Water Resources of North-Central Oahu, Hawaii

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1899-D

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 J. C. ROSENAU, E. R. LUBKE, *and* R. H. NAKAHARA

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

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WATER RESOURCES OF NORTH-CENTRAL OAHU, HAWAII

By J. C. ROSENAU, E. R. LUBKE, and R. H. NAKAHARA

ABSTRACT

North-central Oahu consists of 152 square miles and includes mountainous terrain, the Schofield Plateau, and a narrow coastal plain. Half the area is above an altitude of 1,000 feet and receives 71 percent of the 580 mgd (million gallons per day) average annual precipitation. Recharge to ground-water reservoirs from precipitation is estimated to be about 225 mgd.

Streamflow to the ocean is negligible, except during floods, owing to diversions by way of numerous mountain ditches into reservoirs. As it is used for irrigation of sugarcane, a large part of the diverted water percolates into underlying ground-water reservoirs.

Ground water is available from wells drilled into lava flows of the Koolau and Waianae Volcanic Series and from shallow sedimentary material in the coastal plain. About 200 mgd discharges to the ocean from ground-water reservoirs underlying the coastal plain.

Water use in a dry year is about 93 mgd—75 mgd for irrigation and 18 mgd for domestic, industrial, and miscellaneous uses. Two-thirds of the total is from ground-water sources, and one-third is from streams and reservoirs. Long-term ground-water pumpage for all uses averages 48 mgd, of which nearly 42 mgd is for irrigation. Average annual streamflow diversion is 57 mgd, and irrigation application is approximately 36 mgd.

Salt-water intrusion of the shallow sedimentary material or of the deeper water-bearing lava is not yet a major problem. Water from a few heavily pumped coastal wells has become moderately saline, but a reduction in pumping at these sites, a dispersal of wells, or an inland placement of new wells would minimize intrusion.

INTRODUCTION

This report summarizes the findings of a study of a part of northern Oahu (fig. 1). It briefly describes the distribution of rain-

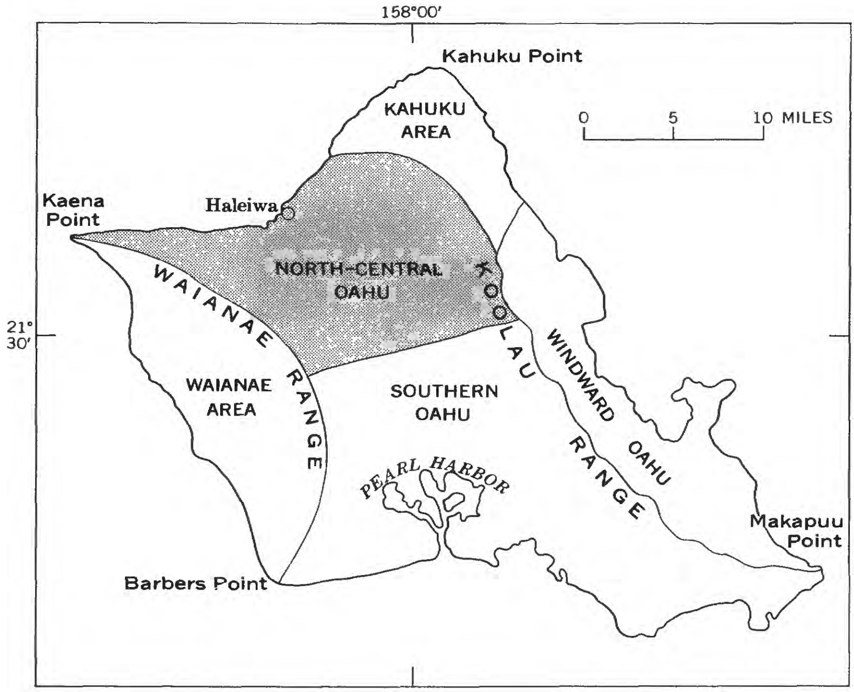

FIGURE 1.—Island of Oahu, Hawaii, showing areas of this study and of related investigations.

fall and of irrigation water, outlines the geology, and discusses the occurrence, quality, and quantity of water available.

The demand for water for municipal and irrigation use is increasing in the Mokuleia-Waialua area. Subdivision development and other aspects of urbanization are shifting the pattern of water use. Information is needed, therefore, on the quantity and quality of water that is available for development.

The study was made by the U.S. Geological Survey in cooperation with the Division of Water and Land Development, Department of Land and Natural Resources, State of Hawaii. It is one of a series of studies on Oahu designed to provide information for use in the development and efficient management of the water supply of the island. Related studies have been made in southern Oahu (Visher and Mink, 1964), the Waianae area (Zones, 1963), windward Oahu (Takasaki and others, 1969), and the Kahuku area (Takasaki and others, 1966) (fig. 1). Other related studies are in progress.

Previous studies of Oahu were made by Stearns and Vaksvik (1935, 1938) and Stearns (1940). Geology and topography were described, records of wells were given, and ground-water resources of the study area were discussed in a general way in reports resulting from these studies. The Board of Water Supply, City and County of Honolulu, and the Waialua Sugar Co. have, in their files, unpublished reports by D. C. Cox, H. S. Palmer, H. T. Stearns and G. A. Macdonald, and W. B. Thomas.

The writers are indebted to the Board of Water Supply, City and County of Honolulu, and to the Waialua Sugar Co. for making valuable hydrologic data available.

The study area includes 152 square miles. Figure 2 shows the northern half of Oahu, illustrated as seen from an altitude of about 10,000 feet and north of the island. The study area is bounded by the crest of the Koolau Range and the drainage basin of Kamananui Stream on the east, by the crest of the Waianae Range on the west, by the ocean on the north, and by the summit of the Schofield Plateau in the area of Wahiawa and Schofield Barracks on the south.

The Koolau Range, rising to 2,763 feet above sea level, dominates the physiography of northern Oahu. Its broad and gently sloping west side stretches to Schofield Barracks, to the base of the Waianae Range, and to the ocean, and is cut by many streams that converge into six major valleys. These deep and narrow valleys are separated by ridges planted to sugarcane and pineapple up to altitudes of about 1,600 feet.

The Waianae Range is higher than the Koolau Range, having a maximum altitude of 4,025 feet at Kaala. The north and east sides of the Waianae Range are steep and extensively gullied, and the ridges are generally too narrow for cultivation.

Through irrigation, sugarcane is cultivated in the dry coastal areas and part way up the slopes of the Koolau Range and the Schofield Plateau. Pineapple is grown without irrigation throughout most of the upper Schofield Plateau area. Aside from sugarcane, vegetal cover is controlled by the local climate. Kiawe (algaroba) covered dry areas and patches of pricklypear cactus border the shore and extend partly up the flanks of the adjacent mountains. The higher altitudes are generally wetter than the lower and are covered by guava, koa, and other plants of the wet-forest type.

GEOLOGY

The geologic history of the Hawaiian Archipelago was described by Stearns (1966 and 1967). Stearns and Vaksvik (1935) and Stearns (1939, 1940) mapped and described the geology of Oahu

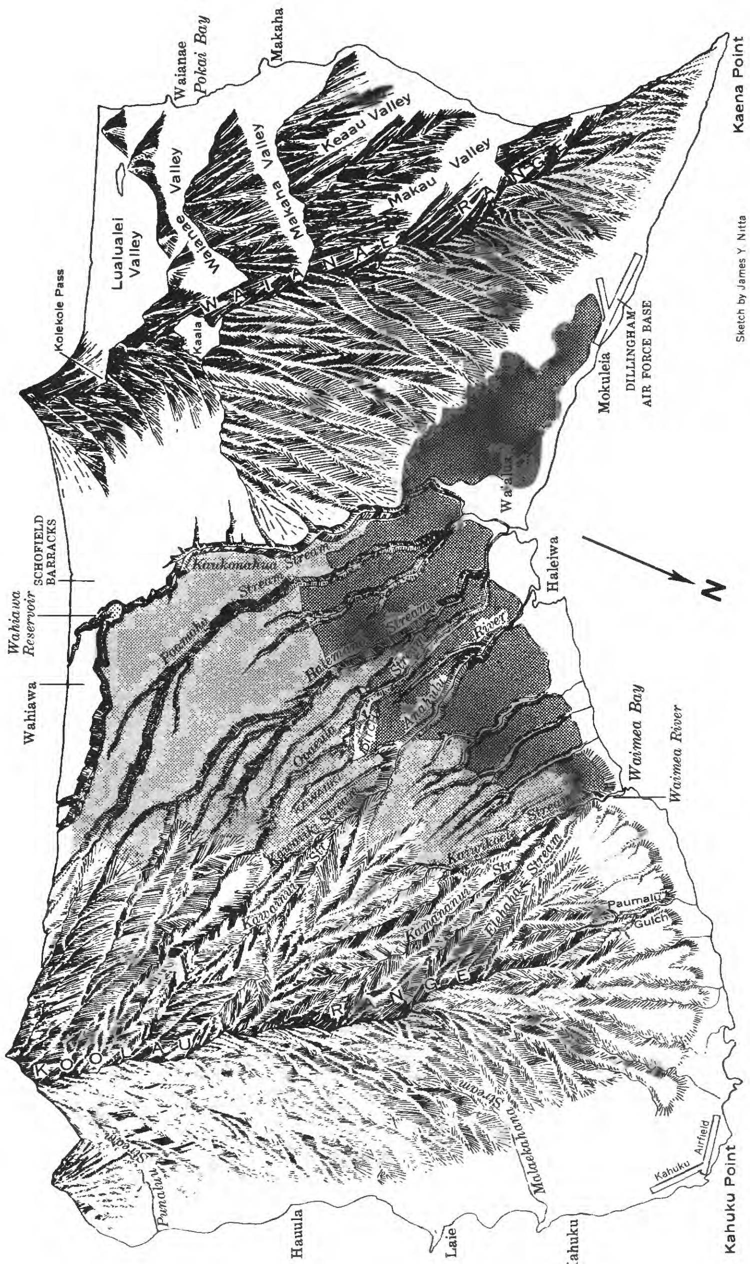

FIGURE 2.—A southeasterly aerial view of northern Oahu, showing the massive Koolau Range on the east and the more eroded Waianae Range on the west topped by the 4,025-foot Kaala. Sugarcane in north-central Oahu is grown on the lower gentle slopes (dark tone), and pineapple is grown on parts of the higher slopes (light tone).

(fig. 3). Owing to the scarcity of outcrops, wells, and test holes in critical areas, additional detailed geologic information is lacking upon which to base hydrologic interpretations.

The oldest rocks of northern Oahu are lava flows of the Waianae volcano, which are partly overlapped by younger flows of the Koolau volcano and separated locally by alluvium from the younger flows. Erosion has diminished the Waianae and Koolau volcanoes, cutting deep, narrow valleys into their flanks. The eroded material forms extensive alluvial deposits in the lowlands.

The Waianae Range is built of the basaltic lava flows and dikes of the Waianae Volcanic Series of Pliocene(?) age (G. A. Macdonald and D. A. Davis, in Avias, 1956, p. 135-136). (For general description, see G. A. Macdonald, in Stearns, 1967, p. 110-112.) Stearns and Vaksvik (1935, p. 67) divided the series into three members: the lower consists of 2,000 feet of thin-bedded pahoehoe; the middle is similarly thick but contains more aa; the upper consists of 2,300 feet of massive aa flows. A dike-complex zone lies west of the present crest of the Waianae Range, but only a few dikes have been found on the east side, where vegetation is extensive and the surface is only lightly eroded. G. A. Macdonald (in Stearns, 1940, p. 63-91) modified and elaborated on part of the earlier work of Stearns and Vaksvik. He wrote that lava of the lower member was thinly bedded and gently dipping olivine basalt; that lava of the middle member was thicker, more massive, and nearly horizontal olivine basalt; and that lava of the upper member was similar to that of the middle member but typically consisted of basaltic andesite.

