Water Resources of Windward Oahu, Hawaii

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1894

Prepared in cooperation with the State of Hawaii, Department of Land and Natural Resources, Division of Water and Land Development

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By K. J. TAKASAKI, G. T. HIRASHIMA, *and* E. R. LUBKE

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WATER RESOURCES OF WINDWARD OAHU, HAWAII

By K. J. Takasaki, G. T. Hirashima, and E. R. Lubke

ABSTRACT

Windward Oahu lies in a large cavity—an erosional remnant of the Koolau volcanic dome at its greatest stage of growth. Outcrops include volcanic rocks associated with caldera collapse and the main fissure zone which is marked by a dike complex that extends along the main axis of the dome. The fissure zone intersects and underlies the Koolau Range north of Waiahole Valley. South of Waiahole Valley, the crest of the Koolau Range is in the marginal dike zone, an area of scattered dikes. The crest of the range forms the western boundary of windward Oahu.

Dikes, mostly vertical and parallel or subparallel to the fissure zone, control movement and discharge of ground water because they are less permeable than the rocks they intrude. Dikes impound or partly impound ground water by preventing or retarding its movement toward discharge points. The top of this water, called high-level water in Hawaii, is at an altitude of about 1,000 feet in the north end of windward Oahu and 400 feet near the south end in Waimanalo Valley. It underlies most of the area and extends near or to the surface in poorly permeable rocks in low-lying areas. Permeability is high in less weathered mountain areas and is highest farthest away from the dike complex.

Ground-water storage fluctuates to some degree owing to limited changes in the level of the ground-water reservoir—maximum storage is about 60,000 million gallons. The fluctuations control the rate at which ground water discharges. Even at its lowest recorded level, the reservoir contains a major part of the storage capacity because most of the area is perennially saturated to or near the surface. Tunnels have reduced storage by about 26,000 million gallons—only a fraction of the total storage—by breaching dike controls. Much of the reduction in storage can be restored if the breached dike controls are replaced by flow-regulating bulkheads.

Perennial streams intersect high-level water and collectively form its principal discharge. The larger streams are those that cut deepest into high-level reservoirs. Except near the coast in the northern end of the area, where dikes are absent, total base flow of streams equals total ground-water discharge. Development of high-level water by tunnels and wells diverts ground-water discharge from streams, decreasing the base flow of these streams. Construction of Haiku tunnel decreased the flow of Kahaluu Stream, 2½ miles away, by about 26 percent.

The dependable flow of water is estimated at 118 mgd (million gallons per day), of which 84 mgd is discharged by streams, tunnels, springs, and wells. The remaining 34 mgd is underflow, most of it discharging into the sea near the northern end of the area. Average flow is estimated at 220 mgd, of which 159 mgd is inventoried flow and 61 mgd is estimated underflow.

Specific capacity of wells tapping lava flows of the Koolau Volcanic Series ranges from less than 1 to 11 gallons per minute per foot of drawdown in the dike-complex zone and from 2 to 100 in the marginal dike zone. A transmissivity of 4,000,000 gallons per day per foot was determined for the basal aquifer. Permeabilities of rocks in high mountainous areas penetrated by water-development tunnels were compared by recession constants determined from free-flow drainage.

Evapotranspiration was estimated from regression curves obtained by correlating median annual rainfall and median annual pan evaporation. Evapotranspiration values from these curves compared favorably with values obtained from water-budget listings of rainfall and measured ground-water flow.

The chemical quality of water in wells and tunnels tapping rocks of the Koolau and Honolulu Volcanic Series is excellent. Except in a few isolated areas near the shore, the chloride content of the water from these sources is generally less than 100 parts per million. Wells tapping calcareous materials are subject to sea-water contamination under heavy pumping.

INTRODUCTION

PURPOSE AND SCOPE

The purpose of studies discussed in this report was to determine occurrence, chemical quality, and quantity of water in windward Oahu (fig. 1). Occurrence of water and geologic features that control its movement and availability are described. The report outlines methods of development of water, describes areas that are most promising for further development, and gives estimates of quantity and quality of water.

The work was done by the U.S. Geological Survey in cooperation with the Division of Water and Land Development, Hawaii State Department of Land and Natural Resources, and is a part of comprehensive investigations of the water resources of the whole island of Oahu. Other parts of Oahu where studies are underway or are complete are southern Oahu (Visher and Mink, 1960, 1964), the Waianae District (Zones, 1963), the Mokuleia-Waialua area, and the Kahuku area (fig. 1).

ACKNOWLEDGMENTS

The writers appreciate the cooperation and assistance of the Board of Water Supply, City and County of Honolulu, and especially John F. Mink, formerly of that board. Thanks are given also to the Kahuku Plantation Co., the Hawaiian Sugar Planters' Association, and the Waiahole Water Co. for supplying hydrologic and geologic data.

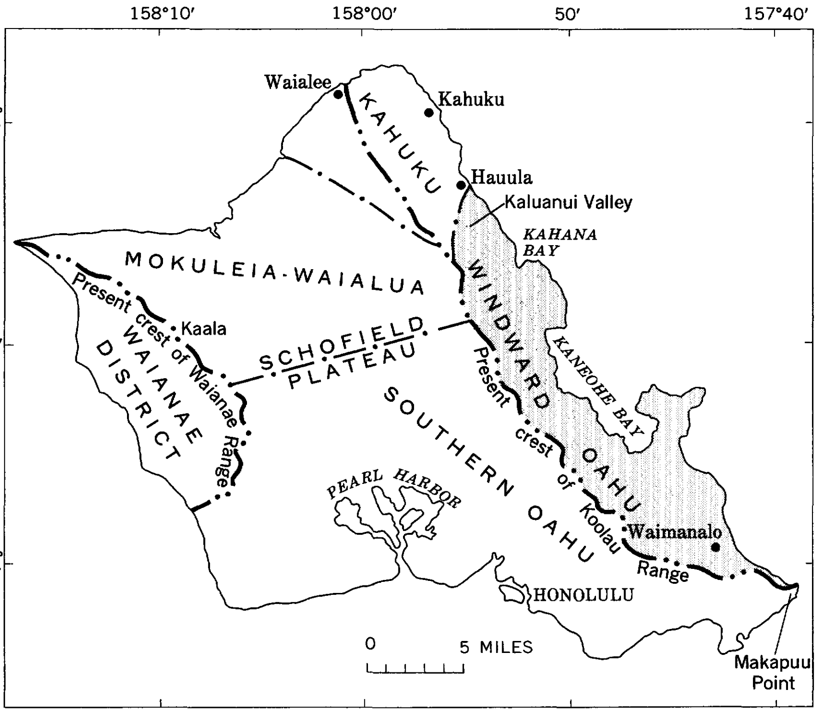

FIGURE 1.—Area of study.

LOCATION AND EXTENT

Oahu, which has an area of 604 square miles and is the third largest of the eight major islands of the Hawaiian Archipelago, lies at approximately lat 21°30′ N. and long 158° W. The area of investigation is on the windward or northeastern side of the island. The area is about 25 miles long and 3½ miles wide and extends from Makapuu Point northwestward to Kaluanui Valley (lat 21°35′ N., long 157°55′ W.). It is bounded on the northeast by the ocean and on the southwest by the crest of the Koolau Range.

PREVIOUS INVESTIGATIONS

Geology and ground-water resources of windward Oahu were first studied systematically by Stearns and Vaksvik (1935, 1938) and by Stearns (1939, 1940). These works described stratigraphy, structure, and petrography of the volcanic rocks, generally discussed ground-water resources, and gave records of wells. In a detailed study of the Honolulu Volcanic Series, Winchell (1947) discussed occurrence and petrography of rocks of that series in windward Oahu, and Wentworth and Winchell (1947) included the area in a discussion of structure and petrography of basalt of the Koolau Range.

Records of streamflow in windward Oahu were first published by the U.S. Geological Survey (Martin and Pierce, 1913). Since that time, records of streamflow have been published annually by the Geological Survey. In a report for the Honolulu Sewer and Water Commission, Kunesh (1929) included the windward area in an evaluation of the surface-water supply of Oahu during 1908–29.

GEOGRAPHY

PHYSIOGRAPHY

Windward Oahu is composed of eroded remnants of a volcanic dome, the Koolau Range, which constitutes the eastern three-fourths of the island. The Waianae Range constitutes the remainder. The highest point in the Koolau Range is 3,150 feet above sea level near Puu Konahuanui (lat 21°21′ N., long 157°47′ W.).

Topographic contours controlled only by points at crests of resistant spurs and ridges of an eroded volcanic dome may indicate the former shape of the dome at its greatest stage of growth. This indication is especially true of a young dome, such as the Koolau, where erosion has been operative only during a comparatively short span of geologic time.

Topographic contours were drawn at 400-foot intervals at crests of spurs and ridges of the Koolau and part of the Waianae Ranges (fig. 2).

Although incomplete, owing to extensive erosion of windward slopes, the shape defined by the contours in the southern half of the Koolau Range suggests that the crest of the dome at its greatest stage of growth was higher than, and east of, the present crest. In the northern part of the range, where control was better, the contours define an asymmetrical mountain mass whose shape and size closely resemble the present mountain.

A profile perpendicular to the crest of the Koolau Range and across the head of Kaluanui Valley (*A–A′*, figs. 2, 3) shows that the present crest and the inferred crest at the greatest stage of growth nearly coincide. However, the present crest at the head of Kahana Valley (*B–B′*, figs. 2 and 3), which is only 3 miles southeast of Kaluanui Valley, is 1½ miles southwest of the inferred crest at the greatest stage of growth.

Precipitous fluted cliffs or palis of the windward side of the range extend for 20 miles and include the famed Nuuanu Pali (lat 21°22′30″ N., long 157°47′40″ W.). The slope of the cliffs ranges from about 45° to nearly 85° and is steepest between altitudes of 600 and 1,500

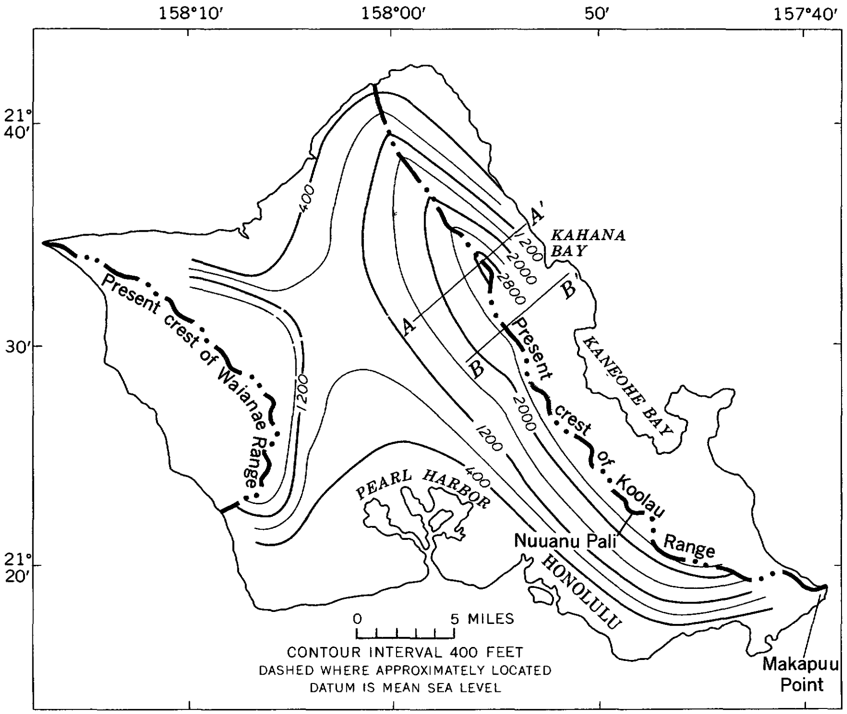

FIGURE 2.—Topographic contours that suggest the shape, at the greatest stage of growth, of part of the Koolau and Waianae Ranges. *A–A′* and *B–B′* shown in figure 3.

feet at heads of valleys. Above 1,500 feet to the crest, the slope is about 60°. A talus slope generally obscures the lower parts of the cliffs below an altitude of 600 feet. The gradient of streams decreases abruptly to about 4½° at the upper edge of the talus slope. Below an altitude of about 200 feet, the stream gradient is about 2°.

Development of physiographic features was controlled by geologic structure of the rift zone of the Koolau volcano, by late volcanic activity, and by changes in sea level and climate.

The center of the rift zone coincides with the crest at the head of Kaluanui Valley. South of Kaluanui Valley the center of the rift zone is east of the crest; its position indicates that the inferred crest at the greatest stage of growth was east of the present crest.

The principal physiographic features are almost vertical cliffs, from which plunge high waterfalls, and valley that abruptly terminate headward at the cliffs. The present crest of the Koolau Range and the trend of dikes in the rift zone may be correlative, for the crest is nearly parallel to the strike of nearby dikes (fig. 4).

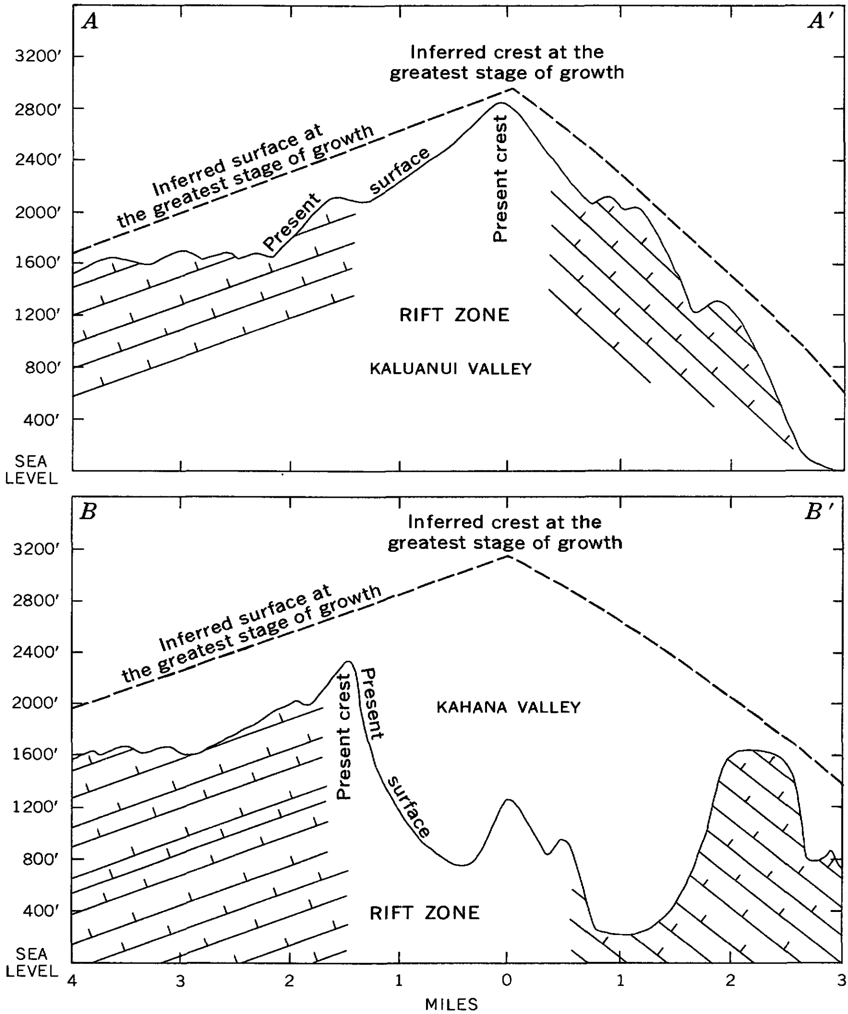

FIGURE 3.—Profiles across the heads of Kaluanui and Kahana Valleys perpendicular to the crest of the Koolau Range. Trace of profiles shown in figure 2.

According to Stearns (1940, p. 49), rocks of Olomana Peak (lat 21°22′ N., long 157°45′ W.) and Ulumawao (lat 21°23′ N., long 157°-46′30″ W.) are dissected remnants of lava flows and breccia that filled the Koolau caldera. Only the steep line of northeastward-facing cliffs in the southern Kaneohe area stand as erosional remnants of the original caldera wall.

The most conspicuous volcanic feature in the southeastern part of the area is Mokapu Peninsula, including Ulupau Head and Ulupau

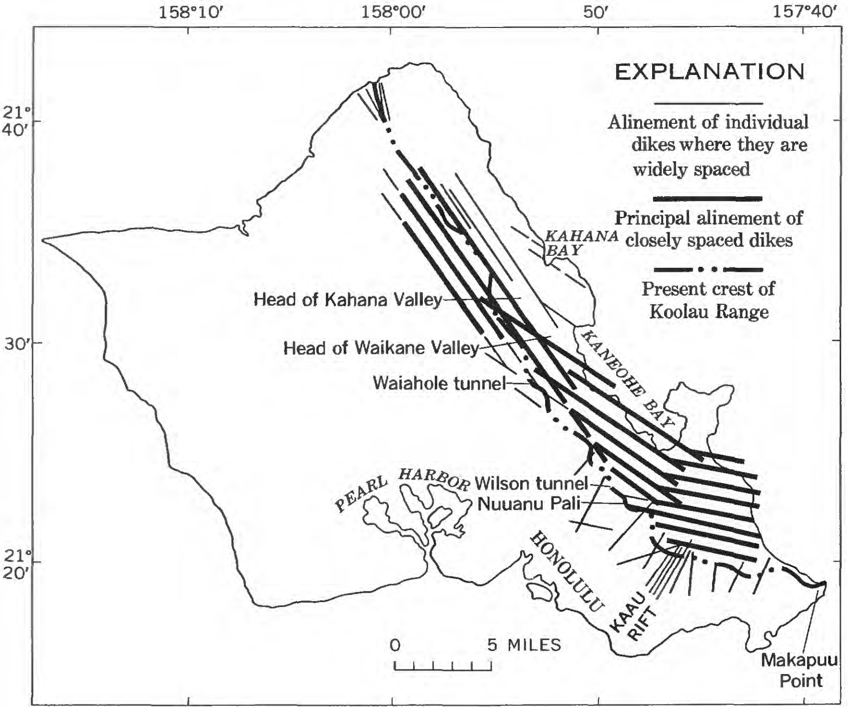

FIGURE 4.—Density distribution and general alinement of dikes in the Koolau Range.

Crater, at the southern end of Kaneohe Bay. Less conspicuous are scattered cinder and tuff cones and lava-filled valleys.

Widespread depositional and erosional features resulted from changes in sea level and climate. More than 70 percent of the area lies below an altitude of 600 feet and is underlain by alluvium. A coastal plain, underlain by Recent alluvium, dune sand, or marsh, generally reaches an altitude of about 20 feet.

DRAINAGE

Windward Oahu is drained by many streams, all short and flowing generally northeastward from the crest. Upper reaches of the streams are in amphitheater-headed valleys, which are drained by many short tributaries. The tributaries join to form streams flowing in narrow valleys in hilly terrain. Many of the narrow valleys coalesce to form broad, flat-bottomed valleys near the shore.

CLIMATE

The climate of Oahu is dominated by northeast trade winds. Windward Oahu includes two of the seven Hawaiian climatic regions defined by Blumenstock (1961, p. 12). The coastal and central lowlands fit his "windward lowlands" region, where trade-wind showers are frequent and rainfall is moderate, and the highlands fit his "rainy windward mountain slopes" region, where rainfall is high and cloudiness is common. Highest median annual rainfall is about 325 inches at the head of Punaluu Valley (lat 21°32′20″ N., long 157°55′ W.), near the crest, and the lowest is about 23 inches at Makapuu Point.

Distribution of median annual rainfall is shown in figure 5. Rainfall increases sharply near the crest and from southeast to northwest.

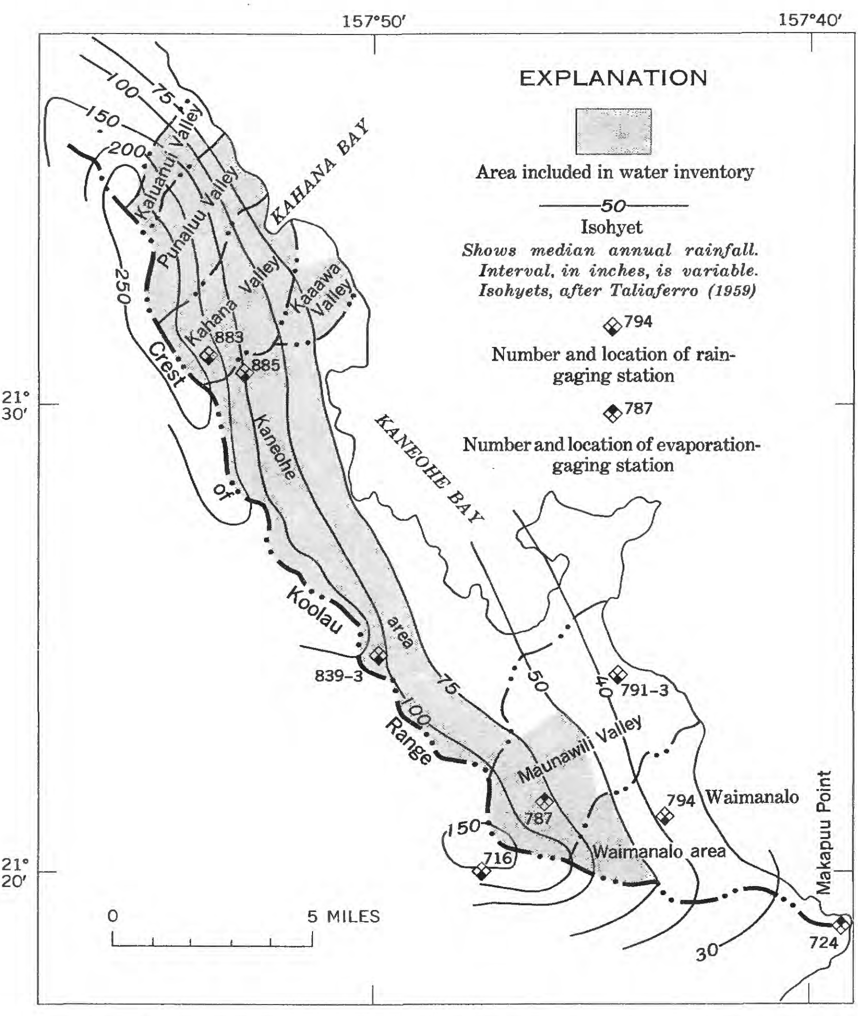

Figure 5.—Area included in water inventories, median annual rainfall and location of meteorological stations.

Predominantly orographic, this rainfall pattern results from cooling of warm moist trade-wind air as it rises over the range.

Rainfall differs greatly in time and in place. Figure 6 is a plot of annual rainfall at gaging stations in Waimanalo (southeast), Waikane, and Kahana Valleys (northwest) during 1920–60. Departures from the mean of as much as 78 percent occurred at individual stations during the period. Generally, greatest relative departures from the mean are in areas of lesser rainfall.

Distribution of rainfall through the year differs markedly from dry coastal areas to the wet interior. Rainfall on the coast is usually greater in winter than in summer. In the Kahana area, where annual rainfall exceeds 200 inches, highest monthly rainfall generally is in April and August; but there are three pairs of high-rainfall months, March–April, July–August, and November–December (fig. 7). This precipitation pattern is typical of high-rainfall areas in the Hawaiian Islands.

Occasional cold-front storms and kona (southerly) winds bring rain to the entire island, usually during winter. They account for the greater winter rainfall in dry areas, such as Makapuu Point.

Average yearly temperature at altitudes below 550 feet is about 74°F, and average monthly temperature ranges from 69° to 79°. Temperature is highest in August or September and lowest in January or February.

POPULATION

The population of windward Oahu has risen rapidly since the end of World War II, especially in the Lanikai, Kailua, and Kaneohe areas, largely as a result of population overflow from Honolulu. Those areas have changed from agricultural to suburban, and population increased from 9,000 in 1940 to 60,000 in 1960.

HISTORY OF WATER DEVELOPMENT

At the turn of the century, water was principally used to irrigate taro, rice, and sugarcane. Water was diverted from spring-fed streams through ditches and flumes.

By 1940 cultivation of rice and taro had diminished, and irrigation water was principally used for cane in the Waimanalo area and north of Punaluu Valley. In the Kaneohe area, rice and taro farming had given way to truck farming. Since its completion in 1915, Waiahole ditch tunnel has transported water from windward streams through the Koolau Range to cane fields in the Pearl Harbor area. Maunawili ditch was started in 1878 to transport water from Maunawili Valley to the Waimanalo area. Punaluu ditch was built in the 1920's to irrigate cane on the coast north of Punaluu Valley.

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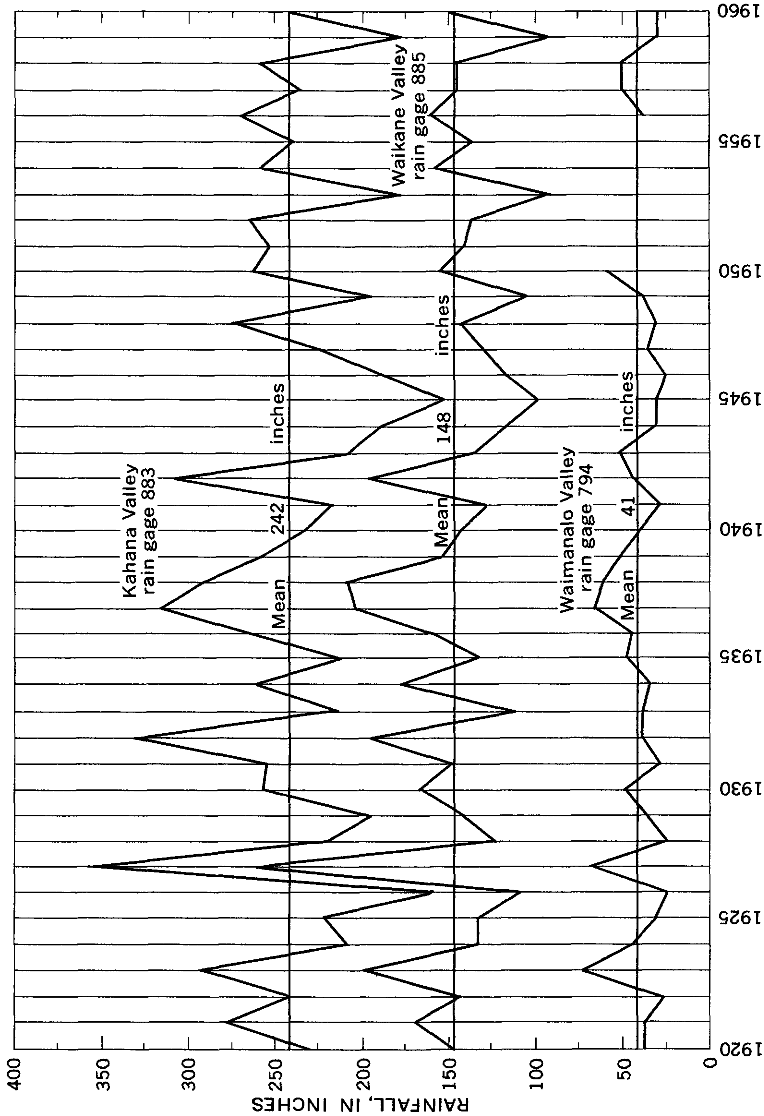

FIGURE 6.—Annual rainfall in Waimanalo, Waikane, and Kahana Valleys during 1920–60.

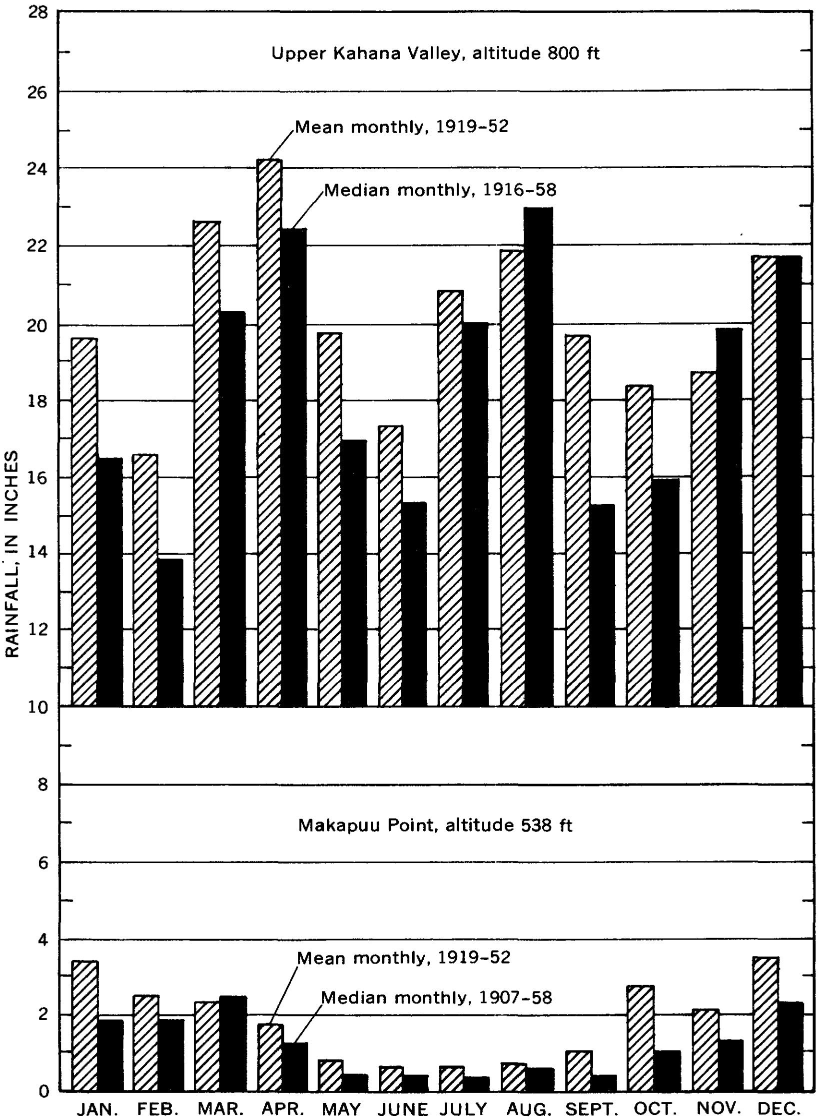

FIGURE 7.—Annual distribution of rainfall recorded at Makapuu Point and in upper Kahana Valley.

After 1940 principal water use shifted from irrigation to municipal supply because of demands of rapidly growing communities and gradual abandonment of truck farming in the Kailua-Kaneohe area and termination of operations by the Waimanalo Sugar Co. Development of municipal water supplies from tunnels and wells progressed rapidly, and use of domestic water in the Kailua-Kaneohe area increased from less than 1 mgd (million gallons per day) in 1940 to about 7 mgd in 1962.

GEOLOGY

VOLCANIC ACTIVITY

Stearns wrote in considerable detail of the volcanic history of Oahu. Briefly, he showed that Oahu developed through the building and coalescence of two shield volcanies—Waianae volcano, forming the western part of the island, and Koolau volcano, forming the eastern part. (Stearns, 1946, p. 73.) The initial phase of mountain building ended in a period of quiescence during which the volcanoes were deeply eroded. Waianae volcano became dormant before Koolau, and westward-dipping flows of the Koolau Volcanic Series overlapped the eroded eastern slope of the Waianae shield in the central part of the island.

The main Koolau rift zone and caldera are principal structural features. The rift zone, described by Stearns and Macdonald (1946, p. 14) as the locus of repeated fissure eruptions, occupies most of the windward area. The rift zone of an active volcano consists of a narrow zone of fissures and a line of cinder and spatter cones. Where erosion has exposed rift zones of extinct volcanoes to considerable depth, the zones are marked by numerous parallel or nearly parallel dikes. Where dikes are numerous and closely spaced, the term "dike complex" is applicable (Stearns and Vaksvik, 1935). The dikes, and especially the dike complex of the Koolau Volcanic Series, exercise much control in the occurrence and movement of ground water in the area of study.

Coarse breccia about 2 square miles in extent crops out as a ridge that separates Kaneohe Bay from Kawainui Swamp, and about half a square mile crops out on nearby Ulumawao Ridge (Stearns and Vaksvik, 1935, p. 97). Stearns concluded that these rocks are throat breccia built up chiefly as talus within a crater or caldera and that they mark the site of the main vent of Koolau volcano. The breccia is not jointed and is well cemented.

Volcanism ended in the southeastern end of the Koolau Range during late Pleistocene and Recent time (Winchell, 1947), leaving several intravalley lava flows, cinder cones, and many tuff cones. This activity produced the rocks of the Honolulu Volcanic Series. These rocks are confined to small scattered exposures.

WATER-BEARING PROPERTIES OF THE ROCKS

The main rocks consist of lava flows, breccia, cinders, tuff, and sedimentary rocks derived from volcanic material. The coastal plain includes sedimentary rocks of volcanic origin, calcareous reef material, and windblown calcareous beach sand.

Stratigraphy (after Stearns, 1939) is summarized in table 1. Distribution of the principal rock units is shown in the generalized geologic map (pl. 1).

KAILUA VOLCANIC SERIES

Lava flows of the Kailua Volcanic Series are exposed in an area about 5 miles across between Kaneohe and Waimanalo. Compared with the highly permeable, thin-bedded flank lava flows that constitute most of Koolau dome, the Kailua lava flows are dense and massive and poorly permeable—characteristic of restricted caldera-filling

TABLE 1.—*Stratigraphic units, windward Oahu*

Age	Geologic unit	Rock assemblage	Water-bearing properties
Recent and Pleistocene	Calcareous sedimentary material	Coral and coral rubble, dunes, and recent beach sand.	Generally highly permeable except for consolidated sand dunes. Water likely to be brackish near coast where pumping is heavy.
	Alluvium	Older and younger alluvium. Older alluvium moderately to well consolidated and weathered in its entirety; mainly silt and clay and lesser amounts of sand, gravel, and cobbles. Younger alluvium reworked older alluvium in and near stream channels; mainly poorly consolidated fragments of older alluvium.	Generally poorly permeable; small quantities of water from shallow wells. Brackish near coast.
	Honolulu Volcanic Series	Lava flows, cinders, and tuff.	Lava flows moderately to poorly permeable; cinders are moderately to highly permeable and locally contain small perched bodies of fresh water; tuff is permeable where fresh but mostly poorly permeable because of alteration of volcanic glass to clay.
		—Major erosional unconformity—	
Pliocene(?)	Koolau and Kailua Volcanic Series	Lava flows, dikes, and breccia. Rocks free of dikes only in small area in northern part. Elsewhere rocks are intruded by numerous closely spaced dikes in dike complex and by scattered dikes in marginal dike zone. Kailua flows restricted to dike complex in and near Maunawili Valley. Breccia in minor quantities generally restricted to dike complex.	Lava flows highly permeable where free of dikes, moderately permeable in marginal dike zone, and generally poorly permeable in dike complex. Permeability also decreases with degree of weathering and secondary mineralization. Chief aquifer of high-level and basal water sources.

lava. Permeability of the massive lava was further reduced by secondary hydrothermal mineralization, which filled joints and other open spaces. Wells tapping these rocks have comparatively poor yields.

KOOLAU VOLCANIC SERIES

The principal aquifer comprises the lava flows of the Koolau Volcanic Series, into which dikes of low permeability have been intruded. The commonly high permeability of flank flows is decreased by weathering, by secondary mineralization, by increasing number of dikes, and generally with proximity to lava vents. Permeability is generally greater in aa flows than in the pahoehoe flows. Consequently, hydrologic properties of the aquifer differ from place to place, according to the resultant of the above factors.

Heavy parallel lines in figure 4 represent the principal strike of dikes in the dike complex of the Koolau Range. Wentworth (1951, p. 10) suggested that 100 or more dikes per mile should constitute a dike complex. The term "dike complex" is applied in this study to areas where dikes constitute more than 5 percent of the rock.

The dike complex extends northwestward in an arc about 30 miles long from the Waimanalo area to Waialee on the north coast of Oahu, which is the northwestern end of the Koolau dome. In the southeastern part of the area, the dike complex is nearly 5 miles wide. From Waimanalo to the vicinity of Nuuanu Pali, the principal dikes strike N. 75° W. Near the Pali, these dikes mingle with others striking N. 55° W., which is the dominant strike northward almost to the head of Waikane Valley where the dikes striking N. 55° W. become less numerous; other dikes striking about N. 35° W. increase until at the head of Kahana Valley the dikes striking N. 35° W. predominate. Near Waialee, the strike is N. 10° W. Numerous dikes in the southeastern part of the range are related to the Kaau rift zone but strike northeastward at right angles to those of the main Koolau rift zone. (See fig. 4.)

