Water in the Kahuku Area, Oahu Hawaii

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1874

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

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CONTENTS

ILLUSTRATIONS

TABLES

WATER IN THE KAHUKU AREA, OAHU, HAWAII

By K. J. TAKASAKI and SANTOS VALENCIANO

ABSTRACT

The Kahuku area comprises the north end of the Koolau Range and its bordering coastal plain. This part of the range is less deeply eroded than other parts, and except for long, narrow valleys and cliffs near the shore, it has retained the general shape of the original volcanic dome. A 2½-mile-wide dike zone of parallel and subparallel dikes along the crest is the remnant of the fissure zone of eruption. Outcrops are mostly permeable lava flows of the Koolau Volcanic Series, which are intruded by dikes inside the dike zone and are free of dikes outside it. The lava flows constitute main aquifers, and water bodies in them are called dike water inside the dike zone and basal water outside it.

Dikes, because they are less permeable than the lava flows they intrude, impound ground water, thereby controlling its movement, discharge, and storage. The top of the dike-impounded water is at an altitude of at least 1,000 feet near the south end of the Kahuku area. Dike water is discharged as leakage, the amount of which fluctuates in response to changes in storage, as flow into streams, where they intersect saturated rock, and as underflow to the basal-water body.

Basal water occurs on either side of the dike zone, which forms both a structural and hydrologic boundary. It is artesian on the windward side wherever it underlies the coastal plain, and the altitude of water levels ranges from 7 to 22 feet. Leeward of the dike zone, basal water occurs only under water-table conditions because of the near absence of a coastal plain, and the altitude of water levels ranges from less than 1 foot to about 3 feet.

The quality of dike water is excellent except near the north end, where it is slightly contaminated by infiltration of irrigation water that contains as much as 1,200 mg/l (milligrams per liter) chloride. Irrigation water is also a source of contamination of the basal-water body. The major contaminant, however, is sea water, which underlies the basal-water body. In the Kahuku subarea—where pumpage from the basal-water body is greatest—sea-water contamination is a major concern. Natural contamination by encroaching sea water extends more than 2 miles inland in the Waimea-Kawela subarea and generally precludes development of large quantities of basal water.

At low altitudes where the perennial flow is small, all streams are intermittent except Kaluanui and Kamananui. Some streams are perennial in their upper reaches because of persistent rainfall, and some are perennial in their middle reaches owing to the discharge of dike water; however, most flows are small in the lower reaches because most of the flow has infiltrated into the ground-water reservoir. For these reasons, streamflow cannot be economically developed and is not a reliable source of water supply.

Average rainfall is about 240 mgd (million gallons per day). Of this amount, about 220 mgd is in the mountains. On the basis of a rainfall input of 220 mgd and estimates of stream runoff and evapotranspiration, ground-water flow is estimated to be 85 mgd, a figure which compares favorably with estimates based on analyses of pumping-test data. Of this amount, an average of 30 mgd is discharged by wells and the remaining 55 mgd is eventually discharged to the sea by underflow or to the atmosphere by evapotranspiration.

The most promising areas for developing basal water are in the Hauula and Laie subareas, where draft is low and ground-water flow is high. The Waimea-Kawela subarea is not promising owing to low ground-water flow even though draft is low. Least promising for development is in the Kahuku subarea where an overdeveloped condition prevails in which draft for sugarcane irrigation exceeds the ground-water flow. The development of dike water is promising in the Waimea-Kawela subarea where ground-water flow greatly exceeds the draft.

INTRODUCTION

PURPOSE AND SCOPE

Water is a major natural resource in the Kahuku area. Development of this part of northern Oahu into a major agricultural, recreational, and cultural area has depended wholly on the availability of water. The proper management of water and development of new supplies is necessary to further the economic and cultural growth of this area.

The importance of water and the need for basic information regarding it led to a series of studies by the U.S. Geological Survey in cooperation with the State of Hawaii, Division of Water and Land Development. The study of the Kahuku area (fig. 1) began in 1962.

Water supplies and geologic features that control availability of water are described in this report, and the extent of water development and areas that seem promising for future development are delineated. Hydrologic properties of rocks, their distribution, and their role in transporting water are also described, as are the flow characteristics of two gaged and several ungaged streams. Potential ground-water development in four subareas is estimated, and effects of present development and use of water on the chemical quality of water are discussed.

LOCATION AND EXTENT OF AREA

The area of study, 61 square miles, comprises the north end of the Koolau Range and its bordering coastal plain. That part east of the crest of the range is bounded by the valley of Kaluanui Stream, and that west of the crest is bounded by the valley of Waimea River (pl. 1). To facilitate study and discussion, the area was divided into four subareas, each composed of several drainage basins. The subareas, outlined on plate 1, are Hauula, Laie, Kahuku, and Waimea-Kawela.

DEVELOPMENT

The economy since the early 1880's has been based primarily on the cultivation of sugarcane. After the Second World War, however, recreational, cultural, and military-training activities became important, and in recent years a college, an experimental livestock farm, and several residential subdivisions have been established. In 1960, the population of the Kahuku area was about 6,400.

In 1968, when this report was in its final review and publication stages, the Kahuku Plantation Co. announced that the company was terminating its sugar operation in the Kahuku area at the end of 1971. Reduction in sugarcane acreage, about 4,400 acres in 1968, will probably begin sometime in 1970, and by the end of that year, the total cultivated area will be reduced about 50 percent; thus water use, likewise, will be reduced about 50 percent by the end of 1970. Water for the irrigation of sugarcane represents more than 90 percent of the water use in the Kahuku area in 1968. Therefore, unless some other crop replaces sugarcane, water use in the Kahuku area will be reduced by more than 90 percent by the end of 1971.

PREVIOUS INVESTIGATIONS

Records of flow of Kaipapau Stream in 1906–7 at an altitude of 1,900 feet and Kaluanui Stream at altitudes of 1,900 and 2,500 feet

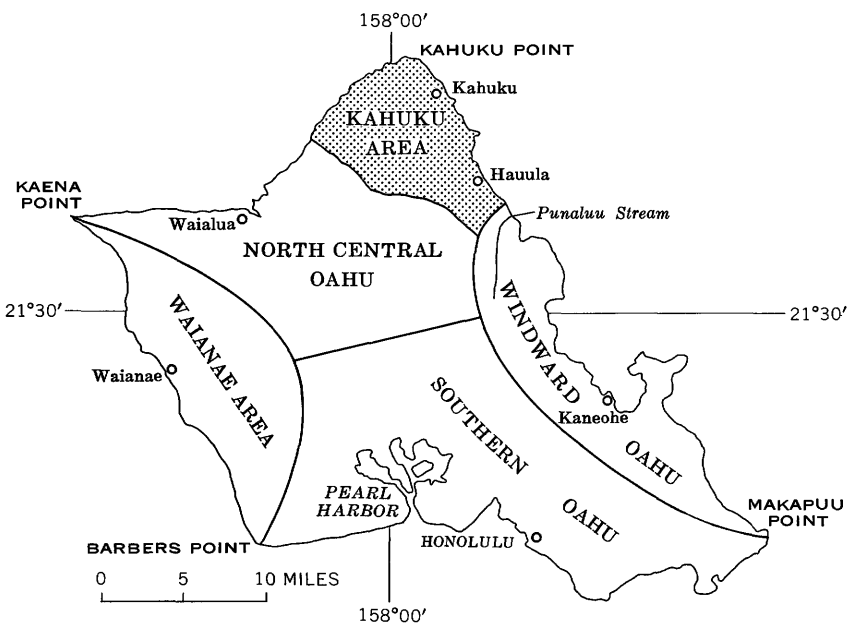

FIGURE 1.—Location of the Kahuku area and other areas of water study.

were first published by the U.S. Geological Survey (Martin and Pierce, 1913). From 1915 to 1918 gaging stations were operated by the Geological Survey on the east and middle branches of Malaekahana (sta. 3090 and 3100), the east branch of Kahawainui (3080), Wailele (3070), and Koloa Streams (3060). Records of the flow of those streams were published annually by the Geological Survey and by the Honolulu Sewer and Water Commission (Kunesh, 1929). Locations of the gaging stations are shown on plate 1.

The Kahuku area has been included in surveys of the geology and ground-water resources of Oahu (Stearns and Vaksvik, 1935, 1938; Stearns, 1939; Stearns and Macdonald, 1940). Results of several ground-water studies by Doak C. Cox from 1945 to 1959 are given in unpublished reports to the Kahuku Plantation Co. Harold S. Palmer, in 1957 and 1958, described the general occurrence of ground water in two unpublished reports prepared for the Honolulu Board of Water Supply. Chester K. Wentworth, in 1963, outlined a general water-development plan in an unpublished report to the trustees of the James Campbell Estate. The Kahuku area was included in a planning report compiled by the Honolulu Board of Water Supply (1963); this report described the general occurrence of water in Oahu and outlined plans for future development.

ACKNOWLEDGMENTS

The writers express their appreciation to the Kahuku Plantation Co. and the Board of Water Supply, City and County of Honolulu, for their generous assistance and cooperation. Special thanks are given Doak C. Cox, who made the results of his work available.

GEOLOGY

The Kahuku area includes the northern part of the Koolau Range and its bordering coastal plain. This part of the range is less deeply eroded than the other parts, and except for long, narrow valleys and cliffs near the shore, it has retained the general shape of the volcanic dome at its greatest stage of growth. That shape before sculpture by erosion can be reasonably inferred by a map on which contour lines are projected and smoothed across the least eroded and most projecting of the volcanic spurs. Such a map is shown in figure 2.

The coastal plain occupies most of the area between the shore and the steep wave-cut cliffs. It is widest, 1½ miles, at the north end, where it mainly consists of extensive marshes. Isolated calcareous dunes, conspicuous in a flat terrain, also occupy this part of the coastal plain. Although the plain constitutes only a small part of the Kahuku area, it includes more than half the agricultural land, and most of the population lives on it. A view of part of the plain is shown in figure 3.

VOLCANIC ACTIVITY

The geologic history and rocks of Oahu were discussed in considerable detail by Stearns and Vaksvik (1935), Stearns (1939), and Stearns and Macdonald (1940). The island was depicted as developing from the coalescence of two shield volcanoes—Waianae on the west and Koolau on the east. Waianae volcano became dormant first and was deeply eroded before lava from Koolau volcano overlapped its eroded east slope.

The Kahuku area includes about a third of the Koolau dome. In the buildup of the dome, lava flowed seaward to the flanks in a direction generally at right angles to the fissures. Magma approached or reached the surface through fissures in previous flows, where it cooled and solidified into dikes as activity ceased. The zone of fissures is about 2½ miles wide and 10 miles long and is mapped as the dike zone in figure 4. The Koolau caldera is probably centered near Kaneohe, south of the Kahuku area (fig. 1).

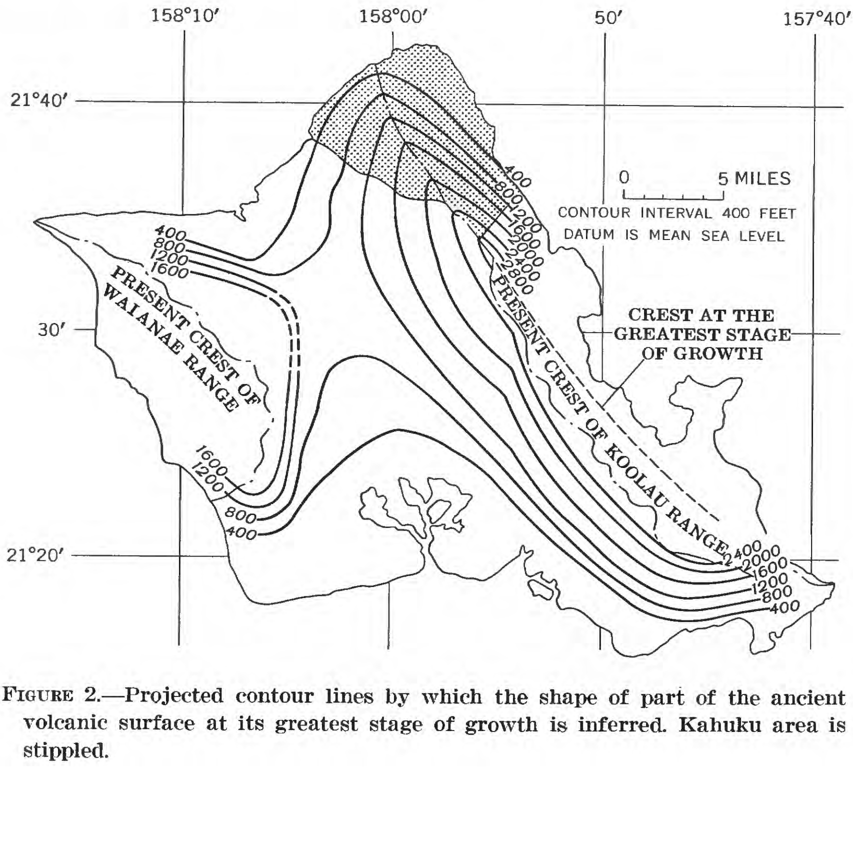

Figure 2.—Projected contour lines by which the shape of part of the ancient volcanic surface at its greatest stage of growth is inferred. Kahuku area is stippled.

FIGURE 3.—Northeastern part of Kahuku area. View is toward the southeast. Town of Kahuku in foreground. (Photograph, courtesy of Camera Hawaii, Inc.)

AREAL DISTRIBUTION OF ROCKS

Basaltic lava of the Koolau Volcanic Series forms the bulk of the Koolau Range. Talus and alluvium underlie the lower reaches of valleys, and interbedded marine and terrestrial materials form a wedge along the shore.

The top of the coral limestone has been mapped by Stearns (1939) at an altitude of 80 feet. Information from drillers' logs indicates that the coastal-plain sedimentary material extends at least 200 feet below sea level at the shore near the north end of the study area.

Conspicuous consolidated sand dunes on the coastal plain near Kahuku and Laie are remnants of deposits of calcareous sand once continuous along the entire northeastern coast. The sand dunes near Laie reach an altitude of 280 feet, and their maximum thickness is about 125 feet (Stearns and Vaksvik, 1935, p. 169).

Distribution of the principal rock units is shown in the generalized geologic map (fig. 4).

WATER-BEARING PROPERTIES OF ROCKS

LAVA FLOWS OF THE KOOLAU VOLCANIC SERIES

The permeability of lava flows of the Koolau Volcanic Series is generally high. Tests of this aquifer throughout Oahu indicate an apparent increase in permeability with distance from the dike zone. The aquifer leeward of the crest is generally two to three times more permeable than that windward of the crest. Leeward wells are more than 6 miles from the center of the dike zone, and windward wells are generally less than 3 miles from it.

Average dip of flows on the windward flank of the crest is about 10°, and that of the flows on the leeward flank is about 5°. Lava flows have an apparent dip of about 8° N. in the spur of the dike zone that extends seaward at the north end of the range. Individual flows are generally more than 10 feet thick in and near the dike zone. In contrast, flows less than 10 feet thick predominate on the flanks.

Structural features associated with lava flows determine permeability. Features that contribute most to high permeability are clinker sections associated with aa flows, voids between flow surfaces, and shrinkage joints and fractures. Thin-bedded aa flank flows have the highest proportion of these features and are most permeable, whereas thick, massive flows have the lowest proportion and are least permeable. Except where flows have ponded, permeability generally increases with distance from the dike zone. Permeability is highest parallel to the lava's flow direction, where interflow voids and clinker sections

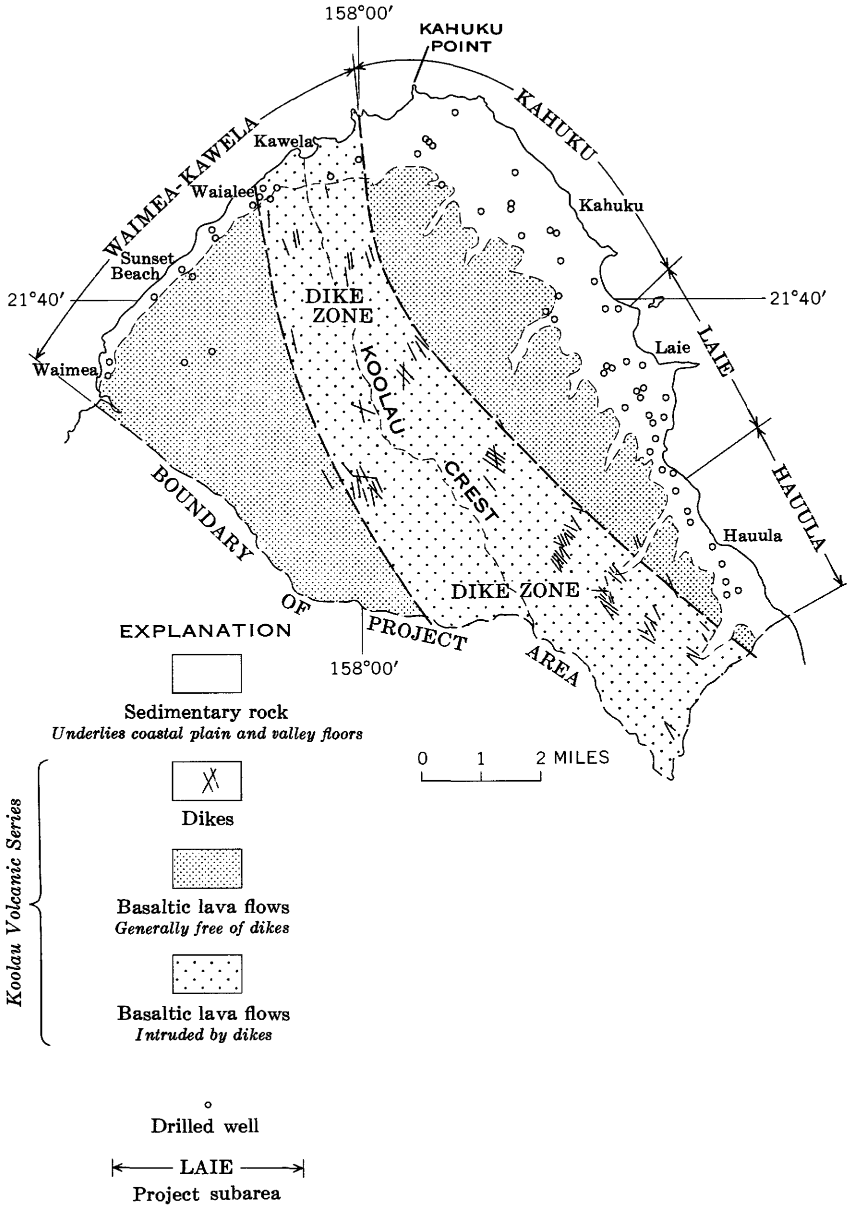

FIGURE 4.—Generalized geologic map of the Kahuku area. Sedimentary rock and part of the dikes from Stearns (1939).

are most continuous, and lowest vertically through flows, where permeability is dependent on shrinkage joints and fractures.