The northern part of the Koolau Range was formed by basaltic flows of the Koolau Volcanic Series, also of Pliocene(?) age (G. A. Macdonald and D. A. Davis, in Avias, 1956, p. 106-107). The series, which is more than 3,100 feet thick, consists of flows of pahoehoe and aa that range from 10 to 80 feet in thickness. Even the thick flows consist of several layers (Stearns and Vaksvik, 1935, p. 93). The flows were extremely fluid and succeeded one another fairly rapidly. The landward flanks of the two ranges are similar, as are the seaward flanks. The landward flanks, however, lack the outcrops, the dikes, and the na pali ku'i, or joined succession of cliffs, that are typical of the seaward flanks of both ranges (fig. 2).

Basaltic rocks of the island are generally permeable, but the Koolau rocks are more permeable than those of the Waianae. High permeability, the favorable geologic framework (Takasaki and others, 1962, p. 4-7), and high rates of precipitation and

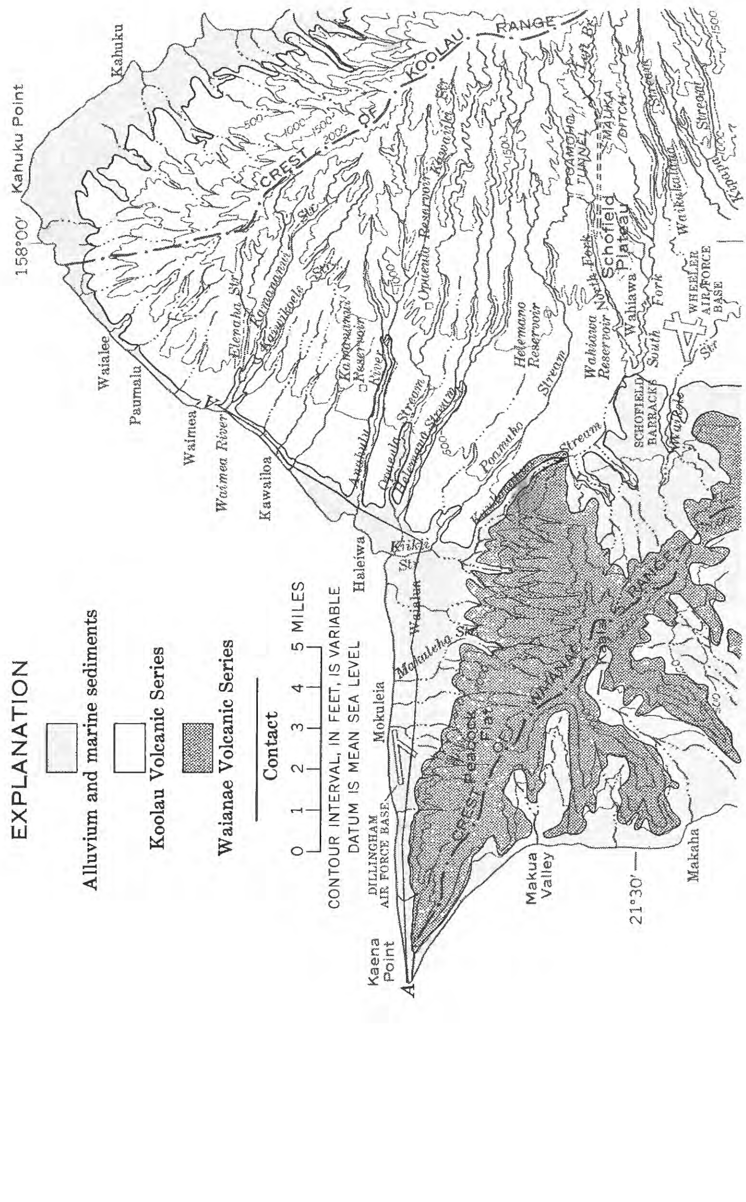

FIGURE 3.—Generalized geologic map; section *A-A′* shown in figure 4. (After Stearns, 1939.)

recharge make the Koolau Range the largest source of water on the island.

Alluvium and marine sediments of sand and coral are shown as a group in figure 3 because they are small in volume and areal extent and are limited mostly to nearshore locations. These materials overlie lava flows in the coastal plain (fig. 4) from Kaena Point eastward to the Waimea River and confine the underlying artesian aquifers. They are known to be as thick as 500 feet in the Mokuleia area and 200 feet at Waialua and to decrease in thickness to a variable veneer east of the Anahulu River.

CLIMATE

The climate of northern Oahu is characterized by mild temperatures (fig. 5), northeast trade winds, and between 25 and 300 inches of rainfall annually (fig. 6). Rainfall gradients are steep. Orographic lifting of moisture-laden trade-wind air causes frequent light lowland showers and moderate to heavy mountain showers throughout the summer and part of the winter. Although trade-wind rainfall is the most consistent water source, storms are important to the replenishment of ground water in the Koolau Range and of even greater importance in the Waianae Range. As many as seven major storms may occur in 1 year, bringing torrential rains and perhaps violent winds (Blumenstock, 1961).

Figure 5 includes a group of graphs that shows the effect, at a low coastal station (847) and at a mountain station (844.4), of the winter storms in 1963. A comparison of 1963 rainfall with mean monthly rainfall at these stations shows that 1963 was a wet year because of the storms in January, March, April, and May—in spite of near- or below-normal rainfall during the rest of the year.

The size and intensity of individual storms can be inferred from table 1. March 1964 rainfall at Wheeler Air Force Base (sta. 810, fig. 6) was large, even larger than that on top of Kaala (sta. 844.2), whereas December rainfall was large throughout the study area—a third or more of annual rainfall at many stations.

Humidity is generally between 60 and 80 percent in northern Oahu. Air temperature has a small annual and daily range—the difference between the coldest and warmest months averages only 6.5°F (3.6°C). A curve of mean monthly temperature at the Waialua Sugar Co. office (sta. 847) is included in figure 5.

The authors established a group of storage-type rain gages in the watershed area of the Waianae Range. The gages were concentrated on the north and northeast slopes of the range, as rain-

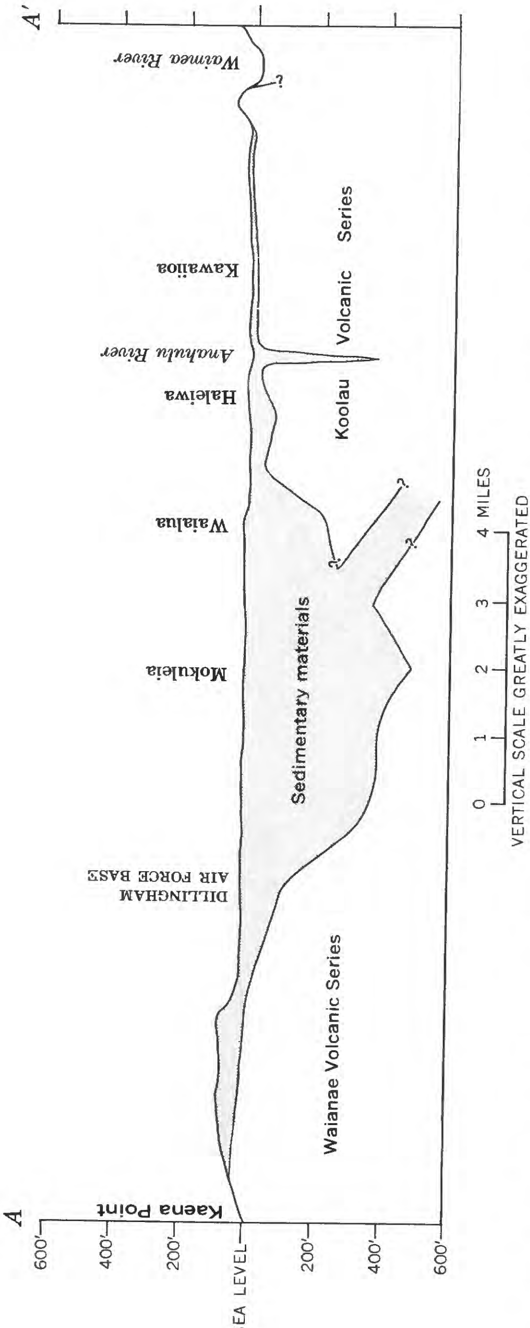

FIGURE 4.—Geologic section through the coastal plain of north-central Oahu, showing thickness of sediments overlying the rocks of the Koolau and Waianae Volcanic Series. Location of section shown in figure 3.

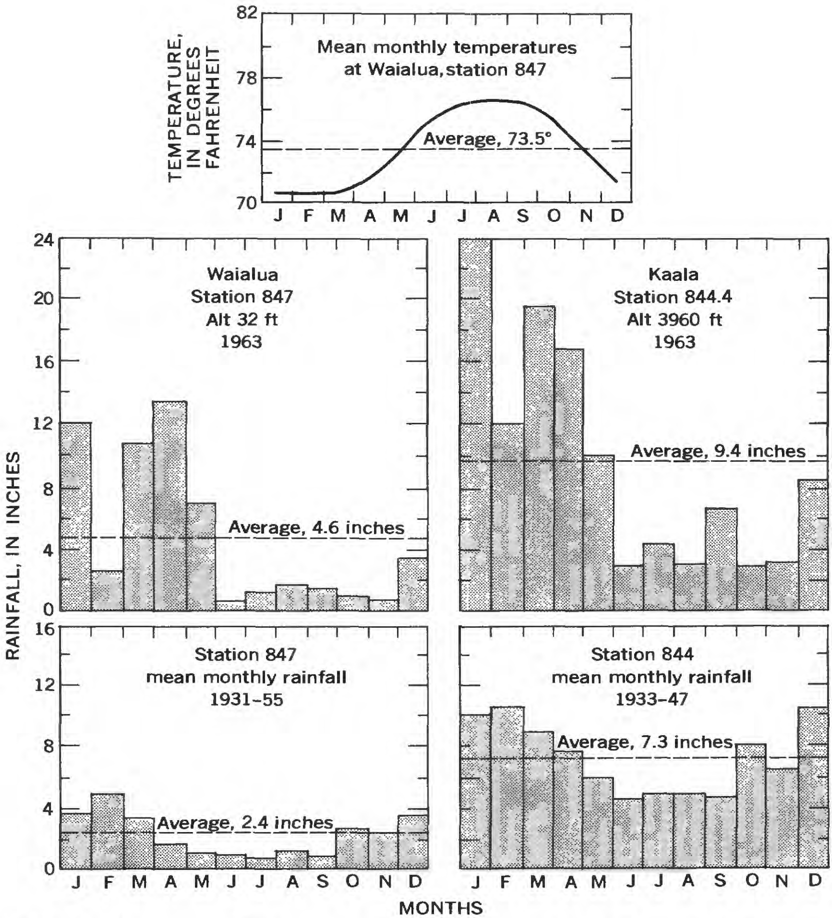

FIGURE 5.—Mean monthly temperature at Waialua (sta. 847) and the monthly rainfall for 1963 and the mean monthly rainfall for the period of record at Waialua (sta. 847) and at Kaala (sta. 844.4 and 844).

fall data from there were sparse or nonexistent. Table 2 lists the number, name, and altitude of rain-gage stations shown in figure 6.

WATER RESOURCES

HYDROLOGIC SETTING

Rain is the source of fresh water. Upon reaching the ground, part of the rain evaporates and part is transpired, a part flows to the sea in streams, and the remainder filters down through the soil and rock to the water table and recharges the ground-water reservoir.

TABLE 1.—*Monthly rainfall in inches, at selected stations in 1964 in northern Oahu*

[These rain-gage stations are identified by number, name, and altitude in table 2, and their locations are shown in figure 6]

	Station number								
	843.1	844.2	841.9	857.2	802.2	810	870	892	887
January	2.6	8.6	4.00	2.6	3.7	3.74	7.37	6.15	3.46
February	.3	3.9	2.70	.9	.3	2.24	3.48	2.63	1.08
March	5.1	14.3	2.10	8.5	8.1	16.63	5.45	5.80	4.96
April	1.4	4.8	1.21	1.0	1.7	1.85	3.70	2.14	1.52
May	.3	4.4	.38	.4	.9	1.00	1.43	1.67	.47
June	.1	1.8	.11	.3	.3	.50	2.10	2.24	.28
July	2.2	9.0	1.34	1.2	1.4	2.41	3.35	3.32	1.25
August	.2	2.9	.35	.4	.5	.74	3.11	3.18	.99
September	.2	3.0	.36	.4	1.4	.85	3.07	2.13	.48
October	2.2	8.5	2.27	1.4	2.0	1.46	2.28	2.59	1.78
November	2.5	12.6	2.50	5.1	8.0	10.60	8.79	5.85	3.55
December	17.0	27.2	11.60	10.0	16.0	15.87	13.11	16.53	15.50
Total	34.1	101.0	28.92	32.2	44.3	57.89	57.24	54.23	35.32

Rain on the 152 square miles of the study area is equivalent to an average of 580 mgd (million gallons per day), as determined from the data shown in figure 6. Of this quantity, 413 mgd, or 71 percent, falls in the 80 square miles that lies above an altitude of 1,000 feet. About 12 mgd falls in the 10 square miles between sea level and an altitude of 40 feet, and the remaining 155 mgd, or 27 percent, falls in the area between.

