ft to the lower limit of the most frequent temperature-inversion base height at about 6,560 ft (fig. 3) (Giambelluca and Nullet, 1991). Using digitized rainfall maps of this area and fog drip/rainfall ratios estimated from a study on the windward side of Mauna Loa on the island of Hawaii, the fog-drip rate in the study area was estimated to be about 176 Mgal/d or an average of 65 in/yr in the fog area (Shade, 1999). Estimates of fog-drip rates for individual gaged stream subbasins within the study area range from 0.45 to 9.28 Mgal/d (table 1, fig. 6).

The total precipitation (rainfall plus fog drip) in each individual subbasin is linearly related to the size of the individual stream subbasin because almost all of the subbasins lie in areas of similar rainfall (table 1). The exception to this trend is at gaging station 5528 at 4,487 ft altitude on Waikamoi Stream (fig. 3). At this site, the total precipitation is low in relation to the area of the stream subbasin when compared with the other gaging stations. This difference is because this stream subbasin is in an area of lower rainfall and fog drip.

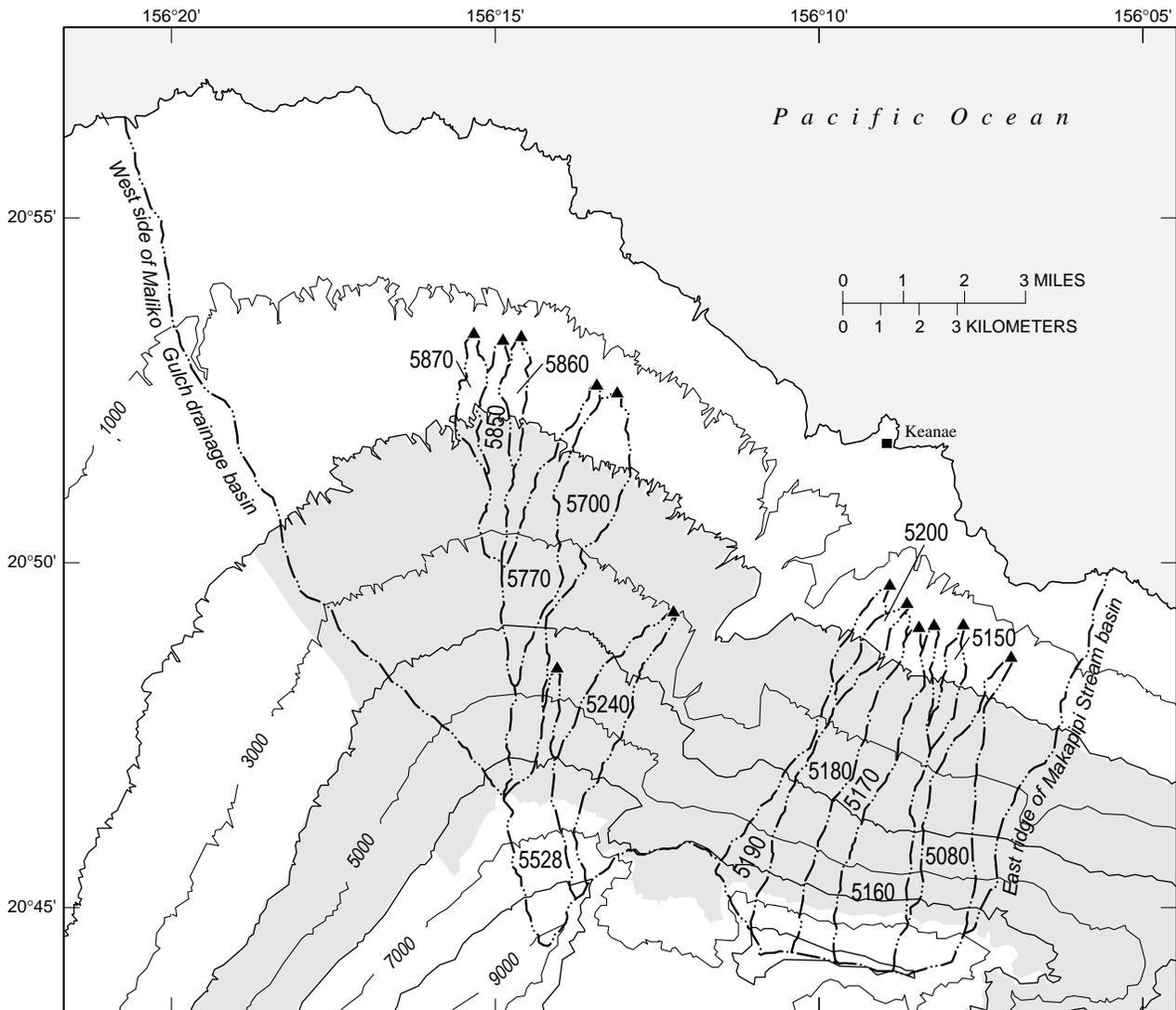
Evapotranspiration

No published pan-evaporation records exist for any sites in the study area. The nearest site is about 1 mi

Table 1. Water-budget components for selected gaged stream basins, northeast Maui, Hawaii

[mi², square miles; Mgal/d, million gallons per day; ET, evapotranspiration. The difference of the quantity of rainfall plus fog drip minus runoff, ET and recharge may not equal zero due to rounding. Drainage basins shown in figure 3; gaging-station number is preceded by 16 and ends in 00; drainage-basin areas determined digitally from geographic information system (GIS) coverages]

Gaging-station number	Gaging-station location	Drainage-basin area (mi ²)	Inflow			Outflow				Ratio of base flow to recharge (in percent)	
			Rainfall (Mgal/d)	Fog drip (Mgal/d)	Total (Mgal/d)	Runoff (Mgal/d)	ET (Mgal/d)	Recharge (Mgal/d)	Total (Mgal/d)		Base flow (Mgal/d)
East of Keanae Valley											
5080	Hanawi Stream	3.46	32.27	8.91	41.18	12.00	4.63	24.56	41.19	3.66	15
5150	Waiohue Gulch	0.52	7.25	1.49	8.74	3.91	0.87	3.96	8.74	3.57	90
5160	Kopiliula Stream	3.91	31.96	8.69	40.65	13.87	5.50	21.27	40.64	4.18	20
5170	East Wailuaiki Stream	3.11	30.20	8.46	38.66	14.90	4.33	19.43	38.66	4.82	25
5180	West Wailuaiki Stream	3.67	33.11	9.28	42.39	18.75	5.05	18.59	42.39	4.53	25
5190	West Wailuanui Stream	1.92	16.22	4.18	20.40	7.27	2.93	10.20	20.40	2.24	22
5200	East Wailuanui Stream	0.51	7.10	1.29	8.39	4.07	0.85	3.47	8.39	1.65	48
West of Keanae Valley											
5240	Honomanu Stream	2.55	19.63	6.05	25.68	7.05	3.65	14.98	25.68	0.81	5
5528	Waikamoi Stream	2.46	9.19	1.18	10.37	1.29	3.22	5.87	10.38	0.05	1
5700	Nailiilihaele Stream	3.61	34.79	8.81	43.60	17.46	6.30	19.84	43.60	6.92	37
5770	Kailua Stream	2.39	23.92	7.22	31.14	15.17	3.62	12.36	31.15	4.16	35
5850	Hoolawanui Stream	1.34	12.48	3.12	15.60	5.13	2.39	8.09	15.61	2.68	33
5860	Hoolawaliilii Stream	0.57	5.18	0.45	5.63	2.52	1.29	1.82	5.63	2.34	128
5870	Honopou Stream	0.65	5.36	0.58	5.94	1.93	1.30	2.72	5.95	1.21	44



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**
- FOG AREA
 - DRAINAGE BASIN DIVIDE
 - TOPOGRAPHIC CONTOUR--Interval 1,000 feet
 - 5850** ABBREVIATED STREAM-GAGING STATION NUMBER (COMPLETE NUMBER IS 16585000)
 - SURFACE-WATER GAGING STATION

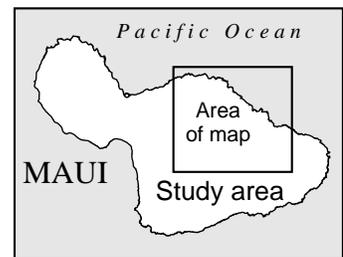
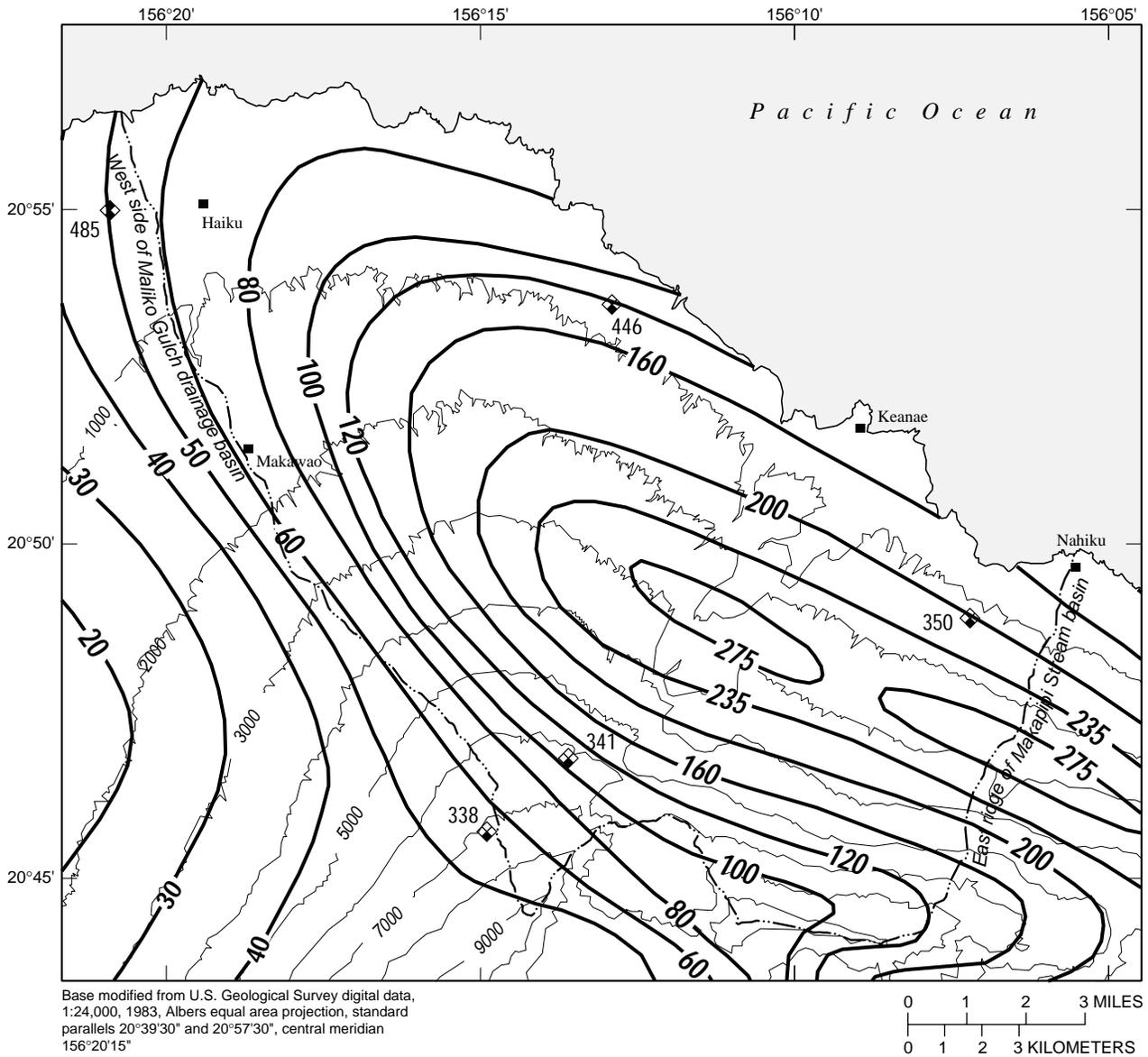


Figure 3. Selected drainage basins and fog area for windward east Maui, Hawaii (modified from Shade, 1999).



EXPLANATION

- 40— LINE OF EQUAL MEAN ANNUAL RAINFALL--
Interval, in inches, is variable
- 1000— TOPOGRAPHIC CONTOUR--Interval 1,000 feet
- BOUNDARY OF STUDY AREA
- 338 ◆ RAIN GAGE AND NUMBER
- 485 ◆ RAIN GAGE AND EVAPORATION STATION AND NUMBER

Figure 4. Mean annual rainfall, selected rain gages, and evaporation stations in northeast Maui, Hawaii (modified from Giambelluca and others, 1986).

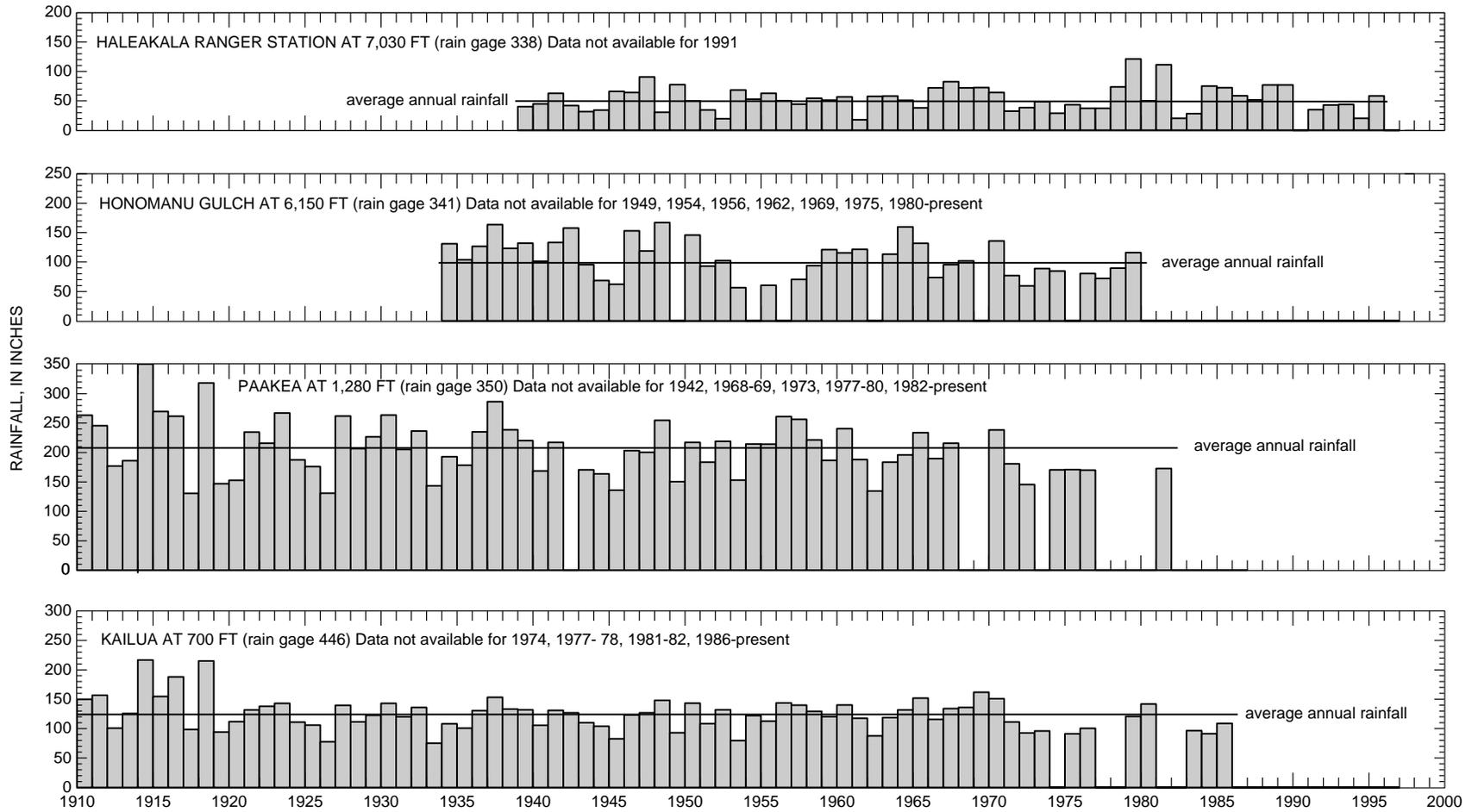


Figure 5. Annual rainfall at Haleakala Ranger Station, Honomanu Gulch, Paakea, and Kailua rain gages, northeast Maui, Hawaii.

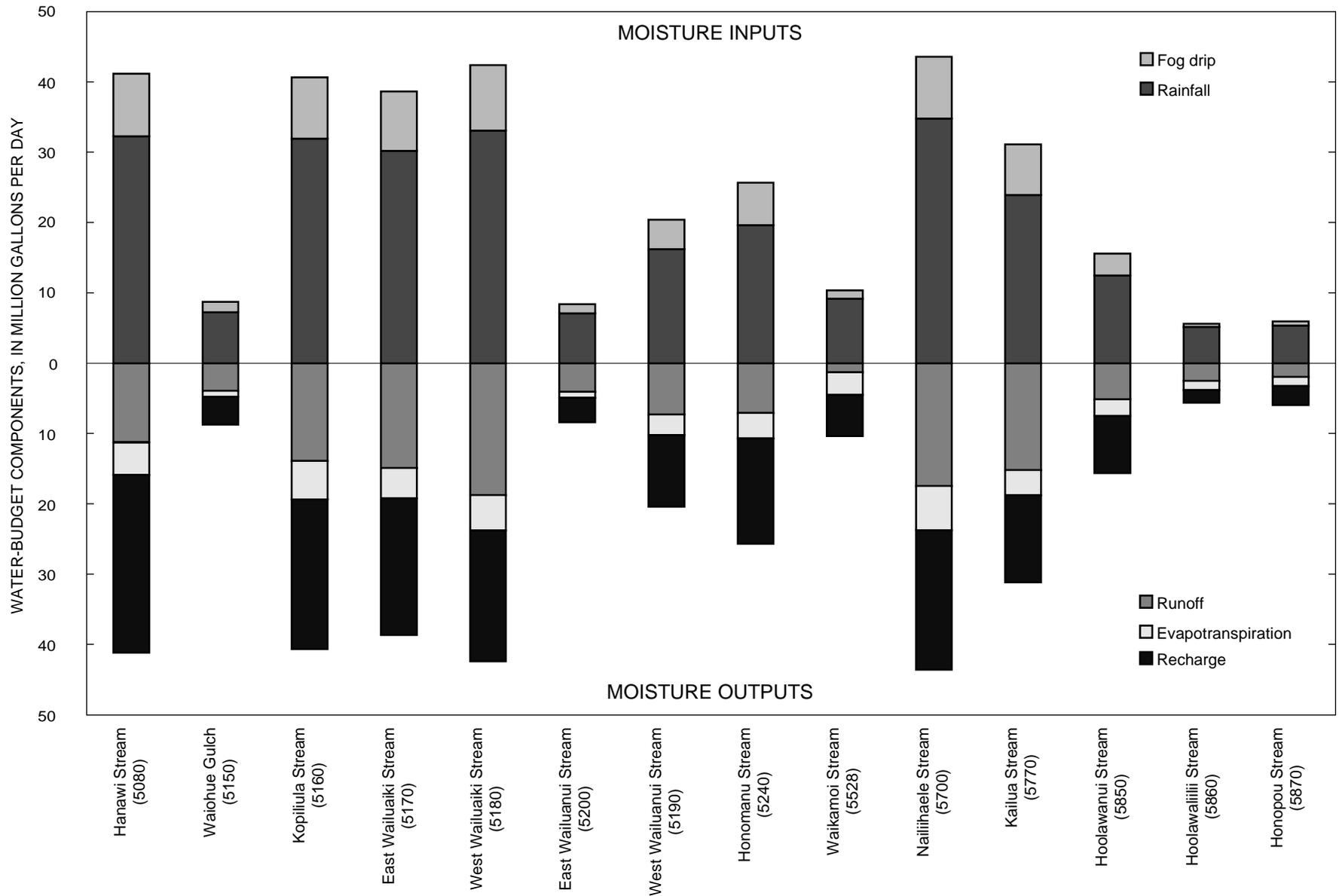


Figure 6. Average annual water-budget components for selected gaged drainage basins, northeast Maui, Hawaii.

to the west of Maliko Gulch (station 485, fig. 4) where the station was at 320 ft altitude. During 1963–70, measured pan evaporation at this station ranged from 85.15 to 102.62 in. (Ekern and Chang, 1985). Shade (1999) estimated a distribution of pan-evaporation values for the study area as a function of the rainfall distribution and used a one-to-one relation between pan evaporation and potential evapotranspiration in the water-budget model. According to the model, an average of about 19 percent of rainfall and fog drip or 220 Mgal/d is lost to evapotranspiration in the study area (Shade, 1999). The amount of potential evapotranspiration could be underestimated because the ratio of pan evaporation to potential evapotranspiration for wet forested areas could be closer to 1.3 to 1 (Giambelluca, 1983). Estimates of evapotranspiration rates for the individual gaged stream subbasins range from 0.85 to 6.30 Mgal/d (table 1, fig. 6).

Streamflow

Streams in the study area drain radially from the summit of East Maui Volcano northward to the ocean. Valley development is in a youthful stage as streams are eroding downward into the volcano slope, forming steep-sided valleys and leaving nearly uneroded upland areas (planezes) between the stream valleys. Streamflow consists of runoff, base flow, and in some cases, flow added to streams from a network of irrigation ditches that cross the study area. Base flow is groundwater discharge to the stream. Nearly 30 named perennial streams enter the ocean between Maliko Gulch and Makapipi Stream and there are numerous other minor intermittent streams. Currently, the USGS operates four gaging stations (5080, 5180, 5870, and 5950) on streams in the study area (plate 1). In the past, the USGS operated gaging stations on 22 streams (table 2, at end of report) and all the major diversion systems (table 3) in the study area (Fontaine, 1996).

Streamflow in the study area is flashy because of the steep sides of the stream valleys and the common high-intensity rainfall at middle altitudes. The highest recorded streamflow in the area was greater than 7,000 Mgal/d in Hanawi Stream at gaging station 5090 on March 21, 1937 (Grover and Carson, 1939). The highest average annual daily flow (25.85 Mgal/d) in the study area was also measured at this gaging station (table 2).

The ratio of runoff to rainfall ranges from 14 percent to 63 percent in the 14 stream subbasins included in the water-budget study (Shade, 1999). For streams on the highly permeable Hana Volcanics, runoff is described as low and most of the rain is expected to enter the ground as recharge (Takasaki and Yamanaga, 1970). But the two stream subbasins in the study area (Waiohue and Hanawi) having only Hana Volcanics at the ground surface have about the same average runoff-to-rainfall ratio (46 percent) as the 11 stream subbasins containing mostly Kula Volcanics (45 percent).

Estimates of streamflow and base flow are based on streamflow records of varying length and from different times. The error associated with comparing these records is not considered significant because the average annual values used in the comparisons are expected to be within about 10 percent of the true value in most cases. A statistical analysis of five streamflow records, each with more than 60 years of record, shows that the average annual discharge for any 10-year period within that record has a standard error of 12 percent when compared with the whole record (Fontaine, 1996). When the length of the subset is increased to a 50-year period, the standard error only improves to 5 percent. Thirty nine of the streamflow records for the study area are equal to or greater than 10 years long.

For this study, the length of the period of record at each gaging station was determined to be unimportant by comparing each record to three reference records from the study area. The three longest streamflow records, 5080 (73 years), 5180 (76 years), and 5870 (85 years) were chosen as reference records. For each other individual record, a time period equal to the length of that record was chosen. A subset of a reference record was then selected from this same time period and the average flow during that time period was compared with the total reference record to estimate the ratio of flow during the subset period to the reference period. This analysis was made for all three reference records and the result was averaged to obtain a period-of-record scale factor for each of the other records. The scale factor ranged from 0.88 to 1.13 (table 2). This variability is consistent with the statistical analysis reported by Fontaine (1996). This range of accuracy is considered sufficient for the type of comparisons made in this study, and therefore, no corrections were made to any of the records to account for differences in length or period of record.

Table 3. Information from gaging stations on surface-water diversion systems, northeast Maui, Hawaii
[ft, feet; Mgal/d, million gallons per day; gaging-station number is preceded by 16 and ends in 00; --, not known]

Station number	Diversion system	Year completed	Period of record used in calculation	Years of complete record	Station altitude (ft)	Average annual flow (Mgal/d)	Lowest average annual flow (Mgal/d)	Highest average annual flow (Mgal/d)
5310	Upper Kula Pipeline	1912	1946–85	40	4,320	0.50	0.29	1.24
5060	Koolau/Wailoa Ditch	1905/1923	1949–65	17	1,300	2.87	2.28	3.46
5120	Koolau/Wailoa Ditch	1905/1923	1900; 1920–85	67	1,289	22.01	9.24	36.32
5230	Koolau/Wailoa Ditch	1905/1923	1911–12; 1919–85	69	1,238	65.26	33.80	107.89
5510	Koolau/Wailoa Ditch	1905/1923	1923–29	7	1,260	69.32	49.15	77.77
5410	Koolau/Wailoa Ditch	1905/1923	1933–87	55	1,240	74.24	39.79	120.50
5880	Koolau/Wailoa Ditch	1905/1923	1924–87	64	1,208	110.35	65.19	149.82
5380	Spreckels Ditch	1879	1923–29; 1931–85	62	1,471	15.54	8.34	27.27
5520	Spreckels Ditch	1879	1929–30; 1932–38	9	1,340	8.17	1.91	14.57
5655	Spreckels Ditch	1879	1919–29	11	960	5.77	0.78	17.72
5890	New Hamakua Ditch	--	1919–85	67	1,170	23.25	7.52	61.69
5900	Old Hamakua Ditch	--	1919–21; 1936–64	30	1,117	1.80	0.30	6.07
5415	Manuel Luis/Center/Lowrie Ditch	1900/1893/1900	1919–24; 1926–85	66	920	5.31	1.38	11.92
5610	Manual Luis/Center/Lowrie Ditch	1900/1893/1900	1921–24; 1926–29	8	720	13.61	7.82	15.30
5920	Manual Luis/Center/Lowrie Ditch	1900/1893/1900	1911–26; 1931–85	71	598	23.44	5.73	51.51
5940	Haiku Ditch	1885	1911; 1914; 1916–28; 1931–85	70	422	15.51	3.32	49.15

Surface-Water Diversion Systems

Six major surface-water diversion systems carry water across the study area from east to west in a complex series of ditches, tunnels, flumes, and pipelines (plate 1, tables 3 and 4). The two highest-altitude systems, the Upper and Lower Kula Pipelines, divert water for domestic supply and the rest divert water mainly for irrigation in central Maui. With few exceptions, the diversion systems capture all of the base flow and an unknown percentage of total streamflow at each stream crossing. Records of reported total diversion-system flow are most complete at Honopou Stream (Neal Fujii, Commission on Water Resource Management, written commun., 1998). During 1925–97, total flow for all of the diversion systems at Honopou Stream averaged about 163 Mgal/d (fig. 7). The highest average flows were measured in the Koolau/Wailoa Ditch system where total flow crossing Honopou Stream (gaging station 5880) averaged 110.35 Mgal/d for 1924–87 (table 3 and fig. 7). Average flows in the other diversion sys-

tems were all much lower: Manuel Luis/Center/Lowrie and New Hamakua Ditch systems each averaged about 23 Mgal/d, Spreckels and Haiku Ditch systems each averaged about 15 Mgal/d. Total flow in the Upper and Lower Kula Pipelines is not gaged by the USGS. Water-sale records indicate that total flow through these two systems averaged less than 5 Mgal/d between 1970 and 1983 (Belt, Collins, and Associates, 1984).