Permeability of flows is reduced by dikes, which retard the flow of water at right angles to their strike. Retardation increases with increasing number of dikes, and where dikes are numerous and crisscross, water movement is restricted in all directions; in such areas, permeability depends on fractures and breaks in the dikes. A single dike or a few scattered dikes can lower the high permeability of thin-bedded flows considerably by cutting across the flows, as shown in figure 5. In figure 5, block *A* represents a section of thin-bedded flows that are highest in permeability parallel to the flow direction, as shown by the length of the arrow; block *B* represents a comparable section in which permeability has been considerably reduced by intrusion of dikes at right angles to flow direction.

Permeability, greatest in fresh dike-free flank flows, is generally reduced considerably by weathering, which decreases the size of voids and fractures. The reduction of permeability in basaltic rocks is usually proportional to the degree of weathering. Weathering is mostly confined to near-surface rocks and is rare at a depth of more than 100 feet outside of valleys. Deep weathering is generally confined to valley floors, where poorly permeable weathered rocks at depths of 200 feet or more are common.

SEDIMENTARY MATERIAL

Most sedimentary material is in the coastal plain, except for isolated deposits of alluvium and talus in the middle and lower reaches of stream valleys. Water-bearing properties of this sedimentary material range from near impermeability in compact alluvium to high permeability in unconsolidated talus.

The coastal plain includes most of the area between the shore and the base of steep wave-cut cliffs. It is well developed along the north and east coasts but is poorly developed along the west coast from Waialee to Waimea Bay. The sedimentary material underlying the plain is thickest at the shore and thins inland. It is composed mostly of coralline limestone, consolidated and unconsolidated dune sand, and calcareous beach deposits interbedded with alluvium. The bulk lies below sea level and is saturated with water ranging from fresh to saline in character. The isolated deposits of alluvium and talus are generally above the water table.

Textures differ widely, ranging from nearly impermeable clay to highly permeable calcareous beach sand; thus water-bearing properties are variable, too. The sedimentary material and weathered lava constitute a mass of rock that is less permeable than the underlying

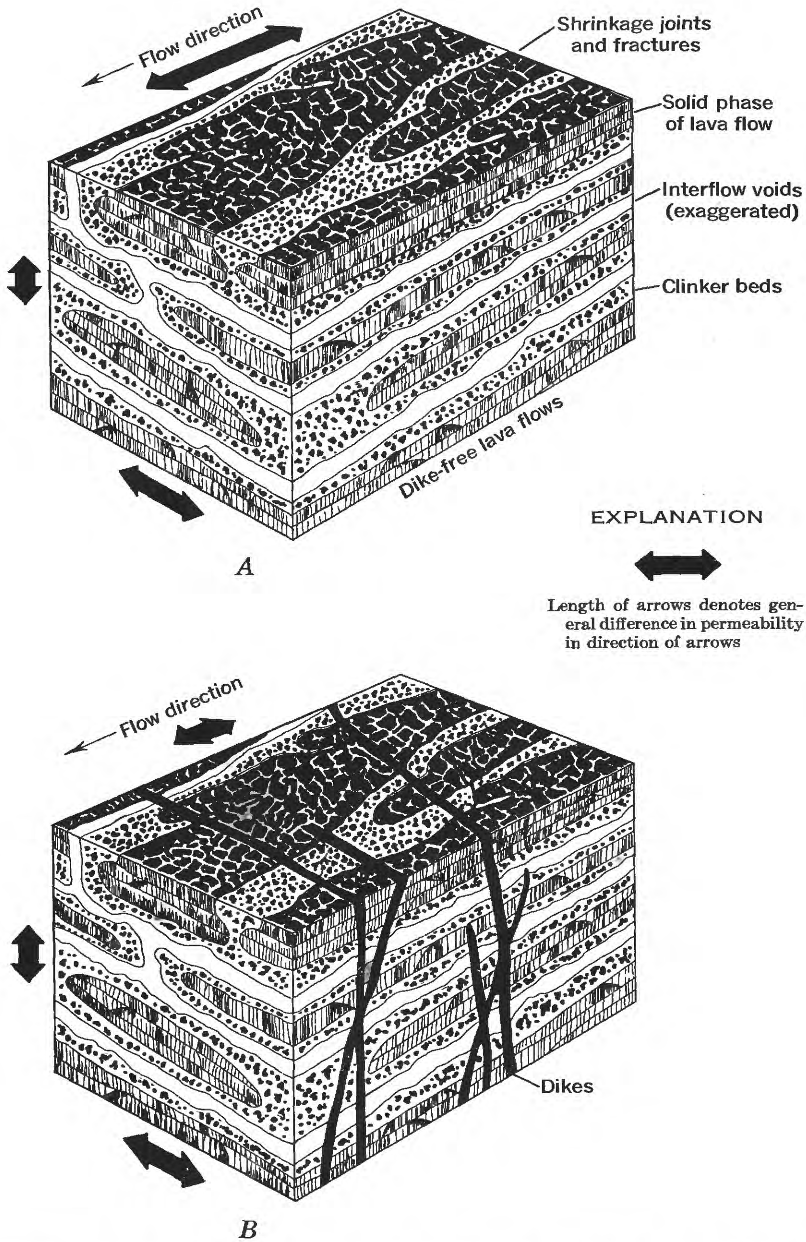

FIGURE 5.—Structural features associated with lava flows (A) in which highest permeability is in the flow direction and (B) in which permeability is significantly lowered by dikes intruded at right angles to the flow direction.

fresh lava. Wherever this rock mass, locally known as caprock, overlies fresh lava, artesian conditions prevail in the fresh lava; however, permeability of the caprock does not prevent water from leaking upward into permeable zones within the caprock itself. The permeable zones include deposits of coralline limestone and coral rubble.

CLIMATE

The climate is mild and is generally uniform throughout the year. The mean annual temperature and rainfall near the town of Kahuku are 74.9° F and 38.8 inches, respectively, and studies by Blumenstock (1961) indicate a mean annual wind speed slightly in excess of 10 miles per hour and a mean annual relative humidity of about 70 percent. Mean monthly temperature, rainfall, solar radiation, and pan evaporation at station 912 near the town of Kahuku are shown in figure 6. In general, rainfall and humidity increase from sea level to the crest of the range, and temperature, solar radiation, and potential evaporation decrease.

The highest rainfall on Oahu, slightly more than 300 inches per year (mean annual), occurs near the crest of the Koolau Range in the southeastern part of the Kahuku area (fig. 7). Most of the rain results from rapid cooling of warm, moist trade-wind air as it is orographically lifted. Trade-wind rainfall is heaviest near the crest and decreases rapidly downslope; it occurs throughout the year, but is most frequent in summer, when trade winds are strongest. Occasional frontal rainfall is generally more uniformly distributed areally and provides most of the rain that falls in coastal areas.

Figure 8 shows the distribution of mean monthly rainfall at five gages located in an area where mean annual rainfall for the period 1931–60 ranges from 40 inches on the coast to 250 inches in the mountains.

Planimeter measurements of areas on the rainfall map (fig. 7) suggests that rainfall in the area is 273,000 acre-feet per year, equivalent to 243 mgd (million gallons per day). Water development is entirely from ground-water sources. Streamflow is not used because perennial flow is small at altitudes suitable for economical diversion. Thus, as the development of and the need for information on ground water is preeminent, most of the study was directed toward an evaluation of the ground water.

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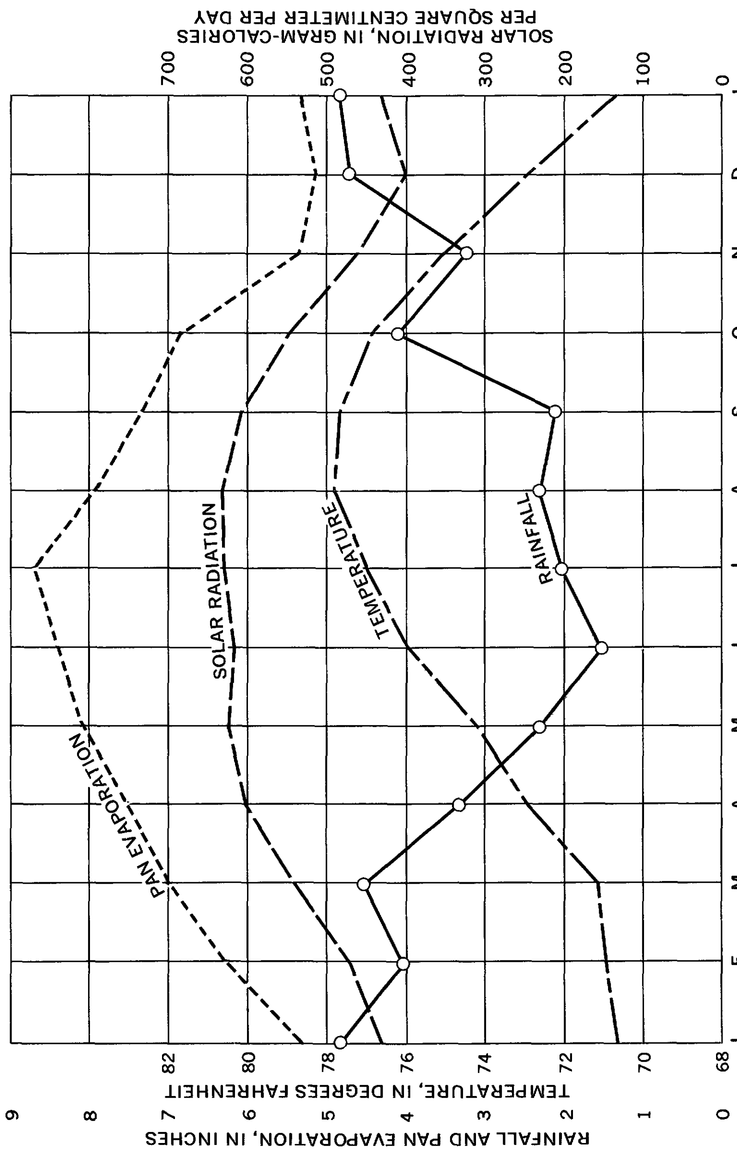

FIGURE 6.—Mean monthly rainfall, temperature, solar radiation, and pan evaporation at station 912 near the town of Kahuku. Rainfall and temperature data from U.S. Weather Bureau; solar radiation and pan evaporation data from Hawaiian Sugar Planters' Association.

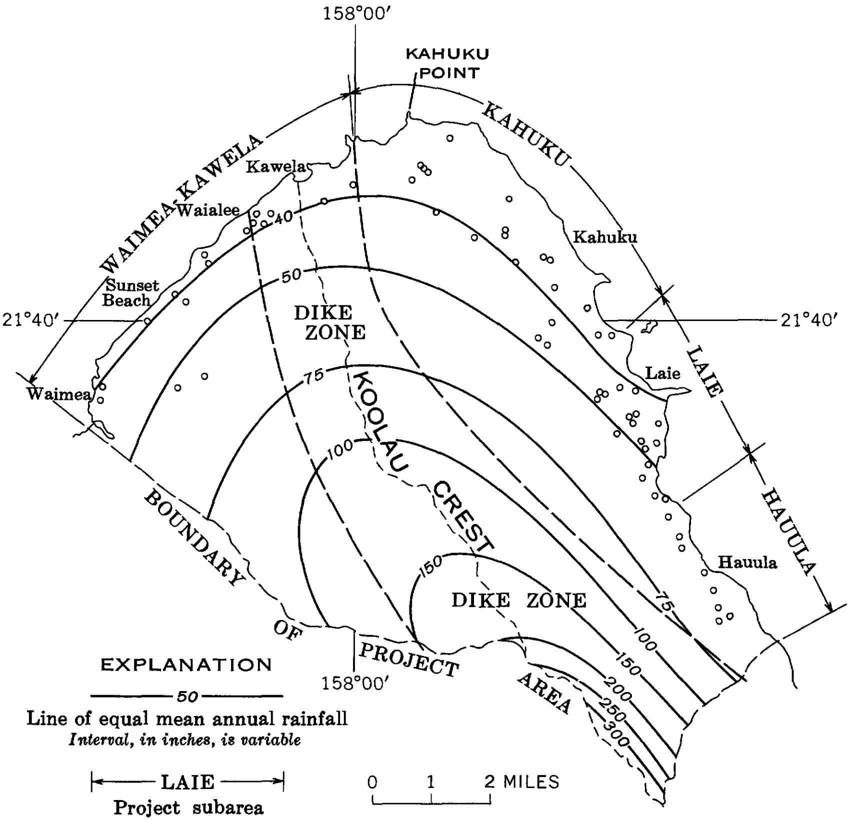

FIGURE 7.—Distribution of mean annual rainfall. Rainfall data furnished by the Honolulu Board of Water Supply, 1963.

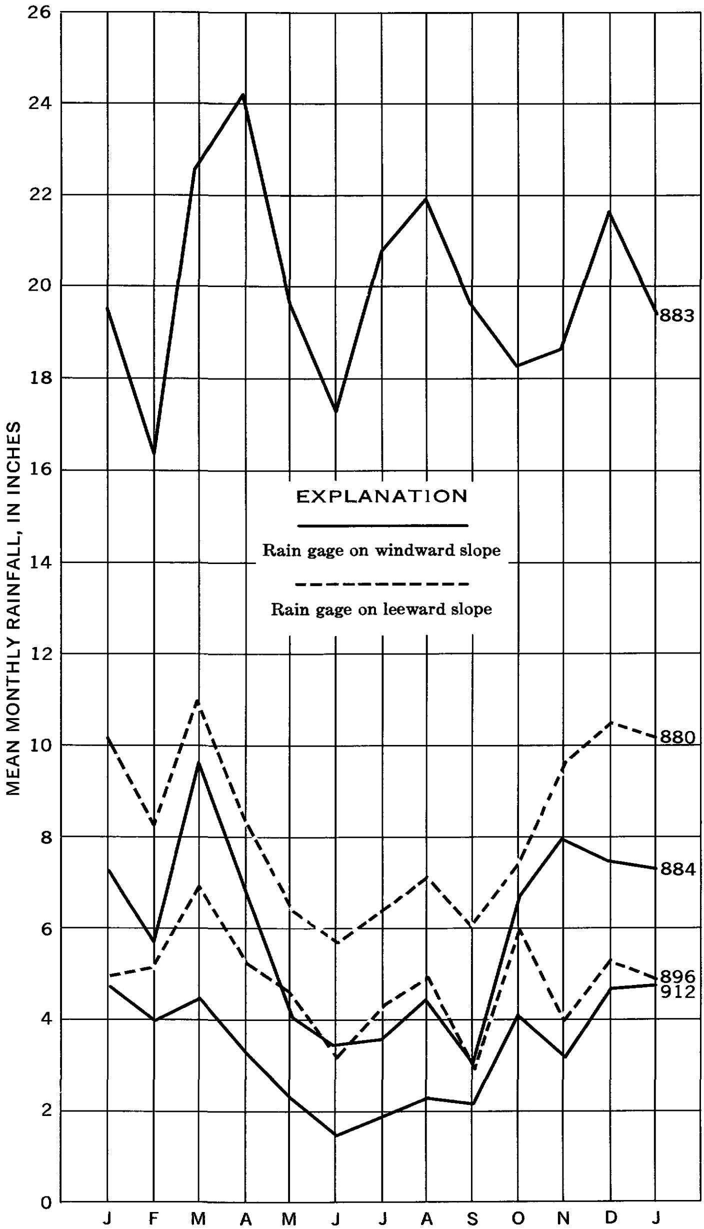

FIGURE 8.—Mean monthly rainfall at five gages in and near the Kahuku area.

WATER RESOURCES

STREAMS

STREAMFLOW CHARACTERISTICS

Streamflow is little developed because it is small and unevenly distributed both in time and place. All streams except Kaluanui and Kamananui are intermittent at low altitudes. Streams heading high in the range are perennial in their upper reaches because of persistent rainfall, and some are fed in their middle reaches by a small but perennial discharge of dike water; however, most of the perennial flow infiltrates outside the dike zone or even within that zone where near-surface rock is unsaturated. Streamflow depends primarily on rainfall and where that varies widely, as in the Kahuku area, streamflow also varies widely.

The streams have steep gradients, meander sharply, and mainly flow in bedrock. They are typical of streams in Hawaii that drain only slightly eroded and weathered volcanic terrane. Streams that drain much weathered and eroded volcanic terrane are less steep and are generally straighter. The sharp meandering of streams in young volcanic terrane probably results from initial channeling by natural depressions in and between lava flows. The resultant meander patterns are maintained until deep weathering causes the lava flows to become less resistant to stream erosion, at which time the streams begin to straighten their course.

RECORDS AVAILABLE

Gages in operation in 1966 were on Kamananui Stream (3250 and 3300) and on Malaekahana Stream (3089.9). In addition, three crest-stage stations (3045, 3105.01, and 3110) have been maintained since 1957. Continuous streamflow records are available for the east and middle branches of Malaekahana (3090 and 3100), the east branch of Kahawainui (3080), Wailele (3070), Koloa (3060), and Kaluanui (3040) Streams for the period 1915–18. To provide a better geographical sampling, miscellaneous streamflow measurements were made on several other streams during the present study. The location of gaging stations, crest-stage gage stations, and miscellaneous measurement sites are shown on plate 1.

FLOW-DURATION CURVES

Flow characteristics of a stream throughout its range of daily discharge can be shown by a flow-duration curve. The curve is a cumulative frequency curve and shows the percentage of time specified discharges were equaled or exceeded during a given period. The shape of the flow-duration curve reflects the hydrologic and geologic characteristics of the drainage basin, and the slope of the curve is a measure of the variability of streamflow. Slopes of flow-duration curves are flatter at the lower ends for streams that have well-sustained flow in dry weather than for streams that do not.

Flow-duration curves for stations 3250 and 3300 on Kamananui Stream are shown in figure 9. The 1959–65 curve for station 3250 is based on a composite record made up of 2 years of observed daily discharges and 5 years of daily discharges estimated on the basis of records at station 3300. Curves for short-term gaging stations on Kaluanui (3040) and Malaekahana Streams (3089.9) are shown in figures 10 and 11, respectively. A flow-duration curve for Punaluu Stream (sta. 3030) which is outside the study area, is shown in figure 12. Punaluu Stream is included because dike water originating in the study area contributes to its base flow, and some water is diverted from it for irrigation within the study area. Data on daily flows of other streams, where records are available, are given in table 1.