Ground water sustains high-altitude streamflow during dry periods in the Waianae and Koolau Ranges. Most streamflow is diverted for irrigation or eventually infiltrates through the streambeds; streamflow reaches the ocean only after periods of intense or prolonged rainfall.

Near the coast a large part of the ground water reaches the ocean as underflow. Some of the water discharges at ground level from springs or as seepage into low-lying swamps. A considerable quantity of water also is pumped for irrigation from wells along the coast, but about 40 percent of the applied irrigation water reenters the ground-water body by deep percolation (Dale, 1967).

About 90 percent of the water diverted from streams and pumped from lava aquifers is used for irrigating approximately 10,000 acres of sugarcane—3,000 acres with surface water and

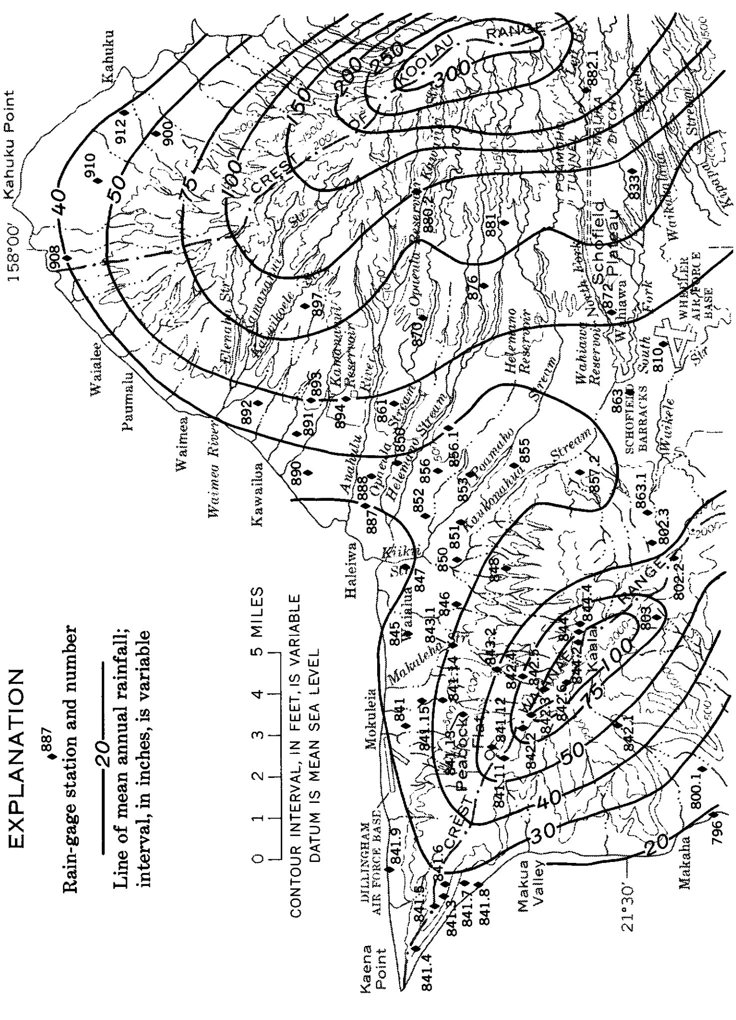

FIGURE 6.—Mean annual rainfall and the locations of rain-gage stations. (Adapted from Honolulu Board of Water Supply, 1963.)

TABLE 2.—*Rain-gage stations in northern Oahu*

[Numbers assigned by Hawaii State Division of Water and Land Development. *, Maintained by the U.S. Geological Survey]

Station	Name	Altitude (ft.)	Station	Name	Altitude (ft.)
796	Makaha Kai	25	847	Waialua	32
800.1	Makaha Valley	160	848	Puu Iki	1,040
*802.2	Quarry (Schofield)	1,580	850	Kemoo 2	45
*802.3	Range 1–2 (Schofield)	1,350	851	Kemoo 5	285
803	Waianae Mauka	1,575	852	Helemano 4	180
810	Wheeler Air Force Base	845	853	Kaheeka	520
833	Koolau Dam	1,060	854	Helemano 9	310
841	Kawaihapai	20	855	Kemoo Camp 8	730
841.3	Kaena Point	1,300	856	Helemano 6	470
*841.4	KP–5 (Kaena Point)	880	856.1	Helemano 6C	700
*841.5	KP–4 (Kaena Point)	1,200	*857.2	McCarthy 5 (Schofield)	960
*841.6	KP–3 (Kaena Point)	1,300	861	Opaeula 8	690
*841.7	KP–2 (Kaena Point)	400	863	Wahiawa Dam	855
*841.8	KP–1 (Kaena Point)	45	863.1	Area BB (Schofield)	1,160
*841.9	Bowman cottage	60	870	Opaeula	1,060
*841.11	PFR–6 (Peacock Flat)	2,050	872	Wahiawa	920
*841.12	PFR–4 (Peacock Flat)	1,610	876	Waialua Mauka	1,250
*841.13	PFR–3 (Peacock Flat)	1,060	880.2	Kawai Iki Intake	1,180
*841.14	PFR–2 (Peacock Flat)	360	881	Helemano Intake	1,275
*841.15	PFR–1 (Peacock Flat)	80	882.1	North Fork Kaukonahua	1,150
*842.1	Makaha (USGS)	970	887	Opaeula 2	110
*842.2	PFR–5 (Peacock Flat)	2,190	888	Opaeula 3	245
*842.3	PFR–7 (Peacock Flat)	2,050	890	Kawailoa	170
*842.4	KR–3 (Kaala Rd.)	1,725	891	Waimea 8	320
*842.5	KR–4 (Kaala Rd.)	2,190	892	Waimea	420
*842.6	KR–5 (Kaala Rd.)	2,700	893	Kawailoa 15	520
*843.1	KR–1 (Kaala Rd.)	240	894	Kawailoa 19	660
*843.2	KR–2 (Kaala Rd.)	920	897	Waimea Mauka	920
844	Kaala	4,000	900	Malaekahana (Kahuku)	190
*844.2	KR–7 (Kaala Rd.)	3,965	908	Pump 4 (Waialee)	40
*844.4	KR–8 (Kaala Rd.)	3,960	910	Pump 10 (Kahuku)	200
845	Pump 16 (Mokuleia)	20	912	Kahuku	25
846	Ranch (Mokuleia)	190			

7,000 acres with ground water. About two-thirds of the water used is pumped from wells or shafts, and the remainder is diverted from streams in the Koolau Range.

Ground-water withdrawal in north-central Oahu has increased slightly since 1924. Average daily pumpage from year to year has fluctuated between 28 and 70 mgd (fig. 7). This fluctuation is the result of irrigation demands, which vary seasonally and annually according to rainfall.

Municipal pumpage has increased from less than 0.5 mgd in 1938 to as much as 8 mgd in 1965. Most of the increase has been on the Schofield Plateau, where water is needed for both civilian and military uses. From 2 to 5 mgd is used for air conditioning and small-truck-farm and forage-crop irrigation.

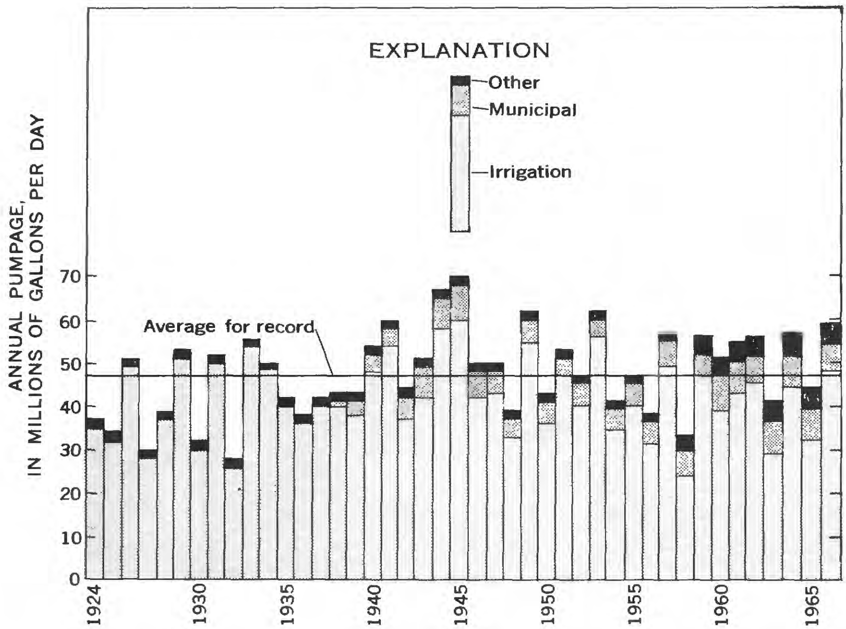

FIGURE 7.—Annual pumpage and the use of ground water in north-central Oahu, 1924-66. Municipal pumpage before 1938 was less than 0.5 mgd and is not shown.

STREAMFLOW

KOOLAU RANGE

About one-third of the water used in north-central Oahu is diverted from streams in the upper part of the Koolau Range. The streams are generally perennial in their upper reaches but dry in their lower reaches owing to water being diverted. Highly permeable streambeds facilitate infiltration of undiverted flows. Except for Kiikii Stream and Anahulu River, which are fed by spring flow near sea level, no streams flow to the sea unless rainfall is heavy and of long duration or is unusually intense.

The Geological Survey has maintained stream-gaging stations in north-central Oahu since 1911. Major stations are identified by number and name of stream-gaging station in table 3 (Hoffard and Vaudrey, 1966) and in figure 8.