Ground-Water Recharge

Ground-water recharge in the study area was estimated to be 529 Mgal/d (Shade, 1999) (fig. 8). Annual water budgets were estimated for individual stream sub-basins with gaging stations upstream of any surface-water diversions. The recharge estimate represents an average recharge of about 86 in/yr over the entire 129 mi² study area. However, recharge varies areally from a minimum of less than 10 in/yr in some western areas near the coast to a maximum greater than 150 in/yr in

Table 4. Summary of surface-water diversion influence on selected streams, northeast Maui, Hawaii

[ne, no effect; all values represent the approximate altitude where the diversion system intercepts the stream; all diversion systems take water from stream unless otherwise noted]

Stream system	Diversion system					
	Upper Kula Pipeline	Lower Kula Pipeline	Koolau/Wailoa Ditch	Spreckels Ditch	Manuel Luis/Center/Lowrie Ditch	Haiku Ditch
Makapipi	ne	ne	1,300	ne	ne	ne
Hanawi	ne	ne	1,300	ne	ne	ne
Kapaula	ne	ne	1,320	ne	ne	ne
Paakea	ne	ne	1,300	ne	ne	ne
Waiohue	ne	ne	1,300	ne	ne	ne
Kopiliula	ne	ne	1,300	ne	ne	ne
Wailuaiki	ne	ne	1,300	ne	ne	ne
Wailuanui	ne	ne	1,300	ne	ne	ne
Honomanu	ne	3,043	1,300	1,720	ne	ne
Haipuaena	4,320	3,030	1,300	1,460	900	ne
Puohokamoa	4,310	2,984–3,016	1,300	1,290	900	ne
Waikamoi	4,240	2,961–2,985	1,300	1,200	700	ne
Kolea	ne	ne	1,250	ne	760	ne
Kaaiea	ne	ne	1,250	920	700	ne
Opuola	ne	ne	1,250	ne	700	ne
Nailiilihaele	ne	2,880	1,200	660	660	ne
Kailua	4,300	2,970	1,200	660 ^a	640	480
Hoolawa	ne	ne	1,200	ne	620	460
Honopou	ne	ne	1,200	ne	580	440

^a Adds water to stream

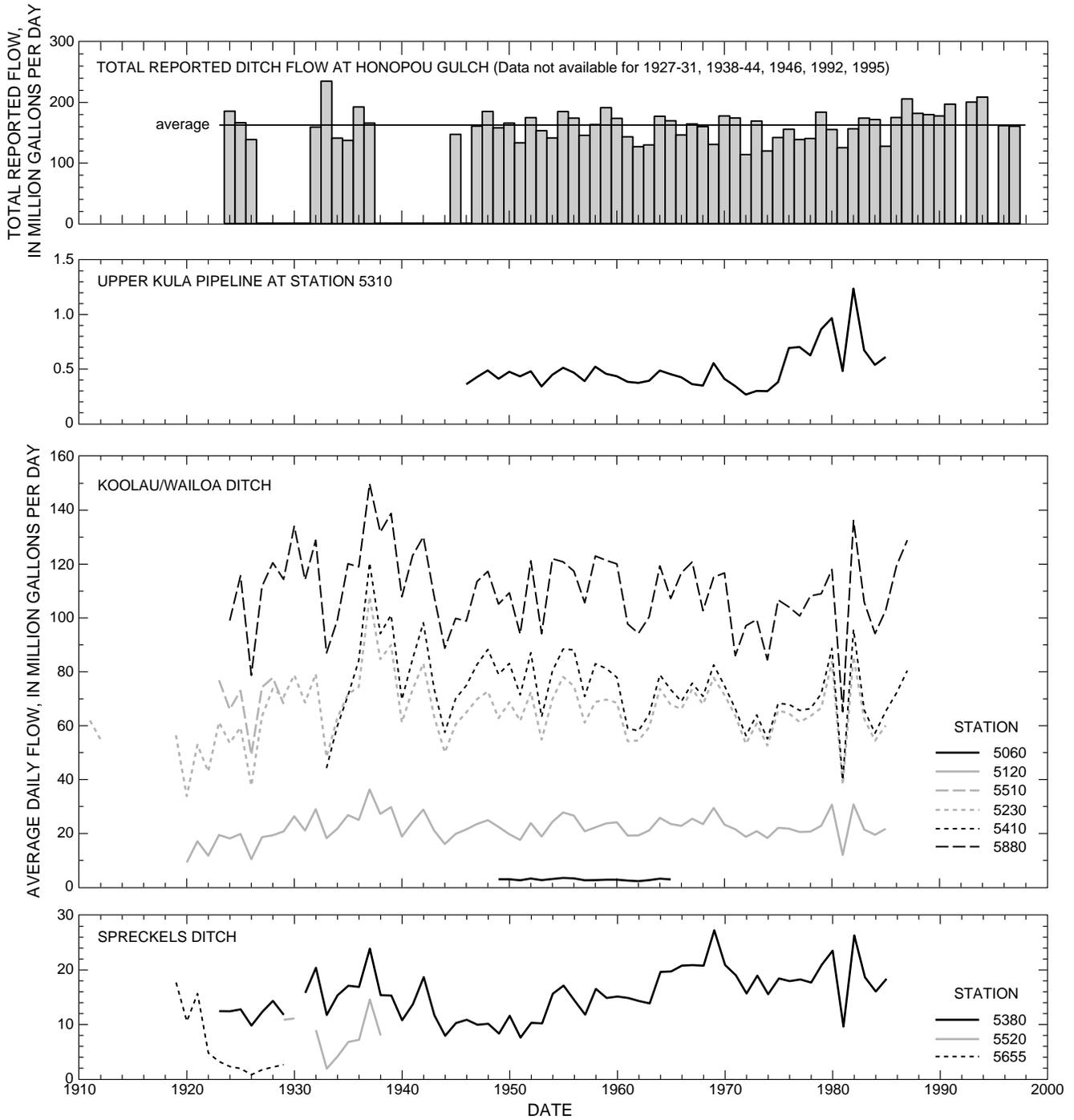


Figure 7. Average annual total diversion-system flow and flow in selected diversion systems for the period 1910-98, northeast Maui, Hawaii.

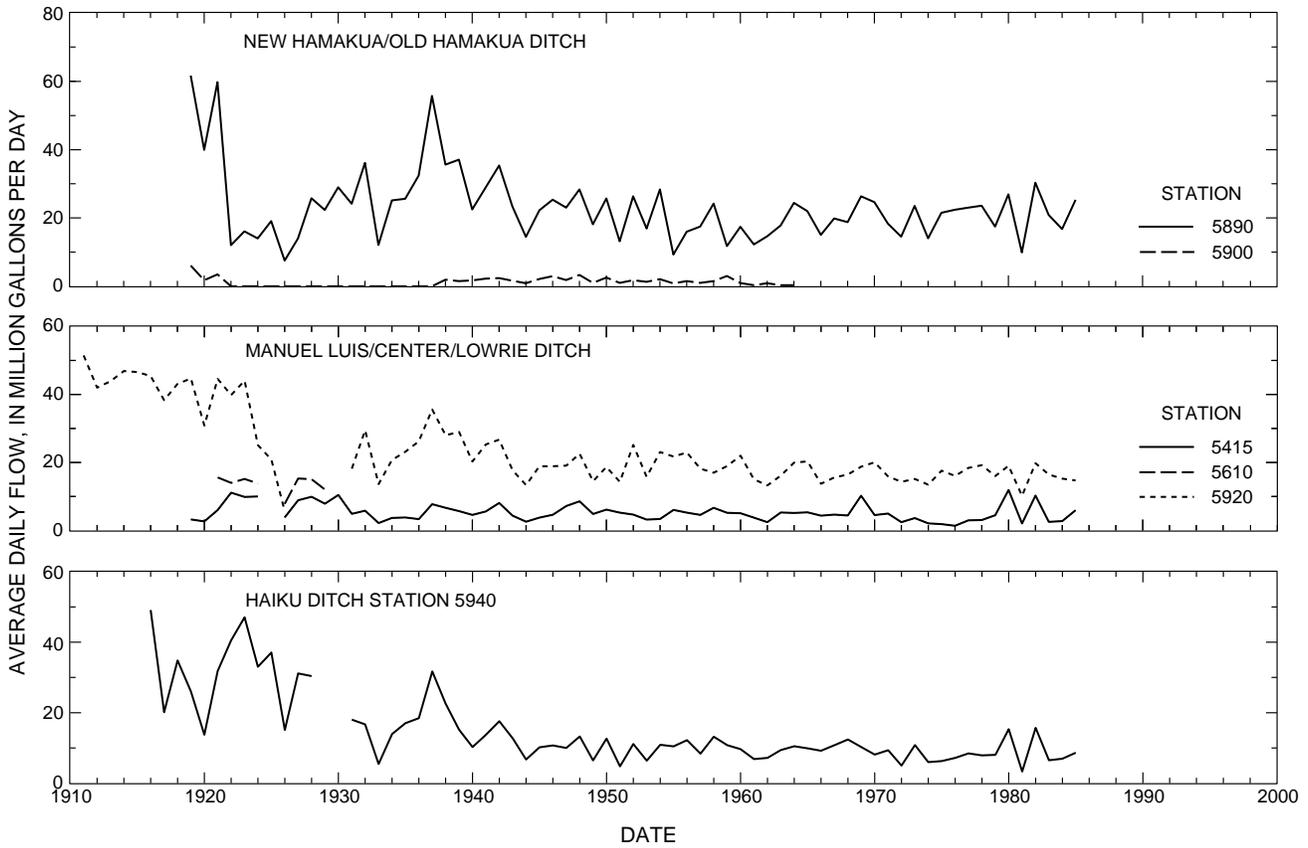
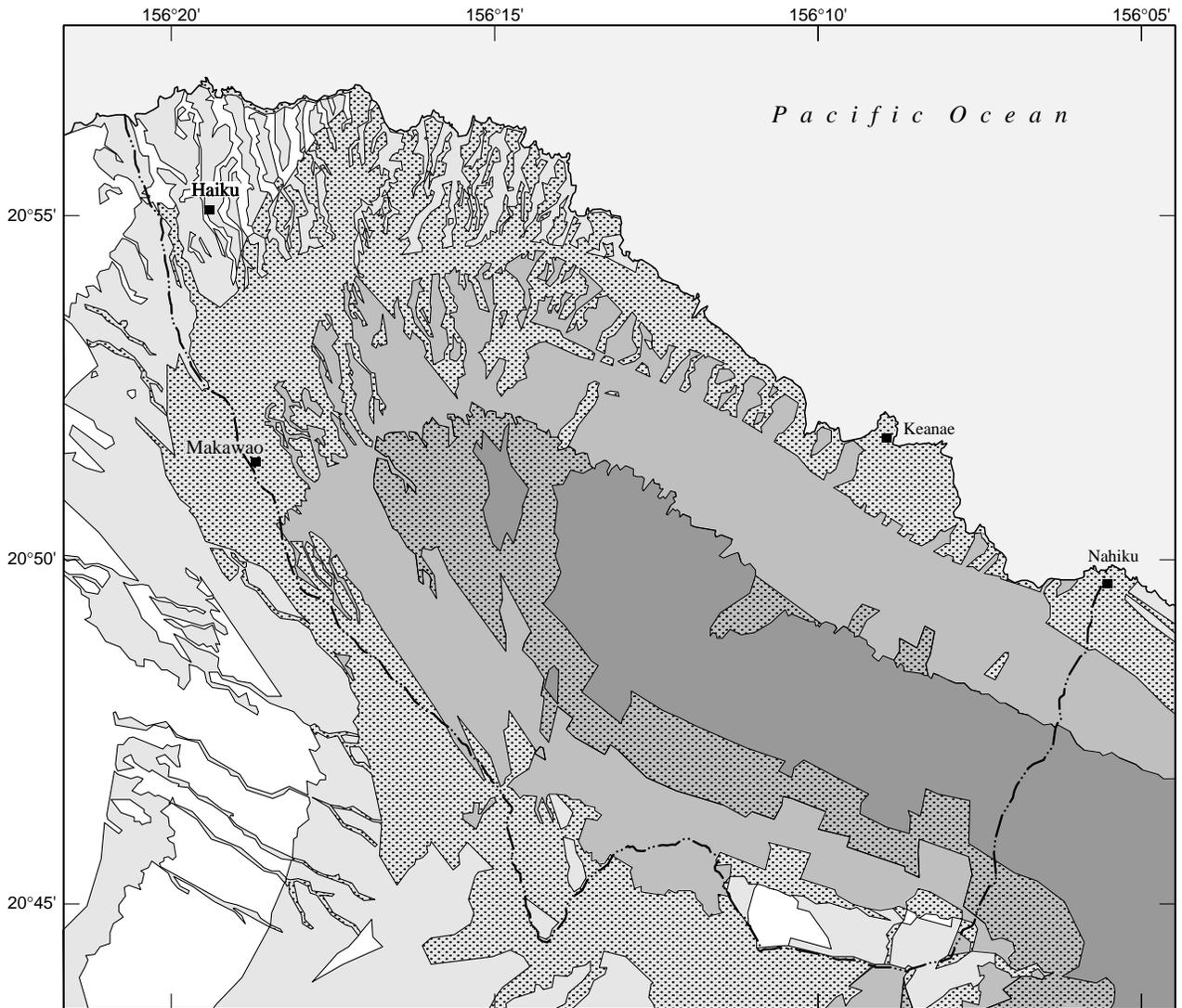
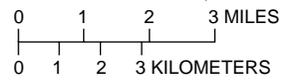


Figure 7. Average annual reported total diversion-system flow and flow in selected diversion systems for the period 1910-98, northeast Maui, Hawaii -- *Continued.*



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

ESTIMATED AVERAGE ANNUAL GROUND-WATER RECHARGE, IN INCHES PER YEAR

-  Less than or equal to 10
-  Greater than or equal to 10 and less than 25
-  Greater than or equal to 25 and less than 50
-  Greater than or equal to 50 and less than 100
-  Greater than or equal to 100 and less than 150
-  Greater than or equal to 150

 BOUNDARY OF STUDY AREA

Figure 8. Estimated ground-water recharge, northeast Maui, Hawaii (modified from Shade, 1999).

the areas of highest rainfall and fog drip between altitudes of 2,000 and 6,000 ft. The estimated recharge of 529 Mgal/d is about 45 percent of precipitation (rainfall plus fog drip) in the study area. Recharge estimates for individual gaged stream subbasins range from 1.82 to 24.56 Mgal/d (table 1, fig. 6). These recharge rates range from 32 to 60 percent of the precipitation rate for each individual subbasin. The average ratio of recharge to precipitation for the two streams in the Hana Volcanics is slightly higher than in the other streams for which water budgets were determined.

Ground-Water Withdrawal

In the study area, ground water is withdrawn from public and private wells and from the tunnels and ditches constructed for the irrigation system. Of the ground water currently withdrawn from wells, most is from only three, well 5520-01 in Maliko Gulch, well 5108-01 at Keanae, and well 4806-48 near Nahiku (fig. 9). Water from well 5520-01 is pumped to the Haiku water-diversion system for irrigation. The records of yearly pumpage at this well show that the annual ground-water withdrawal averaged 2.8 Mgal/d during 1913–96. This average value includes 1954–61 when the pumps in the well were not operating (fig. 10). Monthly pumpage from the well varied seasonally from zero to as much as 17 Mgal/d. Water from well 5108-01, drilled in 1984, is used for domestic supply and, according to records supplied by the Maui County Department of Water Supply, withdrawals have averaged about 0.04 Mgal/d since 1988 (fig. 10). According to East Maui Irrigation, Inc. (EMI) records, withdrawals at well 4806-48 have averaged about 0.28 Mgal/d since 1956 (fig. 10). This water is pumped into the Koolau Ditch diversion system on a seasonal basis for irrigation in central Maui. Unreported withdrawals from domestic wells in the area probably total less than 0.3 Mgal/d on the basis of well-installation specifications listed on well-permit applications. A well (5318-01) presently being constructed (1999) near Kaupakulua (fig. 9) is proposed to withdraw 1.5 Mgal/d from the Honomanu Basalt (State of Hawaii Department of Land and Natural Resources application for well-construction permit, 1997). Proposed withdrawal rates for additional wells in the Haiku area total about 16.5 Mgal/d, an increase in withdrawal of about 400 percent.

The network of water-diversion systems contains many tunnels that capture ground water, which is transported to central Maui for irrigation, but records of flow are incomplete. Stearns and Macdonald (1942) estimated the average tunnel yield to be about 6 Mgal/d for 22 tunnels totaling more than 20,600 ft in length that were constructed by EMI in the Nahiku area. Attempts have also been made to enhance discharge from several small springs in the study area by tunneling for water but average yields are reported to total less than 0.1 Mgal/d (Stearns and Macdonald, 1942). Ground-water seepage directly into an unlined part of the Koolau Ditch has been estimated to be about 3.8 Mgal/d per mile of ditch between the start of the ditch and gaging station 5120 (plate 1) (William Meyer, USGS, written commun., 1998). No other information exists describing what sections of the ditches gain water, so estimating the total effect of ground-water capture by the ditches crossing the study area is not possible.

CONCEPTUAL MODELS OF GROUND-WATER OCCURRENCE AND MOVEMENT

Fresh ground water in northeast Maui occurs under two general conditions: (1) as a high-elevation saturated zone in relatively low-permeability rocks above an unsaturated zone, and (2) as a freshwater-lens system underlain by denser saltwater. West of Keanae Valley, a high-elevation saturated zone in the upper rock unit, the Kula Volcanics, is separated from a freshwater lens near sea level by an unsaturated zone in the underlying Honomanu Basalt as described in the report for the Haiku area (Gingerich, 1999). East of Keanae Valley, the ground-water system appears to be a freshwater-lens system that is fully saturated above sea level to altitudes greater than 2,000 ft, similar to the system described in the Nahiku area (Meyer, in press). The freshwater-lens system is in direct connection with the underlying saltwater.

West of Keanae Valley

Within the study area and west of Keanae Valley, ground water is found at high elevations in the Kula Volcanics and as a freshwater lens floating on denser underlying saltwater in the Honomanu Basalt (fig. 11). The rocks beneath the contact between the low permeability Kula Volcanics and the underlying Honomanu

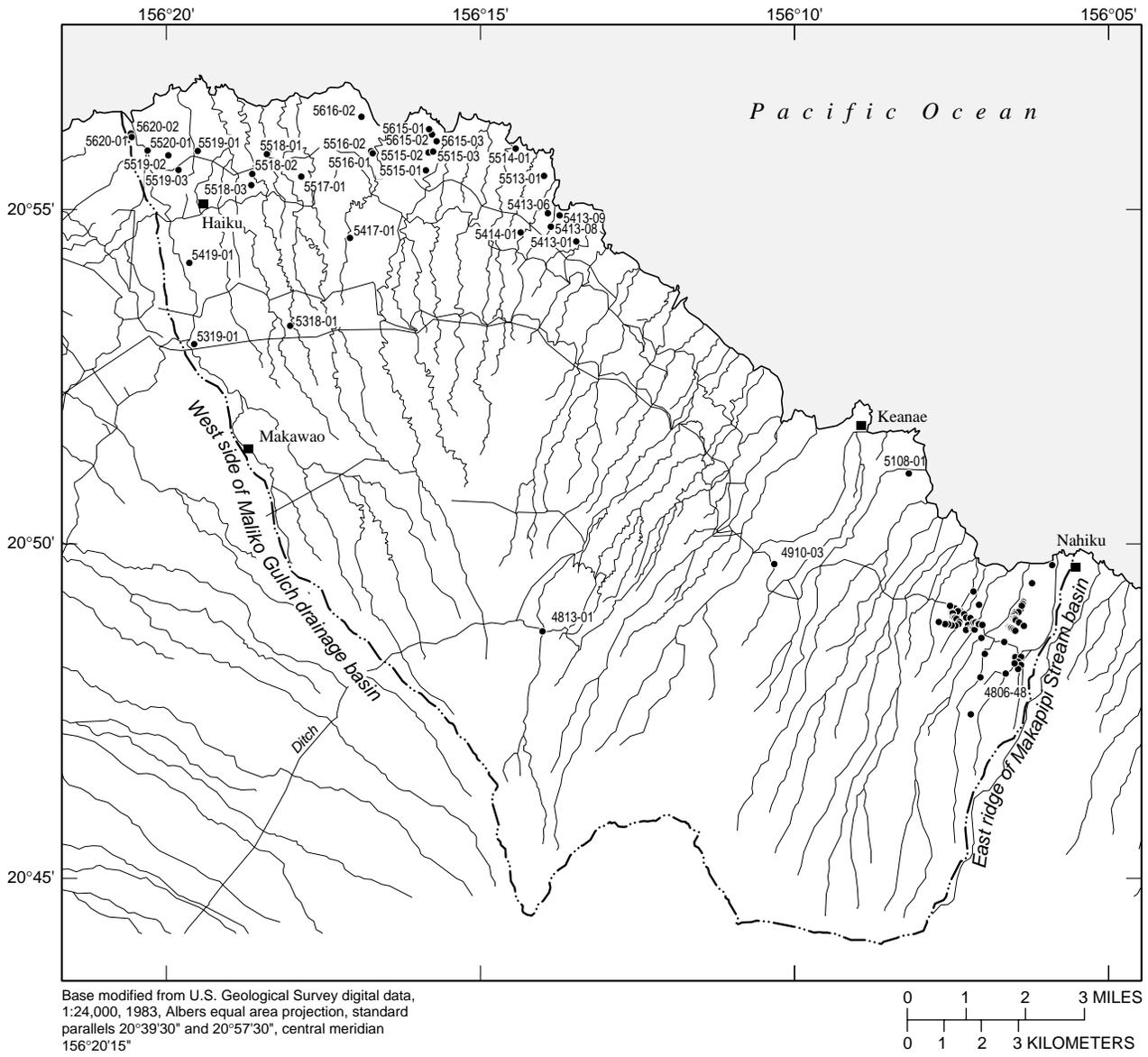


Figure 9. Selected wells in northeast Maui, Hawaii.

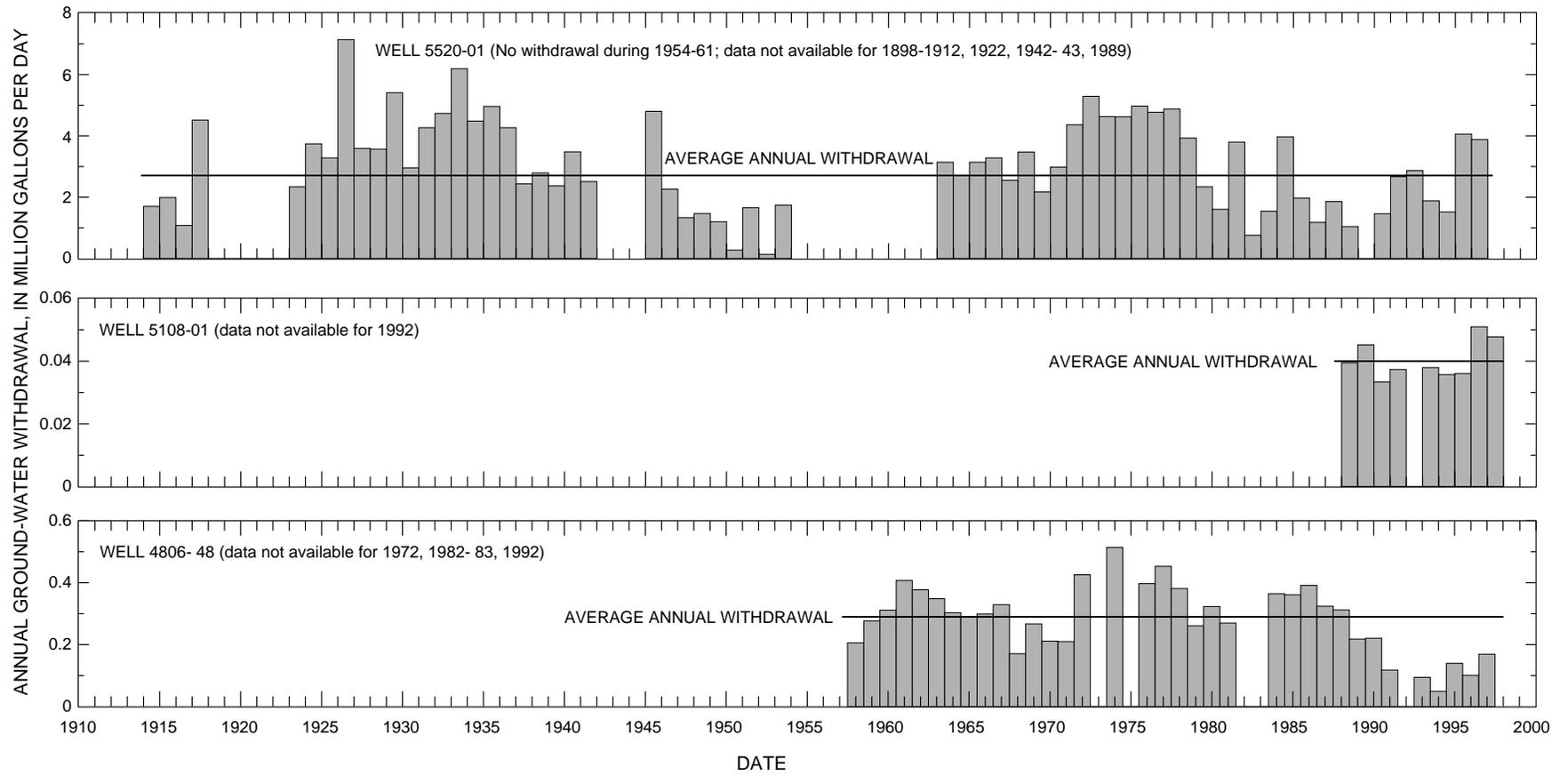


Figure 10. Annual withdrawal of ground water from selected wells, northeast Maui, Hawaii.

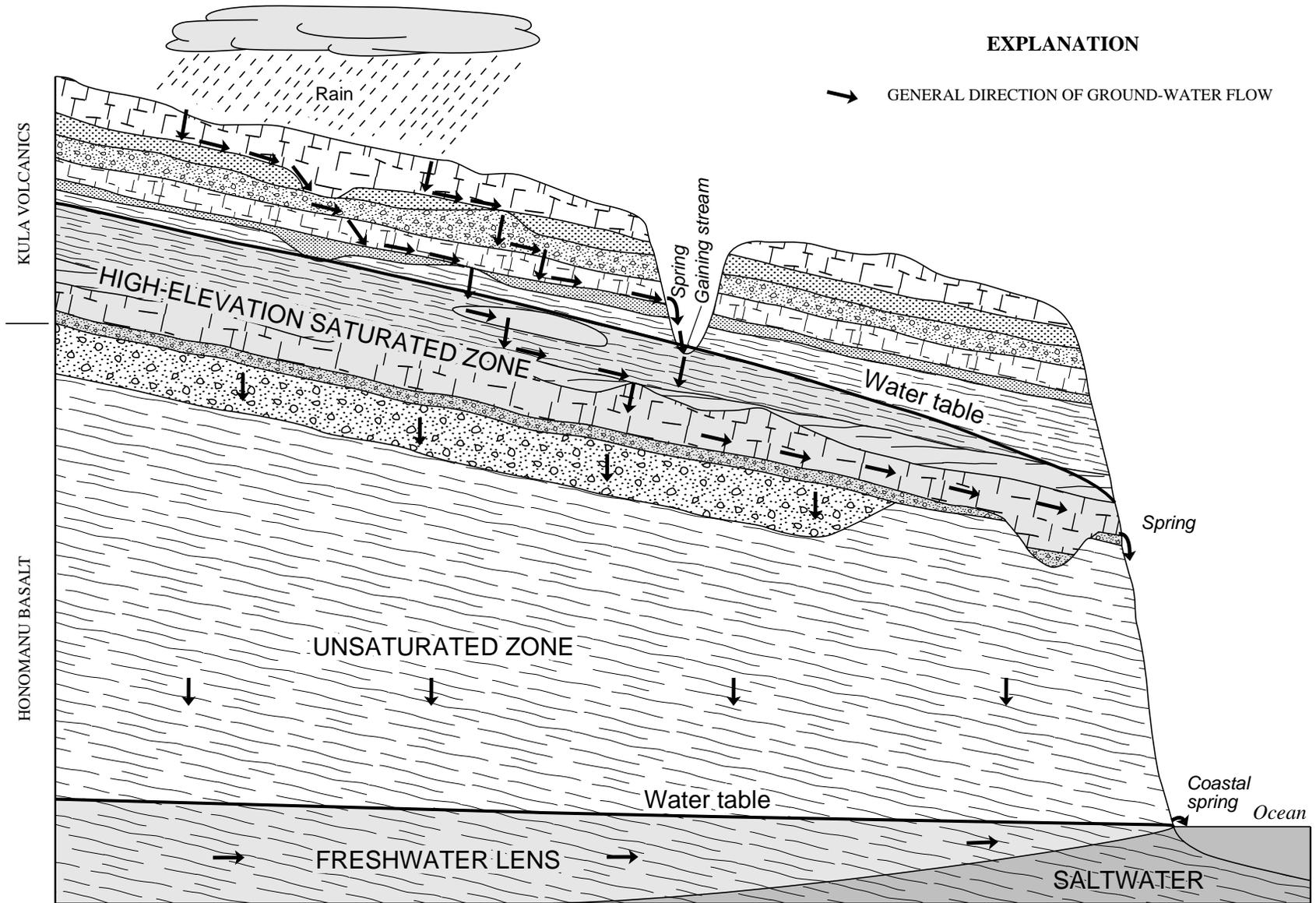


Figure 11. Diagram illustrating the variably saturated ground-water system west of Keanae Valley, northeast Maui, Hawaii (arrows indicate general direction of ground-water flow).