Dikes of the Waiahole ditch tunnel system are shown in figure 8, and their thickness relative to total rock penetrated is shown in table 2.

Dikes in the southeastern half of Koolau dome generally range in thickness from 1 to 3 feet. Some are more than 10 feet thick. Dikes in the northwestern half are generally 3 to 7 feet thick, but dikes thicker than 10 feet are common.

The zone adjacent to the dike complex is called the marginal dike zone and is characterized by scattered dikes which constitute less than 1 percent of the rock. Although the strike of dikes is generally the same in both zones, the dike complex and the marginal dike zone are distinct, and no transition zone intervenes.

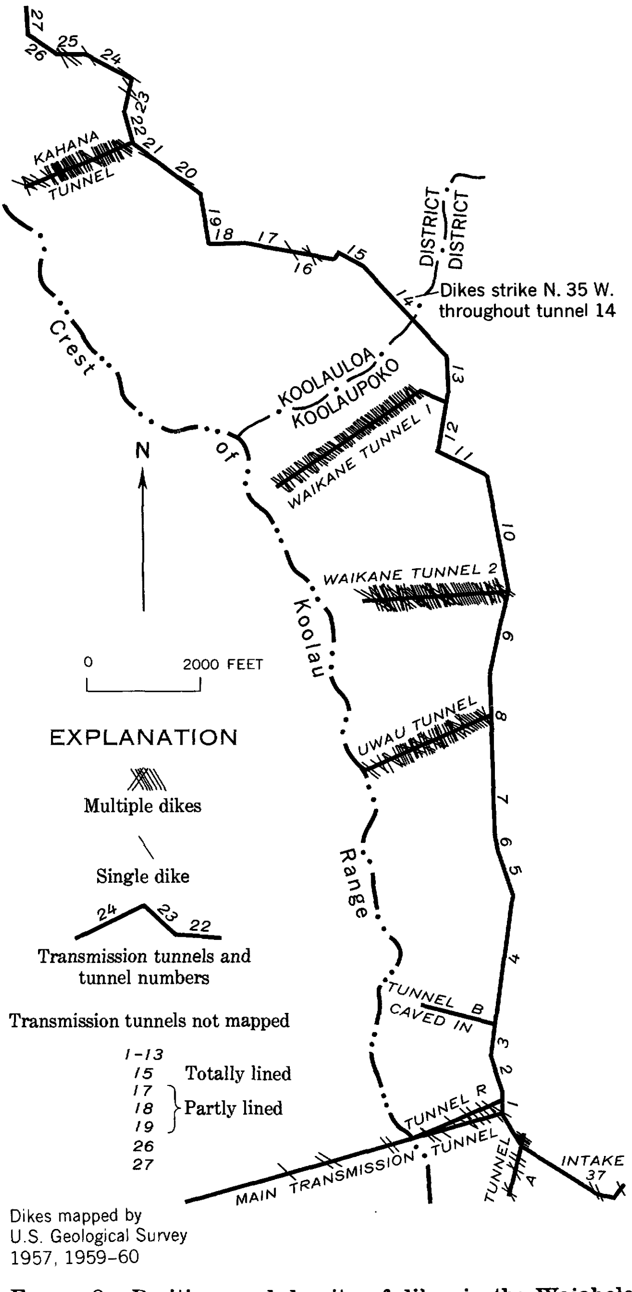

FIGURE 8.—Positions and density of dikes in the Waiahole ditch tunnel system.

TABLE 2.—*Dikes in tunnels of the Waiahole ditch tunnel system*

Tunnel	Dikes that strike northwestward (total thickness of dikes, in feet)						Dikes that strike other than northwestward	All dikes	
	0–30°	31–40°	41–50°	51–60°	61–70°	71–90°	Total thickness, in feet	Total thickness, in feet	Percentage of total dike thickness to total rock
Main bore	1	24	31	13	21	0	0	90	<1
Tunnel A	0	5	0	55	0	0	0	60	5
Tunnel R	3	0	0	43	7	0	0	53	3
Uwau	0	180	6	326	15	6	0	533	23
Waikane 2	73	454	346	348	0	0	0	1,227	48
Waikane 1	61	261	230	729	197	18	0	1,496	51
Kahana	3	429	4	120	22	0	0	578	30

In both the dike complex and the marginal dike zone, the dikes largely control the occurrence of ground water. The flows that make up the mass of the Koolau Range are divided by many crisscrossing nearly vertical dikes that are almost impermeable. The dikes dam water behind them that constitutes the high-level ground water, which is hydrologically distinct from the basal water found in dike-free areas.

In dike-complex and marginal-dike zones, differences in water-yielding properties of lava flows can be determined by the rate at which stored water is depleted by water-development tunnels. A good approximation to the recession curve derived from the dewatering is given by the exponential equation $Q_t = Q_0 e^{bt}$. The discharge is Q at time t (days) after the initial discharge Q_0; b is the recession constant governed by the characteristics of the reservoir. This equation plots as a straight line on semilog paper when Q is plotted on the log scale, and the slope of this line is $b \log e$. Because the logarithm of e (the base of Napierian logarithms) is a constant, b may be used in place of $b \log e$ as a measure of the water-yielding property of the reservoir rock of different tunnels; the higher the value of b, the greater the transmissivity.

Changes in direction of ground-water flow caused by dikes are hydrologically significant. Where an aquifer is free of dikes, the principal movement of water is seaward. Where an aquifer is cut by dikes, water tends to move parallel to dikes to points of discharge where the aquifer is cut by valleys. A dike complex retards movement of water across its boundaries.

Transmissivity (transmissibility as defined by Ferris and others, 1962, p. 71) determined from pumping tests of wells (table 3) ranged from 2,000 to 13,000 gpd per ft (gallons per day per foot) in a dike-complex aquifer and from 1,400,000 to 4,000,000 gpd per ft in a dike-free lava-flow aquifer.

The most permeable aquifer of the Koolau Volcanic Series is com-

TABLE 3.—*Transmissivity*

Well (pl. 1)	Coefficient of transmissivity (gpd per ft)	Aquifer	Well (pl. 1)	Coefficient of transmissivity (gpd per ft)	Aquifer
418-C [1]	2,000	Dike complex.	T-65	13,000	Dike complex.
422	2,500	Do.	398	1,400,000	Dike-free lava flows.
T-63	3,000	Do.	402-2A	4,000,000	Do.
T-64	8,000	Do.	402-2B	4,000,000	Do.

[1] Given incorrectly as well 418 on pl. 1.

posed of relatively dike-free lava flows adjacent to and beneath the coastal plain north of Punaluu Valley. South of Punaluu Valley, flows are intruded by dikes that reduce transmissivity.

Water-bearing properties of breccia depend largely on degree of cementation and to some extent on weathering. Poorly cemented breccia in Waiahole development tunnels, in the dike-complex zone north of Waiahole Stream, yields water copiously, whereas moderately cemented to well cemented breccia in the marginal dike zone of Punaluu and Kahana Valleys does not.

Specific capacity is the yield of a well in gallons per minute per foot of drawdown. Specific capacity of wells in windward Oahu is shown on plate 2. In dike-complex areas, where aquifers are least permeable, yield of wells ranges from less than 1 to 11 gpm per ft of drawdown. Wells pumped at more than 100 gpm generally yield less than 3 gpm per ft of drawdown. In the marginal dike zone, wells yield from 2 to 100 gpm per ft of drawdown, and in dike-free flows they yield from 80 to 500 gpm per ft of drawdown at pumping rates that exceed 500 gpm.

HONOLULU VOLCANIC SERIES

Rocks of the Honolulu Volcanic Series have been identified at eight sites. Seven are between Aniani Nui Ridge and Haiku Stream, near the southeastern end of Kaneohe Bay. The other is near Makapuu Head. Rocks of this series are only a minute fraction of the island mass. They consist mostly of lava flows, tuff, and cinders.

A test hole near Baskerville Springs (lat 21°25′ N., long 157°49′-10″ W.) indicates that lava flows of the Honolulu Volcanic Series are at least 50 feet thick, and another near the mouth of Kaneohe Stream shows them to be at least 30 feet thick. Wentworth (1951, p. 18) reported tuff deposits as thick as 30 feet in the banks and channels of the head branches of Haiku Stream. These rocks were extruded on a deeply eroded surface of the Koólau Mountain mass and were generally confined to deeper valleys. Individual flows of the Honolulu Volcanic Series generally are more massive than those of the Koolau Volcanic Series.

Cinder and tuff cones indicate former eruptive centers and fire fountains of Quaternary volcanic activity (Honolulu Volcanic Series). A few of the less eroded cones have a height of about 200 feet above their preeruption surfaces. In general, cinder cones are inland and tuff cones are near the coast or a short distance offshore.

The Honolulu Volcanic Series represents only a brief interval in the geologic history of the island. Low silica content and greater textural and petrographic variations are the most significant differences between rocks of the Honolulu Volcanic Series and the uniform basalt of the Koolau Volcanic Series (Winchell, 1947, p. 28).

Wells in the lava flows of the Honolulu Volcanic Series have low to moderate yields. Wells in lava flows in Haiku Stream valley were pumped at 40 to 45 gpm, and specific capacity ranged from 2 to 40 gpm per ft of drawdown.

Lava flows of the Honolulu Volcanic Series generally are less permeable than those of the Koolau Volcanic Series, so where the Honolulu overlies the Koolau it retards upward movement of water from the Koolau. Water from the Koolau under these circumstances is usually discharged at edges or toes of lava flows; Api (lat 21°21′ N., long 157°46′ 30″ W.), Ainoni (lat 21°20′30″ N., long 157°46′ W.), and Baskerville Springs are examples.

Widely scattered cinder beds are the most permeable rocks of the Honolulu Volcanic Series, but they constitute only a fraction of total rock volume. Locally they yield small quantities of water to wells.

ALLUVIUM

Alluvium is exposed from an altitude of about 600 feet in valleys to sea level at the coast. Alluvium and calcareous sedimentary materials underlie about 70 percent of the project area. In the Waimanalo area they are more than 700 feet thick.

OLDER ALLUVIUM

Moderately consolidated to well consolidated weathered alluvium forms an apron at the base of projecting Koolau basaltic ridges and spurs. This alluvium is composed of silt and clay, lesser amounts of sand and gravel, and a few beds of poorly sorted gravel and cobbles. Despite weathering, structure is generally well preserved, even to vesicles in the cobbles and boulders.

Permeability of near-surface older alluvium is low; this alluvium, together with the weathered zone of lava flows, forms a rather impermeable capping that confines water in the underlying unweathered lava. Yield of wells in windward Oahu in alluvium is generally low. A 730-foot well in the Waimanalo area has a specific capacity of 9 gpm per ft of drawdown.

YOUNGER ALLUVIUM

Poorly to moderately well sorted younger alluvium of gravel, sand, and silt, consisting chiefly of reworked older alluvium, extends up most stream valleys to an altitude of about 200 feet south of Kaaawa and to about 100 feet north of Kaaawa. The young alluvium is generally more permeable than the older.

CALCAREOUS SEDIMENTARY MATERIAL

CORAL AND CORAL RUBBLE

Coral and coral rubble underlie all coastal areas except Kaneohe, where they are sparse. Drillers' logs indicated coral as deep as 214 feet below sea level at well 408 in the Waimanalo area and as deep as 50 feet below sea level near Punaluu.

Coral and coral rubble are generally permeable. Specific capacities of wells tapping those formations in the Waimanalo area range up to 150 gpm per ft of drawdown. Coral aquifers are highly susceptible to sea-water contamination if excessively pumped.

Sand consisting of fragments of calcareous algae, coral, foraminifera, and other marine organisms form extensive beaches except in the Kaneohe area. The sand is extremely permeable but is underlain by brackish and saline water.

CALCAREOUS DUNES

Lithified dune sand blown inland from ancient beaches is extensive near the coast in the Waimanalo and Maunawili areas. In the Waimanalo area, dunes extend inland for more than 1 mile. Their water-bearing properties differ widely, depending on the extent of solution cavities and channels. A well dug in consolidated dune sand supplied part of the domestic water needs of the town of Waimanalo for many years.

Wind-blown sand from present beaches forms extensive dunes near the coast in the Waimanalo and Maunawili areas. Although the dunes are extremely permeable, most of these deposits lie above the water table.

WATER RESOURCES

Rainfall is the source of water in the windward area. Some rainfall evaporates or is transpired by plants, some replenishes soil moisture, some percolates to ground-water reservoirs, and the remainder enters stream channels and runs off.

In high-rainfall areas, much rain becomes ground water, whereas in low-rainfall areas, most rain evaporates or is transpired. The amount of water that runs off differs with rain intensity and geology and topography of each stream basin. Generally direct runoff from light orographic rains is small. During infrequent severe storms and for short periods, however, runoff may approach the volume of the rainfall. Ground water maintains the base flow of streams and the water available to tunnels and wells. A part of the ground water moves to sea as underflow, most of it north of Kaneohe Bay where permeable basalt extends to the sea.

The surface-drainage divide between leeward and windward Oahu is the crest of the Koolau Range. Although the ground-water divide has not been exactly determined, it runs roughly parallel with and probably leeward of the crest. Ground-water divides between valleys also may not coincide with topographic divides.

Locations of principal streams, major basin divides, gaging stations, ditches, tunnels, and wells are given on plate 1.

PRECIPITATION

Precipitation on individual basins or on groups of basins was computed from figure 5, which was taken from the isohyetal map of median annual rainfall on Oahu prepared by the Hawaii Water Authority (Taliaferro, 1959). The map is based on data for the 25-year period, 1933–57. Precipitation was computed by multiplying the area between isohyets, measured by planimeter, by median precipitation. Annual precipitation on the entire project area is estimated by this method to be about 145 billion gallons. The area included in surface-water and ground-water inventories is shown in figure 5; annual precipitation on this area is about 110 billion gallons. Median daily precipitation is about 400 million gallons on the entire project area and about 300 million gallons on the area included in the water inventories.

EVAPOTRANSPIRATION

Water vapor enters the atmosphere from free water surfaces and from moist soil by direct evaporation and from plants by transpiration. These natural demands for water, commonly referred to as evapotranspiration, must be met by precipitation before it can contribute to the water resources of an area.

Evapotranspiration research in Hawaii by the sugar industry (Baver, 1954; Campbell and others, 1959; Chang, 1956) and by the pineapple industry (P. C. Ekern, written commun., 1962) shows that evapotranspiration differs widely from place to place. Annual variations at any one place seem to be small, however, and if water is constantly available, as it is for irrigated sugarcane, evapotranspiration approximately equals evaporation from a Class A evaporation pan of the U.S. Weather Bureau. In Hawaii, where a humid climate generally prevails, the oasis effect which accentuates pan evaporation in arid and semiarid climates is probably minimal.

According to Kozlowski (1964), evapotranspiration depends mainly on available heat and theoretically is independent of vegetation type, provided that there is adequate plant cover and water availability is high. Transpiration and soil evaporation are so interrelated that an increase in the rate of one is accompanied by a decrease in the other.

Evapotranspiration probably approaches its potential of evaporation from a free water surface in windward Oahu where water is constantly available to plants owing to the proximity of ground water in coastal areas and the high frequency of rainfall in the mountainous areas. However, with most research confined to cultivated areas in Hawaii, methods using only easily accessible climatic data are needed for determining evapotranspiration applicable to natural cover. The method by Thornthwaite (1948), which expresses potential evapotranspiration mainly as a function of the mean monthly air temperature, was found inapplicable in Hawaii where temperature variations are small.

Mink (1962, p. 158) recognized a relation between rainfall and pan evaporation. Cox (in Campbell and others, 1959, p. 648) said: "The factors controlling evapotranspiration are to some extent correlative with rainfall, hence it is possible to discuss evapotranspiration empirically as a function of rainfall." The present writers are in general accord with conclusions of Mink and Cox.

One major problem in all hydrologic studies in Hawaii is general lack of evapotranspiration data and a scarcity of pan-evaporation data as well. Most of the pan-evaporation stations are maintained by sugar and pineapple companies in cultivated areas which comprise but a small percentage of the total land area; the stations are therefore poorly distributed by areas and by altitudes. In 1963 there were 67 active stations in the State, 35 of which were installed after 1960. Short-term records were available from 29 stations. In windward Oahu, where no sugarcane or pineapple is grown, data are available from only two stations (Hawaii Division of Water and Land Development, 1961).

To cope with the scarcity of data in windward Oahu, pan evaporation in the area was estimated from relations of median annual pan evaporation to median annual rainfall in Hawaii shown in figure 9. The equation $\log_{10}E$ (median annual pan evaporation) $=1.9387 - 0.0035R$ (median annual rainfall) describes closely the data for stations recording wind movement of less than 20,000 miles per year. Records of pan evaporation, rainfall, wind movement, and temperature from 18 stations used in developing the relations shown in figure 9 are

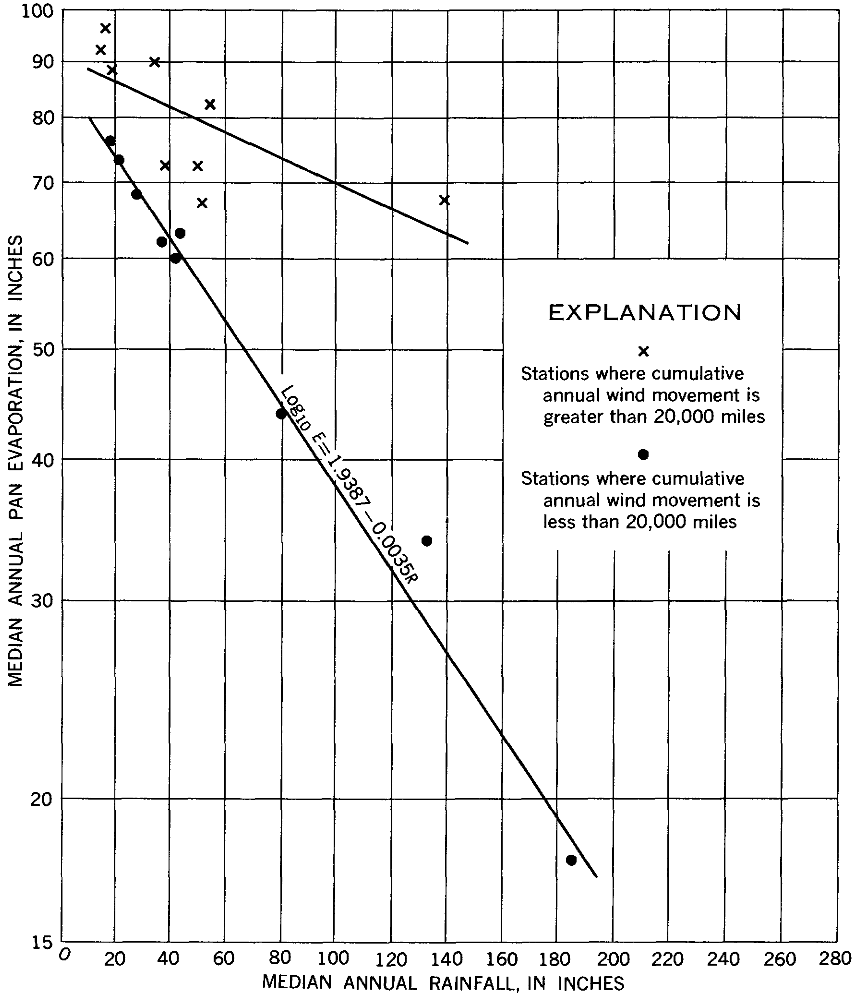

FIGURE 9.—Relations of median annual pan evaporation to median annual rainfall in the Hawaiian Islands.

given in table 4. Wind movement is an essential climatic factor in the relations; thus, only records from pan-evaporation stations recording wind movement were used.

Average annual evapotranspiration was estimated for windward Oahu by assuming that the equation $\log_{10}E=1.9387-0.0035R$ was applicable for the entire area. The indicated evapotranspiration was multiplied by the areas delineated by the rainfall isohyetal lines (fig. 5), and the products were summed to obtain the total for the entire area. Annual evapotranspiration, thus computed for windward Oahu, is estimated to be 221,000 acre-feet (46 in.). The estimate for the area

TABLE 4.—*Pan-evaporation stations, State of Hawaii*

Station	Name	Median annual rainfall,[1] in inches	Pan evaporation, in inches		Mean annual wind movement, in miles	Mean annual temp, in °F	Island
			Median annual	Years of record			
21	Pahala	43.4	63.1	14	14,024	73.5	Hawaii.
87	Hilo Airport	139.2	67.7	7	24,714	73.0	Do.
310	Waikapu	14.9	96.3	5	102,404	75.8	Maui.
316	Field 405	13.8	91.9	6	76,387	75.1	Do.
396	Puunene	18.3	88.2	7	62,108	75.5	Do.
413	Kaheka	34.2	89.7	8	95,396	75.8	Do.
702	U.S. Magnetic Station	18.9	76.0	4½	18,450	75.1	Oahu.
707	H.S.P.A	36.7	72.9	4	64,092		Do.
782	Lower Luakaha	132.0	33.6	6	7,700		Do.
787	Maunawili Branch	79.4	43.7	10½	16,466	72.5	Do.
798	Waianae	20.5	73.6	8½	4,750	76.0	Do.
813	Robinson Camp	34.5	62.7	24	14,090	71.8	Do.
820.2	PRI Wahiawa	[2] 49.0	72.7	6½	23,433	71.7	Do.
826	Waipio	50.8	68.5	24	65,189	71.7	Do.
847	Waialua	28.2	68.0	3	1,534	73.5	Do.
861	Opaeula	42.4	60.1	3	6,150	69.6	Do.
882.1	NF Kaukonahua	186.3	17.7	4	[2] 5,000		Do.
1020.1	Lihue Airport	55.7	82.5	7½	29,308	74.0	Kauai.

[1] Hawaii Water Authority.
[2] Estimated.

included in water inventories (shaded area in fig. 5) is 96,000 acre-feet per year (35 in. per yr). The estimates for evapotranspiration tend to be small for areas having high winds and large for areas where water is not constantly available. The estimates are reasonably good because the area having wind in excess of 20,000 miles per year is judged small.

Evapotranspiration determined through hydrologic-budget studies for part of the area compares favorably with that computed by the equation $\log_{10}E=1.9387-0.0035R$. An 11-year tabulation of rain, base flow, and storm runoff of the drainage basin of the Haiku stream-gaging station is given in table 5. The net difference of the annual means for the 11-year period between rainfall and the sum of base flow and storm runoff is presumed to be evapotranspiration and amounts to 1,680 acre-feet (33 in. per yr). This figure is compared with evapotranspiration of 37 inches per year for the basin, computed by using the 11-year mean annual rainfall of 104 inches in the equation. It is also compared with evapotranspiration of 46 inches per year for the project area and 35 inches per year for the area included in water inventories, computed by using the median annual rainfall of 92 inches and 125 inches, respectively.

In the hydrologic-budget study, annual rainfall was computed by multiplying the rainfall recorded at a gage in the middle of the area by the area and assumed no variations in rainfall within the area. Base flow of the basin was taken as the sum of the flow of Haiku tunnel, located in the area, and the computed base flow at the gaging station. Storm runoff was taken as the difference between total runoff and the

TABLE 5.—*Water budget of upper Haiku Valley*

[Drainage area, 621 acres (0.97 sq mi); gaging station, alt 272 ft; Haiku tunnel, alt 550 ft

Year	Rain		Base flow [1] (acre-feet)	Storm runoff (acre-feet)	Water yield (acre-feet)	Difference (acre-feet)
	Feet *a*	Acre-feet *b*	*c*	*d*	*c+d*	(*b*)−(*c*+*d*)
1947	8.7	5,380	3,140	630	3,770	1,610
1948	9.0	5,590	3,220	450	3,670	1,920
1949	7.8	4,850	2,960	510	3,470	1,380
1950	9.2	5,730	2,820	520	3,340	2,390
1951	9.9	6,130	3,430	990	4,420	1,710
1952	7.1	4,430	3,290	310	3,600	830
1953	5.3	3,300	3,090	90	3,180	120
1954	9.0	5,590	2,910	490	3,400	2,190
1955	9.0	5,590	3,210	1,030	4,240	1,350
1956	11.8	7,330	3,420	690	4,110	3,220
1957	8.7	5,390	2,900	670	3,570	1,820
Total	95.5	59,310	34,390	6,380	40,770	18,540
Mean	8.7	5,390	3,130	580	3,770	1,680
	(104 inches)	(4.8 mgd)	(2.8 mgd)	(0.5 mgd)	(3.3 mgd)	(1.5 mgd)

[1] Sum of measured Haiku tunnel flow and computed ground-water increment of streamflow at gaging station.

computed base flow of the stream. Net storage change during the 11-year period was assumed negligible.

Evapotranspiration cannot be determined by water budgeting for short periods, such as a year, because storage changes may be large and are not negligible. The change in storage for short periods is the difference between rainfall and the sum of base flow, storm runoff, and evapotranspiration. For long periods this difference becomes small in Haiku Valley.

The evapotranspiration rate (33 in. per yr) determined by water budgeting may be lower than the rate (37 in. per yr) computed by the rainfall–pan-evaporation relation for the following reasons:

1. Error in judgment.
2. Error in assumptions, mainly that all water leaving basin is measured.
3. Net change in storage for the 11-year period is not negligible.
4. Use of topographic divide instead of ground-water divide as boundary of basin to compute inflow from rainfall where underflow into basin may be significant.

WATER YIELD

Water yield was estimated by subtracting the estimated evapotranspiration from rainfall as shown in tables 6 and 7. The rainfall values were obtained by dividing drainage areas into subareas between isohyetal lines and multiplying by the median rainfall. Evapotranspiration was then computed for these subareas using the median rainfall in the equation $\log_{10}E = 1.94 - 0.0035R$. Water yield is the sum of the differences of these values—that is:

$$(R_n - E_n)A_n = Y_n$$
$$\Sigma Y_n = Y_{DA}$$
$$\Sigma Y_{DA} = Y_{WO}$$

where R_n=median rainfall for area between isohyetal lines in each drainage basin
E_n=median evapotranspiration for area between isohyetal lines
A_n=area between isohyetal lines
Y_n=water yield for area between isohyetal lines
Y_{DA}=water yield of drainage basin
Y_{WO}=water yield of windward Oahu

Water yield of windward Oahu (Y_{WO}) is shown in tables 6 and 7. It is the sum of water yields computed for that part of the study area

TABLE 6.—*Water yield of windward Oahu*

	Windward Oahu		Inventoried area in windward Oahu		Noninventoried area in windward Oahu	
	Acre-feet per year	Million gallons per day	Acre-feet per year	Million gallons per day	Acre-feet per year	Million gallons per day
Precipitation	444,000	395	342,000	305	102,000	90
Potential evapotranspiration	221,000	195	96,000	85	125,000	110
Water yield	[1] 234,000	210	246,000	220	[2] −23,000	−20

[1] Y_{WO}; includes Waimanalo Valley, where potential evapotranspiration is greater than precipitation. See table 7.
[2] Evapotranspiration is greater than precipitation.

TABLE 7.—*Water yield of drainage basins in windward Oahu (all quantities rounded)*

	Area		Precipitation (acre-feet)	Potential evapotranspiration (acre-feet)	Water yield		Ratio of evapotranspiration to precipitation
	Square miles	Acres			Acre-feet	Mgd	
Drainage basin:							
Waimanalo	11.2	7,170	26,200	36,900	[1] 0	0	1.42
Maunawili	18.0	11,500	58,500	52,100	6,400	5.7	.89
Kaneohe	40.0	25,600	190,000	94,900	95,500	85.3	.50
Kaaawa	3.6	2,300	13,100	9,600	3,500	3.1	.73
Kahana	8.4	5,380	67,100	12,800	54,300	48.5	.19
Punaluu	6.6	4,220	64,400	9,400	55,000	49.1	.15
Kaluanui	3.0	1,920	24,300	4,900	19,400	17.3	.20
Total	91	58,100	444,000 (395 mgd)	221,000 (195 mgd)	[2] 234,000	210	[3] .50
Part of drainage basin included in water inventory:							
Waimanalo	2.4	1,540	8,500	6,700	1,800	1.6	.79
Maunawili	6.7	4,290	30,900	15,800	15,100	13.4	.51
Kaneohe	22.9	14,700	142,000	42,600	99,400	89.0	.30
Kaaawa	2.7	1,730	10,100	7,100	3,000	2.7	.70
Kahana	8.4	5,380	67,100	12,800	54,300	48.5	.19
Punaluu	6.6	4,220	64,400	9,400	55,000	49.1	.15
Kaluanui	1.7	1,090	18,800	1,600	17,200	15.3	.09
Total	51	33,000	342,000 (305 mgd)	96,000 (85 mgd)	246,000	220	[3] .28

[1] Evapotranspiration is greater than precipitation.
[2] Y_{WO}.
[3] Mean.

311-591 O—69——3

in which a water inventory was made (shaded area in figure 5) and that part of the area not inventoried (unshaded area in figure 5). The computations indicate that evapotranspiration exceeds rainfall in the noninventoried area where rainfall is low (see table 6) and that the water yield in the water-inventory area is larger than the sum of the water yields in the two areas (see table 7).

The water-inventory area includes the total drainage area of all the larger streams at the points of measurable maximum base flow. Downstream from these points the streams are generally too sluggish to be accurately measured, or when measurable they are disturbed by the inflow of shallow ground water in coastal sedimentary material.

GROUND WATER

SOURCE AND OCCURRENCE

Rain is the source of all ground water in windward Oahu. In addition to direct rainfall, some rain on the leeward side of the crest may contribute to the windward ground-water supply. In one area, however, owing to the Waiahole ditch tunnel system, main transmission tunnel, the situation is reversed. Rainfall is highest and, consequently, recharge is greatest in the Koolaus, where permeable lava is exposed. Generally, the percentage of recharge of rainfall decreases from high- to low-rainfall areas, owing to surface rocks of lower permeability and greater evapotranspiration in low-rainfall areas.

Most ground water occurs in lava flows of the Koolau Volcanic Series, and lava flows make up the bulk of the range. Dikes generally retard and control ground-water movement; but near the coast, at the northern end of the area, these lava flows are relatively free of dikes and their hydrologic control. In the southeastern part of the area, water is perched in small scattered bodies in rocks of the Honolulu Volcanic Series.

The term "high-level water" was first used by Palmer (1927, p. 5) to describe water derived from springs or from tunnels driven into the mountains near Honolulu. The term has come into general Hawaiian use in classifying ground water isolated from sea water by dikes or other material of low permeability (see p. 16). Recharge to the high-level water occurs almost entirely by infiltration and percolation of rain.

Basal ground water in an island was described by Meinzer (1930, p. 10) as a great body of water below the main water table that lies near sea level. The term is now generally applied in the Hawaiian Islands to all ground water floating on sea water in permeable rocks below the water table.

Basal water occurs in lava flows near the coast at the northern end of the area and in calcareous sedimentary rocks at the southern end. It may also occur in the marginal dike zone adjacent to the ocean. Basal-water bodies are recharged by direct leakage from high-level water or by seepage from streams fed by high-level water. Direct rainfall and irrigation water applied to crops also may contribute significantly to recharge of basal-water bodies.

STORAGE

The rocks underlying windward Oahu store a very large but indeterminate amount of water. Water is stored in the rainy mountainous areas to an altitude of as much as 1,000 feet and throughout the area at depths considerably below sea level. The only exception is the area underlain by rocks which are free of dikes (pl. 2) where water levels extend to about 22 feet above sea level and the fresh-water body is limited to a depth of about 1,000 feet below sea level. Elsewhere in the dike complex and in the marginal dike zone, the limiting height and depth to which water is stored depend on the geometry of the dike pattern and the ability of the dikes to retain water stored behind them. The limiting depth also depends on the porosity of the rocks, which at some depth approaches zero, owing to increasing pressures at which the rocks were originally extruded at great depths below sea level. Of principal concern in this report is the variability of storage in the dike complex and marginal dike zone, where most of the recharge occurs and where the potential exists for regulating the water body.

The stored dike water discharges where the streams have cut notches in the dikes, and some of the water probably discharges as underflow, through or around the dikes. The base flow of the stream fluctuates with the level of storage in the dike reservoirs, which fluctuates in accord with the precipitation recharging the ground-water body. Between periods of recharge the base flow recedes, the rate of recession being predictable from past records. The regimen of the base flow can be defined, therefore, throughout the range of recorded reservoir level. The volume of storage available between any two levels can be calculated by integrating the area under the recession curve. (See p. 106.)

The tunnels that were constructed to develop the stored water have provided lower points of discharge from the dike reservoirs. The base-flow regimen of the streams is affected, and probably part of the underflow is intercepted. The uncontrolled flow from the tunnels varies with reservoir level similarly to the variations in base flow of the streams. The combined flow from tunnels and streams probably exceeds on the average the flow from the streams before the tunnels were added. The additional flow is composed of intercepted underflow and the increase in recharge. Recharge likely is increased because the tunnels drain the stored water faster between storms, thereby providing more space in the reservoir. Storm water that formerly might have run off directly to the streams, when the ground-water reservoir was full, now may infiltrate and enter the dike reservoir.

The flow from only 1 of the 21 tunnels in windward Oahu can be regulated effectively. The discharge rates are controlled by a valve in the bulkhead at a critical dike in the tunnel. With similar installations in other tunnels, storage can be further regulated to meet the water-demand pattern. (See p. 105.) Extrapolation of data obtained during and following construction indicates that tunnels have reduced the average storage by about 26,000 million gallons; this storage reduction represents a small part of the total storage and is only from water stored above an altitude of 800 feet in the northern half of the area and 600 feet in the southern half.

Some quantitative estimates of storage variations can be made from available records. The measured base flow from streams and tunnels and the estimated underflow indicate the combined flow ranges from about 85 to 255 mgd. If a recession curve of the base-flow discharge of windward Oahu were available, the volume of water released from storage between record wet and dry periods could be calculated by integrating the area under the curve in which the base-flow discharge ranges from a maximum of 255 mgd to a minimum of 85 mgd. Although such a recession curve is not available, the volume of water released from storage can be estimated provided the shape of the curve can be reasonably duplicated. The basis for duplicating the curve and the estimate of the water released from storage in windward Oahu are given in the following paragraphs.

The hydrograph of the base flow of Waihee Stream, shown in figure 10, reflects periods of high rainfall (1941–43) followed by low rainfall (1943–46). Storage in the Waihee Stream basin and likewise in windward Oahu probably approached its upper and lower limits during the period represented by the hydrograph. The dark area shows the range of fluctuation of the base flow of Waihee Stream and also of the base-flow discharge of windward Oahu. The slope of the recession curve during this period of low rainfall combines the steepest segments of the base-flow hydrograph. The equation of the line is $Q_t = Q_0 e^{bt}$. The volume of water released from storage is calculated from the equation by integrating the area under the curve. The values used are $Q_t = 85$ mgd, $Q_0 = 255$ mgd, and $t = 900$ days, in which Q_t and

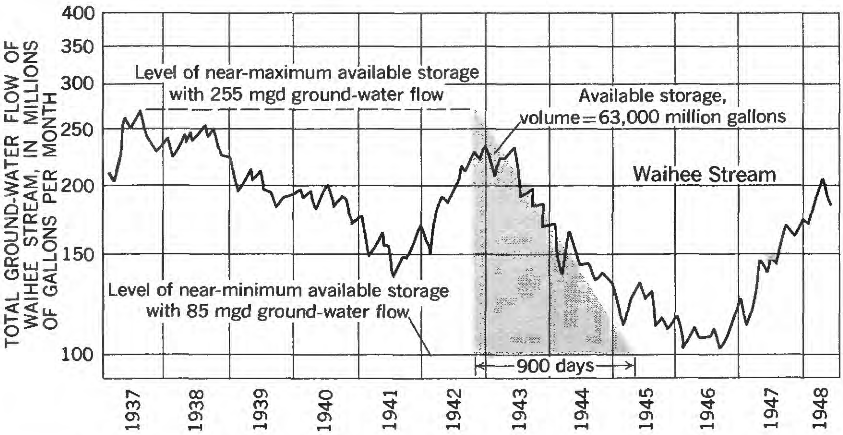

FIGURE 10.—Ground-water component of flow in Waihee Stream during a period when storage approached its maximum and minimum.

Q_0 are base-flow discharge of windward Oahu instead of the base flow of Waihee Stream. Total discharge for the 900-day period was 139,000 million gallons, of which 76,500 million was minimum recharge (85 mgd × 900 days). The volume of water released from storage is the difference between the two, or 62,500 million gallons.