The flashiness of streams in the Koolau Range is illustrated in figure 9, which shows the gage-height record of Opaeula Stream (sta. 3450) during a 12-hour period on January 31, 1963. During

TABLE 3.—*Stream-gaging stations in northern Oahu*

[*, crest-stage gage site]

Station	Period of record	Name of station	Altitude (ft.)	Drainage area (sq mi)	Peak flow Mgd	Peak flow Cfs
2080	1957–	South Fork Kaukonahua Stream at East Pump Reservoir, near Waihiawa	860	4.04	3,530	5,460
2085	1958–	Right Branch South Fork Kaukonahua Stream near Wahiawa	980	.86	880	1,360
2000	1913–53, 1960–	North Fork Kaukonahua Stream above Right Branch, near Wahaiwa	1,150	1.38	3,550	5,490
2040	1946–	North Fork Kaukonahua Stream near Wahiawa	970	4.86	3,010	4,660
2030	1947–	Mauka Ditch near Wahiawa	1,140	—	10	16
2109	1958–	Poamoho Tunnel near Wahiawa	1,120	—	128	198
2110	1947–	Poamoho Stream near Wahiawa	1,150	1.79	1,710	2,650
3450	1959–	Opaeula Stream near Wahiawa	1,120	2.98	1,810	2,800
*3500	1955–	Opaeula Stream near Haleiwa	20	5.96	2,660	4,120
*3400	1957–	Anahulu River near Haleiwa	70	13.5	2,500	3,870
3250	1963–	Kamananui Stream at Pupukea Military Road, near Maunawai	590	3.13	844	1,310
3300	1958–	Kamananui Stream at Maunawai	20	9.79	2,230	3,450
*2113	1958–	Makaleha Stream near Walalua	180	4.24	2,352	3,640

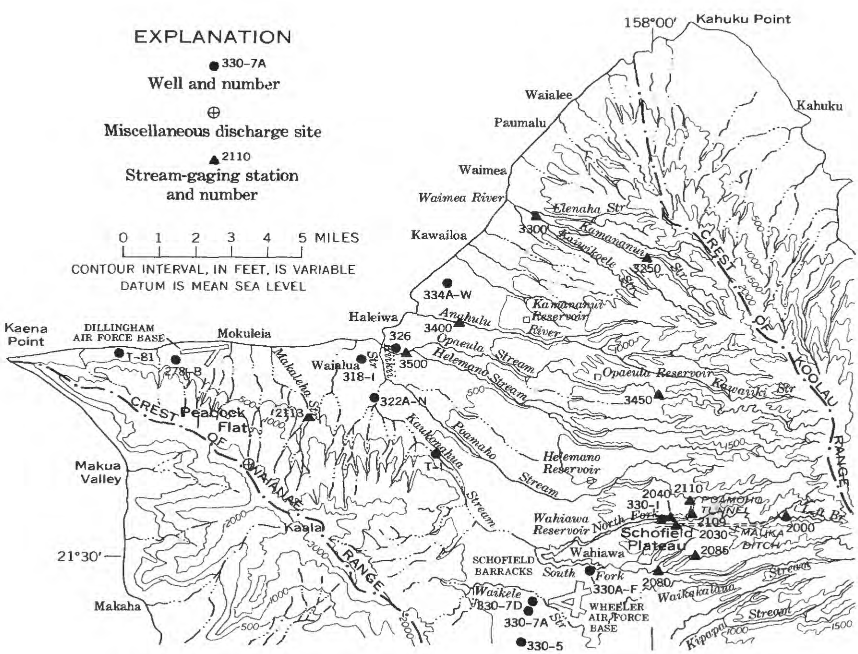

FIGURE 8.—Locations of hydrologic data sites.

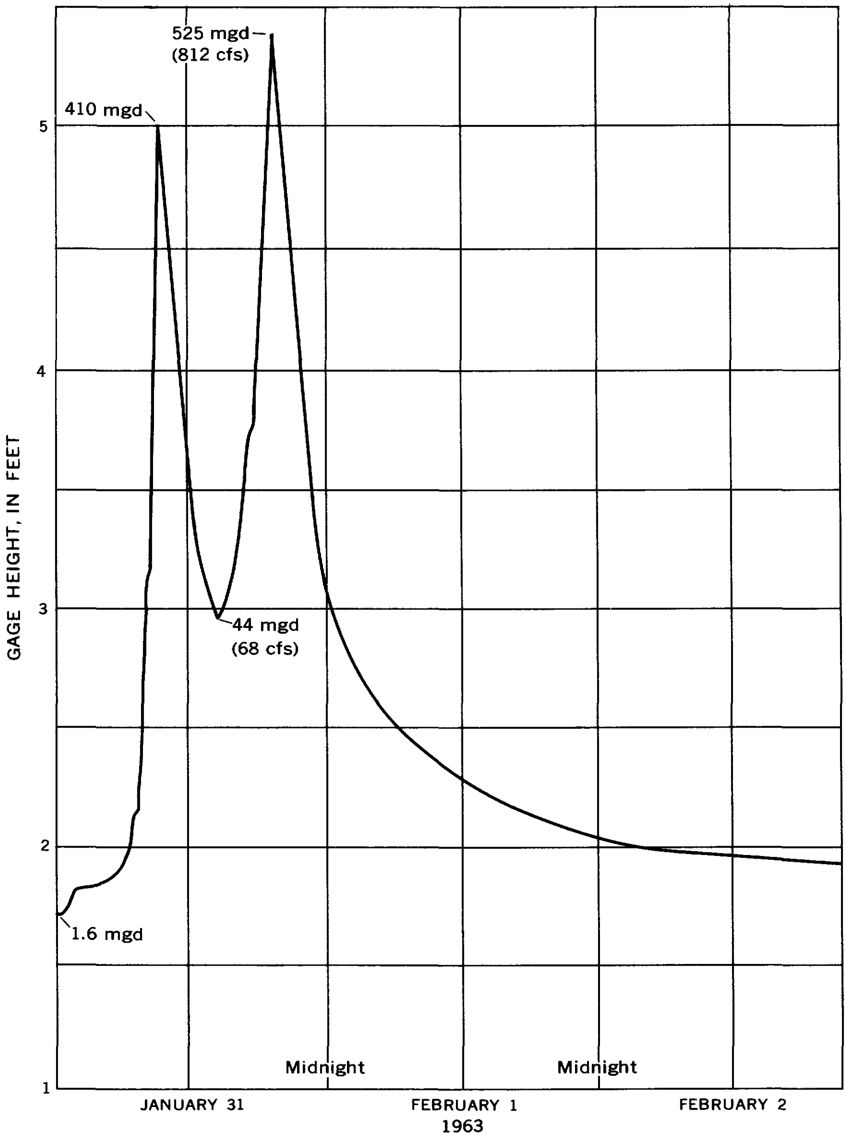

FIGURE 9.—Gage height of Opaeula Stream near Wahiawa (sta. 3450) for the period January 31 through February 2, 1963. Instantaneous discharges are given at various gage heights.

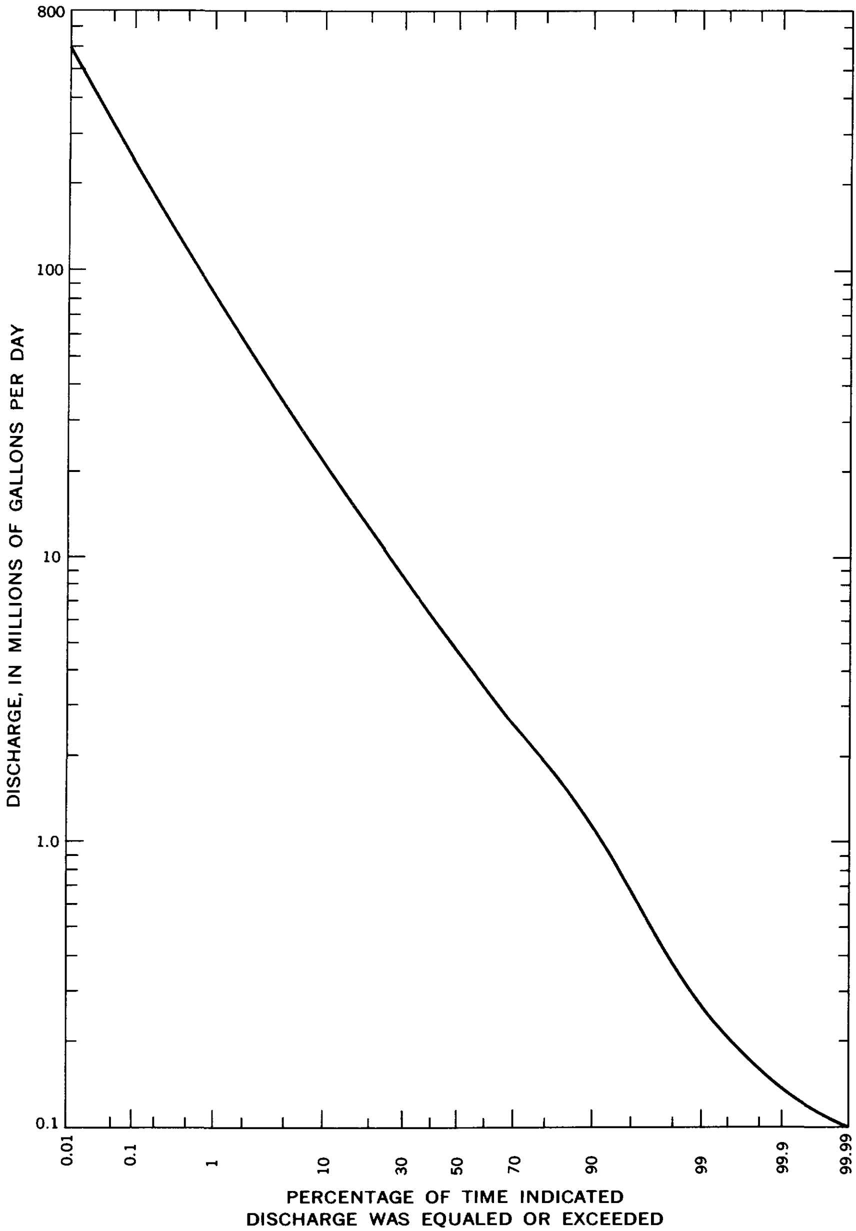

FIGURE 10.—Flow-duration curve of the North Fork Kaukonahua Stream above Right Branch near Wahiawa. The period of record is 1927-53 and 1961-62.

the passage of two storms 4½ inches of rain fell, causing instantaneous discharge as great as 525 mgd, or 812 cfs (cubic feet per second). Similar storms are fairly common during the winter and can occur any time of year.

Variability of streamflow is illustrated in figure 10, which is a flow-duration curve for North Fork Kaukonahua Stream above Right Branch (sta. 2000). The steep slope throughout the curve reflects the extreme variability of flow resulting from a very small ground-water source and the rapid response of runoff to rainfall. The curve shows that average daily flow exceeded 1.1 mgd about 90 percent of the time, 10 mgd about 25 percent of the time, and 100 mgd less than 1 percent of the time.

The Waialua Sugar Co. diverts about 55 mgd of water from streams on the west side of the Koolau Range and applies about 35 mgd for the irrigation of sugarcane through four diversion-collection-distribution systems. The Wahiawa Reservoir (fig. 8) is the largest reservoir in the system and in the islands. It has a storage capacity of 2.5 billion gallons and is formed by impounded water of the 17-square-mile Kaukonahua drainage system and the flood flow of the upper Poamoho system. Helemano Reservoir (fig. 8) receives the normal flow of Poamoho Stream and the flow of Helemano Stream above an altitude of 1,074 feet. Opaeula Reservoir receives Opaeula and Kawaiiki streamflow above altitudes of 1,100 and 1,160 feet, respectively. The Kamananui Reservoir receives water from Kawainui Stream above an altitude of 713 feet. The lower parts of Poamoho and Helemano Streams are not tapped, nor is any of the Waimea River complex, which is a part of the northeast boundary of the study area.

Rainfall variations cause annual fluctuations in the amount of streamflow available from the seven major drainage systems of north-central Oahu. The 5-year average annual streamflow of these systems, measured above the diversions, is 83 mgd. Streamflow in a dry year (1962) was only 53 percent of the 5-year average. The following tabulation compares streamflow and water diversions during that year with those during a 5-year period (1962-66).

Streams	Streamflow: 5-year average annual (mgd)	Streamflow: 1962 (mgd)
Kaukonahua	39	24
Helemano and Poamoho	5	5
Opaeula and Kawaiiki	16	8
Kawainui	6	2
Kamananui	9	5
Total	83	44

Reservoirs	Water diverted to reservoirs: 5-year average annual (mgd)	Water diverted to reservoirs: 1962 (mgd)
Wahiawa	39	23
Helemano	6	2
Opaeula	8	4
Kamananui	4	2
Total	57	31

Sixty-nine percent of the 83 mgd average annual measured streamflow was diverted to reservoirs, and an average of 36 mgd was eventually applied to approximately 3,000 acres of sugarcane. The remaining 20 mgd and the 26 mgd that was not diverted recharged the aquifer, evaporated, ran off to the sea during storm periods, or was transpired.

WAIANAE RANGE

Streams in the higher part of the Waianae Range have perennial flow, which probably originates from perched springs at altitudes of about 2,000 feet. Except during periods of intense rainfall and excessive runoff, their flow infiltrates before the streams reach the ocean.