Basalt and above the freshwater lens appear to be unsaturated.

In the Haiku area, water levels measured in shallow wells indicate that a water table lies several tens of feet below the ground surface of the undissected uplands and represents the top of a saturated zone in the thick lava flows and interbedded soils of the Kula Volcanics (Gingerich, 1999). This water-table surface mimics topography but is more subdued and rises away from the coastline with a slope of about 340 ft/mi (fig. 12) (Gingerich, 1999). Near the coast and in a few of the gulches, this high-elevation saturated zone is not present because erosion has removed the low-permeability layers formed by the Kula Volcanics. Ground-water flow is predominantly to the north from high to low altitudes along the dip of the geologic layers and vertically downward from the base of the saturated zone.

Where valleys have been incised into the high-elevation water table, ground water discharges at springs or directly in streambeds. Conversely, streamflow infiltrates into the aquifer where the streambed lies above the high-elevation water table and is sufficiently permeable. Where valley floors consist of Kula Volcanics all the way to the ocean, the streams commonly flow all the way to the ocean.

The rocks beneath the contact between the Kula Volcanics and the underlying Honomanu Basalt and above the freshwater lens appear to be unsaturated on the basis of several observations, some first discussed for the Haiku area (Gingerich, 1999):

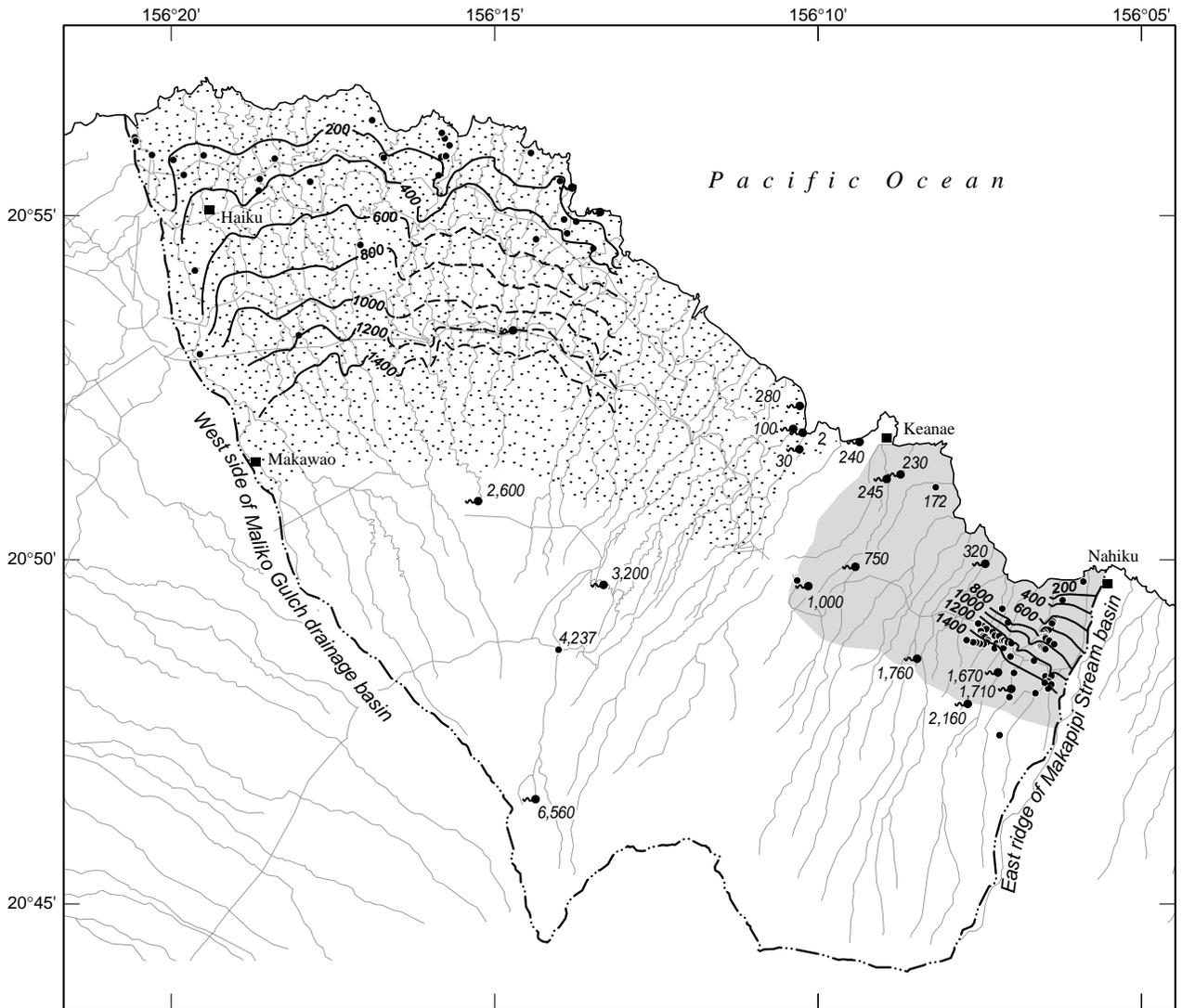
- (1) Stream channels incised into the Honomanu Basalt (Maliko and Kakipi Gulches in the Haiku area, and Oopuola, Honomanu, and Haipuaena Streams further to the east) are dry or lose streamflow during base-flow conditions. After flowing over the less permeable Kula Volcanics, streamflow seeps into the more permeable Honomanu Basalt downstream.
- (2) The hydraulic conductivity of the Honomanu Basalt, on the basis of aquifer tests, is too high to support a thick ground-water lens with the estimated recharge to the study area.

- (3) Small springs are commonly found along sea cliffs in this part of the study area at the base of the Kula Volcanics but no springs have been observed lower in the Honomanu Basalt but above sea level.
- (4) Wells that penetrate through the contact have penetrated cascading water from above the contact and dry lava tubes in the Honomanu Basalt.

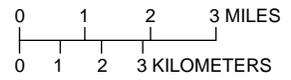
Water levels from wells penetrating to sea level indicate that the surface of the freshwater lens in the Haiku area forms a hydraulic gradient of about 3 ft/mi inland (Gingerich, 1999). The source of freshwater in the lens is ground-water recharge from overlying high-elevation saturated zones and rainfall infiltration. Fresh ground water flows from the inland areas to the coast where it discharges at springs and by diffuse seepage at and below sea level. In coastal aquifers, a saltwater-circulation system exists beneath the lens (Souza and Voss, 1987). Saltwater flows landward in the deeper parts of the aquifer, rises, and then mixes with seaward-flowing freshwater. This mixing creates a freshwater-saltwater transition zone. No wells in the study area are known to penetrate the transition zone or underlying saltwater.

For hydrostatic conditions, the freshwater-lens thickness can be estimated by the Ghyben-Herzberg principle. If the specific gravities of freshwater and saltwater are assumed to be 1.000 and 1.025, respectively, then the Ghyben-Herzberg principle predicts that every foot of freshwater above sea level must be balanced by 40 ft of freshwater below sea level. For dynamic conditions, the Ghyben-Herzberg principle tends to overestimate the freshwater-lens thickness in the recharge zone and underestimate the freshwater-lens thickness near the discharge zone.

Volcanic dikes, which commonly impede the flow of water because of their low permeability, appear to be a factor controlling the shape of both the high-elevation water table and the freshwater lens within the north rift zone of East Maui Volcano (Gingerich, 1999). Ground-water flow could be impeded more from east to west in a direction perpendicular to the preferred dike orientation in the dike complex. But dike impoundments do not appear to be present seaward of the 2,000-ft topographic contour in the Haiku area. Because the principal



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

- | | |
|---|--|
| <p>—400— WATER-TABLE CONTOUR--Shows altitude of water table. Interval 200 feet. Dashed where approximate. Datum is mean sea level</p> <p>●4,237 WELL AND FIRST WATER LEVEL REPORTED, IN FEET ABOVE MEAN SEA LEVEL</p> <p>●1,000 SPRING AND ALTITUDE, IN FEET ABOVE MEAN SEA LEVEL</p> <p>--- BOUNDARY OF STUDY AREA</p> | <p> AREA WITH HIGH-ELEVATION WATER TABLE PERCHED ABOVE A FRESHWATER LENS--Contours show the top of the perched water body in variably saturated ground-water system (modified from Gingerich, 1999)</p> <p> AREA WITH VERTICALLY EXTENSIVE FRESHWATER LENS--Contours show the top of fully saturated water body in fully saturated ground-water system (modified from Meyer, in press)</p> |
|---|--|

Figure 12. Generalized water table and altitude of selected springs, northeast Maui, Hawaii.

direction of ground-water flow is parallel to the dike complex, it appears that volcanic dikes are either not numerous enough or are oriented parallel to each other so that structures to impound ground water to high levels did not form to a significant extent.

West of Keanae Valley, wells that are open to the aquifer only at or below sea level will pump ground water from the freshwater lens. The discharge of freshwater from the lens at the coast will be reduced by the amount of ground water withdrawn by the pumped wells. Removal of ground water at these wells should not affect the upper high-elevation water table because the thick unsaturated zone will prevent the vertical ground-water flow gradient from changing significantly. Ground-water withdrawal from wells open to the high-elevation water body can reduce streamflow and reduce the amount of recharge that infiltrates to the freshwater lens below.

No reliable water-level measurements exist from wells drilled to sea level between Kakipi Gulch and Keanae Valley or above 1,200 ft altitude anywhere in the study area to confirm whether ground water is found in both a high-elevation saturated zone and a freshwater lens in these areas as well. Most of the wells drilled near the coast immediately west of Kakipi Gulch encounter water in the Kula Volcanics, but do not penetrate to sea level. A test hole (4813-01) drilled in Kula Volcanics at about 4,300 ft altitude near Waikamoi Stream (fig. 9) encountered water 63 ft below the ground surface and the hole had about 5 ft of water in it when it was 650 ft deep (unpublished records in USGS Hawaii District files). The well was reported to be dry by Stearns and Macdonald (1942, p. 215) because the water was thought to be drilling fluid and not representative of the water table.

The existence of a high-elevation water body overlying a freshwater lens is inferred from the presence, similar to that found in the Haiku area, of losing stream sections where surface water flows from the Kula Volcanics onto the Honomanu Basalt. Oopuola, Haipuaena, and Honomanu Streams all have gone dry downstream of the Kula Volcanics/Honomanu Basalt contact. Other streams in the area may be losing but do not go dry because they have not incised below the contact.

At most wells in the study area, only single water-level measurements are available, so temporal varia-

tions in ground-water levels are difficult to determine. At three wells drilled into the freshwater lens in the Haiku area, water-level measurements are available over several-year periods (Gingerich, 1999). Pumped water levels in well 5520-01, near the coast, were about 2 ft lower than non-pumped water levels and daily tidal fluctuations were about 0.2 to 0.4 ft. Occasional measurements made in wells 5519-01 and 5419-01 show that the water level appears to mimic rainfall variations (Gingerich, 1999).

Water Chemistry.--The chemical characteristics of ground water and surface water that have been measured at most sites is limited to chloride concentration, specific conductance, and temperature. Chloride concentration is commonly used as an indicator of saltwater intrusion into the ground-water system. Generally, greater withdrawal from a well in a freshwater lens will cause an increase in the chloride concentration of the pumped water as more saline water is induced to flow towards the well. The only long-term chloride-concentration record available in the study area is for well 5520-01 in Maliko Gulch (Gingerich, 1999). Between 1925 and 1996, measured chloride concentration ranged from 270 to 1,668 mg/L depending on the amount of withdrawal from the well. Chloride-concentration values from other wells in or near the Haiku study area that penetrate the freshwater lens range from 49 to 200 mg/L (Gingerich, 1999). The highest concentrations were in samples from wells nearest the coast where the freshwater lens is thinnest.

Chloride concentrations from springs west of Keanae Valley average about 10 mg/L (table 5). All of these springs are assumed to be discharging from the high-elevation saturated zone. Ground-water chloride concentrations in these springs decrease with increasing altitude and distance from the ocean (Gingerich, 1999). Chloride ions in seawater aerosols carried by the tradewinds are deposited on land as salts with decreasing concentrations as the distance from the ocean is increased. Rainfall dissolves the deposited salts and recharges the high-elevation saturated zone with water of varying chloride concentration. Water that recharges the saturated zone at the highest altitude (farthest from the ocean) will typically have the lowest chloride concentration.

Table 5. Temperature, specific conductance, and chloride concentration at selected springs, northeast Maui, Hawaii [°C, degrees Celsius; $\mu\text{S}/\text{cm}$, microsiemens per centimeter; mg/L , milligrams per liter; --, no data; all altitudes estimated from U.S. Geological Survey topographic maps, Haiku, Keanae, Kilohana, and Nahiku quadrangles]

Location	Altitude (feet above sea level)	Date	Water temperature (°C)	Water specific conductance ($\mu\text{S}/\text{cm}$)	Chloride concentration (mg/L)	Comments
Akeke Spring	750	9/11/97	18.7	131	8	
Big Spring	787	1/12/94	15.5	227	--	
		2/24/94	15.5	234	--	
		2/22/95	15.5	229	--	
		9/13/95	15.7	225	10	
		9/9/96	15.6	233	4	
Hanawi Spring at 1,325 ft	1,325	1/11/94	19.3	64	--	West bank near gaging station 5080
		9/13/95	19.2	63	10	
Hanawi Spring 1	770	1/12/94	19.6	53	--	
		9/13/95	20.5	55	10	
Hanawi Spring 2	660	1/11/94	19.1	51	--	
		2/24/94	19.2	49	--	
Honoluluui Spring	1,000	9/10/96	19.9	47	7	
Honomanu Spring at shore	2	2/26/96	20.2	366	80	Honomanu 1
Honomanu Spring at 30 ft	30	9/10/95	20.9	156	15	Honomanu 3b
		2/26/96	21.1	158	12	
Hoolawa Spring at 1,200 ft	1,200	2/5/98	20.0	75	15	Hoolawa 12.2
Hosmer Grove Spring	6,560	10/17/94	13.0	30	--	Waikamoi 74
		9/12/95	10.9	46	5	
		2/25/96	10.7	25	3	
		9/8/97	13.9	28	3	
Kaumahina Spring at 280 ft	280	5/23/95	22.7	136	--	Kaumahina 4
Kaumahina Spring at 240 ft	240	5/23/95	22.8	124	--	Kaumahina 5
Kaumahina Spring at 100 ft	100	5/23/95	22.7	138	--	Kaumahina 7
Mossman Spring	1,020	9/10/96	19.9	47	7	
		3/2/97	19.3	49	8	
Nuaailua Roadcut Seep	240	2/26/96	22.7	111	23	Inland side of highway from PVC collection pipe
		3/3/97	21.9	113	23	
		9/9/96	23.8	107	21	
		9/11/97	22.5	105	24	
Ohia Spring	230	2/26/96	17.8	147	6	
		9/9/96	18.3	132	4	
		3/2/97	17.7	137	5	
		9/11/97	18.6	114	6	
Tavares Spring	40	9/5/96	22.8	526	121	
Waikamoi Spring at 3,200 ft	3,200	9/9/97	18.0	37	6	Spring along old flume

Specific conductance is related to the type and concentration of ions in solution and can be used for approximating the dissolved-solids content of the water. For sample-collection sites at sea level, a high specific conductance probably means that the sample has a higher chloride concentration in it (such as at Honomanu coastal springs in table 5). The specific-conductance measurements of the water samples collected above sea level west of Keanae Valley range between 16 and 521 $\mu\text{S}/\text{cm}$. For water samples collected higher than sea level, the variations in specific conductance are probably caused by a number of factors including the abundance of sea-spray deposition, the residence time of the water in the aquifer, and the aquifer-rock age and petrology. It is not possible given the data to determine the effects on ground water in the study area of each of these factors individually.

Water temperature can be an indication of the elevation the water recharged the aquifer or, in the case of elevated temperature, the effects of geothermal activity. Because none of the temperatures appear to be elevated, geothermal activity does not appear to play a significant role in the ground-water flow system of the study area. Therefore, ground water with the lowest temperature is assumed to have originated at the highest elevations. Measured ground-water temperatures west of Keanae Valley range from 10.9°C at Hosmer Grove Spring (6,560 ft altitude) to 24.9°C in Uluini Stream (310 ft altitude).

In and East of Keanae Valley

In and east of Keanae Valley, the freshwater lens appears to be vertically extensive, similar to the conditions found in the Nahiku area. In the Nahiku area and as far west as Waiohue Gulch (plate 1), the rocks are described as fully saturated from sea level to greater than 2,000 ft altitude on the basis of water-level information from test holes and streamflow measurements (Meyer, in press). The saturated zone extends from the Honomanu Basalt at sea level up through the Kula Volcanics and into the Hana Volcanics (fig. 13). Streams intersect the vertically extensive freshwater-lens system and are perennial downstream of about 2,100 ft altitude. These streams continue to gain water from all three rock units as they descend in altitude to sea level. Discharge from high-elevation springs in the area is from this ver-

tically extensive freshwater-lens system. Because the rocks in this area are fully saturated, withdrawal of ground water from wells open to any part of the aquifer will reduce streamflow and ground-water discharge at the coast. The vertically extensive saturated zone results directly from the combination of high ground-water recharge rates, low rock hydraulic conductivity, and the ground-water flow-system geometry (Meyer, in press). Recharge to parts of this area is greater than 150 in/yr (fig. 8).

The relatively low hydraulic conductivity of the rocks (about 1 ft/d) has been demonstrated by the analysis of a 7-day aquifer test done at well 4806-48 which is open to the Honomanu Basalt between altitudes of 488 and 134 ft. The hydraulic conductivity of the Honomanu Basalt is related to the characteristics of the lava flows as they were emplaced and cooled. The nature of flow emplacement is controlled by both the lava petrology and the features onto which the lava is flowing. As discussed previously, the exposures of Honomanu Basalt in the Nahiku area above sea level are transitional in petrology between Honomanu Basalt and Kula Volcanics and are more similar to rocks of the Kula Volcanics (Stearns and Macdonald, 1942). Because of the transitional petrology, the hydraulic conductivity of the Honomanu Basalt in this area may be lower than typically expected elsewhere and therefore similar to the hydraulic conductivity of Kula Volcanics.

Several volcanic features in the area indicate that the Honomanu Basalt may not have been emplaced as typical flat-lying flank lava flows and therefore the hydraulic conductivity of the rocks may not be typical either. A volcanic dike in the sea cliff west of Kapaula Gulch (Stearns and Macdonald, 1942, pl. 1, inset B) and a 2-ft thick layer of lithic-vitric tuff (common near eruptive vents) in the sea cliff west of Hanawi Stream (Stearns and Macdonald, 1942, pg. 71) indicate that the area may once have been the site of local eruptions. Also, Stearns and Macdonald (1942) recognized that the "Hanawi artesian structure," a permeable layer confined above and below by less permeable layers, is unique for supposed shield-stage basalts and nothing similar has been described elsewhere in Hawaii's aquifers.

The primary factor controlling the altitude to which the water table will reach in a freshwater-lens system is the hydraulic conductivity of the aquifer at sea

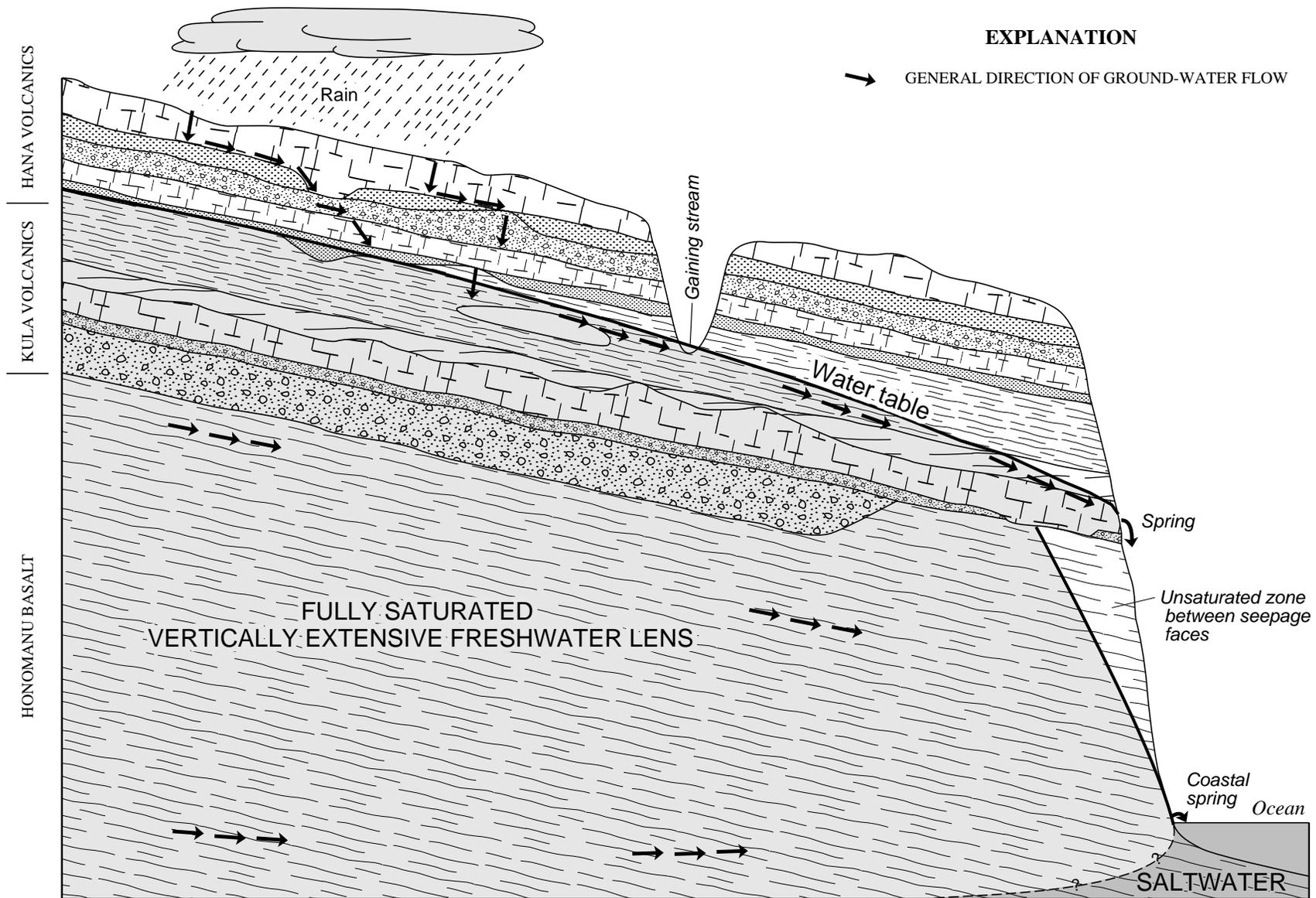


Figure 13. Diagram illustrating the fully saturated ground-water system east of Keanae Valley, northeast Maui, Hawaii (arrows indicate general direction of ground-water flow).

level. As seen from equation 1 (p. 7), for a given recharge rate, an aquifer with lower hydraulic conductivity will have a higher water table than an aquifer with higher hydraulic conductivity. A numerical model has shown that the recharge estimated for the Nahiku area will produce a freshwater-lens system with a water table hundreds to thousands of feet above sea level given a hydraulic conductivity of about 1 ft/d (Gingerich, 1998). With hydraulic conductivity values in the range of 1,000 ft/d, freshwater heads will only be a few feet above sea level several miles inland. At Nahiku, the aquifer is Honomanu Basalt from below sea level to a minimum of 150 ft above sea level at the coast to at least 650 ft above sea level at well 4806-48. Above the Honomanu Basalt, the low-permeability Kula Volcanics is nearly 500 ft thick. The Hana Volcanics is mainly a veneer on the surface of the shield- and postshield-stage lavas and this unit has little control on the regional ground-water flow system. Therefore, there is a layered sequence of at least 600 ft of low-permeability rock above sea level at the coast and a greater extent inland in which a vertically extensive freshwater-lens system could develop.

In a vertically extensive freshwater-lens system, regional ground-water flow above sea level is toward the coast and downward from areas of recharge to areas of discharge in streams and at the coast. Ground water will flow from areas of higher hydraulic head to areas of lower hydraulic head. Meinzer (1923, p. 41) described ground water that has greater pressure head than an underlying body of ground water, from which it is, however, not separated by any unsaturated rock. This description applies to a vertically extensive freshwater-lens system in a layered aquifer: "... after the water table is struck in drilling a well, the well contains water at all depths which it reaches but the water level in the well sinks below the original water table..." (Meinzer, 1923).

In a layered aquifer, the head gradient may not be uniform with depth because each layer penetrated may have a different hydraulic conductivity and a different degree of connection to a discharge point in a stream or at the ocean. An abrupt water level drop as a new layer is penetrated may mean only that a layer of significantly lower hydraulic head has been encountered. An abrupt decline in water levels during drilling is not necessarily an indication that a perched water body has just been penetrated. Stearns and Macdonald did not consider the

concept of a layered system with a vertical head gradient when analyzing the "Hanawi artesian structure" leading them to conclude "The structure must be perched, because when the [test] holes penetrate the supporting member the water level drops" (Stearns and Macdonald, 1942, p. 260).

Drilling records of water levels from wells penetrating a perched water body above a thin basal freshwater-lens system would be expected to show abrupt declines to a few tens of feet above sea level, reflecting the height of the water table in the basal freshwater lens. This scenario is apparent in the Haiku area where the basal freshwater lens in highly permeable Honomanu Basalt has a water table of a few feet above sea level. Stearns and Macdonald (1942, p. 255) stated that the Nahiku area was underlain by permeable Honomanu Basalt with a thin basal freshwater lens but their assumption was based on inference from other areas and not on any field data from the Nahiku area. Six wells were drilled to depths near to or below sea level in the Nahiku area and the lowest water level encountered was 47 ft above sea level in a test hole 300 ft from the ocean (Meyer, in press). At well 4806-48, (about 2 mi inland from the ocean) the deepest water level encountered was 969 ft above sea level when the well bottom was at -9 ft altitude (unpublished records from Doak C. Cox, geologist, Experiment Station, Hawaiian Sugar Planters Association in files of U.S. Geological Survey, Honolulu). In most of the test holes drilled in the area, the water levels dropped during drilling as would be expected in a vertically extensive freshwater-lens system but still remained higher than the top of the Honomanu Basalt even when drilled as deep as 259 ft below sea level (Meyer, in press). The pattern of high water levels indicates that there are no layers of the Honomanu Basalt with relatively high hydraulic conductivity or a good connection to a discharge zone even as deep as several hundred feet below sea level.

The water-level data indicate that the water table of the vertically extensive freshwater-lens system is as high as the Hana Volcanics in much of the Nahiku area (Meyer, in press). This water-table surface mimics topography and slopes toward the coast at about 800 ft/mi (fig. 12). The thickness of the freshwater lens below sea level would be unreasonably large if the depth to the theoretical freshwater-saltwater interface were based on the assumption that the Ghyben-

Herzberg principle was applicable. However, in areas where significant downward movement of ground water exists, the depth to the freshwater-saltwater interface will be shallower than predicted by the Ghyben-Herzberg relation (Izuka and Gingerich, 1998). Meyer (in press, fig. 28) used this finding to estimate the position of the interface on the basis of the water-level information obtained from the test holes penetrating to near sea level. The interface position was estimated to be about 400 ft below sea level near the coast and greater than 1,000 ft below sea level about 2 mi inland.