Although the quantity of water released from storage is determinable, the area represented, and thus the total volume of material dewatered within the zones of fluctuation, are not determinate owing to interconnection between drainage basins and hidden geohydrologic features that control ground-water movement.

CHANGES IN STORAGE IN HAIKU VALLEY

The boring of Haiku tunnel in upper Haiku Valley reduced storage by about 1,400 million gallons (Hirashima, 1963). The tunnel was driven in saturated rock intruded by at least four dikes. After tunneling, storage in the valley continued to fluctuate in accord with varying rates of recharge and discharge, but its upper and lower limits were reduced. Changes in storage in the zone of fluctuation can be analyzed for the 11-year period, 1947–57, by using the data in table 5 and assuming the following conditions:

1. Net-storage change during the period was negligible.
2. Annual evapotranspiration was constant and equaled 1,680 acre-feet per year (33 in. per yr), the net difference between rainfall and water yield.
3. Rainfall recorded at an altitude of 600 feet near the center of the drainage area was the mean for the area.

4. Measured tunnel flow and streamflow represented all ground and surface water moving through the area.
5. Excess of precipitation (less evapotranspiration) over the measured flow went into storage, and excess in the measured flow over precipitation (less evapotranspiration) came out of storage.

Annual additions to and withdrawals from storage are shown in figure 11 where they are plotted against annual precipitation. The annual changes in storage approach zero as annual precipitation approaches its 11-year mean.

Seasonal totals for the same 11-year period show the effects of wet and dry periods during the year. The results are plotted in figure 12 and show that storage generally increases from November to February, when rainfall is usually above the monthly mean, and generally decreases from May to August, when rainfall is usually below the monthly mean. Figure 12 also shows that less rainfall is required to

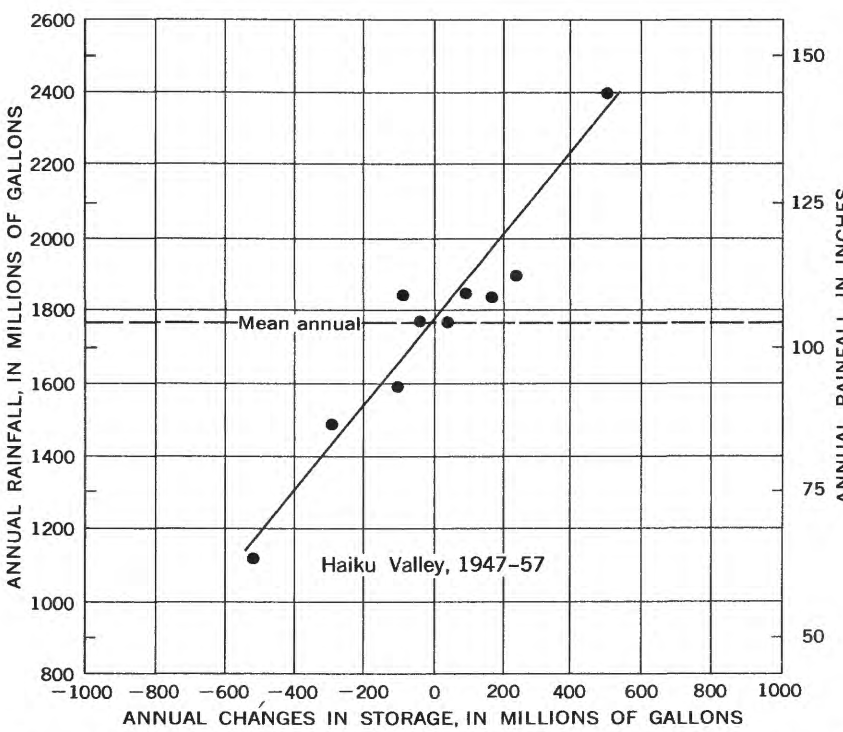

FIGURE 11.—Relation of annual precipitation and annual change in storage in upper Haiku Valley for the period 1947–57.

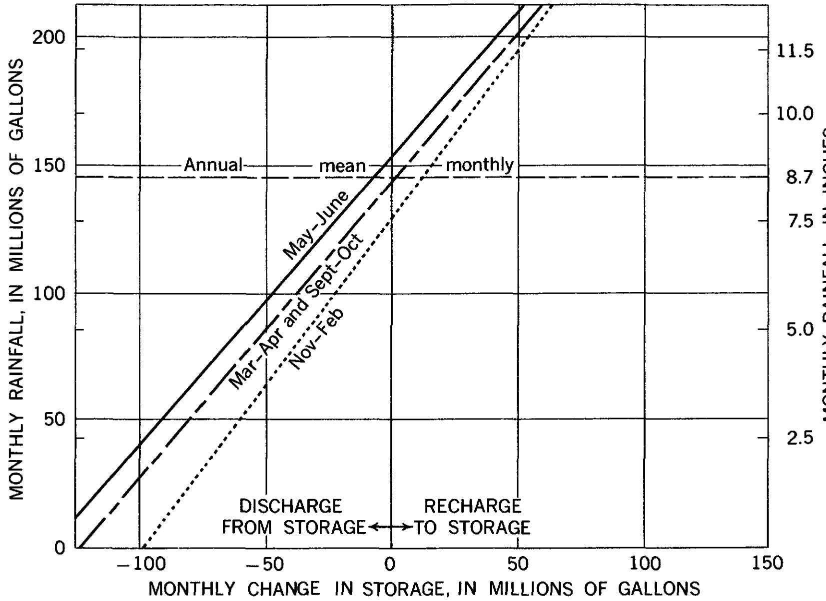

FIGURE 12.—Relation of monthly precipitation and monthly change in storage in upper Haiku Valley for the period 1947–57.

recharge storage with an equal quantity of water from November to February than during other seasons.

STREAMS

With the exception of Kaluanui Stream, all streams are gaining, and maximum flow is at low altitudes near the shore. Periodic measurements were made at points of maximum flow of each stream; these were correlated with concurrent discharges at gaging stations on the same or nearby streams. Wherever correlation was good, a regression equation was computed and was used to estimate long-term average discharge and index of dependable flow, Q_{90} (flow equaled or exceeded 90 percent of the time).

The flow patterns of three major streams, Kamooalii, Punaluu, and Kahana, are shown in figures 13, 14, and 15, respectively. Streamflow at different altitudes is given as a percentage of the flow at each gaging station.

GAGING STATIONS AND RECORDS

Sixteen gaging stations were in operation in windward Oahu during the investigation, and many others have been in operation for short periods.

Although records of Haiku Stream have been collected for more than 28 years (1914–19, 1939–present), only those through October

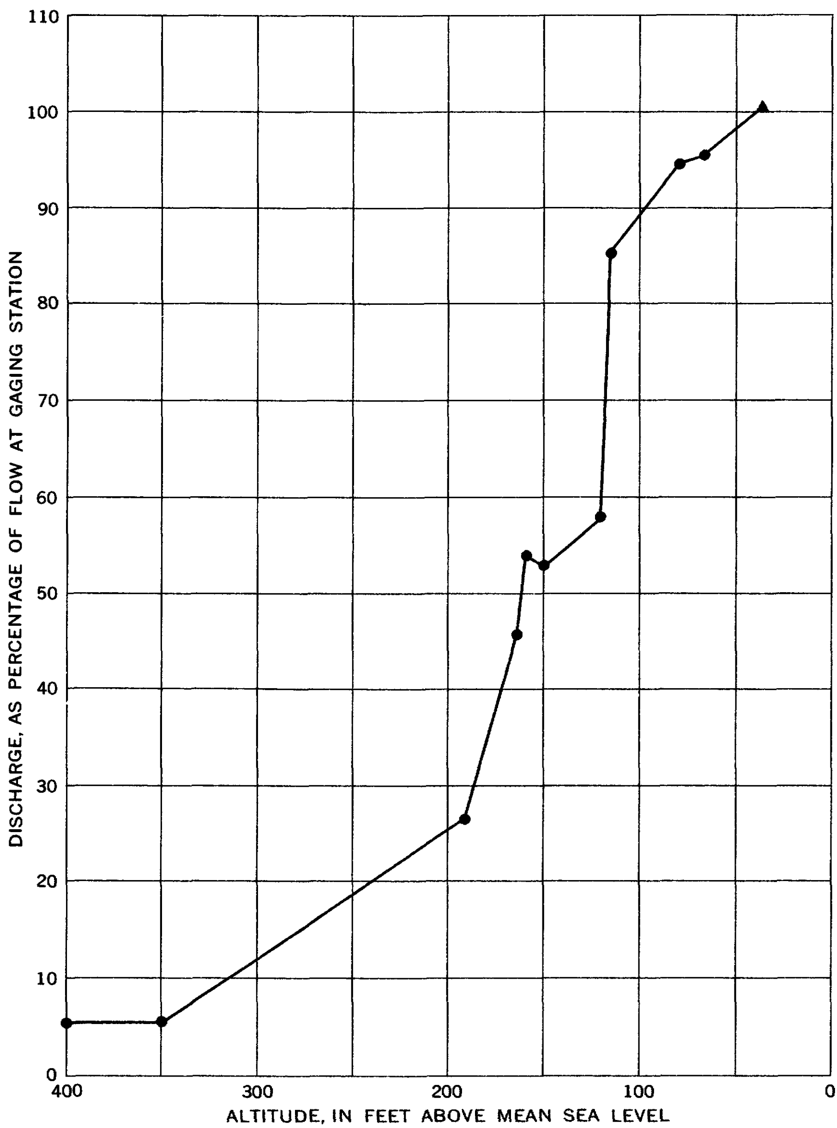

FIGURE 13.—Kamooalii Stream—streamflow gains and losses with altitude.

1940 are representative of natural conditions, owing to the boring of the Haiku tunnel in November 1940. Drainage from that tunnel decreased the flow of Haiku Stream as well as that of Kahaluu and Iolekaa Streams (Hirashima, 1963).

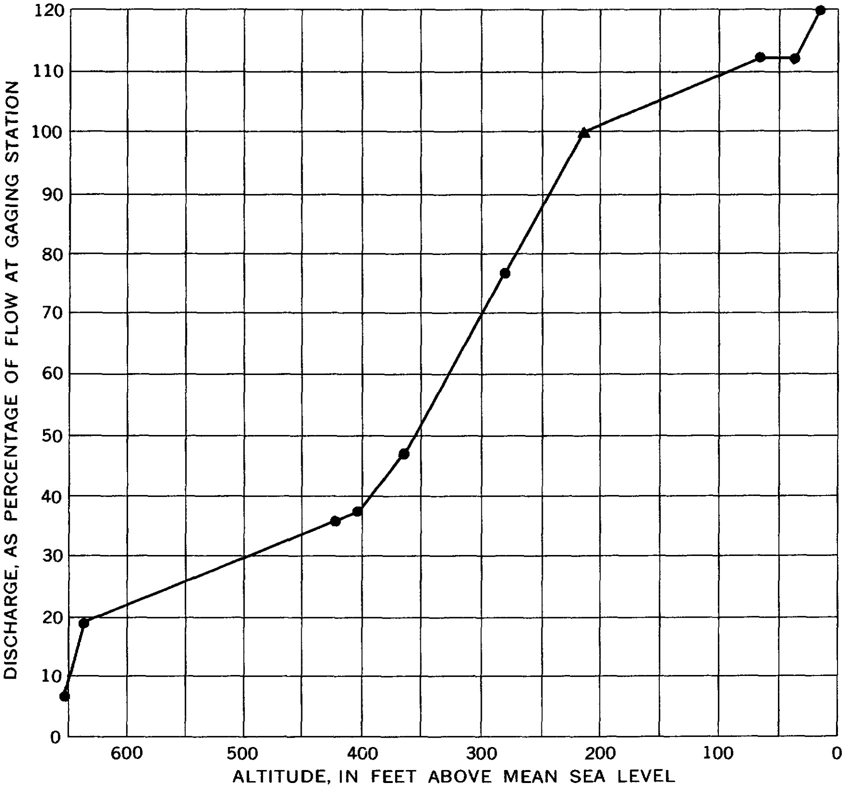

FIGURE 14.—Punaluu Stream—streamflow gains and losses with altitude.

Waihee Stream has the longest period of record of natural flow—from January 1936 to January 1955. After that time, flow was affected by withdrawal of water from the Waihee tunnel (Hirashima, 1965).

Many measurements at sites other than the established gaging stations were made for more streamflow information. Those made from 1959 to 1962 are shown on plate 3.

USE OF RECORDS

The period July 1, 1926, to June 30, 1960, was selected as the base period of record for this report, and East Branch Manoa Stream (station 2390, lat 21°19′50″ N., long 157°48′10″ W.) was used as the principal correlation stream. Although it is in southern Oahu on the leeward side of the Koolau Range, this stream is hydrologically similar to windward streams, and it has a long continuous record of observation under natural conditions. It therefore provides a better base for comparison than does the record of any stream on the windward side.

Graphs in figure 16 show correlation of base flow of Waihee Stream in windward Oahu with base flow of East Branch Manoa Stream on the leeward side. The figure also shows that water levels in wells on

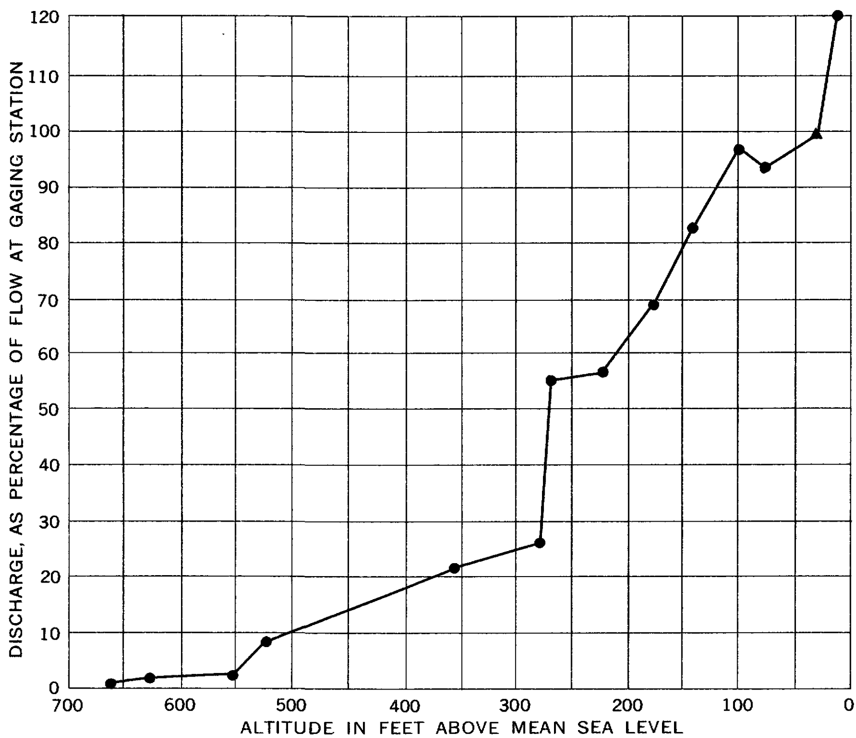

FIGURE 15.—Kahana Stream—streamflow gains and losses with altitude.

opposite sides of the Koolau Range correlate with base flows of Waihee and East Branch Manoa Streams.

LONG-TERM AVERAGE DISCHARGE

Long-term average discharges of streams were estimated by the use of regression lines; that is, monthly mean discharges of gaged

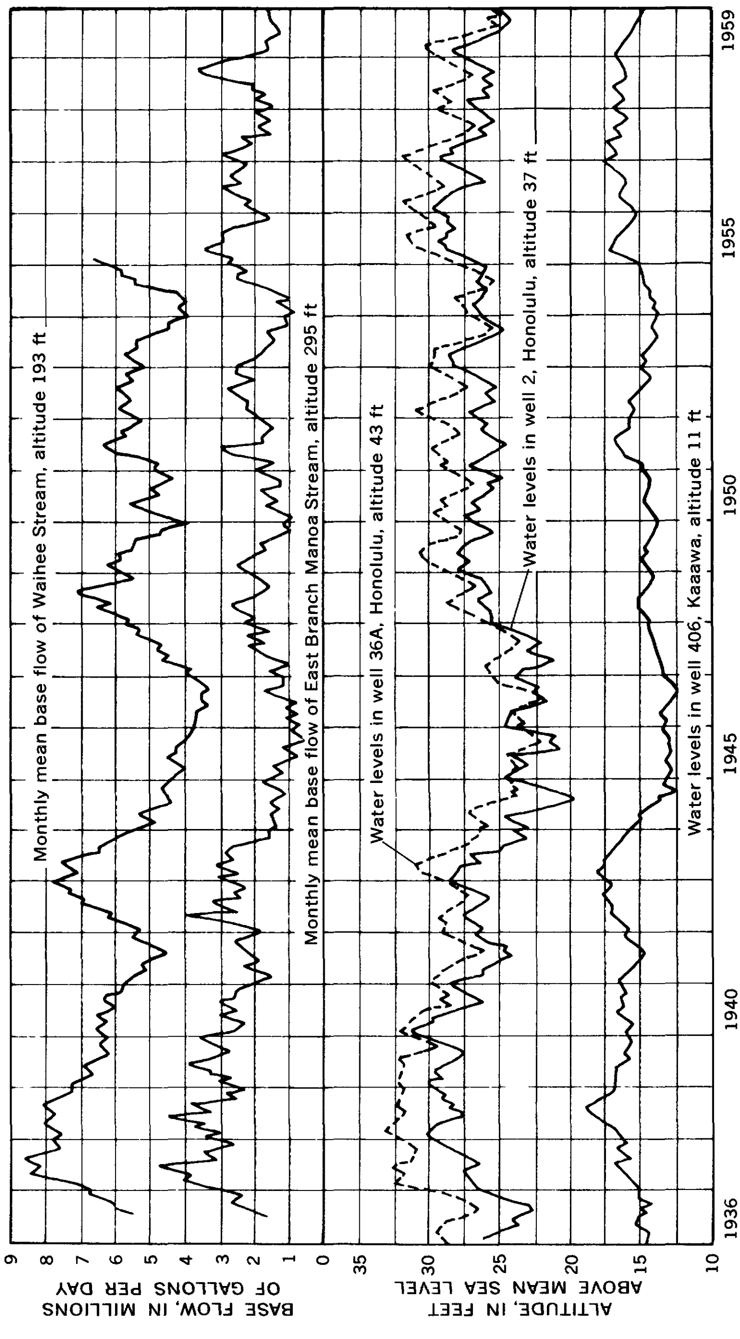

FIGURE 16.—Base flow and water level in windward and leeward Oahu.

windward Oahu streams were correlated with concurrent monthly mean discharges of East Branch Manoa Stream. For ungaged streams, concurrent daily discharges of comparable gaged streams were used to obtain the regression lines from which the long-term average discharges of the ungaged streams were estimated.

Table 8 shows the observed and computed long-term (1927–60) discharges at gaging stations in windward Oahu. An inventory of streamflow for all perennial streams in windward Oahu is shown in table 9.

FLOW DURATION

A flow-duration curve is a cumulative-frequency curve which shows the percentage of time specified discharges were equaled or exceeded during a period of record. It may be considered a probability curve and used to estimate the probable occurrence of a specified discharge in the future. Duration curves may be used to study the characteristics of streams. Curves for windward streams are flatter than those for leeward streams, owing to the large and consistent component of ground water in the flow of windward streams.

Figures 17 to 26 show short-term and adjusted long-term flow-duration curves for 10 gaging stations. The method for deriving adjusted curves is described by Mitchell (1950, p. 12–18).

Long-term average discharges were computed by integrating the area under the long-term duration curves. Most of the averages were found to be in close agreement with those determined by the regression method. Such agreement indicates that the adjusted long-term duration curves may be used to estimate the probable occurrence of various rates of flow.

The surface-water and ground-water components of flow in hydrographs of some of the windward streams can be readily separated because of the large sustained ground-water component. Such a separation for Waihee Stream (fig. 27) shows that from January 1936 to January 1955 the ground-water component ranged from 82 to 95 percent of the flow, averaging 90 percent.

FLOODS

The streams are short and have steep gradients. All are flashy, and stages can rise and fall several feet in a few hours. Although 10 streams are gaged, only 4—Haiku, Iolekaa, Kahaluu, and Waihee—have been gaged for fairly long periods. The annual maximum discharge of those streams generally occurs in the cooler months, October through April. Maximum discharges range from 255 mgd per square mile, Iolekaa Stream, to 2,810 mgd per square mile, Haiku Stream.

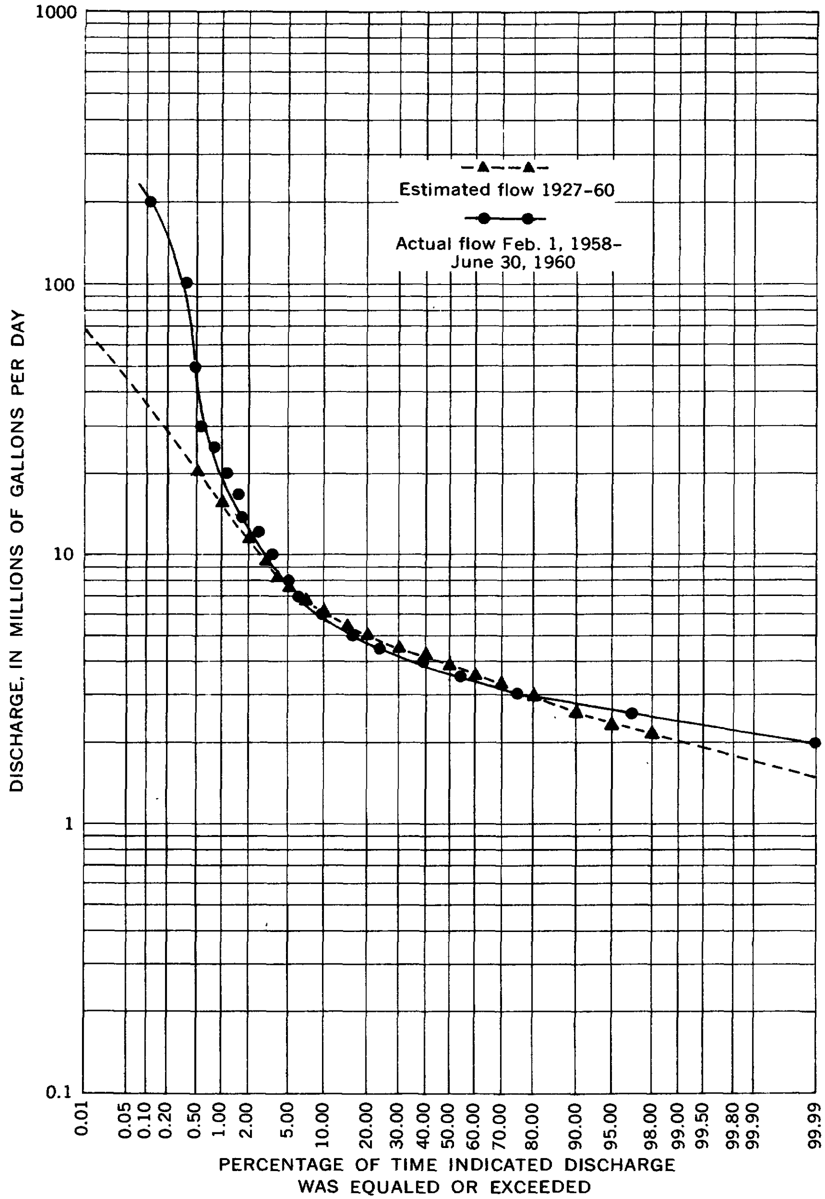

FIGURE 17.—Makawao Stream, computed and observed flow-duration curves.

TABLE 8.—*Observed and computed long-term (1927–60) discharges at gaging stations in windward Oahu*

Site (pl. 3)	Gaging station	Station	Drainage area (sq mi)	Observed discharges			Computed long-term (1927–60) discharges			Remarks
				Q_{ave} (mgd)	Q_{90} (mgd)	Period	Q_{ave} (mgd)	Q_{90} (mgd)	Ratio $\frac{Q_{90}}{Q_{ave}}$	
32	Makawao Stream.	2540	2.04	4.43	2.7	Jan. 1958 to June 1961.	4.3	2.6	0.60	Includes Maunawili ditch flow.
84	Kamooalii Stream.	2739	4.38	7.74	4.6	Feb. 1959 to June 1961.	8.5	4.1	.47	
105	Haiku Stream	2750	.97	2.94	2.0	Feb. 1914 to Sept. 1919 and July 1939 to Sept. 1940.	2.4	1.2	.54	Computed long-term figures are for natural flow condition.
108	Iolekaa Stream	2780	.28	.41	.25	Mar. 1940 to June 1942 and July 1943 to June 1960.	1.0	.52	.52	Do.
126	Kahaluu Stream.	2830	.28	3.93	3.1	Nov. 1935 to July 1941.	3.5	2.7	.77	Do.

159	Waihee Stream	2838	.93	6.21	4.0	Jan. 1936 to June 1954.	6.5	4.2	.65	
255	Waiahole ditch tunnel at north portal.	2870	------	26.3	21.0	Feb. 1951 to June 1960.	26.1	19.5	.75	Includes wastage from tunnel and excludes pumpage from stream.
177	Waiahole Stream at altitude 250 ft.	2910	.99	4.75	3.4	July 1955 to June 1960.	4.9	3.1	.63	Includes pumpage to tunnel and excludes wastage from tunnel.
193	Waikane Stream at altitude 75 ft.	2949	2.25	4.63	1.6	Jan. 1960 to June 1961.	4.2	1.4	.33	
225	Kahana Stream at altitude 30 ft.	2965	3.74	18.6	10.8	Jan. 1959 to June 1961.	20.2	9.3	.46	
244	Punaluu Stream	3030	2.78	15.9	10.0	June 1953 to June 1960.	16.6	9.1	.55	Includes Punaluu ditch flow.
Total							98.2	57.7	-------	

TABLE 9.—*Inventory of streamflow for all perennial streams in windward Oahu*

Site (pl. 3)	Stream	Computed discharges Q_{ave} (mgd)	Computed discharges Q_{90} (mgd)	Remarks
2, 3, 4	Waimanalo	0.7	0.26	Waimanalo drainage area totals 2.43 sq. mi.
41	Maunawili	7.8	4.2	Includes the flow of Maunawili ditch. Maunawili Valley drainage area includes sites 41 and 47 and totals 6.74 sq. mi.
47	Kahanaiki	1.0	.5	
51	Kawa at altitude 70 ft	1.0	.15	Kaneohe drainage area includes sites 51 through 205 and totals 22.9 sq. mi.
84	Kamooalii	8.5	4.1	
90	Kaneohe tributary at alt. 60 ft.	2.8	1.8	
99	Keaahala	3.4	2.2	
105	Haiku	2.4	1.2	Natural flow at gaging station.
108	Iolekaa	1.0	.52	Do.
111	Heeia at alt. 90 ft	2.1	1.1	Gain from Haiku (site 105) and Iolekaa (site 108) gaging stations.
122	Ahuimanu	4.1	.9	
126	Kahaluu at alt. 358 ft	3.5	2.7	Natural flow at gaging station.
136	Kahaluu	1.9	.6	Gain from gaging station to confluence with Ahuimanu.
159	Waihee	6.5	4.2	
166	Waihee at alt. 160 ft	2.7	1.8	Gain from gaging station to Higa ditch intake.
175	Kaalaea at alt. 90 ft	2.4	.6	
255	Waiahole ditch tunnel, north portal station.	26.1	19.5	Natural flow of tunnel system at north portal station.
	Waiahole ditch tunnel, main bore.	2.6	1.8	Gain in main bore between north portal station and adit 8.
178	Waiahole	6.9	3.9	
185	Waianu	1.2	.5	
193	Waikane at alt. 75 ft	4.2	1.4	
205	Hakipuu	1.1	.38	
	Kaaawa	1.0	.14	Discharges estimated for Kaaawa Valley; 2.70 sq. mi.
	Kahana	29.5	11.2	Discharges estimated for Kahana Valley; 8.38 sq. mi.
	Punaluu	24.2	10.9	Discharges estimated for Punaluu Valley; 6.59 sq. mi.
257	Kaluanui	3.4	.17	Kaluanui Valley drainage area totals 1.70 sq.mi.
Total		152.0	76.7	

A program of flood-data collection from crest-stage gages was begun on Oahu in 1957. Under this program peak discharges of 16 streams in the windward area, including those of the 10 regular gaging stations, were obtained. The locations of crest-stage gages are shown in plate 1, and peak discharges are given in table 10. The crest-stage gages are the last six stations listed. Discharge was not determined for Kahaluu Stream, station 2835, or for an unnamed stream between Kaaawa and Kahana Valleys, station 2959. These streams had peak flows on the dates indicated and maximum gage heights of 4.79 feet and 2.48 feet, respectively.

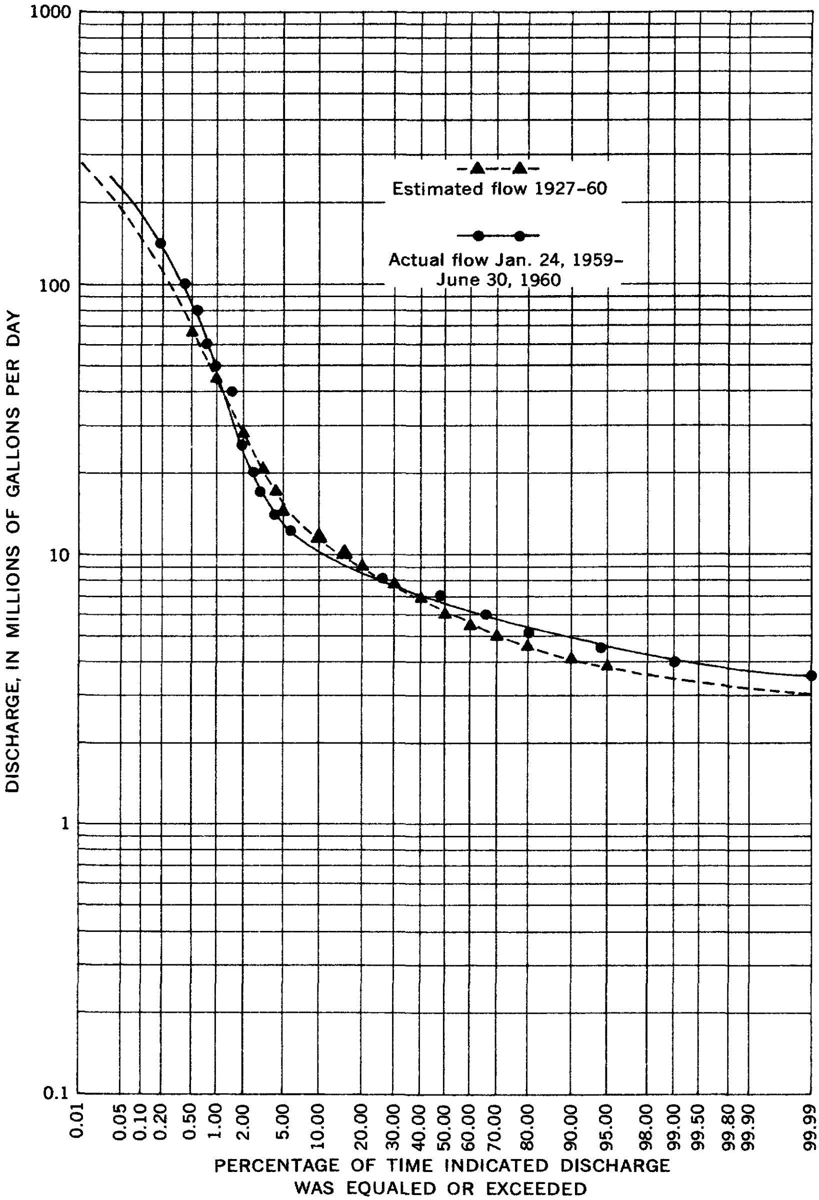

FIGURE 18.—Kamooalii Stream, computed and observed flow-duration curves.

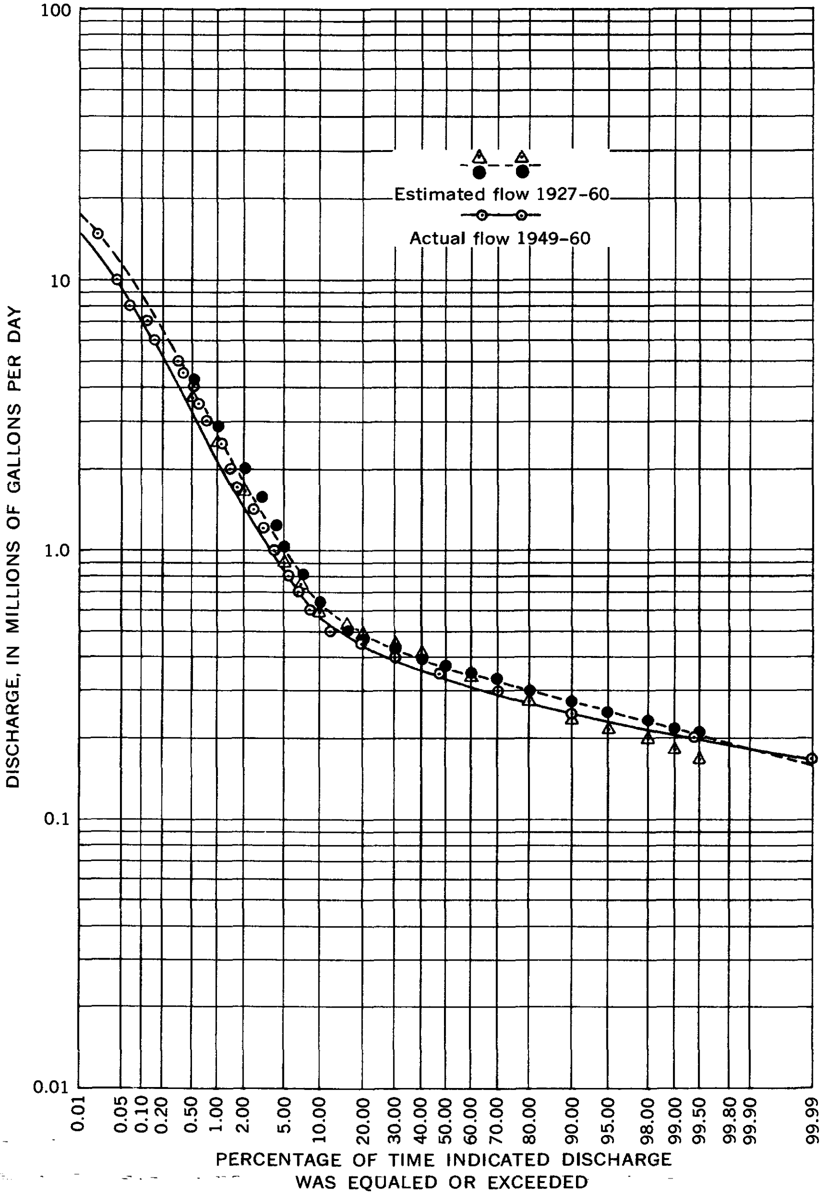

FIGURE 19.—Iolekaa Stream, computed and observed flow-duration curves.