LOW-FLOW FREQUENCY CURVES

A low-flow frequency curve shows the recurrence interval, in years, at which the annual minimum mean flow for a selected number of consecutive days may be as low as a specified discharge. Low-flow frequency data for Kamananui Stream (3300) are shown as a family of curves in figure 13. The stream has been dry for periods as long as 23 days. Table 2 shows the lowest mean discharges for periods of 14, 30, 60, and 120 consecutive days for Kamananui Stream (3250) at an altitude of 590 feet based on relations to data for Kamananui Stream (3300) at an altitude of 20 feet. The recurrence intervals in years in table 2 are averages and do not imply any regularity of occurrence.

FLOODS

During the short period of available record, floods were most prevalent in March, but occurred in all months. Floods are characterized by sharp peaks of short duration. The relation between rainfall and runoff on Kamananui Stream (3250) during the flood of February 4, 1965, is shown in figure 14.

The largest flood recorded during 1958–66 occurred on April 15, 1963, at the crest-gage site on Malaekahana Stream (3105.01). Peak discharge was 3,000 mgd, and discharge per square mile of drainage area was 740 mgd. For comparison, peak flow of Kamananui Stream (3300) during the same day was 2,230 mgd, or 228 mgd per square mile of drainage area.

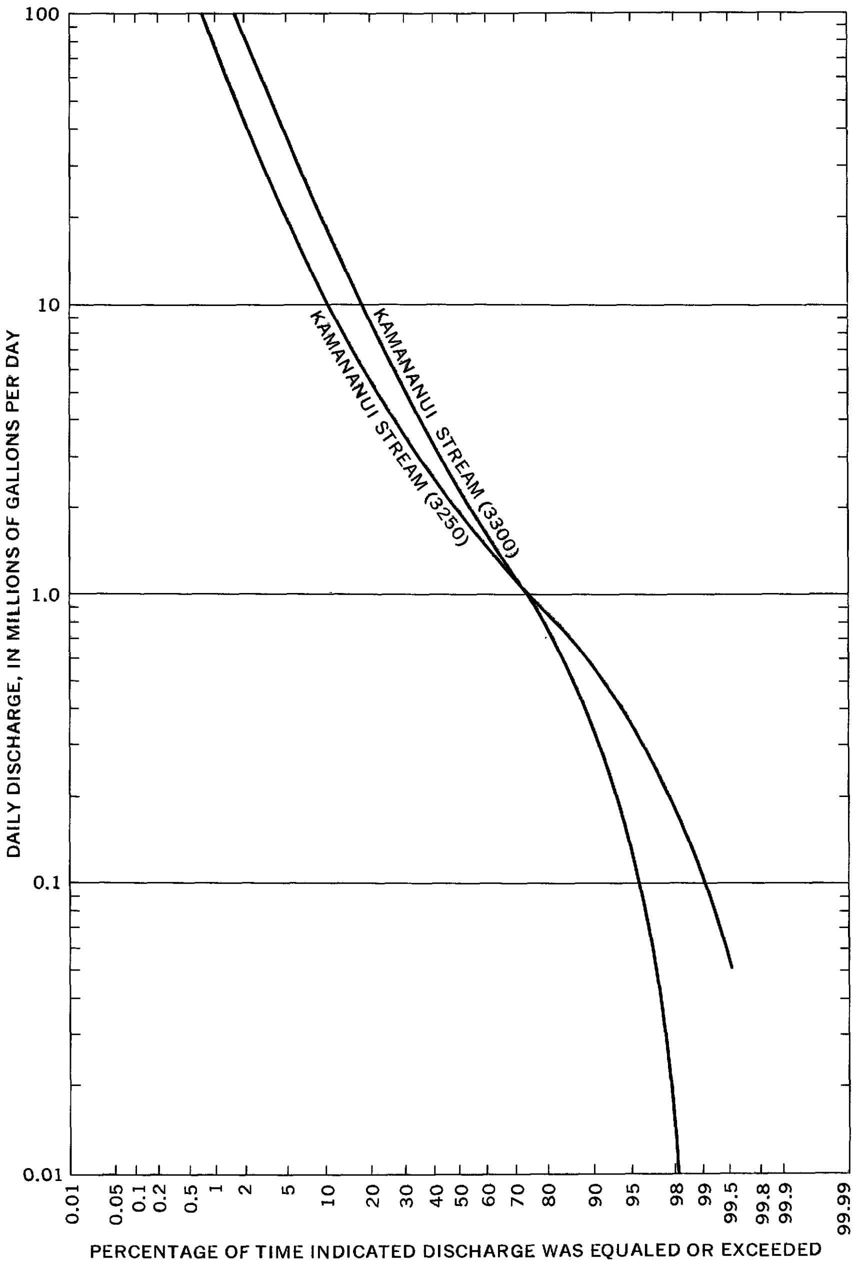

FIGURE 9.—Flow-duration curves of daily flows for Kamananui Stream (sta. 3300 and 3250), 1959–65.

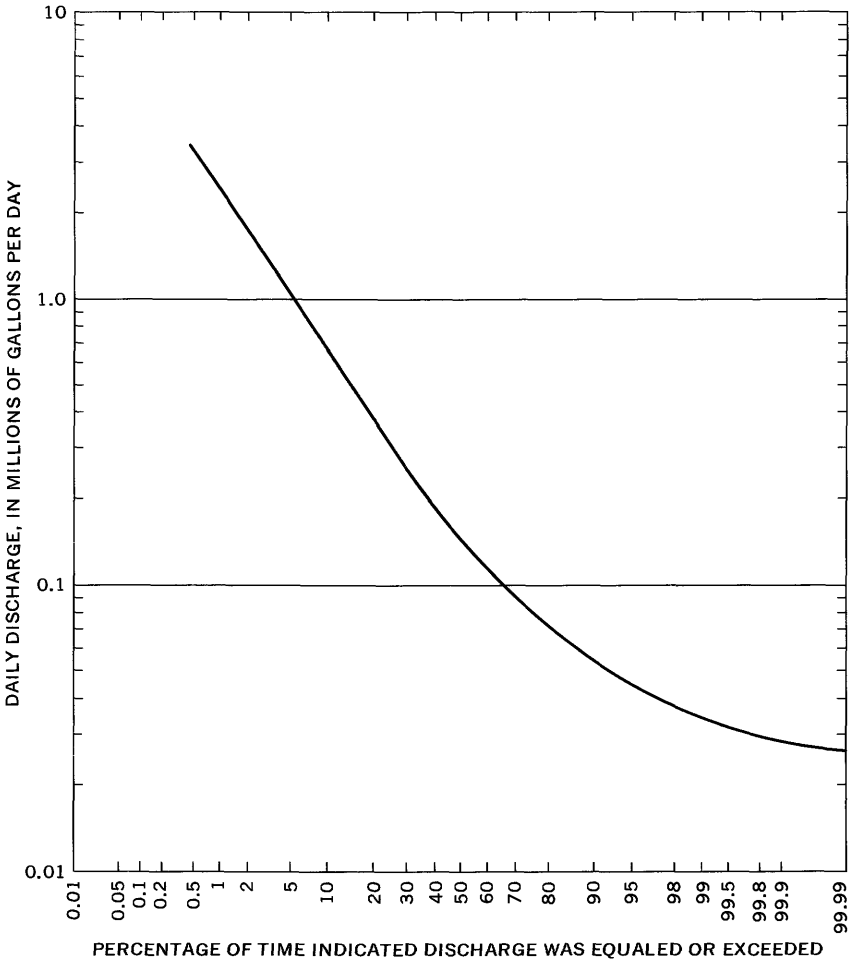

FIGURE 10.—Flow-duration curve of daily flows for Kaluanui Stream (sta. 3040), 1916–17.

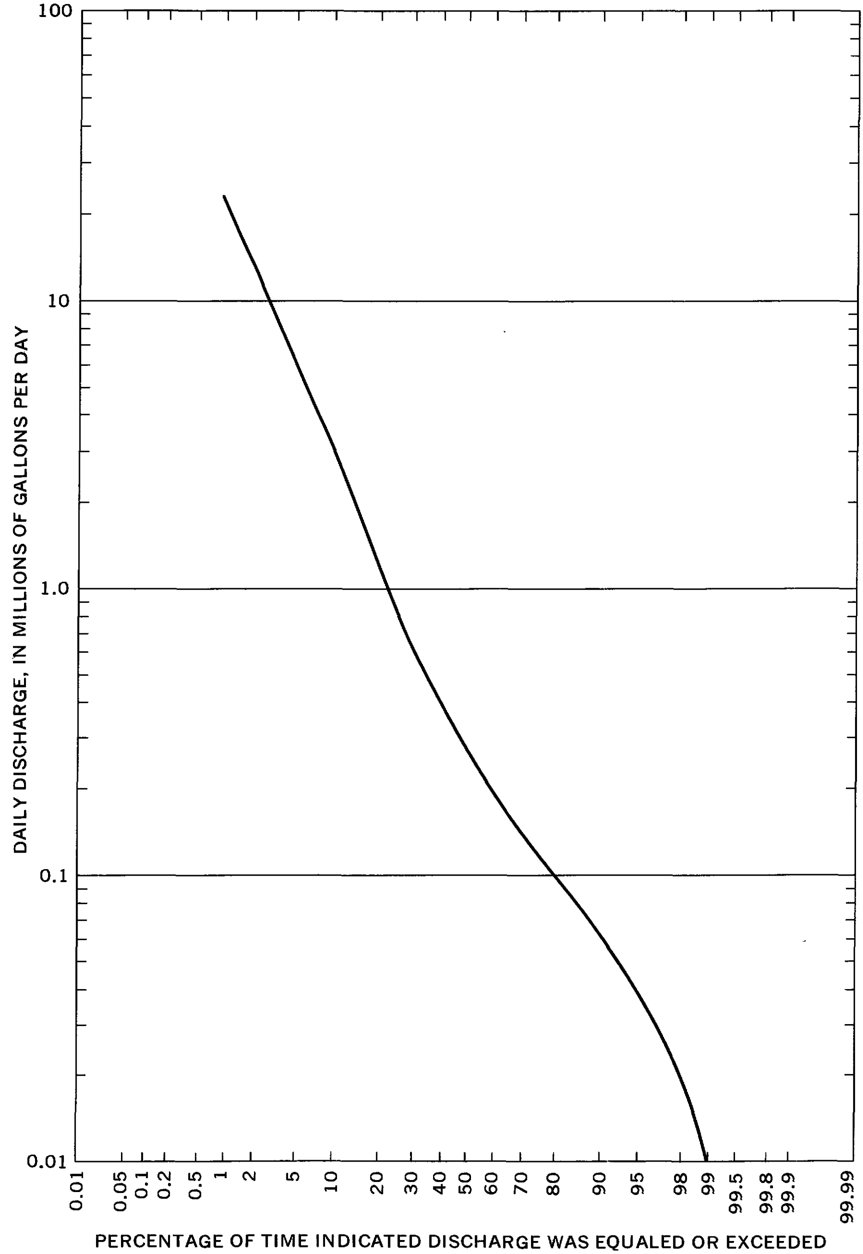

FIGURE 11.—Flow-duration curve of daily flows for Malaekahana Stream (sta. 3089.9), 1964–65.

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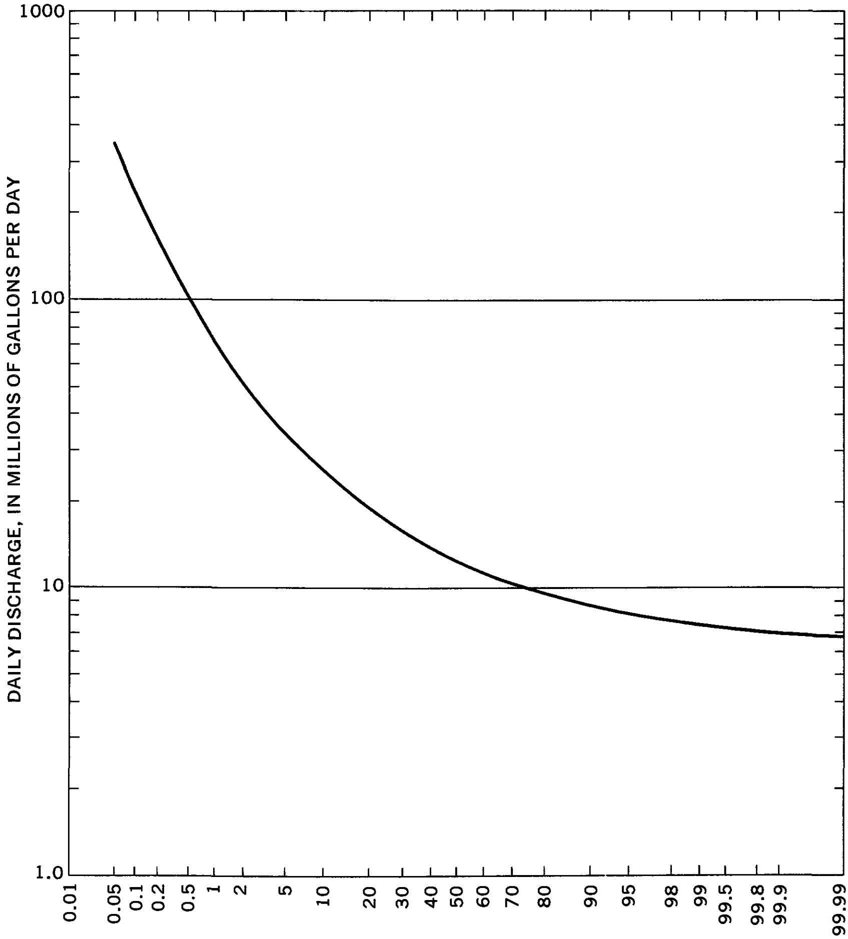

FIGURE 12.—Flow-duration curve of daily flows for Punaluu Stream (sta. 3030), 1954–65.

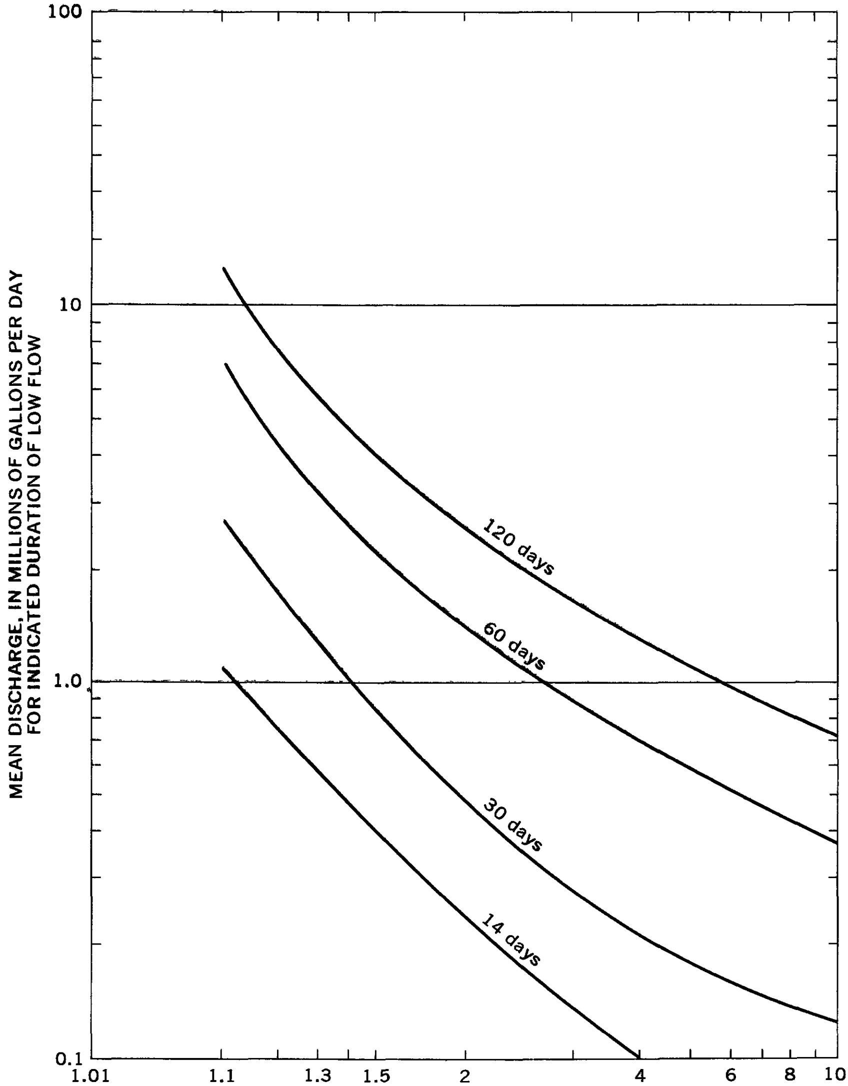

FIGURE 13.—Low-flow frequency curves for Kamananui Stream (sta. 3300) computed from the period of record, July 1959 to June 1965.

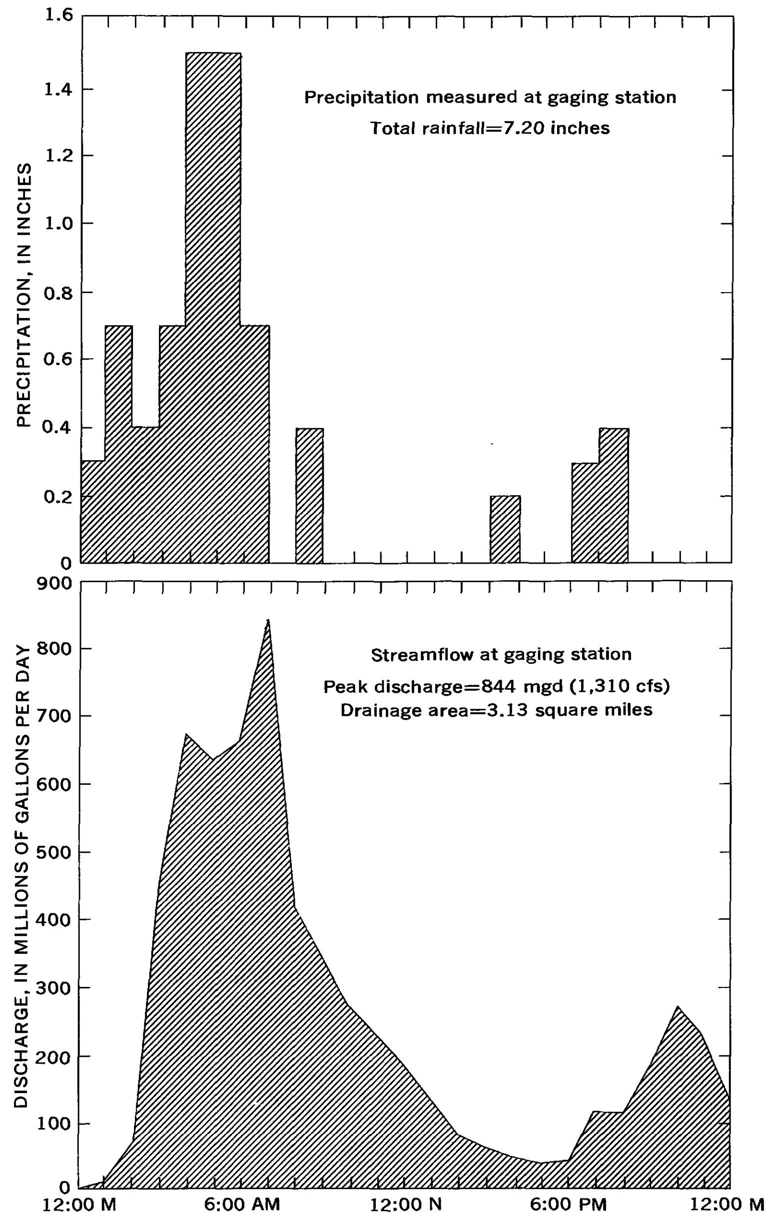

FIGURE 14.—Relation between runoff and precipitation at the Kamananui Stream gaging station (3250), February 4, 1965.

