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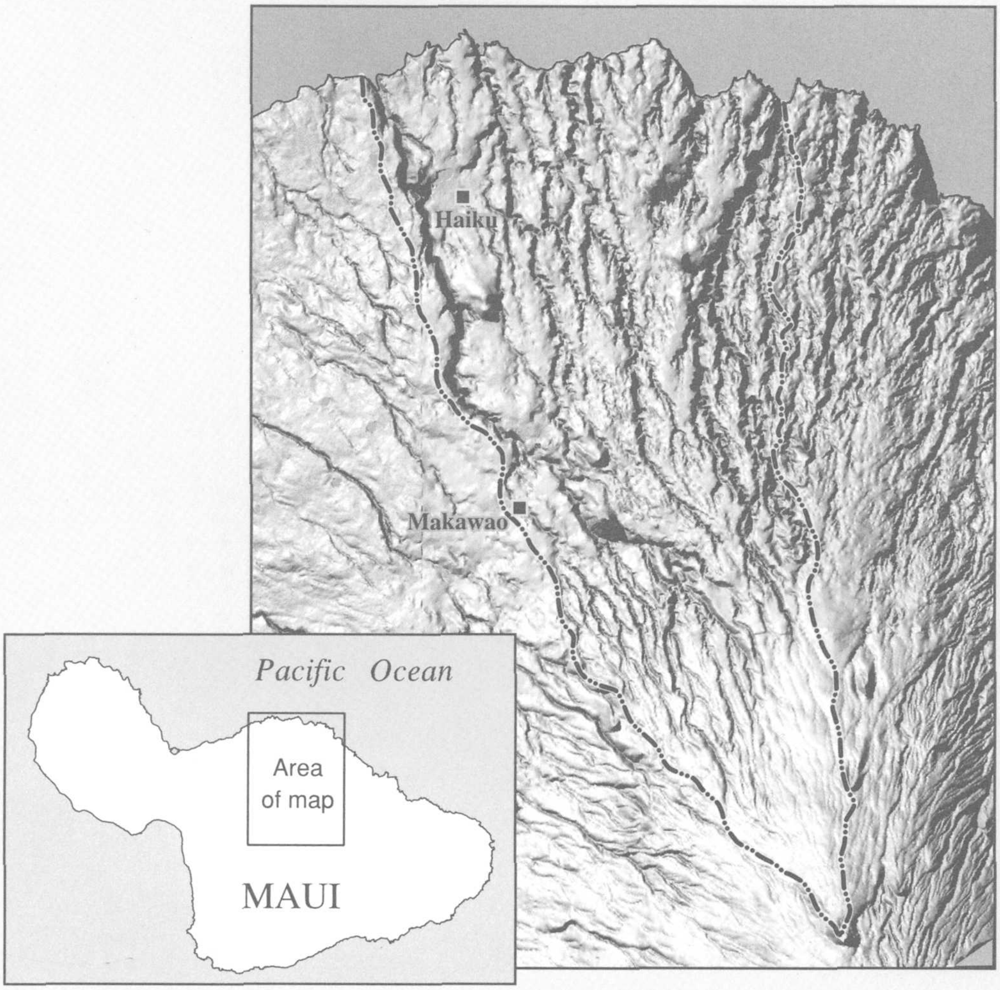
Ground Water and Surface Water in the Haiku Area, East Maui, Hawaii

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 98-4142



Prepared in cooperation with the

COUNTY OF MAUI DEPARTMENT OF WATER SUPPLY
STATE OF HAWAII COMMISSION ON WATER RESOURCE MANAGMENT

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Ground Water and Surface Water in the Haiku Area, East Maui, Hawaii

By Stephen B. Gingerich

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Honolulu, Hawaii
1999

U.S. DEPARTMENT OF THE INTERIOR
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Ground Water and Surface Water in the Haiku Area, East Maui, Hawaii

By Stephen B. Gingerich

Abstract

The Haiku study area lies on the gently sloping eastern flank of the East Maui Volcano (Haleakala) between the drainage basins of Maliko Gulch to the west and Kakipi Gulch to the east. The study area lies on the northwest rift zone of East Maui Volcano, a geologic feature 3 to 5 miles wide marked by surface expressions such as cinder, spatter, and pumice cones. The study area contains two geologic units, the main shield-building stage Honomanu Basalt and the Kula Volcanics. The hydraulic conductivity of the Honomanu Basalt was estimated to be between 1,000 and 3,600 feet per day on the basis of aquifer tests and 3,300 feet per day on the basis of the regional recharge rate and observed ground-water heads. The hydraulic conductivity of the Kula Volcanics is expected to be several orders of magnitude lower.

An estimated 191 million gallons per day of rainfall and 22 million gallons per day of fog drip reach the study area and about 98 million gallons per day enters the ground-water system as recharge. Nearly all of the ground water currently withdrawn in the study area is from well 5520-01 in Maliko Gulch, where historic withdrawal rates have averaged about 2.8 million gallons per day. An additional 18 million gallons per day of ground-water withdrawal is proposed.

Flow in Waiohiwi Gulch, a tributary to Maliko Gulch, is perennial between about 2,000 ft and 4,000 ft altitude. At lower altitudes in Maliko Gulch, flow is perennial at only a few spots downstream of springs and near the coast. The Kuiaha and Kaupakulua Gulch systems are usually dry from sea level to an altitude of 350 feet and gain water from about 350 feet to about 900 feet altitude. The two main branches of the Kaupakulua Gulch system alternately gain and lose water as high as 2,400 feet altitude. Kakipi Gulch has perennial flow over much of its length but is often dry near the coast below 400 feet altitude.

Fresh ground water occurs in two main forms: (1) as perched high-level water held up by relatively low-permeability geologic layers, and (2) as a freshwater lens floating on denser, underlying saltwater. 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: (1) streams are dry or losing water where they are incised into the Honomanu Basalt, (2) the hydraulic conductivity of the Honomanu Basalt is too high to support a thick ground-water lens given the estimated recharge to the study area, and (3) wells that penetrate through the contact have encountered conditions of cascading water from above the contact and dry lava tubes in the Honomanu Basalt. More than 90 percent of the recharge to the study area is estimated to flow downward through the perched high-level water body to reach the freshwater lens.

A cross-sectional, steady-state, variably saturated ground-water flow model using the computer code VS2DT was constructed to evaluate whether a two-layer, variably saturated ground-water flow system could exist given the hydrologic and geologic conditions of the Haiku study area. Using 25 inches per year of recharge and hydraulic characteristics representative of the Kula Volcanics and the Honomanu Basalt, the model demonstrates that a 13-foot thick geologic layer with a saturated vertical hydraulic conductivity less than 6.6×10^{-2} feet per day can impede vertical ground-water flow enough to produce two separate saturated zones with an unsaturated zone between them. Subsequent lower

vertical hydraulic conductivity values for the impeding layer allow even less water to reach the lower layer.

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, Hawaii. 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 of ground water from the Haiku area between Maliko and Kakipi Gulches (County of Maui Department of Water Supply, 1992). An additional withdrawal of 1.5 Mgal/d from a private well is proposed. 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 provides a critical habitat for several endangered and threatened native animal species. Current knowledge of the relation between surface water 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. Because additional ground-water development is projected to first occur in the Haiku area, a significant part of the study was focused on this area. Historic and new streamflow and ground-water data were collected and analyzed to determine gains and losses of streamflow 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 describe (1) the regional relation between surface water and ground water, (2) the conceptual model of ground-water occurrence, and (3) flow characteristics of individual streams in the Haiku area of northeastern 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 done throughout much of the study area. Streamflow measurements were made along selected streams in the study area to characterize the gains and losses along the stream length. Water-level maps were produced on the basis of water-level information contained in the drilling records of wells in the area. A two-dimensional, variably saturated numerical ground-water flow model was constructed to evaluate whether the observed geologic and hydrologic conditions could support a multi-layered variably saturated flow system. An understanding of the dynamics of the ground-water flow system is important for evaluating the effects of ground-water withdrawal on streams in the area.

Surface-Water Gaging Station Numbers

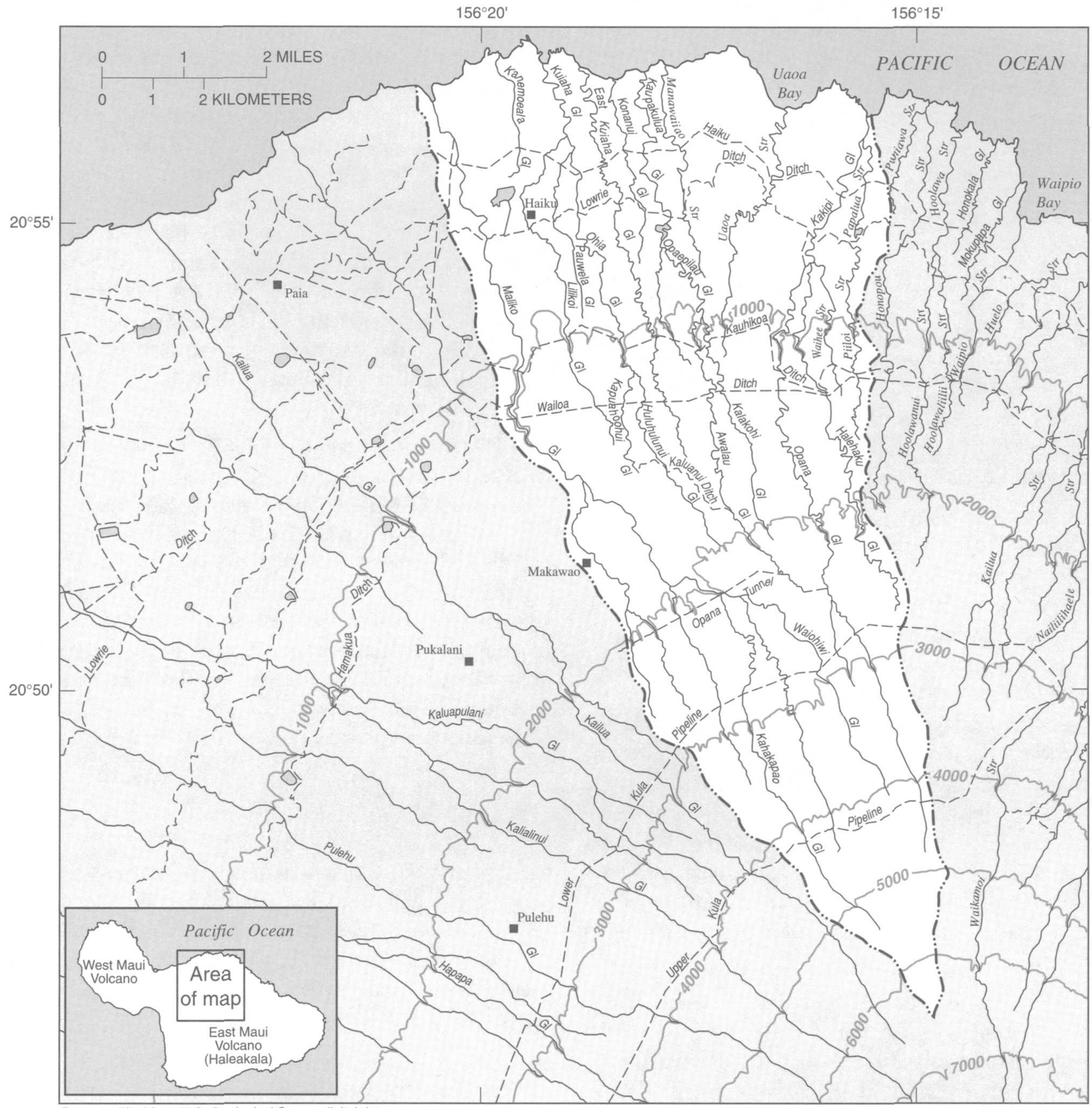
The surface-water gaging stations mentioned in this report are numbered according to the USGS numbering system. For this report, however, the complete 8-digit number is abbreviated to the middle 4 digits; for example, station 16596200 is referred to as 5962.

Acknowledgments

Garret Hew of East Maui Irrigation Co., Inc. and many private land owners in the study area provided cooperation and assistance. Mike Robertson of Wailani Drilling provided useful information on several wells in the study area.

DESCRIPTION OF STUDY AREA

The Haiku study area lies on the gently sloping eastern 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 (fig. 1). The wedge-shaped study area, covering about 42 mi^2, is bounded to the north by about 5 mi of coastline and lies between Maliko Gulch to the west and tributaries of Kakipi Gulch to the east (fig. 1). About 7 mi from the coast at an altitude of 2,400 ft, these two gulches are

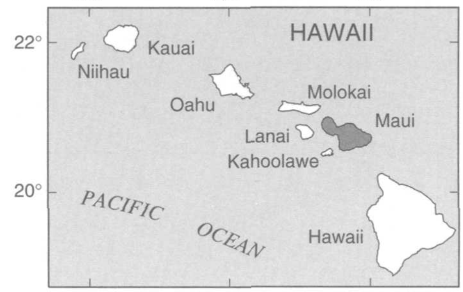


Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 20°39'30" and 20°57'30", central meridian 156°20'15"

EXPLANATION

—··—··— STUDY-AREA BASIN BOUNDARY

—1000— TOPOGRAPHIC CONTOUR--Interval 1,000 feet



LOCATION MAP

Figure 1. Haiku study area, east Maui, Hawaii.

less than 0.5 mi from each other. The upper tributaries of the gulches are roughly parallel above this altitude to near an altitude of 5,000 ft where they are no longer distinguishable on a 1:24,000 scale topographic map. The area above 5,000 ft to the summit near 9,000 ft lies in the drainage basins of Kailua Gulch to the west or Waikamoi Stream to the east.

Land use at lower altitudes (below 4,000 ft) in the study area has changed from primarily livestock grazing prior to the 1920's to primarily pineapple cultivation in the 1920's and 1930's and then to pineapple cultivation mixed with livestock grazing and some residential areas from the 1940's to the present (1998) (Territorial Planning Board, 1939; Economic Planning and Coordination Authority, 1957; Soil Conservation Service, 1982). At higher altitudes, much of the land has historically been forested State conservation land or used for livestock grazing.

Rainfall distribution on the northern flank of the volcano is primarily governed by the orographic effect. Precipitation is heaviest where the prevailing northeasterly trade winds encounter the flank of the volcano, forcing warm, moist air into the cool, higher altitudes. The highest rainfall amounts are usually recorded between 2,000 and 6,000 ft altitude. The study area lies on the western side of where these effects are most predominant (fig. 2). Mean annual rainfall increases from about 60–80 in/yr at the coast to nearly 200 in/yr at an altitude of 2,500 ft on the eastern side of the study area and then decreases to about 60–80 in/yr near 5,000 ft altitude (Giambelluca and others, 1986). Above an altitude of 1,000 ft, rainfall contours are nearly perpendicular to the coast.

Annual rainfall at 7,030 ft altitude (Haleakala Ranger Station, rain gage 338, fig. 2) ranged from about 18 to 111 inches during 1939–96 (fig. 3). Downslope at 2,520 ft altitude (Kailiili, rain gage 436, fig. 2), annual rainfall ranged from about 57 to 201 inches during 1925–80 (fig. 3). Nearer the coast at 485 ft altitude (Pauwela, rain gage 490, fig. 2), rainfall ranged from about 36 to 94 inches annually during 1919–69.

The 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, in press). On the basis of Shade's data, the total volume of average rainfall in the Haiku study area is estimated to be 191 Mgal/d, or 96 in/yr averaged over the entire study area.

Studies on the islands of Hawaii, Lanai, and Oahu (Juvik and Nullet, 1995; Giambelluca and Nullet, 1991; Ekern, 1964; and Ekern, 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 (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 amount of fog drip in the Haiku study area was estimated to be about 22 Mgal/d in the water-budget study of east Maui (Shade, in press).

No published pan-evaporation records exist for any sites in the study area. The nearest site is about 1 mi to the west of Maliko Gulch (station 485, fig. 2) where the station altitude was 320 ft. During 1963–70, measured pan evaporation at this station ranged from 85.15 to 102.62 inches (Ekern and Chang, 1985). Shade used a one-to-one relation between pan evaporation and potential evapotranspiration to estimate that about 33 percent of rainfall and fog drip or 70 Mgal/d is accounted for by evapotranspiration in the Haiku study area (Shade, in press).

HYDROGEOLOGY

East Maui Volcano is formed primarily by extrusive shield- and post-shield-stage lavas and secondarily by rejuvenated-stage volcanic rocks which cover the summit and southern and eastern regions (fig. 4). Intrusive volcanic rocks in the form of dikes associated with rift zones and volcanic vents are found along three axes.

Extrusive Volcanic Rocks

Geology

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. Aa flows contain massive central cores typically sandwiched between rubbly clinker layers.