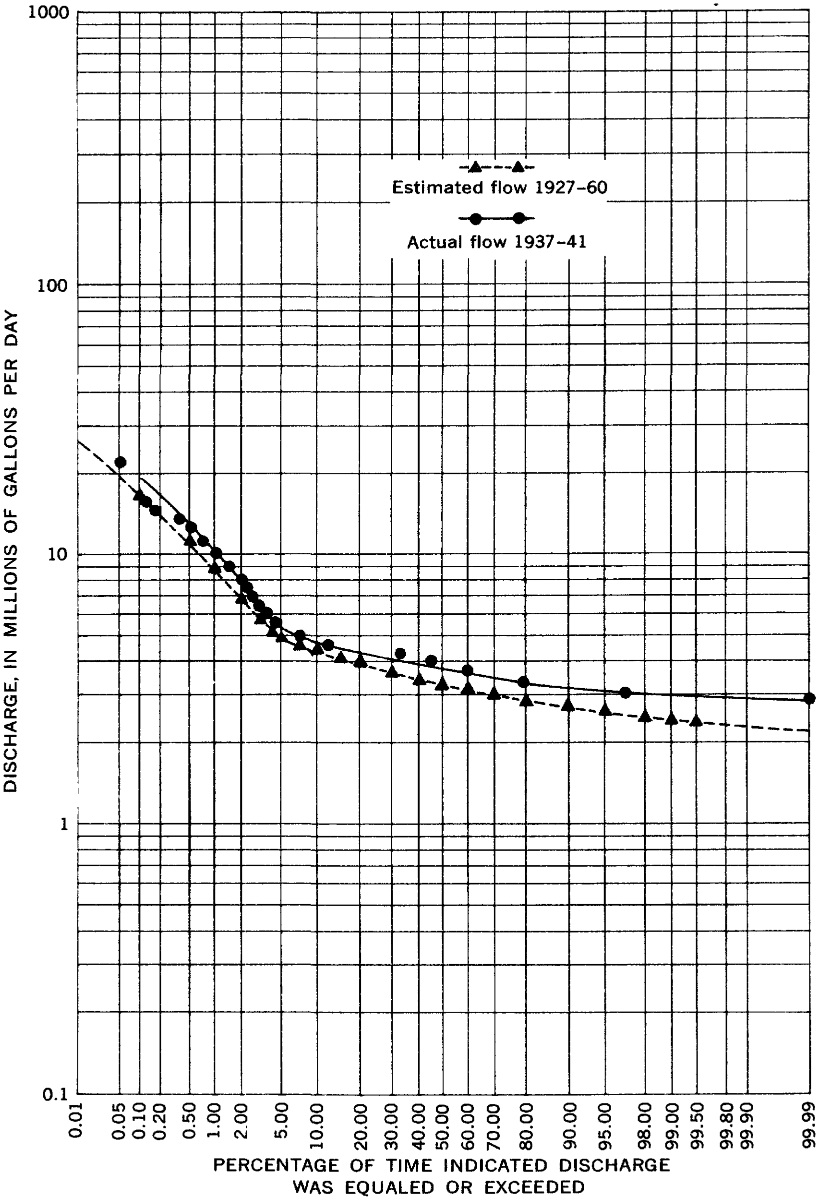

FIGURE 20.—Kahaluu Stream, computed and observed flow-duration curves.

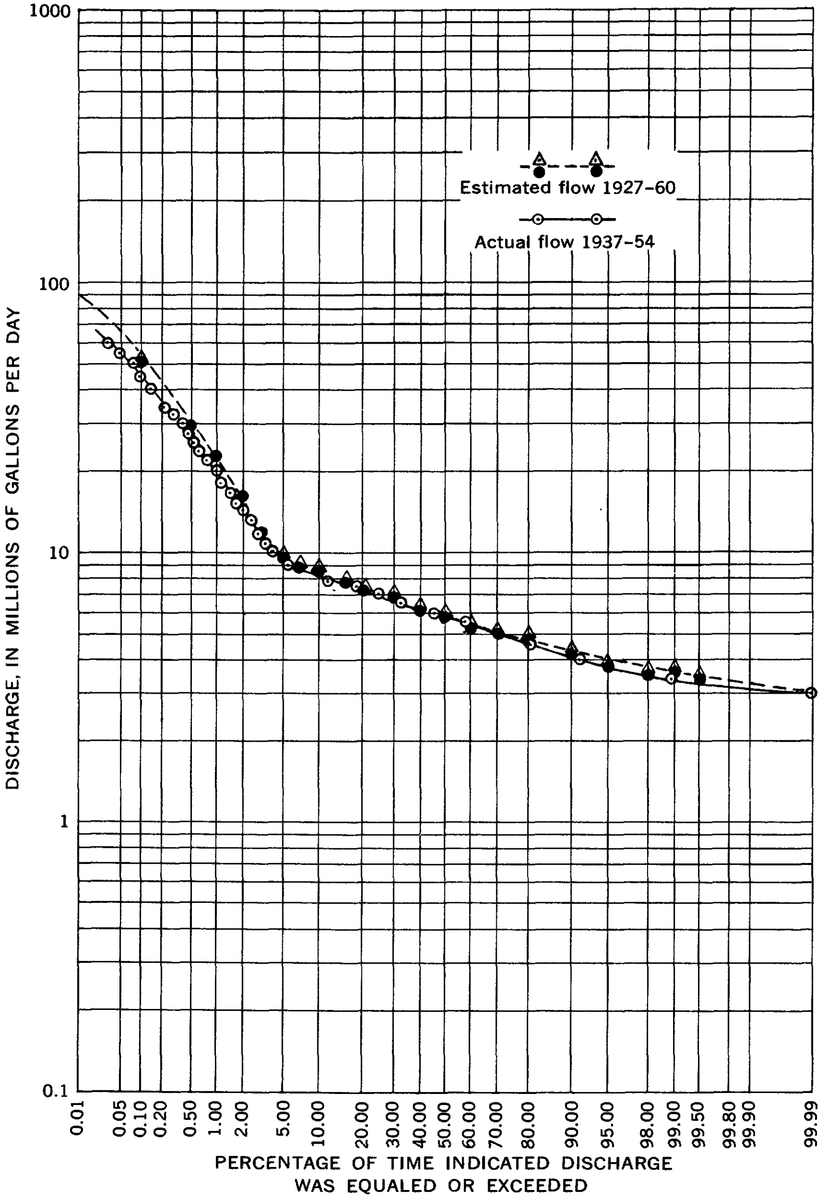

FIGURE 21.—Waihee Stream, computed and observed flow-duration curves.

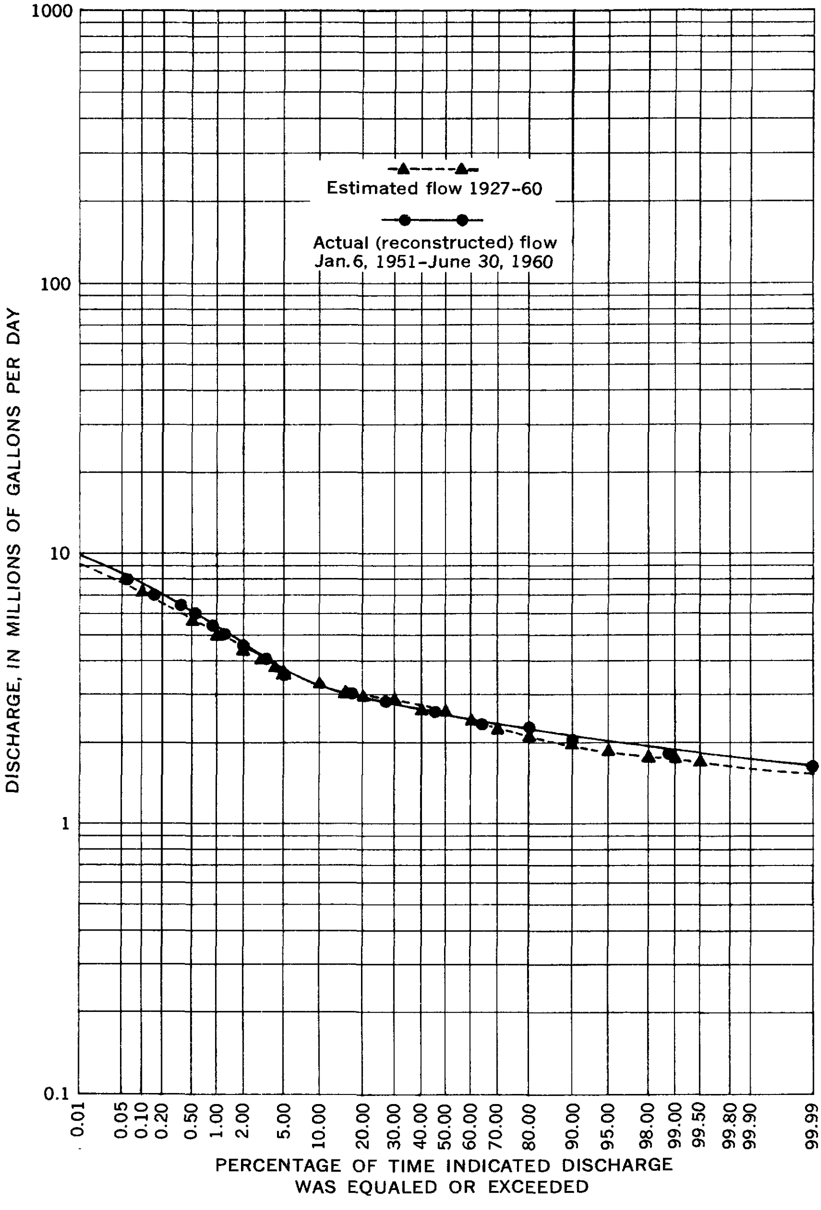

FIGURE 22.—Waiahole ditch tunnel, north portal, computed and observed flow-duration curves.

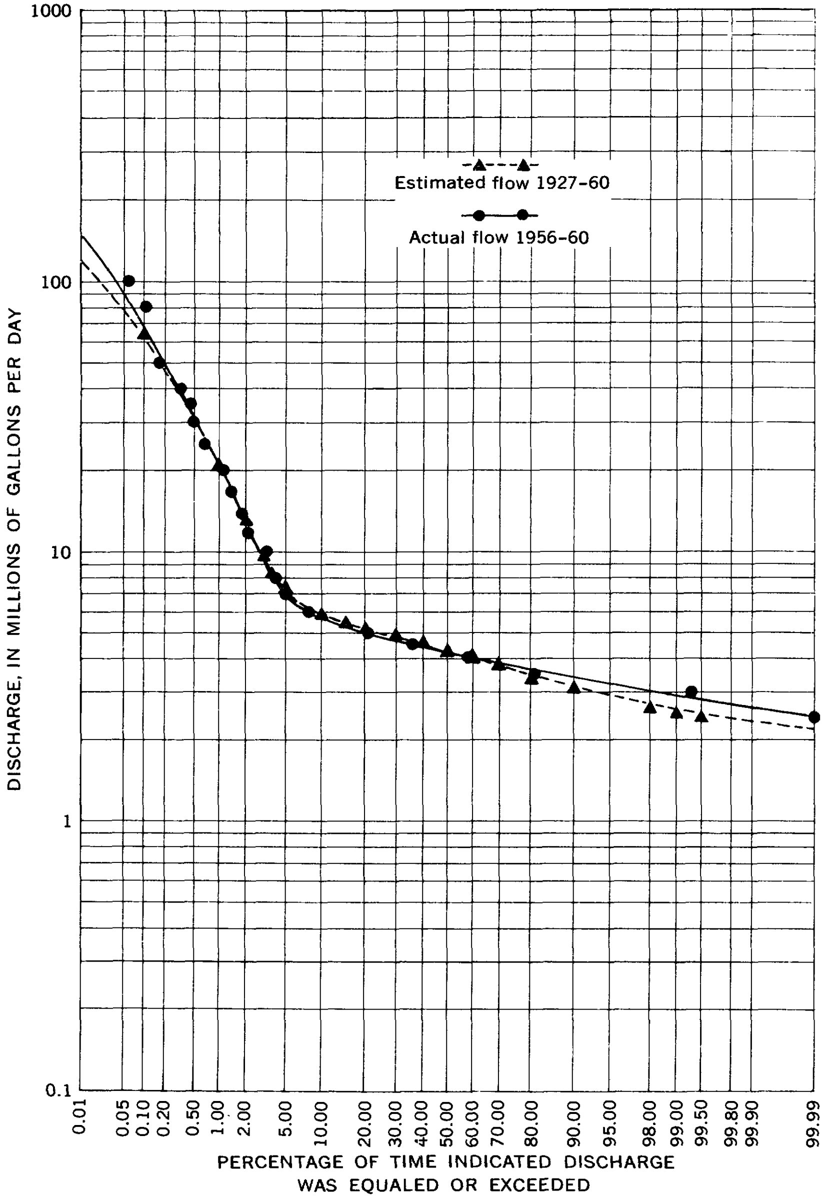

FIGURE 23.—Waiahole Stream, computed and observed flow-duration curves.

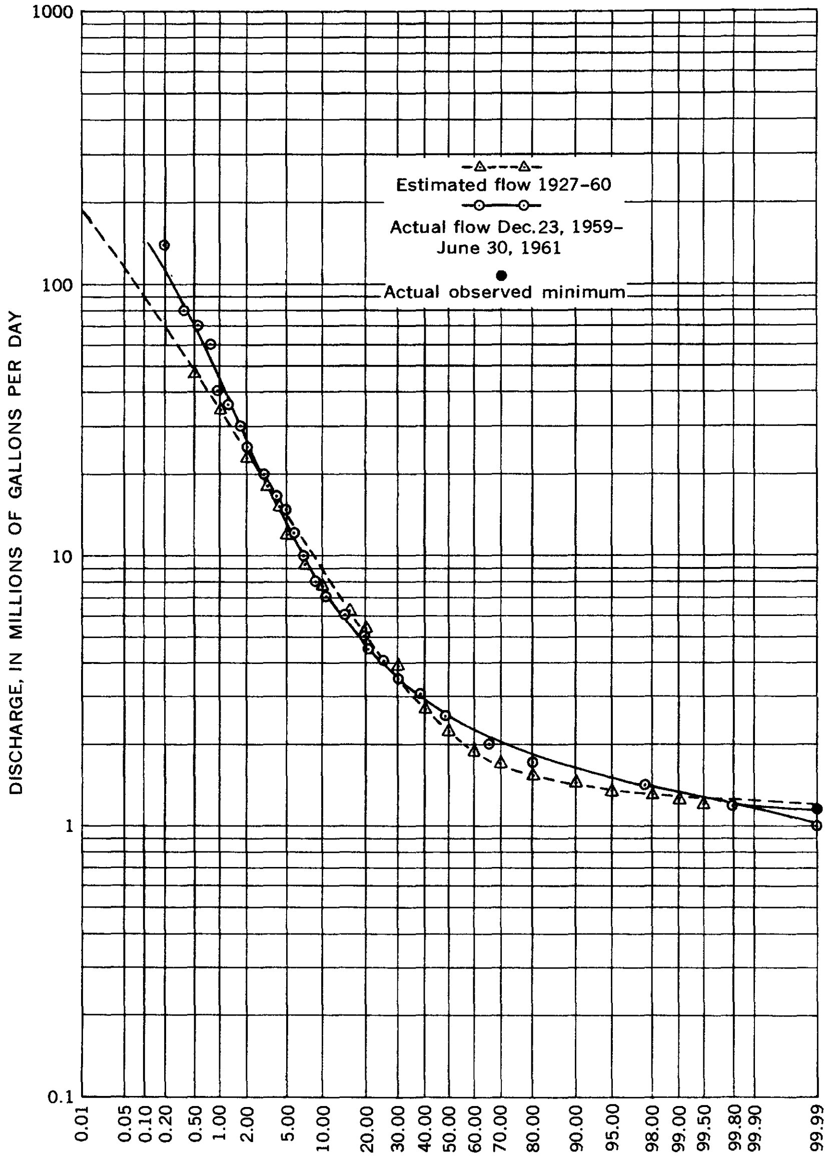

FIGURE 24.—Waikane Stream, computed and observed flow-duration curves.

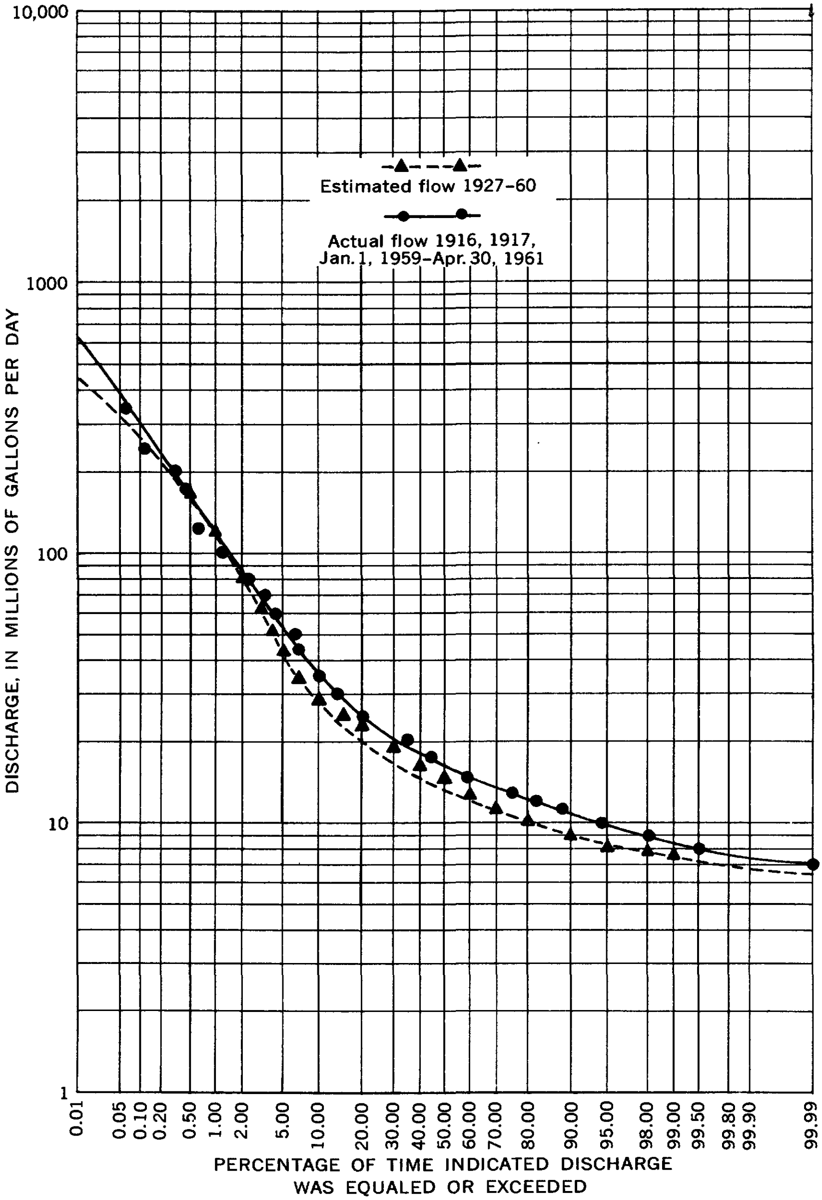

FIGURE 25.—Kahana Stream, computed and observed flow-duration curves.

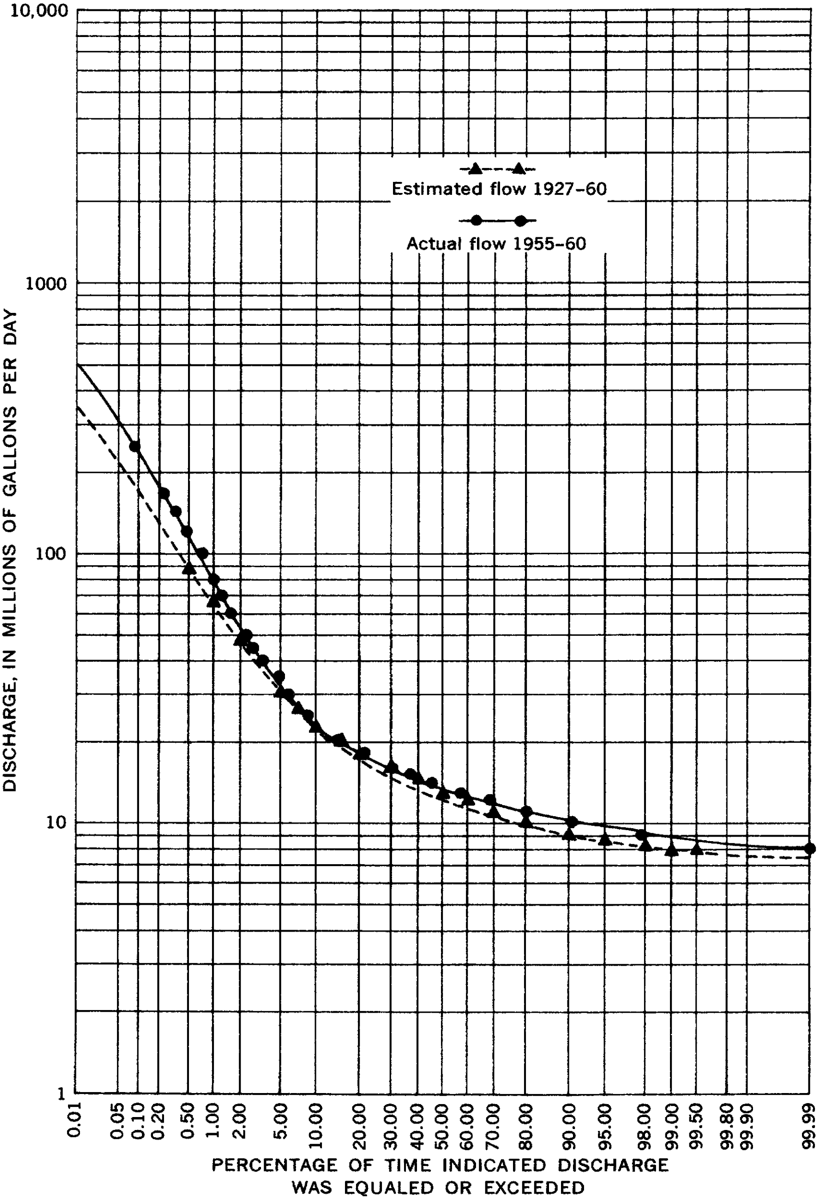

FIGURE 26.—Punaluu Stream, computed and observed flow-duration curves.

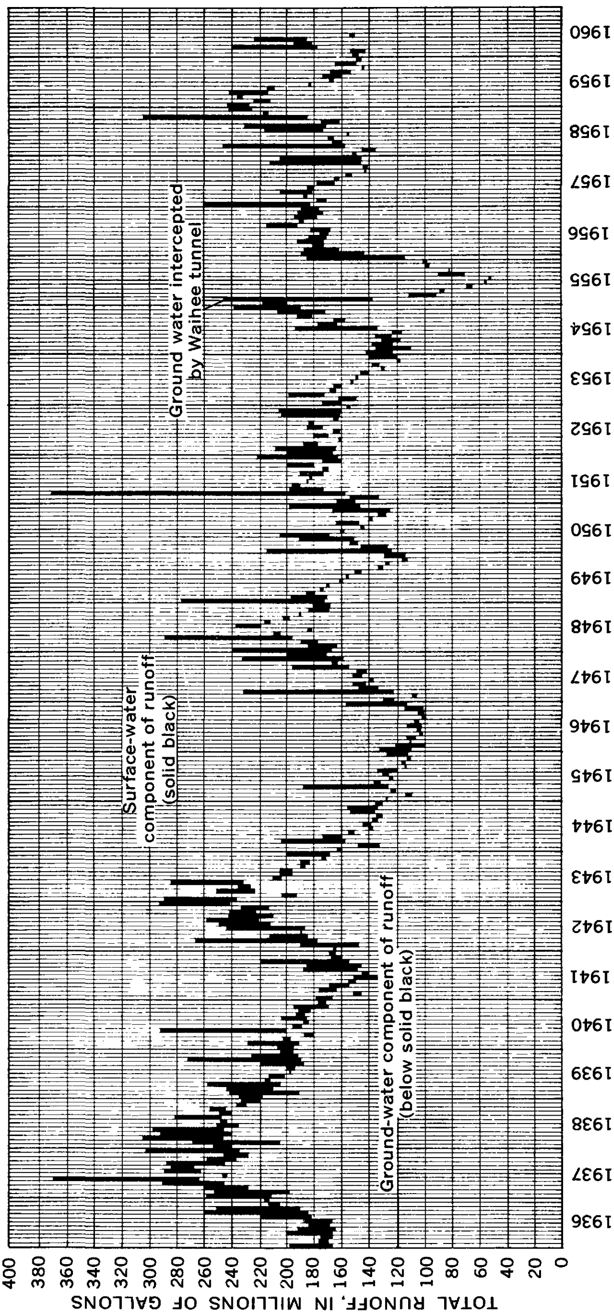

FIGURE 27.—Monthly runoff of Waihee Stream showing surface-water and ground-water components. Ground water was first intercepted by Waihee tunnel in February 1955. Discharge was uncontrolled from February through July 1955 and has been controlled since August 1955.

TABLE 10.—*Peak discharges of 16 streams in the windward area*

Stream name and gaging station	Years of record	Drainage area, in square miles	Maximum peak discharge for period of record		Date of maximum peak discharge
			Mgd	Mgd per square mile	
Makawao, 2540	7	2.44	1,380	565	Mar. 5, 1958
Kamooalii, 2739	3	4.34	3,550	818	Oct. 23, 1958
Haiku, 2750	27	.97	2,730	2,810	Mar. 26, 1951
Iolekaa, 2780	21	.28	71	255	Oct. 23, 1958
Kahaluu, 2830	25	.28	290	1,040	Sept. 27, 1937
Waihee, 2840	26	.93	466	502	Oct. 23, 1958
Waiahole, 2910	6	.99	625	631	Apr. 16, 1960
Waikane, 2949	2	2.25	1,530	680	May 12, 1960
Kahana, 2965	5	3.74	3,480	930	Oct. 17, 1960
Punaluu, 3030	8	2.78	1,760	633	Aug. 30, 1955
Unnamed, 2488	4	1.21	384	317	Mar. 5, 1958
Maunawili, 2605	4	5.62	780	139	Do.
Keaahala, 2744.99	4	.59	1,120	1,900	Do.
Kahaluu, 2835	1	3.70			Apr. 16, 1960
Unnamed 2959	4	.53			Oct. 23, 1958
Kaluanui, 3045	4	2.12	1,380	651	Dec. 6, 1957

QUALITY

Contamination of fresh water by underlying sea water is a common problem in Hawaii. In windward Oahu, this type of contamination is restricted to the basal-water aquifer of the coastal area.

Chloride content is a useful index of atmospheric contamination of high-level water and of sea-water contamination of basal water. Chloride content of water from high-level sources generally ranges from 10 to 25 ppm—except near the coast, where salt-ladened air increases chloride content to as much as 50 ppm. Chloride content of basal water varies considerably. Chloride in basal water in basalt of the northern part of the area ranges from 20 to 12,000 ppm. Water from wells in permeable limestone or dune sand may be contaminated with sea water; chloride may exceed 2,000 ppm. The range in chloride content is shown on plate 2.

Chemical analyses of water are given in table 11. The water is well within recommended limits of potability for domestic use, as established by the U.S. Public Health Service (1946). The pH generally ranges from 7 to 8. Hardness ranges from 25 to 175 ppm—high-level water, 25 to 110 ppm, and basal water, 55 to 175 ppm.

Ground-water temperature ranges from 65° to 79°F in individual wells. Water from basaltic aquifers ranges in temperature from 65° to 73°, depending on altitude and climate. Water from limestone aquifers ranges in temperature from 77° to 79°, depending on ocean temperature, climate, and the amount and temperature of irrigation water recharging the aquifer.

TABLE 11.—*Chemical analyses of water-supply sources in windward Oahu*

[Constituents in parts per million. Analytical data by Hawaii State Dept. of Health except as noted]

Source	Date	Silica (SiO_2)	Alumina (Al_2O_3)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium plus potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (residue at 180° C)	Hardness as $CaCO_3$	Alkalinity as $CaCO_3$	pH
Wells																	
392	June 1956	7.6	0.6	0.1	<0.1	8.2	13.0	22.8	65	12.5	30	0.2	0.4	160	74.4	53	6.5
394	Oct. 1953	34.4	0.3	0.1	0.0	23.7	17.2	19.5	55	1.2	33	0.1	1.6	186	131.1	45	7.4
	Jan. 1955	22.0	0.3	<0.1	0.0	22.9	9.3	18.7	65	14.5	33	0.2	0.2	186	96.0	53	7.5
402	June 1940	36	2.8	0.0	--	15.4	10.9	41.4	63	14.5	74	--	--	258	75.5	52	7.8
404-1	Sept. 1954	26.4	1.1	0.1	0.0	30.0	10.2	31.1	56	30.2	88	0.0	0.6	274	117.5	46	7.8
	Jan. 1938	34.8	1.1	--	--	8.5	11.4	46.3	71	8.6	75	--	--	257	70	58	7.6
405	June 1960	29.2	0.3	<0.1	<0.1	12.8	8.8	26.3	85	17.4	37	0.2	1.2	218	79.8	70	8.0
407-1	Nov. 1937	19.8	2.3	0.2	--	5	8.1	27.9	105	8.2	22	--	--	198	40	86	7.6
416	Jan. 1961	2.0	0.1	<0.1	<0.1	6.5	4.6	10.7	46	8.2	14	0.1	0.1	92	35.3	38	7.7
416-1	May 1955	24.0	0.3	<0.1	0.0	23.0	6.7	10.2	71	7.2	20	0.1	0.4	163	85.7	58	7.5
418-b and Api Spring	Nov. 1958	20.4	0.2	0.1	--	13.7	11.8	14.6	93	11.2	37	0.2	0.5	203	83.2	76	7.0
422	Aug. 1953	41.6	0.7	0.1	0.0	27.9	9.5	28.9	68	18.4	30	0.3	0.8	226	109.3	56	7.6
Shaft																	
10	Oct. 1953	35.2	0.3	0.1	0.0	34.3	21.5	30.9	71	8.8	47	0.1	--	249	175.5	58	7.3
	Jan. 1955	43.2	2.3	<0.1	0.0	34.5	11.1	25.1	82	11.1	45	0.2	0.8	255	132.4	67	7.4
Tunnels																	
C & C Waimanalo	Aug. 1953	12.0	1.9	0.1	0.0	16.3	6.3	15.4	37	8.7	18	0.1	0.4	116	67.1	30	8.0
Haiku	Nov. 1948	23.2	1.2	0.3	0.0	5.7	2.4	12.4	39	3.3	14	0.1	0.4	102	28.3	32	--
Kahaluu	Aug. 1953	17.6	1.1	0.1	0.0	14.8	6.0	8.4	29	10.2	12	0.1	0.4	100	62.1	24	8.2
	Nov. 1954	30.4	0.3	<0.1	0.0	15.2	5.1	5.4	39	9.3	18	0.0	0.1	123	59.7	32	7.6
Plantation																	
Waimanalo	Aug. 1953	22.4	1.1	0.1	0.0	17.2	7.0	13.4	42	8.7	22	0.1	0.4	134	72.0	34	7.9
Waiahole Adit 8	Sept. 1943	13.6	0.1	<0.1	--	4.0	1.4	15.0	39	2.8	11	--	--	87	28.0	32	7.8
Waihee	Mar. 1958[1]	31	0.4	0.1	0.0	11	4.9	13.6	61	6.1	17	0.0	0.4	146	48.0	--	7.3
	Dec. 1958	31.2	0.2	<0.1	0.1	9.2	5.7	12.9	58	10.9	17	0.3	0.0	146	48.6	48	7.4

[1] U.S. Geol. Survey.

WATER RESOURCES OF MAJOR DRAINAGE AREAS

WAIMANALO AREA

GEOLOGIC SETTING

The Waimanalo area includes approximately 11 square miles at the southeastern end of windward Oahu (fig. 8). Aniani Nui Ridge, composed mostly of rock of the dike complex of the Koolau and Kailua Volcanic Series, separates the area from Maunawili Valley on the northwest. Its northeastern margin is a continuous shoreline of Recent calcareous sedimentary material. The southern margin is the crest of the Koolau Range, where altitude ranges from 2,600 feet on the west to 1,000 feet on the east. These mountains consist of eroded southward-dipping thin-bedded lava flows of the Koolau Volcanic Series and form a line of high cliffs (fig. 28). Over much of the area, alluvium covers the eroded basalt. Near the coast, the alluvium is overlain by dune sand, some consolidated, and a narrow strip of Recent calcareous beach deposits.

The subsurface distribution of rocks is shown by two generalized profiles drawn along lines *A–A′* and *B–B′* in plate 1. The profiles, based on drillers' logs of wells and test borings, indicate that sedimentary rocks extend more than 700 feet below sea level at well 408; the upper 210 feet contains about 150 feet of coralline limestone. About 80 percent of the area is underlain by sedimentary material.

According to W. O. Clark (1935, unpub. data), samples of basaltic bedrock from exploratory holes in the western part of the area show that secondary mineralization has reduced the original porosity of the lava flows underlying the older alluvium. Rock penetrated in well 420, about 2 miles east of Aniani Nui Ridge, had no secondary mineralization.

DIKES

The areal distribution of dikes is not well known because of lack of outcrops; outcrops are concentrated in narrow zones at high altitudes. Scattered dikes along the southern part of the Koolau Range generally strike northward or northeastward, at right angles to the crest. (See fig. 4.) The absence of dikes having northwestward strikes suggests that the main rift zone lies partly seaward of the crest and partly beneath the alluvial fill.

The part of Aniani Nui Ridge near the crest has scattered dikes striking northward to northeastward, but about a mile to the north, or downslope, numerous dikes strike generally N. 75° W. These probably extend eastward beneath the alluvium.

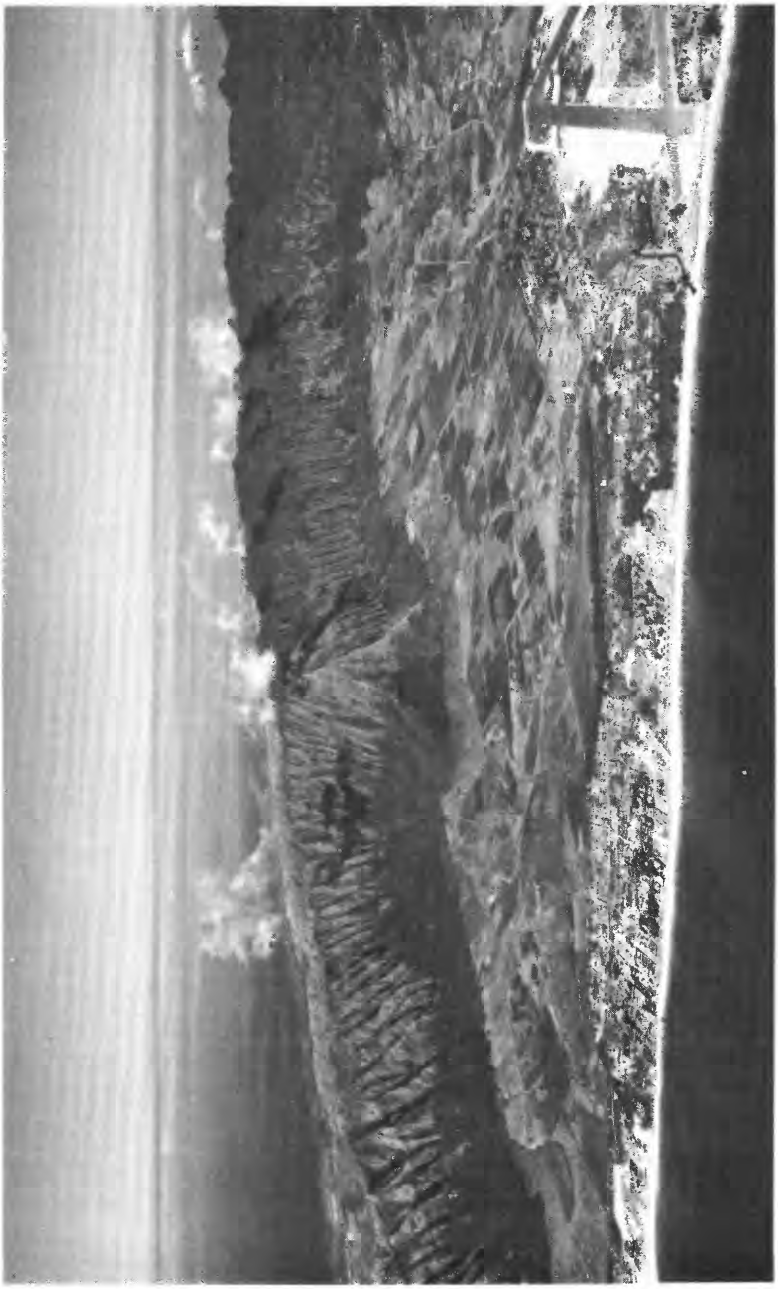

FIGURE 28.—Waimanalo area near southeastern end of Koolau Range.

GROUND WATER

OCCURRENCE AND MOVEMENT

The Waimanalo area has both high-level and basal water. Water-table conditions prevail in the uplands (high-level water), where the water level is well below the weathered lava. High-level water occurs in dike-intruded bedrock and in overlying sedimentary rocks and is under pressure where weathered lava or alluvium extends below the water table in the uplands. Basal water is restricted to calcareous sedimentary material and younger alluvium near the shore.

The northwestward-striking dikes that cut Aniani Nui Ridge dam the ground water and are partly responsible for the shallow water levels of the ridge area. A part of the high-level water probably moves from the bedrock through the alluvium and into the calcareous sedimentary material as underflow, eventually discharging to the ocean. (See pl. 1.)