TABLE 1.—*Duration of flow at gaging stations, 1915–18*

[Periods of missing records for stations listed were estimated on the basis of hydrographic comparison with daily discharge of North Fork Kaukonahua Stream above Right Branch (2000)]

Station	Stream	Drainage area (sq mi)	Flow, in million gallons per day, which was equaled or exceeded for indicated percentage of time																
			99.5	99	98	95	90	80	70	60	50	40	30	20	10	5	2	1	0.5
3060	Koloa Gulch	≈0.9	0.07	0.10	0.13	0.20	0.30	0.49	0.60	0.94	1.3	1.7	2.4	3.6	6.9	13	25	38	58
3070	Wailele Gulch	≈.5				.05	.10	.21	.33	.48	.68	.92	1.3	1.9	3.5	6.0	12	20	30
3080	East Branch Kahawainui Stream	.53						.01	.04	.10	.19	.32	.54	.92	2.1	4.5	10	17	26
3090	East Branch Malaekahana Stream	1.66						.01	.07	.14	.25	.40	.70	1.2	2.6	5.0	10	16	27
3100	Middle Branch Malaekahana Stream	.69										.01	.04	.36	1.2	2.8	6.1	10	15

TABLE 2.—*Magnitude and frequency of annual low flow in Kamananui Stream (3250), 1959–65*

Period (consecutive days)	Annual low flow, in million gallons per day, for indicated recurrence intervals, in years						
	1.1	1.5	2	3	5	8	10
14	0.86	0.72	0.52	0.29	0.17	0.12	0.10
30	1.7	1.3	.96	.55	.27	.17	.13
60	2.6	2.1	1.7	1.2	1.1	.80	.76
120	5.2	3.8	3.0	2.2	1.8	1.6	1.5

GAINS AND LOSSES IN STREAMFLOW WITH ALTITUDE

Seven streams were measured during fair weather at different altitudes inside and outside the dike zone to determine gains or losses in streamflow associated with changes in altitude or in geologic features. Significant gains were interpreted to represent ground-water contribution to streamflow, and losses were interpreted to represent infiltration of streamflow to the ground-water reservoir. Stream profiles and measurements at different altitudes along the profiles are shown on plate 1.

SUMMARY OF STREAMS

Streams flow perennially in their upper and middle reaches because of persistent rainfall and, in part, because of discharge of dike water. The perennial streamflow area (pl. 1) is mainly in the dike zone. Streams outside the dike zone, except for Kamananui Stream, lose most of their flow in a short distance owing to infiltration. The area of rapid infiltration, where water levels are at depth, also is shown on plate 1. Streams are mostly dry at lower altitudes until they reach the coastal plain, where some flow perennially because of contributions to streamflow by shallow ground water.

The estimated average flow of 3.4 mgd of Kaluanui Stream (3045) and the recorded average of 10.1 mgd of Kamananui Stream (3300) is about 20 percent of the average rainfall in their respective basins. That percentage is probably representative throughout the Kahuku area.

Only three stream gages are in operation—too few to adequately estimate total streamflow. To augment streamflow data, numerous miscellaneous measurements on ungaged streams were correlated with recorded flows at gaging stations. The correlations are generally fair because the geologic terrane through which the gaged and ungaged streams pass is similar, as are the characteristics of the two types of streams. A summary of streamflow data is given in table 3.

TABLE 3.—*Summary of streamflow data*

Station	Stream	Drainage area (sq mi)	Altitude (ft)	Period of record	Flow, in million gallons per day: Average	Maximum	Date	Minimum	Date
	Hauula subarea								
3040	Kaluanui	0.5	1,900	April 1915 to August 1917	2.96	200	Mar. 9, 1917	0.25	Feb. 25, 26, 1917
3045	Kaluanui [1]	2.12	30	October 1957 to June 1965	[2] 3.4	1,600	Apr. 15, 1963	----------	
	Laie subarea								
3060	Koloa Gulch	.9	500	August 1914 to June 1918	2.73	755	Sept. 25, 1914	0	
3070	Wailele Gulch	.5	525	August 1914 to June 1915, November 1916 to June 1918.	1.56	390	Apr. 11, 1918	0	
3080	East Branch Kahawainui	.53	500	September 1914 to June 1918	.78	650	Sept. 25, 1914	0	
	Kahuku subarea								
3089.9	Malaekahana	.64	450	July 1963 to June 1965	1.43	323	Jan. 6, 1964	0	
3090	East Branch Malaekahana	1.66	380	October 1914 to June 1918	1.12	378	Sept. 25, 1914	0	
3100	Middle Branch Malaekahana	.69	440	August 1914 to June 1918	.39	200	Jan. 7, 1916	0	
3105.01	Malaekahana [1]	4.05	30	August 1958 to June 1965	----------	3,000	Apr. 15, 1963	----------	
3110	Oio [1]	2.13	60	October 1957 to June 1965	----------	692	Apr. 15, 1963	----------	
	Waimea-Kawela subarea								
3250	Kamananui	3.13	590	June 1963 to June 1965	----------	844	Feb. 4, 1965	.61	July 19, Sept. 6–9, 29, 30, 1964
3300	Kamananui	9.79	20	February 1958 to June 1965	10.1	2,230	Apr. 15, 1963	0	

[1] Crest-stage station.
[2] Estimated by correlation with Right Branch of North Fork Kaukonahua Stream (2010).

GROUND WATER

The ground-water body is recharged mainly by rainfall in the dike zone and by deep percolation on moderate slopes or in shallow stream channels on moderate slopes. Dikes are usually thin and nearly vertical to vertical and probably do not impede downward movement of water through the unsaturated zone, which, near the crest, extends hundreds of feet below the surface. Ground water in the dike zone will be referred to as dike water in this report (fig. 15). Dike water is synonymous with high-level water, which was the term used by Stearns and Vaksvik (1935) and Stearns and Macdonald (1940) to describe ground water between dikes.

Ground water outside the dike zone occurs as basal water, the fresher part of which forms a lens-shaped body floating on ground water, whose salinity is the same as that of sea water. Recharge to the basal-water body is from leakage or underflow of dike water, rainfall, percolation of streamflow that originates in the dike zone, and infiltration of irrigation water.

DIKE WATER

Water occurs throughout the interior of the Koolau Range in the Kahuku area in a dike zone roughly 2½ miles wide and 10 miles long (fig. 15). Annual rainfall on the zone ranges from 300 inches at the southeast end to 40 inches at the northwest end. The zone constitutes about 40 percent of the study area and receives about 60 percent of the rainfall. Abundant, persistent rainfall, low evapotranspiration, and high infiltration capacity of surface rocks generally allow a large part of the rain to infiltrate into the ground-water reservoir.

The highest water levels in the dike zone, inferred from observations of discharge of water into streams, are probably at an altitude of about 1,000 feet in the rainy southeastern part. Apparent ground-water gradients along the dike trend are about 100 feet per mile to the northwest and about 250 feet per mile to the southeast. The steep apparent gradient to the southeast reflects the large discharge of dike water into the Punaluu Stream, which cuts deeply into saturated rock. At right angles to the dike trend, the gradient is generally steep, but may be steplike. The water level probably drops sharply at the outer edge of the dike zone owing to the greater permeability of dike-free lava flows (fig. 16.)

The amount of discharge of dike water is proportional to the level of dike water, which, in turn, is proportional to recharge from precipitation. That discharge determines the quantity of effluent flow into streams and underflow to the basal-water reservoir outside the dike

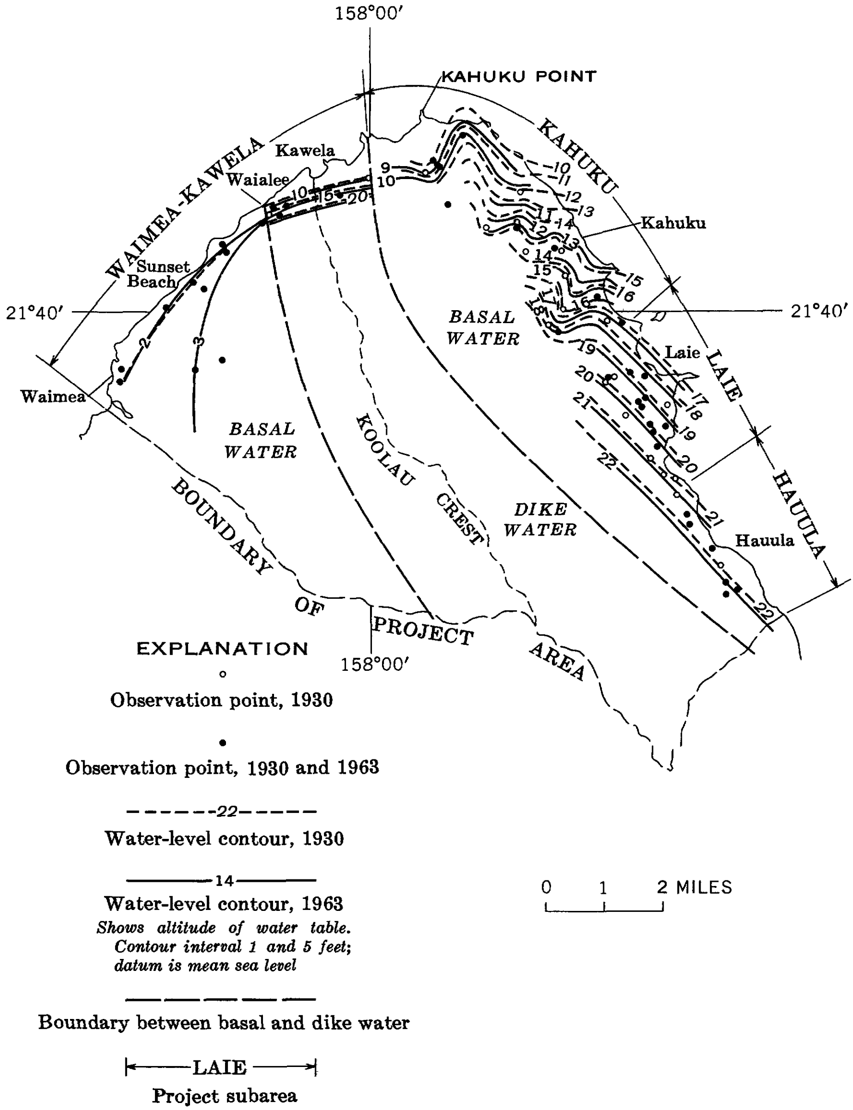

FIGURE 15.—Water-level contours based on measurements made in 1930 and in 1963 and location of dike water and basal water.

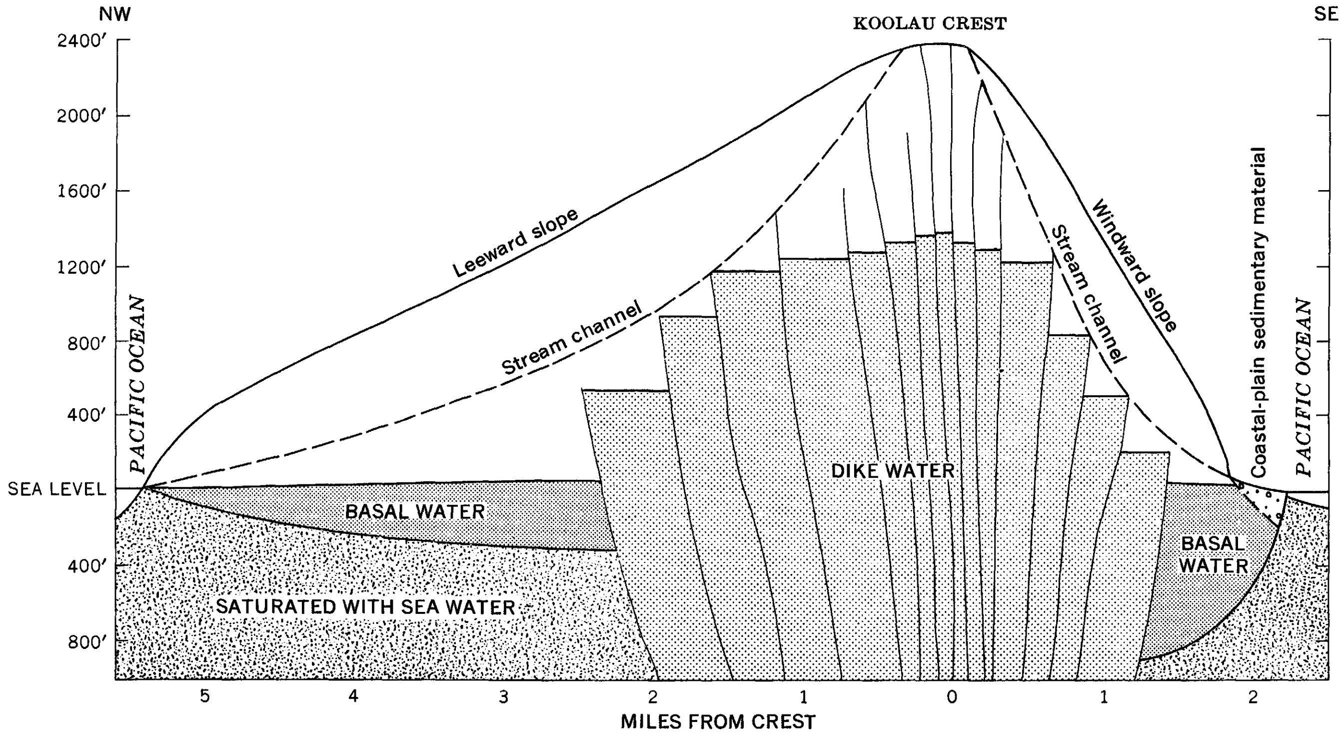

FIGURE 16.—Generalized positions of the dike zone, dike water, basal water, saline ground water, and coastal-plain sedimentary material, near the southern end of the Kahuku area.

zone, and changes in the underflow to the basal-water body are reflected by changes in the level of the basal-water body.

Dike water discharges wherever the ground surface intersects saturated rock in the dike zone. An undetermined quantity of dike water discharges as streamflow between an altitude of 600 and 1,000 feet in Maakua Gulch and Kaipapau Stream (pl. 1). All the flow infiltrates outside the dike zone below an altitude of 600 feet, and the streams go dry. It is likely that dike water discharges at comparable altitudes in the valley of the Waimea River on the leeward side of the Koolau crest. Small springs and marshes near the shore at the north end of the dike zone are fed by dike water.

BASAL WATER

Basal water occurs on either side of the dike zone (figs. 15, 16), which forms both a structural and hydrologic boundary. Basal water east of the dike zone is artesian wherever it underlies the coastal plain, and water levels range from about 7 feet to more than 20 feet above sea level. West of the dike zone, basal water occurs entirely under water-table conditions owing to the near absence of caprock; water levels in wells range from less than a foot to about 3 feet above sea level.

GROUND WATER IN SEDIMENTARY MATERIAL

A small but usable supply of ground water occurs near and below sea level in the coastal-plain sedimentary material. It ranges from fresh to saline, the salinity depending mostly on the proximity of the supply to the sea or to the ground surface, where the salt content is increased by high evapotranspiration. It is recharged from the basal-water body, rainfall, and infiltration or irrigation water.

DEVELOPMENT

The first successful artesian well in the Hawaiian Islands was drilled in 1879 near Pearl Harbor. The first well in the Kahuku area, a flowing well, was drilled in 1880 or 1881. By 1898, at least 16 flowing wells had been drilled near Laie by Mormons, who have colonized the area since 1865. The Mormon Church operated the Laie Plantation and was irrigating sugarcane, taro, rice, and cotton by means of artesian wells in the early eighties before any other of the larger plantations in Oahu were organized. In 1930, there were 24 drilled wells, mostly flowing, on lands of the Laie Plantation, which had been extended to Kahana Valley by a merger with the Koolau Agricultural Co. in 1919. The Laie Plantation merged with the Kahuku Plantation Co. in 1931.

The Kahuku Plantation Co. was organized in 1890. At first the company depended on available streamflow and springflow for irrigation, but those sources became inadequate as acreage in sugarcane increased. The company drilled eight wells in 1900, five in 1901, two in 1902, and one in 1903. By 1930, a total of 34 wells drilled by the plantation yielded a maximum of 20 mgd.

A graph of annual pumpage and acreage harvested by the Kahuku Plantation Co. and the progress of well drilling in the area is shown in figure 17.

QUALITY

The values for the quality of ground water, as measured by its dissolved solids, range from about 100 mg/l (milligrams per liter)[1] for dike water discharged into streams to about 2,500 mg/l for basal well water. The dissolved-solids content of rainwater in the west Koolau mountains is generally less than 20 mg/l, and that of sea water is as much as 35,000 mg/l.

Under natural conditions, the sources of dissolved solids in ground water on Oahu are the atmosphere, organic and inorganic matter in the soil mantle, subsurface rocks through which the water passes, and the saline ground water, which underlies the basal water.

Man's activities, which include irrigation, fertilization of crops, sewage disposal, and weed control, also affect the chemical composition of ground water. On a regional scale, large concentrated withdrawal of basal water from basaltic aquifers, which induces sea-water intrusion, contributes most to the deterioration of ground-water quality. Locally, use of saline irrigation water and leaching of fertilizer salts significantly increase the dissolved-solids content of ground water.