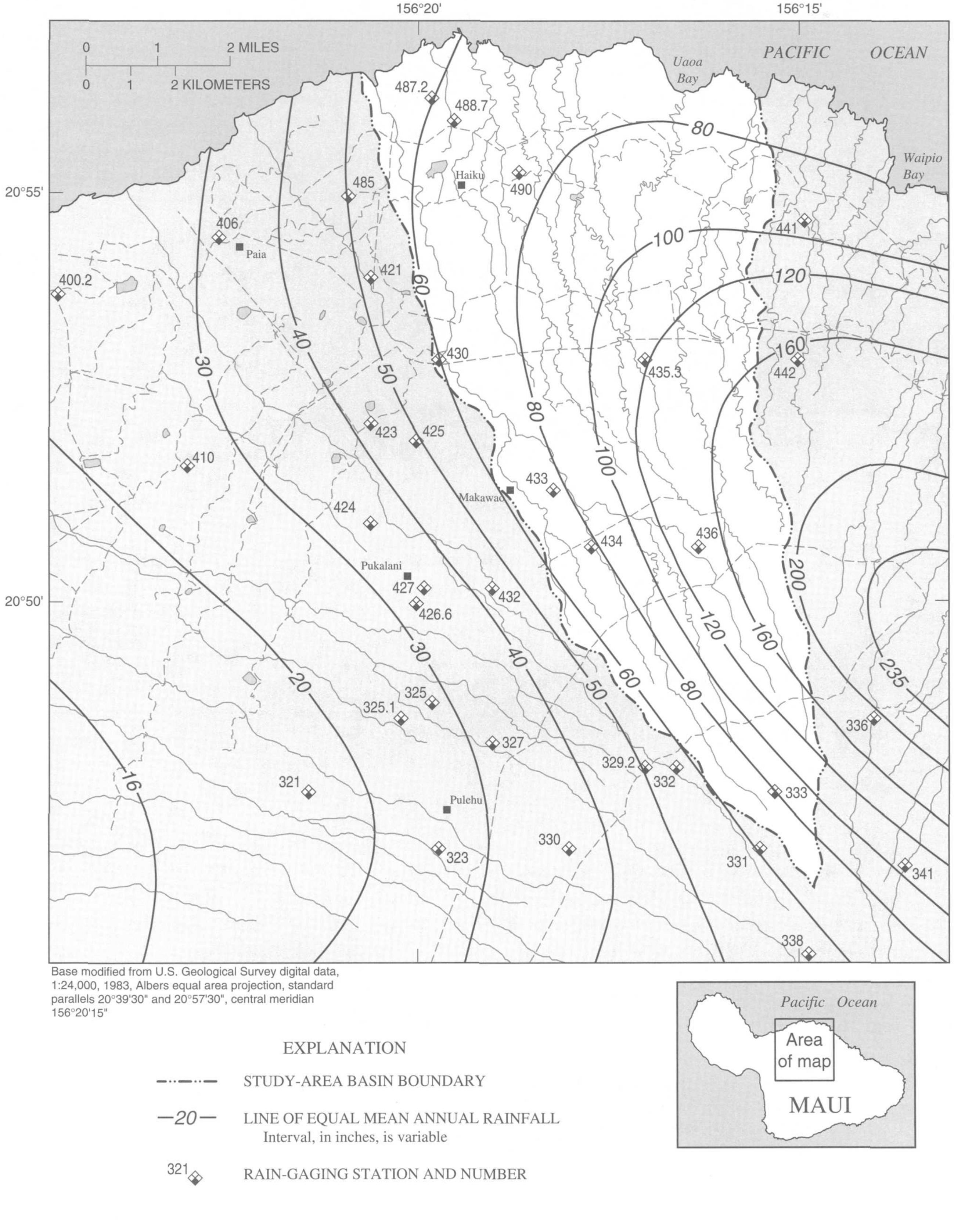


Figure 2. Mean annual rainfall in the Haiku study area, east Maui, Hawaii (modified from Giambelluca and others, 1986).

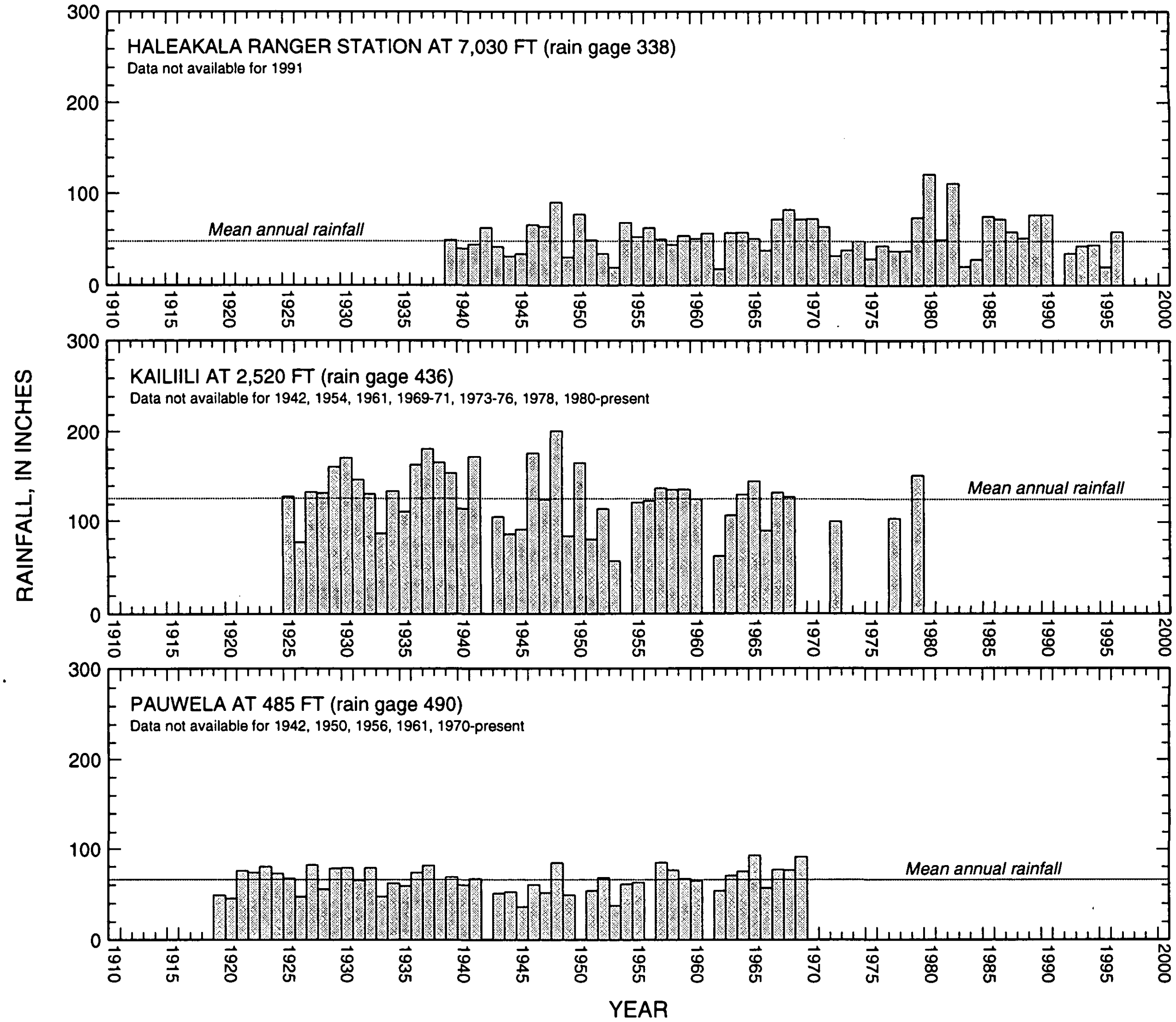


Figure 3. Annual rainfall at Haleakala Ranger Station, Kailiili, and Pauwela rain gages, east Maui, Hawaii (Data from U.S. Department of Commerce digital data, National Climatic Data Center, and East Maui Irrigation Co., Inc.. in unpub. files, U.S. Geological Survey, Hawaii District office).

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. 4) 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° with the flatter dips near the isthmus where flows approached the West Maui Volcano. The basalts were laid down as very 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 typically 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 study area, exposures of Honomanu Basalt are found in Maliko Gulch, Kakipi Gulch, and along the coast between the two gulches (Stearns, 1942). Exposures are easily identified as Honomanu Basalt in the

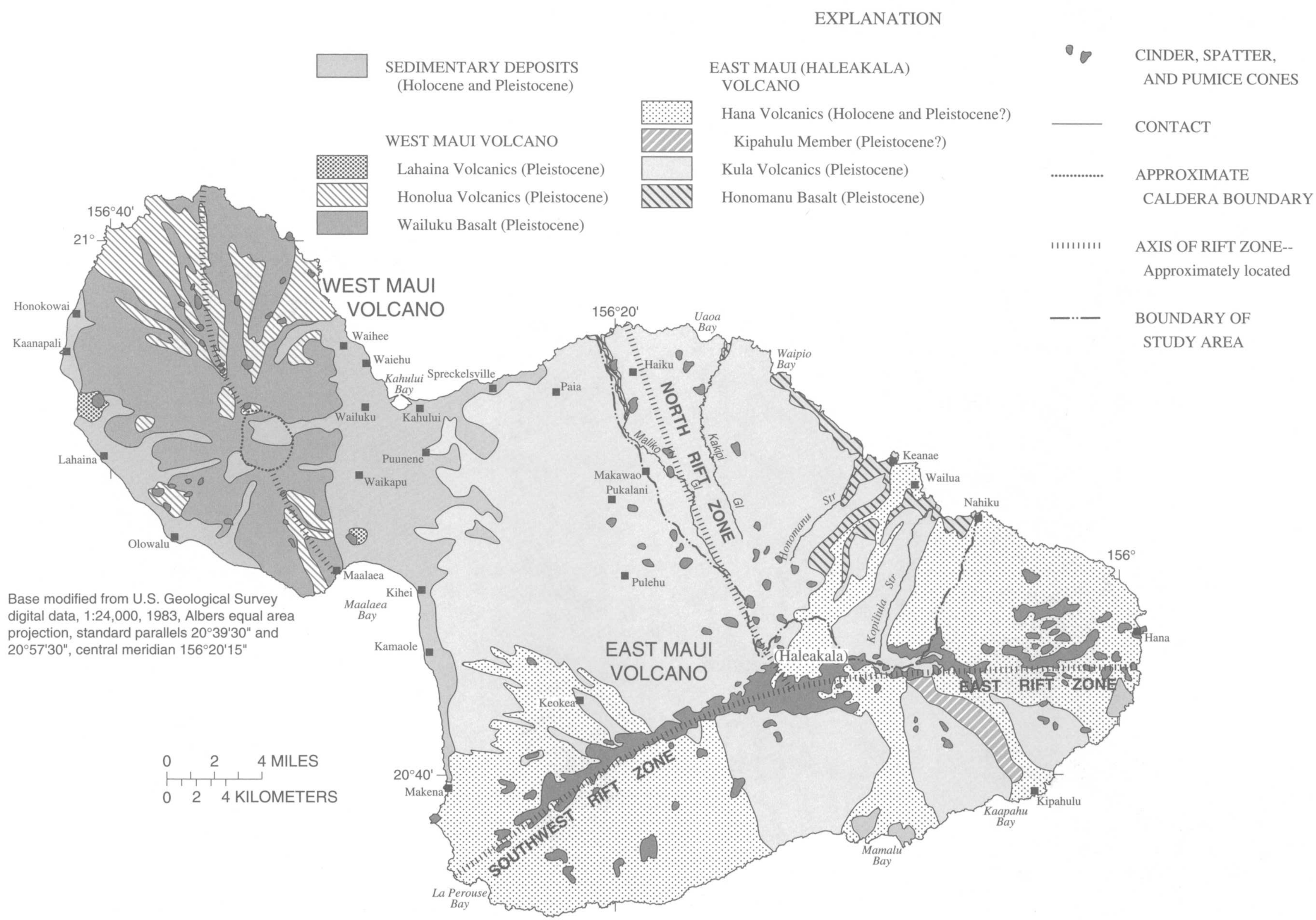


Figure 4. Generalized surficial geology, Maui, Hawaii (modified from Langenheim and Clague, 1987).

field when they are thin bedded, porphyritic, and commonly show characteristics typical of pahoehoe flows. Field reconnaissance has shown that exposures of Honomanu Basalt can be found nearly 4 mi from the coast at an altitude of about 600 ft in Maliko Gulch and almost 1 mi from the coast in Kakipi Gulch at an altitude of about 100 ft. These exposures are much more extensive than those shown on the map by Stearns (1942) which shows the Honomanu Basalt exposed in Maliko Gulch for less than a mile from the coast and no exposures in Kakipi Gulch.

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). Rocks from this transitional phase are 50 to 100 ft thick and can be 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 undoubtedly 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 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 generally thicker and narrower than the Honomanu Basalt and have more lenticular bedding due to the filling of swales and valleys eroded into the underlying rocks. Flows of the Kula Volcanics cover almost all of the study area (fig. 4).

Rejuvenated-stage lavas of alkalic basalt and basanite, named the Hana Volcanics, are exposed only in the southern and eastern areas of east Maui (fig. 4) and are not found in the study area.

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 high 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. No published estimates are available of hydraulic conductivity for rocks in the study area and few are available for Maui in general.

The horizontal hydraulic conductivity of the Honomanu Basalt in the study area was estimated to be 3,600 ft/d on the basis of a single-well aquifer test done at well 5419-01 (C.D. Hunt, Jr., hydrologist, USGS, written commun., 1997). An analysis of a variable-discharge test at well 5420-01, which is open to the Honomanu Basalt and located just west of the study area, yielded a horizontal hydraulic conductivity estimate of greater than 1,000 ft/d (unpub. data, aquifer-test archive, USGS, Hawaii District). Stearns and Macdonald (1942) classify 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).

In the absence of more long-term aquifer tests, a comparison of specific capacities of wells open to the Honomanu Basalt can be made to evaluate the relative yield of the aquifer penetrated by each well. The specific capacities of nine wells in or near the Haiku study area, which penetrate below sea level and are therefore expected to be in the Honomanu Basalt, average about 600 gal/min/ft of drawdown (table 1). The values decrease toward the east and range from 1,400 gal/min/ft of drawdown at the westernmost well (5320-01) to 0.67 gal/min/ft of drawdown at the easternmost well (5514-01).

Hydraulic conductivity can also be estimated using an equation for a water-table surface in a coastal aquifer (modified from Marsily, 1986, p. 224):

$$h^2 = \frac{2\beta Q}{K(1+\beta)L}x \,, \qquad (1)$$

where:

h = hydraulic head, in feet;
β = density ratio between freshwater and saltwater, 0.025;
Q = ground-water flow, in cubic feet per day;
K = hydraulic conductivity, in feet per day;
L = width of cross section of ground-water flow, in feet; and
x = distance from coast, in feet.

Table 1. Specific capacities of selected wells, Haiku study area, east Maui, Hawaii

[All well information is from unpublished data, USGS, Hawaii District well files unless otherwise noted; drawdown values are not corrected for well loss; --, not measured or no data; datum is mean sea level; <, less than; >, greater than]

State well number	Well name	Withdrawal rate (gallons per minute)	Length of test (minutes)	Drawdown (feet)	Specific capacity (gallons per minute per foot of drawdown)	Altitude of bottom of open interval (feet)
6-5317-01	Kulamalu	1,400[a]	5,210	18.3	77	-128
6-5320-01	Hamakuapoko 2	700; 840	6,000; 8,640	0.4; 0.6	1,750; 1,400	-32
6-5413-01	Huelo 1	6	360	180	0.03	230
6-5413-09	Hagar	14	250	0.25	56	-33
6-5419-01	Haiku	350; 500; 700	4,320; 4,680; 10,080	0.6; 0.95; 1.0	583; 526; 700	-43
6-5420-01	Maui High School	150–500	4,315	0.2–1.7	750–294	-22
6-5420-02	Hamakuapoko 1	492	6,090	1.5	328	-34
6-5513-01	Tavares	10	130	145	0.07	79
6-5514-01	Marquard	21; 25	14; 483	78; 37	0.27; 0.68	-61
6-5516-01	Feehan	1	27	67	0.01	185
6-5519-01	Pauwela	480	3,900	0.46	1,043	-34
6-5519-02	Behnke	7	--	78	0.09	132
6-5520-01	HC&S 11 A,B	2,354	--	1.9	1,239	-93
6-5616-02	Martin	35	480	< 0.1	> 350	-39

[a] Austin, Tsutsumi and Associates, Inc. (1998)

Ground-water flow, Q, was set equal to the $1.3\times10^7 ft^3/d$ recharge (from the section "Ground-Water Recharge" later in this report), head in the aquifer was measured at well 5317-01 located 20,000 ft from the coast (location shown on fig. 5) so h was set equal to 12 ft (also from the section entitled "Ground-Water Levels") and L was set equal to 26,400 ft (5 mi). Using equation 1 and solving for K yields an estimate for hydraulic conductivity of about 3,300 ft/d. At well 5519-01, located 5,300 ft from the coast, the head is 5.4 ft and the resulting hydraulic-conductivity estimate from equation 1 is 4,400 ft/d.

No estimates are available for the hydraulic conductivity of the Kula Volcanics in the study area. An aquifer test was done on well 4806-48, near Nahiku, Maui which penetrates about 350 ft of the transitional rocks of the lower Kula Volcanics and the upper Honomanu Basalt and the resulting horizontal hydraulic conductivity estimate was 0.83 ft/d (unpub. data, aquifer-test archive, USGS, Hawaii District). The specific capacities of four wells that presumably are open to the Kula Volcanics range from 0.01 to 0.09 gal/min/ft of drawdown. 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.