Between Waiohue Gulch and Keanae Valley, no water-level information is available, but the existence of a vertically extensive freshwater-lens system can be inferred from the presence of continuously gaining streams all the way to the ocean. Although flow measurements are unavailable, visual observations by the author along both East and West Wailuaiki Streams showed streamflow gains from about 1,000 ft altitude downstream to the coast, including the presence of many small springs and seeps a few tens of feet above sea level. Several features along the eastern side of Keanae Valley indicate the presence of the vertically extensive freshwater-lens system. Akeke Spring (Banana Spring in Stearns and Macdonald, 1942) and Plunkett Spring discharge a total of about 4 Mgal/d from the Honomanu Basalt at altitudes of 750 ft and 1,000 ft, respectively (fig. 12), and the water level in a test hole (4910-03; fig. 9) drilled through Hana Volcanics into 30 ft of Honomanu Basalt near Plunkett Spring was reported to be greater than 900 ft altitude. The configuration of the vertically extensive freshwater-lens system near the coast in Keanae Valley is unknown and is probably complicated by the flows of the Hana Volcanics and extensive alluvial deposits, which are found at sea level in this area.

The nature of the transition from a variably saturated system to the west of Keanae Valley to a fully saturated freshwater-lens system east of Keanae Valley is unknown. Because recharge immediately on either side of the valley is similar, the significant difference between the two areas is probably the hydraulic conductivity of the Honomanu Basalt underlying each area. West of Keanae Valley at Honomanu Stream, where the type section for the Honomanu Basalt is located, more typical Honomanu Basalt flows are found at sea level and the hydraulic conductivity of these rocks is proba-

bly higher. No evidence exists to indicate whether the change is gradational from higher conductivity rocks at sea level at Honomanu Stream to low conductivity rocks at sea level at Nahiku, perhaps because of a regional dip of the rock units, or abrupt, perhaps because of a structural feature from the shield stage of East Maui Volcano or an erosional feature associated with Keanae Valley.

East of Makapipi Stream streams are intermittent except at lower altitudes near the coast. These streams are all less incised than streams in the study area. At 600 ft altitude in the study area east of Keanae Valley, stream valleys are incised from 200 to 260 ft below the upland surface. The next ten stream valleys east of the study area are only incised about 20 to 80 ft below the upland surface. Apparently, the stream valleys are not incised deep enough to intercept the water table except at the coast and therefore, do not contain persistent base flow at higher altitudes.

Water chemistry.--Water chemistry data are available for two wells and several springs and streams in and east of Keanae Valley. The chemical characteristics of ground water and surface water that have been measured at most sites are limited to chloride concentration, specific conductance, and temperature. The chloride concentration of water from wells 4806-48 and 5108-01 was 6 mg/L and 16 mg/L, respectively on September 9, 1996 (G.W. Tribble, USGS, written commun., 1998). Both wells are drilled below sea level. The specific conductance of the well water was 966 and 236 $\mu\text{S}/\text{cm}$, respectively, indicating that the chemistry of water from well 4806-48 is unusual. Chloride concentrations from two springs in Keanae Valley were less than 10 mg/L.

The specific-conductance measurements of the water samples from springs and streams ranged between 12 and 234 $\mu\text{S}/\text{cm}$. Water temperatures in or east of Keanae Valley ranged from 15.5°C at Big Spring (787 ft altitude) to 21.4°C in Hanawi Stream (3,550 ft altitude).

BASE FLOW AND HYDROLOGIC BUDGETS FOR INDIVIDUAL STREAM SUBBASINS

The base-flow component of streamflow was estimated using a computerized base-flow separation

method described by Wahl and Wahl (1995). 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 adjacent minimums, 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.

West of Keanae Valley

All of the streamflow-gaging stations operated by the USGS in the study area west of Keanae Valley were at stream sites underlain by the Kula Volcanics. Therefore, all of the base flow measured at each of the sites represents ground-water discharge from the high-elevation saturated zone. No gaging stations in this part of the study area measure discharge from the freshwater lens. Most of the surface-water gaging stations were upstream of the Koolau/Wailoa diversion system at 1,200 ft to 1,300 ft altitude. Data for estimating streamflow and base flow are therefore scarce below about 1,200 ft altitude.

None of the gaged streams west of Keanae Valley have gone dry near 1,200 ft altitude during the period they were gaged. The total average annual streamflow of these gaged streams is about 140 Mgal/d at 1,200 ft to 1,300 ft altitude. It is not possible to estimate the total average annual streamflow at the coast from existing records because of the scarcity of gaging stations and the presence of the diversion systems, which divert nearly all base flow in the area and an unknown percentage of runoff. Perennial streamflow has been measured at altitudes greater than 3,000 ft in several of the streams (Kailua, Waikamoi, and Honomanu Streams) during the entire period each station was operating. Eight stations have recorded periods of no flow during their respective periods of record (table 2). All of these eight sites were at altitudes higher than 2,800 ft (plate 1).

Discharge from the high-elevation saturated zone is persistent even during periods of little rainfall. Although rainfall between the altitudes of 2,000 to 6,000 ft averages almost 1 in/d, periods of days or

weeks occur with less than one inch of total rainfall. During an exceptionally dry period from December 27, 1952 to February 6, 1953 only 1.6 in. of rain fell at Paakea (rain gage 350, fig. 2); no rainfall was recorded 21 out of 42 days (fig. 14). Streamflow records show steady declines in discharge to nearly constant rates toward the end of this dry period, but no gaged streams went dry. This indicates that a significant ground-water source exists upstream of the gaging stations. On February 6, the last day of the driest period, the total flow of the gaged streams west of Keanae Valley was about 6.7 Mgal. All of this flow was measured above about 1,200 ft altitude.

Total average daily ground-water discharge from the high-elevation saturated zone upstream of 1,200 ft altitude and west of Keanae Valley is greater than 38 Mgal/d, all of which is eventually removed from the streams by surface-water diversion systems. This value was estimated by adding the estimated base flow at each gaging station upstream of 1,200 ft to 1,300 ft altitude from Honopou to Honomanu Streams (table 2). Estimates of average annual base flow in gaged subbasins west of Keanae Valley range from about 0.05 to 6.9 Mgal/d with the lowest estimates corresponding to gaging stations at the highest altitudes (table 2). Base flow in five subbasins for which a water budget was estimated averages about 39 percent of the recharge to these same subbasins (Shade, 1999). Therefore, about 60 percent of the recharge follows a deeper flow path and either discharges from the high-elevation saturated zone further downstream or infiltrates to the freshwater lens and discharges at the coast. Not enough streamflow records nor measurements are available to estimate the ground-water discharge rate from the Kula Volcanics at altitudes lower than 1,200 ft. Measurements in 11 streams west of Keanae Valley at 500 ft altitude show gains totaling about 1.9 Mgal/d downstream of 1,200 ft altitude (table 2). Four of the streams were dry at 500 ft altitude.

Honopou Stream

Honopou Stream is headed at about 2,200 ft altitude 5.3 mi inland along the eastern limit of the north rift zone of East Maui Volcano (plate 1). From sea level, the stream gradually rises to 600 ft altitude 1.9 mi from the coast (a gradient of about 320 ft/mi). At this altitude the stream valley is incised 80 ft below the upland surface. Along most of this length, the valley lies on a late

flow of the Kula Volcanics (Stearns and Macdonald, 1942, fig. 11). Currently, streamflow is captured by three of the surface-water diversion systems (table 4).

Honopou Stream has never been dry at any of the four USGS gaging stations between 1,208 ft and 383 ft altitude (table 2, plate 1) although three diversions systems capture base flow in this altitude range. Base-flow estimates from long-term streamflow records indicate that the average annual gains from ground water are 2.3 Mgal/d upstream of 383 ft altitude (station 5950) with 50 percent originating upstream of 1,208 ft altitude (station 5870) (table 2, fig. 15A).

Plots of the estimated base flow at pairs of adjacent stations on the stream show a linear relation (fig. 16). The slope of the line is an indication of the rate the stream is gaining base flow between the two gaging stations and the y-intercept of the regression line represents the amount of base flow at the downstream station when the upstream station is dry. The data points used in these plots were obtained from the daily base-flow estimates that were calculated from the base-flow separation method. About 100 points (less than 2 percent of the data) were filtered out manually because they were results of obvious misfitting of the base-flow curve during high-flow conditions. Because diversion systems intercept all of the base flow between each gaging station, the base flow measured at any one gaging station is added to the total base flow measured at all gaging stations upstream of the gaging station of interest to obtain the total undiverted base flow at that gaging station. Because the regression lines all have slopes greater than 1.0, apparently the stream has a net gain of water between each gaging station, and the gain per unit length of stream increases with decreasing stream altitude.

The scatter of the data points around the regression line shows that the base-flow distribution along the stream on any given day can vary significantly. This indicates that flow measurements made during 1 day along a stream will not provide a complete description of the stream's base-flow characteristics. For example, representative streamflow records showing low base-flow conditions on 2 different days show gains in base flow range 0.4 to 1.0 Mgal/d between the highest and lowest altitude gaging stations (table 6).

In a water budget of the 0.65-mi² area upstream of the highest-altitude gaging station, 5870, Shade (1999) estimated that 5.36 Mgal/d of rainfall and 0.58 Mgal/d

of fog drip are apportioned into 1.93 Mgal/d of runoff, 1.30 Mgal/d of evapotranspiration, and 2.72 Mgal/d of recharge (table 1, fig. 6). The estimated base flow at the gaging station (1.21 Mgal/d) is about 44 percent of the recharge to the subbasin.

Hoolawa Stream

Hoolawa Stream splits into two branches at 550 ft altitude; Hoolawanui Stream to the west, headed at 2,400 ft altitude, and Hoolawaliilii Stream to the east, headed at 1,800 ft altitude (plate 1). The highest stream head is 5.5 mi inland along the eastern limit of the north rift zone of East Maui Volcano. The stream gradually rises from sea level to 600 ft altitude 1.8 mi from the coast (a gradient of 330 ft/mi) and the stream valley is incised 120 ft below the upland surface at this altitude. Similar to Honopou Stream, Hoolawa Stream lies on flows of the Kula Volcanics along most of its length (Stearns and Macdonald, 1942, fig. 11) and streamflow is currently captured by three of the surface-water diversion systems (table 4).

Hoolawa Stream has never been dry at the two gaging stations on branches upstream of the Wailoa Ditch at 1,200 ft altitude (stations 5850 and 5860) (table 2, plate 1). Base-flow estimates indicate that the average annual gains from ground water are 2.68 and 2.34 Mgal/d for the west and east branches, respectively (table 2, fig. 15B). Streamflow measurements made on February 5, 1998 during low-flow conditions show gains in flow of 3.59 Mgal/d along the entire stream length (table 7). On the basis of these measurements, Hoolawa Stream does not appear to have any sections that are losing water. Because the stream flows only on the Kula Volcanics, it gains water continuously from the high-elevation saturated zone all the way to the coast.

In the Hoolawanui Stream water budget (Shade, 1999) of the 1.34-mi² area upstream of gaging station 5850, 12.48 Mgal/d of rainfall and 3.12 Mgal/d of fog drip is apportioned into 5.13 Mgal/d of runoff, 2.39 Mgal/d of evapotranspiration, and 8.09 Mgal/d of recharge (table 1, fig. 6). For Hoolawaliilii Stream, the area upstream of gaging station 5860 is smaller, only 0.57 mi², hence rainfall (5.18 Mgal/d), fog drip (0.45 Mgal/d), runoff (2.52 Mgal/d), evapotranspiration (1.29 Mgal/d), and recharge (1.82 Mgal/d) are smaller. But even though recharge for this subbasin is only about 22 percent of the recharge to Hoolawanui Stream subbasin,

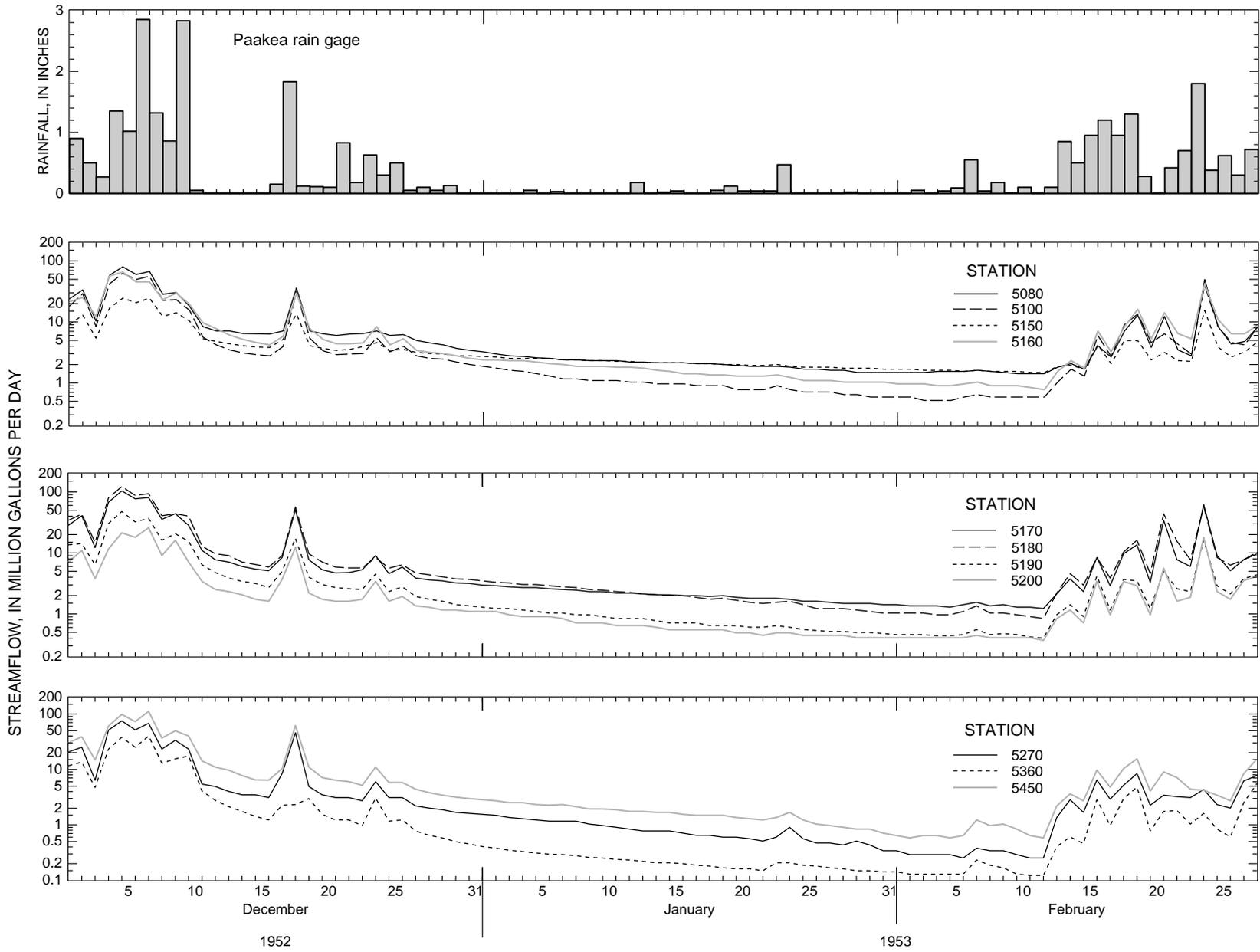


Figure 14. Daily rainfall at Paakea (rain gage 350) and daily streamflow at selected gaging stations, December 1, 1952 to January 27, 1953, northeast Maui, Hawaii.

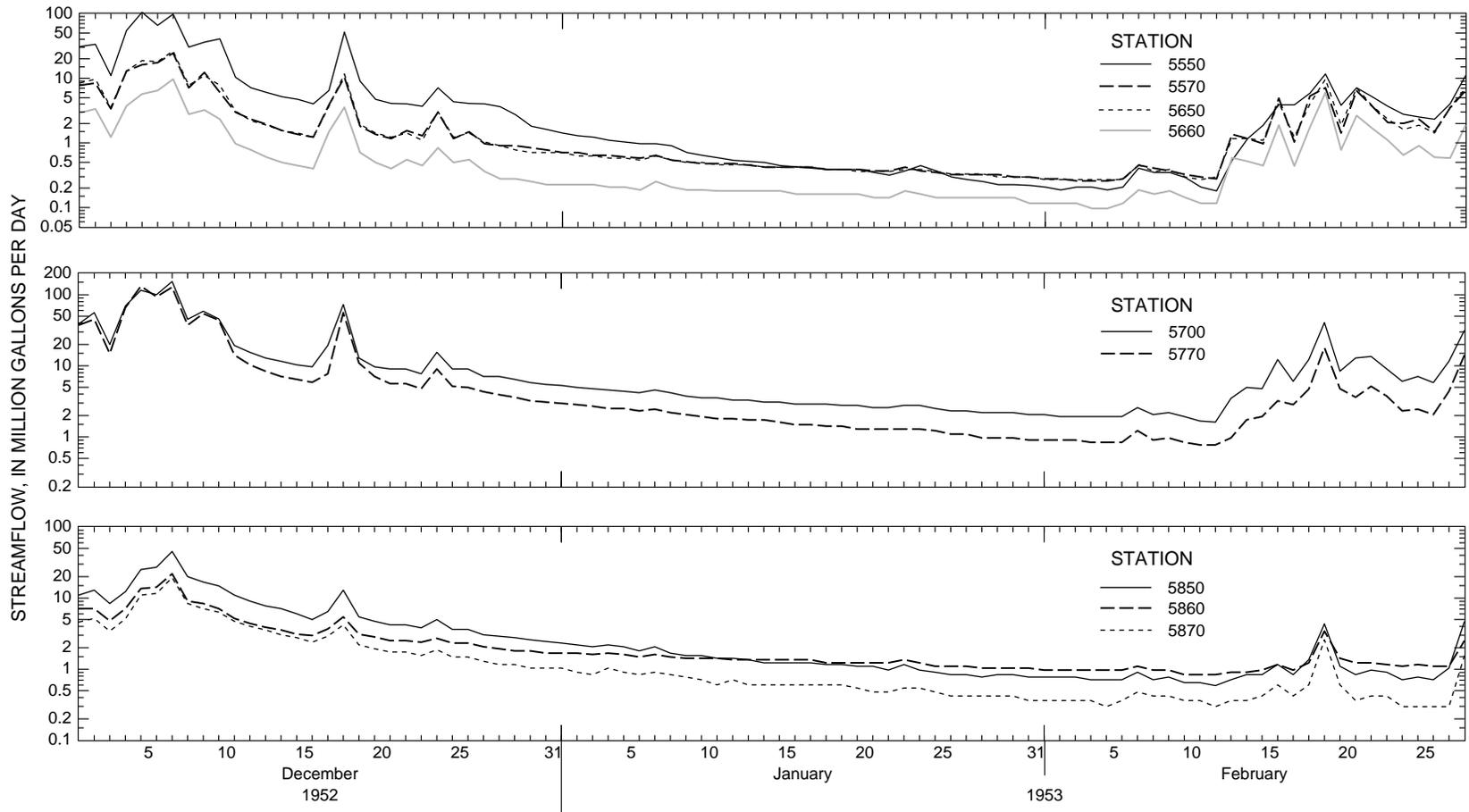
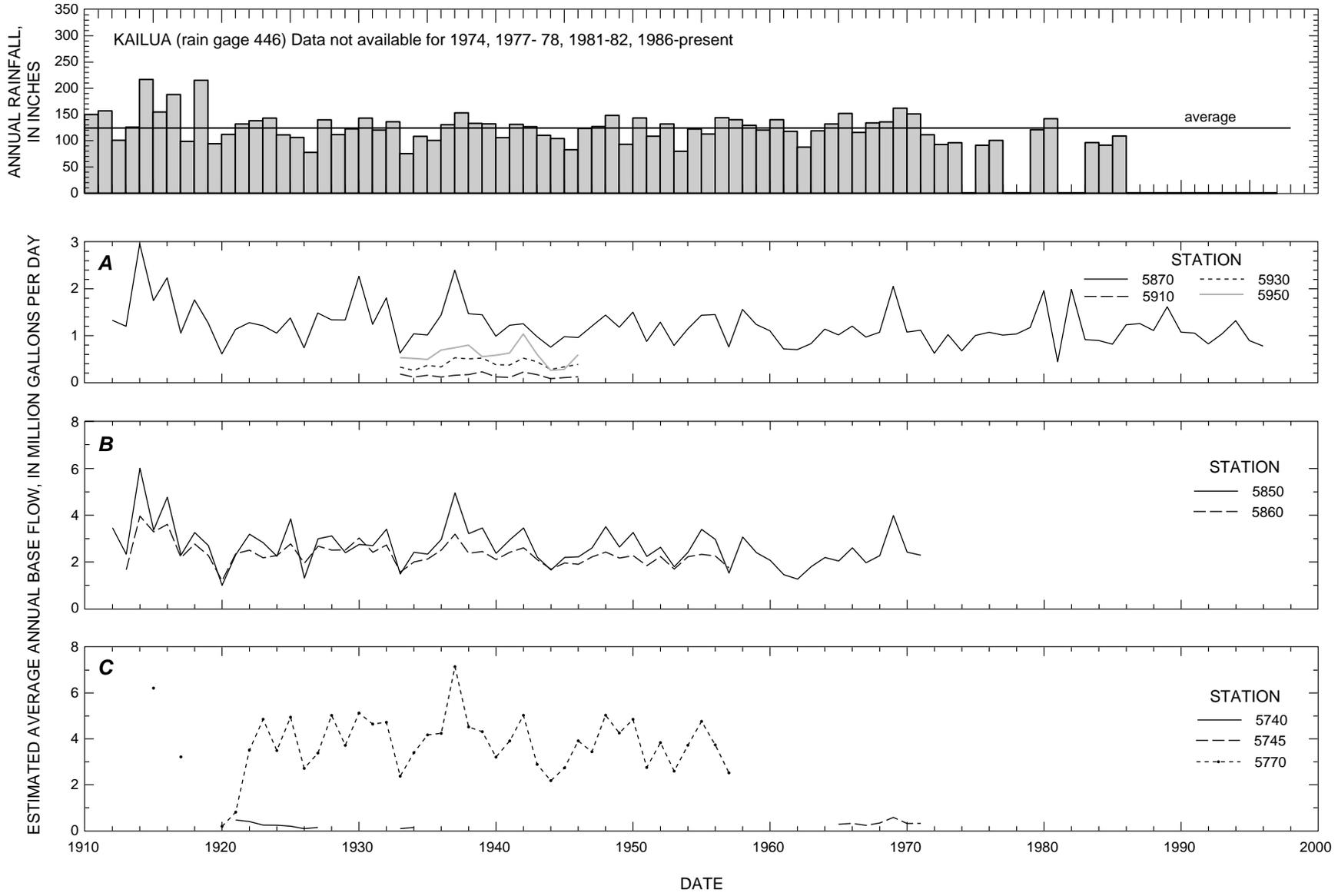


Figure 14. Daily rainfall at Paakea (rain gage 350) and daily streamflow at selected gaging stations, December 1, 1952 to January 27, 1953, northeast Maui, Hawaii -- *Continued.*



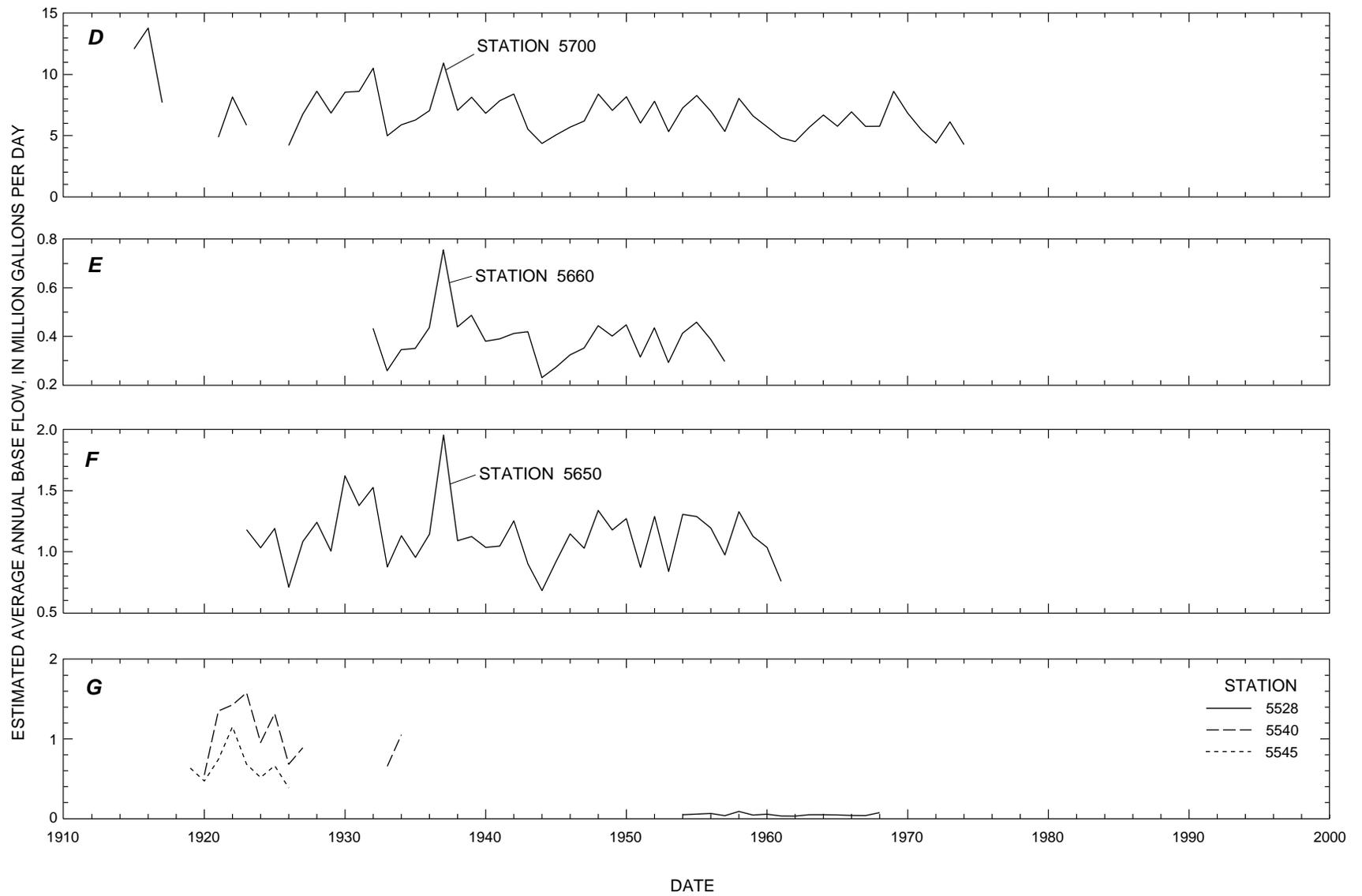
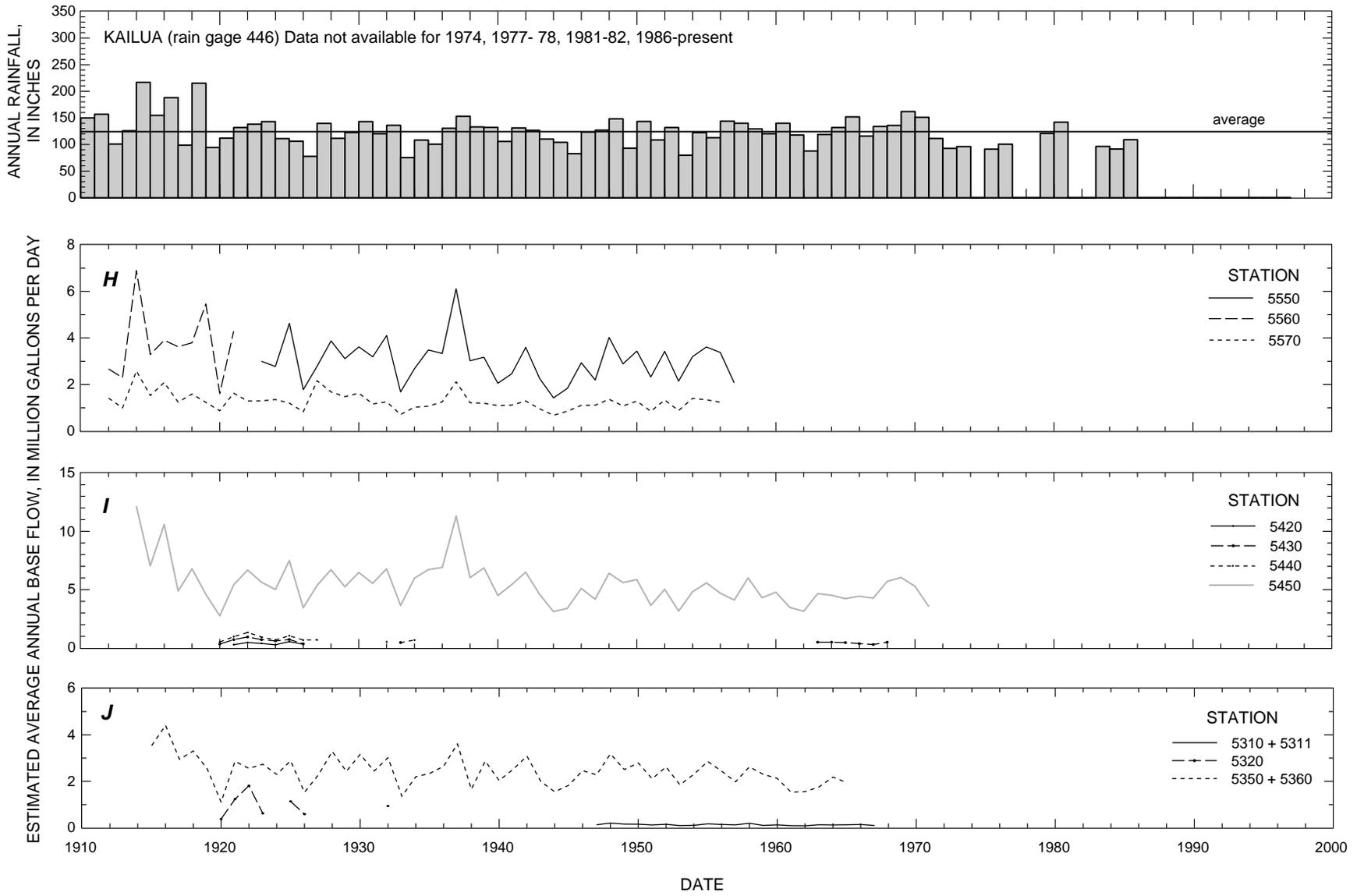


Figure 15. Annual rainfall and estimated average annual baseflow at selected east Maui stream gages, Hawaii.