A small unnamed stream about a mile southeast of Peacock Flat (fig. 8, miscellaneous discharge site, lat 21°32′05″ N., long 158°10′50″W.) at an altitude of 2,040 feet was measured at regular intervals between April 1962 and February 1966 (fig. 11*A*). Streamflow at the gage site generally varies seasonally, and the surface-drainage area is about 0.01 square mile. The low-flow period normally occurs between September and November, but in 1964 it began in June and continued until the first winter storm in late October (fig. 11*B*). That storm caused the 7.2-inch October

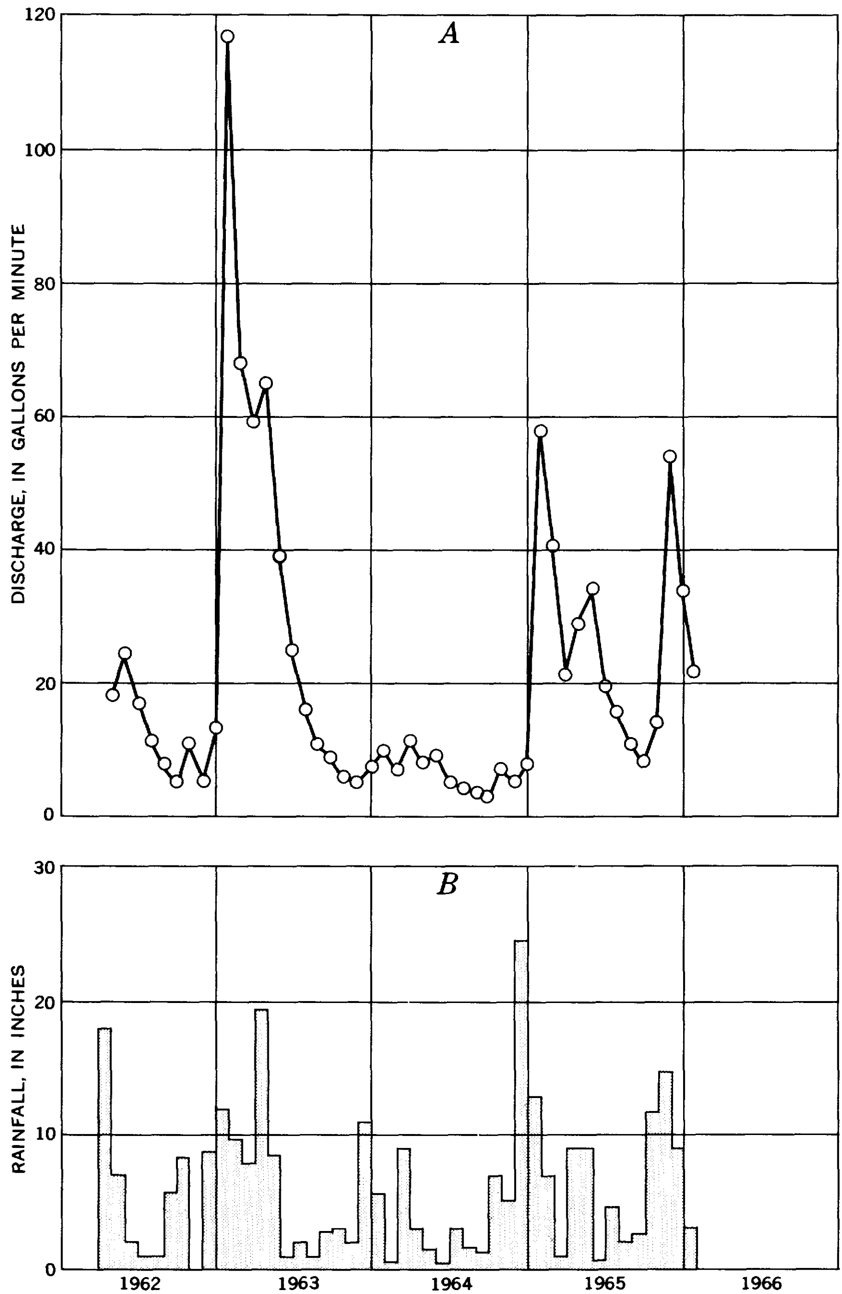

FIGURE 11.—Rainfall and runoff in the Waianae Range. *A*, Instantaneous stream-flow measurements obtained at miscellaneous discharge site near rain gage 842..2. *B*, Monthly rainfall at gage 842.2.

rainfall at station 842.2. In September 1964, after 15 months during which average monthly rainfall was only 3 inches, the flow of the stream had declined to its record low of 2.9 gallons per minute (about 4,200 gpd). Flows exceeding 200,000 gpd (gallons per day) are known to have occurred in response to heavy rainfall.

Half a mile southeast of the previous site are a group of springs (lat 21°31′13″ N., long 158°10′25″ W.) that apparently are the source of the west branch of Makaleha Stream. Measured a short distance below the springs, at an altitude of 1,750 feet and where the surface-drainage area is 0.06 square mile, the stream has a low flow of 30,000 gpd and a maximum flow estimated to exceed 1 mgd.

A mile and a half west of Dillingham Air Force Base, a small spring-fed stream (lat 21°34′40″ N., long 158°14′15″ W.) supplies water to the Bowman cottage (sta. 841.9, fig. 6). The spring is at an altitude of about 700 feet and has a drainage area of 0.01 square mile. It has a low flow of 14,000 gpd, and a maximum flow estimated to exceed half a million gallons per day.

Streams on the lower slopes of the range are ephemeral and have occasional flows that last only hours or a few days, depending on duration and intensity of rainfall. Streamflow records have been kept for Makaleha Stream near Waialua (sta. 2113, fig. 8) since 1958. The stream has a surface-drainage area of 4.20 square miles, and the crest-stage gage is at an altitude of 160 feet. Although Makaleha Stream is dry most of the time, a peak flow of 2,350 mgd (3,640 cfs) occurred on November 13, 1965.

GROUND WATER

Most ground water in northern Oahu is in permeable volcanic rock. It is impounded at high levels in compartments formed by dikes that cut lava flows in the central parts of the Koolau and Waianae Ranges (fig. 12). Ground water occurs similarly in compartments under the Schofield Plateau (fig. 13) and in small scattered bodies perched on weathered ash beds and dense lava flows.

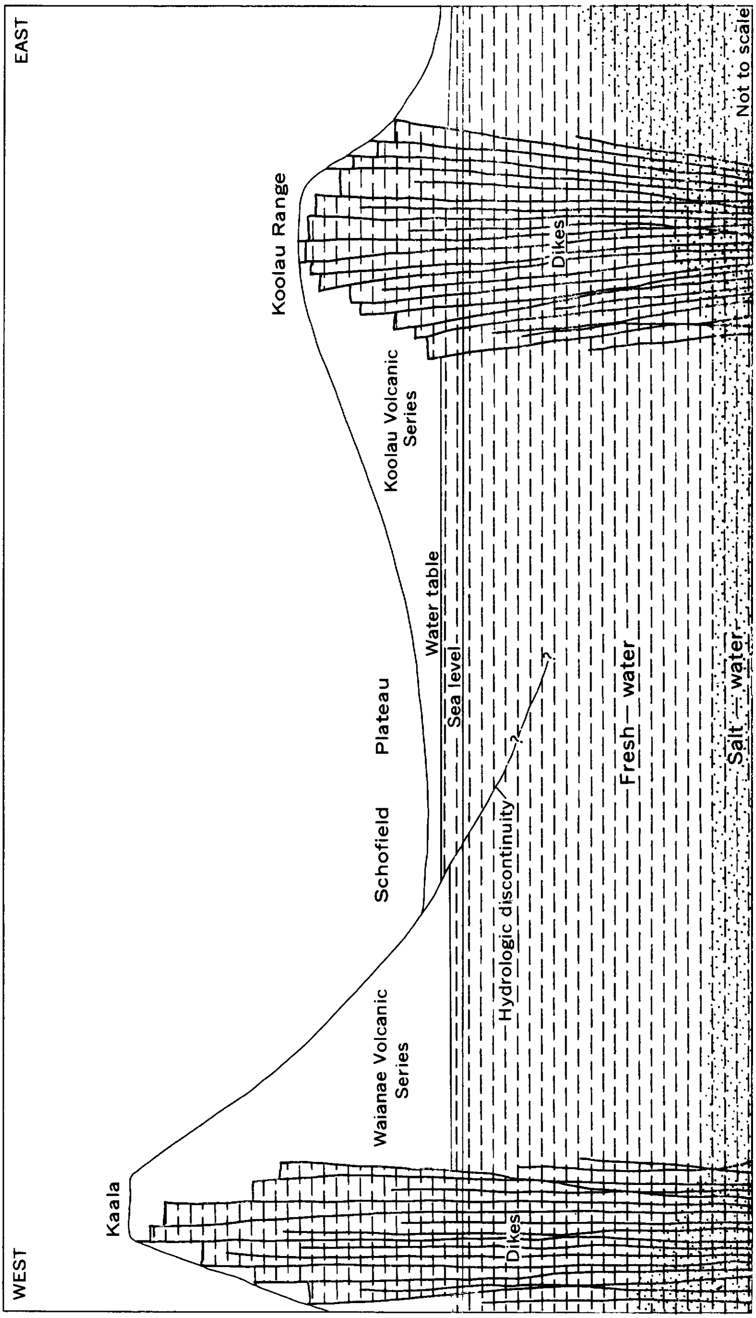

FIGURE 12.—Generalized geohydrologic section from Kaala east through central Oahu and the Koolau Range.

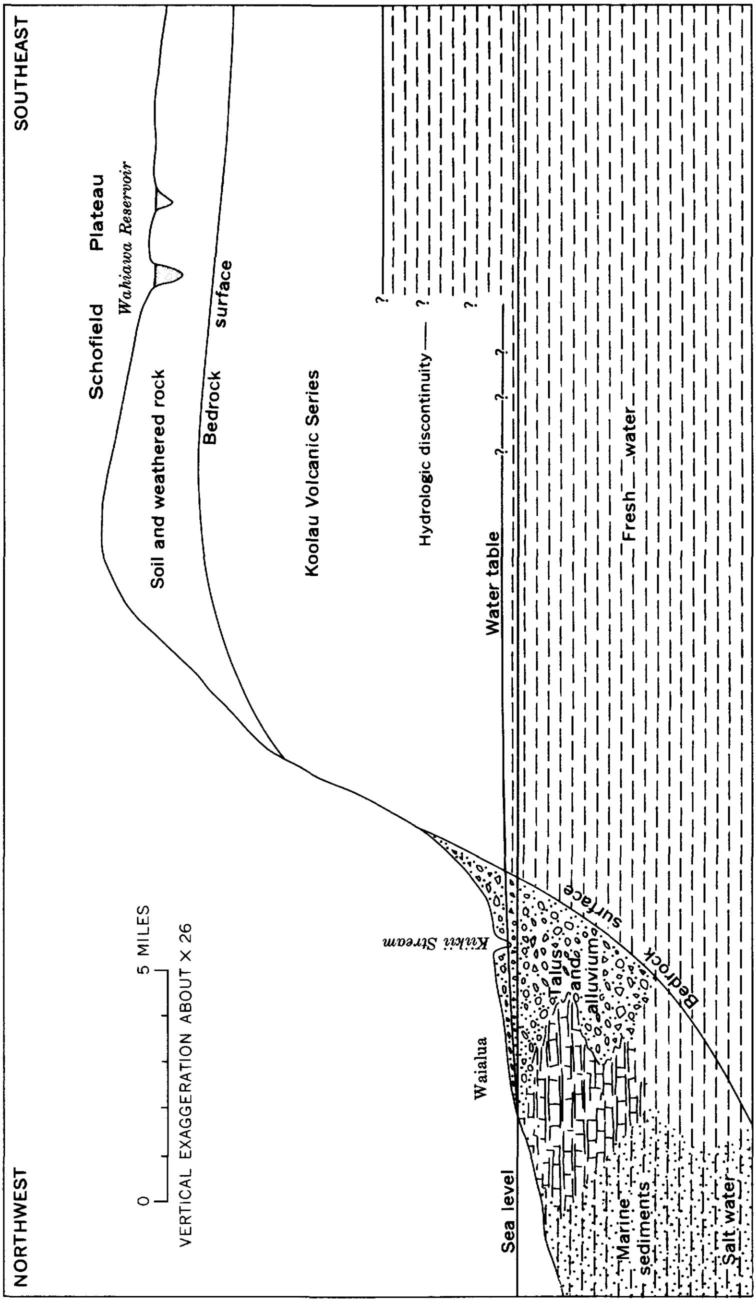

FIGURE 13.—Generalized geohydrologic section from Waialua to the Schofield Plateau.