Ground water moves eastward from a high-rainfall recharge area in the western part of the area (pl. 2). The steep gradient, 200 feet or more per mile, probably results from the low permeability of the secondarily mineralized lava. Seaward, the gradient decreases to 100 feet or less per mile in the alluvium and underlying bedrock and to 10 feet or less in the more permeable calcareous shore deposits.

Rainfall is slightly more than 60 inches per year in the western part and less than 40 inches in the eastern part of the Waimanalo area. Short-term hydrographs suggest that trends of ground-water levels are similar to those in other places in windward Oahu. Figure 29 is a graph of the monthly rainfall at rain-gage 794 plotted against the hydrographs of well 408 and a nearby dug well. Rain, return irrigation water, and leakage from ditches are the source of ground-water recharge.

The flow of ground water above the level of the Maunawili ditch is estimated to be 1 mgd, about half of which is withdrawn from five water-development tunnels for domestic use. An additional domestic supply of 0.2 mgd is withdrawn from two wells below ditch level. Maunawili ditch system diverts 2 mgd of water from Maunawili Valley into the Waimanalo area for irrigation. A part of this water again becomes ground water and eventually discharges at the shore or into stream channels. The low flow of two streams measured at the Kalanianaole Highway crossings was 0.6 mgd, most of which is probably return irrigation water. If imported water from Maunawili Valley were excluded, water moving below the ditch probably would not exceed 1 mgd.

During rainless periods, flow of streams near the shore is maintained by ground-water discharge from calcareous sedimentary material near

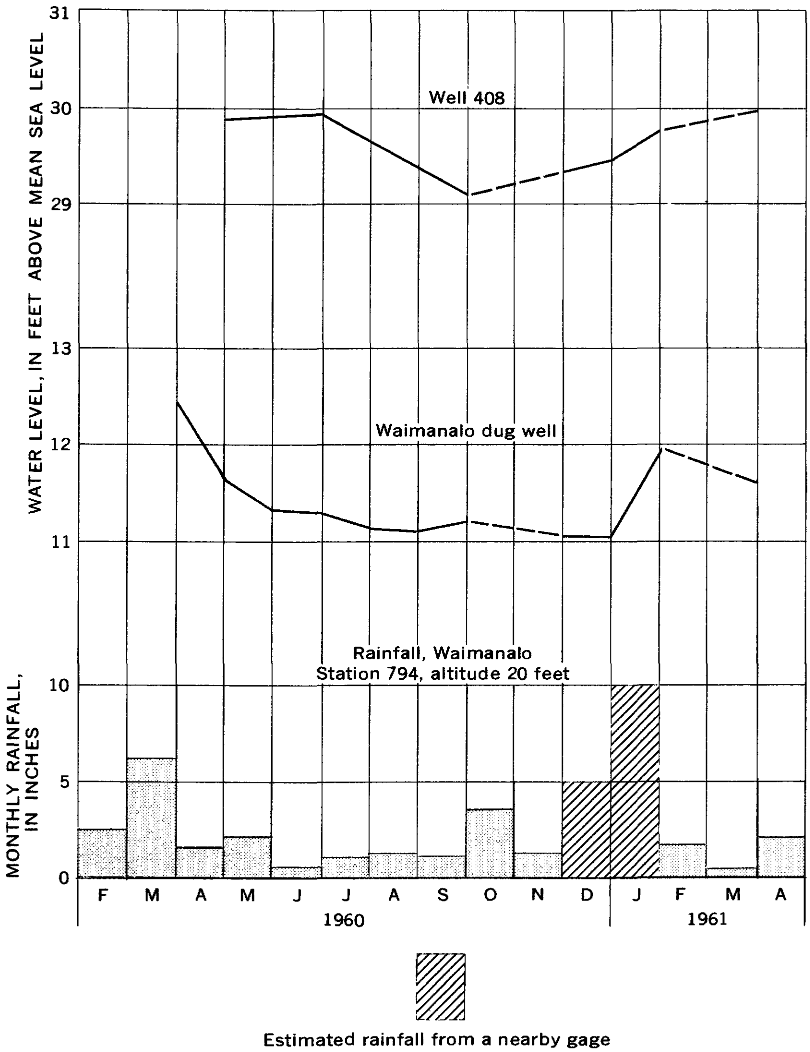

FIGURE 29.—Water levels in well 408 and in a nearby well and rainfall in the Waimanalo area.

the shore. During one of these periods a survey was made to determine chloride content of water in the lower part of the two streams in the area. Results of the survey are plotted in figure 30.

POTENTIAL AREAS FOR GROUND-WATER DEVELOPMENT

Water of best quality is above the level of Maunawili ditch. The base flow of the area averages 1.0 mgd, about half of which is now being diverted to water-development tunnels. As much as 0.5 mgd

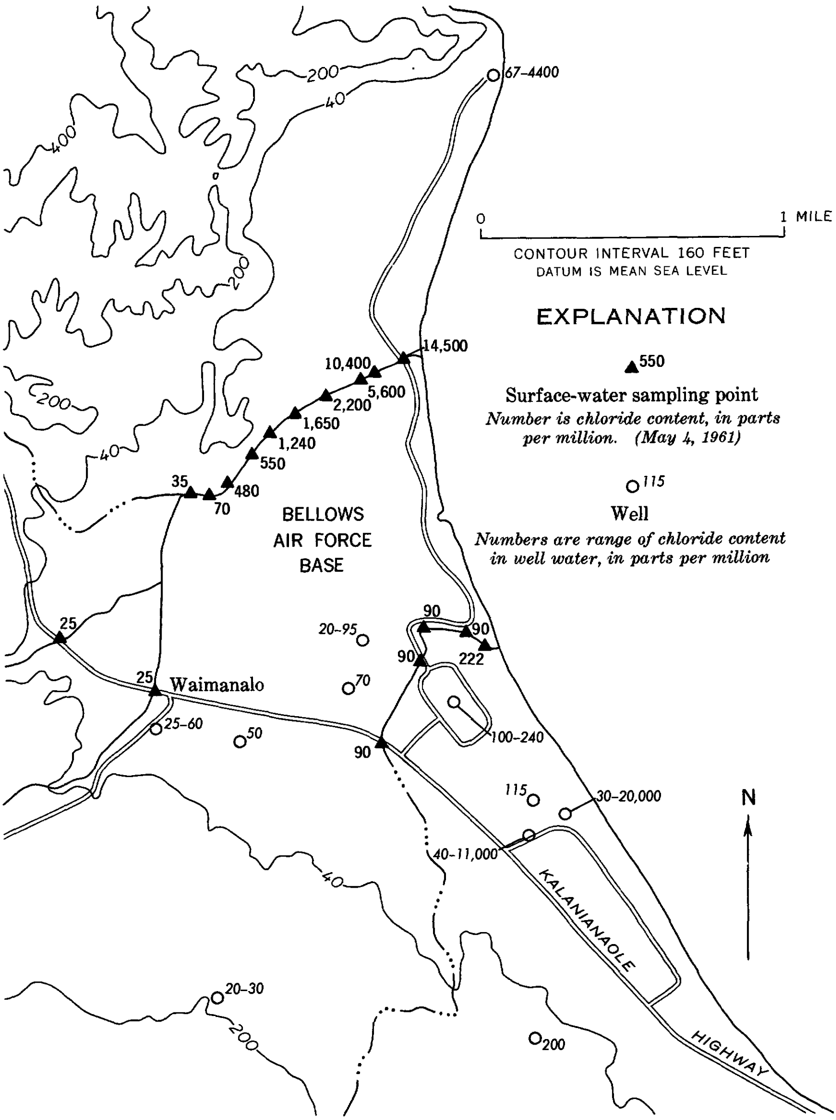

FIGURE 30.—Progressive seaward increase in chloride content of water from two streams in the Waimanalo area.

might be diverted to additional tunnels. Below Maunawili ditch and between wells 408 and 420 (pl. 1), bedrock sources of water might be successfully developed.

Water in the calcareous sedimentary material near the shore, although suitable for irrigation, is susceptible to contamination from the surface and sea water; careful selection of well sites, however, would minimize contamination.

STREAMS

Waimanalo Stream is the only perennial stream in the area. The only gaging station is below Aniani Nui Ridge on Maunawili ditch. The flow of Maunawili ditch, 1954–61, averaged 1.95 mgd.

On July 31, 1959, the flow of three tributaries to Waimanalo Stream was measured above Maunawili ditch (pl. 3). Measurements were as follows: Site 2, 0.13 mgd; site 3, 0.11 mgd; and site 4, 0.03 mgd (a total of 0.27 mgd). This water was intercepted by Maunawili ditch at an altitude between 300 and 400 feet. Flow in Waimanalo Stream was reestablished below the ditch; it increased downstream to 0.28 mgd at an altitude of 50 feet. Irrigation return water probably accounts for some of this flow below Maunawili ditch, so the point of maximum natural base flow of Waimanalo Stream is just above the ditch. A comparison of the July 31, 1959, flow of Waimanalo Stream with that of the hydrologically similar East Branch Manoa Stream indicates that Q_{90} (flow available 90 percent of the time) of Waimanalo Stream is 0.26 mgd and that average flow is about 0.7 mgd.

MAUNAWILI VALLEY

GEOLOGIC SETTING

Maunawili Valley, 18 square miles in area, drains into Kailua Bay. Lava flows of the Koolau Volcanic Series form high cliffs along the southwestern side, and two prominent volcanic ridges extending northeastward separate the area from Waimanalo to the southeast and the Kaneohe area to the northwest (fig. 31). These ridges are composed of rocks of the Koolau and Kailua Volcanic Series. Pyroclastic rocks and basaltic lava flows of the Honolulu Volcanic Series are scattered throughout the valley and make up a significant percentage of exposed volcanic rocks.

Older alluvium forms an apron at the base of cliffs and extends far into the valley. Younger alluvium underlies the lower part of stream valleys and consists of peat, which floors most of the swamp areas in the coastal flats, clay, and silt. Several test borings in Kawainui Swamp indicate that in places silty and clayey marl interbedded with coral detritus and alluvium extends to a depth of more than 100 feet. Dune sand beach deposits and sparse outcrops of coralline limestone occur along the entire coastline and front swampy areas.

A geologic profile of the valley drawn along *C–C′* is shown in plate 1.

FIGURE 31.—Maunawili Valley, showing Kawainui Swamp and Kaelepulu Pond in foreground.

DIKES

Numerous northeastward-striking dikes in Palolo and Manoa Valleys, on the leeward side of the Koolau Range, extend into Maunawili Valley and intrude basaltic lava flows of the Koolau Volcanic Series nearly at right angles to the crest of the high cliffs at the head of the valley. Dikes striking at an average of N. 75° W. in Aniani Nui Ridge, about 1 mile downslope from the crest of the range, continue northwestward into the valley under the alluvium and rocks of the Honolulu Volcanic Series. A third set of dikes in a volcanic ridge about 1 mile northeast of Nuuanu Pali strike predominantly N. 55° W. and extend southwestward under the alluvium and into the valley. These three sets of dikes probably intersect in the valley about 1 mile northeast of the crest.

GROUND WATER

OCCURRENCE AND MOVEMENT

High-level water predominates and is generally unconfined where lava of the Koolau Volcanic Series and pyroclastic rocks and lava flows of the Honolulu Volcanic Series crop out. The water is artesian where confined by poorly permeable weathered volcanic rocks or alluvium. Basal water in calcareous sedimentary material and alluvium near the shore is brackish. The basal water level of Maunawili wells is at an altitude of less than 2 feet, and the high-level water level is more than 650 feet.

Maunawili Valley is similar to the Waimanalo area in that ground water near the crest probably moves northeastward, owing to geologic controls. Altitude and gradient of water levels depend in part on locations of principal discharge points, most of which are springs near the upper edge of the alluvium at an altitude of about 600 feet. Water levels away from the crest are close to ground level, owing to controlling dikes that strike nearly parallel to the crest and to the shoreline. Ground water generally moves northward, as shown in plate 2, feeding Kawainui Swamp and two stream systems.

The most permeable rocks are lava flows of the Koolau Volcanic Series in the upper valley, excluding rocks of the dike-complex zone. Permeability in the southeastern part of the valley is reduced by secondary mineralization. Four test holes were drilled in the upper valley during 1953–54 in an effort to obtain basal water.[1] Table 12 is a consolidation and modification of data collected in that study. Drilling indicated high-level water but no basal water.

Permeability of lava flows of the Kailua Volcanic Series is generally

[1] Cox, D. C., 1954, Notes on test drilling in upper Maunawili Valley: Unpub. rept. to the Board of Water Supply, City and County of Honolulu.

TABLE 12.—*Test drilling results*

[After D. C. Cox]

Hole	Altitudes, in feet	Rock conditions	Altitude of water levels and remarks
T-48, T-48A	1,272 to 1,200	Weathered	Unsaturated(?).
	1,200 to 1,095	Lava flows, moderate to low permeability.	1,170 ft; perched water.
	1,095 to 42	do	Unsaturated to about 615 ft; high-level water.
T-49	777 to 763	Weathered	Unsaturated(?).
	763 to 527	Lava flows, low permeability	Unsaturated or perched at about 572 ft.
	527 to 122	do	Artesian(?), 630 ft; artesian, 697 ft.
	122 to −33	do	Artesian, 630, 703, and 637 ft.
T-50	1,009 to 917	Weathered	Unsaturated.
	917 to −27	Lava flows of moderate permeability and dikes.	667 ft.

low, and wells 418-C and 422 had a specific capacity of only 0.5 and 1.5 gpm per ft of drawdown, respectively.

The ground-water reservoir is recharged mainly near the crest, where maximum mean annual rainfall exceeds 100 inches. The dependable water supply is about 6.7 mgd. Maunawili ditch diverts an average of 2 mgd from the area. At least 2.7 mgd enters the streams below ditch level and flows into Kawainui Swamp. About 0.1 mgd of water for domestic use is obtained from wells and springs below Maunawili ditch.

Water evaporates and is transpired from swamps and other areas of shallow water table. Diurnal fluctuation of the water table, measured in wells where it is as deep as 12 feet, indicates that transpiration is a significant element in discharge of ground water.

POTENTIAL AREAS FOR GROUND-WATER DEVELOPMENT

Base flow of Maunawili Valley above an altitude of 400 feet probably does not exceed 3 mgd. Of this amount, about 2 mgd is exported to the Waimanalo area by Maunawili ditch. Some ground water could be developed above the ditch, but such development would reduce the ditch supply. The most permeable rocks are above an altitude of 400 feet west of the ditch.

STREAMS

MAUNAWILI STREAM

Maunawili Valley is drained by Maunawili and Kahanaiki Streams and their tributaries. In January 1958 the U.S. Geological Survey established a gaging station on Makawao Stream, a tributary to Maunawili Stream, at an altitude of 75 feet (fig. 32). As most of the flow of Maunawili ditch is diverted from Makawao Stream and its tributaries, the flow of the ditch was added to the flow of Makawao Stream

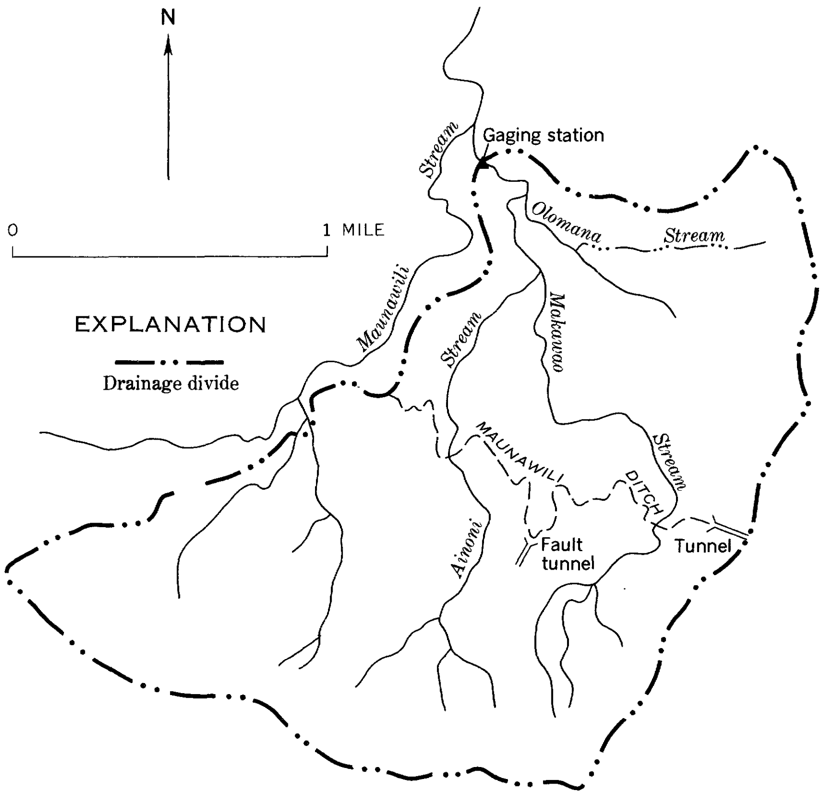

FIGURE 32.—Makawao Stream drainage area.

at the gaging station, and the combined flow was regarded as the natural flow of Makawao Stream.

A long-term average discharge of 4.5 mgd was obtained for Makawao Stream from the adjusted long-term flow-duration curve for Makawao, as transposed from East Branch Manoa Stream. As a check of this figure, long-term average discharge was computed from a regression equation derived from concurrent monthly mean discharges of the two streams; the computed result was 4.3 mgd. Because the two averages agree closely, 2.6 mgd (from fig. 17) is considered to be a good estimate of Q_{90} for Makawao Stream.

The flow of Maunawili Stream increases steadily downstream to a maximum near the upper margin of Kawainui Swamp. Measurements at this point were correlated with concurrent flows recorded at the Makawao Stream gaging station. From this correlation, long-term average flow of Maunawili Stream is estimated to be 7.8 mgd; Q_{90} is 4.2 mgd.

KAHANAIKI STREAM

Maximum base flow of Kahanaiki Stream, as in Maunawili Stream just to the south, is at the upper end of Kawainui Swamp. From measurements at this point, long-term average flow is estimated to be 1.0 mgd, and Q_{90}, 0.5 mgd.

Average flows of Maunawili and Kahanaiki Streams total 8.8 mgd, and total long-term Q_{90} is 4.7 mgd. Net average flow is 6.8 mgd because of the diversion by Maunawili ditch.

KANEOHE AREA

GEOLOGIC SETTING

The Kaneohe area, as defined in this report, is that part of windward Oahu that drains into Kaneohe Bay; it includes about 40 square miles. Deep amphitheater valleys and precipitous cliffs that rise to the crest mark the southwestern border. Valley divides are steep-sided basaltic ridges that project northeastward from the range (fig. 33). Four of the ridges extend to Kaneohe Bay. Most of the volcanic rock is a dike complex of the Koolau Volcanic Series, but a part of the crest is in the marginal dike zone.

Exposures of the Honolulu Volcanic Series are scattered in the southeastern part of the area; they consist chiefly of lava flows, tuff, and cinders. Test holes near Baskerville Springs, in Haiku Valley, penetrated at least 50 feet, and a well near the mouth of Kaneohe Stream penetrated at least 30 feet of lava. A 30-foot thickness of tuff is exposed in upper Haiku Valley and Ulupau Head; a tuff cone on Mokapu Peninsula rises to an altitude of more than 650 feet.

Thick alluvium fills parts of the valleys. The older alluvium, moderately to well consolidated, may be found from an altitude of about 600 feet, buttressing steep valley walls, to below sea level in lower reaches of valleys. At lower altitudes, in valleys and along the coastal plain, a younger and generally poorly sorted alluvium overlies the older.

Calcareous material is widely exposed on Mokapu Peninsula, and test borings indicate coralline limestone at least 50 feet thick. Near Baskerville Springs, test boring T–71 penetrated coral between 1 and 19 feet above mean sea level. Thin zones of calcareous rock were penetrated by well 407–13, near the shore at Kaalaea, and by well 407–1, near the mouth of Kahaluu Stream. With these exceptions, information from well logs indicates that calcareous material is not extensive.

A north-south geologic section, D–D′, which roughly parallels the coast, is shown in plate 1. The information is from drillers' logs of wells.

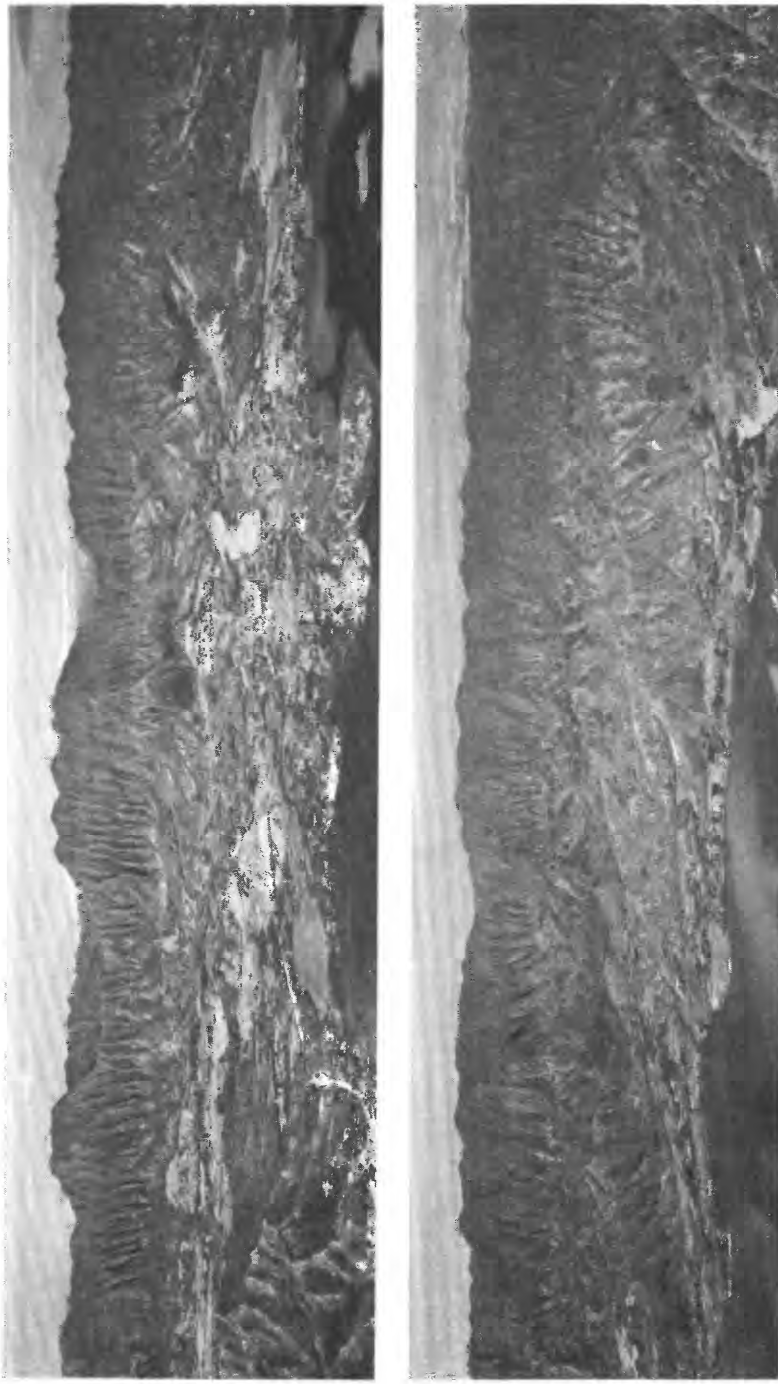

FIGURE 33.—Kaneohe area. *Upper:* Southern part showing drainage basins of Kamooalii and Heeia Streams. *Lower:* Northern part showing drainage basins of Kaalaea, Waiahole, Waianu, Waikane, and Hakipuu Streams.

DIKES

Dikes that strike N. 75° W. in Maunawili Valley continue into the Kaneohe area. The dikes, numerous but scattered, are exposed at altitudes ranging from 800 to 600 feet for nearly 1 mile along the ridge projecting northeastward from Nuuanu Pali. Three thin dikes striking N. 55° W., N. 58° W., and N. 60° E. are exposed in Wilson vehicular tunnel at an altitude of 800 feet and about 1½ miles northwest of Nuuanu Pali. Closely spaced multiple dikes striking predominantly N. 55° W. are exposed about a mile northeast of Nuuanu Pali. (See fig. 4.) This complex is probably the southern boundary of the dike complex that extends northwestward into the heads of Waiahole and Waikane Valleys. It is at least 4 miles wide at its southern end and about 1 mile wide at its northern terminus. The southwestern side of this complex is northeast of the crest; the northeastern side probably extends under Kaneohe Bay. The complexity of Koolau dikes, as exposed in the Waiahole ditch tunnel system, is shown in figure 8.

Strike of dikes in the upper Waikane area apparently shifts. Strikes of N. 55° W. are less numerous than they are in the southern Kaneohe area; strikes of about N. 35° W. predominate. The marginal dike zone includes nearly all uplands of the Koolau Range. Strike in this zone generally is the same as that in the adjacent dike complex.

GROUND WATER

OCCURRENCE AND MOVEMENT

The most reliable source of water is the high-level water in basaltic lava flows of the Koolau Volcanic Series. High-level ground-water reservoirs maintain the base flow of streams and water-development tunnels and the draft from pumped wells, altogether about 47 mgd. Ground water moves predominantly southeastward from the mountains and into windward valleys. The ground-water divide is probably west of the crest because of the shorter distance and lower discharge points in deeper valleys east of the crest.

Since 1913, when the Waiahole ditch tunnel system was begun, ground-water flow in the Koolau Mountains has been readjusting to the new outlets. Tunnels intercept water that once discharged at springs. By providing a lower outlet, a tunnel shifts the ground-water divide. In his low-flow studies, Hirashima (1963) concluded that the tunnel in Haiku Valley intercepted 1 mgd of water that once flowed in Kahaluu Valley, 2½ miles to the northwest.

The total base flow of the central and southern parts of the Kaneohe area is shown in figure 34. All discharge measurements are free flow, except that for the pumped hospital well, and were made in July 1959 during a prolonged period of low rainfall.

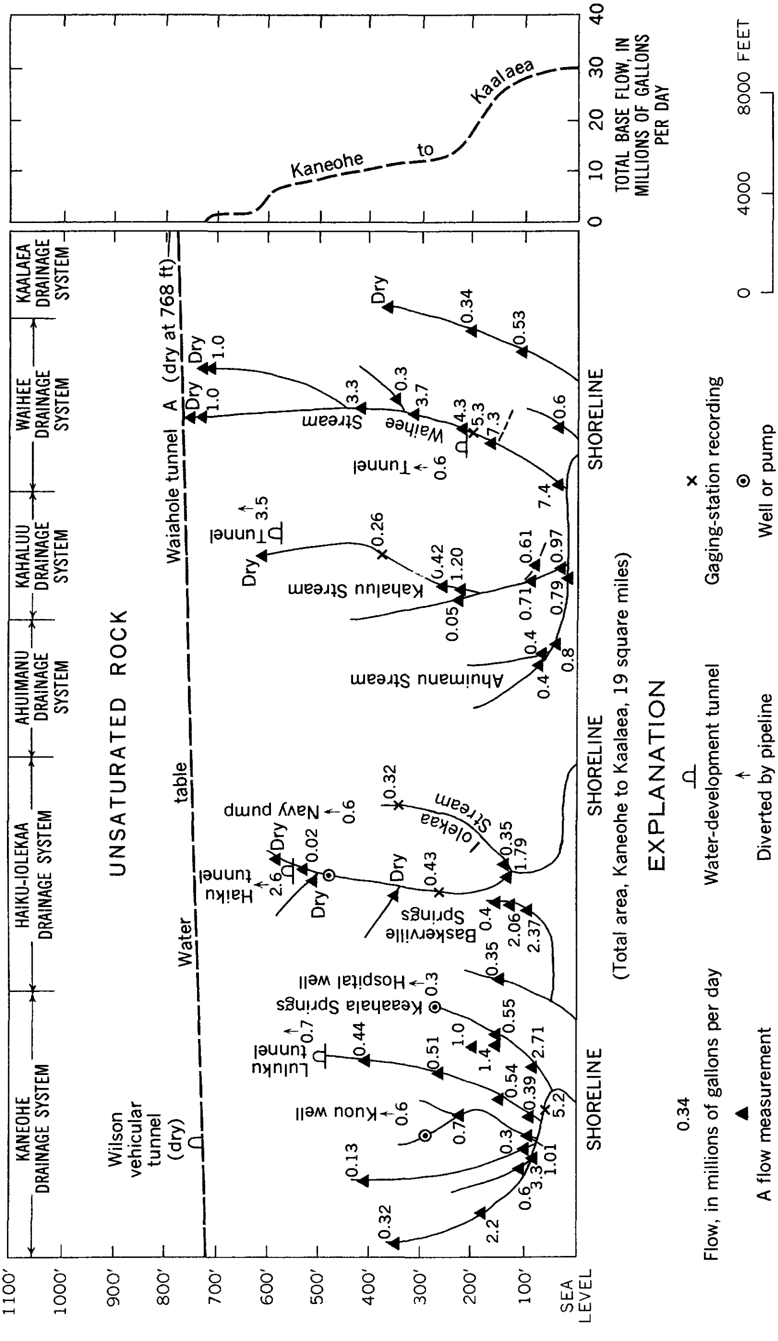

FIGURE 34.—Part of Kaneohe area, showing base-flow discharge of streams and tunnels and discharge of wells.

Slightly more than half the total base flow enters streams as diffused ground-water effluent between altitudes of 225 and 150 feet. The recently developed Kuou well and Waihee tunnel, both of which penetrate basaltic aquifers above 225 feet, indicate that much ground water could be intercepted before it enters streams. Between an altitude of 225 and 550 feet perennial streams are gaining, but their gain is less than one-sixth of the total base flow.

An undetermined quantity of ground water discharges directly to sea as underflow or as leakage through weathered basaltic rocks and alluvium, as shown in figure 35. Underflow is through rocks of low permeability along more than 12 miles of coast.

Specific capacity of wells in dike complex areas ranges from less than 0.5 to as much as 10, at pumping rates that range from 6 to 275 gpm. Low specific capacity is generally associated with areas of high dike density and considerable weathering. Wells drilled in the marginal dike zone in the southern part of the Kaneohe area generally yield greater quantities of water with less drawdown than those in the dike-complex areas. Specific capacity of these wells ranges from 3 to 100, at pumping rates of 760 to 1,500 gpm. Three test wells were drilled into lava flows of the Honolulu Volcanic Series near Haiku. Specific capacity ranged from 2 to 37, at bailing rates that ranged from 30 to 40 gpm.

POTENTIAL AREAS FOR GROUND-WATER DEVELOPMENT

The most favorable area for future development is between the upper and lower zones of discharge. This area is in the marginal dike zone and above an altitude of 200 feet in major stream valleys. Most high-level water above an altitude of 500 feet is being diverted by tunnels. New tunnels at this level or higher would intercept additional water only if they were long enough to intercept water now moving toward the leeward side of Koolau Range. Least favorable is the area below the lower zone of discharge because of its poorly permeable weathered dike complex.

STREAMS

The Kaneohe area is mainly drained by Kawa, Kaneohe, Keaahala, Heeia, Kahaluu, Waiahole, and Waikane Streams and their tributaries. (See pl. 3.) Waiahole ditch tunnel system diverts water to leeward Oahu, and its flow must be considered in appraising water resources.

KAWA STREAM

Kawa Stream discharges at the south end of Kaneohe Bay and heads in the ridge separating the Kaneohe area from Maunawili Valley. Its maximum base flow was 0.15 mgd on June 17, 1959, at

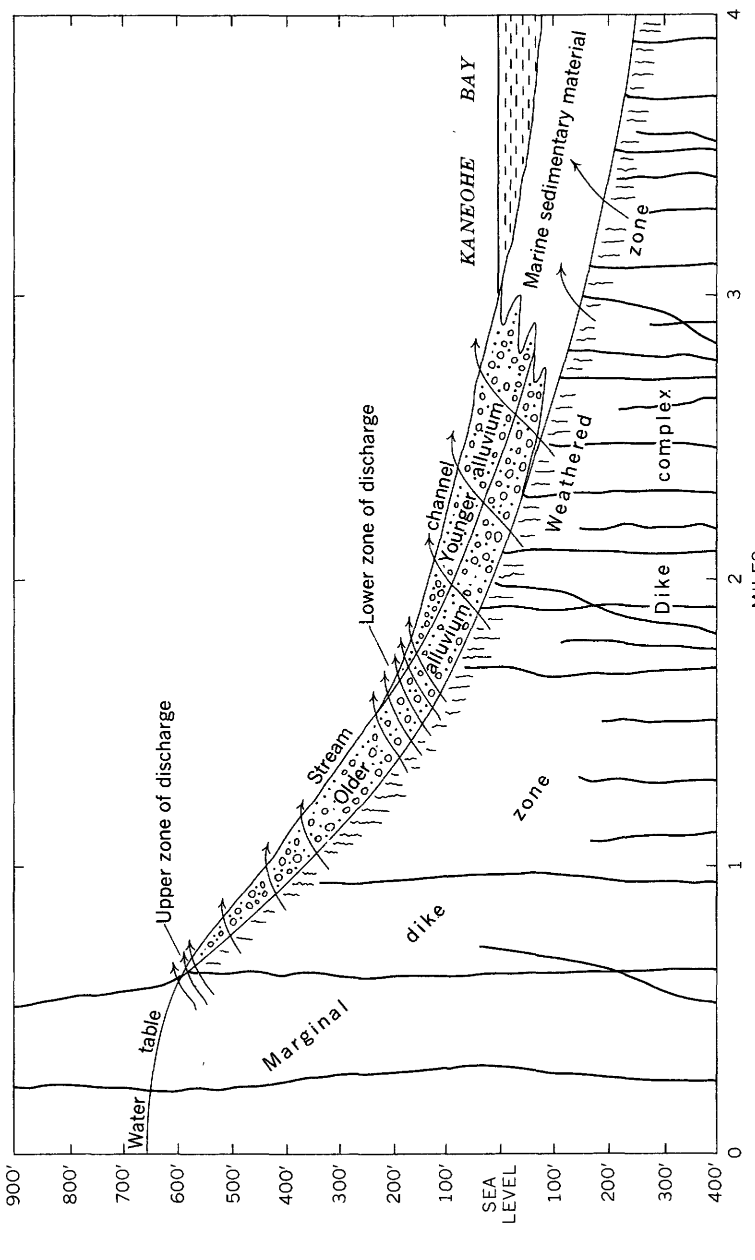

FIGURE 35.—Typical stream channel in Kaneohe area, showing positions of discharge zones.

site 51 (table 9, pl. 3). That amount is estimated to be its long-term Q_{90}. Long-term average flow of 1.0 mgd is estimated on the basis of 1914–15 staff-gage records.

KANEOHE STREAM

Kaneohe Stream discharges into the southern part of Kaneohe Bay just north of Kawa Stream. It starts at the confluence of its main tributary, Kamooalii Stream, and an unnamed stream just east of Kamehameha Highway, and it is less than 1 mile long. (See pl. 3.)

Kamooalii Stream drains 4.34 square miles and has been gaged since 1959 (site 84, pl. 3). On the basis of correlations of 23 months of data for the station with those for East Branch Manoa Stream, long-term average discharge of Kamooalii Stream is estimated to be 8.5 mgd (site 84, table 8). Integration of the adjusted long-term flow-duration curve for Kamooalii Stream (fig. 22), transposed from Iolekaa Stream, gives nearly the same quantity. Therefore, the Q_{90} of 4.1 mgd taken from the adjusted long-term flow-duration curve is probably fairly accurate.

The unnamed tributary of Kaneohe Stream is north of Kamooalii Stream, and its perennial flow begins at a spring at an altitude of 180 feet. Flow increases downstream, peaking at an altitude of 60 feet (site 90). Flow measurements at site 90 during 1960–62 ranged from 1.89 to 2.56 mgd.

Because flows of streams in the windward area are affected by tunnels, flow of this stream was estimated by comparison with Keaahala Stream. (See site 99, table 9.) Measurements on April 4, 1962, show that the ratio of the flow of this tributary to that of Keaahala Stream is about 0.83. By use of this ratio, the long-term Q_{90} of this tributary is estimated to be 1.8 mgd. Long-term average discharge is estimated to be 2.8 mgd, assuming that the ratio of Q_{90} to average discharge is the same as that of Waihee Stream (fig. 21).

KEAAHALA STREAM

Keaahala Stream starts as a spring that had a measured flow of 0.22 mgd on October 5, 1961. This flow was increased by 2.04 mgd from Baskerville Springs (pl. 3). The measured total at the point of maximum flow (site 99, table 8) on October 5, 1961, was 2.08 mgd. Dry-weather flow at site 99, 1960–61, ranged from 2.08 to 2.64 mgd.