In the Hawaiian Islands, where the sea is the principal source of dissolved solids, it is convenient to use the chloride ion as an index of water quality. According to Visher and Mink (1964), the chloride ion maintains a constant ratio to other constituents in sea water and maintains that approximate ratio when it mixes with fresher water. Also, the chloride ion does not readily enter into chemical reactions with other constituents in the ground-water environment, nor is it subject to appreciable ion exchange.

The chloride content of rain in the Koolau mountains is less than 10 mg/l (Stearns and Vaksvik, 1935, p. 346), whereas that of sea water is more than 18,000 mg/l. The chloride content of effluent dike water in the upper reaches of streams is about 15 mg/l (Visher and

[1] For the concentration ranges of surface and ground water in the Kahuku area milligrams per liter and parts per million are numerically equal.

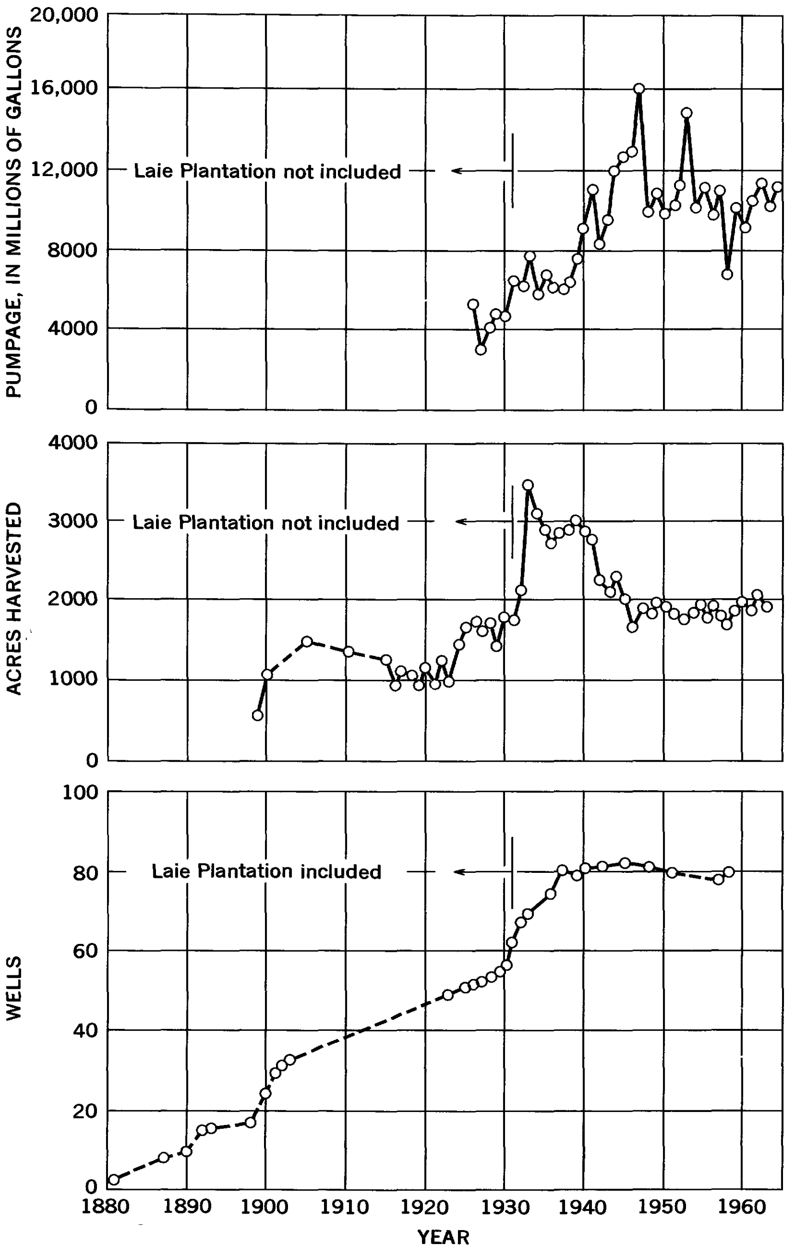

FIGURE 17.—Number of wells, acres of sugarcane harvested, and pumpage in the Kahuku area, 1880–1964.

Mink, 1964, p. 91), whereas that of water from well 347, a basal well near the coast, is about 1,200 mg/l.

AVAILABLE RECORDS

CHLORIDE DATA

The earliest, 1908, available chloride data for the Kahuku area are U.S. Geological Survey chloride determinations of water from three wells. Monthly records, from 1912, are available for the Survey's observation wells 356 and 396 (Stearns and Vaksvik, 1938). The Survey's records also include chloride data for at least 10 wells each year since 1912. The earliest available Kahuku Plantation Co. record is for 1931. The plantation, since 1937, has determined the chloride content of water from their major wells monthly.

Monthly chloride data were obtained by chemical analysis for about 40 wells from July 1962 to June 1964, and water from 10 wells was analyzed in 1965. In addition, the conductivity of water in streams, ditches, and swamps was determined by testing many samples a day with a portable conductivity meter. Curves used to determine chloride content of samples are shown in figure 18. The upper curve was used wherever the water sampled was taken from or was in contact with calcareous material.

NITRATE DATA

A program was begun in August 1964, in cooperation with the State Department of Health, to monitor the nitrate content of water from selected wells to determine effects of infiltration of irrigation water. As uncontaminated ground water contains less than 1 mg/l of nitrate, any nitrate content greater than 1 mg/l was used as a criterion of possible contamination from agricultural fertilizers (Mink, 1962). After an initial analysis of water taken from 32 wells and associated structures in August 1964, samples from wells 338–1, 339A, 341A, 341B, and 358 were analyzed at monthly intervals for 9 months.

The nitrate and chloride content of water from sources sampled in August 1964 are tabulated in table 4. No significant changes in the concentration of chloride or nitrate were found in the 9-month sampling period.

CHEMICAL ANALYSES

Chemical analyses of well water are given in table 5. The data were obtained from files of the Hawaii State Department of Health and from annual reports of the Honolulu Board of Water Supply.

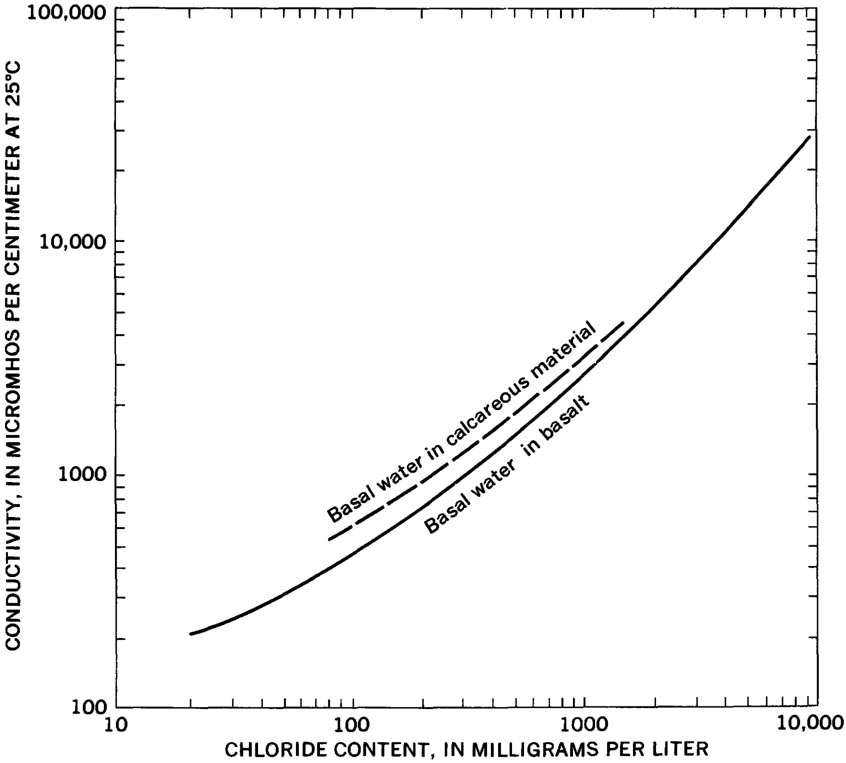

FIGURE 18.—Relations between conductivity and chloride content of basal water in basalt and in calcareous material.

TABLE 4.—*Nitrate and chloride content, in milligrams per liter, of water sources on August 21, 1964*

Source	Nitrate (NO_3)	Chloride (Cl)	Source	Nitrate (NO_3)	Chloride (Cl)
Well 335-4	3.1	256	361B	3.0	85
335-7	2.8	1107	362	4.1	138
335-10	1.5	100	362-1	2.8	57
337-4	2.5	38	363	1.7	226
338	2.0	98	364	1.2	640
338-1	2.1	118	365	2.4	61
339	6.2	315	377	1.4	60
341A	5.2	295	382	.7	48
341B	3.9	453	387	.8	27
345	1.7	517	388	.6	28
351	3.1	207	393	.7	34
Reservoir fed by well 352	1.4	738	396	.7	53
Well 353	3.9	182	398	1.2	63
357	1.5	886	403-1	1.0	63
358	1.7	138	Punaluu Ditch	.1	6
361A	2.2	57	Ditch adjacent to well 341	2.8	763

TABLE 5.—*Chemical analyses, in milligrams per liter, of water from wells*

[Analytical data by Hawaii State Department of Health, except as noted]

Well	Date	Silica (SiO_2)	Alumina (Al_2O_3)	Iron (Fe_2O_3)	Calcium (Ca)	Magnesium (Mg)	Sodium and Potassium (Na+K)	Sulfate (SO_4)	Chloride (Cl)
335-4	Oct. 1947	56	0.7	0.1	18	25	140	36	250
	May 1956	17	.3	.1	7	36	117	44	390
	June 1956	51	.6	.2	16	27	23	48	276
335-5	Jan. 1962 [1]	58	----	----	13	18	92	32	148
337-1	Sept. 1938	47	1.3	.1	17	20	102	30	195
337-2	Oct. 1953	17	1.0	.2	24	9	21	14	39
	Mar. 1955	38	.3	.1	28	10	21	16	52
	Nov. 1959	35	.6	.2	10	13	12	11	42
337-4	Jan. 1962 [1]	42	----	----	8	9	27	7	39
339	June 1956	44	.3	.1	47	52	93	34	340
345	June 1956	32	.6	.2	94	61	112	37	480
353	Feb. 1956	46	.3	.1	66	29	28	26	128
	Mar. 1962	46	2.2	.2	27	19	57	19	112
	Oct. 1962	37	.2	.2	45	26	32	25	196
371	Sept. 1954	27	.1	1.5	37	11	18	36	72
375	June 1957	----	2.3	.1	13	12	44	14	43
	Nov. 1960	41	.2	.1	22	13	31	20	74
382	Mar. 1962	33	1.4	.2	12	10	31	9	47
392	June 1956	8	.6	.2	8	13	23	12	30
394	Oct. 1953	34	.3	.1	24	17	20	1	33
	Jan. 1955	22	.3	.1	23	9	19	14	33
	Feb. 1962 [1]	34	----	----	11	8	26	5	36
402	June 1940	36	----	----	15	11	41	14	74
	Nov. 1954	14	.3	.1	25	9	19	21	10

Well	Date	Fluoride (F)	Nitrate (NO_3)	Dissolved constituents (residue at 180°C)	Hardness as $CaCO_3$ (Ca+Mg)	Alkalinity as $CaCO_3$	Specific conductance in micromhos at 25°C	pH
335-4	Oct. 1947	0.1	1.3	616	145	63	----	7.3
	May 1956	.2	1.2	746	168	52	----	7.3
	June 1956	.2	.1	808	164	64	----	7.3
335-5	Jan. 1962 [1]	.15	2.6	438	107	60	683	6.9
337-1	Sept. 1938	----	----	565	110	----	----	7.3
337-2	Oct. 1953	.1	.2	266	98	44	----	7.3
	Mar. 1955	.2	.4	234	112	49	----	7.7
	Nov. 1959	.1	.2	202	70	50	----	7.6
337-4	Jan. 1962 [1]	.1	1.7	198	59	52	254	7.7
339	June 1956	0	4.0	1,008	332	70	----	6.9
345	June 1956	0	.4	1,394	484	46	----	7.0
353	Feb. 1956	.2	1.2	508	286	56	----	7.6
	Mar. 1962	.15	2.4	426	146	81	----	7.8
	Oct. 1962	.05	1.8	612	217	64	----	7.4
371	Sept. 1954	0	.4	270	139	29	----	7.3
375	June 1957	.15	.8	224	80	47	----	8.1
	Nov. 1960	.2	.2	314	109	63	----	7.6
382	Mar. 1962	.1	.5	208	70	62	----	7.9
392	June 1956	.2	.4	116	74	53	----	6.5
394	Oct. 1953	.1	1.6	154	131	45	----	7.4
	Jan. 1955	.2	.2	164	96	53	----	7.5
	Feb. 1962 [1]	.05	.5	190	58	58	258	7.9
402	June 1940	----	----	248	76	52	----	7.8
	Nov. 1954	0	.2	118	102	41	----	7.6

[1] Analytical data by Board of Water Supply, City and County of Honolulu.

SEA-WATER ENCROACHMENT

Sea water encroaches into coastal aquifers even under natural conditions, owing to a rise in tide level or to reductions in seaward flow of fresh water caused by drought. Such encroachment, however, is generally neither permanent nor continuous.

Withdrawal of basal water by man ultimately reduces seaward flow and causes encroachment of sea water. If withdrawal is small relative to seaward flow, encroachment of sea water is generally not detectable. If withdrawal is large, encroachment is pronounced, and basal-water storage is permanently reduced. If withdrawal exceeds the flow of fresh water available, encroachment continues until sea water eventually replaces fresh water at the point of withdrawal.

CONTAMINATION BY INFILTRATION OF IRRIGATION WATER

Natural flow through most of the basal aquifer is generally large enough that infiltration of soluble fertilizer salts in irrigation water does not significantly contaminate the ground-water reservoir. Where chloride content of applied irrigation water is high, however, as it is in parts of the Kahuku area, irrigation water is a major source of chloride contamination. A section of the Kahuku area where the upper part of the ground-water reservoir has been contaminated by infiltration of irrigation water and the lower part by sea-water encroachment is shown in figure 19, drawn from analyses of the chloride and nitrate content of water samples taken on August 21, 1964. Chloride content is high near the top of the ground-water reservoir, decreases near the middle, and then rises to its highest point near the bottom. Nitrate content, on the other hand, is highest near the top and decreases downward. Contamination by infiltration of irrigation water may be distinguished by the high nitrate and chloride content of the ground water; contamination by sea water, on the other hand, may be distinguished by the high chloride and low nitrate content.

Because the quantity of infiltrated irrigation water is small in comparison with that of natural ground water, it is readily diluted. Moreover, natural flow in the upper part of the reservoir facilitates its discharge toward the sea and prevents its deep infiltration. Mink (1964) discussed the limited vertical dispersion of infiltrated water and distinguished ground water cooled by infiltrated rain in the mountains from that heated by infiltrated irrigation water.

The effects of infiltration of irrigation water on the chemistry of basal water in southern Oahu were discussed in some detail by Visher and Mink (1964, p. 108). Much of their discussion is applicable to the Kahuku area because soil profiles, aquifers, and fertilizers applied are generally similar in both areas.

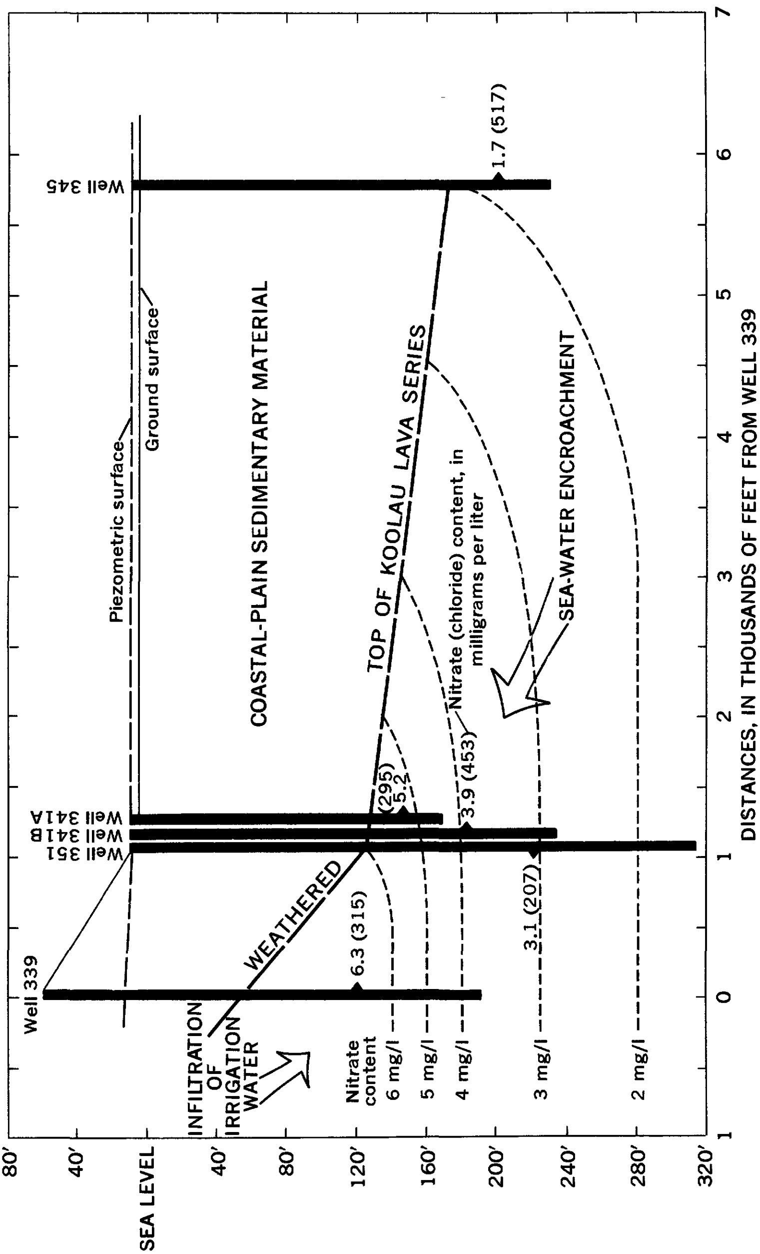

FIGURE 19.—A part of the basal-water reservoir near Kahuku, showing contamination by infiltration of irrigation water and by sea-water encroachment.

SUMMARY OF GROUND-WATER QUALITY

The quality of ground water in the Kahuku area is summarized by subareas in table 6, and change in the chloride pattern from early 1930 to August 1962 is shown in figure 20. The chloride content of water in reservoirs, ditches, and marshes in the northeastern part of the Kahuku area is shown in figure 21, and the location of the pumping plants in this area and the chloride content of water from them are shown in figure 22.