Intrusive Volcanic Rocks

Geology

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 lies on one of these, the northwest rift zone (fig. 4). Because of the relative youth of East Maui Volcano, exposures of dikes are scarce and limited to the walls of the summit and the larger valleys (Stearns, 1942) (fig. 4). But 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: 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 dike complex associated with the northwest rift zone of East Maui Volcano appears to be about 3 mi wide near the coast and could be greater than 5 mi wide

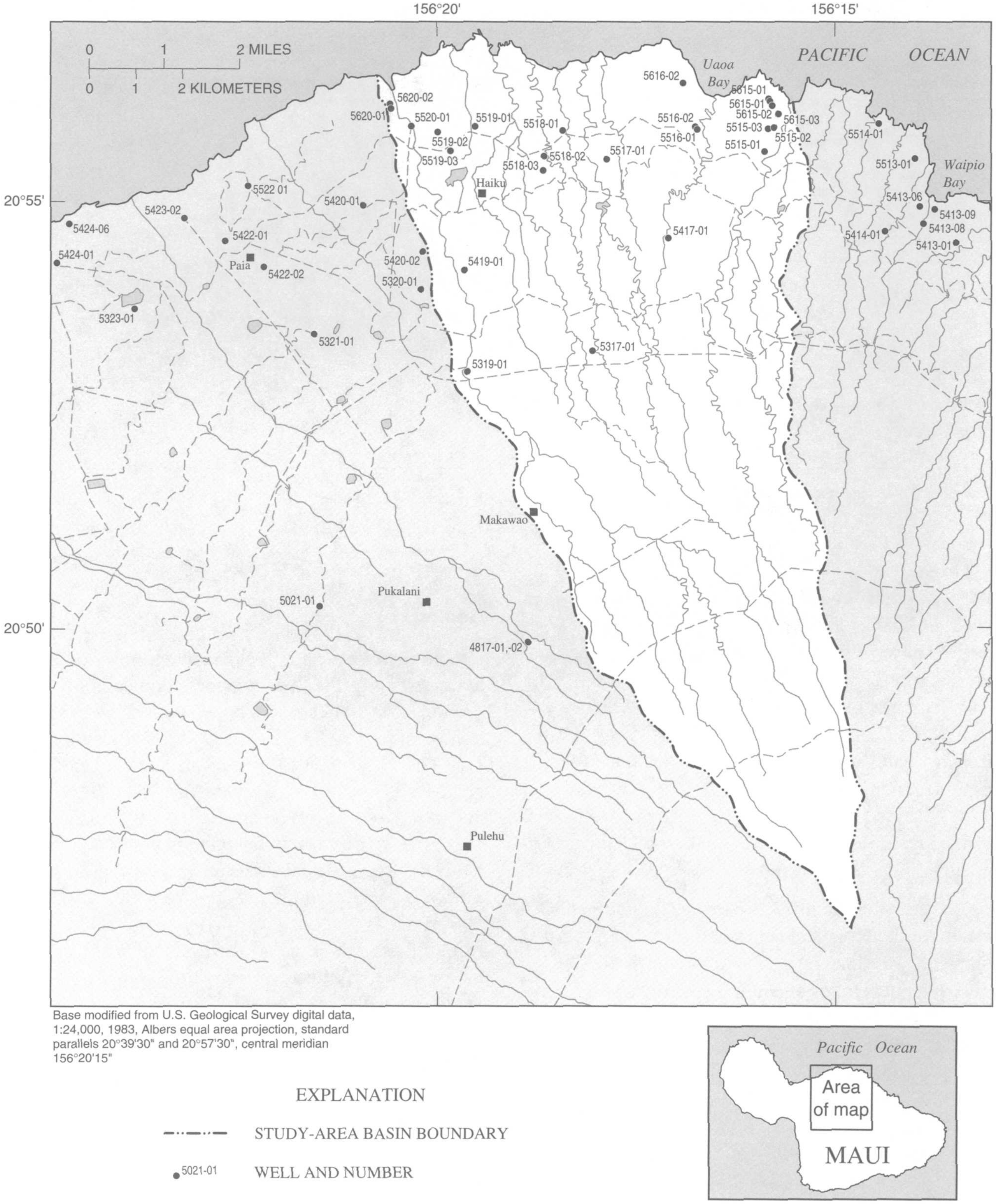


Figure 5. Selected wells in the Haiku study area, east Maui, Hawaii.

at an altitude of 4,000 ft on the basis of the locations of the cinder and spatter cones which are in two parallel and roughly linear patterns (fig. 4). The entire study area lies within this dike complex. On Oahu, the dike complexes 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 dike complexes are hydrologically important because dikes have low permeability and tend to impound ground water to high altitudes between dikes.

Hydraulic Conductivity

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 in the direction parallel to the strike of the dikes rather than perpendicular to the strike. On the basis of a numerical model, Meyer and Souza (1995) estimated that dikes have a hydraulic conductivity of 10^{-5} to 10^{-2} ft/d and that the dikes reduce the average, effective hydraulic conductivity of the dike complex to about 0.01 to 0.1 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.

HYDROLOGY

Ground-Water Recharge

Ground-water recharge in the Haiku study area was estimated to be 98 Mgal/d on the basis of a monthly water budget for all of east Maui calculated for natural vegetation conditions (Shade, in press) (fig. 6). This estimate represents an average recharge of about 49 in/yr over the 42 mi^2 study area. However, recharge varies areally from a minimum of less than 10 in/yr in some areas near the coast to a maximum of almost 150 in/yr in the areas of highest rainfall and fog drip between altitudes of 2,000 and 6,000 ft. The recharge estimate represents the average of two different monthly water-budget computation methods which differ by 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 21 percent. The 98 Mgal/d of estimated recharge is about 46 percent of the rainfall and fog drip in the study area.

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). The Haiku study area has had areas of pineapple cultivation that have been, in the 1960's, as large as about 9 mi^2, or 21 percent of the study area (University of Hawaii Land Study Bureau, 1967). Therefore, the estimate of recharge calculated on the basis of natural vegetation conditions is probably slightly low when the effects of pineapple cultivation are considered. Also, a small amount of water probably recharges the aquifer by infiltration from the surface-water diversion ditches and tunnels and from associated surface reservoirs, but this amount is unknown.

Ground-Water Withdrawal

Nearly all of the ground water currently withdrawn in the study area is from well 5520-01 in Maliko Gulch (fig. 5). The well, which consists of ten vertical borings as deep as 90 ft below sea level connected with two lateral tunnels and two pumps (pumps 11A and 11B), was drilled during 1897–99 into Honomanu Basalt (Stearns and Macdonald, 1942, p. 217), although one account suggests that the well draws water from the gravel in the base of Maliko Gulch (K.N. Vaksvik, 1929, unpublished note in files of the USGS, Hawaii District). Water from this system is pumped to the Haiku Ditch for irrigation. The records of yearly or monthly pumpage show that the annual ground-water withdrawal averaged 2.8 Mgal/d during 1913–96, which includes the period 1954–60 when the pumps in the well were not in operation (fig. 7). Monthly pumpage from the well has

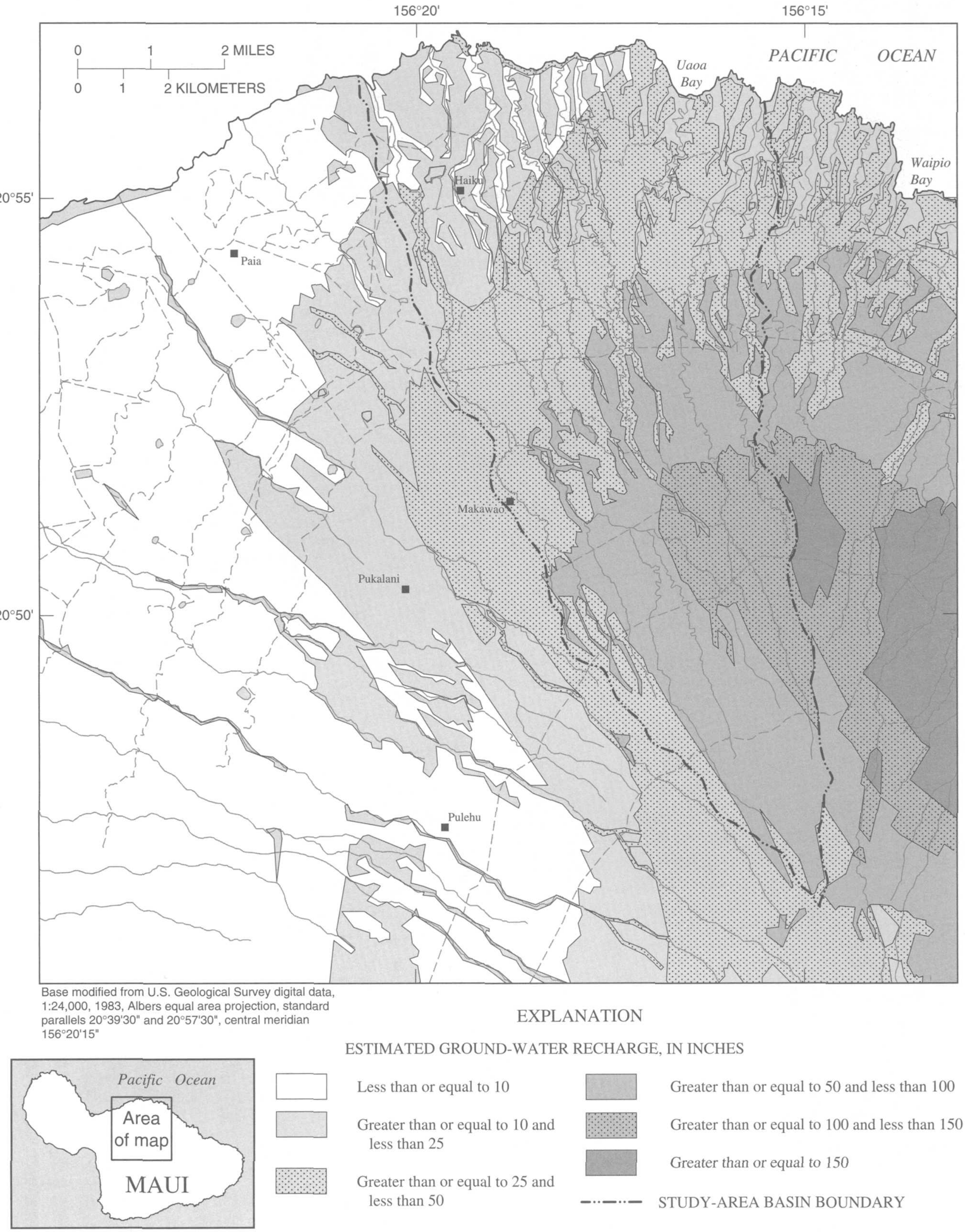


Figure 6. Average annual ground-water recharge in the Haiku study area, east Maui, Hawaii (modified from Shade, 1999).

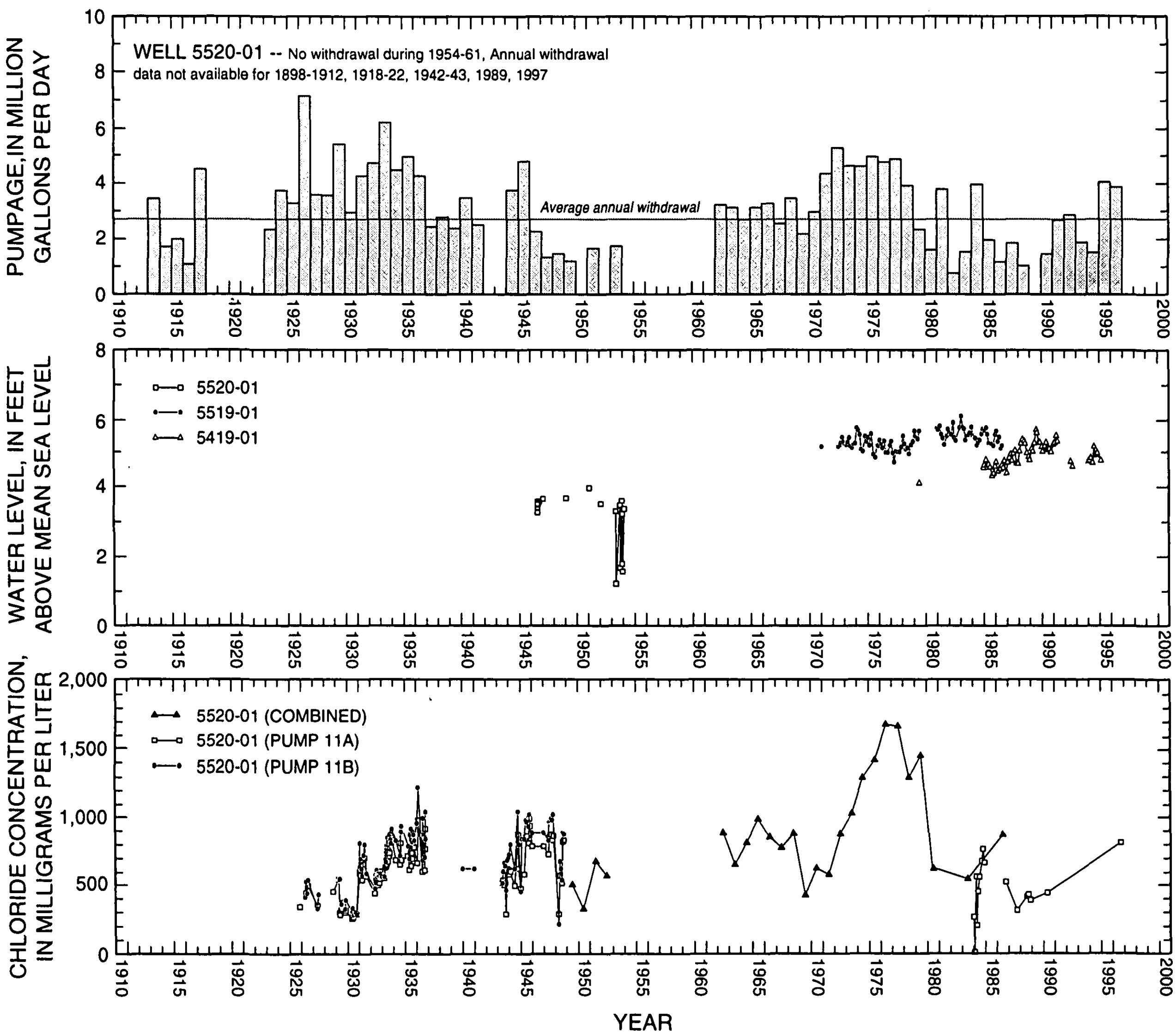


Figure 7. Monthly or annual withdrawal, selected water levels, and chloride concentrations of ground water from selected wells, Haiku study area, east Maui, Hawaii.

varied seasonally from zero to as much as 17 Mgal/d. Unreported withdrawals from domestic wells in the area probably total less than 0.2 Mgal/d on the basis of well-installation specifications listed on various well-permit applications (Department of Land and Natural Resources). A well (5318-01) presently being constructed (1998) near Kaupakulua (fig. 5) is proposed for withdrawal of about 1.5 Mgal/d from the Honomanu Basalt (Department of Land and Natural Resources pump installation permit, 1998).

Attempts have been made to enhance discharge from several small springs in the area by tunneling to obtain water for domestic supplies. Waihou Spring (wells 4817-01, -02; fig. 5) supplied about 15,000 gal/d to Haleakala Ranch from three short tunnels in a lava-covered cinder cone in the Kula Volcanics at an altitude of 3,350 ft (Stearns and Macdonald, 1942, p. 213) but the water-supply system is now abandoned. Kawaikoa tunnel is reported to be a 100-ft long tunnel at an altitude of 10 ft in Maliko Gulch that intercepts about 5,000 gal/d of water from a soil and gravel layer between the

Table 2. Summary of influence of surface-water diversions on streams, Haiku study area, east Maui, Hawaii
[Datum is mean sea level]

Diversion system	Approximate altitude of system (feet)	Kakipi Gulch system: includes Kakipi, Halehaku, and Opana Gulches	Kaupakulua Gulch system: includes Kaupakulua, Opaepilau, Kalakohi, and Awalau Gulches	Kuiaha Gulch system: includes Kuiaha, Ohia, Huluhulunui, Kapuaahoohui, Pauwela, and Lilikoi Gulches	Maliko Gulch system: includes Waiohiwi and Kahakapao Gulches
Upper Kula Pipeline	4,200	takes water	does not cross	does not cross	no effect
Lower Kula Pipeline	2,800	no effect	does not cross	does not cross	no effect
Opana Tunnel	2,200	takes water	adds then takes water	does not cross	no effect
Kaluanui Ditch	1,600	does not cross	takes water	adds water	abandoned
Wailoa Ditch	1,200	takes water	no effect	no effect	no effect
Kauhikoa/New Hamakua Ditch	1,000	adds then takes water	takes water	takes water	no effect
Lowrie Ditch	600	takes water	takes water	takes water	no effect
Haiku Ditch	400	takes water	takes water	takes water	no effect

Kula Volcanics and the Honomanu Basalt (tunnel 24, Stearns and Macdonald, 1942, p. 213). But the geologic map (Stearns, 1942) shows tunnel 24 at an altitude of about 1,110 ft on the east side of Maliko Gulch. This site matches the location of well 5319-01 (fig. 5) in the State records named Silveno Spring (Department of Land and Natural Resources, 1991) so there appears to be a discrepancy in the naming of this tunnel. Silveno Spring could be the same spring that is called both Pukalani Spring and spring 17 by Stearns and Macdonald (1942, p. 212). This spring is located about 200 ft upstream of the Wailoa Ditch siphon on the floor of Maliko Gulch at an altitude of about 840 ft and discharges from an interbedded ash and soil layer in the Kula Volcanics. Both the tunnel and the spring lie well above the contact between the Honomanu Basalt and the Kula Volcanics. Well 5620-01 (fig. 5) is a 130-ft long tunnel that also intercepts water from a soil and gravel layer between the Kula Volcanics and the Honomanu Basalt at an altitude of 50 ft near the mouth of Maliko Gulch (tunnel 23, Stearns and Macdonald, 1942, p. 213). According to Stearns and Macdonald (1942), well 5620-01 supplies about 10,000 gal/d of water, some of which is currently used as a domestic supply for several homes in the area.