Under the lower slopes of the ranges and in coastal areas, the water table is near sea level. Near shore, the fresh-water lens is normally confined in lava flows by semipermeable alluvium interbedded with coralline limestone. Water in the sedimentary material is mostly brackish.

Ground water in the study area ranges from fresh to saline. Inland, chloride content is between 10 and 50 mg/l (milligrams per liter). Near the shore, it ranges from less than 50 to more than 2,000 mg/l. This wide range is attributed largely to pumping, which causes mixing of fresh and salt water.

Six major ground-water reservoirs were identified, and their boundaries are shown in figure 14. They are in the upper parts of

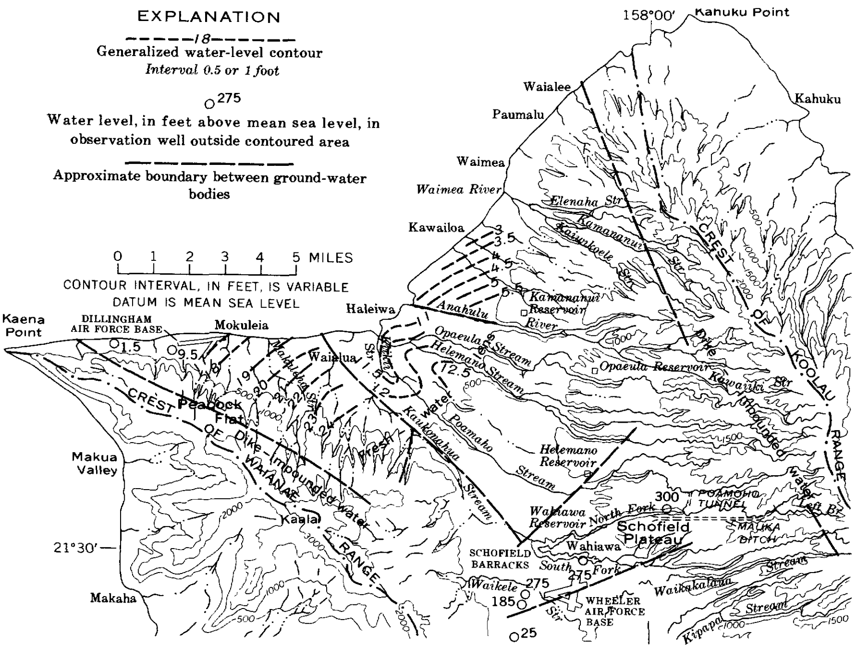

FIGURE 14.—Location and water levels of ground-water bodies in volcanic rock. Water-level contours are based on measurements made in wells during January 1963.

the Koolau and Waianae Ranges, the Schofield Plateau, the Mokuleia area, the Waialua-Haleiwa area, and the Kawailoa area.

KOOLAU RANGE

The ground-water reservoir in the Koolau Range is in dike-compartmented lava flows of the Koolau Volcanic Series (fig. 14). It underlies the Koolau Range, and its west boundary is roughly parallel with and about 2 miles west of the crest. Dikes, which retard lateral movement of ground water within lava flows, cause the water table to stand about 1,000 feet above sea level near the crest.

Rainfall averages 491 mgd (table 5), and recharge to the lava reservoir may exceed 200 mgd (Dale, 1967). Water moves westward and northwestward from the intake area—primarily the west flank of the Koolau Range—to the Mokuleia, Waialua-Haleiwa, and Kawailoa areas and eventually to the sea by way of surface and subsurface springs.

As ground water maintains the flow of streams in the Koolau Range at altitudes above 1,000 feet, the chloride content of the stream water is probably similar to the chloride content of the ground water. Chloride content of water in streams west of the 300-inch rainfall zone (fig. 6) ranges from 10 to 12 mg/l, and that in streams north of the 300-inch zone ranges from 16 to 23 mg/l.

WAIANAE RANGE

Ground water is impounded by dense dike rock in permeable lava flows near the crest of the Waianae Range (fig. 14). Tunneling in the west side of the Waianae Range indicates that the water table near Kaala is above an altitude of 1,500 feet. About 4 miles northeast, however, the water table is less than 30 feet above sea level. The ground-water body in the dike-compartmented lava is recharged by rainfall that averages about 60 mgd. Most of the recharged water probably reaches the sea as ground-water flow in the Mokuleia area, but some may move eastward into adjoining lava flows of the Koolau Range. The chloride content of ground water in the central part of the Waianae Range is from 16 to 31 mg/l.

Ground water in the northwest end of the Waianae Range is perched upon weathered ash beds, which are fairly extensive above an altitude of 200 feet. The quantity of this perched water discharged by springs is small—estimated by Stearns and Vaksvik (1935, p. 439) to be 70,000 gpd. Only a small quantity of the spring water, probably less than 10,000 gpd, is used. Chloride content ranges from 100 to 160 mg/l.

MOKULEIA AREA

A fresh-water reservoir occupies the lava under the lower north slope of the Waianae Range (fig. 14) from Waialua toward Kaena Point and borders that high-level water impounded in dike-compartmented lava flows. The east boundary of the fresh water is west of Waialua, and the boundary is probably formed by a nearly impermeable weathered surface of buried lava of the Waianae Volcanic Series or by overlying alluvium that impedes ground-water movement into overlapping lava of the Koolau Volcanic Series (fig. 12). Ground water along the coast near Mokuleia is partly confined by alluvium, which overlies the more permeable reservoir rock. Westward the alluvium is thin and has little effect on the movement of water, or it is missing.

The hydrostatic head of the fresh-water reservoir is highest in the southeastern part of the area and declines 1.5 to 2 feet per mile to the northwest. Water levels (fig. 14) suggest that ground water is entering the Mokuleia area from the west side of the Schofield Plateau. They also show that there is an 8-foot drop in head between the east and west ends of Dillingham Air Force Base and that head declines to less than 2 feet above sea level toward Kaena Point.

Ground water discharges directly into the ocean through the marine sedimentary material or from the deeper lava along the Mokuleia–Kaena Point shoreline. It originates from rainfall in the Waianae Range, from the Schofield Plateau area, and from downward-percolating irrigation water, most of which was originally pumped from rocks of the Koolau Volcanic Series. About half the irrigated canefields overlie the alluvium, in which ground water has a greater hydraulic head than in the underlying lava flows. Of an average of 28 mgd of irrigation water applied to the canefields, about 40 percent (Dale, 1967) recharges the underlying ground-water reservoir.

An average of 3 to 4 mgd of ground water is presently being withdrawn in the Mokuleia area, and Stearns and Vaksvik (1935, p. 375) estimated that pumpage in 1933 was 14 mgd. Reduced pumpage for irrigation and the sealing of leaking wells since 1945 have resulted in a rise in ground-water level of about half a foot.

Aquifer testing in the Mokuleia area to determine transmissivity of the lava flows of the Waianae Volcanic Series gave abnormally high values, ranging from 15 to 25 mgd. Transmissivity results obtained in tests of the Koolau Volcanic Series in the Haleiwa and Kawailoa areas were even higher, ranging from 27 to 63 mgd. The median was 40 mgd. If all rainfall in the area, about 89 mgd (table 4), became recharge and channeled through the aquifer at the gradient and within the existing boundaries, the transmissivity would have to be about 20 mgd.

Visher and Mink (1964, p. 44), in their work in the Koolau Volcanic Series of the Pearl Harbor area, were also unable to use individual pumping-test data, but they analyzed the pumpage ". . . records for the local and regional centers of gravity of pumping." They obtained transmissivities ranging from 4.3 to 4.6 mgd. Takasaki, Hirashima, and Lubke (1969) tested the same ground-water reservoir in the Punaluu area of windward Oahu and obtained a transmissivity of 4 mgd.

The average transmissivity of the Waianae Volcanic Series in the Mokuleia area can be estimated by using Darcy's law in the form $Q = TIL$ (Ferris and others, 1962, p. 73). Let Q equal the 14-mgd pumpage estimate given by Stearns and assume that it is total flow through the Mokuleia area under steady-state conditions; I is the hydraulic gradient, or 1.5 feet per mile (fig. 14); L is 3 miles, the cross-sectional area through which the water discharges; and the resulting T is 3 mgd. There are no indications that the 1933 pumpage represented the total discharge of the aquifer, or that steady state had been attained, so these figures can serve only to estimate a somewhat tenuous minimum flow through the Mokuleia area.

A thin body of fresh to brackish water, in which head averages 1 to 2 feet above sea level, occupies permeable coralline limestone along the Mokuleia coast. The water has a chloride content of about 250 mg/l. Although this source of water is not being utilized, pumping tests of the reservoir indicate that limited supplies of shallow ground water are available for development.

SCHOFIELD PLATEAU

The Schofield Plateau lies between the Waianae and the Koolau Ranges and is the saddle that forms the south boundary of the project area. The plateau is underlain by a ground-water reservoir in lava of the Koolau Volcanic Series and probably of the Waianae Volcanic Series. Dikes or other unknown structural features form the reservoir boundaries. The reservoir has an area of about 15 square miles (fig. 14). The north and south limits are inferred, in part, from an electrical resistivity survey made by the Geological Survey in 1938. (See Swartz, 1939, fig. 4, and Swartz, in Stearns, 1940, p. 56-59.) The reservoir is recharged by subsurface leakage from dike-impounded water in the Koolau Range and by infiltration of rainfall and streamflow on the Schofield Plateau. All natural ground-water outflow is by subsurface percolation either northward into the adjoining Waialua-Haleiwa area or southward into the southern Oahu area (fig. 1).

The water table ranges in altitude from 187 to 300 feet and may decline in steps to the north, as it does to the south (fig. 14 and Visher and Mink, 1964, fig. 11). Just south of Wheeler Air Force Base, the difference in water level is 100 feet between wells only 0.2 mile apart and is about 250-feet between wells 1.3 miles apart.

Large-scale ground-water development in the Schofield Plateau began in 1938, and as much as 8 mgd has been pumped for municipal, industrial, and air-conditioning uses. Chloride content of the water ranges from 14 to 37 mg/l.

WAIALUA-HALEIWA AREA

Recharge from rainfall in the Koolau Range maintains an extensive fresh-water lens in uncompartmented Koolau lava flows in the northeastern part of the study area (fig. 14). The lens extends along the coast from Waialua to Waialee and is bounded on the inland side by dike-impounded ground-water reservoirs in lava of the Koolau and the Waianae Volcanic Series. Near the coast the lens is divided into two segments, the Waialua-Haleiwa and the Kawailoa, by the thick alluvial fill and weathered bedrock in the valley of the Anahulu River (fig. 4).

Ground water in the Waialua-Haleiwa area moves generally seaward (fig. 14) at a gradient of about 1 foot per mile and is confined by alluvium as far as 2 miles inland (fig. 3). The alluvium and marine sediments thicken seaward and extend to more than 200 feet below sea level at the coast. They generally confine ground water less effectively than the material in the Mokuleia area because there is more coralline limestone which allows water to discharge from the underlying basalt to the ocean. Stearns (1966, p. 14) watched the sea recede at Haleiwa, during the tsunami of March 9, 1957, and saw fresh ground water rising several inches to a foot above the surface ordinarily inundated by sea water.

Recent pumping of four shallow wells tapping a coral bed that underlies part of the Waialua area shows that fresh water is moving seaward through the coral and that infiltration of applied irrigation water is substantial. Pumping of wells 318-1 (fig. 8) to 318-4 began in 1966. The wells were drilled to depths of 25 to 44 feet below sea level from a surface altitude of about 15 feet; they are 6 feet in diameter and are spaced 200 feet apart on a north-south line perpendicular to the shoreline. Wells 318-1 and 318-4 are at the mill and shore ends of the line, respectively, and about equal distance (1,200 ft) from each end.

The Waialua Sugar Co. seasonally pumps about 10 mgd from these wells for cooling the mill condensers. Although detailed pumpage data are not available, the chloride data for a 3-year period show chlorides increasing with pumpage to as much as 13,000 mg/l in 4 months and decreasing to near prepumping levels shortly after pumping stops. Such rapid freshening results from fresh-water displacement of saline water by the seaward flow of ground water, by infiltration of irrigation water, or by a combination of both.