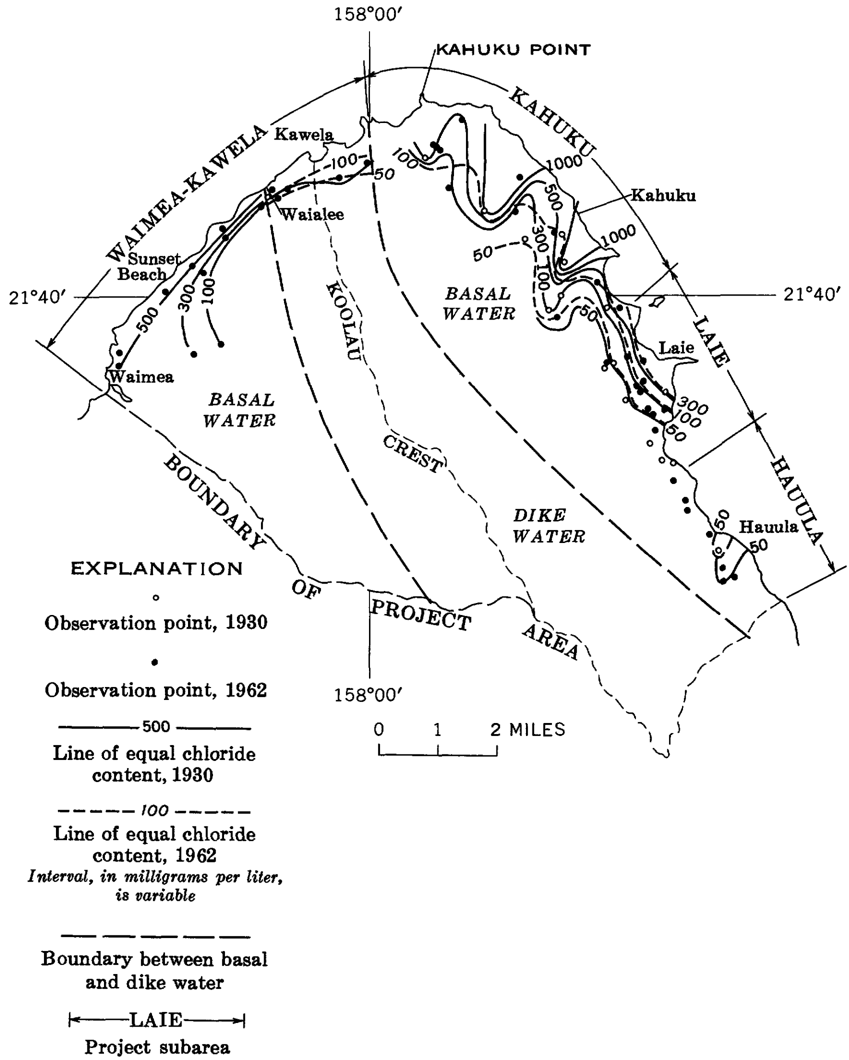

FIGURE 20.—Location of basal water and dike water, and change in chloride pattern from early 1930 to August 1962.

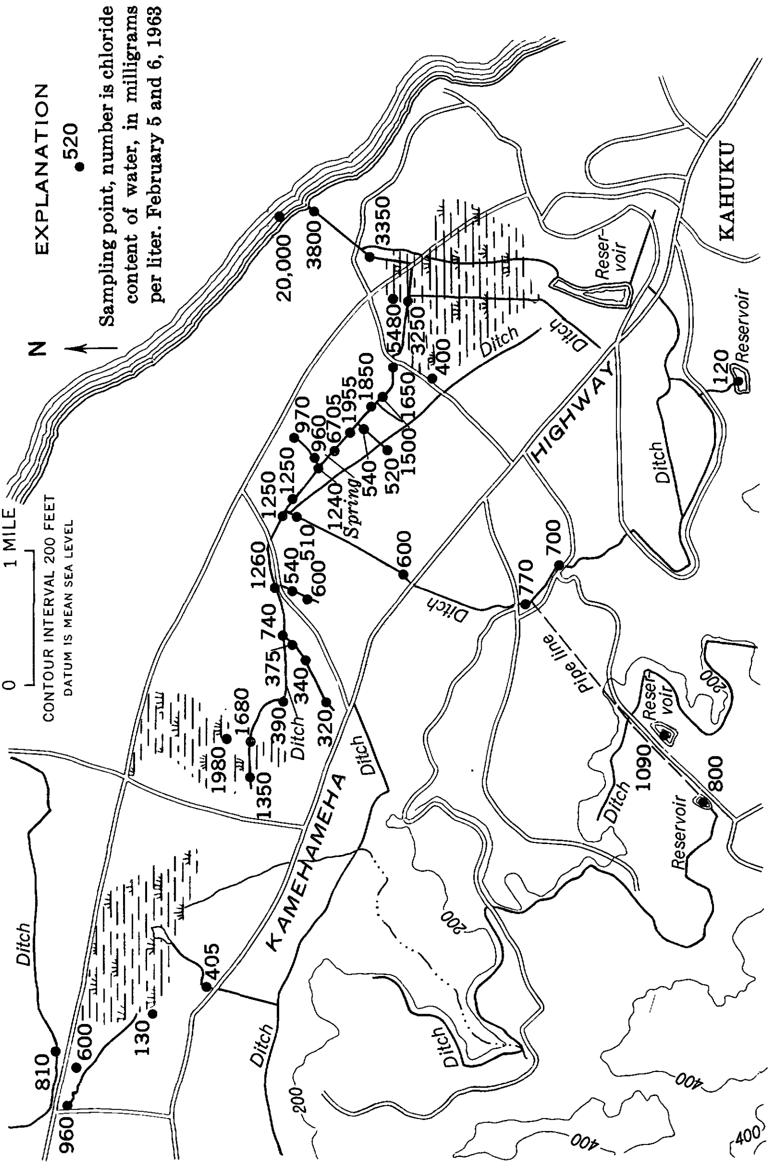

FIGURE 21.—Chloride content of water in reservoirs, ditches, and marshes in the northeastern part of the Kahuku area.

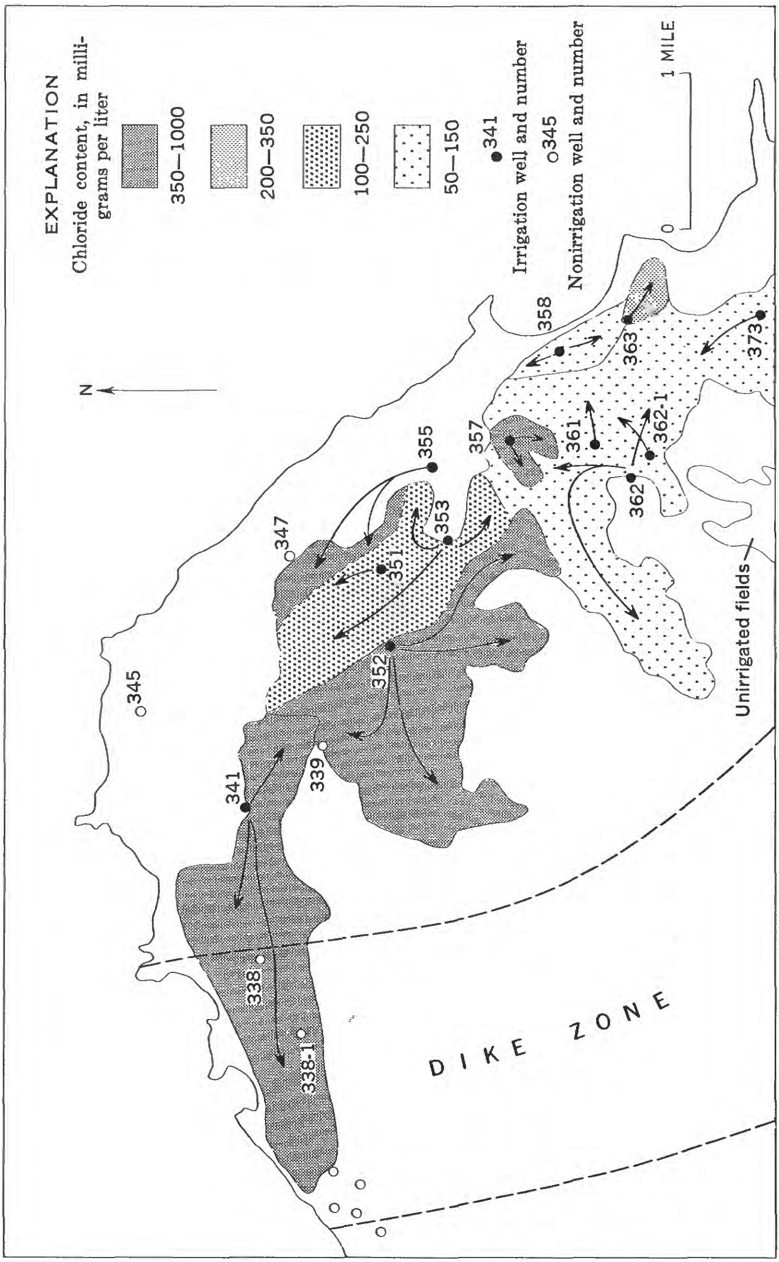

FIGURE 22.—Location of pumping wells in the northeastern part of the Kahuku area and chloride content of water from them during August 1964.

TABLE 6.—*Summary of ground-water quality*

Subarea	Chloride content of water from drilled wells (mg/l)	Nitrate content of water from drilled wells (mg/l)	Chloride content of water in coastal sedimentary material above high-tide level (mg/l)	Remarks
Hauula	30–90	<1-1	250	No wells tap coastal sedimentary material. Temperature of water from flowing wells, 20°–23°C. No significant change in quality from 1930 to 1962. See fig. 20.
Laie	50–600	Southern part, <1-1; northern part, 1-2.5.	250	No significant change in quality from 1930 to 1962 except in northern end, where change reflects heavy pumpage in Malaekahana Valley. Temperature of water from flowing wells, 21°–23°C. See fig. 20.
Kahuku	50–1, 200	2–6	500–1, 000; water standing in marshes subject to evaporation contains as much as 6,000 mg/l. See figure 21.	Chloride content of applied irrigation water is as much as 1,000 mg/l. Infiltration of high-chloride irrigation water is significant source of contamination to basal-water reservoir. See figure 22 for distribution and chloride content of applied irrigation water.
Waimea-Kawela.	100–1, 500	2–3	Water pumped from shallow wells and springs, 125–400.	Infiltration of high-chloride irrigation water transported from the Kahuku subarea is source of contamination to dike-water reservoir. Dike water otherwise of excellent quality. Low draft in area has not significantly changed quality of basal water since 1929. Transition zone extends inland more than 2 miles in southern part, which eliminates large areas from basal-water development.

ESTIMATE OF GROUND-WATER FLOW

Most ground water discharges at or near the shore. Where the basaltic aquifer is overlain by coastal-plain sedimentary material, part of the ground water discharges into it and then into the sea. If the water table is near or at the land surface, ground water also discharges to the atmosphere by evapotranspiration.

Ground-water flow may be estimated by the following methods:

1. By Darcy's law in the form of $Q=TIL$, as defined by Ferris, Knowles, Brown, and Stallman (1962, p. 73), where Q is ground-water flow, in gallons per day; T is transmissivity in gallons per day per foot; I is hydraulic gradient, in feet per mile; and L is width, in miles, of the cross section through which the water discharges, or
2. By a water budget, where rainfall is input. Ground-water flow is the remainder after streamflow and evapotranspiration are subtracted. To eliminate effects of storage, long-term means are used in the computations.

AQUIFER-TEST METHOD

The aquifer-test method was used only for comparison with the water-budget method, as data were insufficient to define transmissivity. Three aquifer tests were made in the Hauula subarea, where consistent values of transmissivity were obtained by the Theis (1935) nonequilibrium formula. In other subareas, transmissivity was determined less consistently by applying the modified nonequilibrium formula (Jacob, 1950) to data from drawdown and recovery traces on recorder charts from wells near permanent pumping plants. The hydraulic gradients were established by a 2-year monthly water-level survey and are reliable.

WATER-BUDGET METHOD

Reliability of any water budget depends on the adequacy of rainfall, streamflow, and evapotranspiration data. Rainfall data are good in coastal areas, fair on mountain slopes, and poor near the crest. Because most rain falls on mountain slopes, the estimate of total rainfall is fair. (See fig. 7.)

About 20 percent of total rainfall is estimated to flow to the sea as runoff. This estimate is based in part on rainfall-runoff studies in other areas on Oahu by Mink (1962) and by the Corps of Engineers in 1964.[2] Long-term average flow of Kaluanui Stream has been

[2] Corps of Engineers, U.S. Army, unpub. rept., Hydrologic Relations in Hawaii, Project ES–182, Project Bulletin No. 1, 30 November 1964.

estimated to be 3.4 mgd by correlating periodic measurements with concurrent discharges at the gaging station on the right branch of North Fork Kaukonahua Stream near Wahiawa (2010). Average flow of Kamananui Stream at Maunawai (3300) is 10.1 mgd. Both averages represent roughly 20 percent of rainfall in their respective basins.

Evapotranspiration estimates are based on the assumption that evapotranspiration approximately equals pan evaporation in the Kahuku area. Research in Hawaii by the sugar industry (Baver, 1954; Campbell and others, 1959; Chang, 1963) showed that if water is constantly available, as it is where sugarcane is irrigated, evapotranspiration approximately equals evaporation from a Class A U.S. Weather Bureau evaporation pan. According to Kozlowski (1964), evapotranspiration depends mainly on available heat and is theoretically independent of vegetal type, provided plant cover is adequate and water availability is high. Water availability is high in much of the study area, because of the proximity of the water table to the ground surface, the intensive irrigation near the coast, and the high frequency of rain in the mountainous areas.

Evapotranspiration was, therefore, assumed to be equal to pan evaporation, which was estimated from the relations of median annual pan evaporation to median annual rainfall in Hawaii, as shown in figure 23. The data used in figure 23 were obtained from Taliaferro (1959) and the Hawaii Division of Water and Land Development (1961). The equations $\log_{10}E$ (median annual pan evaporation) $=1.9387-0.0035R$ (median annual rainfall) and $\log_{10}E=1.9558-0.0011R$ closely describe the data for stations recording cumulative wind movement of less than 20,000 miles per year and more than 20,000 miles per year, respectively. Pan evaporation on the coastal plain was estimated by using the relation $\log_{10}E=1.9558-0.0011R$; above the coastal plain, it was estimated by the relation $\log_{10}E=1.9387-0.0035R$. The estimates tend to be small for areas near the crest, where high winds are common, and large where water is not constantly available. Evapotranspiration is highest near the coast, where rainfall is low and marshes and irrigated cane occupy large areas; it is lowest in the mountains.

The water-budget method is, at best, only fair for estimating ground-water flow. The estimates can, however, be used with pumping-test and water-quality data to better evaluate ground-water flow.

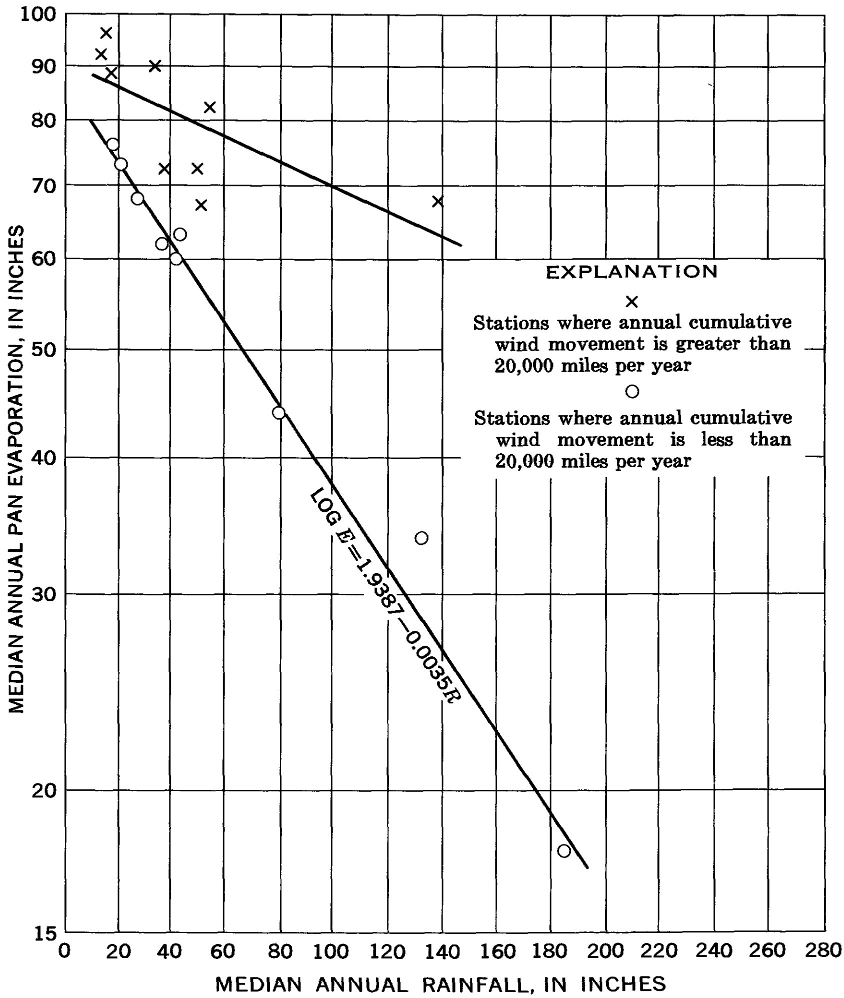

FIGURE 23.—Relations of median annual pan evaporation to median annual rainfall in the Hawaiian Islands.

GROUND WATER IN THE SUBAREAS

HAUULA SUBAREA

The Hauula subarea comprises about 8 square miles and includes the basins of Kaluanui and Kaipapau Streams, Maakua Gulch, and other small water courses (pl. 1). Rainfall averages about 50 mgd, of which at least 40 mgd is in the dike zone (fig. 7). In addition, about 3.5 mgd of water is imported through a ditch, which diverts water from Punaluu Stream on the south.

Most of the coastal plain in the southern half of this subarea is planted to sugarcane. Of the 230 acres of cane, 215 acres requires irrigation during dry periods. As much as 12 mgd of water may be applied, 9 mgd from four wells and 3 mgd from Punaluu Stream, which lies outside the study area.

The town of Hauula (population 1,200) occupies most of the northern half of the coastal plain. Domestic water in Hauula is supplied by two wells, from which are pumped between 100,000 and 200,000 gpd (gallons per day). A small truck farm near the mouth of Kaipapau Stream uses about 25,000 gpd, which is supplied by two wells.