Streamflow

The drainage pattern of the stream valleys on east Maui is radial from the summit of East Maui Volcano to the ocean. The streams in the study area drain to the north. Valley development is in a youthful stage as streams are eroding downward into the original volcano slope, forming steep-sided valleys and leaving nearly uneroded upland areas (planezes) between the stream valleys. Streamflow consists of direct runoff, base flow, and flow added to some streams from the network of irrigation ditches that cross the study area. Base flow represents ground-water discharge to the stream. Maliko and Kakipi Gulches are the major drainage features of the study area (fig. 1). Twelve minor stream valleys (not all shown on fig. 1) enter the ocean between these two gulches and the largest of these minor streams are the Kuiaha and Kaupakulua Gulch drainages. Eight surface-water diversion systems carry water across the study area from east to west and all of these systems either remove water from or add water to at least one stream in the study area (fig. 1, table 2). Currently, the USGS maintains one surface-water gaging station on an upper tributary of Kaupakulua Gulch to measure streamflow-diversion from Kakipi Gulch. The USGS has also historically maintained gaging stations on tributaries of Kakipi Gulch (Fontaine, 1996).

The rate at which a stream is observed to gain water is dependent on hydrogeologic conditions and on the spacing of streamflow measurements made along the stream channel. Ideally, streamflow should be measured at sites spaced at equal distances along the entire length of the channel, but because of the large size of the study area, the rugged terrain, and the presence of surface-water diversion systems, this approach was impractical. Therefore, stream measurements were

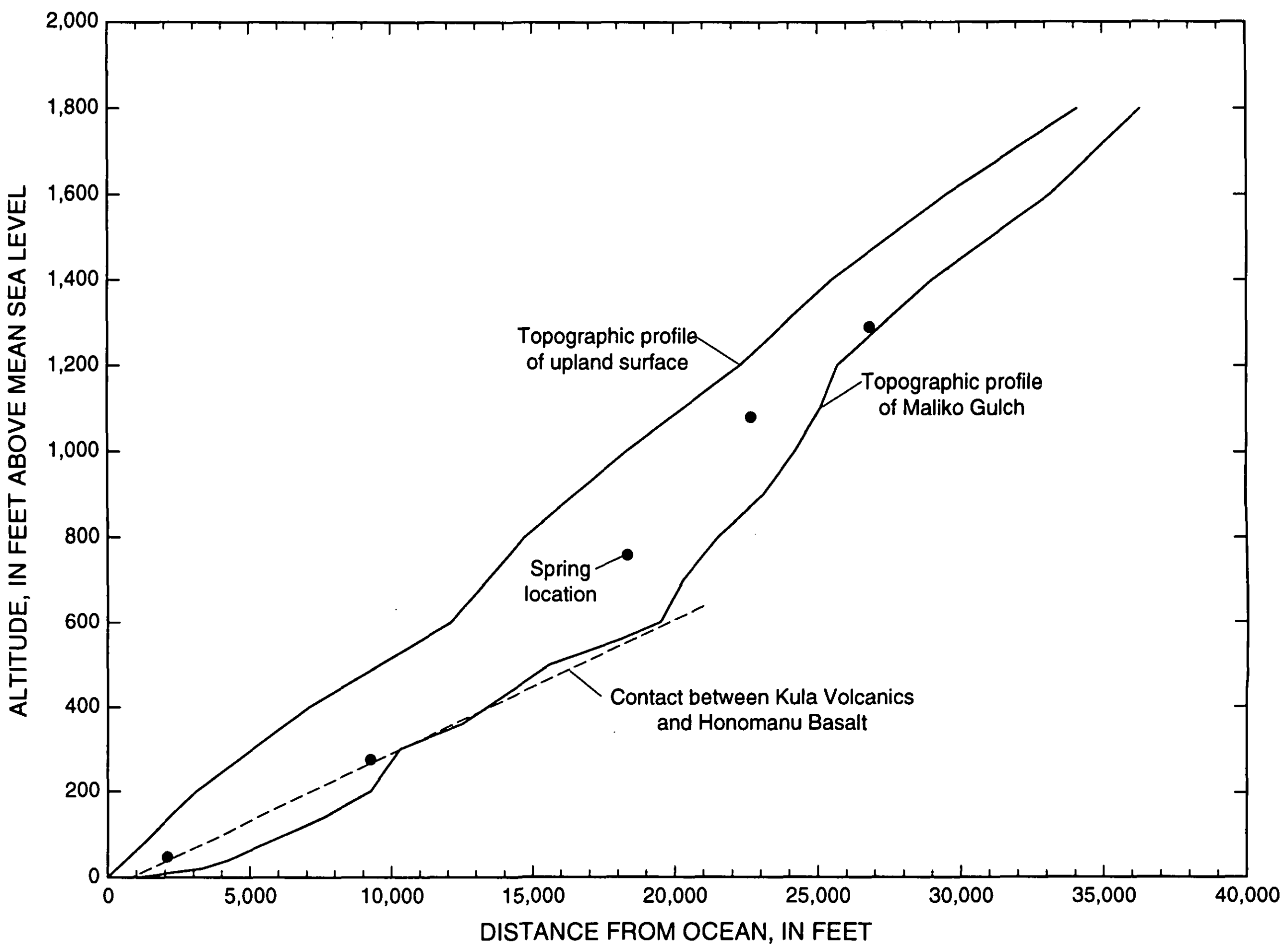


Figure 8. Topographic profile of Maliko Gulch, east Maui, Hawaii.

made at sites determined by accessibility and the location of the streamflow diversions.

Maliko Gulch

Maliko Gulch is the most deeply incised stream valley in the study area with some sections of the valley floor more than 400 ft below the upland surface (fig. 8). The floor of the gulch gradually rises from sea level to about 600 ft altitude at a distance of about 3.4 mi from the coast. Along this entire length, the valley is eroded through the Kula Volcanics into the Honomanu Basalt. Above 600 ft altitude the valley floor lies on the thick flows of the Kula Volcanics, which provide more resistance to erosion. Here the valley profile has a more stairlike configuration with numerous small waterfalls and a steeper gradient; the altitude of the base of the gulch increases from 600 ft to 1,200 ft after only another mile of length inland. The gulch splits into two main tributaries, Kahakapao and Waiohiwi Gulches, at about 1,800 ft altitude and these gulches rise at a gradient of about 840 ft/mi to about 5,400 and 4,000 ft altitude, respectively. None of the eight surface-water diversion systems that cross Maliko Gulch are built to take water from the gulch. Occasionally, water is added to Maliko Gulch at the Wailoa Ditch crossing.

Flow is perennial in Waiohiwi Gulch between 2,000 ft and 4,000 ft altitude. At lower altitudes in Maliko Gulch, flow is perennial at only a few spots downstream of springs and near the coast (fig. 9, table 3). Near the coast, a few feet above sea level, ground water discharges into the streambed from below, but at higher altitudes, streamflow is fed by springs issuing from the walls of the gulch. At sites Maliko 2 through Maliko 6, the springs seem to be associated with an ashy

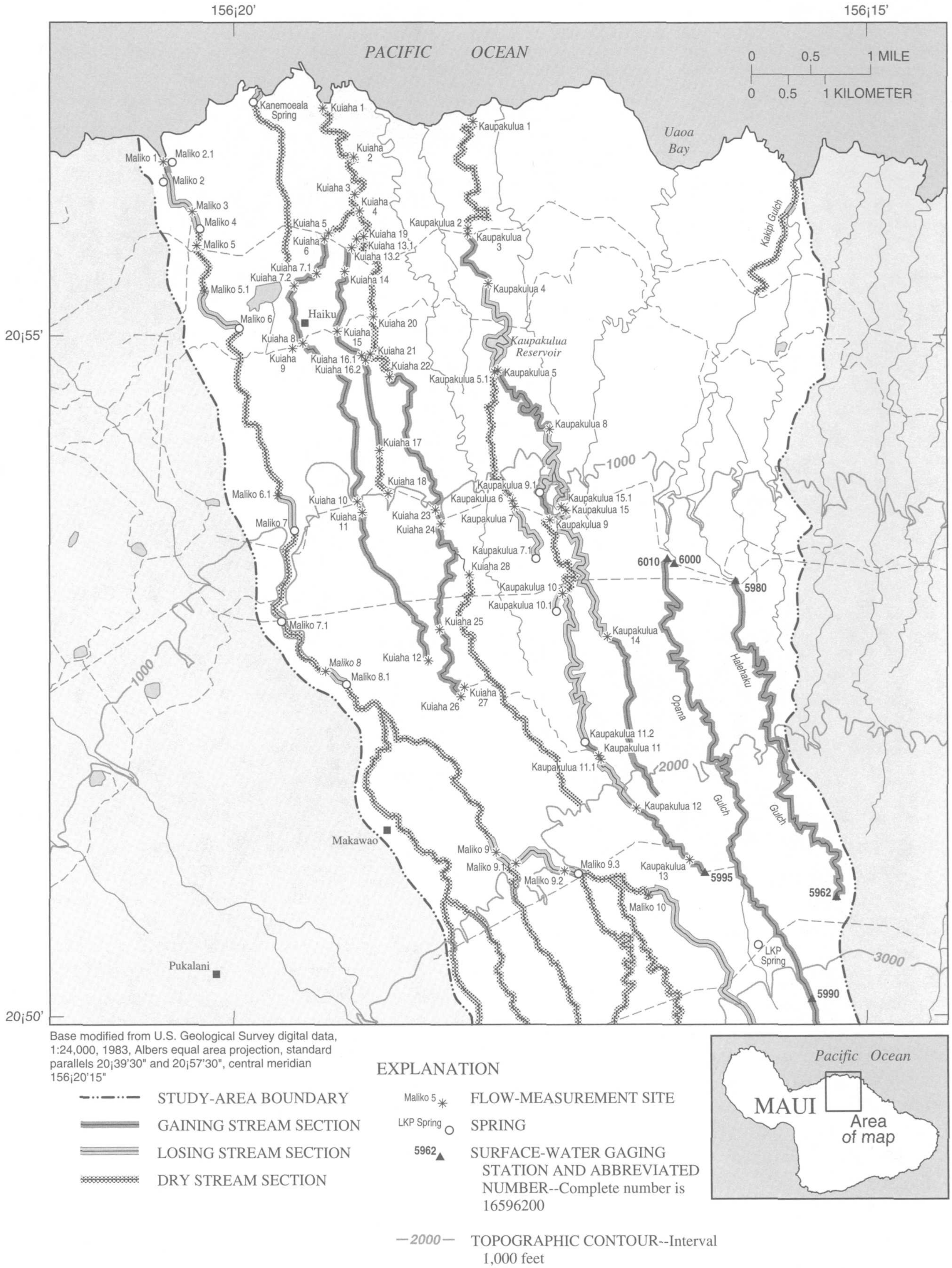


Figure 9. Surface-water gaging stations; springs; and dry, losing, and gaining sections of selected streams, Haiku study area, east Maui, Hawaii.

Table 3. Results of measurements in selected streams, Haiku study area, east Maui, Hawaii

[ft, feet; Mgal/d, million gallons per day; °C, degrees Celsius; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; --, not available, not applicable, or no sample; altitudes estimated from 1983 USGS 1:24,000-scale topographic maps (Haiku and Paia quadrangles); datum is mean sea level; <, less than]

Station number	Stream name	Altitude (ft)	Date	Flow (Mgal/d)	Type of streamflow upstream of site	Water temperature (°C)	Water specific conductance (µS/cm)	Chloride concentration (mg/L)	Comments
Maliko 1	Maliko Gulch	3	11/11/93	0.04	losing	22.2	103	--	
Maliko 2	Maliko Gulch	50	9/28/93	0.05	losing	23.3	294	--	Well 5620-01
			11/11/93	0.05		23.1	258	--	
Maliko 2.1	Maliko Gulch	50	10/7/93	< 0.01	dry	23.6	605	--	Maliko Spring at 50 ft
Maliko 3	Maliko Gulch	60	9/28/93	0.02	losing	25.5	275	--	
Maliko 4	Maliko Gulch (unnamed tributary)	135	9/28/93	0.04	dry	26.6	278	--	Maliko Spring at 135 ft
			11/11/93	0.06		23.7	277	--	
Maliko 5	Maliko Gulch	140	9/28/93	0.03	dry	24.1	411	--	
Maliko 5.1	Maliko Gulch	170	9/28/93	0	losing	--	--	--	all flow sinks into streambed
Maliko 6	Maliko Gulch	200	9/30/93	0.05	dry	24.6	141	--	Maliko Spring at 200 ft
			11/12/93	0.10		20.9	123	--	
Maliko 6.1	Maliko Gulch	500	9/28/93	0	losing	--	--	--	all flow sinks into streambed
Maliko 7	Maliko Gulch	800	11/15/93	--	dry	19.6	158	--	Maliko Spring at 800 ft
			8/20/97	0.05		--	--	--	
			10/27/97	--		21.4	146	24	
Maliko 7.1	Maliko Gulch	840	10/27/97	--	dry	--	--	--	Pukalani Spring; minor amount of
								--	flow was observed on floor of gulch
Maliko 8	Maliko Gulch	1,150	10/5/93	--	dry	24.6	123	--	
Maliko 8.1	Maliko Gulch	1,280	10/5/93	< 0.01	losing	22.1	186	--	Maliko Spring at 1,280 ft
Maliko 9	Maliko Gulch	1,680	9/29/93	0.01	losing	23.1	78	--	
Maliko 9.1	Maliko Gulch	1,740	9/29/93	0.01	losing	22.7	71	--	
Maliko 9.2	Maliko Gulch	1,890	9/29/93	0.03	gaining	21.2	80	--	
Maliko 9.3	Maliko Gulch	1,960	9/29/93	--	dry	23.1	58	9[b]	Waiohiwi Spring at 1,960 ft
Maliko 10	Waiohiwi Gulch	2,080	2/6/98	0	losing	--	--	--	all flow sinks into streambed
Kuiaha 1	Kuiaha Gulch	5	10/29/97	0	dry	--	--	--	
Kuiaha 2	Kuiaha Gulch	110	10/29/97	0	dry	--	--	--	
Kuiaha 3	Kuiaha Gulch	180	10/29/97	0	dry	--	--	--	
Kuiaha 4	Kuiaha Gulch	200	10/29/97	0	dry	--	--	--	
Kuiaha 5	Lilikoi Gulch	305	10/29/97	0	diversion	--	--	--	all water diverted by Haiku Ditch
Kuiaha 6	Lilikoi Gulch	310	10/29/97	0.23	gaining	22.1	189	23	
Kuiaha 7.1	Lilikoi Gulch	360	10/29/97	0.19	gaining	24.9	172	22	

Table 3. Results of measurements in selected streams, Haiku study area, east Maui, Hawaii--Continued

[ft, feet; Mgal/d, million gallons per day; °C, degrees Celsius; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; --, not available, not applicable, or no sample; altitudes estimated from 1983 USGS 1:24,000-scale topographic maps (Haiku and Paia quadrangles); datum is mean sea level; <, less than]