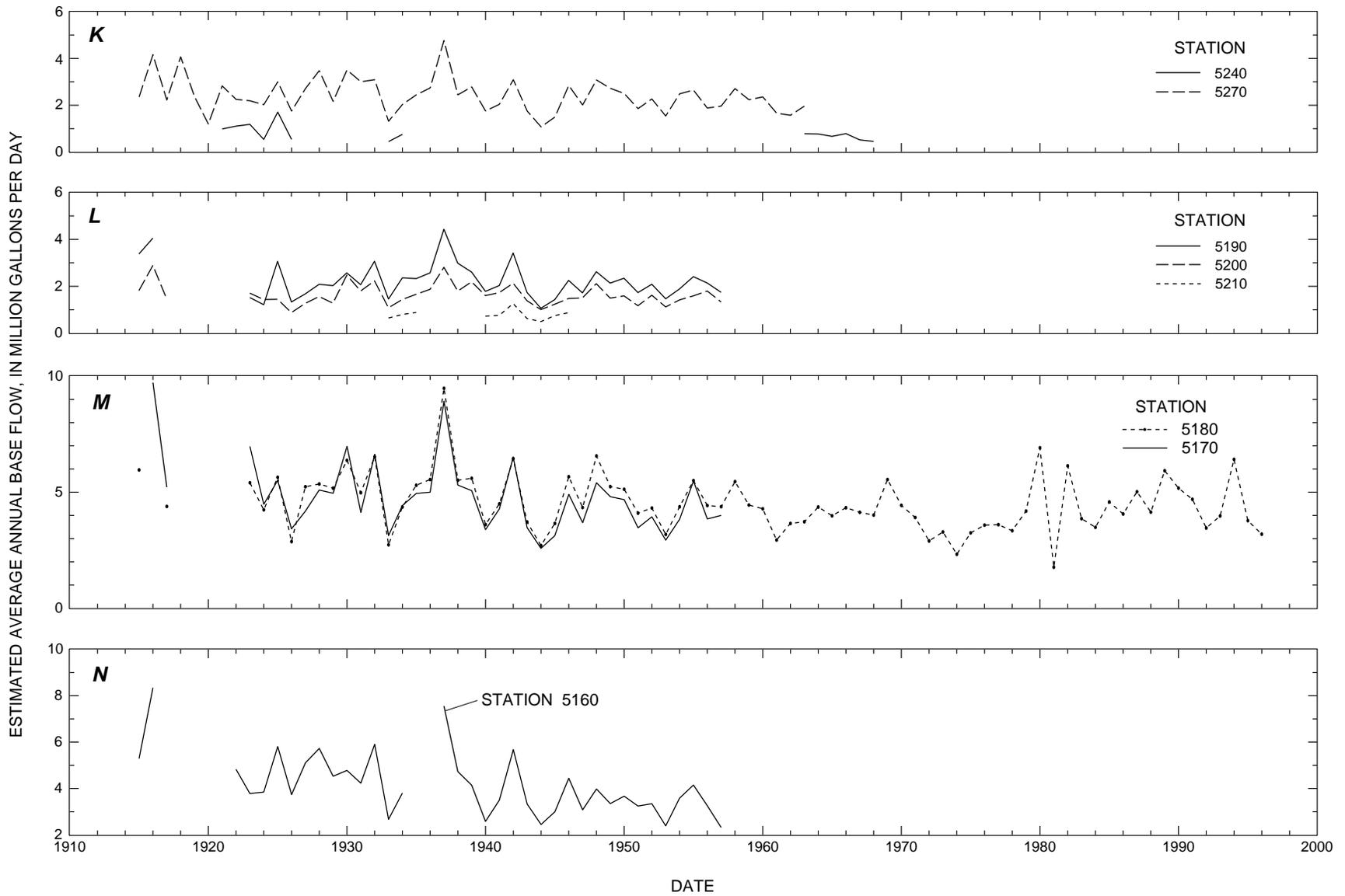
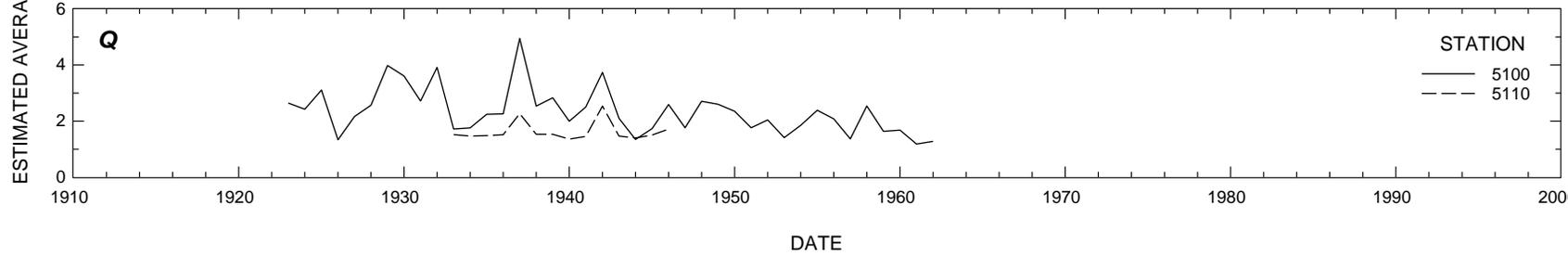
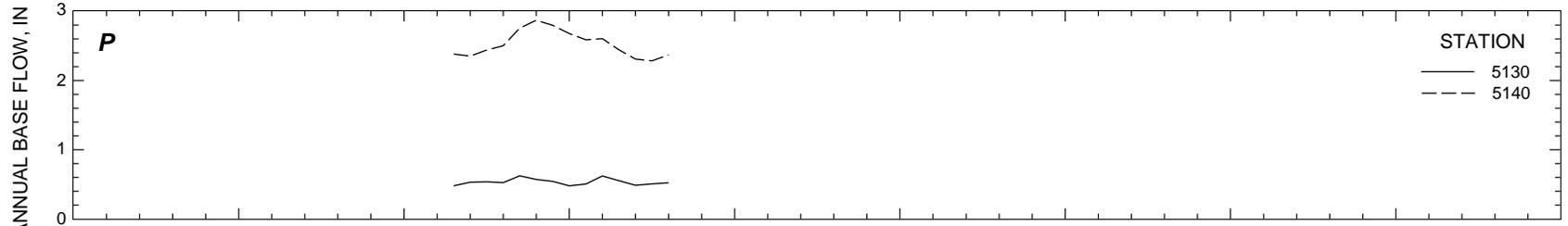
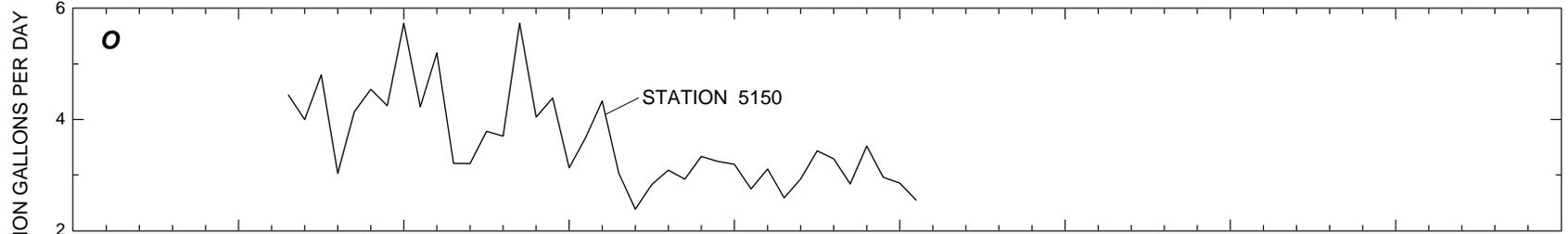
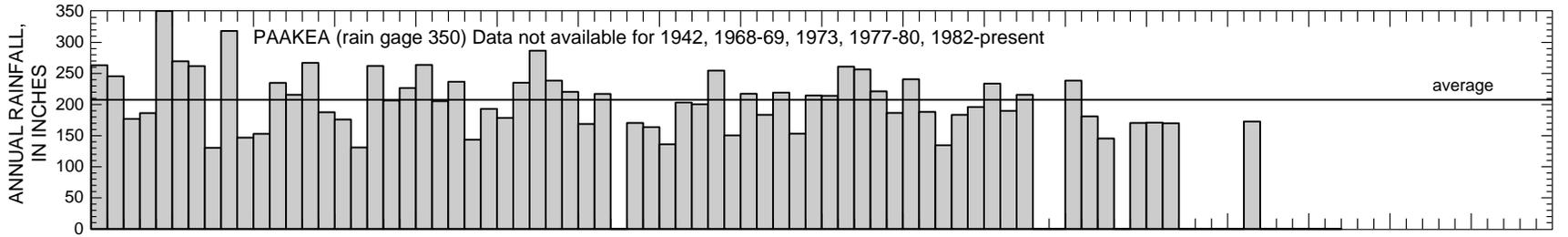


Figure 15. Annual rainfall and estimated average annual base flow at selected east Maui stream gages, Hawaii -- Continued.



1910 1920 1930 1940 1950 1960 1970 1980 1990 2000

DATE

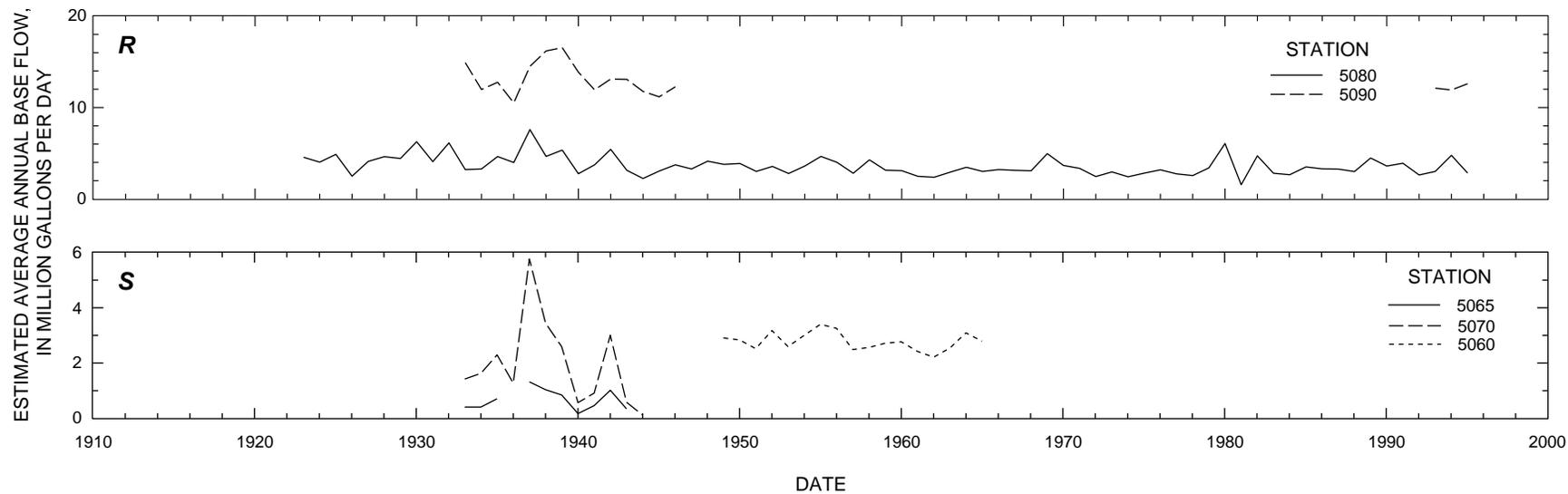


Figure 15. Annual rainfall and estimated average annual base flow at selected east Maui stream gages, Hawaii -- Continued.

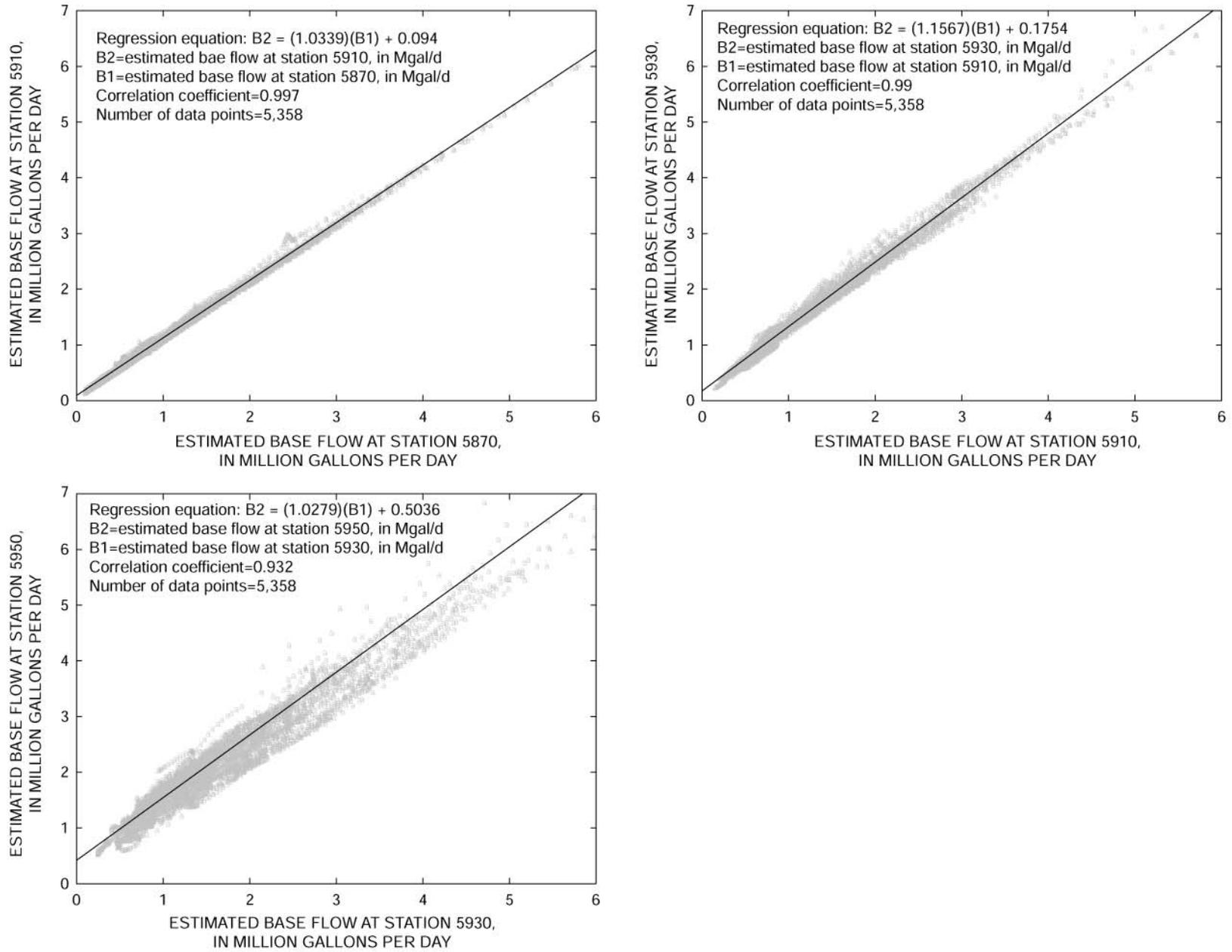


Figure 16. Relation of estimated base flow and linear regression line for gaging stations on Honopou Stream, northeast Maui, Hawaii.

Table 6. Streamflow in Honopou Stream, northeast Maui, Hawaii

[ft, feet; Mgal/d, million gallons per day; 1933 data from Grover and Carson (1936); 1946 data from Paulsen (1950); gaging-station number is preceded by 16 and ends in 00]

Gaging-station number	Stream name	Altitude (ft)	Date	Streamflow (Mgal/d)	Cumulative streamflow without diversion (Mgal/d)	Comments
5950	Honopou	383	10/21/33	0.29	0.54	Daily mean
			7/5/46	0.67	1.42	
5930	Honopou	441	10/21/33	0.10	0.25	Daily mean; upstream of Haiku Ditch diversion
			7/5/46	0.20	0.75	
5910	Honopou	557	10/21/33	0.05	0.15	Daily mean; upstream of Lowrie Ditch diversion
			7/5/46	0.10	0.55	
5870	Honopou	1,208	10/21/33	0.10	0.10	Daily mean; upstream of Wailoa Ditch diversion
			7/5/46	0.45	0.45	

Table 7. Streamflow, temperature, specific conductance, and chloride concentration in Hoolawa Stream, February 5, 1998, northeast Maui, Hawaii

[ft, feet; Mgal/d, million gallons per day; °C, degrees Celsius; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; --, not determined; all altitudes estimated from U.S. Geological Survey topographic map, Haiku quadrangle; gaging-station number is preceded by 16 and ends in 00]

Station number	Stream name	Altitude (ft)	Stream-flow (Mgal/d)	Cumulative streamflow without diversion (Mgal/d)	Water temperature (°C)	Water specific conductance (µS/cm)	Chloride concentration (mg/L)	Comments
Hoolawa 1	Hoolawa	15	0.19	3.59	18.4	161	34	
Hoolawa 2	Hoolawa	315	0.08	3.47	20.9	126	25	
Hoolawa 2a	Hoolawa	420	0.00	--	--	--	--	Diversion takes all flow
Hoolawa 3	Hoolawa	450	0.25	3.39	19.5	97	19	Upstream of Haiku Ditch diversion
Hoolawa 5	Hoolawanui	590	0.07	--	--	--	--	Diversion takes most flow
Hoolawa 6	Hoolawanui	600	0.25	1.49	--	--	16	Upstream of Lowrie Ditch diversion
Hoolawa 7	Hoolawanui	1,080	0.00	--	--	--	--	Diversion takes all flow
Hoolawa 8	Hoolawanui	1,210	1.24	1.24	16.2	54	9	Near gaging station 5850; upstream of Wailoa Ditch diversion
Hoolawa 9	Hoolawaliilii	590	0.03	--	--	--	--	Diversion takes most flow
Hoolawa 10	Hoolawaliilii	620	0.53	1.75	--	--	15	Upstream of Lowrie Ditch diversion
Hoolawa 11	Hoolawaliilii	1,190	0.00	--	--	--	--	Diversion takes all flow
Hoolawa 12	Hoolawaliilii	1,220	1.22	1.22	14.9	55	10	Near gaging station 5860; upstream of Wailoa Ditch diversion
Hoolawa 12.1	unnamed tributary	1,200	0.01	--	--	--	--	

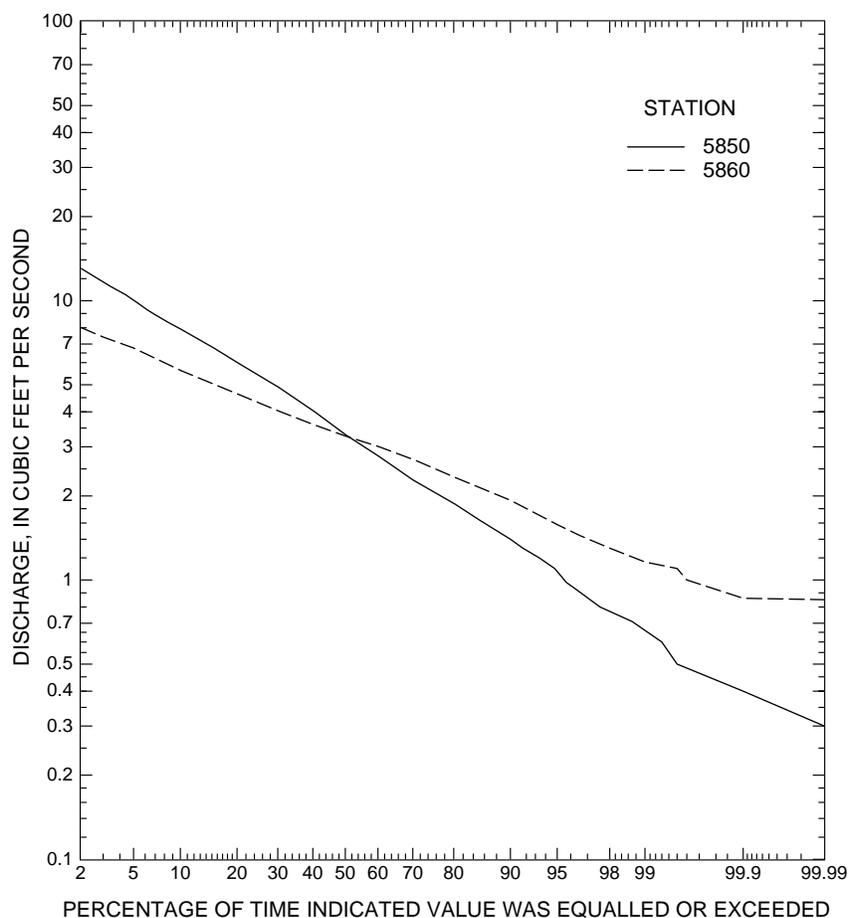


Figure 17. Flow-duration curves showing the percentage of time a given flow was equalled or exceeded at gaging stations 5850 and 5860 on Hoolawa Stream, northeast Maui, Hawaii.

the average annual base flow is 87 percent of the Hoolawanui Stream base flow. The amount of base flow in Hoolawanui Stream is about 33 percent of the estimated recharge to the subbasin while in Hoolawaliilii Stream, the base flow is about 128 percent of the recharge estimated for its subbasin (table 1). This probably indicates that the ground-water divides are significantly different than the topographic divides used in the water-budget estimation and that part of the recharge attributed to the Hoolawanui Stream subbasin actually belongs in the Hoolawaliilii Stream ground-water subbasin. The spatial distribution of the two subbasins also supports this conclusion because much of the Hoolawanui Stream subbasin lies directly upslope of the Hoolawaliilii Stream subbasin (fig. 3). The flow-duration curves of

the base flow at each gaging station show that even though gaging station 5850 measured a higher average annual base flow, base flow at gaging station 5860 is higher about 50 percent of the time (fig. 17) indicating that base flow in Hoolawaliilii Stream is more persistent than in Hoolawanui Stream.

Kailua Stream

Kailua Stream is headed at 4,000 ft altitude 11 mi inland near several cinder cones along the eastern limit of East Maui Volcano's north rift zone (plate 1). The stream rises from sea level to 600 ft altitude 1.4 mi from the coast (a gradient of 420 ft/mi) and at this altitude the stream valley is incised 120 ft below the upland surface.

Table 8. Streamflow in Kailua Stream, November 2, 1932, northeast Maui, Hawaii

[ft, feet; Mgal/d, million gallons per day; all altitudes estimated from U.S. Geological Survey topographic maps, Haiku and Kilohana quadrangles; 1932 flow data from Hofmann (1934) and daily-discharge data from Grover and Carson (1935); gaging-station number is preceded by 16 and ends in 00]

Station number	Stream name	Altitude (ft)	Streamflow (Mgal/d)	Comments
5770	Kailua	1,250	1.70	Daily mean at gaging station; upstream of Wailoa Ditch diversion
5740	Kailua	3,080	0.04	Daily mean at gaging station
Kailua 30	East Branch Kailua Stream	2,420	0.05	
Kailua 40	East Branch Kailua Stream	2,980	0.00	
Kailua 41	East Branch Kailua Stream	3,080	0.03	
5750	Tenth Branch Kailua Stream	3,100	0.03	Daily mean at gaging station
5760	Ninth Branch Kailua Stream	3,080	0.06	Daily mean at gaging station

The stream valley lies on a flow of the Kula Volcanics along much of its length but Honomanu Basalt outcrops at the ocean (Stearns and Macdonald, 1942, fig. 11). Oanui Stream forms a tributary to the west at 1,200 ft altitude. Streamflow is captured by all six surface-water diversion systems but the highest systems probably only capture surface runoff (table 4).

Kailua Stream has never been dry at the five gaging stations upstream of the Wailoa Ditch, which is at 1,200 ft altitude (table 2, plate 1). The average annual gains from ground water are 4.2 Mgal/d between 3,080 ft (station 5745) and 1,253 ft altitude (station 5770) (table 2, fig. 15C). Streamflow measurements made at three sites on November 2, 1932 (Hofmann, 1934) and concurrently at four gaging stations (Grover and Carson, 1935), show gains in flow of 1.6 Mgal/d between 3,080 ft and 1,250 ft altitude during low-flow conditions (table 8). A stream section on the East Branch at about 3,000 ft altitude lost 0.03 Mgal/d of water and went dry, but by 2,420 ft altitude, it had gained all of this water plus 50 percent more back (Hofmann, 1934). This apparent loss is most likely because plastering lavas of the Kula Volcanics have altered the surface of the previous stream channel, allowing water to flow beneath some younger lava flows before reemerging further downstream. No data or observations are available to determine if the stream loses water where it flows over the Honomanu Basalt near the coast.

The area upstream of gaging station 5770 is 2.39 mi² and in the water budget (Shade, 1999), 23.92 Mgal/d of rainfall and 7.22 Mgal/d of fog drip is apportioned into 15.17 Mgal/d of runoff, 3.62 Mgal/d of evapotranspiration, and 12.36 Mgal/d of recharge (table

1, fig. 6). The estimated base flow at the gaging station is about 35 percent of the recharge to the subbasin.

Nailiilihaele Stream

Nailiilihaele Stream is headed near an unnamed cinder cone at 3,400 ft altitude 9 mi inland from the coast (plate 1). The stream rises from sea level at the same gradient (420 ft/mi) as adjacent Kailua Stream; the stream valley is incised to the same depth (120 ft) and is also floored by a flow of the Kula Volcanics (Stearns and Macdonald, 1942, fig. 11). Streamflow is captured by four of the surface-water diversion systems, the highest of which probably captures only surface runoff (table 4).

Of the five gaging stations on Nailiilihaele Stream, only one (station 5700) was a continuous-record station with a long period of record (Fontaine, 1996). Gaging stations 5690 and 5710 have records of less than a year and gaging stations 5691 and 5697 were low-flow partial-record stations where only a few measurements were made. The stream was never dry at 1,205 ft altitude during 1919–75 (station 5700) (table 2, plate 1). Base-flow estimates using this long-term record indicate that the average annual gain from ground water upstream of this gaging station is 6.92 Mgal/d (table 2, fig. 15D). Most of this gain is likely made downstream of 2,820 ft altitude because gaging station 5691 measured periods of no flow at that altitude. Representative streamflow records from 2 days when the three gaging stations were operating concurrently show that base flow is variable and total gains in flow ranged from 2.48 to 11.25 Mgal/d during base-flow conditions (U.S. Geological Survey, 1967, and 1969) (table 9).