Dike water

Dike water, although probably abundant, does not discharge naturally at the surface in large quantities. The only apparent discharge is the small but persistent gain in streamflow in the middle reaches of Maakua and Kaipapau Streams between an altitude of 1,100 and 600 feet (pl. 1). Above and below these altitudes, the streams lose water.

Other than at these discharge points, boundaries of the dike-water reservoir are unknown. Streamflow measurements, however, in Punaluu valley, which lies outside the study area but cuts deep into the dike-water reservoir, suggest that the reservoir is large and that flow from it is also large. Gains in streamflow based on measurements in August through September 1960 of Punaluu Stream with altitude changes are shown in figure 24. Water levels outside the zone indicate that water also moves from the dike zone into dike-free lava flows (fig. 15).

Basal water

The basal-water lens is unusually thick in the Hauula subarea in spite of the high permeability of the aquifer and the short distance from recharge to discharge points. The thick lens results from the combined effects of (1) a deep valley fill and a weathered zone underlying the mouth of Punaluu valley, which act as an effective barrier to basal-water flow southward across the valley, (2) a caprock along the shore, which retards the seaward flow of basal water, and (3) a large flux of ground water moving through the aquifer.

Aquifer constants determined from pumping tests indicate basal-water flow of about 10 mgd per mile width of aquifer in the Hauula subarea. Thus, 25 mgd would flow through a strip 2½ miles wide, the width of the Hauula subarea. A flow of 25 mgd is comparable to that given in the tabulated water-resources summary:

Water-resources summary for the Hauula subarea, excluding the coastal plain

	Million gallons per day	*Percentage of rainfall (rounded)*
(1) Rainfall	46	100
(2) Evapotranspiration	10	20
(3) Net rainfall (1) − (2)	36	80
(4) Runoff	9	20
(5) Ground-water recharge (3) − (4)	27	60
(6) Ground-water draft	3	5
(7) Unused ground-water flow (5) − (6)	24	55
(8) Ground-water flow per coastline mile	10	----------

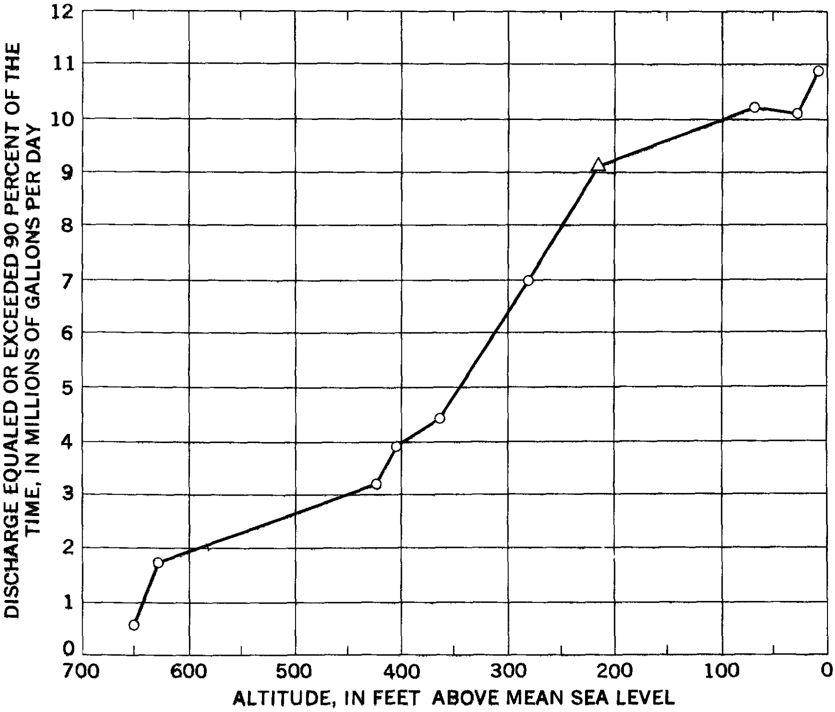

FIGURE 24.—Relations of streamflow gains to altitude changes of Punaluu Stream.

Basal-water draft averages 3 mgd, but at times may be as great as 9 mgd. Most is used to irrigate sugarcane between May and October. About half is from well 398, which is pumped at a rate of 4 mgd. Toward the end of the irrigation period, water levels are depressed as much as 2 feet from static water levels. Water-level contours of August 1962 show the position of the water table after 5 months of pumping (fig. 25).

Long-term net changes in water levels are probably insignificant. Levels in wells measured in 1963 are about the same as they were in 1930; static water levels in the Hauula subarea were higher than average in both years (fig. 15).

Potential areas for development

An effective method of developing basal ground water would be by drilling a line of wells parallel to the contour lines shown in figure 15. A tentative pumping rate of 2 mgd per 1,000 feet parallel to the dike zone is suggested. Well spacing is important because the ground-water reservoir is narrow, owing to the short distance between the recharge and the discharge zones and to the high gradient. Concentrated pumping in a small area at excessive rates might induce sea-water intrusion.

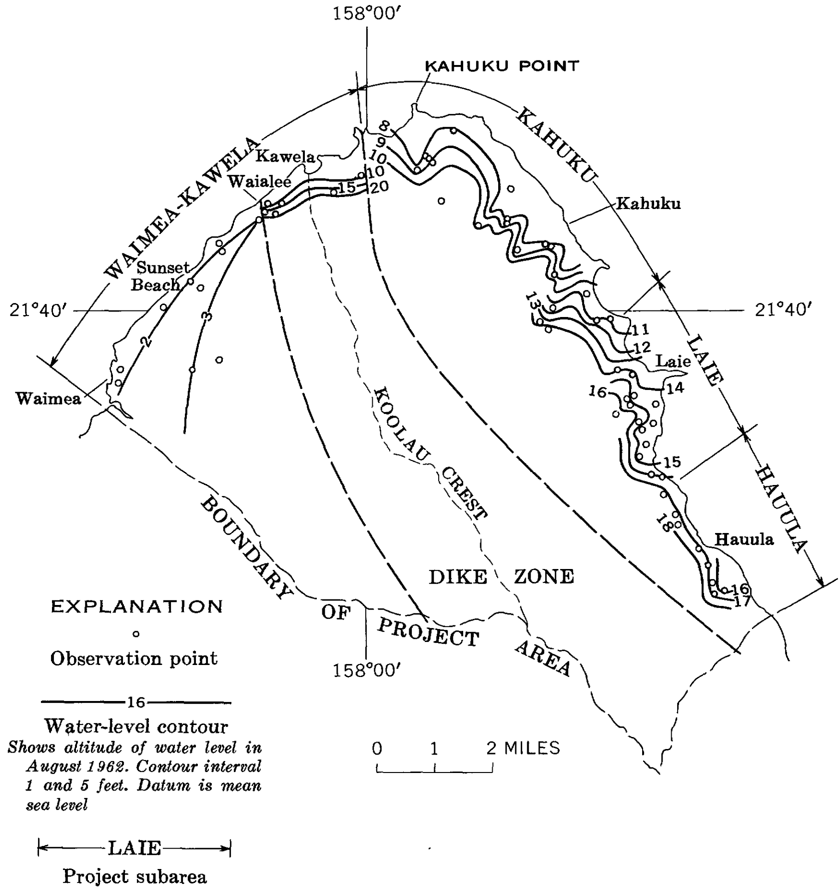

FIGURE 25.—Water-level contours based on measurements made in August 1962 during a period of heavy pumping.

LAIE SUBAREA

The Laie subarea is about 10 square miles in extent and includes Koloa and Wailele Gulches, Kahawainui Stream, and other smaller basins (pl. 1). Rainfall averages about 45 mgd, roughly 30 mgd in the dike zone, 10 mgd in mountainous areas outside the dike zone, and 5 mgd in the coastal plain.

The coastal plain, which is less than half a mile wide in the Hauula subarea, widens to about a mile in the Laie subarea. Except for the town of Laie, the coastal plain is mostly occupied by sugarcane fields. In January 1965, 570 of 725 acres of cane was irrigated.

Fourteen wells and a ditch that taps shallow ground water from coastal sedimentary material supply about 3 mgd for cane irrigation and 1 mgd about equally divided between domestic water needs and irrigation water for diversified farming. During dry periods, irrigation pumpage may be as much as 12 mgd.

Dike water

The occurrence of dike water is not as apparent as it is in the Hauula subarea. Its presence is inferred from the configuration of the basal-water levels, the gradient of which suggests underflow from the dike zone (figs. 15, 25).

Basal water

At least 17 basal-water wells have been drilled, most of them between 1881 and 1900 by Mormon settlers for irrigation of sugarcane, taro, rice, and cotton. Annual draft during 1960–64 averaged 4 mgd.

Water-level contours for 1930 and 1963 show that the basal-water reservoir of the Hauula subarea continues smoothly into the Laie subarea (fig. 15). Hydrologic boundaries that cause high basal-water levels in the Hauula and the Laie subareas are similar—a deep valley fill and weathered zone underlying the mouth of Malaekahana valley retard the flow of basal water to the northeast in the Laie subarea; an effective caprock retards seaward flow of the water; and a large flux of water originates in the dike zone and moves seaward through the basal-water aquifer.

The following water-resources summary was computed in the same manner as that for the Hauula subarea:

Water-resources summary for the Laie subarea, excluding the coastal plain

	Million gallons per day	*Percentage of rainfall (rounded)*
(1) Rainfall	40	100
(2) Evapotranspiration	15	40
(3) Net rainfall (1) – (2)	25	60
(4) Runoff	8	20
(5) Ground-water recharge (3) – (4)	17	40
(6) Ground-water draft	4	10
(7) Unused ground-water flow (5) – (6)	13	30
(8) Ground-water flow per coastline mile	7	----------

Static water levels in wells are about 2 feet lower than they are in the Hauula subarea (figs. 15, 25, 29). Levels are little affected by a steady background draft of about 1 mgd for domestic and diversified farming from eight scattered wells and have shown no apparent long-term change since 1930. They are influenced mostly by draft from wells

377, 387, and 373, which are pumped at rates of 5, 2.5, and 2 mgd, respectively, during periods of heavy irrigation, when total draft may be as great as 12 mgd. The additional 1.5 mgd is supplied by several flowing wells. Water levels in August 1962 (fig. 25) and the water level of well 372 in late 1963 (fig. 29) show effects of heavy summer pumpage.

Heavy prolonged draft in the adjoining Kahuku subarea also depresses water levels in the northern part of the Laie subarea in spite of the low permeability of rocks underlying Malaekahana Stream (fig. 25).

Potential areas for development

An effective method of developing basal ground water would be to drill a line of wells between the 20- and 21-foot water-level contours shown in figure 15. Part of such an alinement now includes wells 377, 387, and 373, which are pumped at rates of 5, 2.5, and 2 mgd about 4 months of the year. New wells should be located so that sustained pumpage along this alinement does not exceed 1.3 mgd per 1,000 feet. Chloride content of water in new wells drilled along the suggested alinement would be about 50 mg/l (fig. 20).

KAHUKU SUBAREA

The Kahuku subarea, about 18 square miles, includes Malaekahana Stream, Ohia Ai and Oio Gulches, and other smaller basins. Rainfall is about 50 mgd distributed roughly as follows: 25 mgd in the dike zone, 15 mgd in mountainous areas outside the dike zone, and 10 mgd in the coastal plain. The subarea includes the town of Kahuku, the offices and sugar mill of the Kahuku Plantation Co., and about 2,800 acres of sugarcane, nearly 65 percent of the plantation's total acreage in 1965. Only about 170 acres are unirrigated. The coastal plain, about 1½ miles wide, is occupied by extensive brackish-water marshes (pl. 1).

The draft of the basal ground water ranges from about 3 mgd during periods of no irrigation to more than 50 mgd when fields are heavily irrigated; the average draft is about 22 mgd. Wells 341B and 353, flowing continuously at a combined rate of 2–3 mgd, contribute most of the draft during the nonirrigation period. Domestic water for about 1,200 people is supplied by wells 341A, 353, and 363, from which are pumped 100,000–200,000 gpd (gallons per day). Pumpage from coastal-plain sedimentary material ranges from 0 to 15 mgd and averages about 5 mgd; it is used for irrigation and for washing cane at the mill. The principal sources of ground-water withdrawal are given in the following tabulation:

Principal sources of ground-water withdrawal in the Kahuku subarea

Location		Maximum withdrawal (mgd)	Average withdrawal 1960–64 (mgd)	Remarks
Pump	Well			
2	341 A, B	10.4	6.2	Two wells tapping a basaltic aquifer (one flowing) discharge 2 mgd into a ditch that contributes 4 mgd; all is pumped by Kahuku Plantation Pump 2.
15	351	2.2	.3	Drilled well.
5	352 A to K	8.6	4.4	Battery of 11 drilled wells.
1 and 11	353 A to C	6.1	3.8	Battery of three drilled wells.
Mill	355 A to D	8.5	1.6	Battery of four drilled wells in basalt and sump in coralline limestone. Wells contribute about 2 mgd.
8	357	3.8	.5	Drilled well.
	358	2.0	1.5	Flowing drilled well.
12	361 A, B	3.8	.8	Two drilled wells.
3 and 17	362 A to F	17.0	5.2	Battery of six drilled wells.
6	362–1	1.9	1.0	Drilled well.
7	363	2.2	.5	Drilled well.
	364	1.0	.1	Drilled well.
Total		67.5	25.9	
Minus		14.9	4.4	Contributed by shallow ground water in coastal-plain sedimentary material at pump 2 and at mill.
Net, rounded		53	22	

Dike water

Most dike-water flow is below ground surface. Malaekahana valley and Ohia Ai Gulch cut the seaward edge of the dike zone above an altitude of 400 feet and drain small quantities of dike water from saturated rock there or at higher altitudes (pl. 1).

Basal water

Figures 15 and 20 show that little or no change occurred in basal-water levels and chloride content of water in wells in the Hauula and Laie subareas during the period 1930–63. During the same period, basal-water levels in the Kahuku subarea declined about 2 feet, and the chloride content of water in some wells rose to as much as 900 mg/l. Natural ground-water outflow exceeds artificial draft in the Hauula and Laie subareas, and artificial draft exceeds natural ground-water outflow in the Kahuku subarea.

The water-resources summary as given in the following tabulation indicates a draft of about 10 mgd in excess of natural recharge:

Water-resources summary for the Kahuku subarea, excluding the coastal plain

	Million gallons per day	*Percentage of rainfall (rounded)*
(1) Rainfall	40	100
(2) Evapotranspiration	20	50
(3) Net rainfall (1) − (2)	20	50
(4) Runoff	8	20
(5) Ground-water recharge (3) − (4)	12	30
(6) Ground-water draft	22	55
(7) Overdraft (5) − (6)	−10	
(8) Infiltration of irrigation water	5	
(9) Overdraft, including infiltration of irrigation water (8) + (7)	−5	
(10) Ground-water flow per coastline mile	3	

The overdraft is somewhat alleviated by infiltration of about 5 mgd of irrigation water applied to fields. The infiltration is that quantity exceeding potential evaporation (fig. 23). Between 120 and 130 inches of water per year, including rain, is applied to fields by the Kahuku Plantation Co. As rainfall averages about 40 inches per year in irrigated areas, between 80 and 90 inches of irrigation water is applied per year.

Natural ground-water flow, estimated to be 10 and 7 mgd per mile in the Hauula and Laie subareas, respectively, probably ranges between 2 and 4 mgd per mile in the Kahuku subarea and decreases somewhat from the southern to the northern part. During the dry summer, the flow is much less than the draft, which is 10 mgd per linear mile or a total of 50 mgd for sustained 6-day periods. Draft at this rate depresses water levels as much as 4 feet near the end of the irrigation period each year (figs. 25, 29).

The water-level, chloride, and pumpage data given in figure 26 relate to an area of about 2 square miles in the vicinity of Kahuku. Pumpage increased in the early 1940's from an annual average of about 5,000 million to about 6,000 million gallons, which caused a decline in water level and an increase in chloride content of the water. Since 1930, the net decline in water level has been about 2 feet (figs. 15, 26).

The combined effect of low ground-water flow and heavy pumping probably accounts for the nonuniformity of water-level contours and lines of equal chloride content (fig. 27). This figure, which shows extensions of valleys and gulches, suggests that poorly permeable rocks underlying these extensions are interfering with the flow of ground water across them. Where the natural ground-water outflow is high and the draft is low, as in the Hauula and Laie subareas, interference to the flow of ground water by the extensions is less noticeable, and water-level contours and lines of equal chloride content are uniform.

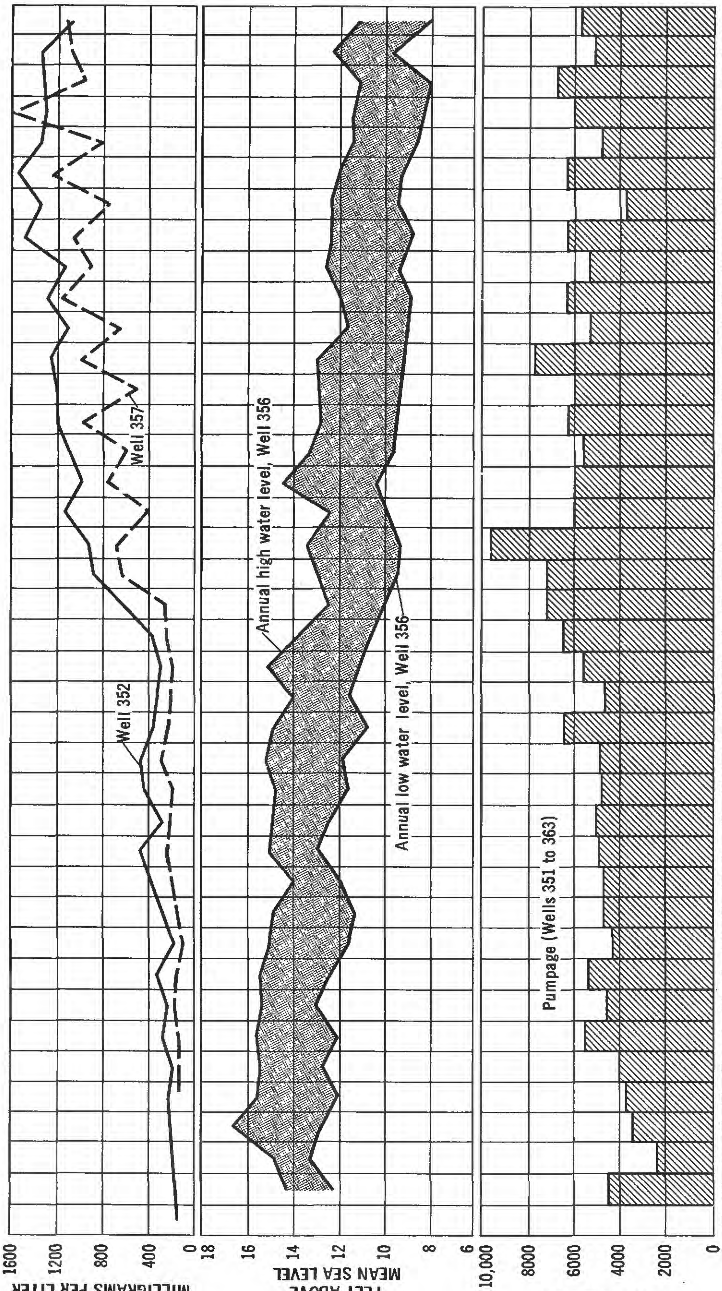

FIGURE 26.—Annual high and low water levels in well 356, maximum chloride content of water in wells 352 and 357, and annual pumpage near Kahuku, 1926–64.