Most ground water discharges into the ocean by percolation through the semiconfining material, but some of it may move northward into the Kawailoa area. From 2 to 4 mgd discharges in the coastal area as seepage into low-lying swamps, or as spring flow; a part of this discharge is pumped or is diverted for irrigating sugarcane and other farm crops. Springs on the south bank of the Anahula River at Haleiwa discharge about 3 mgd from lava flows.

An average of 30 to 40 mgd is pumped from wells tapping the Koolau Volcanic Series, in the Waialua-Haleiwa area, about half of which is applied to canefields in the Mokuleia area. All but 2 mgd of the other half is used to irrigate canefields overlying lava flows in the Waialua-Haleiwa area, where as much as 10 mgd (Dale, 1967) of the applied water may infiltrate back into the ground-water reservoir. Additional recharge originates from irrigation water diverted from Koolau streams. Total recharge from irrigation water is estimated to be 15 to 20 mgd.

KAWAILOA AREA

A 6-foot difference in water level across Anahulu River distinguishes the Kawailoa ground-water reservoir from that of the Waialua-Haleiwa area (fig. 14). Water levels are highest near the river and decline northeastward toward Waimea at about 1.5

feet per mile. The high water levels south of the river indicate that some ground water probably moves northeastward through or under the alluvium-filled valley of the Anahulu River.

A lack of confining alluvial material in the Kawailoa area allows free movement of ground water to the ocean. Fresh-water springs have been reported offshore, and water discharges from lava near shore and through sedimentary material into a large coastal swamp in the southwestern part of the area.

Ground-water development is restricted to the narrow coastal plain, where as much as 8 mgd is pumped from wells. About 7 mgd is used for sugarcane irrigation. A part of this water plus irrigation water diverted from streams infiltrates to the ground-water reservoir.

SALT-WATER INTRUSION

Further development of fresh-water supplies in north-central Oahu is limited, in part by the possibility of increasing salt-water intrusion. Intrusion has occurred along the coast, where withdrawals are from lenses of fairly fresh water (fig. 15). Those

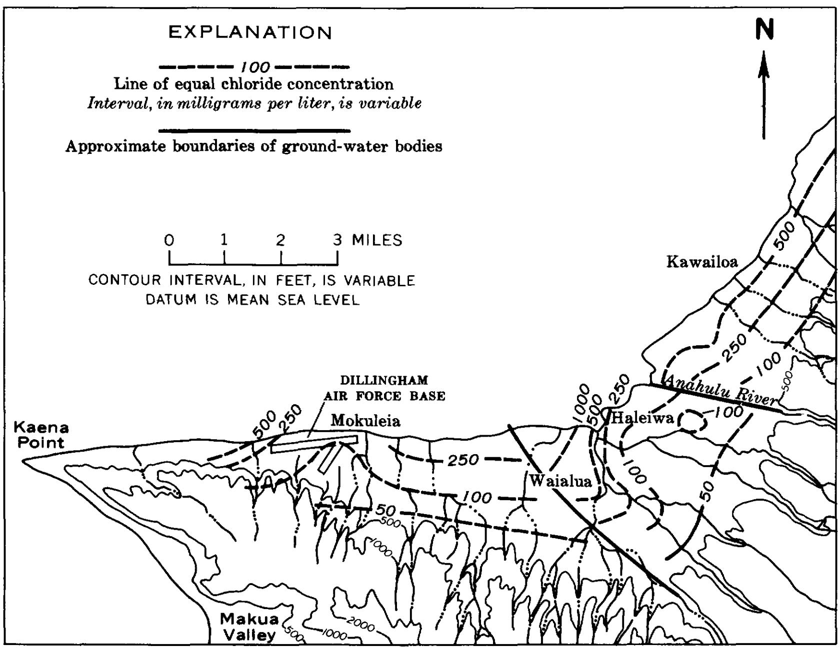

FIGURE 15.—Chloride content, August 1964, of water in basaltic aquifers, Mokuleia, Waialua-Haleiwa, and Kawailoa areas.

lenses, floating on salt water, exist because of density differences between fresh and salt water and extend to a depth of about 40 times the height of the fresh-water head above sea level. Toward the bottom of the lens is a transition zone of mixed fresh and salt water, which becomes increasingly saline with depth. The extent to which salt water intrudes the lens is related to changes in fresh-water head caused by variations in recharge, in tidal and barometric fluctuations, and in pumping. The chloride content of water in lenses along the northern Oahu shore is generally greater than 250 mg/l.

Coastal pumping induces intrusion in direct relation to its rate. Pumping is generally cyclical during the year. Pumping and chloride content of the pumped water reach a maximum during the summer and fall. Increase in chloride content, however, seems to be largely localized at pumping wells, suggesting that movement of the underlying sea water is more vertical than horizontal. The relation of pumping to chloride content is shown in figure 16. Waialua Sugar Co. pumps 2 and 2A (wells 322A-N, fig. 8) are

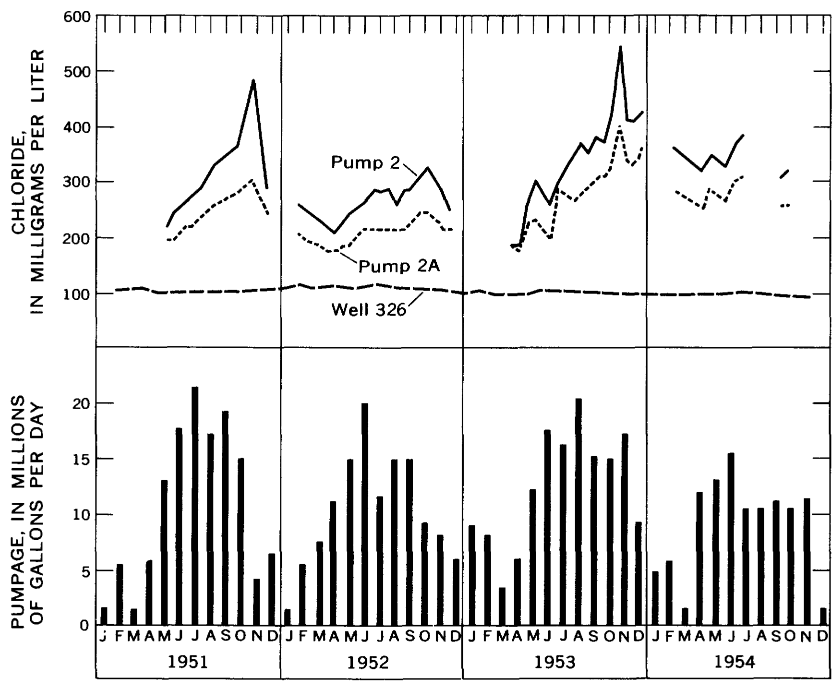

FIGURE 16.—Relation of monthly average discharge of Waialua Sugar Co. pumps 2 and 2A (wells 322A-N) and the chloride content in water at pumps 2 and 2A and at well 326, Waialua.

within 100 feet of each other, and each withdraws water from separate batteries of wells at respective rates of about 11 and 9 mgd. Although the overall range in chloride content is large, water withdrawn by the pump of smaller capacity, 2A, is less saline than that withdrawn by pump 2. The range in chloride content of water from well 326, which taps the same ground-water reservoir but is usually not pumped, is considerably smaller.

The seaward edge of the fresh-water lens is higher in chloride content and thinner in the eastern half of the Mokuleia area, where it underlies sedimentary material at great depth. The increase in chloride content of ground water near Dillingham Air Force Base (fig. 15) coincides with an abrupt decrease in head from 17 to 9.5 feet (fig. 14). The high chloride content of water in the Mokuleia area probably results from changes in the rate of recharge (from rainfall and irrigation) and from tidal fluctuations.

In the Waialua-Haleiwa area, the chloride content of the lens is generally less than 100 mg/l, but it is higher at pumping sites. It is also higher where the lens is confined to greater depths—seaward from the town of Waialua, for example, where chloride content increases to more than 1,000 mg/l.

The seaward edge of the lens in the Kawailoa area is brackish, and ground water with a chloride content of more than 250 mg/l extends a mile inland from the coast. As much as 14 mgd is pumped from a battery of wells (fig. 8, wells 334A-W) only half a mile from the ocean, where, during the past 40 years, chloride content has ranged from 200 to 1,000 mg/l.

ESTIMATE OF GROUND-WATER FLOW

To manage the water resources of an area, the location, quality, and quantity of the resource must be known. It is possible to measure rainfall and its variations in time and space, and to gage the flow of streams, but it is impossible to measure directly the ground-water component of the hydrologic system. Major aquifers of north-central Oahu are identified and the quality of their waters is discussed in this report, but the quantity of ground water available can only be estimated.

The measured discharge from wells and springs in north-central Oahu is about 50 mgd, or about 9 percent of the estimated rainfall, 580 mgd. In the adjacent Pearl Harbor area of southern Oahu, measured ground-water discharge is 50 percent of rainfall (Dale, 1967). Owing to similarity in rainfall pattern, geology, and infiltration capacity of the rocks of these two areas, it is reasonable to expect that the rainfall-discharge relations are similar or comparable. If the above assumption is correct, ground-water discharge now measurable in north-central Oahu, 50 mgd, is about one-fifth the total discharge; the remainder must discharge to sea as submarine springs.

To obtain the best estimate of the amount of water constituting total discharge, the water regimen of north-central Oahu was evaluated by determining rainfall means by zones (fig. 6) and obtaining runoff and evapotranspiration estimates (tables 4 and 5) from curves showing their relation to rainfall. The remainder is identified as recharge to the aquifer, most of which is considered to discharge as underflow to the sea.

The water regimen of an area may be delineated by the equation $P = R_s + R_g + ET + \Delta S$, where rainfall ($P$) is balanced against surface runoff (R_s), recharge (R_g) or ground-water flow, evapotranspiration (ET), and changes in ground-water storage (ΔS). Because long-term average annual data were used to determine recharge for north-central Oahu, it is assumed that storage changes (ΔS) are negligible. The validity of this assumption is supported by the long-term stability of water levels and the continuing flow of springs. The use of the water-distribution equation, as written, results in recharge being available only after the demands of runoff and evapotranspiration are satisfied.

Table 4 gives estimates of rainfall, runoff, evapotranspiration, and recharge, other than that from irrigation, by rainfall zones. It is based on isohyetal (fig. 6) and on empirical relations developed for other areas on Oahu and verified by the few data and observations available in the study area. The zones between the isohyets were planimetered to determine their area. Rainfall was calculated for each zone and is shown in millions of gollons per day. Runoff, evapotranspiration, and recharge are similarly shown but with an additional column that shows the percentage of each in relation to total zone rainfall. Although runoff from each zone may contribute to the recharge in the adjacent topographically lower zone, this contribution and applied irrigation water are ignored in the analysis, so that computed recharge is less than actual recharge.