Table 9. Streamflow in Nailiilihaele Stream, northeast Maui, Hawaii

[ft, feet; Mgal/d, million gallons per day; --, not determined; 1966 data from U.S. Geological Survey (1967); 1967 data from U.S. Geological Survey (1969); gaging-station number is preceded by 16 and ends in 00]

Gaging-station number	Stream name	Altitude (ft)	Date	Streamflow (Mgal/d)	Cumulative streamflow without diversion (Mgal/d)	Comments
5700	Nailiilihaele	1,205	11/28/66 10/4/67	10.99 2.46	11.25 2.48	Daily mean; upstream of Wailoa Ditch diversion
5691	Nailiilihaele	2,820	11/28/66 10/4/67	0.03 0.00	-- --	Instantaneous measurement; downstream of Lower Kula Pipeline diversion
5697	West Branch Nailiilihaele	2,860	11/28/66 10/4/67	0.26 0.03	0.26 0.03	Instantaneous measurement; upstream of Lower Kula Pipeline diversion

In a water budget of the 3.61 mi² area upstream of gaging station 5700, Shade (1999) estimated that 34.79 Mgal/d of rainfall and 8.81 Mgal/d of fog drip is apportioned into 17.46 Mgal/d of runoff, 6.30 Mgal/d of evapotranspiration, and 19.84 Mgal/d of recharge (table 1, fig. 6). The estimated base flow at the gaging station is about 37 percent of the recharge estimated for the subbasin.

Oopuola Stream

Oopuola Stream is headed at 1,900 ft altitude 4 mi inland from the coast (plate 1). This stream rises from sea level to 600 ft altitude 1.2 mi from the coast (a gradient of 490 ft/mi) and the stream valley is incised 200 ft below the upland surface at this altitude. For 2,000 ft inland, the stream valley has eroded into the Honomanu Basalt, upstream it lies on lava flows of the Kula Volcanics (Stearns and Macdonald, 1942, fig. 11). Streamflow is captured by two of the surface-water diversion systems (table 4).

During 1930–57, gaging station 5660 was operated at 1,205 ft altitude and Oopuola Stream was never dry (table 2, plate 1). The estimated average annual base flow at this gaging station is 0.39 Mgal/d (table 2, fig. 15E). Gaging station 5670 was operated during 1910–15 at 960 ft altitude (Grover and Larrison, 1917) but upstream, the New Hamakua Ditch diverted only part of the streamflow so it is impossible to estimate what percentage of the recorded flow originated downstream of the diversion point. This stream was observed to be dry in March 1928 by EMI personnel at about 500 ft altitude during a period of low flow (table 10). On May 5, 1998, the author observed a small flow of water over a 50-ft

Table 10. Streamflow in selected streams, March 16–20, 1928, northeast Maui, Hawaii

[ft³/s, cubic feet per second; Mgal/d, million gallons per day; all data from unpublished notes in files at U.S. Geological Survey, Honolulu, Hawaii of H.T. Stearns, January 8, 1942 referencing earlier measurements made by East Maui Irrigation Co. Inc.; all measurements were made at about 500 ft altitude]

Site name (plate 1)	Stream name	Streamflow (ft ³ /s)	Streamflow (Mgal/d)
E1	Pa Stream	0.31	0.2
E2	Oopuola Stream	0.00	0.0
E3	Kaaiea Stream	0.15	0.1
E4	Kolea Stream	0.16	0.1
E5	Waikamoi Stream	0.31	0.2
E6	Wahinepee Stream	0.46	0.3
E7	Puohokamoa Stream	0.16	0.1
E8	Haipuaena Stream	0.00	0.0
E9	Punalau Stream	0.00	0.0
E10	Honomanu Stream	0.00	0.0
E11	Nuaailua Stream	0.31	0.2
E12	Piinaau Stream	0.47	0.3
E13	Waiokamilo Stream	3.7	2.4
E14	Wailuanui Stream	0.31	0.2
E15	West Wailuaiki Stream	0.78	0.5
E16	East Wailuaiki Stream	0.31	0.2
E17	Kopiliula Stream	0.00	0.0
E18	Puakaa Stream	0.62	0.4
E19	Waiohue Stream	0.62	0.4
E20	Paakea Stream	2.8	1.8
E21	Waiaka Stream	0.62	0.4
E22	Kapaula Stream	2.3	1.5
E23	Hanawi Stream	20.5	13.2

high waterfall 2,000 ft upstream from the coast at 40 ft altitude. This flow seeped into the streambed within a few hundred feet downstream of the waterfall and the stream was dry at the coast. The waterfall seemed to be formed by a thick lava flow thought to be part of the Kula Volcanics and the stream went dry on thin-bedded lava flows thought to be the Honomanu Basalt. A water budget was not calculated for this stream subbasin.

Kaaiea Stream

Kaaiea Stream is headed near 3,000 ft altitude between Nailiilihaele and Waikamoi Streams (plate 1). The stream rises from sea level at a steep gradient to 600 ft altitude 0.6 mi from the coast (a gradient of 1,000 ft/mi) and the stream valley is incised 200 ft below the upland surface. The valley lies on the Honomanu Basalt for 1,000 ft from the coast and the Kula Volcanics from there to the headwaters (Stearns and Macdonald, 1942). Streamflow is captured by three of the surface-water diversion systems (table 4).

Kaaiea Stream was never dry during 1921–62 at gaging station 5650 at 1,310 ft altitude (table 2, plate 1). Base-flow estimates from long-term streamflow records indicate that the average annual gains from ground water are about 1.13 Mgal/d upstream of this altitude (table 2, fig. 15F). A measurement made by EMI personnel during a period of low flow at 500 ft altitude showed a streamflow of 0.1 Mgal/d (table 10). All of this water was gained downstream of the lowest diversion system at 700 ft altitude. No water budget was calculated for this stream subbasin.

Waikamoi Stream

Waikamoi Stream is one of the longer streams in the study area. The stream is 8.5 mi long from the ocean to the head of several tributaries near Hosmer Grove Spring at 6,560 ft altitude (plate 1). Alo Stream, a major tributary, branches to the east at about 840 ft altitude. Waikamoi Stream rises from sea level to 600 ft altitude 0.8 mi from the coast (a gradient of 790 ft/mi) and at this altitude the stream valley is incised 280 ft below the upland surface. Waikamoi Stream lies on Honomanu Basalt for 3,000 ft from the coast and then on Kula Volcanics to the stream head where cinder cones of the volcano's north rift zone are located (Stearns and Macdonald, 1942). Streamflow is captured by five surface-water diversion systems (table 4).

Waikamoi Stream has not gone dry at any of the gaging stations downstream of 3,000 ft altitude during the periods of record despite the presence of Upper and Lower Kula diversion systems (table 2, plate 1). The stream has gone dry upstream of these diversion systems at gaging stations 5530 (4,250 ft altitude), 5528 (4,487 ft altitude), and 5526 (5,750 ft altitude). Base flow at 3,000 ft altitude in the two stream branches above gaging stations 5540 and 5545 is 1.7 Mgal/d and increases to 3.02 Mgal/d at 1,300 ft altitude (station 5550), a gain of 1.3 Mgal/d (table 2, fig. 15G–H). Alo Stream, headed at about 2,400 ft altitude, also gains an average of about 1.3 Mgal/d upstream of 1,248 ft altitude (station 5570), but along a shorter stream distance (plate 1).

Streamflow measurements made on October 18 and 24, 1994 during low-flow conditions show gains in flow of 1.68 Mgal/d between 3,160 ft and 490 ft altitude (table 11). The cumulative streamflow data were obtained by converting the October 24 measurements to equivalent October 18 measurements using a ratio of flow measurements made at site Waikamoi 33 on both days. Measurements were not made downstream of 490 ft altitude because the terrain prevented access. On the basis of the streamflow measurements, Waikamoi Stream (1) appears to be perennial upstream of 500 ft altitude and at the least downstream of 3,000 ft altitude, and possibly as high as 4,200 ft altitude and (2) does not have any measured sections that are losing water. No measurements were made where the stream flows on the Honomanu Basalt.

In the Waikamoi Stream water budget (Shade, 1999) of the 2.46-mi² area upstream of gaging station 5280, 9.19 Mgal/d of rainfall and 1.18 Mgal/d of fog drip is apportioned into 1.29 Mgal/d of runoff, 3.22 Mgal/d of evapotranspiration, and 5.87 Mgal/d of recharge (table 1, fig. 6). Because the gaged subbasin lies at higher altitudes with less precipitation than the rest of the subbasins included in Shade's study (fig. 3), it has a smaller ratio of precipitation to the stream subbasin area (fig. 6). Hence, the water-budget components are all proportionately smaller. The amount of base flow estimated from the streamflow record is only about 1 percent of the recharge to the subbasin (table 1). Most of the recharge is apparently following deeper ground-water flow paths and discharging downgradient of this gaging station.

Table 11. Streamflow, temperature, and specific conductance in Waikamoi Stream, northeast Maui, Hawaii

[ft, feet; Mgal/d, million gallons per day; °C, degrees Celsius; μS/cm, microsiemens per centimeter; --, not determined; all altitudes estimated from U.S. Geological Survey topographic maps, Haiku, Keanae, and Kilohana quadrangles; measured flow from October 24 was scaled by 0.828 to make flow equivalent to October 18 flow for cumulative flow calculation; 1931 flow data is from Hofmann (1934); all other data is unpublished in files of U.S. Geological Survey, Hawaii District office]

Station number	Stream name	Altitude (ft)	Date	Streamflow (Mgal/d)	Cumulative streamflow without diversion, October 18, 1994 (Mgal/d)	Water temperature (°C)	Water specific conductance (μS/cm)	Comments
Waikamoi 7a	Waikamoi	490	10/18/94	0.14	1.68	22.0	108	
Waikamoi 8	unnamed tributary	500	10/18/94	--	--	21.9	87	Tributary from spring on east bank
Waikamoi 8a	Waikamoi	510	10/18/94	0.11	1.65	21.9	153	
Waikamoi 9	Waikamoi	515	9/10/95	--	--	21.9	153	Waikamoi Spring at 515 ft, on west bank at highway
Waikamoi 9a	Waikamoi	520	10/18/94	--	--	21.2	119	Waikamoi Spring at 520 ft, on east bank
			9/10/95	--	--	22.8	119	
Waikamoi 10	Waikamoi	530	10/18/94	0.02	1.56	23.0	84	
Waikamoi 11	Waikamoi	680	10/18/94	0.01	1.54	22.2	74	Most flow diverted
Waikamoi 14	Waikamoi	720	10/18/94	0.37	1.54	22.4	80	Upstream of Manuel Luis Ditch diversion
Waikamoi 15	Waikamoi	760	10/18/94	0.32	1.50	22.8	78	
Waikamoi 16	Waikamoi	820	10/18/94	0.36	1.53	23.3	75	Downstream of confluence with Alo Stream
Waikamoi 17	Waikamoi	860	10/18/94	0.15	1.32	23.2	81	Upstream of confluence with Alo Stream
Waikamoi 29a	Alo	1,210	10/24/94	0.69	--	20.3	42	Upstream of Wailoa Ditch diversion
Waikamoi 32	Waikamoi	1,190	10/18/94	0.01	1.19	--	--	
Waikamoi 33	Waikamoi	1,250	10/18/94	0.53	1.19	21.8	42	Upstream of Wailoa Ditch diversion
			10/24/94	0.64	--	20.2	40	
Waikamoi 40	Waikamoi	1,780	10/24/94	0.55	1.11	20.6	37	
Waikamoi 45	Waikamoi	2,360	10/24/94	0.33	0.93	19.4	36	Downstream of confluence with East Branch Waikamoi
Waikamoi 45a	Waikamoi (east branch)	2,420	10/20/31	0.34	--	--	--	
Waikamoi 45b	Waikamoi (east branch)	2,560	10/20/31	0.20	--	--	--	
Waikamoi 46	Waikamoi	2,375	10/24/94	0.19	0.82	18.0	36	Upstream of East Branch Waikamoi
Waikamoi 55a	flume inflow	3,135	10/18/94	0.13	--	18.5	18	
Waikamoi 56	Waikamoi	3,160	10/18/94	0.72	0.72	19.0	38	Upstream of flume inflow
Waikamoi 60	Waikamoi	4,270	10/18/94	0.00	0.00	--	--	Downstream of Upper Kula Pipeline diversion dam
Waikamoi 65	Waikamoi	4,500	10/18/94	0.02	0.02	16.0	16	
Waikamoi 72	Waikamoi	6,290	10/17/94	0.00	0.00	--	--	
Waikamoi 73	Waikamoi (west branch)	6,400	10/17/94	0.00	0.00	--	--	

^a Estimated flow

Table 12. Streamflow in Puohokamoa Stream, northeast Maui, Hawaii

[ft, feet; Mgal/d, million gallons per day; all altitudes estimated from U.S. Geological Survey topographic maps, Haiku, Keanae, Kilohana, and Nahiku quadrangles; 1920 flow data from Hofmann; written commun. to Foss, 11/17/32, in U.S. Geological Survey Hawaii District files and daily-discharge data from Grover and Stewart (1924); 1932 and 1933 flow data from Hofmann (1934) and daily-discharge data from Grover and Carson (1935); all 1962 data from U.S. Geological Survey (undated[a]); 1963 daily-discharge data from U.S. Geological Survey (undated[b]); gaging-station number is preceded by 16 and ends in 00]

Station number	Stream name	Altitude (ft)	Date	Streamflow (Mgal/d)	Comments
5450	Puohokamoa	1,322	1920	1.60	Daily mean at gaging station; upstream of Spreckels Ditch diversion
			2/3/20	1.60	
			10/29/32	1.20	
			10/30/32	1.70	
			6/12/33	2.60	
			4/10/62	3.62	
			4/11/63	2.59	
Puohokamoa 11	Puohokamoa	1,500	1920	1.53	
Puohokamoa 12	Puohokamoa	1,650	1920	1.49	
Puohokamoa 13	Puohokamoa	1,900	1920	1.20	
Puohokamoa 14	Puohokamoa	2,050	1920	0.96	
5440	West Branch Puohokamoa	2,800	1920	1.53	Daily mean at gaging station
			10/30/32	0.40	
			4/11/63	0.36	
			4/10/62	0.21	
Puohokamoa 21	West Branch Puohokamoa	2,850	4/10/62	0.28	
5430	Middle Branch Puohokamoa	2,400	6/12/33	0.26	Daily mean at gaging station
			2/3/20	0.20	
5430	Middle Branch Puohokamoa	2,900	6/12/33	0.31	Daily mean at gaging station
			4/10/62	0.32	
			4/11/63	0.15	
			4/10/62	0.28	
Puohokamoa 31	Middle Branch Puohokamoa	3,080	4/10/62	0.28	
Puohokamoa 32	Middle Branch Puohokamoa	3,200	4/10/62	0.14	
5420	East Branch Puohokamoa	2,460	10/29/32	0.25	Daily mean at gaging station
			2/3/20	0.05	
			10/29/32	0.14	
			4/11/63	0.13	

Puohokamoa Stream

Puohokamoa Stream splits into three main branches at 2,100 ft altitude; the longest is the middle branch that is headed at 4,400 ft altitude 6.4 mi inland (plate 1). The stream rises steeply from sea level to 600 ft altitude 0.6 mi from the coast (a gradient of 930 ft/mi) and at this altitude the stream valley is incised 200 ft below the upland surface. With the exception of 3,000 ft of Honomanu Basalt at the coast, this stream lies on lava flows of the Kula Volcanics along most of its length (Stearns and Macdonald, 1942). Streamflow is captured by five of the surface-water diversion systems (table 4).

Puohokamoa Stream was never dry during 1913–71 at gaging station 5450 at 1,322 ft altitude (table 2, plate 1). At the gaging stations at about 2,800 ft altitude

on the three stream branches, streamflow was perennial in the west (station 5440) and middle (station 5430) branches but went dry in the shorter east (station 5420) branch during 1919–27 when the gaging stations were operated concurrently. Base-flow estimates from long-term streamflow records indicate that the average annual gains from ground water are about 5.46 Mgal/d upstream of 1,322 ft altitude, 2.8 Mgal/d of this flow is gained downstream of 2,800 ft altitude (table 2, fig. 15I).

Several sets of streamflow measurements in sections of the stream branches also show continuous streamflow gains upstream of 1,300 ft altitude (table 12). Measurements were made some time in the 1920's between 2,050 and 1,300 ft altitude that show a gain of about 0.6 Mgal/d (written commun. from J.H. Hofmann

to J.H. Foss, November 17, 1932 in USGS Hawaii District files). Streamflow data from February 3, 1920 confirm this pattern (table 12). Measurements were also made on October 29–30, 1932 and June 12, 1933 between 2,900 ft and 2,400 ft altitude during base-flow conditions that show gains of about 0.1 Mgal/d in the east and west branches and a slight loss of about 0.05 Mgal/d in the middle branch (Hofmann, 1934). The latter measurement represents only a 15 percent difference between the upstream and downstream measurements; therefore, this value is probably about the same magnitude as the measurement error inherent in the method used in that particular study. Four measurements were made on April 10, 1962, three on the middle branch between 3,200 ft and 2,900 ft altitude and one on the west branch at 2,850 ft altitude (U.S. Geological Survey, undated [a]). These measurements show a gain of about 0.2 Mgal/d in the middle branch. A measurement made in March 1928 by EMI shows a gain of about 0.1 Mgal/d between 900 ft and 500 ft altitude (table 10). No measurements were made where the stream flows over the Honomanu Basalt. No water budget was calculated for the Puohokamo Stream subbasin.

Haipuaena Stream

Haipuaena Stream is headed near 5,200 ft altitude between Waikamoi and Honomanu Streams, 6.5 mi from the coast (plate 1). The Haipuaena Stream valley is similar in gradient and incision to adjacent Puohokamo Stream valley at 600 ft altitude but is steeper at the coast. The contact between the Honomanu Basalt and the overlying Kula Volcanics is within 1,000 ft of the shore, which accounts for the steep gradient of Haipuaena Stream near the coast (Stearns and Macdonald, 1942). Streamflow is captured by five of the surface-water diversion systems (table 4). In addition, water was diverted at 1,880 ft altitude into Kolea Stream to the east from 1938 to 1960 to generate electricity.

Seven gaging stations were operated on Haipuaena Stream and two of the diversion ditches (Fontaine, 1996) (table 2, plate 1). At the Upper Kula Pipeline near 4,300 ft altitude, gaging station 5310 recorded the diverted flow and gaging station 5311 recorded streamflow past the diversion. These two records were added together to obtain the total flow at this altitude (0.97 Mgal/d) and the estimated average annual base flow (0.14 Mgal/d) for 1947–67 (fig. 15J). Three gaging sta-

tions measured flow for less than a year on three stream branches at about 2,900 ft altitude. Streamflow diverted into Kolea Stream was measured at gaging station 5350. This record was added to the streamflow record from gaging station 5360 (1,512 ft altitude) upstream of Spreckels Ditch to obtain a record of the total streamflow (table 2) and a base-flow estimate at this altitude (fig. 15J). The base-flow estimates indicate that the average annual gains from ground water are 2.5 Mgal/d between 4,300 ft and 1,500 ft altitude.

Streamflow measurements were also made on two occasions along several stream sections (table 13, plate 1). Measurements were made some time in the 1920's between 2,860 and 1,510 ft altitude that show continuous gains totaling about 0.9 Mgal/d (written commun. from J.H. Hofmann to J.H. Foss, November 17, 1932 in USGS Hawaii District files). Streamflow data from gaging stations 5360 and 5320 on two dates in 1962 and 1965 confirm this pattern (table 13). Measurements were also made on October 13, 1932 between 2,860 ft and 2,500 ft altitude during low base-flow conditions (table 13). These measurements, along with concurrent records from gaging stations, show a gain of about 0.1 Mgal/d in this short reach of the main branch of Haipuaena Stream (Hofmann, 1934). Overall, Haipuaena Stream appears to gain water continuously upstream of 1,500 ft altitude from at least as high as 4,300 ft altitude. EMI records from March 1928 show that the stream was dry at about 500 ft altitude indicating no gain in flow downstream of the lowest diversion system at about 900 ft altitude (table 10). A water budget was not estimated for this subbasin.

Honomanu Stream

Honomanu Stream is one of the longest streams in the study area (8.7 mi) and headed at one of the highest altitudes (7,800 ft) (plate 1). The stream also has the most deeply incised valley in the study area (excluding Keanae Valley), nearly 1,000 ft below the upland surface at 600 ft altitude. Accordingly, the stream gradient near the coast is low compared with adjacent streams, about 470 ft/mi. Honomanu Basalt is well exposed along the valley walls and floor for 2.5 mi from the coast but upstream of this point (1,600 ft altitude) only Kula Volcanics are present (Stearns and Macdonald, 1942). Unconsolidated alluvial deposits are found as far as 3,000 to 4,000 ft upstream from the coast. Stream-

Table 13. Streamflow in Haipuaena Stream, northeast Maui, Hawaii

[ft, feet; Mgal/d, million gallons per day; all altitudes estimated from U.S. Geological Survey topographic maps, Keanae, Kilohana, and Nahiku quadrangles; 1920 flow data from Hofmann; written commun. to Foss, 11/17/32, in U.S. Geological Survey Hawaii District files; 1932 flow data from Hofmann (1934) and daily-discharge data from Grover and Carson (1935); 1963 daily-discharge data from U.S. Geological Survey (undated[b]); 1965 daily-discharge data from U.S. Geological Survey (1967); gaging-station number is preceded by 16 and ends in 00]

Station number	Stream name	Altitude (ft)	Date	Streamflow (Mgal/d)	Comments
5360	Haipuaena	1,512	1920	1.10 ^a	Daily mean at gaging station; upstream of Spreckels Ditch diversion
			10/13/32	0.70	
			10/18/62	1.00	
			1/12/65	1.00	
Haipuaena 20	Haipuaena	1,750	1920	0.83 ^a	
Haipuaena 30	Haipuaena	1,850	1920	0.97 ^a	
Haipuaena 40	Haipuaena	1,950	1920	0.61 ^a	
Haipuaena 41	Third Branch Haipuaena	2,000	1920	0.11 ^a	
Haipuaena 42	Haipuaena	2,000	1920	0.50 ^a	
Haipuaena 50	Haipuaena	2,500	1920	0.36 ^a	
			10/13/32	0.39	
Haipuaena 51	Haipuaena	2,580	10/13/32	0.35	
Haipuaena 52	Haipuaena	2,680	10/13/32	0.30	
Haipuaena 53	Haipuaena	2,800	10/13/32	0.29	
5320	Haipuaena	2,860	1920	0.20 ^a	Daily mean at gaging station; upstream of Lower Kula Pipeline diversion
			10/13/32	0.26	
			10/18/62	0.23	
			1/12/65	0.24	
5340	First Branch Haipuaena	3,000	10/13/32	0.01	Daily mean at gaging station
5330	Third Branch Haipuaena	2,950	10/13/32	0.10	Daily mean at gaging station
5310; 5311	Haipuaena	4,320	10/18/62	0.03	Combined flow at gaging stations; at Upper Kula Pipeline diversion
			1/12/65	0.07	

^a Instantaneous measurement

flow is captured by three of the surface-water diversion systems (table 4).

Honomanu Stream has never been dry at gaging station 5270 immediately upstream of the Spreckels Ditch at 1,733 ft altitude nor at gaging stations 5240, 5260, and 5250 at 2,900 ft altitude on three stream branches (table 2, plate 1). Base-flow estimates from the two long-term streamflow records on the main branch indicate that the average annual gains from ground water are about 0.6 Mgal/d between gaging station 5240 at 2,900 ft altitude and gaging station 5270 at 1,733 ft altitude (table 2, fig. 15K). Independent sets of streamflow measurements were made three times (table 14). Measurements were made some time in the 1920's between 3,030 ft and 1,733 ft altitude that show a gain of about 1.6 Mgal/d (written commun. from J.H. Hofmann to J.H. Foss, November 17, 1932 in USGS Hawaii District files). Streamflow data from August 19, 1920 confirm this pattern (table 14). A set of measurements

along a 3,000-ft section between 2,900 ft and 2,500 ft altitude on October 7, 1932 shows gains of about 0.10 Mgal/d (Hofmann, 1934). As part of this study, streamflow measurements were made on June 20, 1995 between 3,050 ft altitude and the coast. These measurements show a total gain of about 1 Mgal/d upstream of 1,733 ft altitude and a minor gain downstream to about 360 ft altitude. EMI records indicate that the stream was dry in March 1928 at about 500 ft altitude (table 10). Because several waterfalls make access to the stream at 500 ft altitude difficult, this measurement was likely made at the base of the falls near 360 ft altitude. Downstream of 360 ft altitude (Honomanu 10a, plate 1, at the base of a large waterfall), base flow decreased and the stream was dry between 90 ft and 2 ft altitude. During low-flow conditions no total gain downstream of about 1,733 ft altitude probably exists until close to sea level. Near sea level, about 1.4 Mgal/d of flow issues from several springs in the Honomanu Basalt. These springs

Table 14. Streamflow, temperature, and specific conductance in Honomanu Stream, northeast Maui, Hawaii

[ft, feet; Mgal/d, million gallons per day; °C, degrees Celsius; µS/cm, microsiemens per centimeter; --, not determined; altitudes estimated from U.S. Geological Survey topographic maps, Keanae, Kilohana, and Nahiku quadrangles; 1920 flow data from Hofmann; written commun. to Foss, 11/17/32, in U.S. Geological Survey Hawaii District files and daily-discharge data from Grover and Stewart (1924); 1932 flow data from Hofmann (1934) and daily-discharge data from Grover and Carson (1935); all other data is unpublished in files of U.S. Geological Survey, Hawaii District office unless otherwise noted; gaging-station number is preceded by 16 and ends in 00]

Station number (plate 1)	Stream name	Altitude (ft)	Date	Streamflow (Mgal/d)	Cumulative streamflow without diversion, June 20, 1995 ^a (Mgal/d)	Water temperature (°C)	Water specific conductance (µS/cm)	Comments
Honomanu 2	Honomanu (east branch)	2	6/20/95	0.59	--	20.6	184	
Honomanu 2a	Honomanu (west branch)	2	6/20/95	0.78	--	20.6	264	
Honomanu 4	Honomanu	30	6/20/95	0.0	0.00	--	--	
Honomanu 5	Honomanu	35	6/20/95	0.0	0.00	--	--	
Honomanu 6	Honomanu	50	6/20/95	0.0	0.00	--	--	
Honomanu 7	Honomanu	90	6/20/95	0.0	0.00	--	--	
Honomanu 8a	Honomanu	240	6/20/95	0.06	0.06	24.6	110	
Honomanu 9	Uluini	310	6/20/95	0.01	--	24.9	50	
Honomanu 10a	Honomanu	360	6/20/95	0.08	1.01	22.3	36	
Honomanu 11a	Honomanu (east unnamed tributary)	1,750	6/20/95	0.0	--	--	--	Downstream of Spreckels Ditch diversion
Honomanu 11	Honomanu (east unnamed tributary)	1,770	6/20/95	0.67	--	20.6	32.5	Upstream of Spreckels Ditch diversion
Honomanu 12 5270	Spring Honomanu	1,810 1,733	6/20/95 1920 8/19/20	0.01 1.90 ^b 1.90	-- --	21.6 --	67 --	Daily mean at gaging station; upstream of Spreckels Ditch diversion
Honomanu 13a	Honomanu	1,670	6/20/95	0.0	0.93 ^c	--	--	Downstream of Spreckels Ditch diversion
Honomanu 14a	Honomanu (west unnamed tributary)	1,720	6/20/95	0.0	--	--	--	Downstream of Spreckels Ditch diversion
Honomanu 18a	Honomanu	1,950	1920	1.57	--	--	--	
Honomanu 18b	Honomanu	2,250	1920	1.08	--	--	--	
Honomanu 18c	Honomanu	2,350	1920	0.99	--	--	--	
Honomanu 18d	Honomanu	2,500	1920 10/7/32	0.66 0.19	-- --	-- --	-- --	
Honomanu 18e	Honomanu	2,600	10/7/32	0.17	--	--	--	
Honomanu 18f 5240	Honomanu Honomanu	2,740 2,900	10/7/32 1920 8/19/20 10/7/32	0.14 0.36 ^b 0.35 0.10	-- --	-- --	-- --	Daily mean at gaging station
Honomanu 20	Honomanu	3,030	1920 6/20/95	0.28 0.20	-- 0.34	-- 19.2	-- 34	Downstream of diversion
Honomanu 23	Honomanu	3,050	6/20/95	0.14	0.14	20.0	27	Upstream of diversion

^a Assumes negligible unmeasured leakage past diversion structures

^b Instantaneous measurement

^c Estimated using base-flow record from gaging stations 5240 and 5270

are likely issuing from the top of the freshwater lens. The stream valley downstream of the waterfall is floored by alluvial deposits all the way to the coast so the springs could also represent streamflow which had been lost to interbed flow reemerging near sea level.