By correlating 1953–54 flow measurements of Keaahala Stream with concurrent flows of Waihee Stream (fig. 21), long-term Q_{90} for Keaahala Stream is estimated to be 2.2 mgd, and long-term average discharge is 3.4 mgd, assuming that the ratio of Q_{90} to average discharge is the same as that of Waihee Stream.

HEEIA STREAM

Flowing eastward from near the crest, Haiku and Iolekaa Streams join at an altitude of 120 feet to form Heeia Stream, which then meanders about 2 miles before discharging into Kaneohe Bay at Heeia Pond.

A gaging station was operated on Haiku Stream from 1914 to 1919 at site 105 (pl. 3) and was reestablished in July 1939. Soon after the station was reestablished, flow of the stream was affected by the boring of Haiku tunnel, which necessitated correlation of earlier data with data of East Branch Manoa Stream. From the correlation the long-term average flow of Haiku Stream is estimated to be 2.4 mgd. (See site 105, table 8.)

Because records of natural flow of Haiku Stream do not include low flows for the base period (1927–60), the adjusted long-term flow-duration curve would not give correct discharges at the lower end. Consequently, the long-term Q_{90} of 1.2 mgd for Haiku Stream is estimated from the correlation with East Branch Manoa Stream.

Flow of Iolekaa Stream (site 108, table 8) was also decreased by Haiku tunnel. Iolekaa Stream gaging station was established in March 1940, and the base flow of the stream during the 8 months preceding the boring of the Haiku tunnel averaged 0.80 mgd, or 13.5 percent of the flow of Waihee Stream. From July 1941 to February 1942, base flow was 0.32 mgd, or 6.5 percent of the flow of Waihee Stream.

A long-term average discharge of 0.50 mgd and a Q_{90} of 0.26 mgd were derived for Iolekaa Stream (fig. 19) from the long-term flow-duration curve, which was adapted from East Branch Manoa and Kalihi Streams (station 2290, lat 21°22′00″ N., long 157°50′50″ W.). The preceding figures show the effects of tunneling. The natural yield is estimated at 1.0 and 0.5 mgd for the long-term average and Q_{90} flow, respectively.

Three measurements of the flow of Heeia Stream were made at site 111 to determine base-flow gain below Haiku (site 105) and Iolekaa (site 108) gaging stations. This part of the drainage system has an approximate long-term Q_{90} of 1.1 mgd and a long-term average discharge of 2.1 mgd. Heeia Stream below site 111 flows through a low and swampy area, and gain is probably negligible. The entire Heeia drainage system under natural conditions has a long-term Q_{90} of 2.8 mgd and a long-term average flow of 5.5 mgd.

AHUIMANU STREAM

Ahuimanu Stream originates near the crest and flows northward until it joins Kahaluu Stream. Ahuimanu Stream has one major unnamed tributary, which also heads high in the Koolaus and flows about half a mile south of and generally parallel to Ahuimanu Stream. Measurements were made of the flow along the tributary at sites 112–114. Flow of the tributary is included with that of Ahuimanu Stream.

At its confluence with Kahaluu Stream (site 122), base flow of Ahuimanu Stream is at a maximum, 0.70 to 2.71 mgd during 1959–62. From a comparison with Waikane Stream (fig. 24), long-term Q_{90} of Ahuimanu Stream is estimated to be 0.9 mgd. By using the ratio of drainage areas and the long-term average flow of Waikane Stream, long-term average flow of Ahuimanu Stream is estimated to be 4.1 mgd.

KAHALUU STREAM

Kahaluu Stream, after being joined by Ahuimanu and Waihee Streams, flows into Kaneohe Bay near Kahaluu Pond. A gaging station on Kahaluu Stream at site 126 has been in continuous operation for 26 years. Owing to construction of Haiku tunnel, however, only 5 years of record represent natural flow. These records were correlated with those of Waihee Stream, and the adjusted long-term duration curve for Kahaluu Stream was derived (fig. 20). As the record used to establish the correlation included flow approaching minimum for the base period (1927–60), the adjusted duration curve is fairly accurate. By integrating the area under the adjusted duration curve, long-term average discharge of the upper part of Kahaluu Stream (site 126, table 8) is estimated to be 3.5 mgd. Long-term Q_{90} is 2.7 mgd.

Base flow of Kahaluu Stream above Ahuimanu Stream is at a maximum at the confluence of Kahaluu and Ahuimanu Streams; measurements at that location during 1959–62 show that below site 126 Kahaluu Stream gained from 0.46 to 1.43 mgd. A comparison of these gains with the flow of Waikane Stream (fig. 24) indicates that the long-term gain would approximate 0.6 mgd 90 percent of the time. By using the ratio of drainage areas and the long-term average flow of Waikane Stream, long-term average gain of Kahaluu Stream between sites 126 and 136 is estimated to be 1.9 mgd.

Total long-term average discharge of Kahaluu Stream at its confluence with Ahuimanu Stream is 5.4 mgd, and total Q_{90} is 3.3 mgd. Below the confluence, combined long-term average discharge is 9.5 mgd, and Q_{90} is 4.2 mgd.

WAIHEE STREAM

Waihee Stream originates near the crest west of Kahaluu Stream. It flows northeastward and joins Kahaluu Stream after losing much of its flow to Higa ditch (site 166, pl. 3). A gaging station was established on Waihee Stream at site 159 in December 1935, and natural streamflow records were collected until January 1955, the month before

Waihee tunnel was bored. By correlating monthly mean discharges with those of East Branch Manoa Stream, a long-term average flow of 6.5 mgd was estimated for Waihee Stream by the regression method. Because the long-term flow-duration curve, adjusted from East Branch Manoa and Kalihi Streams (fig. 21), when integrated, gives the same average discharge of 6.5 mgd, the Q_{90} discharge of 4.2 mgd (see site 159, table 8) taken from that curve should be reliable.

Flow measurements show a gain in the 1,000-foot reach between the gaging station (site 159) and Higa ditch intake (site 166). This gain is independent of flow above the station and ranged from 1.91 to 2.62 mgd. Minimum gain was measured on January 4, 1962, after water had been withdrawn from Waihee tunnel for 29 days, but as the weather had been dry for more than a month, the difference in gain may have resulted from a natural decline in ground-water inflow.

Natural flow conditions were approached on March 10, 1961, when little or no water was being withdrawn from Waihee tunnel. Measurements made that day showed that flow increased 44 percent between the gaging station and Higa ditch intake. Therefore, long-term Q_{90} at Higa ditch, the point of maximum base flow, should be 6.0 mgd (4.2×1.44). Long-term average flow is estimated to be 9.2 mgd, assuming that the ratio of Q_{90} to average discharge at this point is the same as at the gaging station.

Waihee Stream gains downstream. Measurements on February 27, 1961, showed gains in three places: (1) between altitudes of 371 and 305 feet, (2) at the three springs near the Waihee tunnel portal, at an altitude of 200 feet, and (3) in the 1,000-foot reach between the gaging station, at an altitude of 192 feet, and the intake to the ditch, at an altitude of 160 feet, where the gain is more than 2 mgd (fig. 36, curve *A*). Streamflow apparently declined slightly between the altitudes of 305 and 260 feet.

KAALAEA STREAM

Kaalaea Stream, although flowing parallel to Waihee Stream and less than a mile north of it, has a base flow that is but a fraction of that of Waihee Stream, and Kaalaea Stream takes much longer to reach its base flow after rain. Its runoff characteristics resemble those of Waikane Stream, about 2 miles north. Streamflow was measured at three sites on Kaalaea Stream, and the point of maximum base flow was found to be at site 175. By a comparison of the site 175 measurements with the concurrent flows of Waikane Stream, long-term average flow of Kaalaea Stream was estimated to be 2.4 mgd, and long-term Q_{90}, 0.6 mgd. (See site 175, table 9, pl. 3.)

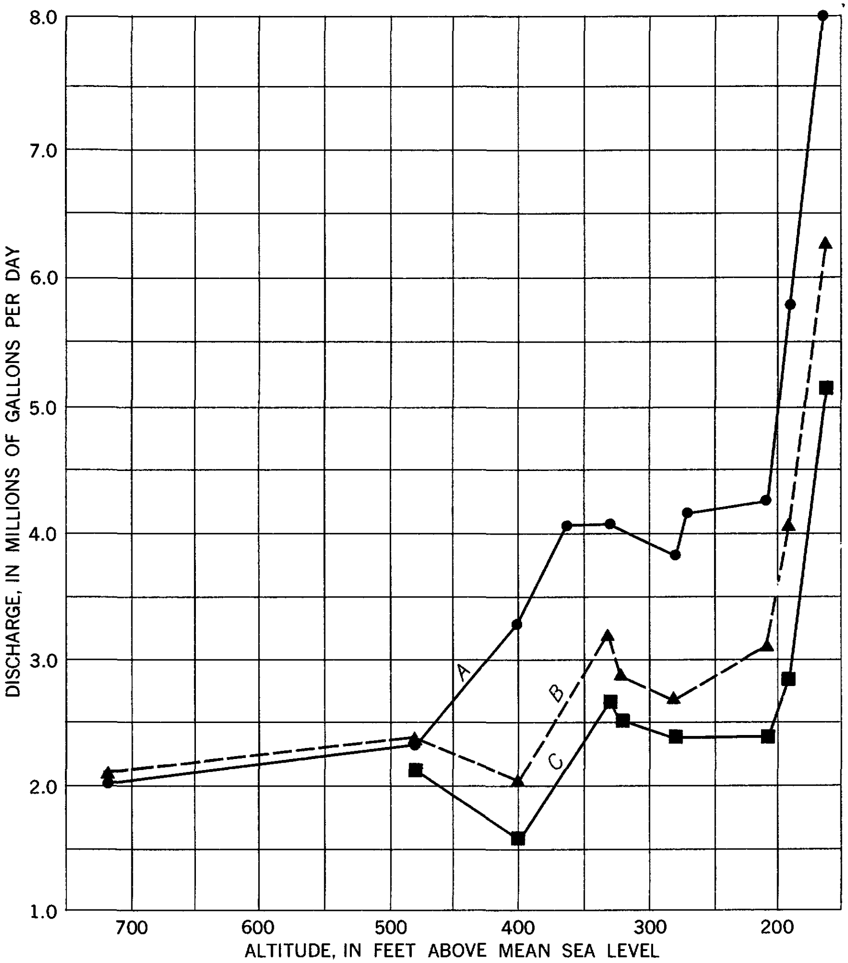

FIGURE 36.—Waihee Stream, showing streamflow gains and losses with altitude. Curve *A* shows gains and losses when little or no water is being withdrawn from Waihee tunnel. Curves *B* and *C* show effects of withdrawal from Waihee tunnel.

HAKIPUU STREAM

Hakipuu Stream is in a valley at the north end of the Kaneohe area. Five flow measurements were made at its point of maximum base flow (site 205, pl. 3) during 1961–62; they ranged from 0.38 to 0.70 mgd. The measured 0.38-mgd streamflow is the estimated long-term Q_{90}, and long-term average flow is estimated to be 1.1 mgd. (See site 205, table 9.)

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STREAMS AFFECTED BY WAIAHOLE DITCH TUNNEL SYSTEM

The flow of Waiahole, Waikane, and Kahana Streams have been affected by the Waiahole ditch tunnel system, which diverts water at an altitude of 800 feet. The tunnel, which penetrates the range, is known as the main bore. The amount of water flowing from areas affected by the tunnel was determined by estimating the present yield of streams and adding the water diverted by the tunnel.

WAIAHOLE DITCH TUNNEL SYSTEM

The gaging station at site 255 (pl. 3, tables 8, 9) is the measuring point for all water diverted by Waiahole ditch tunnel system. Some intercepted storm runoff also is measured. Flow at the station includes water pumped from Waiahole Stream and excludes some water occasionally wasted into Waiahole Stream. Records were adjusted by subtracting pumpage and adding wastage; wastage was obtained from the wasteway station, at intake 31 (site 256).

Adjusted records show that natural yield to the ditch at the gaging station at north portal (site 255, tables 8, 9) from January 1951 to June 1960 averaged 26.3 mgd and that Q_{90} was 21.0 mgd. Monthly means of adjusted records were correlated with concurrent monthly means of East Branch Manoa Stream, and a regression equation was computed; from that equation a long-term average discharge of 26.1 mgd was derived.

The long-term flow-duration curve for Waiahole ditch tunnel at north portal (fig. 22) was transposed from East Branch Manoa Stream. Integration of the area under this adjusted flow-duration curve showed average flow to be 26.4 mgd. Similarity of the two averages indicates that 19.5 mgd (fig. 22) is a good estimate of long-term Q_{90}.

Gain in the main bore of the system.—Average gain in flow in the main bore, between the gaging stations at north portal (2870) and adit 8 (2872, lat 21°27′00″ N., long 157°57′30″ W.), was 5.31 mgd during the period August 1956 to June 1960. Long-term average gain computed from records furnished by the Waiahole Water Co. is 5.25 mgd. By using the ratio of the Waihee Stream Q_{90}, 4.2 mgd, to its average ground-water component of flow, 5.85 mgd, long-term Q_{90} for the main bore is estimated to be 3.7 mgd $(\frac{4.2}{5.85} \times 5.2)$. Before excavation of the main bore, part of this water probably moved to the windward area, and the rest moved leeward from the ground-water divide. Owing to a lack of detailed information, half the average discharge, 2.6 mgd, and half the Q_{90}, 1.8 mgd, are assigned to the windward side. (See table 9, Waiahole ditch tunnel, main bore.)

WAIAHOLE STREAM

Waiahole Stream flows eastward for 3 miles from the range to Kaneohe Bay. It has one main tributary, Waianu Stream, on the north. Both streams are affected by Waiahole ditch tunnel system.

A gaging station was established on Waiahole Stream in July 1955, but streamflow data obtained must be corrected for occasional pumping of water from the stream to Waiahole ditch tunnel and for some wastage of tunnel water to the stream. On the basis of adjusted records from Waiahole Stream station (site 177, table 8), observed average flow of 4.75 mgd and observed Q_{90} of 3.4 mgd were obtained; and, by correlating Waiahole Stream discharges with those of East Branch Manoa Stream, long-term average discharge of 4.9 mgd and long-term Q_{90} of 3.1 mgd were computed. (See fig. 23.)

Flow measurements show that the point of maximum base flow of Waiahole Stream is at its confluence with Waianu Stream (site 178). Base-flow gain between the gaging station and site 178 on July 19, 1960, was 25.4 percent. Long-term Q_{90}, therefore, is 125 percent of 3.1 mgd, or 3.9 mgd. Long-term average discharge is estimated to be 6.9 mgd, which includes the 25-percent ground-water gain and surface-water storm runoff based on a ratio of drainage areas.

WAIANU STREAM

Waianu Stream flows eastward to join its main tributary, Uwau Stream, thence southeastward until it joins Waiahole Stream. The point of maximum base flow is at its confluence with Waiahole Stream. Correlation of base-flow measurements at this point (site 185) with concurrent flows at Waiahole Stream gaging station (site 177) indicates that long-term average and Q_{90} discharges at this point are 1.2 and 0.5 mgd, respectively.

WAIKANE STREAM

Waikane Stream drains into Kaneohe Bay below Waikane village. Its flow is affected by Waiahole ditch tunnel to the extent that, except when the ditch overflows, the streambed is dry immediately below the ditch. A gaging station was established on the stream in December 1959 at site 193 (pl. 3), and flow measurements indicate that the site is close to the point of maximum base flow. Average discharge for the 18-month period of record is 4.63 mgd, and Q_{90} is 1.6 mgd.

Correlation of Waikane Stream data with data of East Branch Manoa Stream indicates a long-term average flow of 4.2 mgd, and integration of the flow-duration curves transposed from East Branch Manoa Stream shows that the average is 4.4 mgd. As the estimates agree fairly well, the Q_{90} of 1.4 mgd taken from the transposed duration curve should be fairly accurate.

SUMMARY

Long-term average flows of Kaneohe area streams total 84.4 mgd where base flow is at a maximum, and long-term Q_{90} flows total 49.4 mgd. Subtracting water diverted by Waiahole ditch tunnel system (28.7 mgd long-term average flow and 21.3 mgd long-term Q_{90}), water available for use totals 55.7 and 28.1 mgd for the average and Q_{90}, respectively.

KAAAWA VALLEY

GEOLOGIC SETTING

Kaaawa Valley is largely isolated from the main Koolau Range by the heads of Waikane and Kahana Valleys (fig. 37). The valley is

FIGURE 37.—Kaaawa Valley.

little more than 2 miles long and extends about halfway into the range. Ridges that bound it are largely northeastward-dipping thin-bedded lava flows of the Koolau Volcanic Series. Dikes are rare except at the end of the southern ridge. The dike-complex zone seems to lie west of the head of the valley.

Alluvium underlies the valley, and Recent beach sand occurs at the coast. Thickness of sedimentary material probably exceeds 100 feet near the mouth of the valley. A coastal plain averaging one-fourth mile in width has developed at the base of the northern ridge. Sedimentary material consisting of alluvium, limestone, and beach sand thins toward the northwest, where the northern ridge projects to the sea.

DIKES

A massive and weathered concentration of dikes which extends 50 feet cuts across the shoreline at the seaward end of the southern ridge. The dikes, which strike N. 55° W., undoubtedly extend under Kaaawa Valley but could not be recognized on the northern side of the valley. A steep northwestward-trending cliff near to and north of shaft 10 (see pl. 1) may be a surface expression of these dikes. A dike 3½ feet wide striking N. 55° W. is exposed about a mile northwest of shaft 10 in a small gulch. These are the only dikes mapped in the valley.

GROUND WATER

OCCURRENCE AND MOVEMENT

The valley receives little or no ground water from adjacent valleys because of its isolation. Koolau mountain ground water that moves seaward in the direction of the valley is probably intercepted by Waikane and Kahana Streams.

The ground-water reservoir is recharged by precipitation. High-level water and basal water in the valley are separated by a transition zone. Recharge in the upper valley, or marginal dike zone, becomes high-level water, whereas recharge near the coast becomes basal water. Basal water is discharged into the lower reaches of the stream, into the extensive marshy area near the coast, or directly into sea as underflow through permeable calcareous material. During a time of extremely low tide, several seeps were observed to discharge a total of about 30,000 gpd of water along the beach near well 405–1.

Low-flow measurements indicate that Kaaawa Stream is effluent from an altitude slightly above 200 feet to about 50 feet and again from about 15 feet to its mouth. Base flow of the stream above 50 feet is probably maintained by leakage from high-level water and that below 15 feet by basal water, which is generally contaminated by sea water.

The principal aquifer is basaltic lava of the Koolau Volcanic Series, which is tapped by several private wells and a municipal-supply well (shaft 10). Of the private wells, only well 406 is in use. Tests of well 405–5 and shaft 10 indicated a specific capacity of 7 and 77 when pumpage was 100 and 500 gpm, respectively. Pumpage from shaft 10 and well 406 totals between 0.1 and 0.2 mgd.

The altitude of the water table is more than 200 feet in the upper part of the valley and decreases to less than 3 feet along the coast. Water-level records of well 406, which date back to 1929, show a range of 12 to 18 feet and a mean of about 15 feet. There is a direct correlation between rain measured in a gage in upper Waikane Valley and water levels in well 406 (fig. 38); rising water levels follow periods of above-normal rainfall. Kaaawa Valley has an area of slightly more than 3 square miles and has a median annual rainfall of 53 inches at the coast and nearly 100 inches at its head. A significant part of the base flow of the valley is discharged as ground-water underflow. This water, estimated to be at least 1 mgd, discharges as diffused flow at or near the coast.

CHLORIDE CONTENT

High-level water entering Kaaawa Stream above an altitude of 50 feet is of excellent quality. Basal-water discharge below an altitude of 15 feet, however, increases in chloride content from about 20 to 180 ppm with increased proximity to the ocean. The chloride content of water from Kaaawa Stream, shaft 10, and wells in Kaaawa Valley is shown in figure 39.

Chloride content of water from shaft 10 (40 ppm) is nearly identical to that of adjacent Kaaawa Stream, but chloride content of water from well 406, which is 500 feet deep, is more than five times as much. The relation of chloride content of water from well 406 to water level and to intensity of rainfall in upper Waikane Valley is shown in figure 40. About 20 gpm of basal water flows from shoreline springs at the head of the north ridge; the chloride content ranges from 1,600 to 5,300 ppm. Wells 405–2 and 405–3 were abandoned, owing to brackish water. Wells drilled farther inland might avoid some or all the sea-water intrusion encountered near the coast.

Chemical analyses of water from shaft 10 and well 405–4 are given in table 11.

POTENTIAL AREAS FOR GROUND-WATER DEVELOPMENT

The most favorable area for further water development in Kaaawa Valley is inland of shaft 10 on the northwestern side of the valley. Owing to possible deep weathering, wells near the center of the valley are not likely to be productive, and because of the dike arrangement

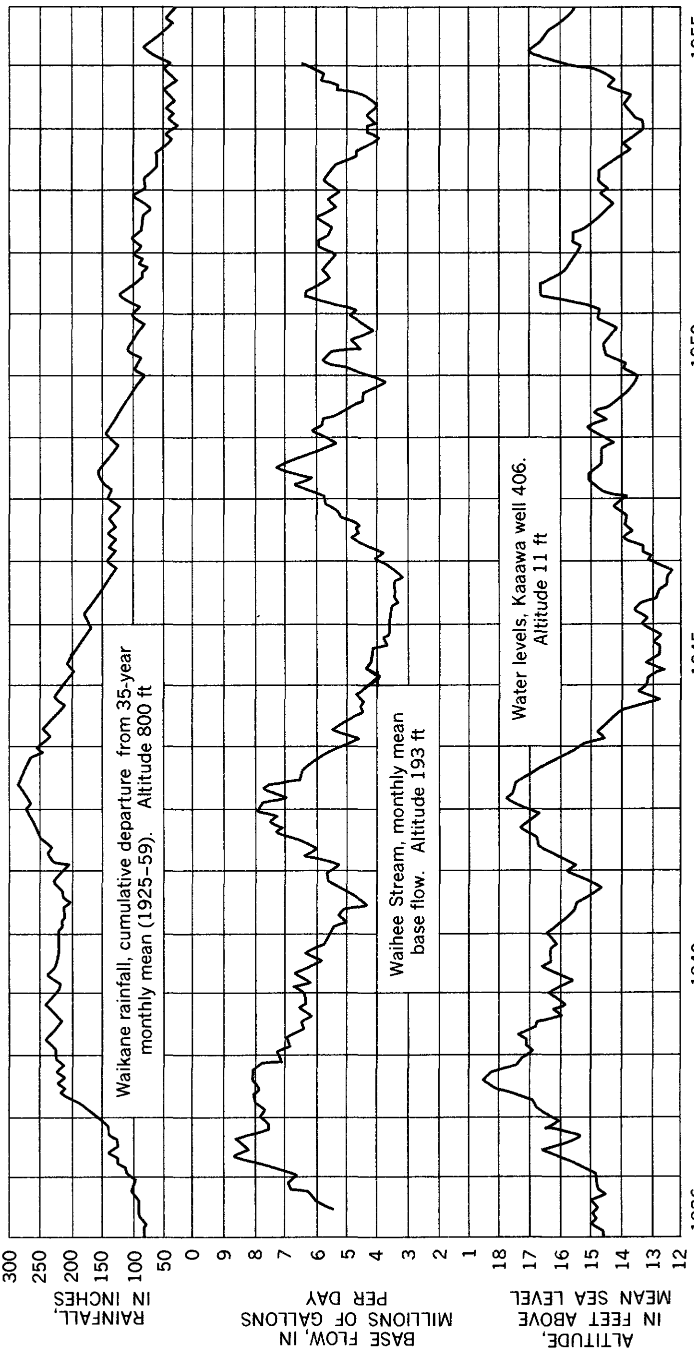
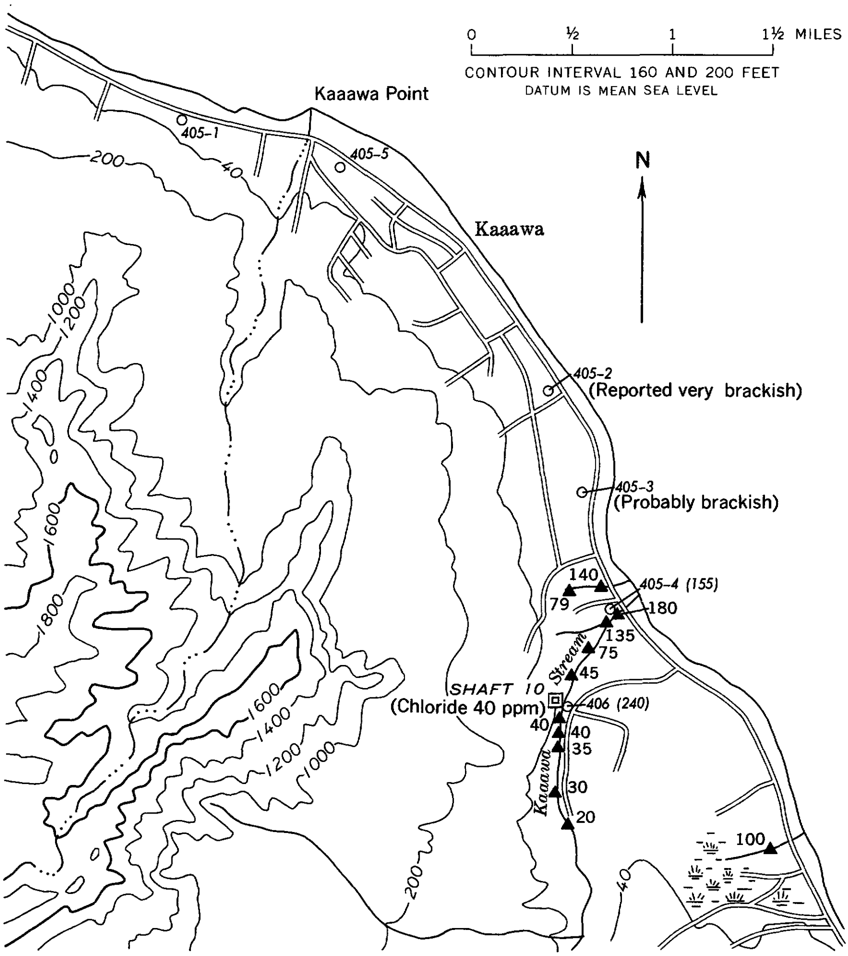


FIGURE 38.—Rainfall in upper Waikane Valley, base flow of Waihee Stream, and water levels in Kaaawa well 406.



EXPLANATION

▲35
Surface-water sampling point
Number indicates chloride content, in parts per million

○ 405-4 (155)
Well number and well
Number in parentheses is chloride content in well water, in parts per million

FIGURE 39.—Lower Kaaawa Valley, showing chloride content in stream and well water.

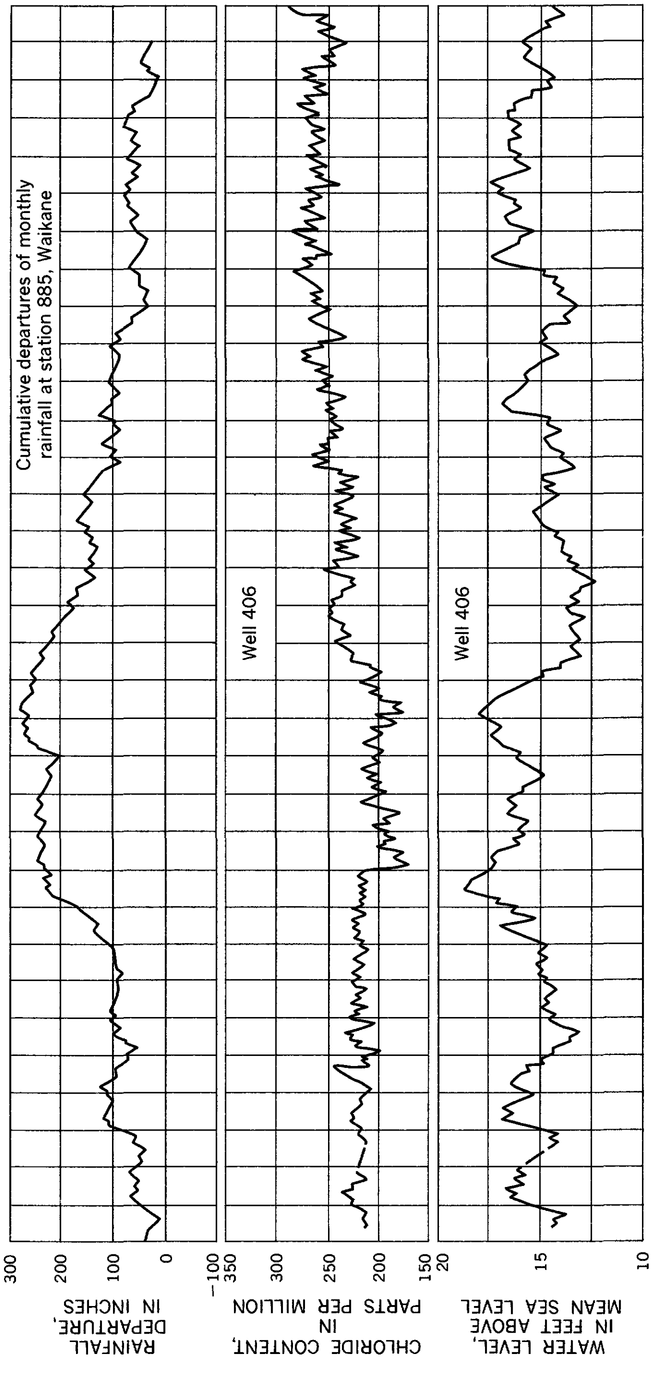


FIGURE 40.—Rainfall in upper Waikane Valley and chloride content of water and water levels in well 406.

below and adjacent to the valley, water-development tunnels are not feasible.

STREAMS

Kaaawa Stream lies north of the Kaneohe area and drains an isolated valley of about 2.5 square miles. Although flow measurements have been made along most of its length, the stream is not gaged. As there are no continuous discharge records for this stream, the minimum measured flow of 0.14 mgd is used as an estimate of long-term Q_{90}. Long-term average flow is estimated to be 1.0 mgd. An intermittent unnamed stream drains the northern part of the valley and discharges into the ocean at Kaaawa Point. (See pl. 3.) No streamflow data are available or have been estimated for this stream.

KAHANA VALLEY

GEOLOGIC SETTING

The valley of Kahana Stream extends inland from Kahana Bay southwestward about 4 miles to the present crest, or more than 1 mile leeward of the crest of the Koolau Range at its greatest stage of growth. (See figures 3 and 41.)

Predominant rocks are the lava flows of the Koolau Volcanic Series that dip into the range in the upper part of the valley and seaward in the lower part. Dike-complex rocks may be found near and above the level of Waiahole transmission tunnel, but dikes are sparse and occur singly in the lower part of the valley.

Breccia composed of many large dike fragments may be found between 1,400 and 1,840 feet from the portal in Kahana development tunnel. It is moderately to well cemented except near dikes, where it is somewhat shattered. Well-cemented breccia of smaller fragments is exposed in the lower part of the main stream channel between altitudes of 120 and 180 feet and in patchs along a horizontal distance of about 2,000 feet. This breccia may be part of the same formation that underlies Waihoi Springs in Punaluu Valley; if so, it has an apparent southeastward dip of 3½°.

Sedimentary material underlies Kahana Valley. Most is alluvial and is interbedded or gradational with marine material near the coast. (See pl. 1.) Well 405 penetrated both alluvial and marine material to a depth of 165 feet (150 feet below sea level). Near-shore material is overlain by Recent calcareous beach sand.

DIKES

An extensive dike system was mapped in the 1,970-foot Kahana development tunnel, at an altitude of about 800 feet. This tunnel bears S. 66° W. and penetrates dikes whose aggregate thickness ex-

FIGURE 41.—Kahana Valley, showing Kahana Bay in foreground and Waianae Range in western part of Oahu in background.

ceeds 600 feet. About 75 percent of the dikes strikes N. 35° W., and 20 percent strikes N. 55° W. The rest strikes in several other directions. Although about 30 percent of the tunnel penetrates intrusive rock, mostly vertical dikes, any 100-foot section may be devoid of dikes or may be a mass of dikes. Dike material decreases sharply in the brecciated part of the tunnel, where only eight dikes, aggregating 58 feet in thickness, were measured in a 440-foot section. Much of the country rock, however, consists of fragments of older dikes.

Dike orientation at the head of the valley is partly exposed in Waiahole ditch tunnel system, as shown in figure 8. Below this level a traverse was made of the southern branch and main channel of Kahana Stream to an altitude of about 100 feet. Eight dikes were identified, aggregating 56 feet in thickness, in a horizontal distance of 7,000 feet. Only one dike is known in the coastal area, a northwestward-striking dike 4 feet thick that is exposed along the highway on the north side of Kahana Bay.

GROUND WATER

OCCURRENCE AND MOVEMENT

An estimated 55 percent of precipitation becomes ground water, 20 percent evaporates or transpires, and 25 percent flows to sea as runoff. Annual rainfall in the valley, an area of 8.38 square miles, ranges from 70 inches at the shore to more than 250 inches at its head, totaling about 60 mgd. Of the calculated 33 mgd that recharges the aquifer, about 20 mgd returns to the surface as tunnel flow or as stream base flow, and about 10 mgd probably leaves the area as underflow, mostly entering the sea near or at the shore.

Because of the lack of valley-wide control, the above estimates for the valley were based on investigations of the 3.74 square-mile area above the gaging station. This area has an annual rainfall of more than 210 inches, or 38 mgd, of which about 70 percent (26± mgd) is estimated to become ground-water recharge. Evapotranspiration is estimated to be 10 percent and storm runoff to be 20 percent of annual rainfall. Of the ground-water recharge above the gaging station, about 4 mgd is discharged by Kahana development tunnel, and about 15 mgd maintains the base flow of Kahana Stream. The remaining 7 mgd probably leaves as underflow below the gaging station.

The base flow of low-altitude streams in windward Oahu may vary as much as 300 percent. Ground-water underflow, therefore, probably varies comparably—from 4 to 12 mgd above the Kahana gaging station and from 6 to 18 mgd in the entire valley.

The water budget for Kahana Valley is summarized in table 13.

Ground-water recharge in most of the valley becomes high-level water in dike-intruded basaltic aquifers. Above an altitude of about

TABLE 13.—*Water budget for Kahana Valley*

	Above gaging station (mgd)	Entire valley (mgd)
Precipitation	38	60
Evapotranspiration	4	12
Water yield	34	48
Direct and indirect runoff after rain	8	15
Water entering ground-water reservoirs	26	33
Ground-water component of tunnel or streamflow	19	23
Ground water unaccounted for and probably leaving area as underflow	7	10

750 feet, these dikes are in the dike complex; below they are sparse and occur singly in the marginal dike zone. In most of the valley, basaltic aquifers seem to be unweathered or only slightly weathered and have moderate to high permeability.

The predominant northwest-southeast alinement of dikes in the valley channels ground water to points of discharge in Kahana development tunnel or in Kahana Stream—which one being dependent on where the dikes are breached. A reconnaissance showed that most seeps and marshes are along the north side of Kahana Stream, which indicates a higher water level to the north and a predominant flow of ground water toward the southeast. The altitude of the high-level water exceeds 800 feet at the head of the valley and decreases toward the shore.

Near the coast the basal aquifer is recharged by leakage from high-level water. The basal-water table probably is lower than an altitude of 30 feet. The good quality of water from well 405, from the seeps near the coast, and from the stream suggests a small inland extension of basal water. Owing to the cutting away of near-shore dikes of Kahana Stream, basal water probably extends inland as a wedge along the axis of the valley. In artesian well 405 (pl. 1) near the mouth of Kahana Stream, the water level has fluctuated between altitudes of 15 and 21 feet during the last 25 years, but near the seaward end of basaltic spurs the water table probably is only a few feet above sea level.

Basal ground water discharges to Kahana Stream and to a small unnamed stream immediately north of well 405, to basal springs near the coast at an altitude of about 10 feet, and directly to sea as underflow.