TABLE 4.—*Average rainfall, runoff, evapotranspiration, and recharge by geologic environment and rainfall zones as estimated for north-central Oahu*

[Figures in parentheses indicate potential evapotranspiration]

Geologic environment and rainfall zones (inches)	Area (sq mi)	Rainfall (P)		Runoff (R_s)			Evapotranspiration (ET)			Recharge (R_g)		
		Inches per year	Mgd	Inches per year	Mgd	Percent of rainfall	Inches per year	Mgd	Percent of rainfall	Inches per year	Mgd	Percent of rainfall
Koolau Volcanic Series												
Less than 40	18	33	28	3	3	9	30 (65)	25 (55)	91	0	0	0
40-50	20	45	43	5	5	11	40 (58)	38 (55)	89	0	0	0
50-75	24	63	73	8	9	13	52	61	83	3	3	4
75-100	19	86	78	12	11	14	43	39	50	31	28	36
100-150	12	120	69	19	11	16	32	19	27	69	39	57
More than 150	18	233	200	48	41	21	12	10	5	173	149	74
Subtotal	111	93	491	15	80	16	36	192	39	42	219	45
Waianae Volcanic Series												
Less than 40	18	33	29	3	3	10	30 (65)	26 (57)	90	0	0	0
40-50	14	44	29	5	3	11	39 (58)	26 (38)	89	0	0	0
More than 50	9	72	31	9	4	13	48	21	67	15	6	20
Subtotal	41	46	89	5	10	11	38	73	82	3	6	7
Total	152	80	580	12	90	15	37	265	46	31	225	39

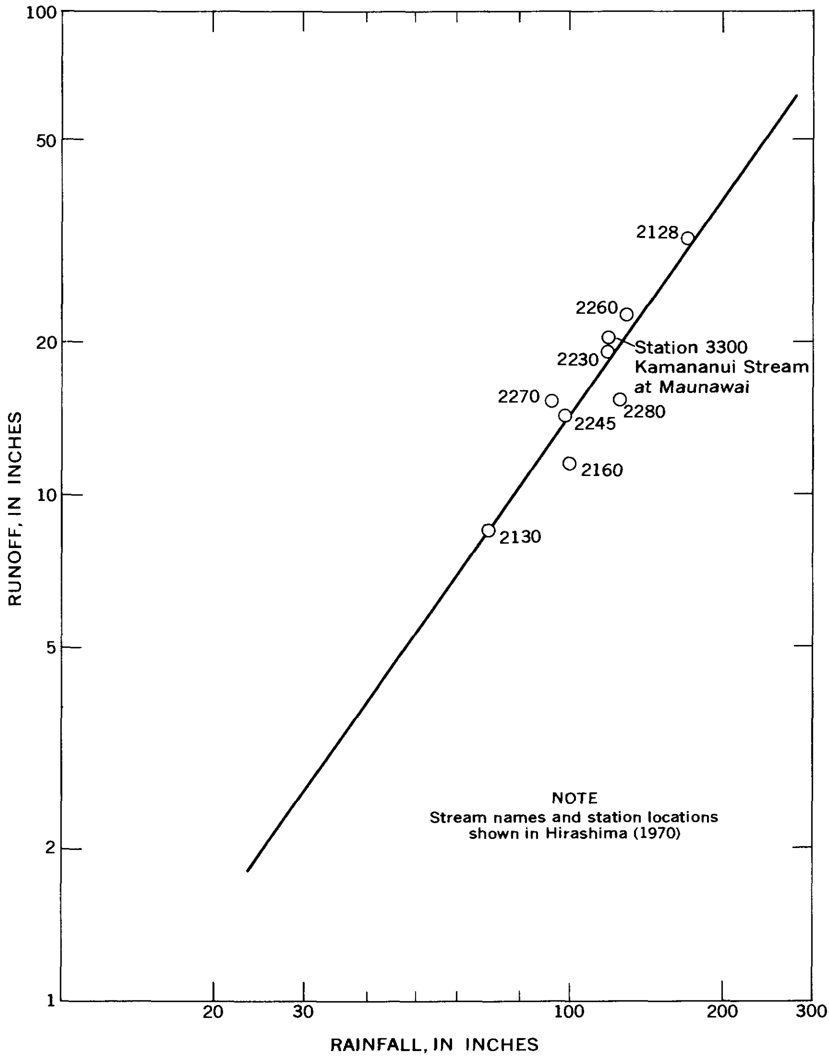

FIGURE 17.—Relation of runoff to rainfall. (Developed by G. T. Hirashima.)

RUNOFF

Hirashima (1970) considered the problem of runoff from an area above Pearl Harbor that is predominantly underlain by lava of the Koolau Volcanic Series. He used long-term average annual rainfall and runoff from seven gaged streams in the Pearl Harbor area to develop a logarithmic curve relating rainfall to runoff (fig. 17). Only Kamananui Stream of north-central Oahu could be used as a check against Hirashima's Pearl Harbor data. An average rainfall of 119 inches on the basin above station 3300 and an adjusted 30-year discharge of 20 inches plots within 8 percent of the curve. Runoff from the Pearl Harbor area (table 5) averages about 13 percent (47 mgd) of average annual rainfall (355 mgd).

Mink (1962b, p. 155), in a study of a basin in the Pearl Harbor drainage area, found that mean annual runoff was 20 to 30 percent of the mean annual rainfall. He stated, however, that runoff might vary, depending on distribution and amount of rainfall and whether cyclonic or orographic rainfall predominated.

The U.S. Army Corps of Engineers [1] reported runoff from the upper half of Kalihi Valley (Honolulu area) to have a normal monthly range of 18 to 23 percent of rainfall and the lower half to have a range of 23 to 30 percent. Mean annual rainfall in the two halves is 101 and 69 inches, respectively.

Hirashima's rainfall-runoff relation seems more applicable to north-central Oahu, being based on 30-year adjusted discharge records for a 90-square mile area, than do the other studies. Mink's study area was 4.3 square miles—the upper one-third of Kipapa Stream basin—and only 3 years of data were used. The Corps of Engineers study area was 5.24 square miles, 20 months of data were used, and the geohydrologic environment was different than that in north-central Oahu in that the area was underlain in part by rocks other than those of the Koolau Volcanic Series.

About 75 percent of north-central Oahu is underlain by lava flows of the Koolau Volcanic Series (table 5 and fig. 3). Under the

[1] Unpub. report, Hydrologic relations in Hawaii, Project ES-182, Project Bull. 1, 30 November 1964.

TABLE 5.—*Average rainfall and runoff for major areas of the island of Oahu*

Area	Square miles	Rainfall		Runoff		
		Inches per year	Mgd	Inches per year	Mgd	Percent of rainfall
Pearl Harbor area	90	83	355	11	47	13
North-central Oahu area	152	80	580	12	90	15
Koolau Volcanic Series of north-central Oahu	111	93	491	15	80	16
Waianae Volcanic Series of north-central Oahu	41	46	89	5	10	11

assumption that rainfall-runoff characteristics are similar to those of the Pearl Harbor area as reported by Hirashima—and that no major geohydrologic dissimilarities are known—runoff from the Koolau Volcanic Series is 80 mgd, or 16 percent of runoff. Estimates for the area of the Waianae Volcanic Series and for north-central Oahu, also based on Hirashima's work, are shown in table 5.

EVAPOTRANSPIRATION

Evapotranspiration in north-central Oahu is estimated to be 265 mgd, or 46 percent of available rainfall (table 4). This loss, which may be satisfied by rainfall or by rainfall and irrigation, represents evaporation from soil and free-water surfaces and transpiration by plants in the cultivated and in the watershed areas.

Experimentation with lysimeters in the areas of sugarcane cultivation has shown that transpiration by sugarcane is equal to pan evaporation (Campbell and others, 1959, p. 643). Lacking experimental data for other than sugarcane areas, Cox wrote in the same paper (p. 648): "In the watershed areas, evapotranspiration is a loss subtractive from the rainfall to obtain net water resources. The factors controlling evapotranspiration are to some extent correlative with rainfall, and hence it is possible to discuss evapotranspiration empirically as a function of rainfall." This is the approach used in developing the evapotranspiration of the study area.

Takasaki, Hirashima, and Lubke (1969) tabulated data from 18 climatologic stations in the Hawaiian Islands that recorded wind movement, pan evaporation, rainfall, and temperature. Owing to the small range in temperature throughout the islands, the effect of temperature variation was found to be negligible in the rainfall-evapotranspiration relation, but wind movement was found to be a major factor.

In his figure 9, Takasaki shows a logarithmic plot giving a relation of rainfall to pan evaporation and identifies those stations where annual wind movement is more than and less than 20,000 miles. Those stations where annual wind movement was less than 20,000 miles plot on the line represented by the equation $\log_{10} E = 1.9387 - 0.0035\ R$, where E is median annual pan evaporation and R is median annual rainfall.

Records of three stations, in addition to records of other partial-record stations in the study area, indicate that there are no stations and that there may be no sites in north-central Oahu where wind movement exceeds 20,000 miles per year. The rainfall-pan-evaporation relation developed by Takasaki, therefore, can be applied. Using his formula, the estimates of evapotranspiration given in table 4 were developed for each of the rainfall zones. Potential evapotranspiration exceeds available rainfall by about 100 percent in coastal and inland low areas. Evapotranspiration is less than rainfall only where rainfall exceeds 50 inches annually.

RECHARGE

Recharge, as used in this water regimen, represents that part of rainfall available for infiltration to the ground-water reservoir after subtraction of runoff and evapotranspiration. Using the figures shown in table 4, the maximum estimate of recharge for north-central Oahu is 225 mgd, or 39 percent of total rainfall. The lack of even minor amounts of recharge in some of the low rainfall areas, although unrealistic, is the arithmetic result of evapotranspiration exceeding rainfall (fig. 6). Areas of no recharge are also those areas predominantly planted to sugarcane (fig. 2). Mink (1962a, p. 672), writing of the great quantity of water needed for effective irrigation of sugarcane in the Pearl Harbor area, stated: "On an annual basis, an average of 123 inches is applied as irrigation, which when combined with average annual rainfall gives a total of 153 inches of water per year * * *" and that, "Hydrologic budgeting has indicated that between 50 and 60 percent of this amount (153 in.) escapes evapotranspiration and returns to the ground water." The recharge estimates developed in this study do not include applied irrigation water.

Although 225 mgd for recharge is low (39 percent of rainfall) compared with recharge (50 percent) in the Pearl Harbor area, it permits determination of a reasonable estimate of the quantity of ground water available for development in north-central Oahu. Ground-water pumpage averages 42 mgd for irrigation, and stream-diverted water about 36 mgd. Of the 78 mgd applied, about 31 mgd infiltrates the ground-water reservoir. Thus, present development leaves about 200 mgd of ground water discharging to sea. A major part of this water may be developed for future supplies.

SUMMARY

The geographic boundaries of the north-central Oahu study area are the Waianae Range on the west, the Waimea River and Koolau Range on the east, Wheeler Air Force Base on the south, and the Pacific Ocean on the north. The major water-bearing rocks are the lavas of the Koolau Volcanic Series, which are recharged by 491 mgd of rain falling on 111 square miles of the Koolau Range. The remaining 41 square miles of the study area receives 89 mgd as rainfall.

Runoff to the sea occurs only during prolonged periods of heavy rainfall, and the lower reaches of all streams are generally dry. Some streams gain water in their tidal reaches owing to discharge from springs. Runoff from north-central Oahu is estimated to be 90 mgd, or 15 percent of the 580 mgd total rainfall.

Evapotranspiration is high in the lowlands—potentially approaching 200 percent of rainfall where rainfall is less than 40 inches—and of little significance in the wet upper parts of the Koolau and Waianae Ranges. It is estimated as 265 mgd, or 46 percent of the total rainfall of north-central Oahu. Evapotranspiration is less than rainfall only where average rainfall is greater than 50 inches annually.

The amount of rain available to recharge the ground-water reservoirs of north-central Oahu is that remaining after runoff and evapotranspiration have been subtracted—that is, about 225 mgd, or 39 percent of average annual rainfall. Ground-water pumpage averages 48 mgd, and stream-diverted water 57 mgd. Of approximately 78 mgd applied for the irrigation of sugarcane, about 31 mgd infiltrates the ground-water reservoirs. Thus, present development leaves about 200 mgd of ground water available for future use. This water is discharging to the ocean in coastal seeps and springs and as submarine flows.

There are three main areas of discharge—through Mokuleia on the west, through Waialua-Haleiwa in the central part, and

through Kawailoa on the east. The shorelines, from Dillingham Air Force Base on the west to the Waimea River on the east, is about 12 miles long and has an average discharge of about 17 mgd per mile. Owing to the high permeability of rocks of the Koolau compared with that of rocks of the Waianae Volcanic Series in the Mokuleia area, the Waialua-Haleiwa-Kawailoa areas are probably discharging more than the 17 mgd per mile average, and the Mokulei area somewhat less.

Future ground-water development should be inland of a line 1½ to 3 miles from the shoreline or, generally, above an altitude of 500 feet. Chloride content of the water inland of this line should be less than 50 mg/l. Water levels may range from 5 to as much as 300 feet above sea level, depending upon geographic location and the aquifer penetrated (basal water in the coastal area and basal and high-level water southward in the vicinity of the Schofield Plateau). The same area is in need of exploratory drilling owing to lack of available subsurface information for this 60 square-mile area.

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