Station number	Stream name	Altitude (ft)	Date	Flow (Mgal/d)	Type of streamflow upstream of site	Water temperature (°C)	Water specific conductance (µS/cm)	Chloride concentration (mg/L)	Comments
Kuiaha 7.2	Lilikoi Gulch	380	10/29/97	0.09	gaining	23.8	147	20	
Kuiaha 8	Lilikoi Gulch	490	10/29/97	0	diversion	--	--	--	all water diverted by Lowrie Ditch
Kuiaha 9	Lilikoi Gulch	530	10/29/97	0.10	gaining	20.9	84	11	
Kuiaha 10	Lilikoi Gulch	930	10/29/97	0.01	diversion	--	--	--	most water diverted by Kauhikoa Ditch
Kuiaha 11	Lilikoi Gulch	960	10/29/97	0.17	gaining	20.5	140	20	
Kuiaha 12	Lilikoi Gulch	1,400	10/28/97	0	dry	--	--	--	
Kuiaha 13.1	Pauwela Gulch	300	10/28/97	0.01	losing	22.4	188	--	
Kuiaha 13.2	Pauwela Gulch	330	10/28/97	0.02[a]	diversion	22.9	175	--	most water diverted by Haiku Ditch
Kuiaha 14	Pauwela Gulch	375	10/28/97	0.26	gaining	22.9	167	24	
Kuiaha 15	Pauwela Gulch	475	10/28/97	0.25	gaining	22.2	159	23	
Kuiaha 16.1	Pauwela Gulch	560	10/28/97	0.04	diversion	22.2	135	23	water diverted from Ohia Gulch
Kuiaha 16.2	Pauwela Gulch	560	10/28/97	0.21	gaining	--	--	--	includes water diverted from Ohia Gulch
Kuiaha 17	Pauwela Gulch	840	10/28/97	0	dry	--	--	--	
Kuiaha 18	Pauwela Gulch	960	10/28/97	0	dry	--	--	--	
Kuiaha 19	Ohia Gulch	240	10/29/97	0	dry	--	--	--	
Kuiaha 20	Ohia Gulch	400	10/28/97	0	dry	--	--	--	
Kuiaha 21	Ohia Gulch	490	10/28/97	0	diversion	--	--	--	all water diverted to Pauwela Gulch
Kuiaha 22	Ohia Gulch	575	10/28/97	0.10	gaining	22.2	135	22	
Kuiaha 23	Ohia Gulch	930	10/28/97	0.01	diversion	--	--	--	most water diverted by Kauhikoa Ditch
Kuiaha 24	Ohia Gulch	960	10/28/97	1.34	gaining	23.5	87	12	
Kuiaha 25	Kapuaahoohui Gulch	1,260	10/28/97	1.29	gaining	20.5	89.3	12	
Kuiaha 26	Kapuaahoohui Gulch	1,420	10/28/97	0	dry	--	--	--	
Kuiaha 27	Kaluanui ditch	1,520	10/28/97	1.20	--	19.7	81	11	water added to stream
Kuiaha 28	Huluhulunui Gulch	1,140	10/28/97	0	dry	--	--	--	
Kaupakulua 1	Kaupakulua Gulch	5	11/17/97	0	dry	21.2	53	8	pool with no flow
Kaupakulua 2	Kaupakulua Gulch	340	11/17/97	0	diversion	--	--	--	all water diverted by Haiku Ditch
Kaupakulua 3	Kaupakulua Gulch	350	11/17/97	0.06-0.07[a]	gaining	21.8	129	21	
Kaupakulua 4	Kaupakulua Gulch	480	11/17/97	0	diversion	--	--	--	all water diverted by Lowrie Ditch

Table 3. Results of measurements in selected streams, Haiku study area, east Maui, Hawaii--Continued

[ft, feet; Mgal/d, million gallons per day; °C, degrees Celsius; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; --, not available, not applicable, or no sample; altitudes estimated from 1983 USGS 1:24,000-scale topographic maps (Haiku and Paia quadrangles); datum is mean sea level; <, less than]

Station number	Stream name	Altitude (ft)	Date	Flow (Mgal/d)	Type of streamflow upstream of site	Water temperature (°C)	Water specific conductance (µS/cm)	Chloride concentration (mg/L)	Comments
Kaupakulua 5	Opaepilau Gulch	630	11/17/97	0.05[a]	gaining	21.1	63	10	
Kaupakulua 5.1	unnamed tributary	630	11/17/97	0	dry	--	--	--	
Kaupakulua 6	unnamed tributary	1,010	11/17/97	0	diversion	--	--	--	all water diverted by Kauhikoa Ditch
Kaupakulua 7	unnamed tributary	1,015	11/17/97	0.11	gaining	20.9	81	--	
Kaupakulua 7.1	unnamed tributary	1,180	11/18/97	--	dry	21.2	129	18	Santos Spring
Kaupakulua 8	Opaepilau Gulch	790	11/17/97	0	losing	--	--	--	
Kaupakulua 9	Opaepilau Gulch	1,030	11/18/97	0	dry	--	--	--	
Kaupakulua 9.1	Opaepilau Gulch	940	11/18/97	0.08	gaining	20.1	93	--	Awalau Spring at 940 ft
Kaupakulua 10	Awalau Gulch	1,230	11/17/97	0	losing	--	--	--	
Kaupakulua 10.1	unnamed tributary	1,420	11/18/97	0.02	dry	20.2	75	--	Awalau Spring at 1,420 ft
Kaupakulua 11	Awalau Gulch	1,780	11/18/97	1.85	losing	17.6	54	7	
Kaupakulua 11.1	Awalau Gulch	1,780	11/18/97	0.02	diversion	18.9	68	--	minor leakage past diversion plus streambed seepage
Kaupakulua 11.2	Awalau Gulch	1,700	11/18/97	0.05	gaining	18.8	81	--	Awalau Spring at 1,700 ft
Kaupakulua 12	Awalau Gulch	2,030	11/18/97	2.06	gaining	18.5	54	7	
Kaupakulua 13	Awalau Gulch	2,250	11/18/97	1.31	diversion	18.3	47	7	some water added to stream from Opana Tunnel
Kaupakulua 14	Kalakohi Gulch	1,400	11/18/97	0.26	gaining	18.9	60	11	
Kaupakulua 15	Kalakohi Gulch	1,030	11/18/97	0.01[a]	losing	--	--	--	
Kaupakulua 15.1	Kalakohi Gulch	1,020	11/18/97	0	diversion	--	--	--	all water diverted by Kauhikoa Ditch

[a] Estimated flow

[b] Chloride sample collected October 29, 1997

soil layer at the contact between the Honomanu Basalt and the Kula Volcanics. The springs at higher altitudes issue from between layers of the Kula Volcanics. At all of the springs located above 100 ft in altitude, flow was observed to continue downstream for a few tens of feet to about 1,000 ft before seeping into the floor of the gulch. The site where perennial flow in Waiohiwi Gulch begins was not visited but no flow was observed at about 4,200 ft altitude. Perennial flow stops at about 2,080 ft (Maliko 10) where all the flow sinks into the valley bottom upstream of Waiohiwi Falls (Maliko 9.3 on figure 9).

The total measured discharge below 2,000 ft altitude in the Maliko Gulch drainage system is about 0.4 Mgal/d, nearly all of which issues from the Kula Volcanics (site Maliko 1 through Maliko 9.3, table 3). Because much of the measured discharge in the gulch eventually seeps back into the ground, this value is possibly an overestimate of the total amount of ground-water discharge because the same flow may be reappearing farther downstream.

Kuiaha Gulch

The next important drainage system to the east of Maliko Gulch is the Kuiaha Gulch drainage system. Kuiaha Gulch splits into three gulches at about 200 ft altitude—Lilikoi Gulch to the west, Pauwela Gulch in the middle, and to the east, the longest and deepest, Ohia Gulch, which splits into Kapuahoohui and Huluhulunui Gulches (fig. 1). Huluhulunui Gulch can be traced to a maximum altitude of about 2,000 ft on the 1983 USGS 1:24,000-scale topographic map (Haiku quadrangle). The Kuiaha Gulch system is incised as much as 180 ft below the upland surface and the valley bottoms are eroded only into the Kula Volcanics.

The Kuiaha system is usually dry from sea level to an altitude of about 300 ft in Lilikoi and Pauwela Gulches (fig. 9). At altitudes of about 300, 480, and 1,000 ft respectively, the Haiku, Lowrie, and Kauhikoa Ditches, cross Lilikoi Gulch and remove nearly all base flow gained between the ditches (table 3). Stream measurements made during October 28–29, 1997 show that sections of the stream in Lilikoi Gulch gained about 0.5 Mgal/d between 1,400 ft and 310 ft altitude. The most substantial gain was measured where a landowner pointed out a 1,000-ft long section of the stream between sites Kuiaha 7.1 and Kuiaha 7.2 that gained water noticeably throughout the year.

Pauwela Gulch, the shortest branch of the Kuiaha Gulch system, is intersected by two surface-water diversion systems. Haiku Ditch, at about 330 ft, intercepts almost all base flow, and a tunnel which diverts water from Ohia Gulch at about 540 ft adds water to Pauwela Gulch. Lowrie Ditch does not intercept any flow in Pauwela Gulch. The amount of streamflow gain measured in Pauwela Gulch on October 28, 1997 was about 0.2 Mgal/d between 840 and 375 ft altitude. The small amount of flow in the gulch bypassing the Haiku Ditch was observed to seep into the floor of the gulch within about 600 ft downstream of the diversion.

Ohia Gulch is usually dry downstream of about 520 ft altitude where a tunnel diverts all base flow to Pauwela Gulch. Upstream of this tunnel to about 1,400 ft altitude the stream gained about 0.2 Mgal/d on October 28, 1997. Upstream of Kauhikoa Ditch, the gulch carries water put into the stream at an altitude of about 1,430 ft from the Kaluanui Ditch but also gained nearly 0.1 Mgal/d on the day of measurement.

The total amount of ground-water discharge measured in the Kuiaha Gulch drainage system is about 1.0 Mgal/d, all of which is discharged from the Kula Volcanics.

Kaupakulua Gulch

The Kaupakulua Gulch drainage system (fig. 1) lies to the east of the Kuiaha Gulch drainage system and the geomorphology of the systems is similar. Base flow is taken from the Kaupakulua Gulch system by surface-water diversion systems at about 350 ft, 550 ft, 1,000 ft, and 1,800 ft altitude, and the gulch carries excess water from the Opana Tunnel for a distance of about 7,000 ft between about 2,400 and 1,800 ft altitude. Kaupakulua Gulch is usually dry from the ocean upstream to about 350 ft altitude where the Haiku Ditch takes all of the base flow of the stream. On November 17, 1997, base flow at an altitude of 350 ft (Kaupakulua 3) was about 0.06 Mgal/d, all of which was gained in a section of the stream below an altitude of 480 ft (Kaupakulua 4) (table 3). At about 640 ft altitude, upstream of the Kaupakulua Reservoir, the gulch splits into two branches, the west branch is unnamed and the east branch is the Opaepilau Gulch, which splits into the Awalau and Kalakohi Gulches farther upstream. Flow in the unnamed tributary, which originates from a spring at an altitude of about 1,180 ft (Kaupakulua 7.1), was 0.11 Mgal/d and all of the flow was diverted to the Kauhikoa Ditch. This tributary was dry downstream between this diversion and the intersection with Opaepilau Gulch. In both Awalau and Kalakohi Gulches, the stream has gaining, losing, and dry reaches at altitudes between 2,400 ft (Kaupakulua 13) and 630 ft (Kaupakulua 5.1) (fig. 9). The highest seepage rates measured during the study were for the reach between 2,250 and 2,030 ft altitude in Awalau Gulch where the stream gained about 0.75 Mgal/d over a 3,000-ft long section.

Ground-water discharge measured in the Kaupakulua Gulch system totaled about 1.4 Mgal/d. Because this system had both gaining and losing reaches, the total discharge estimate possibly includes ground water that discharged in more than one place along the stream channel.

Kakipi Gulch

The Kakipi Gulch drainage system, which lies near the eastern edge of the study area, receives the most rainfall of any system in the study area (fig. 2). Therefore, the Kakipi Gulch system has more tributaries and more perennial streamflow than the Maliko Gulch system. Two small tributaries enter the gulch from the east, downstream of the site about 2 mi from the coast where Kakipi Gulch splits into Opana and Halehaku Gulches at about 600 ft altitude. Opana Gulch can be traced upstream to about 4,800 ft altitude and Halehaku Gulch to about 2,600 ft altitude on the 1983 USGS 1:24,000-scale topographic map (Haiku quadrangle). Base flow in this system is captured by the surface-water diversion systems at altitudes of about 400, 600, 1,000, 1,200, and 2,400 ft, and a part of runoff is captured at 4,200 ft for the Upper Kula Pipeline (fig. 1).

The lower section of Kakipi Gulch is incised as much as 340 ft below the original land surface, similar to the lower section of Maliko Gulch, but the valley floor rises on a much steeper gradient, reaching an altitude of 600 ft within about 1.5 mi from the coast. This steeper gradient occurs because the floor of the gulch lies mainly in the Kula Volcanics and has not eroded deeply into the Honomanu Basalt. The geologic map (Stearns, 1942) shows no outcrops of Honomanu Basalt in Kakipi Gulch but during this study, the contact with the Kula Volcanics was observed to be about 3,500 ft from the shore in the gulch at an altitude of about 100 ft. The gradient of Kakipi Gulch is similar to the gradient of Maliko Gulch above 600 ft altitude where Maliko Gulch lies on the Kula Volcanics.

Kakipi Gulch has perennial flow over much of its length but is often dry near the coast below 400 ft altitude. A small spring at about 10 to 20 ft altitude can be found on the east side of the bay into which the stream valley empties. This spring issues from above a red ash and soil layer, presumably the contact between the Honomanu Basalt and the overlying Kula Volcanics. On December 17, 1997, Kakipi Gulch was dry for at least 4,500 ft from the coast upstream to an altitude of about 120 ft, with the exception of one section. Water was observed to flow into Kakipi Gulch from Papalua Stream at an altitude of about 40 ft and seep into the floor of the gulch within 500 ft downstream of the confluence. The floor of Papalua Stream valley changes from thick lava flows presumably of the Kula Volcanics to thin-bedded pahoehoe flows indicative of the Honomanu Basalt about 200 to 300 ft upstream of the confluence. Therefore, flow that was maintained on the surface of the thick flows of the Kula Volcanics could not be supported for more than 700 to 800 ft downstream by the more permeable thin-bedded rocks of the lower Honomanu Basalt.

Five surface-water gaging stations (fig. 9) have been operated for various lengths of time on Opana and Halehaku Gulches above 1,200 ft altitude to record daily streamflow (Fontaine, 1996). In addition, gaging station 5995 in Awalau Gulch measures water diverted through the Opana Tunnel from Opana Gulch. To estimate the base-flow component of streamflow for two of the records with sufficient length, a computerized base-flow separation method, known as the BFI program (Wahl and Wahl, 1995), was used. 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 nonoverlapping 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.

Gaging station 5990 was operated during the period July 1932 through January 1933 (Grover and Carson, 1935) on Opana Gulch at an altitude of about 3,100 ft (fig. 9). The records, which were not analyzed to determine the base-flow component, show that peak flows were between 13 and 32 Mgal/d several times during the gaging period (fig. 10). The stream did not go

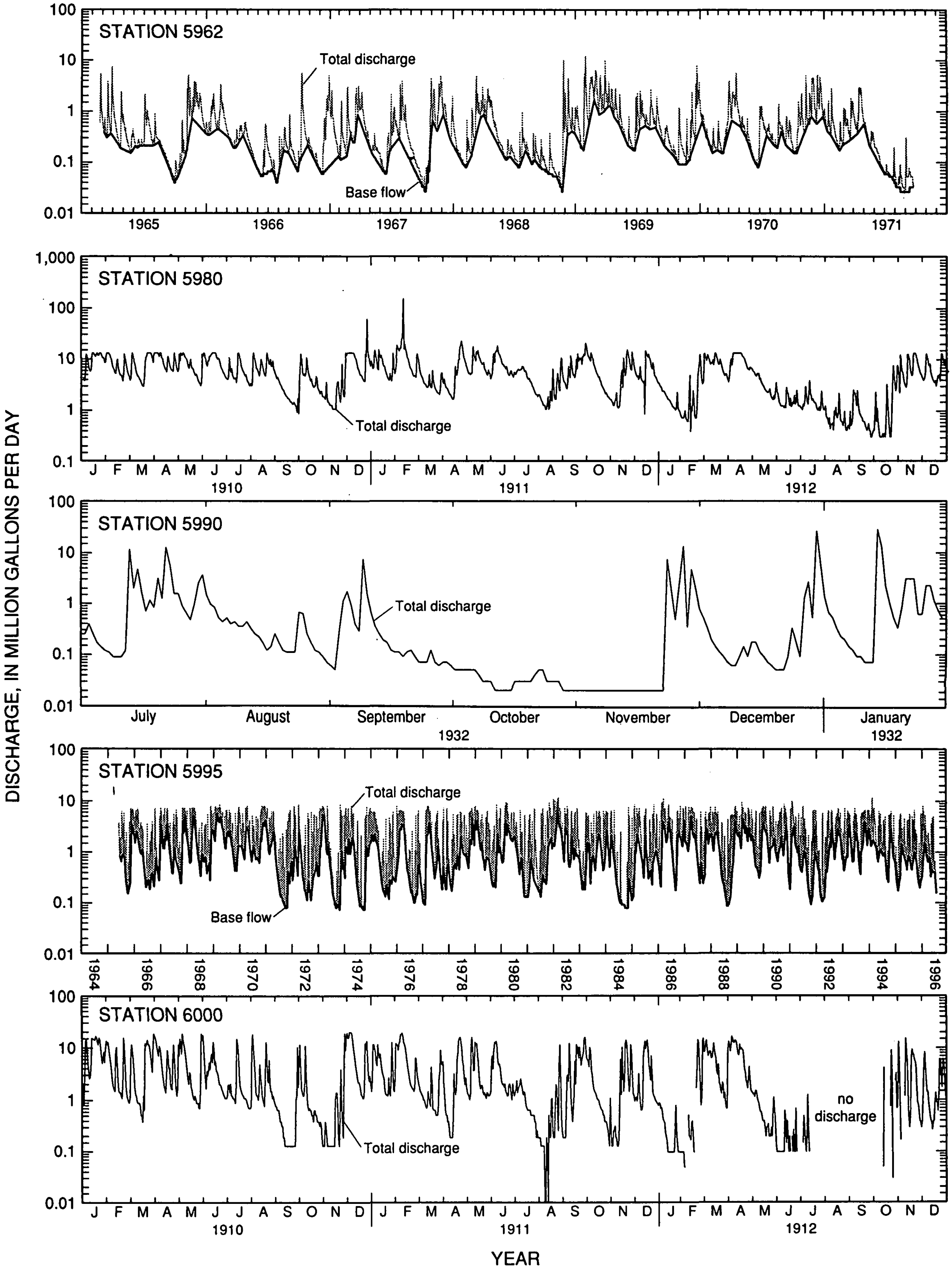


Figure 10. Measured discharge and calculated base flow at selected surface-water gaging stations, Haiku study area, east Maui, Hawaii.

dry at the gaging station during the gaging period, which was one of above average rainfall (fig. 3). Further downstream at an altitude of about 2,400 ft, gaging station 5995 has recorded the amount of water diverted from the gulch through the Opana Tunnel and into a local domestic water-distribution system (fig. 1). The gaging station record covers the period from 1965 to the present and shows all but the peak flows that bypass the diversion to the Opana Tunnel (fig. 1). During the period 1966 to 1996, estimated base flow at gaging station 5995 averaged 1.1 Mgal/d and yearly averages ranged from 0.3 Mgal/d in 1981 to 2.3 Mgal/d in 1969. The stream did not go dry any time during the period of record indicating that ground water was probably continuously discharging to the stream upstream of the gaging station.