A water budget was calculated for the 2.55-mi² area upstream of gaging station 5240 (Shade, 1999). In the water budget, 19.63 Mgal/d of rainfall and 6.05 Mgal/d of fog drip is apportioned into 7.05 Mgal/d of runoff, 3.65 Mgal/d of evapotranspiration, and 14.98 Mgal/d of recharge (table 1, fig. 6). The amount of base flow in this subbasin is only about 5 percent of the estimated recharge to the subbasin. Therefore, it appears likely that most of the recharge follows deeper ground-water flow paths and eventually discharges further downgradient offshore or at the shoreline.

In and East of Keanae Valley

The USGS surface-water gaging stations in the study area east of Keanae Valley were at stream sites both in the Kula Volcanics and the Hana Volcanics. No USGS gaging stations were in Keanae Valley. Because the rocks east of Keanae Valley are considered to be fully saturated, all of the base flow measured at each of the sites represents ground-water discharge from the vertically extensive freshwater-lens system.

None of the gaged streams east of Keanae Valley have gone dry near 1,300 ft altitude during the period they were gaged. The total average annual streamflow of these gaged streams is 109 Mgal/d at 1,300 ft altitude. It is not possible to estimate the total average annual streamflow at the coast from existing records because of the scarcity of gaging stations and the presence of the diversion systems, which intercept nearly all base flow and an unknown percentage of higher streamflow. No streamflow-gaging stations were operated at higher altitudes in this part of the study area, so it is not possible to say at what altitudes these streams become perennial on the basis of long-term records. Two streams (West Wailuaiki and Hanawi) were flowing during low-flow conditions at altitudes greater than 3,000 ft during field visits for this study.

Total average daily ground-water discharge to gaged streams upstream of 1,200 ft altitude in the Kula and Hana Volcanics is 27 Mgal/d, most of which is

removed from the streams by surface-water diversion systems. This number was estimated by adding the estimated base flow at each gaging station from Wailuanui to Hanawi Streams at about 1,300 ft altitude (table 2). Base flow in the five gaged subbasins in this area for which a water budget was estimated averages 27 percent of the recharge to these same subbasins. An additional 10 Mgal/d or more of ground water is estimated to be captured directly by the tunnels and ditches above 1,300 ft altitude. About 22 Mgal/d of ground water discharges through the Kula and Hana Volcanics at altitudes between about 500 and 1,300 ft in the gaged stream subbasins. Of this 22 Mgal/d, about 13 Mgal/d is measured in Hanawi Stream. The total ground-water discharge above 500 ft altitude in this part of the study area is greater than 59 Mgal/d. About 10 Mgal/d discharges from four springs in Keanae Valley at or below 1,000 ft altitude (Stearns and Macdonald, 1942, p. 212).

Waiokamilo Stream

Waiokamilo Stream is headed at about 3,500 ft altitude about 5 mi inland on the upland surface east of Keanae Valley (plate 1). The stream has a flat gradient near the coast where it flows on Hana Volcanics that covered alluvium at the mouth of Keanae Valley (Stearns and Macdonald, 1942). At about 2.5 mi inland, at the east wall of Keanae Valley, the stream altitude abruptly increases from about 800 ft up to 1,200 ft along the next 2,000 ft of stream length. The stream lies on Hana Volcanics along its entire length (Stearns and Macdonald, 1942). All base flow is captured by the Koolau Ditch diversion system at about 1,300 ft altitude (table 4). Several other diversions capture water for taro cultivation in the Wailua area.

Streamflow measurements made on May 11, 1999 during low-flow conditions show that the stream was dry from the Koolau ditch diversion as far downstream as Akeke Spring. The stream gained about 3.8 Mgal/d from the spring which discharges from a ridge of Honomanu Basalt (table 15). Downstream from the spring all the way to the coast, the stream loses water to the subsurface and to at least three diversions. The stream flows on Hana Volcanics along the entire section of stream that is losing water. The vertically extensive freshwater-lens system appears to exist in the Honomanu Basalt, but below the floor of Waiokamilo Stream

Table 15. Streamflow, temperature, and specific conductance in Waiokamilo Stream, May 11, 1999, northeast Maui, Hawaii [ft, feet; Mgal/d, million gallons per day; °C, degrees Celsius; μS/cm, microsiemens per centimeter; --, not determined; all altitudes estimated from U.S. Geological Survey topographic map, Keanae and Nahiku quadrangles]

Station number	Stream name	Altitude (ft)	Stream-flow (Mgal/d)	Water temperature (°C)	Water specific conductance (μS/cm)	Comments
Waiokamilo 1	Waiokamilo	80	0.47	--	--	
Waiokamilo 2	Waiokamilo	110	0.52	--	--	Includes some return flow from taro patch
Waiokamilo 3.1	Waiokamilo	220	0.36	--	--	
Waiokamilo 3.2	diversion	220	0.70	--	--	Taro-patch diversion
Waiokamilo 4.1	Waiokamilo	240	0.23	19.9 ^a	123 ^a	Includes flow from unnamed spring
Waiokamilo 4.2	Hamau	250	0.83	20.3 ^a	135 ^a	Tributary to Waiokamilo Stream
Waiokamilo 5	Waiokamilo	440	2.40	19.1	139	Diversion takes nearly all flow
Waiokamilo 6	Waiokamilo	560	3.66	19.6	137	Upstream from taro-patch diversion
Waiokamilo 7	diversion	540	0.25	--	--	Diversion to taro patch
Waiokamilo 8	Waiokamilo	720	3.80	18.9	147	Downstream from Akeke Spring
Waiokamilo 9	Waiokamilo	750	0.00	--	--	Upstream from Akeke Spring

^a Measured May 28, 1999

in the overlying Hana Volcanics. A water budget was not calculated for this stream basin.

Wailuanui Stream

Wailuanui Stream splits into two branches at 940 ft altitude; the head of the west branch, at 5,600 ft altitude, is 7 mi inland and the head of the east branch, at 2,400 ft altitude, is 3.4 mi inland (plate 1). The stream has a relatively flat gradient near the coast where the valley is floored on alluvial deposits and on a small section of Hana Volcanics that flowed from Keanae Valley (Stearns and Macdonald, 1942). At 3,400 ft inland, the stream altitude abruptly increases from 200 ft to 800 ft along the next 1,000 ft of stream length as the stream valley crosses over Honomanu Basalt into Kula Volcanics. Upstream of 1,200 ft altitude, the West Branch Wailuanui Stream contains a flow of the Hana Volcanics which originally reached the ocean but has since been eroded away (Stearns and Macdonald, 1942). All base flow in both stream branches is captured by the Koolau Ditch diversion system at 1,300 ft altitude (table 4).

The two branches of Wailuanui Stream have never been dry at gaging stations 5190 and 5200 at about 1,300 ft altitude nor at gaging station 5210 at 620 ft altitude (table 2, plate 1). Base-flow estimates indicate that the average annual gains from ground water are 2.24 and 1.65 Mgal/d for the west and east branches

upstream of 1,300 ft altitude, respectively (table 2, fig. 15L). Between 1,300 ft and 620 ft, the stream gains an average of 0.79 Mgal/d. A regression plot of the estimated base flow, obtained the same way that was discussed earlier for Honopou Stream, also shows a linear relation (fig. 18). Because the regression line has a slope greater than 1.0, the stream has a net gain of water between each gaging station. The scatter of the data points around the regression line shows that the base-flow distribution along the stream is variable. Concurrent streamflow records on 2 different days show the expected pattern of gains upstream and between the three gaging stations but the actual values vary significantly (table 16).

In the West Wailuanui Stream water budget (Shade, 1999) of the 1.92-mi² area upstream of gaging station 5190, 16.22 Mgal/d of rainfall and 4.18 Mgal/d of fog drip is apportioned into 7.27 Mgal/d of runoff, 2.93 Mgal/d of evapotranspiration, and 10.20 Mgal/d of recharge (table 1, fig. 6). For East Wailuanui Stream, the area upstream of gaging station 5200 is smaller, only 0.51 mi², hence rainfall (7.10 Mgal/d), fog drip (1.29 Mgal/d), runoff (4.07 Mgal/d), evapotranspiration (0.85 Mgal/d), and recharge (3.47 Mgal/d) are smaller. But as with the water-budget components for Hoolawa Stream, the base flow as a percentage of recharge to each subbasin is unequal; 22 percent in West Wailuanui and 48 percent in East Wailuanui (table 1). Again, this

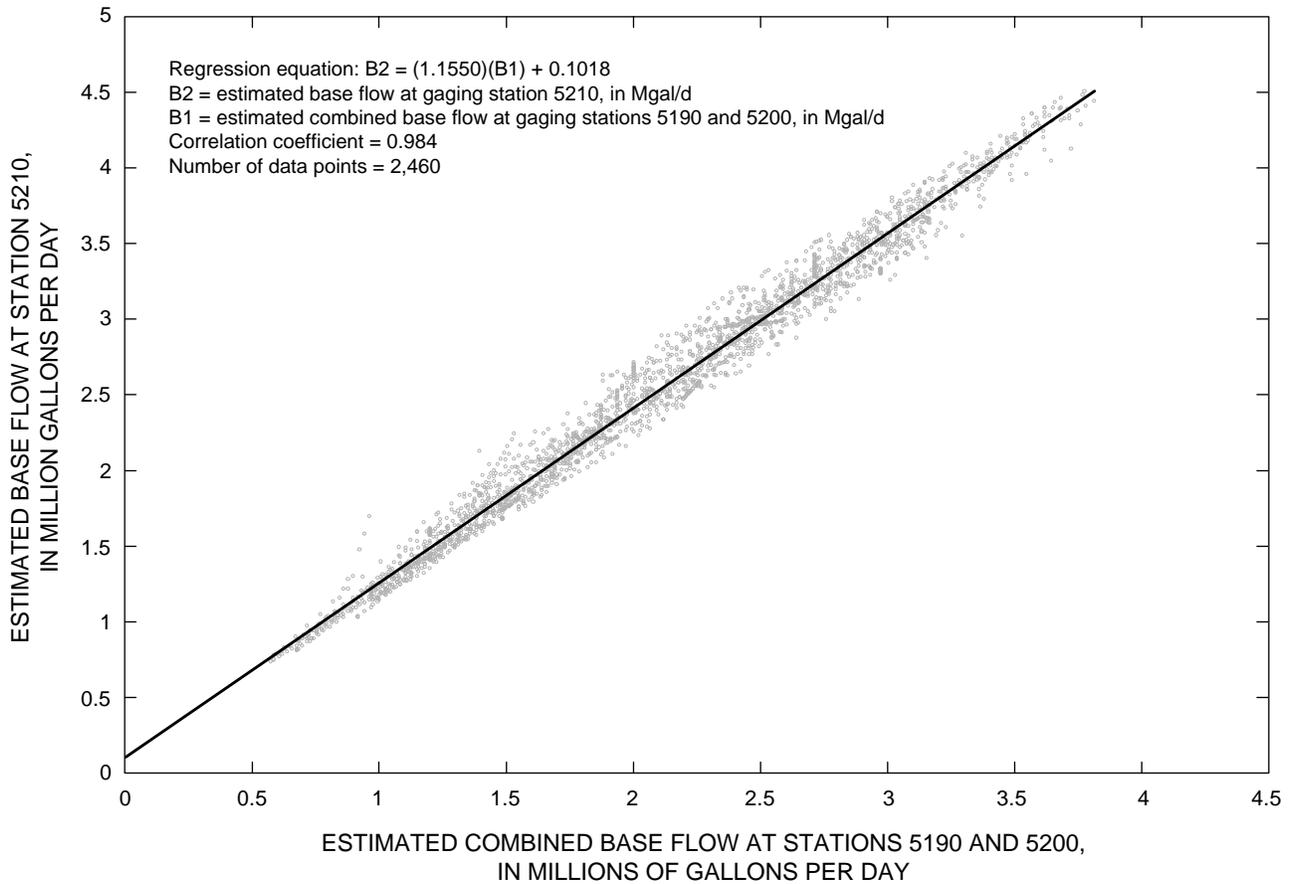


Figure 18. Relation of estimated base flow and linear regression line for gaging stations on Wailuanui Stream, northeast Maui, Hawaii

Table 16. Streamflow in Wailuanui Stream, northeast Maui, Hawaii

[ft, feet; Mgal/d, million gallons per day; all data from Paulsen (1950); gaging-station number is preceded by 16 and ends in 00]

Gaging-station number	Stream name	Altitude (ft)	Date	Stream-flow (Mgal/d)	Cumulative streamflow without diversion (Mgal/d)	Comments
5210	Wailuanui	620	7/4/46	0.30	2.50	Daily mean
			2/23/47	0.17	1.15	
5190	West Wailuanui	1,268	7/4/46	1.11	1.11	Daily mean; upstream from Koolau Ditch diversion
			2/23/47	0.56	0.56	
5200	East Wailuanui	1,287	7/4/46	1.09	1.09	Daily mean; upstream from Koolau Ditch diversion
			2/23/47	0.42	0.42	

Table 17. Streamflow and temperature in West Wailuaiki Stream, northeast Maui, Hawaii

[ft, feet; Mgal/d, million gallons per day; °C, degrees Celsius; --, not determined; all altitudes estimated from U.S. Geological Survey topographic map, Keanae and Nahiku quadrangles; 1962 data from U.S. Geological Survey (undated[a]); 1984 data from Chinn and others (1985); gaging-station number is preceded by 16 and ends in 00]

Station number	Stream name	Altitude (ft)	Date	Stream-flow (Mgal/d)	Water temperature (°C)	Comments
5180	West Wailuaiki	1,343	6/25/62 3/21/84	0.90 1.55	-- --	Daily mean; upstream of Koolau Ditch diversion
West Wailuaiki 12	West Wailuaiki	2,400	3/21/84	0.92	20.5	
West Wailuaiki 13	West Wailuaiki	2,565	3/21/84	0.45	19.0	
West Wailuaiki 14	West Wailuaiki (east branch)	2,570	3/21/84	0.10	20.5	
West Wailuaiki 15	West Wailuaiki (west branch)	2,570	3/21/84	0.34	--	By subtraction
West Wailuaiki 16	West Wailuaiki (east branch)	3,040	6/25/62	0.06	--	
West Wailuaiki 17	West Wailuaiki (west branch)	3,080	6/25/62	0.10	--	

probably indicates that the ground-water divides are significantly different than the topographic divides used in the water-budget estimation. Much of the West Wailuanui Stream drainage subbasin lies directly upslope of the East Wailuanui Stream drainage subbasin (fig. 3). The combined base flow in both streams is about 28 percent of the combined recharge to the two subbasins.

West and East Wailuaiki Streams

Although these streams do not converge, they are quite similar and hence will be discussed together in this section. Both streams are headed 6.6 mi inland at 6,000 ft altitude (plate 1). The streams rise steeply from sea level to 600 ft altitude 0.5 mi from the coast (a gradient of 1,130 ft/mi) and at this altitude, the valleys are incised 240 ft below the upland surface. The stream valleys lie on Kula Volcanics along much of their length but Honomanu Basalt can be found as far as 2,000 ft from the ocean (Stearns and Macdonald, 1942). Streamflow is captured by the Koolau Ditch diversion system at 1,300 ft altitude (table 4).

West Wailuaiki Stream (1921–97) and East Wailuaiki Stream (1922–58) have never been dry at the gaging stations (5180, 5170) upstream of the Koolau Ditch (table 2, plate 1). The average annual gains from ground water upstream of the gaging stations are about 4.53 and 4.82 Mgal/d, respectively (table 2, fig. 15M). A streamflow measurement made on June 25, 1962 at

the West Wailuaiki gaging station shows a flow of 0.90 Mgal/d (table 17). About 82 percent of this flow was gained downstream of 3,000 ft altitude where a set of measurements were made on two stream branches (U.S. Geological Survey, 1962). Measurements made March 21, 1984 on a shorter stream section show that 72 percent of the flow at the gaging station was gained downstream of 2,565 ft altitude and the largest gains were between 2,565 ft and 2,400 ft altitude (Chinn, Tateishi, and Yee, 1985). Measurements made in March 1928 by EMI personnel at 500 ft altitude in both West and East Wailuaiki Streams show gains of 0.5 and 0.2 Mgal/d, respectively, downstream of 1,300 ft altitude (table 10).

The area upstream of gaging station 5180 is 3.67 mi² and in the water budget, 33.11 Mgal/d of rainfall and 9.28 Mgal/d of fog drip is apportioned into 18.75 Mgal/d of runoff, 5.05 Mgal/d of evapotranspiration, and 18.59 Mgal/d of recharge (table 1, fig. 6) (Shade, 1999). The estimated base flow at the gaging station is about 25 percent of the recharge to the subbasin. The results for the 3.11-mi² subbasin upstream of gaging station 5170 are similar; 30.20 Mgal/d of rainfall, 8.46 Mgal/d of fog drip, 14.90 Mgal/d of runoff, 4.33 Mgal/d of evapotranspiration, and 19.43 Mgal/d of recharge (table 1, fig. 6). Although this subbasin receives less total precipitation, it receives slightly more recharge because less runoff and evapotranspiration occur. The base flow for the East Wailuaiki Stream subbasin is about 25 percent of the estimated recharge.

Kopiliula Stream

Kopiliula Stream is headed at 7,800 ft altitude and 7.2 mi inland (plate 1). The stream rises steeply from sea level to 600 ft altitude 0.6 mi from the coast (a gradient of 930 ft/mi) and at this altitude the stream valley is incised 200 ft below the upland surface. A tributary, Puakaa Stream, branches to the east at 60 ft altitude and the stream lies on Honomanu Basalt for 2,000 ft from the coast and then on Kula and Hana Volcanics farther upstream (Stearns and Macdonald, 1942). Streamflow is captured by the Koolau Ditch at 1,300 ft altitude (table 4).

The minimum flow measured in Kopiliula Stream was 0.58 Mgal/d for 1921–58 at gaging station 5160 which is upstream of the Koolau Ditch (table 2, plate 1). Estimates of base flow indicate that the average annual gains from ground water upstream of the diversion are 4.18 Mgal/d (table 2, fig. 15N). EMI records indicate that the stream was dry at 500 ft altitude in March 1928 (table 10). Streamflow on the same day in Puakaa Stream was 0.4 Mgal/d. Apparently the water table had dropped below the base of Kopiliula Stream at the time of this measurement or else flow was within sediments on the stream bottom.

The 3.91-mi² area upstream of gaging station 5160 is the largest drainage subbasin for which a water budget was estimated (Shade, 1999). Shade estimated that 31.96 Mgal/d of rainfall and 8.69 Mgal/d of fog drip is apportioned into 13.87 Mgal/d of runoff, 5.50 Mgal/d of evapotranspiration, and 21.27 Mgal/d of recharge (table 1, fig. 6). The estimated base flow at the gaging station is about 20 percent of the recharge to the subbasin.

Waiohue Stream

Waiohue Stream is a relatively short stream headed 2.5 mi inland at 2,400 ft altitude (plate 1). The stream rises steeply from sea level to 600 ft altitude 0.5 mi from the coast (a gradient of 1,320 ft/mi) and at this altitude the stream valley is incised 260 ft below the upland surface. The stream lies on Honomanu Basalt at the coast and Kula Volcanics farther upstream, but it appears that lava flows of the Hana Volcanics came down the valley and reached the ocean (Stearns and Macdonald, 1942). The Waiohue Stream valley is near the western boundary of the extensive area of Hana Volcanics that cover most of the volcano surface for many

miles to the east (fig. 6). Streamflow is diverted by the Koolau Ditch at 1,300 ft altitude (table 4).

The lowest daily streamflow measured during 1921–63 at gaging station 5150, at 1,316 ft altitude, was 1.36 Mgal/d (table 2, plate 1). The estimated average annual base flow for the 40-year period of record is about 3.57 Mgal/d (table 2, fig. 15O). EMI records indicate that the flow at about 500 ft altitude was 0.4 Mgal/d in March 1928 (table 10). This value represents the gain in flow downstream of the diversion system which is at 1,300 ft altitude.

The drainage subbasin of Waiohue Stream upstream of the gaging station is the smallest used in the water-budget estimates, 0.52 mi² (Shade, 1999). In this area, 7.25 Mgal/d of rainfall and 1.49 Mgal/d of fog drip is apportioned into 3.91 Mgal/d of runoff, 0.87 Mgal/d of evapotranspiration, and 3.96 Mgal/d of recharge (table 1, fig. 6). The estimated base flow at the gaging station is about 90 percent of the recharge to the subbasin. This subbasin is another example where the surface-drainage divides probably do not coincide with the ground-water divides. If the base flow and recharge for Waiohue Stream subbasin are combined with the base flow and recharge for Kopiliula Stream subbasin which lies directly upstream (fig. 3), the ratio of base flow to recharge becomes 31 percent. This value is much more consistent with values for the adjacent Wailuaiki and Wailuanui Stream subbasins.

Paakea and Waiaka Streams

Paakea Stream is headed at 1,800 ft altitude 1.7 mi inland from the coast (plate 1). Waiaka Stream is short, 0.9 mi long, and heads at 1,400 ft altitude. Both streams rise from sea level to 600 ft altitude 0.5 mi from the coast (a gradient of 1,320 ft/mi) and both valleys are incised 260 ft below the upland surface at this altitude. Both stream valleys lie on lava flows of the Hana Volcanics along their entire lengths except for a small exposure of Honomanu Basalt near the coast in Waiaka Stream valley (Stearns and Macdonald, 1942). Numerous springs have been mapped along both streams (plate 1). All base flow in both streams is captured by the Koolau Ditch at 1,300 ft (table 4).

During 1932–47, these streams and Kapaula and Hanawi Streams to the east were gaged at altitudes ranging from 500 to 650 ft to determine the feasibility of extending one of the lower altitude ditches from the

west to capture water gained downstream from the Koolau Ditch (Takasaki and Yamanaga, 1970). On Paakea Stream, gaging station 5140, at 650 ft altitude, measured a minimum daily flow of about 1.29 Mgal/d (table 2, plate 1). The estimated average annual base flow at this gaging station is about 2.53 Mgal/d (table 2, fig. 15P). The minimum daily flow measured at gaging station 5130 on Waiaka Stream was about 0.29 Mgal/d and the estimated average annual base flow is 0.53 Mgal/d (table 2, fig. 15P). No water budgets were calculated for either stream subbasin.

Kapaula Stream

Kapaula Stream is headed at 2,400 ft altitude 1.7 mi inland from the coast (plate 1). This stream has a similar gradient (1,320 ft/mi) and stream-valley incision depth (260 ft) as Paakea and Waiaka Streams to the west and lies entirely on lava flows of the Hana Volcanics (Stearns and Macdonald, 1942). Streamflow is diverted by the Koolau Ditch at about 1,300 ft altitude (table 4).

Two gaging stations were operated on Kapaula Stream, gaging station 5100 upstream of the Koolau Ditch and gaging station 5110 downstream at 540 ft altitude (plate 1). The estimated average annual base flow at the upstream gaging station is 2.34 Mgal/d and the lowest daily flow measured was 0.19 Mgal/d (table 2, fig. 15Q). At the downstream gaging station, the average annual base flow is estimated to be 1.68 Mgal/d and the lowest daily flow measured was 1.10 Mgal/d. All of this flow is gained in the 4,000 ft downstream of the Koolau Ditch. A regression plot of the estimated base flow, obtained the same way that was discussed earlier for Honopou Stream, also shows a linear relation (fig. 19). Because the regression line has a slope greater than 1.0 the stream has a net gain of water between each gaging station. The scatter of the data points around the regression line shows that the base-flow distribution along the stream is variable. Concurrent streamflow records on two different days show the expected pattern of gains between the two gaging stations but the actual values vary somewhat (table 18). A water budget was not calculated for this stream subbasin.

Hanawi Stream

The Hanawi Stream basin has been evaluated more thoroughly than any of the other subbasins in the study area (Meyer, in press). The stream is headed at 7,400 ft

altitude 6.8 mi inland (plate 1). The stream rises steeply from sea level to 600 ft altitude 0.8 mi from the coast (a gradient of 770 ft/mi) and at this altitude the stream valley is incised 240 ft below the upland surface. The stream has eroded into the Honomanu Basalt for 2,000 ft from the coast and in Kula Volcanics to 5,000 ft from the coast (Stearns and Macdonald, 1942). The contact between the two geologic units has been arbitrarily located because in the Nahiku area, the exposed rocks of the Honomanu Basalt are petrographically transitional to the overlying Kula Volcanics and are more like the Kula Volcanics than the typical rocks of the Honomanu Basalt (Stearns and Macdonald, 1942). Hana Volcanics are found further upstream. Base flow is diverted by the Koolau Ditch at about 1,300 ft altitude (table 4).

Two surface-water gaging stations have been operated on Hanawi Stream by the USGS (table 2, plate 1). The upstream gaging station (5080), that records flow upstream of the Koolau Ditch, had a minimum flow of 0.58 Mgal/d and an average annual base flow of 3.66 Mgal/d (table 2, fig. 15R). The downstream gaging station (5090) records streamflow at 500 ft altitude. Streamflow at this altitude includes water discharging at Big Springs, and Hanawi Springs 1 and 2 (plate 1). The lowest recorded streamflow during the 17 years that the gaging station was operated was 8.21 Mgal/d (table 2). The estimate of average annual base flow is by far the largest in the study area, about 12.99 Mgal/d. All of this base flow is gained between the Koolau Ditch at 1,300 ft altitude and the gaging station at 500 ft altitude.