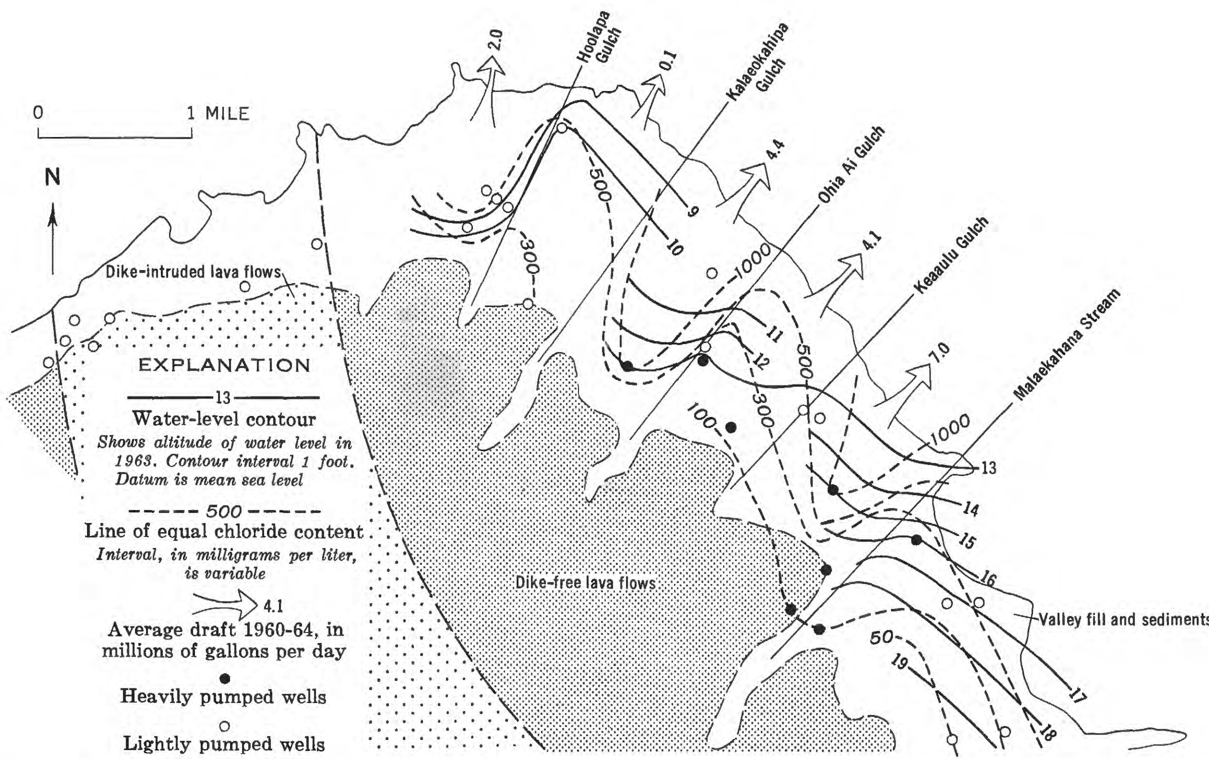

FIGURE 27.—Average draft 1960–64 in the Kahuku subarea and effects of the poorly permeable rocks underlying valley extensions to basal water levels and to chloride content.

Potential areas for development

The basal-water supply in most of the Kahuku subarea is fully developed. The most promising area for additional development is on the south side of Malaekahana Stream. Small quantities of water of good quality can be developed in the mountains, but generally only at the expense of degrading the quality of water downgradient from such a new development.

WAIMEA-KAWELA SUBAREA

The Waimea-Kawela subarea is bounded on the east by Kawela Gulch and on the west by the Waimea River (pl. 1). The subarea, about 25 square miles, is known for its fine beaches at Kawela, Waialee, Sunset Beach, and Waimea. Notable developments include an extensive subdivision in the Pupukea Homesteads area, a livestock farm of the State University at Waialee, and about 370 acres of cane near Kawela.

Rainfall averages about 100 mgd, of which 65 mgd is in the drainage of Waimea River. About 50 mgd is in the dike zone, 45 mgd in mountainous areas outside the dike zone, and less than 5 mgd in the coastal plain.

The coastal plain is occupied by cane fields irrigated by water transported from the Kahuku subarea (pl. 1). The coastal plain narrows from Waialee to the Waimea River.

Domestic water for a population of about 2,000 (1965) is supplied by four wells that tap the basaltic aquifer, two of which are municipal wells. On the basis of a per capita use of 150 gpd, average water consumption is about 300,000 gpd. Other water sources, mostly wells dug in coastal sedimentary material, supply small agricultural and livestock farms. These wells also yield about 300,000 gpd, for a total draft of about 600,000 gpd. The water-resources summary given in the following tabulation shows an unused ground-water flow of 24 mgd:

Water resources summary for the Waimea-Kawela subarea, excluding the coastal plain

	Million gallons per day	*Percentage of rainfall (rounded)*
(1) Rainfall	96	100
(2) Evapotranspiration	53	55
(3) Net rainfall plus 1 mgd (estimated) infiltration of irrigation water	44	45
(4) Runoff	19	20
(5) Ground-water recharge (3) − (4)	25	25
(6) Ground-water draft	0.6	1
(7) Unused ground-water flow (5) − (6)	24	24
(8) Ground-water flow per coastline mile in dike zone (dike water)	10	----------
(9) Ground-water flow per coastline mile in dike-free zone (basal water)	1	----------

The flow of ground water was determined by the relationship $Q=TIL$ (p. 41), in which $Q_{\text{dike water}}=20$ mgd and $Q_{\text{basal water}}=4$ mgd. Transmissivity (T) was determined from analyses of recorder charts taken from observation wells located near pumped wells, where $T_{\text{dike water}}=200{,}000$ and $T_{\text{basal water}}=1{,}000{,}000$ gpd per foot. The water-level gradients (I) and the width of the aquifers (L) were taken from figure 15, in which $I_{\text{dike water}}=50$ feet, $I_{\text{basal water}}=1$ foot, $L_{\text{dike water}}=2$ miles, and $L_{\text{basal water}}=4$ miles.

Dike water

Dike water, undeveloped elsewhere in the study area because of its occurrence only in the high mountains, is the major source of water in the Waimea-Kawela subarea. In 1965, four wells tapping the dike-water aquifer were in use—three for domestic supply and one for the irrigation of a small truck farm; draft was less than 200,000 gpd. Dike water, potentially a large source of water of good quality, remains mostly undeveloped, however. At least 10 wells have been drilled in the dike zone since about 1921; all are within half a mile from shore and do not exceed an altitude of 85 feet.

Lack of development probably was based on a belief that large quantities of dike water were not available owing to generally poor yields of wells. Specific capacity, expressed in gallons per minute of yield per foot of drawdown, is commonly as much as 300 for basal-water wells in the Kahuku area. In comparison, the specific capacity of dike-water wells ranges from 20 to 100; the median is about 35. The low specific capacity can be attributed partly to the shallow depths of wells, which generally penetrate only about 60 feet of saturated rock. Deepening of wells probably would increase specific capacity. Well 337–5, which is deeper than most wells in the subarea, has a specific capacity of about 100.

An undetermined quantity of dike water escapes to the surface at shoreline seeps. Some of this water has been ponded and is used for irrigation.

Basal water

The boundary that separates dike water from basal water is marked by a sharp drop in water levels in wells near the coast at Waialee (fig. 15). That boundary is probably coincident with the edge of the dike zone. The quality of the basal water is good where wells are adjacent to the dike zone, as near Waialee, because the basal water is recharged by leakage of dike water; however, the salinity of the basal water increases markedly with distance from the dike zone where there is no leakage of dike water and where natural ground-water flow is small (fig. 20).

The first basal-water well was drilled in 1938; since then, 12 were drilled, the last in 1959. In 1965 only four of those wells were in use.

At least six shallow dug wells tap coastal sediments or basalt near shore; two were in use in 1965.

The chloride content of the fresher part of the basal-water body underlying the coastal areas is generally less than 500 mg/l. There is, however, a rapid increase in chloride content with pumping because the wells extend far below sea level. The situation cannot be remedied by drilling shallower wells because poorly permeable weathered basalt extends well below the ground surface and into the basal-water body. Shallow drilling generally results only in a well of much reduced yield. Yields are increased to some extent by digging large-diameter wells instead of drilling small-diameter wells.

The relation of well depth to chloride content of the tapped water in thin basal-water bodies is shown by the graphs in figure 28. The graphs show relations between pumpage and chloride content of water from well 335–7 and the Jose Bercina dug well. Both wells are about 700 feet from shore near Sunset Beach (pl. 1).

Potential areas for development

The most promising area for additional ground-water development is in the dike zone. Sources for basal-water development, unless restricted to areas near the edge of the dike zone or in areas far removed from shore, will be subject to contamination by sea water.

The high dissolved-solids content of water from wells 338 and 338–1 in the dike zone is probably derived from the return of imported irrigation water, which has a chloride content as high as 1,000 mg/l. This area of the dike zone is probably confined to the top of the ground-water body because the water-table gradient is steep. Present wells might be deepened if the area is, in fact, thin. If, however, the area of contamination proves to be thick, new wells in the dike zone, drilled inland from irrigated sugarcane fields, appear to offer a potential for development of water of good quality.

SUMMARY OF GROUND WATER IN SUBAREAS

The average recharge to ground-water reservoirs in the Kahuku area is estimated to be about 85 mgd. An average of 30 mgd is discharged by wells. The remaining 55 mgd is eventually discharged to the sea by underflow or to the atmosphere by evapotranspiration. The figures from which the above estimates were made are given in the previous water-resources summaries, which are reiterated together in table 7. Available data on rainfall, streamflow, evapotranspiration, water levels, water quality, and pumping tests, on which the above estimates are based, are judged by the writer to be fair.

On the basis of estimates in table 7, the most promising areas for developing basal water are in the Hauula and Laie subareas, where draft

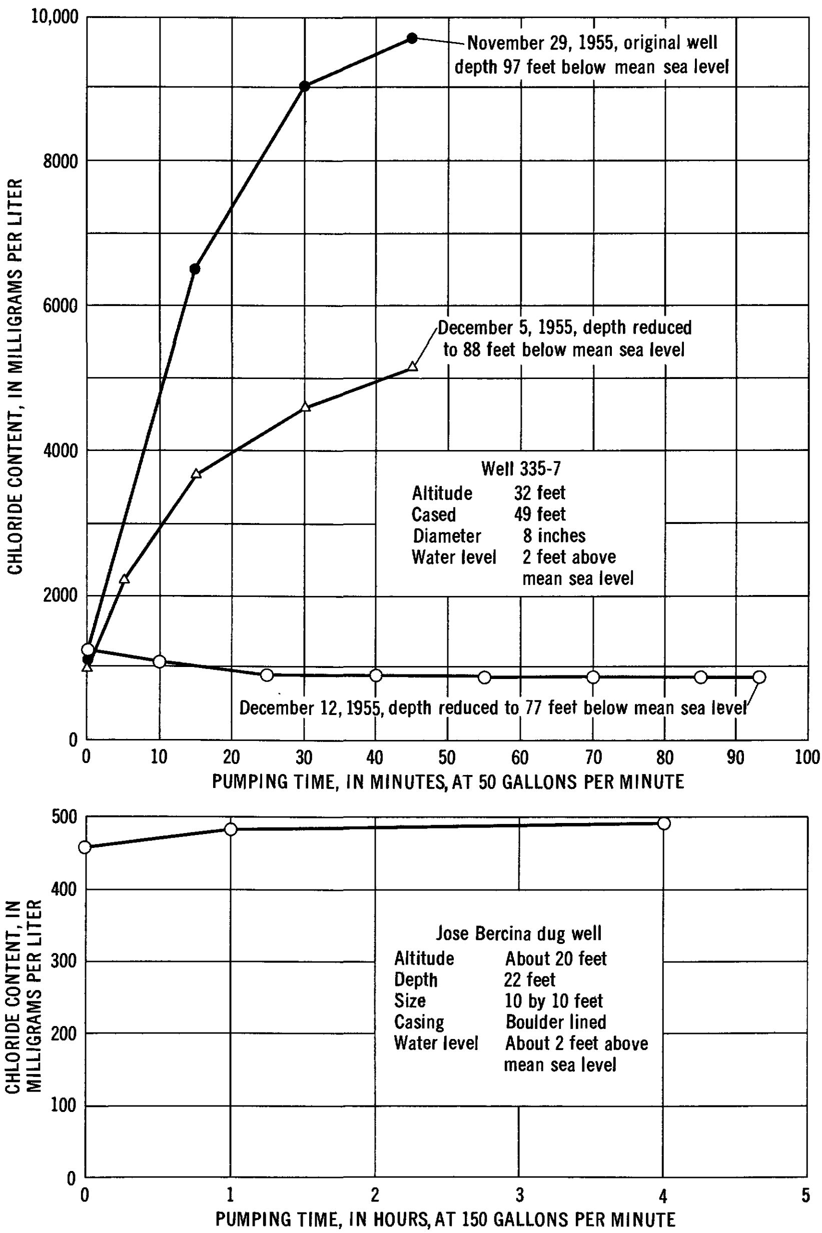

FIGURE 28.—Relations between pumpage and chloride content of water from well 335–7 and the Jose Bercina dug well.

TABLE 7.—*Water-resources summary for the Kahuku area, excluding the coastal plain*

	Subarea				Total (rounded)	Explanation
	Hauula	Laie	Kahuku	Waimea-Kawela		
	Million gallons per day					
(1)	46	40	40	96	220	Rainfall.
(2)	10	15	20	53	100	Evapotranspiration.
(3)	36	25	[1] 25	[2] 44	130	Net rainfall.
(4)	9	8	8	19	45	Runoff.
(5)	27	17	17	25	85	Ground-water recharge.
(6)	3	4	22	0. 6	30	Ground-water draft.
(7)	24	13	−5	24	55	Unused ground-water flow and overdraft.
(8)	10	7	3	[3] 10 [4] 1		Ground-water flow per coastline mile.
(9)	1	1	4	[3] 0. 3 [4] 0. 3		Draft per coastline mile.
	Percentage of rainfall (rounded)					
(1)	100	100	100	100	100	Rainfall.
(2)	20	40	50	55	45	Evapotranspiration.
(3)	80	60	50	45	60	Net rainfall.
(4)	20	20	20	20	20	Runoff.
(5)	60	40	30	25	40	Recharge to ground water.
(6)	5	10	55	1	15	Ground-water draft.
(7)	55	30	0	24	25	Unused ground-water flow.

[1] Includes estimated 5 mgd infiltration of irrigation water.
[2] Includes estimated 1 mgd infiltration of irrigation water.
[3] Dike zone.
[4] Dike-free zone.

per coastline mile is low and flow is high. The Waimea-Kawela subarea is not promising owing to the low flow per coastline mile, even though draft is low. Estimates in table 7 that show a 3:4 ratio of flow to draft per coastline mile indicate overdevelopment of basal water in the Kahuku subarea. On the same basis, a 10:1 ratio indicates that development of dike water in the Waimea-Kawela subarea is promising.

Pumpage in 1963 and its effect on water levels in wells in the subareas are shown in figure 29. Water levels in well 337, a dike-water well, is unaffected by heavy basal-water pumpage in the adjacent Kahuku subarea. Basal-water levels in the Waimea-Kawela subarea, although not shown in figure 29, are also unaffected by pumpage in the other subareas.

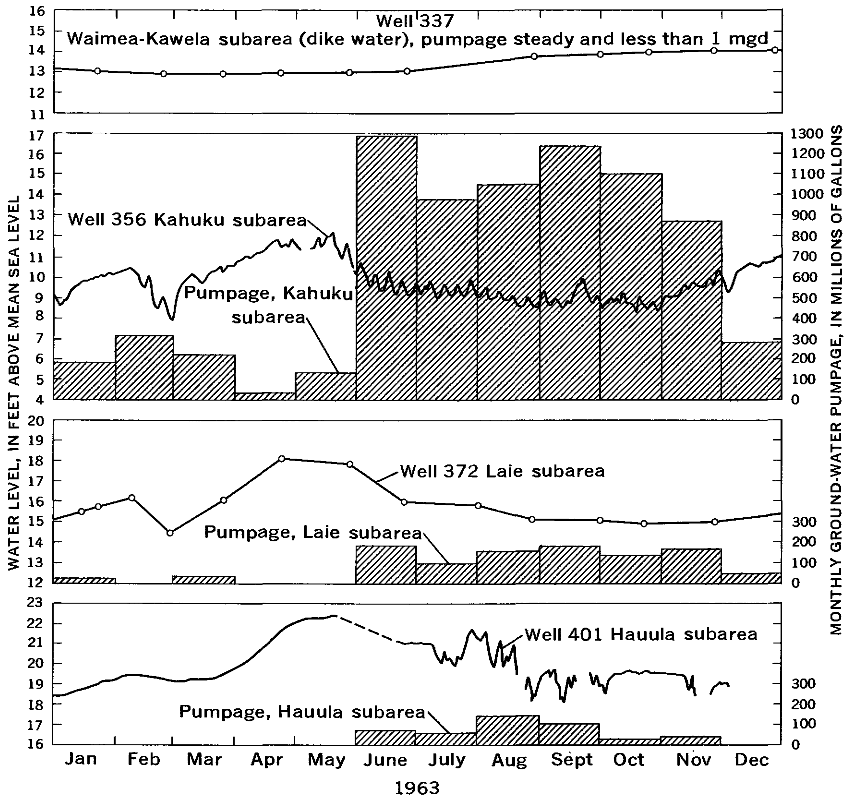

FIGURE 29.—Pumpage from and water-level fluctuations in representative wells in the Hauula, Laie, Kahuku, and Waimea-Kawela subareas in 1963.

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