Gaging station 6000, at an altitude of about 1,200 ft (fig. 9), recorded the amount of diversion of all low and medium flows from Opana Gulch to the New Hamakua/Kauhikoa Ditch from 1910 to 1912 (Martin and Pierce, 1913; Pierce and Larrison, 1914). Gaging station 6010, located at least 400 ft downstream of the diversion was reported to record only flood flows that bypassed the diversion but the records of gage height indicate that there was almost always flow at the gaging station, even when the channel at gaging station 6000 was reported dry (Pierce and Larrison, 1914, p. 196). Therefore, either the diversion did not divert all of the water, even at low flow conditions, or Opana Gulch was gaining water between the diversion and gaging station 6010. The site descriptions and data are insufficient to determine which possibility was most likely.

On Halehaku Gulch, two surface-water gaging stations were operated, one at 2,340 ft altitude (gaging station 5962) and one at about 1,200 ft altitude (gaging station 5980) (fig. 9). Estimated base flow at gaging station 5962 during the period 1966 to 1971 averaged 0.3 Mgal/d and yearly averages ranged from 0.2 to 0.5 Mgal/d (fig. 10). The stream did not go dry during the 7-year period of record. Flow was also continuous at the lower gaging station for the period 1910 to 1912 but the record was not sufficient for analysis using the BFI program (fig. 10). Total flow at the lower gaging station ranged from 0.3 to 13 Mgal/d, the upper limit of the recording instrumentation at the gaging station (Martin and Pierce, 1913).

Ground-Water Levels

Ground-water flow rates and directions are difficult to measure directly, and are usually inferred from water levels. Changes in ground-water levels can also be indicators of changes in recharge or withdrawals from the ground-water system, and can be an indicator of freshwater-lens thickness.

Spatial Distribution

Water levels from wells in and around the study area have been separated into two groups, one containing water levels measured in wells that did not penetrate to sea level at the time of measurement and one containing water levels measured in wells that are open to the aquifer at or below sea level (table 4). Water levels measured during drilling in seven wells (5320-01, 5414-01, 5420-01, 5420-02, 5514-01, 5518-03, and 5519-01) which eventually penetrated below sea level are included in the first group because the base of each well was above sea level at the time of measurement. Water levels measured in these same wells after their completion below sea level are included in the second group. Two water-level maps were constructed on the basis of the water-level information, one for the wells above sea level (fig. 11) and one for the wells at or below sea level (fig. 12). Because these water levels were measured over several decades, short-term variations caused by factors such as ground-water development, irrigation, or reservoir seepage cannot be adequately identified. The short-term effects are probably localized and small because ground-water withdrawal is limited and land use has been relatively stable for decades; thus, although the water-level maps do not represent any instant in time, they provide a view of the region generalized over time. In addition to the well data, the altitudes of springs and gaining sections of streams were used to construct the water-level map of the Kula Volcanics upper rock unit. These areas of ground-water discharge indicate places where the upper water table intersects the ground surface.

The upper water-level surface generally mimics topography but an abrupt increase in water levels from west to east across Maliko Gulch, the western boundary of the assumed dike complex, is apparent. In the middle of the study area, the water table rises away from the coastline with a slope of about 340 ft/mi. Farther to the east, the water-table gradient is steeper (about 500

Table 4. Chloride-concentration data and water-level information used to construct generalized water-table maps, Haiku area, east Maui, Hawaii
[ft, feet; mg/L, milligrams per liter; --, not available; na, not applicable; all well information is from unpublished data, USGS, Hawaii District well files unless otherwise noted. Datum is mean sea level; chloride measurements made after well was completed]

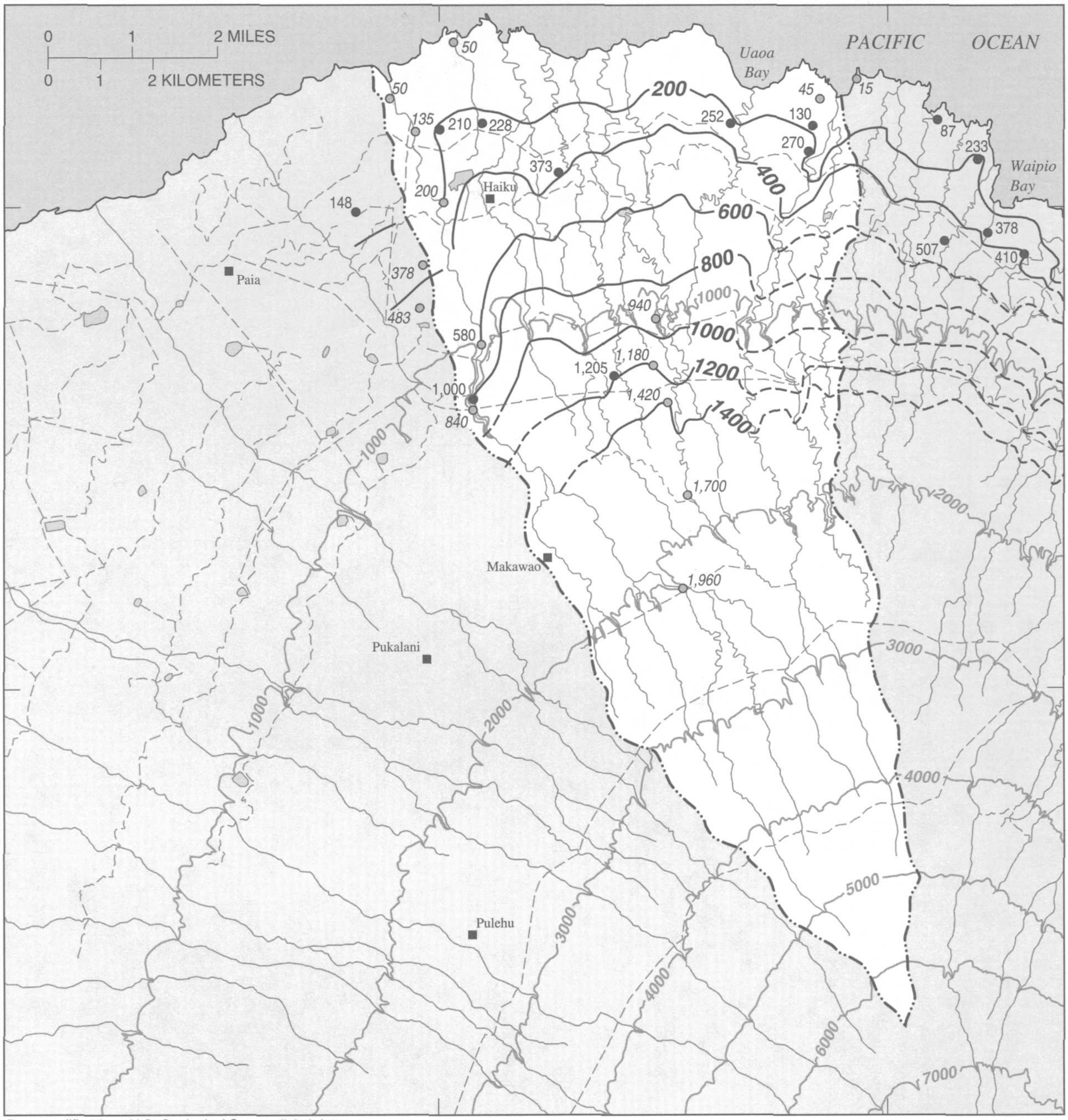
		Well open above sea level				Well open at or below sea level					
State well number	Well name	Altitude of top of open interval (ft)	Altitude of bottom of open interval (ft)	Water-level (ft)	Date of water-level measurement	Altitude of top of open interval (ft)	Altitude of bottom of open interval (ft)	Water-level (ft)	Date of water-level measurement	Chloride concentration (mg/L)	Date of chloride-concentration sample
6-5021-01	Pukalani Terrace	--	--	--	--	1,033	-43	8	4/4/72	550	8/5/86
6-5318-01	Kulamalu	1,217	1,205	1,205	9/97[a]	99	-128	12.2	5/17/98	11	6/2/98
6-5319-01	Kawaikoa tunnel[b]	na	na	1,000[c]	na	na	na	na	na	--	--
6-5320-01	Hamakuapoko 2	780	479	483[d]	1992[a]	0	-32	4.7	1/19/93	49	11/18/92
6-5321-01	Keheka P18	--	--	--	--	12	-6	6.2[e]	12/5/70	--	--
6-5323-01	Paia 2	--	--	--	--	8	-8	3.9[e]	12/5/70	--	--
6-5413-01	Huelo 1	390	230	410	2/7/79	na	na	na	na	--	--
6-5413-08	Lowen	373	358	378	6/18/97	na	na	na	na	20	6/18/97
6-5413-09	Hagar	--	--	--	--	222	-33	--	--	200	6/20/97
6-5414-01	Hipp	547	507	507	5/97[a]	387	-42	--	--	120	6/6/97
6-5419-01	Haiku	--	--	--	--	-1	-43	4.9	4/79-12/94[f]	60	5/29/79
6-5420-01	Maui High School	349	148	<148	na[a]	-1	-22	3.4	6/1/64	81	4/11/66
6-5420-02	Hamakuapoko 1	780	378	378	na[a]	--	-34	3.9	11/12/95	55	4/6/92
6-5422-01	Paia 13	--	--	--	--	10	-4	3.8[e]	12/5/70	--	--
6-5422-02	Paia 17	--	--	--	--	13	-2	4.0[e]	12/5/70	--	--
6-5424-01	Spreckelsville 1	--	--	--	--	--	--	3.5[e]	12/5/70	--	--
6-5513-01	Tavares	138	79	233	12/86	na	na	na	na	96	9/5/96
6-5514-01	Marquard	134	9	87	7/9/90[a]	-41	-61	15	7/13/90	72	9/6/96
6-5515-01	Peahi Gusher	408	200	270	4/73	na	na	na	na	--	--
6-5515-02	Wilson	134	130	130	1996[a]	134	-55	--	--	200	10/30/96
6-5516-01	Feehan 1	320[g]	185	252	12/89	na	na	na	na	--	--
6-5518-03	T118	436	81	373	3/2/48[a]	436	-24	17[h]	3/11/48	--	--
6-5519-01	Pauwela	364	5	228	4/10/67[a]	3	-34	5.4	12/70-5/86	120	5/11/67
6-5519-02	Behnke	360	132	210	2/74	na	na	na	na	--	--
6-5519-03	Baldwin Manor	--	--	--	--	6	-34	5	11/22/86	156	11/25/86

Table 4. Chloride-concentration data and water-level information used to construct generalized water-table maps, Haiku area, east Maui, Hawaii--Continued

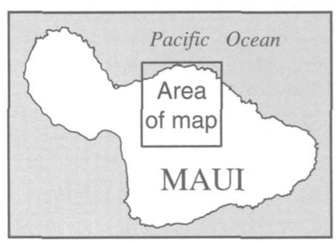
[ft, feet; mg/L, milligrams per liter; --, not available; na, not applicable; all well information is from unpublished data, USGS, Hawaii District well files unless otherwise noted. Datum is mean sea level; chloride measurements made after well was completed]

		Well open above sea level				Well open at or below sea level					
State well number	Well name	Altitude of top of open interval (ft)	Altitude of bottom of open interval (ft)	Water-level (ft)	Date of water-level measurement	Altitude of top of open interval (ft)	Altitude of bottom of open interval (ft)	Water-level (ft)	Date of water-level measurement	Chloride concentration (mg/L)	Date of chloride-concentration sample
6-5520-01	HC&S 11 A,B	--	--	--	--	50	-93	3.2[e,f]	7/46-12/53	270-1,668	1925-96
6-5522-01	Kuau 12	--	--	--	--	15	-5	4.0[e]	12/5/70	--	--
6-5615-02	Phillips	142	45	45	1995[a]	45	-85	--	--	180	10/5/95
6-5620-01	Maliko tunnel[b]	na	na	50[c]	na	na	na	na	na	19	9/6/96

[a] Measured during drilling; Austin, Tsutsumi and Associates, Inc. (1998)
[b] Stearns and Macdonald (1942)
[c] Altitude of tunnel
[d] Depth below lowest mention of "no water" in drillers log
[e] Maui-type shaft (infiltration gallery) at sea level
[f] Arithmetic mean of available data during the indicated time period
[g] Estimated from 1983 USGS 1:24,000-scale topographic map (Haiku quadrangle)
[h] Value noted as questionable in records



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

—400— WATER-TABLE CONTOUR--Shows altitude of water table 1948-97. Interval 200 feet. Dashed where approximate. Datum is mean sea level

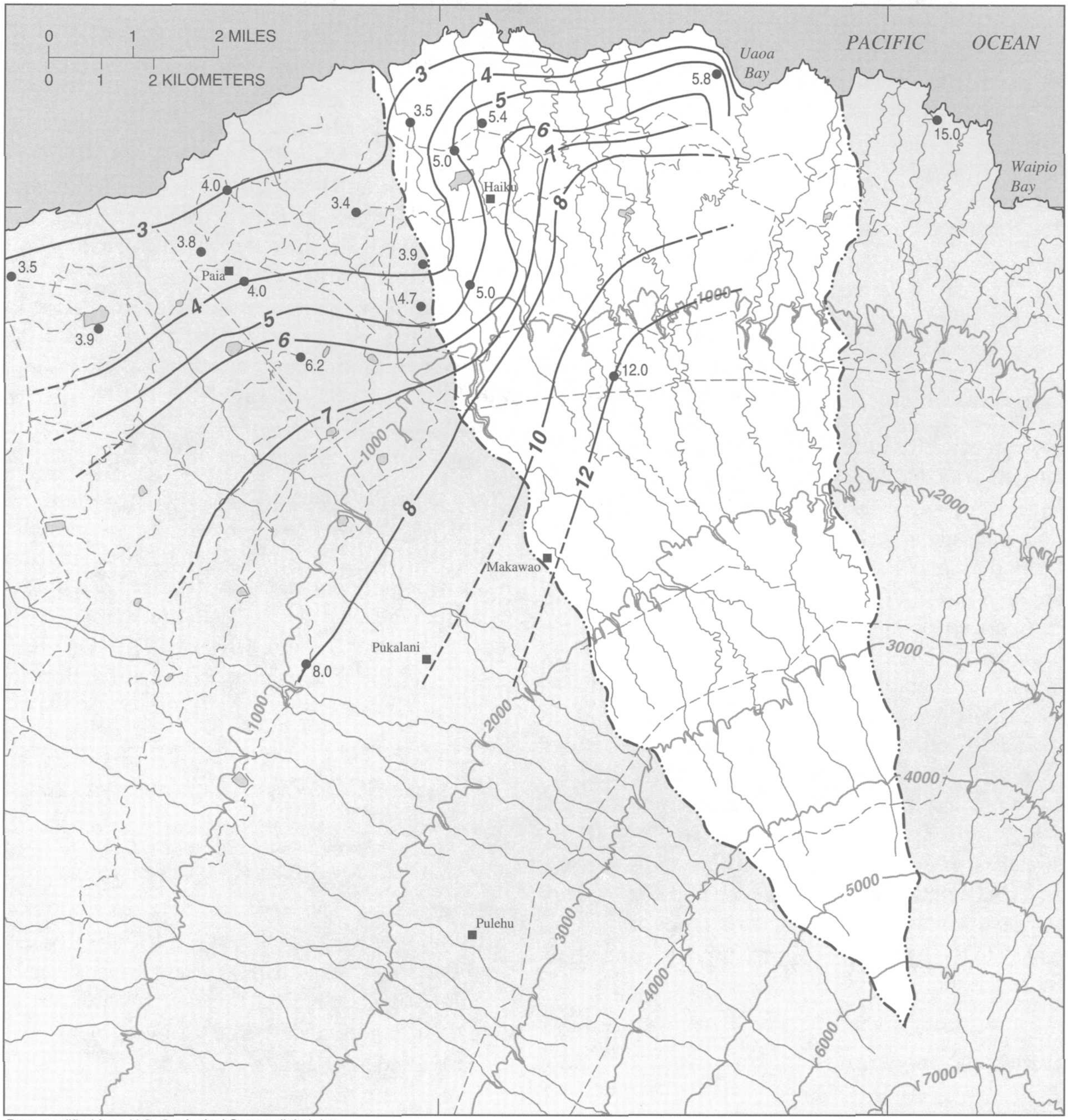
1,000● WELL AND WATER LEVEL, IN FEET ABOVE MEAN SEA LEVEL

840○ SPRING AND ALTITUDE, IN FEET ABOVE MEAN SEA LEVEL

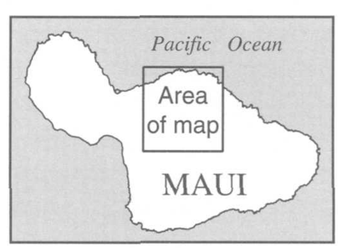
—··—··— STUDY-AREA BASIN BOUNDARY

—1000— TOPOGRAPHIC CONTOUR--Interval 1,000 feet

Figure 11. Generalized water table for selected wells completed above sea level and for springs, 1948-97, Haiku study area, east Maui, Hawaii.