Water levels of well 405, discharge of Kahana development tunnel, and mean monthly departures of upper Kahana Valley rainfall are correlative. (See fig. 42.) Correlation is continued in figure 43 with the addition of a ground-water underflow curve and a Kahana Stream minimum-flow curve. The underflow curve was established by using average underflow as the point of beginning (January 1959) and by

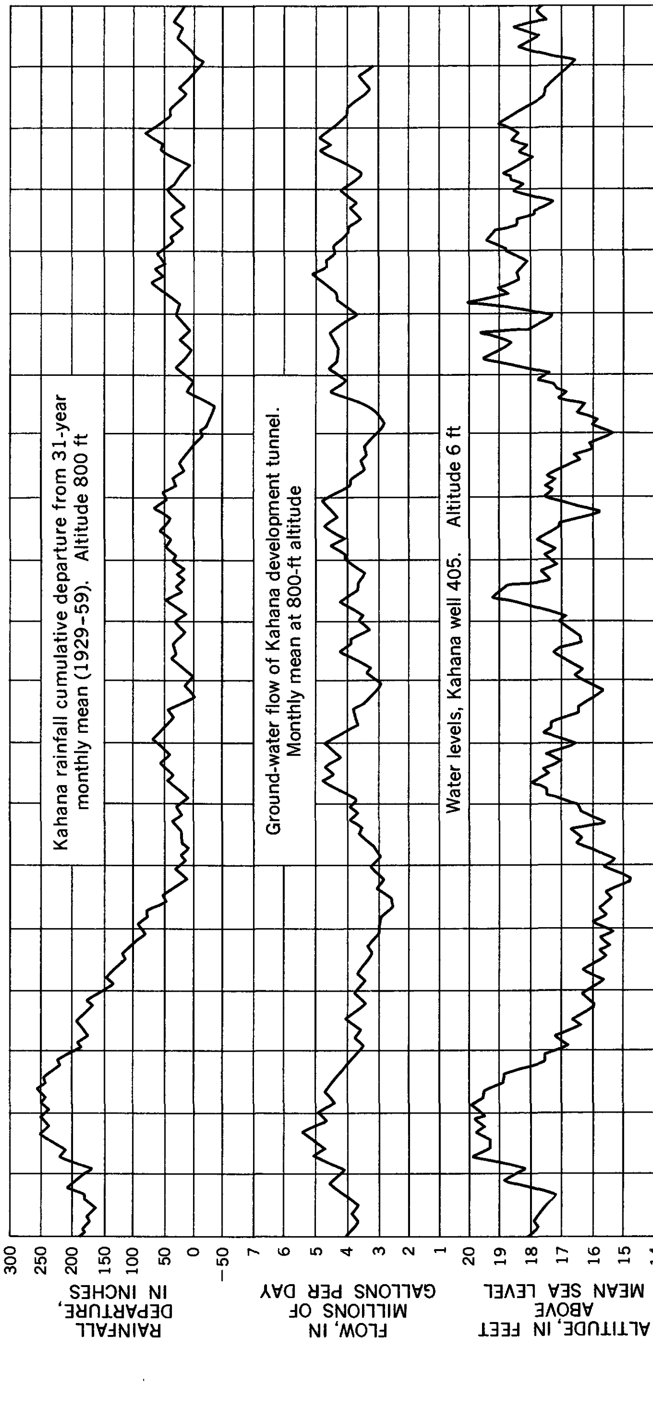


FIGURE 42.—Rainfall in upper Kahana Valley, flow of Kahana tunnel, and water levels in Kahana well 405.

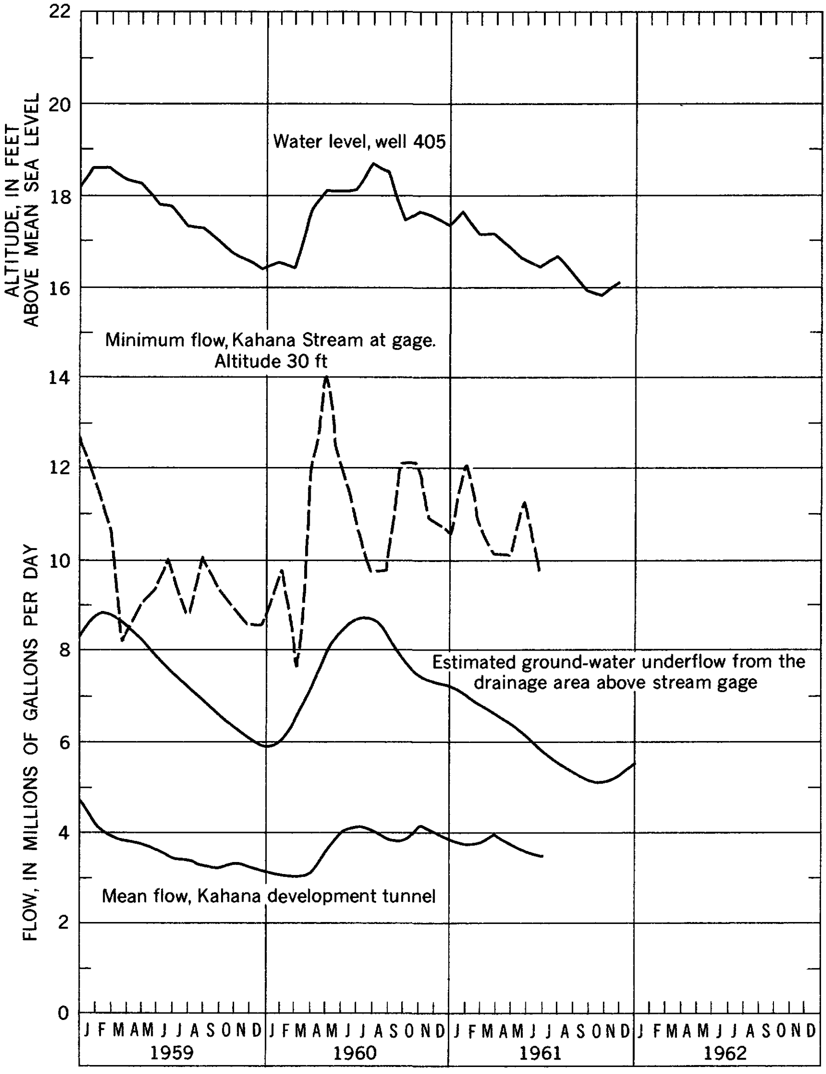


FIGURE 43.—Water level in well 405, mean flow of Kahana development tunnel, minimum flow of Kahana Stream, and estimated underflow in Kahana Valley.

modifying it each month in relation to percentage of measured change in the other three curves.

POTENTIAL AREAS FOR GROUND-WATER DEVELOPMENT

The most promising area for additional development of ground water is at the foot of the high ridge northwest of Kahana Stream gaging station because there is a high water table, a smaller amount of weathered rock, and a greater source of ground water relative to other areas. The center of the valley and toes of basaltic ridges that project to sea appear to be less favorable.

STREAMS

Kahana Stream drains 8.38 square miles and has the largest unused runoff of any single stream in the windward area. Although an average of 4.0 mgd of ground water and 3.2 mgd of surface water is diverted by Waiahole ditch tunnel system, a greater amount is wasted and enters the sea from below the tunnel system.

There is one gaging station in the valley, at an altitude of 30 feet in Kahana Stream. It measures water from a drainage area of 3.74 square miles that, except during storms, originates entirely below the 800-foot tunnel level. Except for a negligible quantity used for irrigation, Kahana Stream water flows unused into the sea.

Streamflow records collected from January 1959 to June 1961 show that average flow for the period was 18.6 mgd and that Q_{90} was 10.8 mgd. By correlation with East Branch Manoa and Punaluu Streams, a long-term average flow of 20.2 mgd and a long-term Q_{90} of 9.3 mgd have been estimated for Kahana Stream at the gaging station.

Measurements in Kahana Valley show an increase in flow of about 20 percent from the gaging station down to an altitude of 15 feet, which is the lowest measuring point. Estimated long-term Q_{90} for the entire valley is 11.2 mgd.

The long-term average flow of 20.2 mgd at the gaging station consists of direct runoff, 5 mgd, and ground-water flow, 15.2 mgd. For determination of the long-term average flow of the entire valley, these flow components were adjusted to the lowest measuring point; the direct-runoff component was increased in proportion to drainage areas, or at a ratio of 8.38 : 3.74, and the ground-water component by 20 percent, based on the observed gain in base flow. The adjusted figures give a direct-runoff component of 11.2 mgd and a ground-water component of 18.3 mgd—a total of 29.5 mgd for the long-term average flow for the entire valley.

PUNALUU VALLEY

GEOLOGIC SETTING

Punaluu Stream valley is the northernmost of large deep valleys in windward Oahu as well as the northernmost of windward valleys that are eroded west of the location of the crest of the Koolau Range at its greatest stage of growth (fig. 44). The position of the valley relative to adjacent valleys is shown in figure 45. Figure 46 shows the profiles of Punaluu and Kaluanui Streams relative to the surface of the basaltic ridge that separates the two streams.

FIGURE 44.—Punaluu Valley, showing sugarcane fields in foreground and Waianae Range in background.

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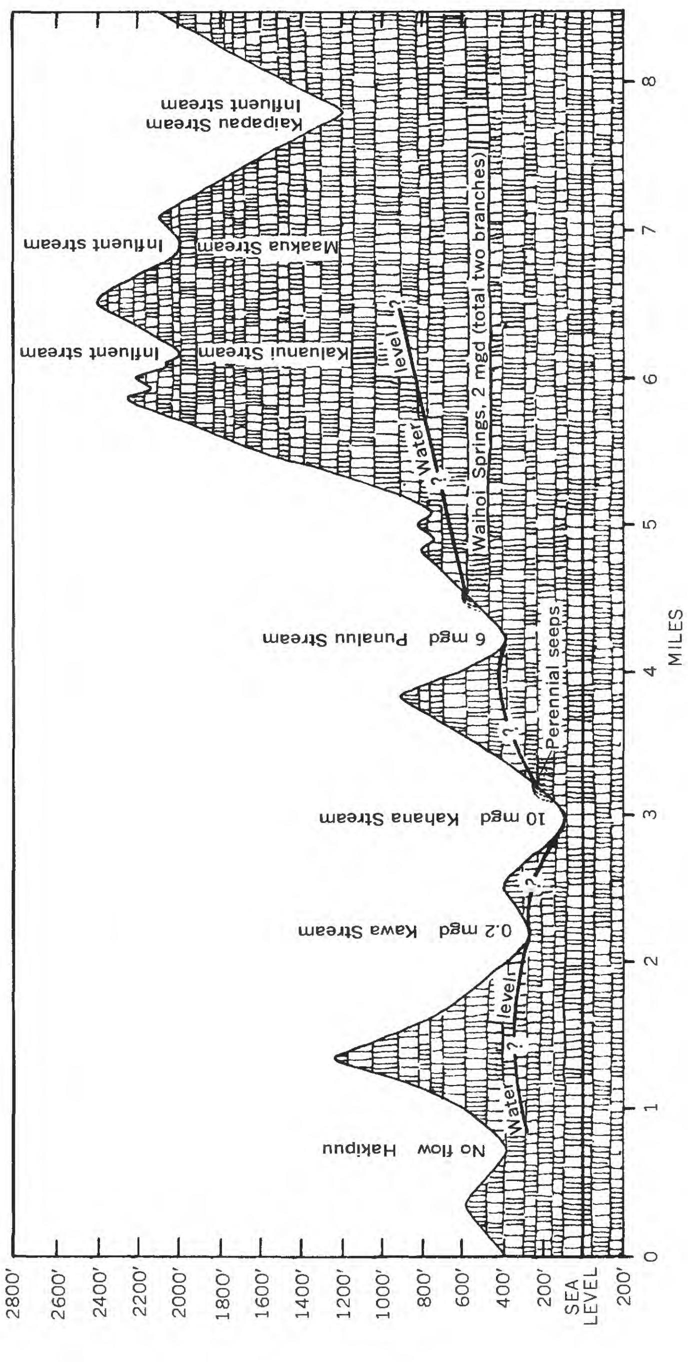

FIGURE 45.—Relative locations of valleys from Hakipuu to Kaipapau Stream.

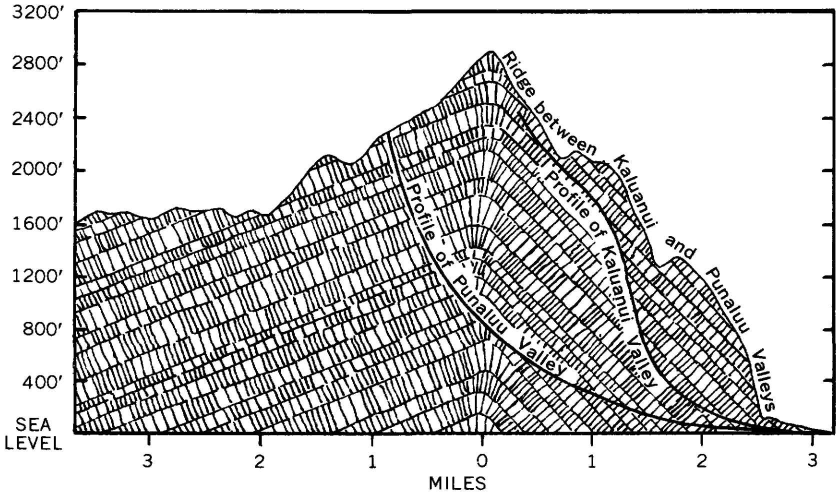

FIGURE 46.—Profiles of Punaluu and Kaluanui Valleys relative to their separating ridge.

Rocks of the valley are mainly lava flows of the Koolau Volcanic Series. The upper valley cuts into what is probably the main rift zone, but only sparse dikes are exposed in most of the valley, especially below an altitude of 600 feet in the stream channel.

Waihoi Springs discharge from breccia along the west wall of the valley (pl. 1). The breccia ranges in thickness from 50 to 75 feet. The top 10 feet is extensively fractured and serves as a conduit for the springs.

Recent and older alluvium underlies the valley. A coastal plain half a mile wide at a maximum altitude of 20 feet occupies the mouth of the valley. It is truncated by a basaltic ridge to the south but is continuous and wider to the north. It is overlain by a veneer of Recent alluvium and is underlain by marine material that extends at least 50 feet below sea level. This marine material is underlain by older alluvium to about 200 feet below sea level at well 403–1 (pl. 1). The older alluvium is thin at the seaward extensions of the basaltic spurs. Recent calcareous beach deposits overlie the marine material near shore. Geologic profile *E–E′* (pl. 1) was drawn from drillers' logs of the Punaluu and Kaluanui areas and shows the relation of the sedimentary section to the lava bedrock.

DIKES

Near the center of the summit arc of the valley, numerous northwestward-striking dikes cut across the crest. They represent a continuation of the rift zone penetrated by the Kahana development tunnel. Dikes are less common in the Punaluu area and are more weathered and shattered than those in the Kahana area.

Dikes at the crest are generally weathered and shattered to such an extent that reliable strike or dip cannot be obtained. Partly owing to difficult terrain and dense cover, no dikes have been reported between the crest and an altitude of about 620 feet, where, on the right side of Punaluu Stream, five dikes with a total thickness of 30 feet were mapped in a horizontal distance of less than 100 feet. Below this altitude only an occasional single dike was found.

GROUND WATER

OCCURRENCE AND MOVEMENT

Ground-water recharge in the valley (6.5 square miles) is about 70 percent (40 mgd) of its estimated 58-mgd rainfall. Evapotranspiration is estimated to be 15 percent (9 mgd), and runoff from heavy rains is about 15 percent (9 mgd). Annual rainfall ranges from nearly 50 inches at the shore to more than 300 inches at the valley head.

Of the ground-water recharge of 40 mgd, about 15 mgd returns to streams as base flow. Of the remaining 25 mgd, 2 mgd is discharged from wells, and 23 mgd leaves the area as underflow—either to the sea or to the Kaluanui area to the north.

The drainage area of Punaluu Stream above the gaging station at an altitude of 212 feet is 2.78 square miles. The gaged area receives about 225 inches (33 mgd) of precipitation per year. Estimated ground-water recharge is about 80 percent of the rainfall; evapotranspiration is about 5 percent. The remainder is runoff after heavy rains. The average base flow of Punaluu Stream at the gaging station is 13 mgd; ground-water underflow to the drainage area below the gaging station is about 13 mgd.

Kaluanui Valley contributes ground water to Punaluu Valley. (See figs. 45 and 46.) About 3 mgd from Kaluanui Valley enters the drainage area above Punaluu gaging station and 6 mgd enters below the station. These quantities were not included in the previous Punaluu underflow tabulations.

The water budget of Punaluu Valley is summarized in table 14.

The principal aquifer in the valley is lava of the Koolau Volcanic Series. High-level water throughout most of the valley and basal water near the coast are separated by a transition zone. High-level water may be found under water-table conditions where the lava is exposed and under artesian conditions where caprock extends below the water level. Basal water is generally under artesian conditions.

High-level water probably does not exceed an altitude of 1,000 feet. No springs discharge above an altitude of 800 feet at the head and

TABLE 14.—*Water budget, in million gallons per day, of Punaluu Valley*

	Above gaging station	Entire valley
Precipitation	33	57
Evapotranspiration	2	8
Water yield	31	49
Direct runoff after rains	4	9
Recharge to ground-water reservoirs	26	40
Ground-water component of streamflow	13	15
Well discharge		2
Underflow leaving area	13	23
Underflow from Kaluanui Valley	3	9
Total underflow leaving area		32

above 600 feet along the left wall of the valley. Flow measurements of Punaluu Stream at an altitude of 640 feet indicate that ground-water discharge is about 2 mgd. Waihoi Springs at an altitude of 560 feet along the north bank of the stream discharges about 2 mgd. The channel of Punaluu Stream is in saturated rock throughout most of its course—below an altitude of 800 feet in the main channel and 600 feet along the left bank. Some basal water presumably enters the stream below an altitude of 20 feet, as chloride content of the stream water increases seaward below that altitude.

The predominant flow of high-level water is toward Punaluu Stream, parallel to the strike of the dikes. Lack of perennial streams and springs along the south side of the valley suggests that ground water is moving from Punaluu to Kahana Valley. Figure 45 shows average base flow of streams and probable position of the water table along a line that is parallel to the trend of the dikes and passes through Waihoi Springs.

Basal water moves northeastward at right angles to the water-level contours, as shown in plate 2. The hydraulic gradient is between 2 and 3 feet per mile, and maximum hydrostatic head is north of Punaluu Stream. The sharp southeastward decrease in head, from 20 feet in wells 403–1 and 402–1, to 12 feet in well 403, and to 6 feet in well 404–2B, may indicate one or more of the following: (1) Decreasing permeability of the basaltic aquifer, (2) a large discharge of basal water into Punaluu Stream, or (3) a hydraulic barrier, consisting of poorly permeable sedimentary material that thickens toward the stream. The last factor is the most probable cause of the head differences, although others also may be effective.

Present development of water in the valley includes Punaluu ditch diversion for irrigation between Punaluu and Kaluanui Streams. Total pumpage from basal-water wells is less than 2 mgd, of which 1.2 mgd is from a free-flowing irrigation well (403–1). Pumpage from domestic well 402–1 is 0.7 mgd.

CHLORIDE CONTENT

Chloride content of high-level water is generally less than 25 ppm. Chloride content of basal water ranges from 20 to 12,000 ppm.

Distribution of chloride content in well water is shown in plate 2, and chloride content of Punaluu Stream water and water from ditches and swamps on the south side of the stream is shown in figure 47. Coastal increase in chloride content of water from Punaluu Stream may indicate mixing with basal water. If so, chloride content of the top of the basal-water body exceeds 500 ppm. Analysis of water from wells 402–1 and 404–1 in the valley is included in table 11.

POTENTIAL AREAS FOR GROUND-WATER DEVELOPMENT

The area on the north side of the valley and along the inner margin of the coastal plain between Punaluu and Kaluanui Valleys is proba-

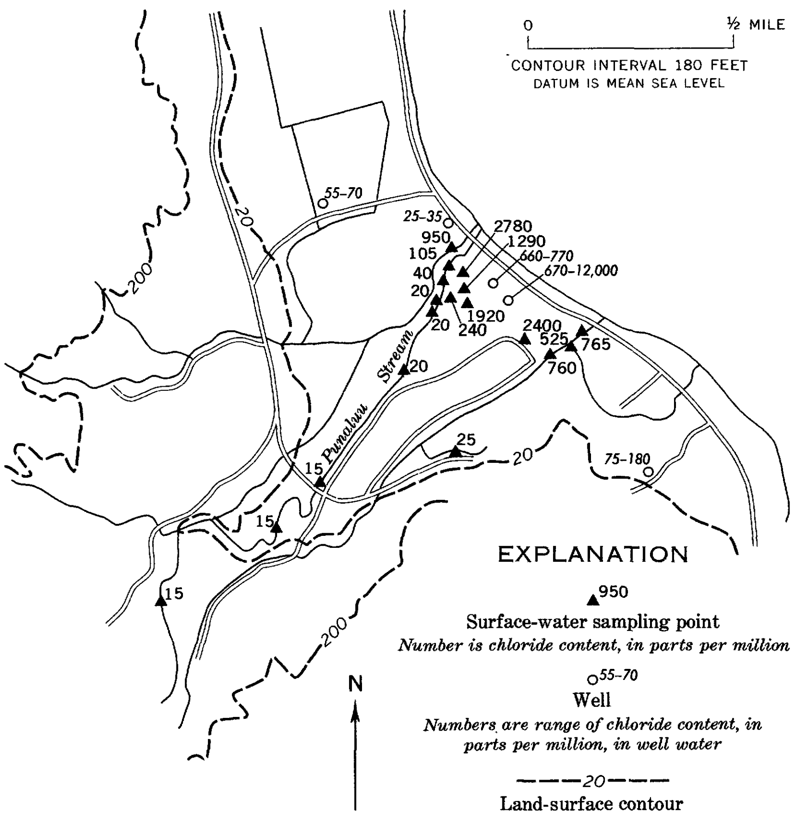

FIGURE 47.—Seaward increase in chloride content of water in Punaluu Stream in lower Punaluu Valley.

bly the most promising for additional development of ground water. Fresh water might be developed on the south side of the valley except in the area extending half a mile inland from the coast.

STREAMS

Punaluu Stream drains about 6.5 square miles. Its flow is measured at an altitude of 212 feet by two gaging stations—one on the stream and the other on Punaluu ditch. Although the stations were established in May 1953, only those records for the 1955–60 fiscal years were used in extending the record for Punaluu Stream. Prior ditch records were affected by unmeasured flow through a wasteway gate.

By use of combined monthly mean flows at the stations and concurrent flows of East Branch Manoa Stream, a regression equation was computed. Long-term average discharge was estimated to be 16.6 mgd. The average, when computed from the long-term flow-duration curve transposed from East Branch Manoa Stream, agrees closely; therefore, the Q_{90} of 9.1 mgd taken from the transposed flow-duration curve should be reliable.

Flow measurements along Punaluu Stream indicate a gain of 19.6 percent between the gaging station and an altitude of 10 feet. The long-term average flow of 24.2 mgd and the Q_{90} of 10.9 mgd for the whole valley were obtained in the same manner as were those for Kahana Valley.

KALUANUI VALLEY

GEOLOGIC SETTING

Kaluanui Valley includes 3.5 square miles. It forms the northern boundary of the project area and is smaller, narrower, and much less deeply cut into the range than valleys to the southeast (fig. 48). Kaluanui and other valleys to the north lack the amphitheater head characteristic of southern valleys that cut the main Koolau rift zone. Rocks are mainly lava flows of the Koolau Volcanic Series, which dip northeastward away from the crest. Sedimentary material underlies the lower part of the valley and the narrow coastal plain. Recent unconsolidated calcareous beach deposits overlie the sedimentary material at the shore. The most significant feature of this valley is its position 1,000 feet or more above Punaluu Valley (figs. 45, 46).

DIKES

A 1-foot-thick vertical dike striking N. 35° W. is exposed in the main stream channel at an altitude of 160 feet, and a 2-foot vertical dike striking N. 45° W. is exposed in the left branch of Kaluanui Stream at an altitude of 280 feet. These isolated outcrops may be segments of a single intrusion. Seven dikes with a total thickness of 20

FIGURE 48.—Kaluanui Valley, showing sugarcane fields in coastal plain in foreground. Waianae Range, in western part of Oahu, is in background.

feet and an average strike of N. 55° W. are exposed along 230 feet of the main stream channel below Sacred Falls. These dikes may represent a segment of the main rift zone, which cuts across the head of Punaluu Valley. In his 1932 field notes, T. F. Harriss described three dikes above Sacred Falls, one at an altitude of about 1,800 feet and two at about 2,200 feet.

GROUND WATER

OCCURRENCE AND MOVEMENT

High-level water occurs in the upper part of the valley and basal water in the lower part. Because the upper part does not penetrate the high-level aquifer, the stream is predominately influent.

Most high-level water underlying the valley moves into Punaluu Valley as underflow. It moves from the upper part of the valley to the southeast, generally parallel to the dike alinement. Dikes are cut at least 1,000 feet lower in Punaluu than in Kaluanui Valley (fig. 45). The water budget for the valley is summarized in table 15.

The boundary between high-level and basal water, although difficult to place, is probably in the vicinity of the dike exposed at an altitude of 160 feet in Kaluanui Stream, roughly a mile inland. Basal

TABLE 15.—*Water budget, in million gallons per day, for Kaluanui Valley*

	Above old gaging station, altitude 1,960 feet	Area included in water inventory	Entire valley
Precipitation	6	17	22
Evapotranspiration	1	2	4
Water yield	5	15	18
Direct runoff after rains	2	3	5
Ground-water recharge	3	12	13
Ground-water component of streamflow	0	0	0
Well discharge	0	2	2
Underflow leaving Kaluanui Valley	3	10	11

water is confined by poorly permeable sedimentary material. Basal water moves northward (pl. 2) toward the Hauula area. During 1961, about 2 mgd of basal water was pumped from irrigation wells, and about 90,000 gpd was pumped from well 396 for domestic supplies. Water-level and chloride data for observation well 396 are available for 1911 and 1912, respectively. These are plotted in figure 49 with ground-water draft in the Punaluu-Hauula area and cumulative departures from the monthly mean rainfall at station 883 in upper Kahana Valley.

Water-level contours before and during test pumping of well 398 are shown in figure 50. Drawdown in observation wells 401, 397, and 396 is plotted in figure 51.

The pumping test indicated that aquifer permeability is high. A pumping rate of 3,000 gpm (4.3 mgd) was maintained throughout the 3-day test; however, sustained pumping of this magnitude might induce salt-water encroachment from the bottom of the fresh-water lens. Aquifer constants determined from the test indicate that the flow of basal water is about 12 mgd. At least 8 mgd is believed by the writers to be underflow to the Kaluanui area from the Punaluu area.

POTENTIAL AREAS FOR GROUND-WATER DEVELOPMENT

The most effective method of developing ground water in the valley would be by scattered pumping of wells in a line parallel to the water-level contour lines shown in plate 2. The low-lying part of the valley, especially the inner margin of the coastal plain, constitutes the most favorable area.

Wells 402–2A and 402–2B were drilled in 1965 and 1966, respectively, by the Board of Water Supply, City and County of Honolulu. The wells were drilled 600 feet apart parallel to about the 21-foot water-level contour line shown in plate 2. Separate pumping tests of the two wells indicated a transmissivity constant of about 4 mgd per ft.

STREAMS

During 1916 and 1917, a gaging station was operated on Kaluanui Stream at an altitude of 1,900 feet. Records show that the flow of

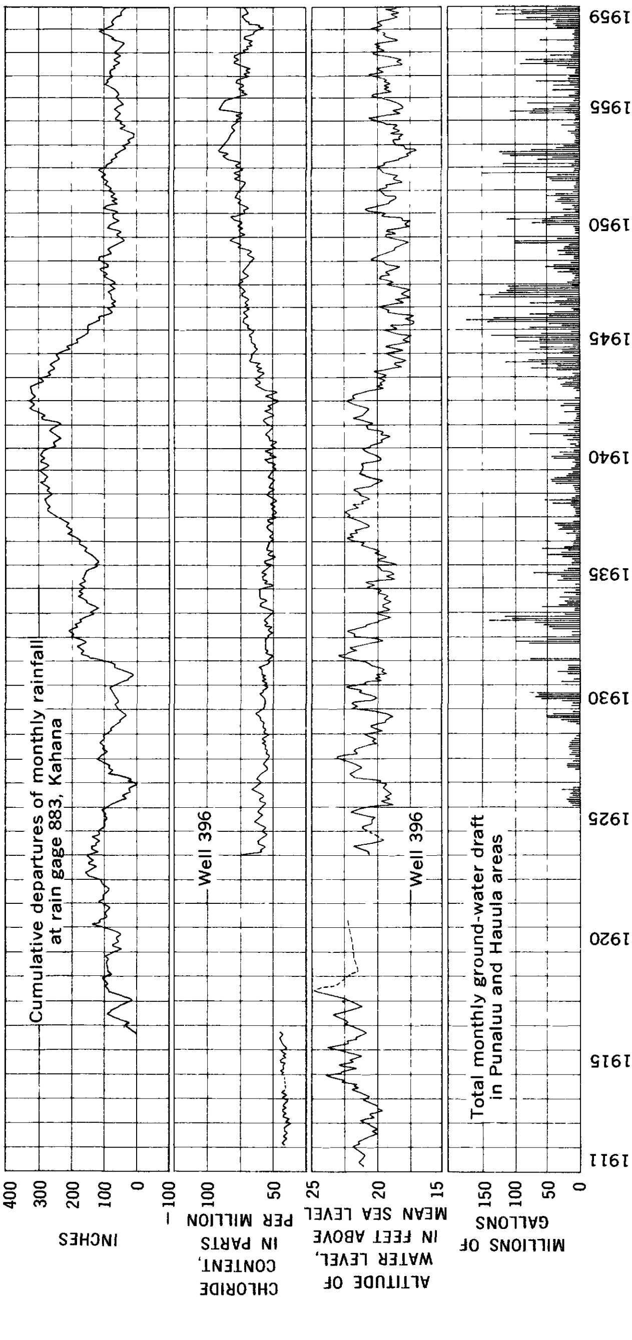

FIGURE 49.—Cumulative departures of mean monthly rainfall at rain gage 883, chloride content of water in well 396, water level in well 396, and ground-water draft in Punaluu and Hauula areas.

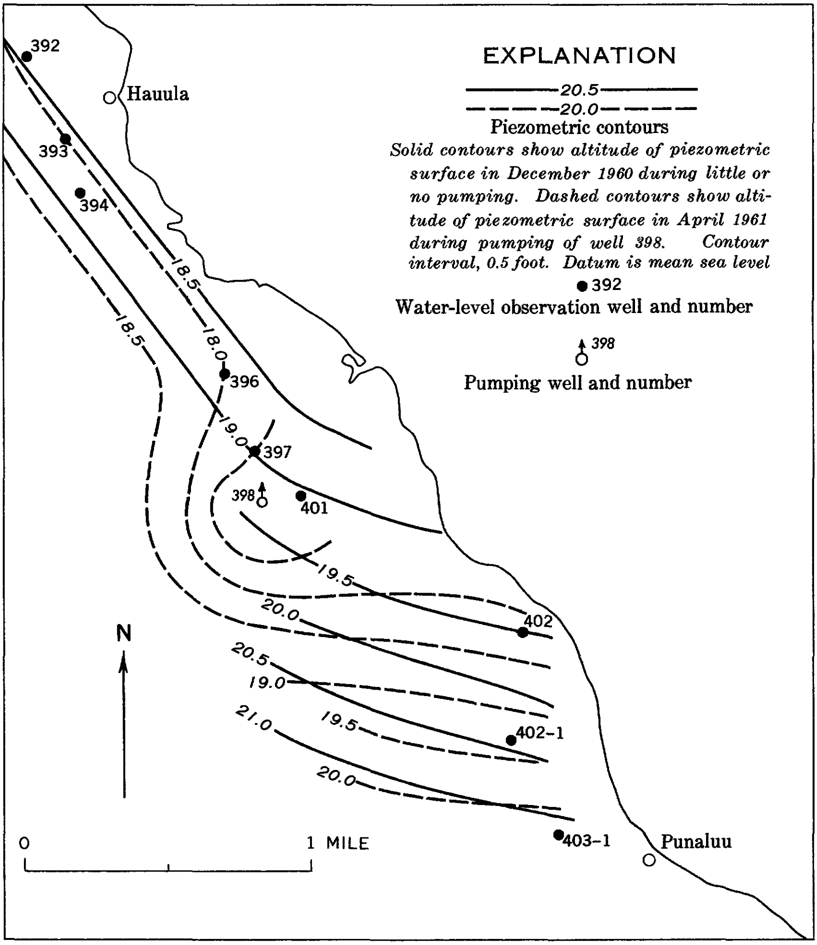

Figure 50.—Water-level contours before and during a pumping test of well 398 in the coastal area in the northern part of windward Oahu.

Kaluanui is more variable than that of other windward area streams. Average flow was 2.96 mgd, and Q_{90} was 0.54 mgd. The stream also differs from others in that its flow is greater at higher altitudes. Measured flow was 0.30 mgd at an altitude of 1,900 feet and only 0.24 mgd, including flow of a tributary, at 80 feet on January 22, 1960.

Although the point of maximum base flow of Kaluanui is higher, the stream was measured periodically at the 80-foot altitude. By correlation of measurements with concurrent daily discharges of the hydrologically similar right branch of North Fork Kaukonahua Stream (station 2010; lat 21°31′10″, long 157°56′52″), long-term average flow of Kaluanui Stream is estimated to be 3.4 mgd, and Q_{90} is 0.17 mgd.

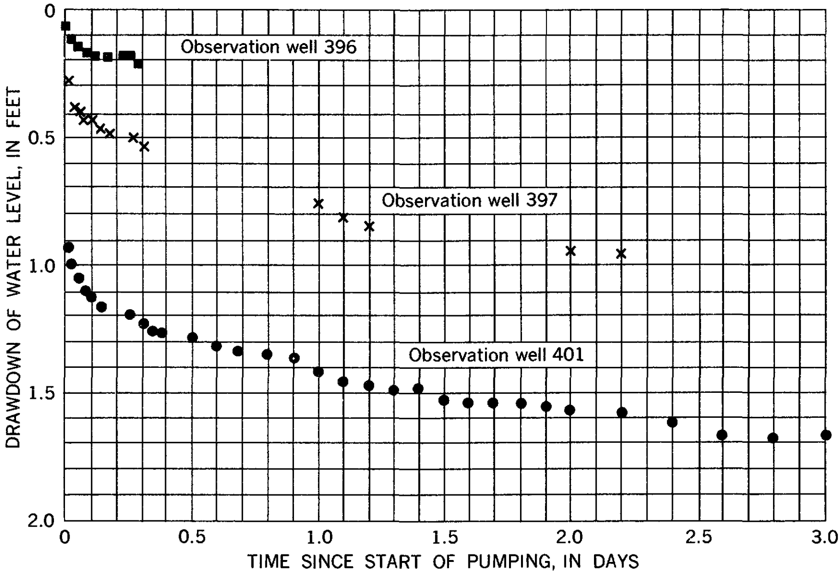

FIGURE 51.—Drawdown in observation wells 396, 397, and 401 during pumping of well 398.

SUMMARY OF WATER RESOURCES OF MAJOR DRAINAGE AREAS

The dependable flow (Q_{90}) of water in the project area is estimated to be about 120 mgd. Of this, about 85 mgd is discharged by streams, tunnels, springs, and wells. The remaining 35 mgd is underflow, most of it discharging to sea near the northern end of the windward area. Average flow (arithmetic mean of all daily flow of record) was estimated to be 220 mgd, of which 160 mgd was inventoried flow and 60 mgd was estimated to be underflow.

The water inventory included 51 square miles of the 91-square-mile area (fig. 5) and generally included that part of each valley above the point of maximum discharge of streams. Because of higher evapotranspiration in the area not inventoried, available water is probably less than the 160 mgd inventoried. Table 16 summarizes average discharge and table 17 summarizes dependable discharge of water.

Dependable underflow was computed according to range in base flow (ground-water flow) of streams. Maximum base flow of streams is about three times minimum base flow. Generally, dependable (Q_{90}) underflow was estimated to be 60 percent of computed average underflow. The base-flow discharge, which is the sum of the base flow of streams and tunnels and the underflow, ranges from about 85 to 255 mgd.