Independent sets of streamflow measurements were made five times, twice as part of this study (table 19). The measurements show flow during extended dry periods as high as 2,120 ft altitude in the stream channel. On the days of measurement, flow at the upstream gaging station ranged from about 1 to 6 Mgal/d. Between 1,300 ft and 1,000 ft altitude, the stream had small gains (1 Mgal/d) and then gained substantially (6 to 7 Mgal/d) downstream to 620 ft altitude. Between 620 ft and 550 ft altitude, additional gains of 4 to 8 Mgal/d were measured. Downstream to about 50 ft altitude, an additional 1 to 2 Mgal/d of flow was gained, but two sections that lost flow were measured in this reach. Between 420 ft and 190 ft altitude, the streamflow decreased by about 6 percent and between 120 ft and 50 ft altitude streamflow decreased by about 2 percent. The downstream measurement site for each respective stream section was considered only fair by the USGS personnel making the measurements because the

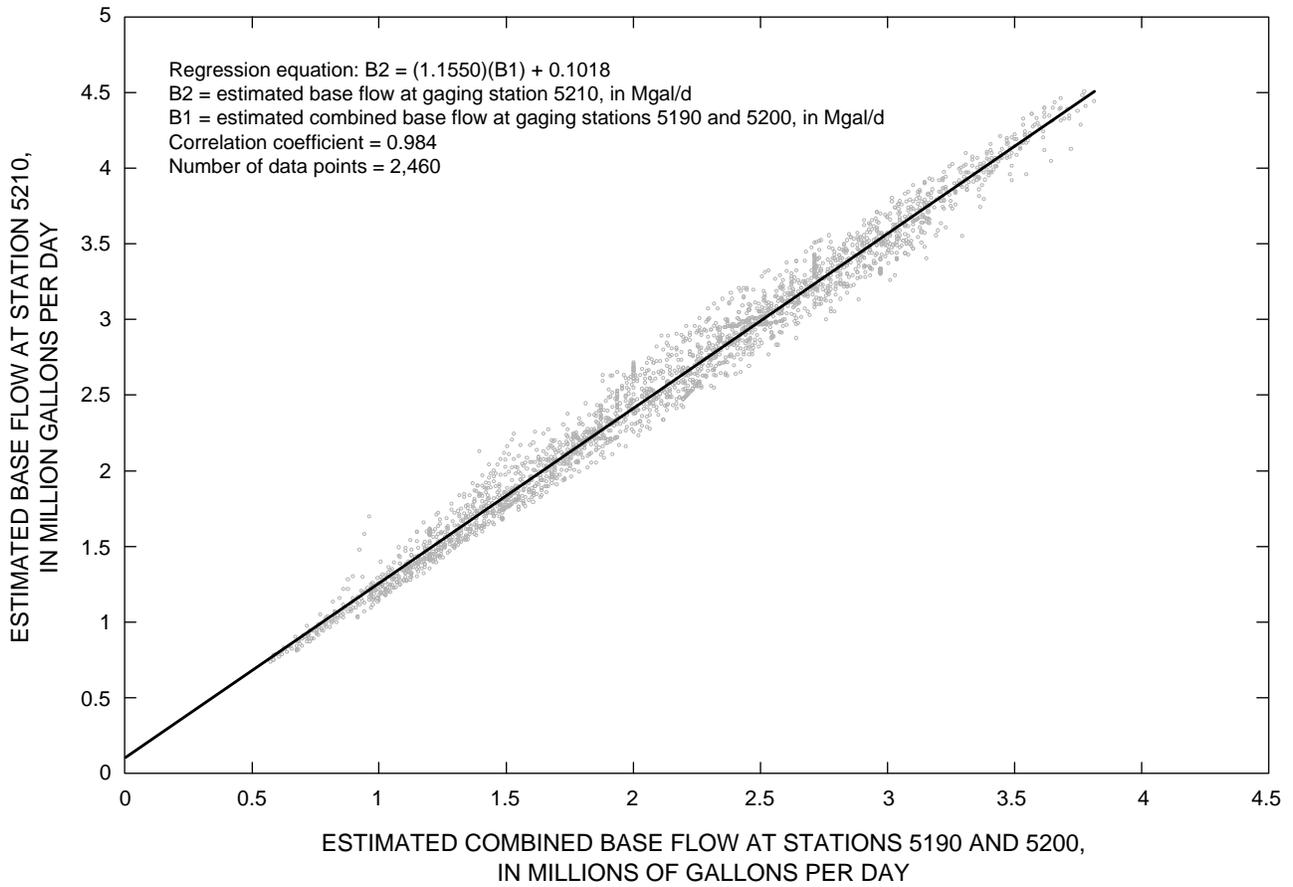


Figure 19. Relation of estimated base flow and linear regression line for gaging stations on Kapaula Stream, northeast Maui, Hawaii

Table 18. Streamflow in Kapaula Stream, northeast Maui, Hawaii

[ft, feet; Mgal/d, million gallons per day; all data from Paulsen (1950); gaging-station number is preceded by 16 and ends in 00]

Gaging-station number	Stream name	Altitude (ft)	Date	Streamflow (Mgal/d)	Cumulative streamflow without diversion (Mgal/d)	Comments
5100	Kapaula	540	9/11/46	1.20	2.17	Daily mean
			2/24/47	1.20	1.97	
5110	Kapaula	1,346	9/11/46	0.97	0.97	Daily mean; upstream of
			2/24/47	0.77	0.77	Koolau Ditch diversion

Table 19. Streamflow, temperature, and specific conductance in Hanawi Stream, northeast Maui, Hawaii

[ft, feet; Mgal/d, million gallons per day; °C, degrees Celsius; µS/cm, microsiemens per centimeter; --, not determined; <, less than; altitudes estimated from U.S. Geological Survey topographic map, Nahiku quadrangle; 1974 and 1975 data from U.S. Geological Survey (1976); 1985 data from Chinn and others (1986); 1994 daily-discharge data from Matsuoka and others (1995); 1995 daily-discharge data from Fontaine and others (1997); all other data is unpublished in files of U.S. Geological Survey, Hawaii District office; gaging-station number is preceded by 16 and ends in 00]

Station number	Stream name	Altitude (ft)	Date	Stream-flow (Mgal/d)	Cumulative streamflow without diversion, July 26, 1994 (Mgal/d)	Water temperature (°C)	Water specific conductance (µS/cm)	Comments
Hanawi 6	Hanawi	50	7/26/94	--	19.6 ^a	--	--	
			2/22/95	14.61	--	17.6	198	
Hanawi 8	Hanawi	120	10/9/74	12.28	--	--	--	
			5/21/75	14.22	--	--	--	
			7/26/94	--	20.0 ^a	--	--	
			2/22/95	14.93	--	18.9	197	
Hanawi 10	Hanawi	190	7/26/94	--	17.6 ^a	--	--	
			2/22/95	12.54	--	19.2	181	
Hanawi 13	Hanawi	420	10/9/74	11.63	--	--	--	
			5/22/75	12.3	--	--	--	
			7/26/94	--	18.4 ^a	--	--	
			2/22/95	13.4	--	--	--	
5090	Hanawi	550	10/9/74	9.0	--	--	--	Daily mean at gaging station
			5/22/75	10.3	--	--	--	
			11/2/84	11.6	--	--	--	
			7/26/94	12.7	17.8	--	--	
			2/22/95	12.8	--	--	--	
Hanawi 23	Hanawi	620	11/2/84	9.7	--	--	--	
			7/26/94	7.5	12.7	--	--	
			2/22/95	7.4	--	--	--	
Hanawi 27a	Hanawi	920	5/21/75	0.36	--	--	--	
Hanawi 27	Hanawi	1,020	7/26/94	1.2	6.3	21.0	40.0	
			2/22/95	0.52	--	19.4	48.7	
Hanawi 29	Hanawi	1,130	7/26/94	0.78	5.9	21.3	40.0	
5080	Hanawi	1,318	10/9/74	0.97	--	--	--	Daily mean at gaging station; upstream of Koolau Ditch diversion
			5/21/75	3.0	--	--	--	
			11/2/84	0.71	--	--	--	
			7/26/94	5.2	5.2	--	--	
			7/28/94	5.8	--	--	--	
			2/22/95	1.5	--	--	--	
Hanawi 38	Hanawi	2,240	7/28/94	1.8	1.8	--	--	Downstream of confluence with tributary
Hanawi 40	Hanawi (east unnamed tributary)	2,280	7/28/94	0.56	0.56	--	--	
Hanawi 45	Hanawi (west branch)	3,500	7/28/94	0.02	0.02	20.9	16	
Hanawi 46	Hanawi (west branch)	3,580	7/28/94	< 0.01	< 0.01	19.5	15	
Hanawi 48	Hanawi (east branch)	3,550	7/28/94	0.06	0.06	21.4	17	
Hanawi 51	Hanawi (west branch)	4,100	7/28/94	0.01	0.01	18.5	12	

^a Estimated on the basis of February 22, 1995 measurements

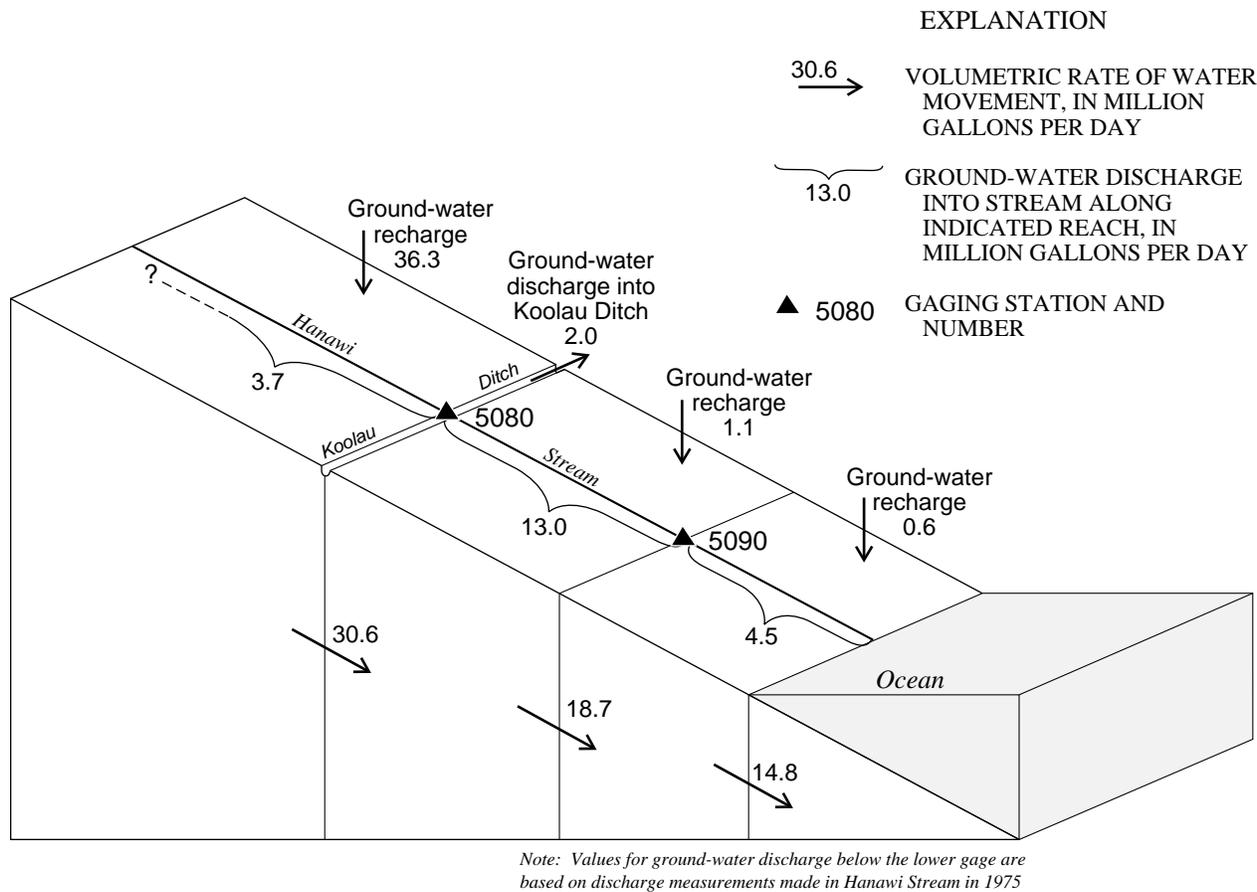


Figure 20. Distribution of mean annual ground-water recharge, discharge, and movement within the Hanawi Stream drainage basin, northeast Maui, Hawaii (modified from William Meyer, U.S. Geological Survey, written commun, 1998).

streambed consisted of cobbly alluvium that probably allowed a part of the streamflow to bypass the measurement site (R.A. Fontaine, USGS, oral commun., 1998). Therefore, the apparent loss of streamflow in these sections is probably not related to actual ground-water/surface-water interaction but may instead be attributed to the difficulty in measuring all of the water flowing in the stream channel. The total flow in Hanawi Stream on July 26, 1994 was estimated to be 19.6 Mgal/d, all of which is assumed to be base flow (table 19).

A water budget for the entire Hanawi Stream drainage basin to the coast has been estimated (Shade, 1999). Water-budget estimates for the other stream sub-basins in the study area included only the area upstream of the upstream gaging station on each respective stream. Total recharge to the basin was estimated to be 38.1 Mgal/d, 61 percent of which discharges into the stream or the Koolau Ditch crossing the basin (fig. 20);

the remaining 39 percent discharges to the ocean. Sixty-two percent of the ground-water discharge to the stream is estimated to be between the altitudes of 1,300 ft and 550 ft where the stream channel is the most deeply incised.

Makapipi Stream

The Makapipi Stream drainage basin lies on the eastern end of the study area and is headed at 1,900 ft altitude 4 mi inland from the coast (plate 1). This stream rises from sea level to 600 ft 0.9 mi from the coast (a gradient of 630 ft/mi) and the valley is incised only 50 ft below the upland surface at this altitude. The stream lies on rocks of the Hana Volcanics along its entire length (Stearns and Macdonald, 1942). Streamflow is diverted by the Koolau Ditch at about 1,300 ft altitude (table 4).

Three gaging stations were operated in the Makapipi Stream drainage basin, one at 1,300 ft altitude (5060, table 3) measuring water flowing from water development tunnels into the Koolau Ditch, one for Makapipi Spring at 1,150 ft altitude (5065), and one at 920 ft altitude (5070) downstream of the Koolau Ditch (table 2, plate 1). The average annual flow at gaging station 5060 during 1949–65 was 2.87 Mgal/d, all of which is assumed to be ground-water discharge. Ground-water discharge at gaging station 5065 averaged about 0.67 Mgal/d during 1932–45 but the spring occasionally went dry during dry weather. The estimated base flow at gaging station 5070 is about 1.96 Mgal/d and the stream has gone dry at this altitude during 1932–45 indicating that the stream is not perennial between the Koolau Ditch and this gaging station (table 2, fig. 15S). A water budget was not calculated for this stream basin.

SUMMARY AND CONCLUSIONS

The study area lies on the northern flank of the East Maui Volcano (Haleakala) and covers about 129 square miles between the drainage basins of Maliko Gulch to the west and Makapipi Stream to the east. The topography is gently sloping except for the steep sides of gulches and valleys that have been eroded by the numerous streams. Most of the study area is made up of forest reserves; rain forests densely cover the intermediate-altitude slopes to about 7,000 ft and small towns and farms can be found at low altitudes along the coast.

Three geologic units are found in the study area: the main shield-building-stage Honomanu Basalt, formed mainly by thick accumulations of thin lava flows, the post-shield-stage Kula Volcanics, which consist mainly of lava flows that are many tens to hundreds of feet thick, and the rejuvenated-stage Hana Volcanics, which consist mainly of aa flows of several feet thick to several hundred feet thick where the flows were contained within the walls of previously eroded valleys.

The hydraulic conductivity of the Honomanu Basalt is estimated to be several thousand feet per day in the western part of the study area and less than one foot per day in the eastern part. No hydraulic conductivity estimates are available for the Kula or Hana Volcanics but the specific capacity estimates for wells in the Kula Volcanics are about four orders of magnitude less

than average of specific capacity estimates for wells open to the Honomanu Basalt.

About 989 Mgal/d of rainfall and 176 Mgal/d of fog drip enters the study area with the highest rates between 2,000 and 6,000 ft altitude. Of the total precipitation, about 529 Mgal/d enters the ground-water system as recharge. Average annual ground-water withdrawal from wells is only about 3 Mgal/d; proposed additional withdrawals in the Haiku area total about 18 Mgal/d. Tunnels and ditches in the eastern part of the study area remove at least 10 Mgal/d from the ground-water system.

The drainage pattern of the stream valleys on east Maui is radial and the streams in the study area drain to the north. Streamflow consists of runoff, base flow, and in some cases, flow added to streams from the network of irrigation ditches that cross the study area. Only five streams where flow is recorded by USGS surface-water gaging stations have gone dry during the respective period of records for each site. Three of these five sites are at altitudes higher than 2,800 ft and the other two are on the most western stream of the study area. Streams continue to flow during periods of very low rainfall indicating that a significant ground-water source exists upstream of the gaging stations.

The total amount of average annual streamflow in the gaged stream subbasins upstream of 1,300 ft altitude is about 255 Mgal/d and the total amount of average annual base flow is about 62 Mgal/d. Six major surface-water diversion systems in the study area have diverted an average of 163 Mgal/d of streamflow (most of which is base flow) for irrigation and domestic supply in central Maui during 1925–97.

Fresh ground water is found in two main forms: (1) as a high-elevation saturated zone in relatively low-permeability geologic layers above an unsaturated zone, and (2) as a freshwater-lens system underlain by denser saltwater. West of Keanae Valley, ground-water flow appears to be dominated by a variably saturated system. A saturated zone in the upper rock unit, the Kula Volcanics, is separated from a freshwater lens near sea level by an unsaturated zone in the underlying Honomanu Basalt. East of Keanae Valley, the ground-water system appears to be a freshwater-lens system that is fully saturated above sea level to altitudes greater than 2,000 ft.

The freshwater-lens system is in direct connection with the underlying saltwater.

West of Keanae Valley, water levels measured in shallow wells indicate that a water table lies several tens of feet below the ground surface and represents the top of a saturated zone in the thick lava flows and interbedded soils of the Kula Volcanics. This water-table surface mimics a subdued version of topography. Ground water discharges where streams have incised into the high-elevation water table. The streams commonly are flowing all the way to the ocean where stream valleys lie on Kula Volcanics all the way to the ocean.

West of Keanae Valley, the rocks beneath the contact between the Kula Volcanics and the underlying Honomanu Basalt, and above the freshwater lens appear to be unsaturated because (1) stream channels incised into the Honomanu Basalt are dry or lose streamflow during base-flow conditions, (2) the hydraulic conductivity of the Honomanu Basalt is too high to support a thick ground-water lens with the estimated recharge to the study area, (3) small springs are commonly found along sea cliffs at the base of the Kula Volcanics but no springs have been observed lower in the Honomanu Basalt, and (4) wells that penetrate through the contact have encountered conditions of cascading water from above the contact and dry lava tubes in the Honomanu Basalt.

The surface of the freshwater lens in the Haiku area forms a hydraulic gradient of about 3 ft/mi inland. The source of freshwater in the lens is ground-water recharge from overlying high-elevation saturated zones and rainfall infiltration. Fresh ground water flows from the inland areas to the coast where it discharges at springs and by diffuse seepage at and below sea level. No wells in the study area are known to penetrate the transition zone or underlying saltwater. The existence of a freshwater lens in the entire study area west of Keanae Valley is inferred from the pattern of losing stream sections where surface water flows from the Kula Volcanics onto the Honomanu Basalt.

All of the base flow measured in the study area west of Keanae Valley was at stream sites in the Kula Volcanics and therefore represents ground-water discharge from the high-elevation saturated zone. The total average annual streamflow of these gaged streams is about 140 Mgal/d at 1,200 ft to 1,300 ft altitude. It is not possible to estimate the total average annual streamflow

at the coast. Perennial streamflow has been measured at altitudes greater than 3,000 ft in several of the streams (Kailua, Waikamoi, and Honomanu Streams). Discharge from the high-elevation saturated zone is persistent even during periods of little rainfall. The total flow of the gaged streams west of Keanae Valley was about 6.7 Mgal after the driest period on record in the area. All of this flow was measured above about 1,200 ft altitude.

Total average daily ground-water discharge from the high-elevation saturated zone upstream of 1,200 ft altitude is greater than 38 Mgal/d, all of which is eventually removed from the streams by surface-water diversion systems. Estimates of average annual base flow in gaged subbasins west of Keanae Valley range from about 0.05 to 6.9 Mgal/d. Base flow in five subbasins for which a water budget was estimated averages about 39 percent of the recharge to these same subbasins.

In and east of Keanae Valley, the rocks are fully saturated from sea level to greater than 2,000 ft altitude. The saturated zone extends from the Honomanu Basalt at sea level up through the Kula Volcanics and into the Hana Volcanics. Streams intersect the vertically extensive freshwater-lens system and are perennial downstream of about 2,100 ft altitude. These streams continue to gain water from all three rock units as they descend in altitude to sea level. The water-table surface mimics topography and slopes away from the coast at about 800 ft/mi. The nature of the transition from a variably saturated system to the west of Keanae Valley to a fully saturated freshwater-lens system east of Keanae Valley is unknown. Stream valleys west of Makapipi Spring are not incised deeply enough to intercept the water table and therefore, they do not contain persistent base flow.

The total average annual streamflow of the gaged streams is about 109 Mgal/d at about 1,300 ft altitude. It is not possible to estimate the total average annual streamflow at the coast and no streamflow-gaging stations were operated at higher altitudes. Two streams (West Wailuaiki and Hanawi) were flowing during low-flow conditions at altitudes greater than 3,000 ft during field visits. All of the base flow measured east of Keanae Valley represents ground-water discharge from the vertically extensive freshwater-lens system. Total average daily ground-water discharge to gaged streams upstream of 1,200 ft altitude is about 27 Mgal/d. Base

flow in five gaged subbasins averages about 27 percent of the recharge to these same subbasins. About 19 Mgal/d of ground water discharges through the Kula and Hana Volcanics between about 500 ft and 1,300 ft altitude in the gaged stream subbasins. Of this 19 Mgal/d, about 13 Mgal/d is measured in Hanawi Stream. The total ground-water discharge above 500 ft altitude in this part of the study area is greater than 56 Mgal/d.

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Table 2. Information from surface-water gaging stations on streams, northeast Maui, Hawaii

[ft, feet; mi², square miles; BFI, base-flow index parameter (Wahl and Wahl, 1995); BFI parameter f is 0.9 for all locations; <, less than; --, not determined; gaging-station number is preceded by 16 and ends in 00; na, not applicable]

Station number	Station location	Station altitude (ft)	Contributing drainage-basin area for base flow (mi ²)	Period of record used in analysis	Years of complete record	Average annual streamflow (Mgal/d)	Lowest daily streamflow (Mgal/d)	BFI parameter (N)	Average annual base flow (Mgal/d)	Period-of-record scale factor
5065	West Makapipi Spring	1,150	na	1932–45	10	0.67	0.00	1	0.67	1.12
5070	Makapipi Stream	920	1.93	1932–45	12	6.58	0.00	4	1.96	1.12
5080	Hanawi Stream ^a	1,318	3.46	1921–95	73	15.54	0.58	4	3.66	1.00
5090	Hanawi Stream	500	na	1932–47 1992–95	17	25.85	8.21	3	12.99	1.05
5100	Kapaula Gulch	1,346	0.69	1921–63	40	10.71	0.19	4	2.34	1.04
5110	Kapaula Gulch	540	na	1932–47	14	7.47	1.10	4	1.68	1.09
5130	Waiaaka Stream	650	0.10	1932–47	14	0.80	0.29	3	0.53	1.09
5140	Paakea Gulch	650	0.34	1932–47	14	4.17	1.29	3	2.53	1.09
5150	Waiohue Gulch	1,316	0.52	1921–63	40	7.43	1.36	4	3.57	1.04
5160	Kopiliula Stream	1,292	3.91	1914–17 1921–58	36	17.93	0.58	4	4.18	1.10
5170	East Wailuaiki Stream	1,329	3.11	1914–17 1922–58	37	19.75	0.84	4	4.82	1.10
5180	West Wailuaiki Stream ^a	1,343	3.67	1913–17 1921–97	76	22.75	0.32	4	4.53	1.00
5190	West Wailuanui Stream	1,268	1.92	1913–17 1922–58	37	9.35	0.19	4	2.24	1.10
5200	East Wailuanui Stream	1,287	0.51	1914–17 1922–58	38	5.59	0.13	4	1.65	1.10
5210	Wailuanui Stream	620	na	1932–36 1938–47	10	8.70	0.11	3	0.79	1.05
5240	Honomanu Stream	2,900	2.55	1919–27 1932–34 1962–68	14	8.22	0.06	4	0.81	1.00
5250	Seventh Branch Honomanu Stream	2,900	0.30	1932-33	<1	1.40	0.06	--	--	--
5260	Fourth Branch Honomanu Stream	2,900	0.10	1932-33	<1	0.62	0.01	--	--	--
5270	Honomanu Stream	1,733	3.17	1913–64	49	14.72	0.06	4	2.42	1.06
5310	Haipuaena Stream	4,320	0.27	1947–67	21	0.97	0.01	4	0.14	
5311										
5320	Haipuaena Stream	2,860	na	1919–26 1932–34	7	3.63	0.13	4	0.96	1.11
5330	Third Branch Haipuaena Stream	2,950	0.06	1932-33	<1	0.34	0.00	--	--	1.11

Table 2. Information from surface-water gaging stations on streams, northeast Maui, Hawaii--Continued[ft, feet; mi², square miles; BFI, base-flow index parameter (Wahl and Wahl, 1995); BFI parameter f is 0.9 for all locations; <, less than; --, not determined; gaging-station number is preceded by 16 and ends in 00; na, not applicable]

Station number	Station location	Station altitude (ft)	Contributing drainage-basin area for base flow (mi ²)	Period of record used in analysis	Years of complete record	Average annual streamflow (Mgal/d)	Lowest daily streamflow (Mgal/d)	BFI parameter (N)	Average annual base flow (Mgal/d)	Period-of-record scale factor
5340	First Branch Haipuaena Stream	3,000	na	1932-33	<1	0.20	0.00	--	--	1.11
5350	Haipuaena Stream	1,866	na	1939-59	21	1.97	0.02	4	1.34	
5360	Haipuaena Stream	1,512	na	1913-67	52	9.65	0.13	5	1.86	1.05
5350 5360	Haipuaena Stream	--	na	1913-67	52	10.50	0.20	5	2.44	1.05
5420	East Branch Puohokamoa Stream	2,800	0.14	1919-27 1932-33	7	1.24	0.00	4	1.41	1.13
5430	Middle Branch Puohokamoa Stream	2,900	0.48	1919-27 1932-34 1962-69	14	2.48	0.04	4	0.48	1.00
5440	West Branch Puohokamoa Stream	2,800	0.45	1919-28 1932-34	10	3.54	0.08	4	0.81	1.12
5450	Puohokamoa Stream	1,322	na	1913-71	58	21.36	0.04	4	5.46	1.04
5526	Waikamoi Stream	5,750	2.10	1949-66	15	0.36	0.00	4	0.0	
5528	Waikamoi Stream	4,487	2.46	1953-68	15	1.33	0.00	4	0.05	0.90
5530	Waikamoi Stream	4,250	na	1945-49	0	--	0.00	--	--	--
5540	Waikamoi Stream	3,000	na	1918 1919-28 1932-34	10	7.90	0.10	4	1.05	1.13
5545	East Branch Waikamoi Stream	3,020	na	1918-28 1932-33	9	2.72	0.07	4	0.65	1.13
5550	Waikamoi Stream	1,294	na	1922-57	35	16.37	0.10	4	3.02	1.07
5560	Waikamoi Stream	1,150	na	1910-22	10	18.24	0.20	5	3.78	1.15
5570	Alo Stream	1,248	0.47	1910-57	46	4.78	0.19	4	1.29	1.09
5650	Kaaiea Gulch	1,310	0.58	1921-62	39	4.41	0.22	4	1.13	1.05
5660	Oopuola Stream	1,205	0.20	1930-57	27	1.74	0.04	5	0.39	1.07
5670	Oopuola Stream	960	na	1910-15	3	5.90	0.20	5	1.83	1.07
5690	Second Branch Nailiilihaele Stream	3,130	0.20	1932-33	<1	0.49	0.00	--	--	1.02
5691	Nailiilihaele Stream	2,820	0.11	1963-68	6	__b	0.00	--	--	1.02
5697	West Branch Nailiilihaele Stream	2,860	0.04	1966-68	3	__b	--	--	--	1.02
5700	Nailiilihaele Stream	1,205	3.61	1910-11 1913-18 1919-24 1925-75	55	24.21	0.45	5	6.92	1.02

Table 2. Information from surface-water gaging stations on streams, northeast Maui, Hawaii--Continued

[ft, feet; mi², square miles; BFI, base-flow index parameter (Wahl and Wahl, 1995); BFI parameter f is 0.9 for all locations; <, less than; --, not determined; gaging-station number is preceded by 16 and ends in 00; na, not applicable]

Station number	Station location	Station altitude (ft)	Contributing drainage-basin area for base flow (mi ²)	Period of record used in analysis	Years of complete record	Average annual streamflow (Mgal/d)	Lowest daily streamflow (Mgal/d)	BFI parameter (N)	Average annual base flow (Mgal/d)	Period-of-record scale factor
5710	Nailiilihaele Stream	1,140	na	1912	<1	--	0.26	--	--	1.02
5740	Kailua Stream	3,080	0.8	1918–28 1932–34	10	4.08	0.01	5	0.21	1.12
5745	Kailua Stream	2,840	1.10	1963–71	8	4.47	0.02	4	0.33	0.88
5750	Tenth Branch Kailua Stream	3,100	0.10	1932–33	<1	0.70	0.08	--	--	0.88
5760	Ninth Branch Kailua Stream	3,080	0.20	1932–33	<1	0.23	0.02	--	--	0.88
5770	Kailua Stream	1,253	2.39	1910–11 1913–18 1919–58	40	18.89	0.07	4	4.16	1.09
5800	Oanui Stream	1,200	na	1910–11 1913–16	2	7.51	0.4	--	--	1.09
5840	Kailua Stream	700	na	1912–13	<1	--	0.14	--	--	--
5850	Hoolawanui Stream	1,219	1.34	1910–71	60	7.77	0.15	5	2.68	1.04
5860	Hoolawaliilii Stream	1,245	0.57	1911–57	45	4.88	0.19	5	2.34	1.09
5870	Honopou Stream ^a	1,208	0.65	1910–97	85	3.12	0.13	5	1.21	1.00
5910	Honopou Stream	557	na	1932–47	14	1.27	0.03	4	0.14	1.09
5930	Honopou Stream	441	na	1932–47	14	1.53	0.08	4	0.40	1.09
5950	Honopou Stream	383	na	1932–47	14	5.04	0.02	3	0.59	1.09

^a Active site

^b Low-flow partial-record site