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

—4— WATER-TABLE CONTOUR--Shows altitude of water table (1948-97). Interval, in feet, is variable. Dashed where approximate. Datum is mean sea level

12.0● WELL AND WATER LEVEL, IN FEET ABOVE MEAN SEA LEVEL

–··–··– STUDY-AREA BASIN BOUNDARY

—1000— TOPOGRAPHIC CONTOUR--Interval 1,000 feet

Figure 12. Generalized water table for selected wells completed below sea level, 1948-97, Haiku study area, east Maui, Hawaii.

ft/mi) which may be attributed to higher recharge and/or lower permeability of the aquifer.

The water-level map for the lower rock units shows a surface that has a much flatter water-level gradient throughout the study area but still includes the rise in water levels across the western boundary of the dike complex. In the Haiku area, the gradient of the lower water-level surface is about 3 ft/mi away from the coastline within the dike complex. To the west of Maliko Gulch, the slope of the water-level surface is about 1 to 2 ft/mi. Farther to the east, the water-level data are sparse but indicate that the gradient of the lower surface is much steeper than 3 ft/mi.

Temporal Variation

At most wells, only single water-level measurements are available. At three wells, water-level measurements are available over several-year periods (fig. 7). Water levels in well 5520-01 were collected occasionally during 1946–53, sometimes when water was being withdrawn. Water levels measured during pump operation were about 2 ft lower than water levels measured when the pump was off. During July 19–24, 1946, total tidal fluctuations in the well were about 0.2 to 0.4 ft. Occasional water-level measurements were made in well 5519-01 during 1970–86 and in well 5419-01 during 1979–95. The water level in both wells appear to mimic the rainfall variations recorded at rain gage 338. The highest measured water levels in well 5519-01 were during 1980–83, a period when the two wettest years (1980 and 1982) were recorded at the rain gage. Water levels in well 5419-01 show a similar rise in response to the two above-average rainfall years of 1989 and 1990.

Chloride Concentration

Chloride concentration is used as an indicator of saltwater intrusion into the ground-water system. The only long-term record of chloride concentration available is for well 5520-01 in Maliko Gulch (fig. 7 and table 4). Between 1925 and 1996, chloride concentration ranged from 270 to 1,668 mg/L. The fluctuation in concentration appears to have been caused by changes in the amount of water withdrawal from the well. Generally, greater withdrawal from a well in a coastal aquifer will cause an increase in the chloride concentration of the pumped water as more saline water is induced to flow towards the well. Much of the chloride-concentration data is reported annually with no indication if the value represents a single sample at the end of the year or a composite of more than one sample collected throughout the year. In most cases, the value probably represents the chloride concentration as the well is being pumped. Overall, the existing data do not indicate any significant long-term change in chloride concentration. Chloride-concentration values from other wells in or east of the Haiku study area that penetrate to below sea level range from 49 to 200 mg/L (table 4). The highest concentrations were in samples from wells located nearest the coast where the freshwater lens is thinnest. All of the chloride concentrations are from samples collected after each well was completed. Water from well 5021-01, west of the study area, has an unexplained high chloride concentration of 550 mg/L.

Chloride concentrations averaged about 20 mg/L in water from well 5413-08, which does not penetrate to sea level; from the Maliko Tunnel, and from streams consisting of only base flow (tables 3 and 4). For comparison, the chloride concentration of rainfall is typically less than 20 mg/L (Swain, 1973). One shallow well (5513-01) has a chloride concentration of 96 mg/L.

CONCEPTUAL MODEL OF GROUND-WATER OCCURRENCE AND MOVEMENT

Ground water is recharged by direct infiltration of rainfall over the entire study area. The area of greatest recharge (near 150 in/yr) lies between 2,000 and 6,000 ft altitude where rainfall and fog drip are greatest. Fresh ground water is found in two main forms: (1) as perched high-level water held up by relatively low-permeability geologic layers, and (2) as a freshwater lens floating on denser, underlying saltwater.

Perched High-Level Ground Water

The water levels measured in shallow wells and the presence of springs indicate that a water table lies several tens of feet below the ground surface in the thick lava flows and interbedded soils of the Kula Volcanics. Where the ground surface is incised into the high-level water table, ground water discharges at springs or directly into streambeds. Conversely, streamflow infiltrates into the aquifer in several places where a stream bottom lies above the high-level water table and is sufficiently permeable. Perennial discharge of ground water to streams has been measured at altitudes greater than 2,400 ft in the Kakipi Gulch system. Total ground-water discharge from the Kula Volcanics to streams in the study area is about 3 to 6 Mgal/d, all of which is either removed from the streams by surface-water diversion systems or which infiltrates back into the ground. This ground-water discharge is only about 3 to 6 percent of the estimated recharge to the study area, therefore more than 90 percent of the recharge must flow downward to the freshwater lens. Because most ground-water flow is vertically downward through the perched high-level water body, ground-water heads should decrease with depth in the high-level water body but no water-level data exist to support this conclusion.

The high-level water-table surface mimics topography and its location depends on the presence of the rocks of the Kula Volcanics. The base of the perched high-level water body is defined by the transition from the lower permeability Kula Volcanics and associated weathered soil and ash beds to the underlying higher permeability Honomanu Basalt. The thickness of the high-level water body is therefore controlled by the thickness of the Kula Volcanics, which is about 100 to 400 ft thick where exposed in the walls of Maliko Gulch (fig. 8).

Volcanic dikes, which commonly impound water because of their low permeability, do not appear to be a major factor in controlling the shape of the high-level water table below about 2,000 ft in the study area. Too few data exist from areas above this altitude to draw any conclusions about the presence or effect of volcanic dikes. Ground-water flow, from south to north, in the high-level water body appears to be mainly controlled by the layered nature of the aquifer. The presence of dikes appears to have little effect on ground-water flow. However, the high-level water-table map (fig. 11) indicates that ground-water flow may be impeded more from east to west in a direction perpendicular to the preferred orientation of the dikes in the dike complex.

Freshwater Lens

Within the high-permeability rocks of the Honomanu Basalt, a lens of freshwater floats on denser underlying saltwater. The freshwater lens system is often referred to as "basal ground water" in Hawaii. The source of freshwater in the lens is ground-water recharge from overlying high-level ground-water areas and infiltration of rainfall. It appears that more than 90 percent of the recharge reaching the high-level water body flows vertically through unsaturated rocks below the high-level water body to recharge the freshwater lens. Fresh ground water flows from inland recharge 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 penetrate the transition zone or underlying saltwater.

For hydrostatic conditions, the thickness of the freshwater lens 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, than 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.

Although the study area is in a dike complex where dike-impounded water is expected, water levels in the freshwater lens form a hydraulic gradient of about 3 ft/mi inland, which is in the range of 1 to 5 ft/mi found in coastal aquifers formed by flank lava flows on other Hawaiian islands (Stearns and Macdonald, 1946; Hunt, 1996). The hydraulic gradient immediately to the west of the dike complex in flank lava flows is about 1 to 2 ft/mi. Because the principal direction of ground-water flow is parallel to the dike complex, it appears that volcanic dikes are not numerous enough or oriented in such a way as to impound ground water to a significant extent. A low ground-water gradient has been observed in the East Rift Zone of Kilauea Volcano on the island of Hawaii where ground-water flow is oriented parallel to the emplacement orientation of volcanic dikes. The reported hydraulic gradient is about 1.7 ft/mi within about 4 mi from the coast in an area where recharge and hydraulic conductivity estimates are similar to those of the Haiku study area (Sorey and Colvard, 1994).

In addition to similar hydraulic gradients, the water-table configuration in the Kilauea's East Rift Zone and in the Haiku area are similar; showing a convex pattern of water-level contours inside the dike complex. This similarity or pattern indicates that volcanic dikes do affect the flow of water perpendicular to the dike orientation and that the preferred ground-water flow direction is downrift rather than across the dike complex. Therefore, the effects of ground-water withdrawal from wells drilled in the dike complex would tend to be more noticeable along the dike complex to the north and south and less noticeable across the dike complex to the east and west.

Variably Saturated Flow System

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.

1. Stream channels incised into the Honomanu Basalt (Maliko and Kakipi Gulch) are dry or losing streamflow during base-flow conditions. All streamflow seeps into the Honomanu Basalt as it travels downstream from the Kula Volcanics.

2. The hydraulic conductivity of the Honomanu Basalt, on the basis of aquifer tests, is too high to support a thick ground-water lens given the estimated recharge to the study area. Kanemoeala Spring is a perennial spring about 700 ft from the coast at an altitude of 50 ft in Kanemoeala Gulch (fig. 9). If the spring, which is located at the Kula Volcanics/Honomanu Basalt contact, were to be discharging ground water from a vertically extensive freshwater lens, the hydraulic conductivity of the aquifer would have to be 7 ft/d on the basis of equation 1:

$$K = \frac{2 \times 0.025 \times 13 \times 10^6 \frac{\text{ft}^3}{\text{d}} \times 700 \text{ ft}}{(50 \text{ ft})^2 \times 1.025 \times 26400 \text{ ft}} = 7 \frac{\text{ft}}{\text{d}} . \qquad (2)$$

   Estimates of the hydraulic conductivity of the aquifer based on aquifer tests are about three orders of magnitude higher. Therefore, it is likely that the freshwater lens is not thick enough to be discharging at this spring.

3. From discussions with several drillers and geologists working in the area, it is apparent that wells that penetrate through the contact have encountered conditions of cascading water from above the Kula Volcanics/Honomanu Basalt contact and dry lava tubes in the Honomanu Basalt.

The existence of an unsaturated zone between the high-level water body and the freshwater lens has important implications for ground-water development and the effect of ground-water withdrawal on streams. Unsaturated hydraulic conductivity values of shield-building lavas are not available but can be estimated from values estimated for coarse gravel. A layer of gravel can be considered analogous to a layer of rubble in an aa interflow zone. The hydraulic conductivity of gravel drops by about 14 orders of magnitude almost immediately after the water content of the gravel drops below saturation (Johnson and others, 1983). Therefore, the effects of pumping from the freshwater lens will be immeasurable at streams that are separated from the freshwater lens by more than 100 ft of the unsaturated basalt because of the very low hydraulic conductivity expected.

Development of Variably Saturated Ground-Water Flow Model

To evaluate the likelihood that a variably saturated system could develop in the Haiku study area, a two-dimensional, cross-sectional ground-water flow model using the computer code VS2DT (Healy, 1990) was developed to simulate steady-state movement of ground water in a variably saturated vertical section. The vertical section was designed to be representative of the geologic and hydrologic properties observed in the Haiku study area. VS2DT is a finite-difference code that simulates the transport of solutes and the flow of water by solving the nonlinear water-flow equation for unsaturated and saturated porous media, and the code can incorporate infiltration, evapotranspiration, and seepage faces. In the version of the code used, the moisture-characteristic curve for the porous media is represented by the van Genuchten (1980) algebraic equation. The VS2DT code is a supplemental version of VS2D described in Lappala and others (1987). Solute transport was not simulated in this study.

Representation of the Physical System

The model was designed to represent a vertical section of a layered aquifer system, about 60 ft high and 3.5 ft wide, with thick-bedded lava flows overlying thin-bedded, highly permeable lava flows and separated by a layer of weathered saprolite about 13-ft thick (fig. 13). The finite-difference grid used to represent this section consists of 7,560 square grid blocks, each 0.164 ft on a side, arranged in a rectangular array with 21 columns and 360 rows (fig. 13). Recharge, varying from 25 to 100 in/yr, was modeled using a specified-flow boundary at the top of the grid. Discharge was allowed along the entire left side of the grid using a specified-head boundary of zero pressure head with the requirement that water leaves the system (Lappala and others, 1987). This type of boundary simulates a seepage face and only allows water to flow out of the system where the aquifer is saturated. The right and bottom sides of the grid are no-flow boundaries. All of the simulations started with the initial conditions of no water in the system and were completed to steady-state conditions.

Hydraulic Characteristics

The hydraulic characteristics of the three layers in the model are shown in table 5. Because there were no data available describing the unsaturated flow characteristics of highly permeable basalt and because no new data were collected, it was necessary to choose characteristics of a rock with similar permeability for which moisture-characteristic parameters have been experimentally determined. Lappala and others (1987, table 1) present hydraulic characteristics for a coarse sand with a saturated hydraulic conductivity of 23,000 ft/d. These unadjusted values were used for the scaling length and pore-size distribution parameter for the upper and lower basalt layers. For the compressed weathered soil layer, the moisture-characteristic values for a clay sample were used (Lappala and others, 1987, table 1) and the saturated hydraulic conductivity was varied for the different simulations.

The model does not include exact representations of unsaturated basalt or weathered soil moisture characteristics, but ultimately the goal of the simulation was to show whether or not a variably saturated system was possible. The possibility of this configuration depends mainly on the saturated hydraulic conductivity of the middle layer and to a lesser degree on the saturated hydraulic conductivity of the upper and lower layers.

Results of the Model Simulations

The series of simulations, in which the hydraulic conductivity of the middle layer was varied, shows that it is possible, using realistic hydraulic properties and hydrogeologic conditions, to create a steady-state variably saturated system with a relatively low permeability weathered soil or clay layer perching water in and above it (table 6, simulations 1–7). Using 25 in/yr of recharge and a saturated vertical hydraulic conductivity value of 1.0×10^{-1} ft/d, the model simulation shows that all of the recharge reaches the bottom layer. The middle layer will perch water in and above it when the saturated vertical hydraulic conductivity is less than 6.6×10^{-2} ft/d and only 1 percent of the recharge will reach the bottom layer when the saturated vertical hydraulic conductivity of the middle layer is reduced to 3.3×10^{-4} ft/d (fig. 14). When the saturated vertical hydraulic conductivity is between 3.3×10^{-4} and 6.6×10^{-2} ft/d, the amount of recharge that reaches the lower layer decreases roughly linearly as the hydraulic conductivity of the middle layer is decreased (fig. 14). The values of hydraulic conductivity for the middle layer used in the simulations fall at the lower end of the range of measurements of saturated hydraulic conductivity of near-surface, uncompressed soils weathered from basalt in central Oahu, which range from 1×10^{-2} to 3×10^{2} ft/d (Miller and others, 1988).

In another set of simulations (table 6, simulations 8, 9), when the recharge to the system, in which the saturated vertical hydraulic conductivity of the middle layer is 4.9×10^{-2}, is doubled and doubled again, the additional water is all perched by the top and middle layers. The amount of recharge reaching the lower layer stays the same but it is a smaller percentage of the total recharge to the system.