TABLE 16.—*Estimate of mean discharge in windward Oahu including storm runoff*

[Quantity in million gallons per day]

Area	Water yield [1]	Flow in streams						Ground-water discharge not measured in flow of streams		
		Flow	Augmented flow (1962)	Depleted flow (1962)	Flow available	Flow used (1962)	Flow unused (1962)	Estimated discharge [2]	Use (1962)	Unused discharge (1962)
Waimanalo	1.6	0.7	[3] 2.0		2.7	2.0	0.7	0.9	0.7	0.2
Maunawili	13.4	8.8		[4] 2.0	6.8	0	6.8	4.6	.1	4.5
Kaneohe	89.1	[5] 77.2	[6] 7.2	[7] 28.7	55.7	6.0	49.7	11.9	2.0	9.9
Kaaawa	2.7	1.0			1.0	0	1.0	1.7	.1	1.6
Kahana	48.5	36.7		[8] 7.2	29.5	0	29.5	11.8	0	11.8
Punaluu	49.1	24.2			24.2	10.9	13.3	[9] 36.8	[9] 4.0	[9] 32.8
Kaluanui	15.3	3.4			3.4	0	3.4			
Total (rounded)	220	152	9	38	123	19	104	68	7	61

[1] Water yield equals precipitation minus evapotranspiration.
[2] Unmeasured ground-water discharge equals water yield less flow in streams.
[3] Diverted from Maunawili area.
[4] Diverted to Waimanalo area; includes flow from tunnels and springs.
[5] Includes flow from Haiku, Kahaluu, Waihee, Waiahole main transmission, Uwau, and Waikane tunnels.
[6] Diverted from Kahana Valley.
[7] Exported from windward Oahu to southern Oahu through Waiahole ditch tunnel.
[8] Diverted to Kaneohe area; includes flow from Kahana tunnel.
[9] Sum for Punaluu and Kaluanui Valleys.

TABLE 17.—*Estimate of dependable discharge in windward Oahu excluding storm runoff*

[Quantities in million gallons per day]

Area	Water yield [1]	Flow in streams						Ground-water discharge not measured in flow of streams		
		Flow	Augmented flow (1962)	Depleted flow (1962)	Flow available	Flow used (1962)	Flow unused (1962)	Estimated discharge [2]	Use (1962)	Unused discharge (1962)
Waimanalo	1.0	0.3	[3] 2.0		2.3	2.0	0.3	0.7	0.7	0
Maunawili	6.7	4.7		[4] 2.0	2.7	0	2.7	2.0	.1	1.9
Kaneohe	53.2	[5] 45.4	[6] 4.0	[7] 21.3	28.1	6.0	22.1	7.0	2.0	5.0
Kaaawa	1.1	.1			.1	0	.1	1.0	.1	.9
Kahana	21.2	15.2		[8] 4.0	11.2	0	11.2	7.0	0	7.0
Punaluu	[9] 34.1	10.9			10.9	10.9	0	[9] 23.0	[9] 4.0	[9] 19.0
Kaluanui		.2			.2	0	.2			
Total (rounded)	118	77	6	27	56	19	37	41	7	34

[1] Water yield equals flow in streams plus estimated ground-water discharge.
[2] Unmeasured ground-water discharge equals approximately 60 percent of average ground-water discharge.
[3] Diverted from Maunawili area.
[4] Diverted to Waimanalo area; includes flow from tunnels and springs.
[5] Includes flow from Haiku, Kahaluu, Waihee, Waiahole main transmission, Uwau, and Waikane tunnels.
[6] Diverted from Kahana Valley.
[7] Exported from windward Oahu to southern Oahu through Waiahole ditch tunnel.
[8] Diverted to Kaneohe area; includes flow from Kahana tunnel.
[9] Sum for Punaluu and Kaluanui Valleys.

Information pertaining to the ground-water inventory is given in tables 18, 19, and 20. Flow of each perennial stream was measured at a point of maximum or near-maximum base flow, and dependable and average flow of each stream was calculated by correlation. The stream inventory is summarized in plate 3 and in tables 8 and 9.

DEVELOPMENT OF HIGH-LEVEL WATER

Most development of high-level water has been by tunneling. At least 21 tunnels have been bored, the earliest in 1888 and the latest in 1955. Data concerning the tunnels are given in table 18, and tunnel locations are shown in plate 1. Total yield of the tunnels is about 30 mgd.

About 35 drilled wells tap high-level water. Except for three, the wells were drilled at low altitudes in weathered rock in the dike complex and yield little water. Most are unused or have been abandoned. Total yield is about 1 mgd.

EFFECT OF TUNNELS ON BASE FLOW OF STREAMS

Perennial streams gain because they cut into and drain high-level-water reservoirs, and streams that cut deepest have the largest base flow. A tunnel is, in effect, an extension of a valley floor and if long enough will partly or completely replace a stream as a drain. Total base-flow discharge probably has not changed significantly with tunneling; only the points of discharge have been shifted.

WAIAHOLE DITCH TUNNEL SYSTEM

During construction of the main bore of the Waiahole ditch tunnel system (1913–16), two Waiahole Valley springs dried up. The combined flow of the springs in June and July 1911 was 5.7 mgd (Stearns and Vaksvik, 1935, p. 403). The main bore extends through the range

TABLE 18.—*Water-development tunnels in windward Oahu*

Name	Location	Owner	Year constructed	Altitude (ft)	Total length (ft)	Use
Ahuimanu	Ahuimanu			540		Domestic and stock.
C&C tunnel 1	Waimanalo	Board of Water Supply		462		Municipal.
C&C tunnel 2	do	do	1940	620	499	Do.
Clark	Maunawili	Castle Estate	1922–26	550	1,117	Irrigation.
Cooke	do	do	1926	500	130	Do.
Fault	do	do	About 1900	450	350	Do.
Haiku	Haiku	Board of Water Supply	1940	550	1,320	Municipal.
Kahana	Kahana	Waiahole Water Co	1929–31	800±	1,975	Irrigation.
Kahaluu	Kahaluu	Board of Water Supply	1946	585	393	Municipal.
Korean	Maunawili	Castle Estate	1923	535	160	Irrigation.
Luluku	Kaneohe	Board of Water Supply		530	481	Municipal.
Plantation tunnel 1.	Waimanalo	do	About 1888	415	125	Do.
Plantation tunnel 2.	do	do	1922–26	425	50	Do.
Plantation tunnel 3.	do	do		462	60	Do.
Tunnel A	Waiahole	Waiahole Water Co	1915	790	1,011	Dry.
Tunnel B	do	do	1915	800	1,260	Do.
Uwau	do	do	1932–35	800±	2,275	Irrigation.
Waiahole (main bore).	do	do	1913–16	724	14,567	Do.
Waihee	Waihee	Board of Water Supply	1955	218	1,785	Municipal.
Waikane 1	Waikane	Waiahole Water Co	1925–27, 1933–34	800±	3,445	Irrigation.
Waikane 2	do	do	1927–29	800±	2,341	Do.

and intercepts some water that would normally flow to the windward side. The flows of Waikane and Kahana Streams also were decreased when Waiahole ditch tunnels were bored in their valleys.

HAIKU TUNNEL

Construction, in 1940, of Haiku tunnel at an altitude of 550 feet drained the high-level-water reservoir to a level where the flow of Kahaluu Stream, 2½ miles away, was decreased 26 percent, and the flow of Iolekaa Stream, half a mile away, was decreased 50 percent. (Hirashima, 1963.)

KAHALUU TUNNEL

Kahaluu tunnel was bored in 1946 at an altitude of 585 feet. Subsequent records for 7 years show that the base flow of the valley was increased by the tunnel, but some of the decline in base flow caused by the boring of the Haiku tunnel was not recovered. The tunnel, 35 feet higher than the Haiku tunnel, is probably too high to reverse the flow of ground water lost to the Haiku tunnel. Two springs at an altitude of 610 feet in the valley were dried up by drainage from the tunnel.

Combined base flow of Haiku, Iolekaa, and Kahaluu Valleys, including the base flow of Haiku and Kahaluu tunnels, was unchanged after initial drainage (Hirashima, 1963).

WAIHEE TUNNEL

An analysis of streamflow records indicates at least two high-level-water reservoirs in Waihee Valley. The upper reservoir is controlled by a 6-foot dike near the head of the valley, and the lower reservoir is controlled by a 12-foot dike near the heading of the Waihee tunnel. The tunnel, which penetrates only the 12-foot dike, drains the lower reservoir, with no discernible effect on the upper reservoir. Waihee, unlike the other tunnels, is not allowed to flow free. It is bulkheaded at the 12-foot dike; therefore, storage can be manipulated. The effects of water withdrawal by Waihee tunnel are discussed in detail by Hirashima (1965). (See fig. 52.)

EFFECT OF TUNNELS ON GROUND-WATER STORAGE

Dikes control most high-level water in windward Oahu. When these dikes are penetrated by tunneling, water stored by the dikes begins to discharge. The discharge of stored water continues generally until tunnel discharge equals the pretunneling base flow of a nearby stream or spring. If the rocks penetrated are sufficiently permeable, such as those in marginal dike zones, the top of the high-level-water body declines to the level of the tunnel. If the rocks are not sufficiently perme-

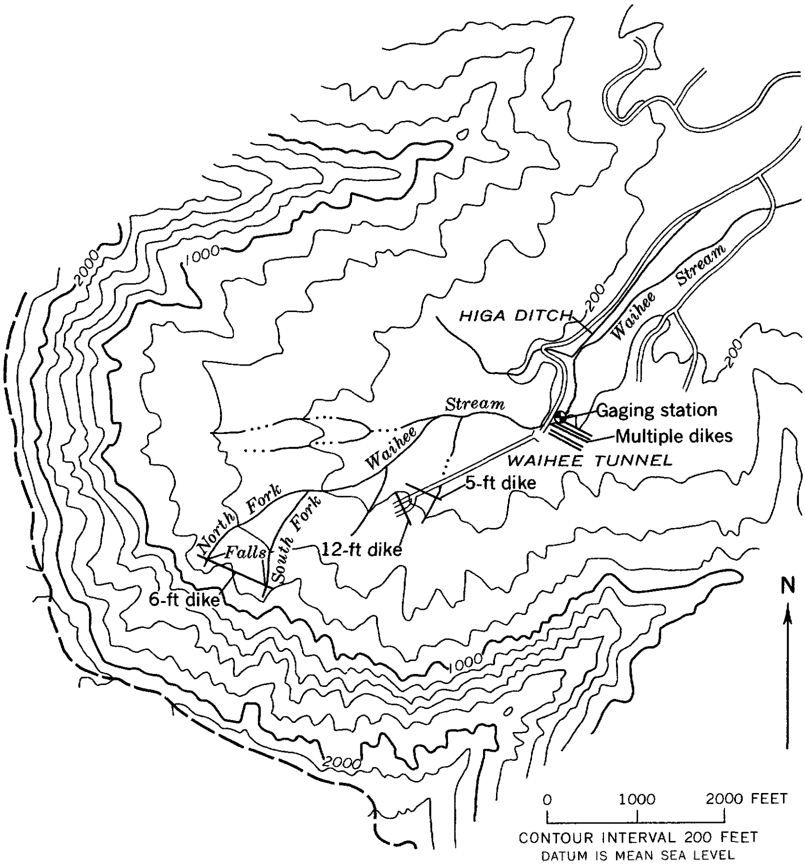

FIGURE 52.—Location of dikes, Waihee tunnel, Waihee Stream gaging station, and Higa ditch in the Waihee Valley.

able, such as those in a dike complex, the top declines to some level above the tunnel.

Estimated reduction of ground-water storage by construction of water-development tunnels is as follows:

Tunnel	*Million gallons*
Waiahole ditch (main bore)	16,000
Waikane 1	740
Waikane 2	2,290
Kahana	3,950
Uwau	1,250
Haiku	1,400
Kahaluu	170
Waihee [1]	2,200
Total	25,800

[1] Storage is controlled by a bulkhead and can be regulated.

DEVELOPMENT BY RESTORATION OF STORAGE

A significant part of the reduction of ground-water storage by tunneling can be restored by constructing bulkheads at the controlling dikes. Once storage is restored in full or in part, it can be manipulated at the bulkhead to regulate supply to meet demand variations. Bulkheads have been installed in several tunnels, but only the one in Waihee tunnel is effective in restoring water to its pretunnel level. Single bulkheads in other tunnels—Haiku, Luluku, and Kahaluu—were not constructed at dikes that originally stored the most water; hence, they are only partly effective in restoration of storage.

Dikes that control the most water can best be determined at the time of tunneling. If records of flow during tunneling are not available and storage is depleted, gain in flow between dikes should indicate the best sites for bulkheads.

Bulkheads are most effective in marginal dike zones, where single dikes generally control large quantities of stored water and where permeability contrast between lava flows and dikes is great. In a dike complex, permeability contrast is too small or dikes are too numerous for bulkheads to be effective. Bulkheads constructed in Uwau and Waikane 2 tunnels are examples. They were removed when they failed to restore water in significant quantities.

Regulation of storage with bulkheads serves two purposes: (1) restoration periods can be coordinated with periods of minimum water demand, and (2) when storage is at a maximum, tunnel flow can be increased to many times base-flow rate for short periods during maximum water demand. For example, base flow of the Waiahole ditch tunnel (main bore) is about 7 mgd, but flow from maximum storage, 16,000 million gallons, would approach 100 mgd. Average base flow of Waihee tunnel is 3.4 mgd, but initial flow at full storage would be about 19 mgd. Average base flow of Haiku tunnel is about 2 mgd, but initial flow at full storage would be about 12 mgd.

RELATION OF THE RECESSION CONSTANT *b* TO DISCHARGE AND STORAGE

The empirical equation $Q_t = Q_0 e^{-bt}$ gives a good approximation of the shape of the base-flow recession curve of tunnels and streams. The negative sign for the recession constant b indicates decreasing discharge with time. For the following discussion, a positive sign was used, indicating increasing discharge with time, and the general equation of the accretion curve may be written as

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$$Q_t = Q_0 e^{+bt}$$

where Q_0 = lower discharge at some initial time;
Q_t = higher discharge at the end of time t;
t = time, in days;
e = base of the Naperian logarithms;
b = accretion constant—equivalent to the recession constant.

Integrating the accretion curve,

$$\text{Storage } S = \int Q_0 e^{bt} dt,$$

$$S = \frac{Q_0 e^{bt}}{b} + C$$

or

where C is the integration constant.

As the expression $Q_t = Q_0 e^{bt}$ is the equation for an accretion curve, at the initial time ($t=0$), $S=0$. Substitution in the storage equation gives

$$0 = \frac{Q_0 e^0}{b} + C$$

$$0 = \frac{Q_0}{b} + C$$

and

$$C = -\frac{Q_0}{b}.$$

Hence,

$$\text{storage } S = \frac{Q_0 e^{bt}}{b} - \frac{Q_0}{b};$$

But

$$Q_0 e^{bt} = Q_t;$$

therefore, the equation becomes

$$S = \frac{Q_t}{b} - \frac{Q_0}{b}$$

or

$$Q_t = bS + Q_0.$$

This equation indicates a linear relation between discharge and storage that can be represented by a straight line on a rectilinear graph with a slope of b and an intercept of Q_0. Because it is a straight line, storage at any discharge or discharge at any storage can be determined.

The storage-discharge curves for Waihee and Haiku tunnels are shown in figure 53 and those for tunnels in the Waiahole ditch system in figure 54. The recession constants computed for these tunnels are also shown in figures 53 and 54 and on the location map on plate 2.

The recession curve is a measure of the drainage rate of groundwater storage. Its shape is a function governed by the constant b, which in turn is governed by the transmissivity of the rocks. Thus, by use of the computed values of b as a measure of transmissivity, selected areas of windward Oahu can be delineated as being promising or un-

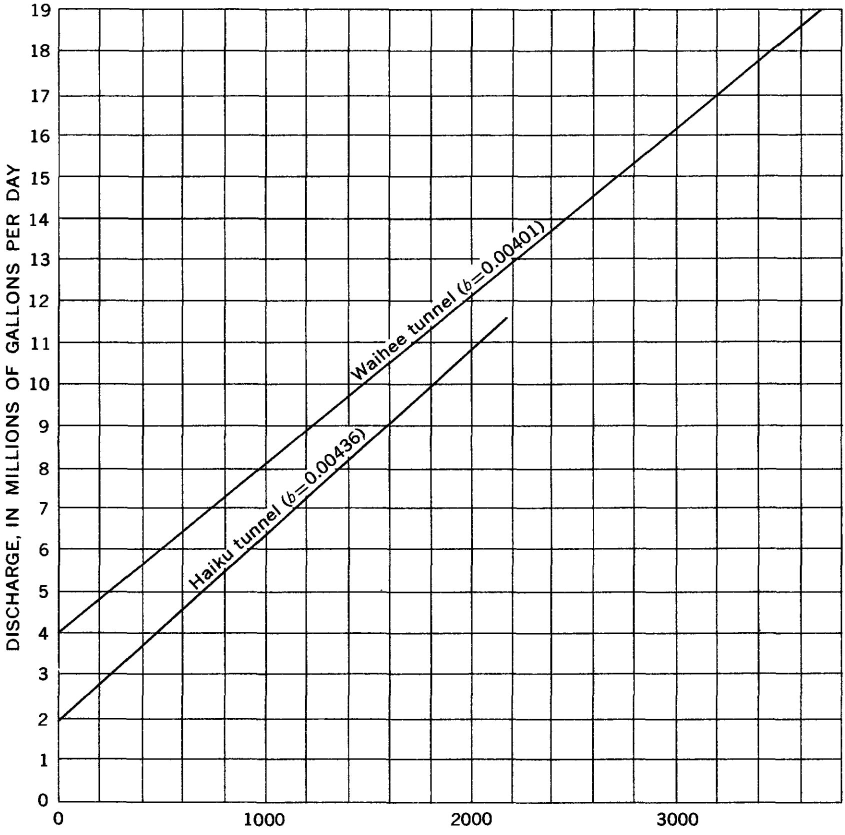

FIGURE 53.—Storage-discharge curves for Waihee and Haiku tunnels. *b*, recession constant.

promising for water development by tunnels. The preceding list shows that the values for the constant *b* are greater for tunnels in the marginal dike zone than they are for tunnels in the dike complex.

MUNICIPAL WATER SUPPLY

The Rural Water Works was created in 1927 under the Division of Water Supply and Sewers in the Public Works Department of the City and County of Honolulu. In 1940 it became the Suburban Water System, a separate division in the Public Works Department, and in January 1959 it was merged with the Honolulu Board of Water Supply. All municipal water-supply systems of Oahu are now operated by that board.

The Rural Water Works was created to put the water-supply systems on a firm financial basis. Improvements started with metering the water-supply system. Only Waimanalo had a water system in

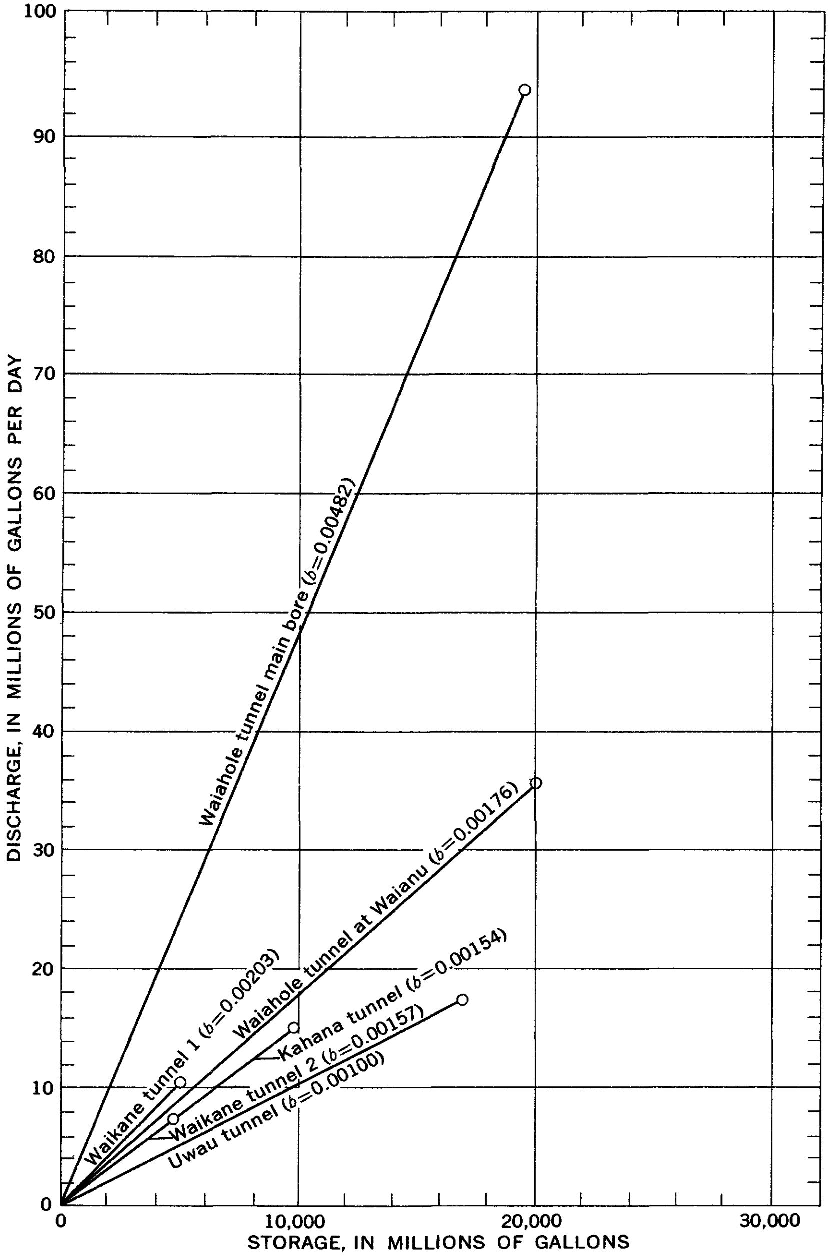

FIGURE 54.—Storage-discharge curves for tunnels in the Waiahole ditch system. *b*, recession constant.

windward Oahu before 1927, although during that year the Hauula system was put into operation and construction of the Kailua-Kaneohe system was begun. The Kaaawa system was put into operation in 1941.

By 1936 flow from Luluku Springs was barely able to supply enough water for the growing civilian and military population of the Kailua-

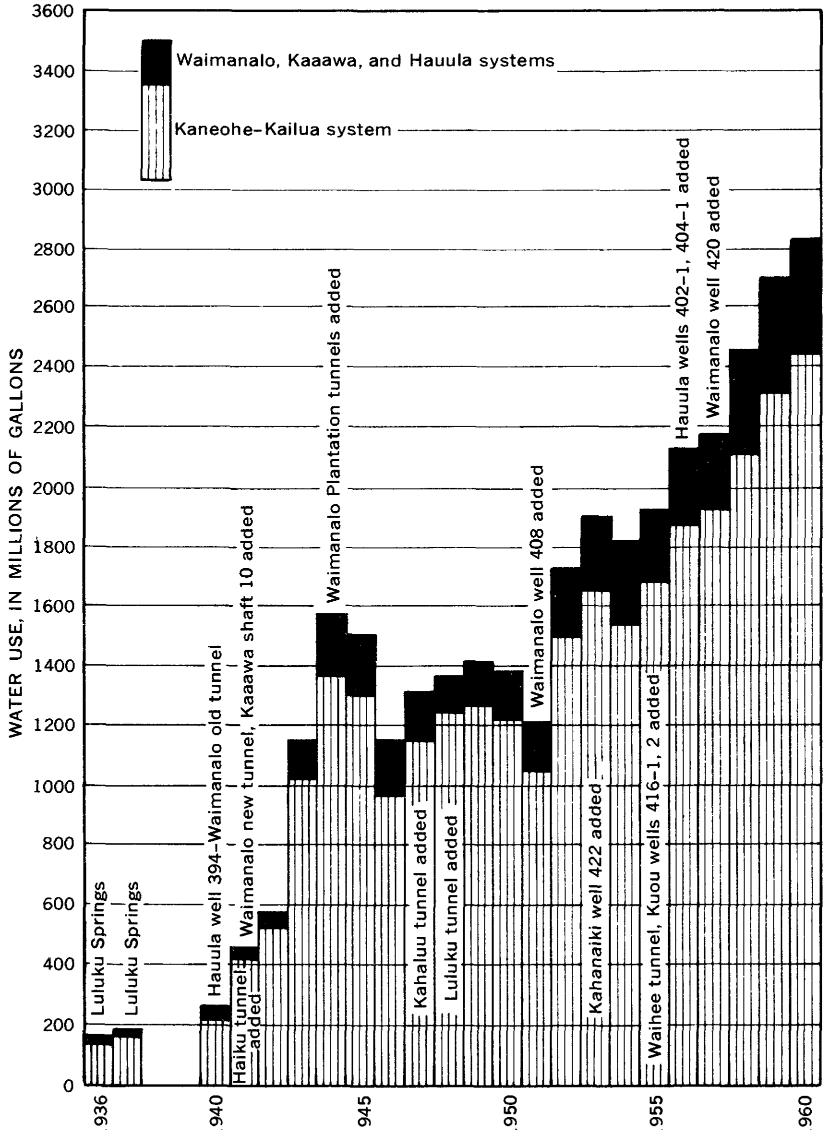

FIGURE 55.—Annual municipal water use since 1936. Data not available for 1938–39.

Kaneohe area; construction of the Haiku tunnel (1941) greatly relieved the water shortage. The annual municipal water use and the new sources of supply, as added since 1936, are shown in figure 55. The water sources now being used by the Honolulu Board of Water Supply are given in table 19.

TABLE 19.—*Municipal water-supply sources in windward Oahu*

Wells

Well	Location	Altitude (ft)	Diameter (in)	Depth (ft)	Draft, 1960 (mgd)	Added to system (yr)	Water system
394	Hauula	20			0.14	1927	Hauula.
402-1	Punaluu	7	12	305	.03	1956	Do.
404-1	do	6	12	163	.03	1956	Do.
408	Waimanalo	26	6	730	.01	1951	Waimanalo.
416-1	Kuou	270	16	418	(1)	1955	Kaneohe-Kailua.
416-2	do	287	16	280	.40	1955	Do.
420	Waimanalo	142	12	280	.12	1957	Waimanalo.
422	Kahanaiki	92	12	349	[2] .00	1953	Kaneohe-Kailua.
Shaft 10	Kaaawa	20	Shaft	17	.11	1941	Kaaawa.

Tunnels

Name	Location	Altitude (ft)	Length (ft)	Yield, 1960 (mgd)	Added to system (yr)	Water system
Plantation 1	Waimanalo	415	[3] 125	0.20	1944	Waimanalo.
Plantation 2	do	425	50	(4)	1944	Do.
Plantation 3	do	462	60	(4)	1944	Do.
C & C 1	do	462		(5)	<1927	Do.
C & C 2	do	620	449	.44	1941	Do.
Luluku	Luluku	530	481	.32	1948	Kaneohe-Kailua.
Haiku	Haiku	550	1,200	2.14	1941	Do.
Kahaluu	Kahaluu	585	393	2.89	1947	Do.
Waihee	Waihee	218	1,624	.91	1955	Do.

[1] Included with well 416-2.
[2] Emergency pump.
[3] Estimated.
[4] Included with plantation 1.
[5] Included with C & C 2.

OTHER WATER SYSTEMS

Data concerning State and private water systems are given in table 20. Their combined yield is approximately 1 mgd, and their storage capacity is 1.1 million gallons. Of this amount, 0.9 million gallons is in storage at State institutions, at Kaneohe and Kawailoa, where daily consumption is about 0.4 mgd.

The three largest private water systems are those of Waiahole, Waikane, and Waihee. They use about 0.6 mgd and have no storage facilities. The water is gravity fed through pipelines from springs and streams to homes at lower altitudes.

MAUNAWILI DITCH

Chinese farmers, in 1876, were the first to cultivate sugarcane in Waimanalo Valley. Water needs increased rapidly, and, by 1878, the first section of the Maunawili ditch transported irrigation water from upper Maunawili Valley into Waimanalo Valley. By 1900, the flume

TABLE 20.—*Other water systems in windward Oahu*

[Modified from year (1960)]

Location	System and owner	Source of water	Consumption (gpd)	User	Storage capacity (gal)
Waimanalo	Bellows Field; U.S. Army.	BWS, Kailua system; BWS, Waimanalo system	[1]67,000; 46,000		None
Maunawili	Koolau and Kawailoa Training Schools; State.	Api Spring, well 418	50,000	400 persons	300,000
Do	Kaimi Farm; Cooke Estate.	Cooke tunnel		5 families	10,000
Do	Castle Estate	Ainoni Springs		7 families	None
Kaneohe	State Hospital; State	Well 416	340,000	1,600 persons	600,000
Ahuimanu	Hygienic Dairy	Ahuimanu tunnel		Domestic and dairy.	10,000
Waihee	Higa	Springs	100,000	20 families	None
Waiahole	Waiahole; McCandless Estate.	Springs	500,000	60 families	None
Waikane	Waikane; McCandless Estate.	Uluwini Springs		15 families	None
Hakipuu	Kualoa Ranch	Hakipuu Stream		Livestock and irrigation.	100,000
Kahana	Foster Estate; Kahuku Plantation.	Well 405		Domestic	3,000
Punaluu	Board of Water Supply, Hauula system; Bishop Estate.	Well 404-1	[1]30,000	do	75,000

[1] Included in figure 55.

and ditch system was 4½ miles long and diverted all of Maunawili Stream water into Waimanalo Valley (pl. 1).

Between 1922 and 1926 the Clark, Cooke, and Korean tunnels were driven, and the Maunawili ditch system was extended. The Hawaii Water Authority took over the operation of the irrigation system in 1953.

The Maunawili ditch system delivers about 2 mgd of water to Waimanalo Valley. It extends from Omao Stream, at an altitude of 470 feet in Maunawili Valley, through a short tunnel under Aniani Nui Ridge, to an area above the University of Hawaii Experimental Farm in Waimanalo Valley, at an altitude of 100 feet.

WAIAHOLE DITCH TUNNEL SYSTEM

Ewa Plantation Co. drilled the first successful artesian well on Oahu in 1879 on a large tract of arid land at Honouliuli near Pearl Harbor. This well had a tremendous effect upon agriculture on Oahu, which had been concentrated on the windward side because of the availability of stream water. Sugarcane acreage on Oahu at that time was only about 2,600 acres. As artesian water became available, sugarcane acreage increased to about 18,000 acres, and most of it is on the leeward side of the range.

By 1911 the Oahu Sugar Co. was lifting water 420 feet from wells located near the coast to irrigate sugarcane. In a 1911 report to the board of directors of the company, J. B. Lippincott estimated that an average of 30 mgd could be diverted from windward streams for use on company land on the leeward side if a transmission tunnel were driven through the range. The report was favorably received, and construction of the Waiahole ditch tunnel system was begun in February 1913. Stearns (in Stearns and Vaksvik, 1935, p. 399–409) described the construction features and the geohydrology of the tunnel system.

Figure 8 is a plan view of the Waiahole ditch tunnel system showing the relative positions and density of the dikes mapped. The total thickness of dike rock and the total thickness of country rock are compared in table 2. Flow measurements in the Waiahole ditch tunnel system are given in table 21. A chronologic record of the tunneling is shown in table 22. The flow record of the tunnels, 1925–61, is shown in figure 56.

Uwau tunnel was extended 228 feet between July 5 and October 31, 1963. Records furnished by the Waiahole Water Co. show that the average yield of the tunnel between July 1964 and June 1966 was 15.6 mgd, or about 5 mgd greater than the yield prior to the extension.

TABLE 21.—*Measured flows in tunnels of the Waiahole ditch tunnel system*

Distance from portal (feet)	*Total tunnel inflow (mgd)*	
Main bore [1] (Feb. 4, 1957):		
0		8.98
1,413	8.98	
1,979	5.34	
3,040	3.49	
3,825	.58	
14,567	.58	
Tunnel A:		
0		0
1,015	0	
Tunnel B:		
0		0
Tunnel R:		
0		0
1,663	0	
Uwau (Sept. 1, 1959):		
0		11.40
500	11.40	
1,000	9.71	
1,500	8.66	
1,935	4.38	
2,195	2.64	
Waikane 2 (Oct. 15, 1959):		
0		0.94
40	.94	
500	.70	
1,000	.71	
1,500	.51	
2,000	.45	
2,215	.29	
Waikane 1 (Oct. 10, 1959):		
0		3.93
500	3.68	
1,000	3.64	
1,500	3.64	
2,000	3.21	
2,500	2.93	
3,000	2.12	
3,300	1.13	
Kahana (Sept 2, 1959):		
0		3.40
500	3.50	
1,000	2.42	
1,400	1.54	
1,700	1.12	
1,965	1.12	
		28.65

[1] Gradient of tunnel away from north portal and through Koolau Range. Inflow figures are quantities calculated if flow is reversed toward the north portal. Distances are odometer measurements.

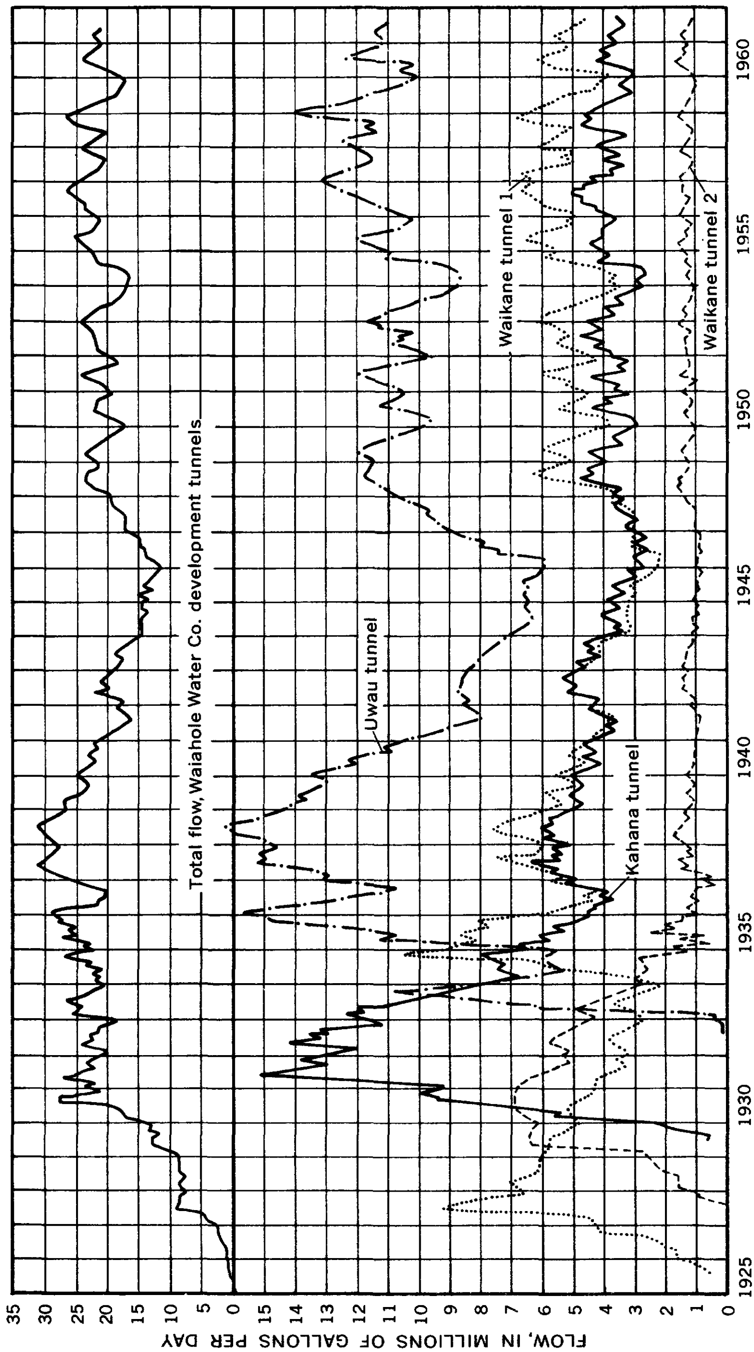

FIGURE 56.—Flows of development tunnels in the Waiahole ditch tunnel system.

TABLE 22.—*Chronological tunneling record of Waiahole ditch tunnel system*

Tunnel	Length of tunnel, in feet	Period of tunneling		Remarks
		From—	To—	
A	0–1,011	?	Jan. 15, 1915	Dry since April 1915.
B	0–1,260	?	May 1915	Dry from start, caved in.
Waikane 1	0–2,635	January 1925	May 9, 1927	
Waikane 1 extension	2,635–3,445	Nov. 13, 1933	Aug. 31, 1934	
Waikane 2	0–2,342	June 1927	Feb. 18, 1929	
Kahana	0–1,975	Apr. 26, 1929	Jan. 16, 1931	
Uwau	0–1,307	May 20, 1932	June 29, 1933	
Uwau extension	1,307–2,275	Nov. 19, 1934	Dec. 4, 1935	
Uwau extension	2,275–2,503	July 5, 1963	Oct. 31, 1963	

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