The limitation of this vertical model is that it is not wide enough to simulate the buildup of head in the layers far away from the seepage face boundary. Higher heads in the upper and middle layers would increase the vertical gradient, forcing more water to move downward through the middle layer. Also, the model does not include the flux of water that would travel through the system along the sloping surface of the layers from upgradient areas. To avoid this problem, the upgradient flux could be added to the right side of the grid or the grid could be extended to represent an actual no-flow boundary of the Haiku system. The first solution is unacceptable because the upgradient flux is difficult to determine and the distribution of this flux to the upper and lower layers cannot be known at the start of the simulation but must be determined as part of the solution. The second solution is also unacceptable because the physical upgradient boundary of the Haiku flow system

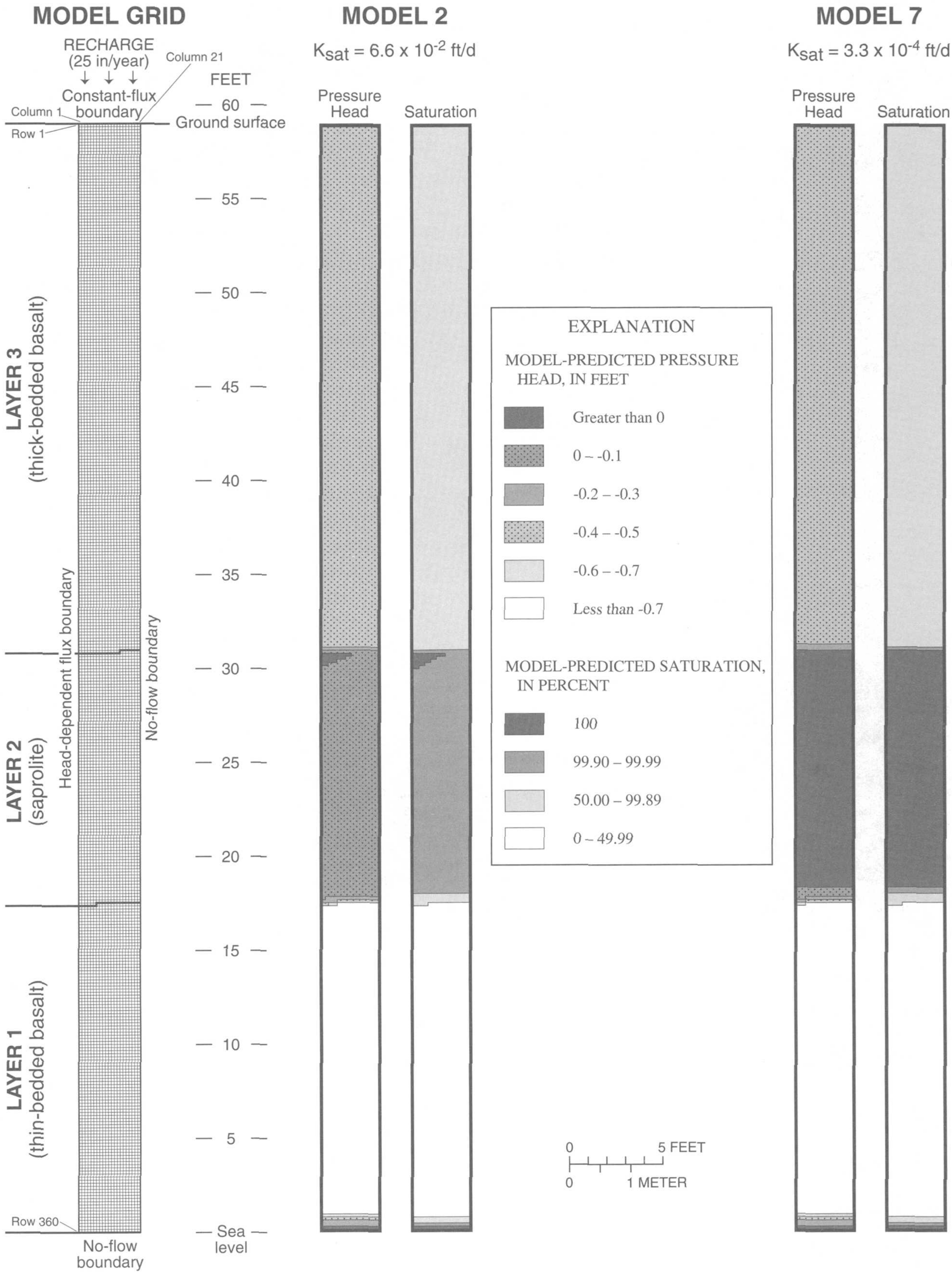


Figure 13. Model grid used to simulate a variably saturated flow system, and model-predicted pressure head and saturation distributions for selected simulations.

Table 5. Summary of VS2DT parameter values held constant in the ground-water flow model, Haiku study area, east Maui, Hawaii

	Geologic feature	Saturated horizontal hydraulic conductivity, K_{sat} (feet per day)	Ratio of vertical to horizontal hydraulic conductivity	Porosity	Van Genuchten (1995) scaling length, α' (feet)	Residual moisture content, Θ_r	Van Genuchten (1995) pore-size distribution parameter, β'
Top layer	thick-bedded lava flows	1	0.1	0.1	-0.466	0.025	6.3
Middle layer	saprolite	varied	1.0	0.495	-1.316	0.175	1.6
Bottom layer	thin-bedded lava flows	1,000	0.1	0.1	-0.466	0.025	6.3

Table 6. Summary of VS2DT parameter values varied in the ground-water flow model, Haiku area, east Maui, Hawaii

Model simulation number	Saturated horizontal and vertical hydraulic conductivity of middle layer, K_{sat} (feet per day)	Recharge, (inches per year)	Amount of recharge reaching lower layer, (percent of total recharge)
1	1.0×10^{-1}	25	100
2	6.6×10^{-2}	25	97
3	5.7×10^{-2}	25	92
4	4.9×10^{-2}	25	83
5	3.3×10^{-2}	25	55
6	1.0×10^{-2}	25	17
7	3.3×10^{-4}	25	1
8	4.9×10^{-2}	50	41
9	4.9×10^{-2}	100	21

is unknown and may very well be the flow divide at the center of East Maui Volcano 10 to 15 miles inland.

DATA NEEDS

Additional data are needed to improve and confirm the understanding of the ground-water flow system in the study area. A few specific data needs are briefly described below.

1. Data from exploratory wells could confirm the existence of an unsaturated layer between the upper and lower water tables. The wells would be open only to a small part of the aquifer (a few tens of feet) above the freshwater lens but still in the Honomanu Basalt. Unsaturated conditions would be confirmed if the well remains dry or negative pressures can be measured in the well.
2. Continuous monitoring of selected springs and streamflow in the area is needed to measure baseline ground-water discharge before the start of proposed additional ground-water withdrawal. Comparisons can then be made to determine if the additional withdrawal is affecting ground-water discharge at the high-level streams or springs.
3. An aquifer test in the Honomanu Basalt with multiple observation wells arranged both parallel and perpendicular to the preferred volcanic-dike orientation is needed to determine if the dike complex does indeed have higher conductivity in the north-south direction compared to the east-west direction. In addition, an observation well open only to the upper water body could be used to monitor any hydrologic effects felt there.

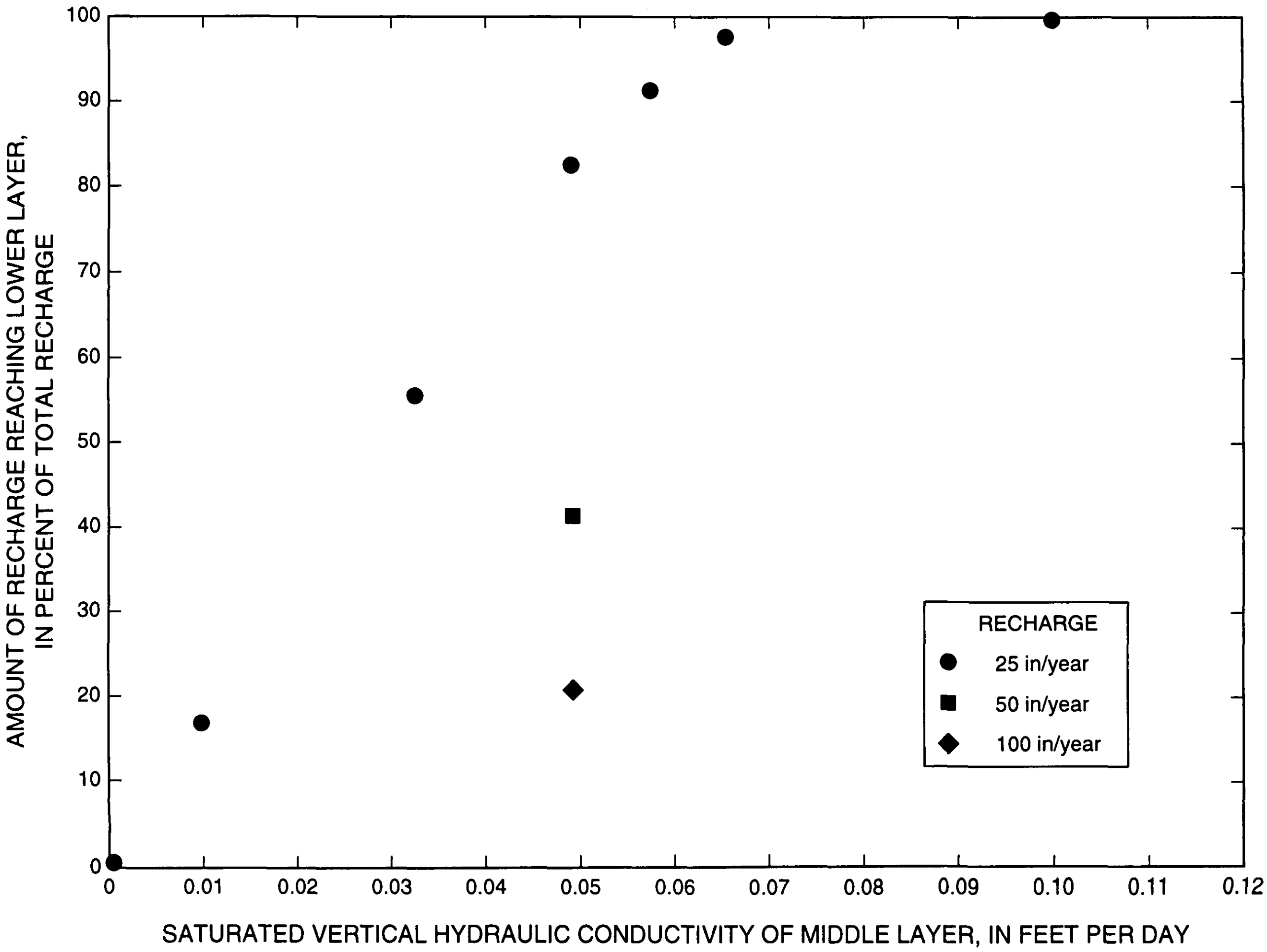


Figure 14. Response of the ground-water flow model to changes in the saturated vertical hydraulic conductivity of the middle layer.

4. Geologic logging of all additional wells drilled in the area could provide more information on the relation of the upper water body to the stratigraphy. Water levels in the wells need to be monitored daily during drilling to determine the vertical-flow gradient in the ground-water system.

SUMMARY AND CONCLUSIONS

The Haiku study area lies on the gently sloping eastern flank of the East Maui Volcano (Haleakala). The wedge-shaped study area, covering about 42 mi^2, is bounded to the north by about 6 mi of coastline and lies between the drainage basins of Maliko Gulch to the west and Kakipi Gulch to the east. About 7 mi from the coast at an altitude of 2,400 ft, these two gulches are less than 0.5 mi apart. Land use is currently dominated by pineapple cultivation, some residential areas, and at higher altitudes by livestock grazing and forested state conservation land.

The study area lies on the northwest rift zone of East Maui Volcano, a geologic feature 3 to 5 mi wide marked by surface expressions such as cinder, spatter, and pumice cones and by a positive gravity anomaly. Rift zones are intruded by magma that cools to form volcanic dikes—hydrologically significant features that can impede the flow of water as a result of their low hydraulic conductivity. The study area contains two geologic units, the main shield-building stage Honomanu Basalt, a thick accumulation of thin lava flows, and above that the Kula Volcanics, which consist mainly of lava flows that are many tens to hundreds of feet thick. The two units may be separated by a transitional phase lava and a red layer of weathered soil and ash.

The hydraulic conductivity of the Honomanu Basalt in the study area was estimated to be between 1,000 and 3,600 ft/d on the basis of aquifer tests and between 3,300 and 4,400 ft/d on the basis of the regional recharge rates and observed freshwater heads. No estimates are available for the hydraulic conductivity of the Kula Volcanics but estimates of specific capacity range from 0.01 to 0.09 gal/min per ft of drawdown. These estimates are about four orders of magnitude lower than the average specific capacity of the wells that penetrate into the Honomanu Basalt.

About 191 Mgal/d of rainfall and 22 Mgal/d of fog drip enters the study area with the highest amounts occurring between 2,000 and 6,000 ft altitude. Of the total precipitation, about 98 Mgal/d enters the ground-water system as recharge. Nearly all of the ground water currently withdrawn in the study area is from well 5520-01 in Maliko Gulch. Historic withdrawal rates have averaged about 2.8 Mgal/d at this site. Total withdrawal at all other wells in the study area is probably about 10 percent of the withdrawal from well 5520-01. An additional 18 Mgal/d of ground-water withdrawal is proposed.

The drainage pattern of the stream valleys on East Maui is radial and the streams in the study area drain north to the ocean. The two most deeply incised stream valleys in the study area, Maliko Gulch and Kakipi Gulch, have floors formed near the coast by the Honomanu Basalt. The upper parts of these valleys and all of the other stream valleys in the study area lie in the Kula Volcanics. Flow in Waiohiwi Gulch, a tributary to Maliko Gulch, is perennial between about 2,000 ft and 4,000 ft altitude. At lower altitudes in Maliko Gulch, flow is perennial at only a few spots downstream of springs and near the coast. The total measured discharge from springs in Maliko Gulch is about 0.4 Mgal/d, nearly all of which occurs from the Kula Volcanics.

The Kuiaha and Kaupakulua Gulch systems are usually dry from sea level to an altitude of about 350 ft. The three branches of the Kuiaha Gulch system gain water from about 900 ft to about 350 ft altitude. The two main branches of the Kaupakulua Gulch system alternately gain and lose water from 2,400 ft to 900 ft altitude. The total amount of ground-water discharge measured in the Kuiaha Gulch and Kaupakulua Gulch systems is about 1.0 Mgal/d and 1.4 Mgal/d, respectively, all of which is discharged from the Kula Volcanics.

Kakipi Gulch has perennial flow over much of its length but is often dry near the coast below 400 ft altitude. Five surface-water gaging stations have been operated for various lengths of time on branches of Kakipi Gulch above 1,200 ft altitude to record daily streamflow. A gaging station at 3,100 ft altitude shows that the stream has gone dry after periods of low rainfall, but at 2,400 ft altitude, streamflow has been continuous from 1966 to the present (1998) and has averaged about 1.1 Mgal/d. In all of the drainage systems of the study area, all of the ground-water discharge from the Kula Volcanics not captured by surface-water diversions eventually returns to the ground-water system through streambed seepage.

Measured water levels in wells completed above sea level and the altitudes of springs and gaining sections of streams were used to construct a map of an upper (high-level) water table. The upper water table generally mimics topography and lies several tens of feet below the ground surface outside of the stream valleys. The upper water body lies entirely in the Kula Volcanics and exists because the relatively low permeability of the interbedded and underlying soil and ash layers impedes the downward movement of the ground water.

Measured water levels in wells that penetrate below sea level were used to construct a map of the fresh ground-water lens. The hydraulic gradient of the lens surface rises away from the coast with a slope of about 3 ft/mi within the dike complex. Although the hydraulic gradient in the dike complex is steeper than the gradient outside the complex, it is still relatively flat and suggests that because ground-water flow is generally in the same direction as the dike orientation, significant impoundment of ground water is not occurring. Temporal variations in water levels show the influence of the ocean tides but seasonal and interannual variations appear to be less than a foot. No long-term trends are apparent in the water levels.

Chloride concentration is used as an indicator of saltwater intrusion into the ground-water system. The only long-term record of chloride concentration available is for well 5520-01 in Maliko Gulch, where between 1925 and 1996, chloride concentration ranged from 270 to 1,668 mg/L and fluctuated in response to changes in the amount of withdrawal from the well. Chloride-concentration values for samples from other wells that penetrate to below sea level range from 49 to 200 mg/L, the highest concentrations were in samples from wells nearest the coast where the freshwater lens is thinnest. Chloride concentrations averaged about 20 mg/L in water from well 5413-08, which does not penetrate sea level, from the Maliko Tunnel, and from streams consisting of only base flow.

Fresh ground water in the study area is found in two main forms: (1) as perched high-level water held up by relatively low-permeability geologic layers, and (2) as a freshwater lens floating on denser, underlying saltwater. 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: (1) streams are dry or losing water where they are incised into the Honomanu Basalt, (2) the hydraulic conductivity of the Honomanu Basalt is too high to support a thick ground-water lens given the estimated recharge to the study area, and (3) wells that penetrate through the contact have encountered conditions of cascading water from above the contact and dry lava tubes in the Honomanu Basalt.

A cross-sectional, steady-state, variably saturated ground-water flow model using the computer code VS2DT (Healy, 1990) was developed to evaluate whether a two-layer, variably saturated ground-water flow system could develop given the hydrologic and geologic conditions of the Haiku study area. Using 25 in/yr of recharge and hydraulic characteristics representative of the Kula Volcanics and the Honomanu Basalt, the model demonstrates that a 13-ft thick geologic layer with a saturated vertical hydraulic conductivity below 6.6×10^{-2} ft/d can impede vertical ground-water flow enough to produce two saturated water bodies with an unsaturated zone between them. Subsequent lower vertical hydraulic conductivity values for the impeding layer allow even less water to reach the lower layer.

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