Availability of Streamflow for Recharge of the Basal Aquifer in the Pearl Harbor Area, Hawaii

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1999–B

Prepared in cooperation with the Board of Water Supply, City and County of Honolulu

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By G. T. HIRASHIMA

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

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CONTENTS

ILLUSTRATIONS

TABLES

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

AVAILABILITY OF STREAMFLOW FOR RECHARGE OF THE BASAL AQUIFER IN THE PEARL HARBOR AREA, HAWAII

By G. T. HIRASHIMA

ABSTRACT

The Pearl Harbor area is underlain by an extensive basal aquifer that contains large supplies of fresh water. Because of the presence of a cap rock composed of sedimentary material that is less permeable than the basaltic lava of the basal aquifer, seaward movement of ground water is retarded. The cap rock causes the basal water to stand at a high level; thus, the lens of fresh water that floats on sea water is thick.

Discharge from the basal ground-water body, which includes pumpage from wells and shafts, averaged 250 million gallons per day during 1931–65. Because the water level in the basal aquifer did not decline progressively, recharge to the ground-water body must have been approximately equal to discharge.

Although pumping for agricultural use has decreased since 1931, net ground-water discharge has increased because of a large increase in pumping for urban use. Substitution of ground water for surface water in the irrigation of sugarcane has also contributed to a net increase in ground-water discharge. The development of Mililani Town will further increase discharge.

The increase in ground-water discharge may cause an increase in chloride content of the water pumped from wells near the shore of Pearl Harbor unless the increased discharge is balanced by increased recharge to the basal aquifer.

The aquifer is recharged by direct infiltration and deep percolation of rain, principally in the high forested area, by infiltration and percolation of irrigation water applied in excess of plant requirements, by seepage of water through streambeds, and possibly by ground-water inflow from outside the area. Recharge is greatest in the uplands, where rainfall is heavy and where much infiltration takes place before rainwater collects in the middle and lower reaches of stream channels. Once water collects in and saturates the alluvium of stream channels, additional inflow to the streams will flow out to sea, only slightly decreased by seepage.

Average annual direct runoff from the 90-square-mile Pearl Harbor area is 47.27 million gallons per day, or 11.1 inches; this is 13.3 percent of the average annual rainfall (83.3 in.) over the area. Average annual direct runoff in streams at the 800- and 400-foot altitudes is 29 and 38 million gallons per day, respectively. Kipapa Stream has the largest average annual direct runoff at those altitudes — 6 and 9 million gallons per day, respectively.

Because streams are flashy and have a wide range in discharge, only 60 percent of the average annual runoff can be economically diverted through ditches to recharge areas. The diversion may be increased slightly if reservoirs are used in conjunction with ditches to temporarily detain flows in excess of ditch capacity.

The planned irrigation use of some of the perennial flow available in Waikele Stream near sea level will decrease pumping from and increase recharge to the basal aquifer.

Suspended-sediment load is mainly silt and clay, and it increases rapidly with increased discharge. Thus, the use of streamflow for artificial recharge poses problems. High flows must be used if recharge is to be effective, but flows must not be so high as to cause clogging of recharge facilities with sediment or woodland debris.

Practical tests are needed to determine the advantages and disadvantages of different types of recharge structures, such as a reservoir or basin, large-diameter deep shafts, deep wells, or combinations of all these structures.

INTRODUCTION

Planned developments in the Pearl Harbor basin indicate a need to increase pumping from the basal aquifer, a basaltic lava, to meet the growing demand. Mililani Town alone will require pumpage greater than 10 mgd (million gallons per day) to supply a projected population of 60,000. The first of about 11 required water-supply wells for this development was drilled in January 1968. The increased draft may cause an increase in chloride content of the water pumped from wells near the shore of Pearl Harbor because of sea-water encroachment. The increase in chloride content can be minimized if recharge to the basal ground-water body is increased.

The purpose of this study was to determine the amount of streamflow that might be available for recharging the basal aquifer in the Pearl Harbor area. The investigation was limited to those streams entering Pearl Harbor.

This report was prepared by the U.S. Geological Survey under the direction of Mearle M. Miller, district chief, Water Resources Division, as part of a water-resources investigation program under cooperative agreement with the City and County of Honolulu, Board of Water Supply, George L. Yuen, manager and chief engineer. Acknowledgment is given the Waiahole Water Co., Waialua Sugar Co., U.S. Navy, and U.S. Army for their cooperation and assistance.

The Pearl Harbor area is defined in this report as the part of the island of Oahu bounded by the southern drainage divide of South Halawa Stream, the crest of the Koolau Range, the northern drainage divide of Waikakalaua and Waikele Streams, and the southwest drainage divide of Waikele Stream (fig. 1).

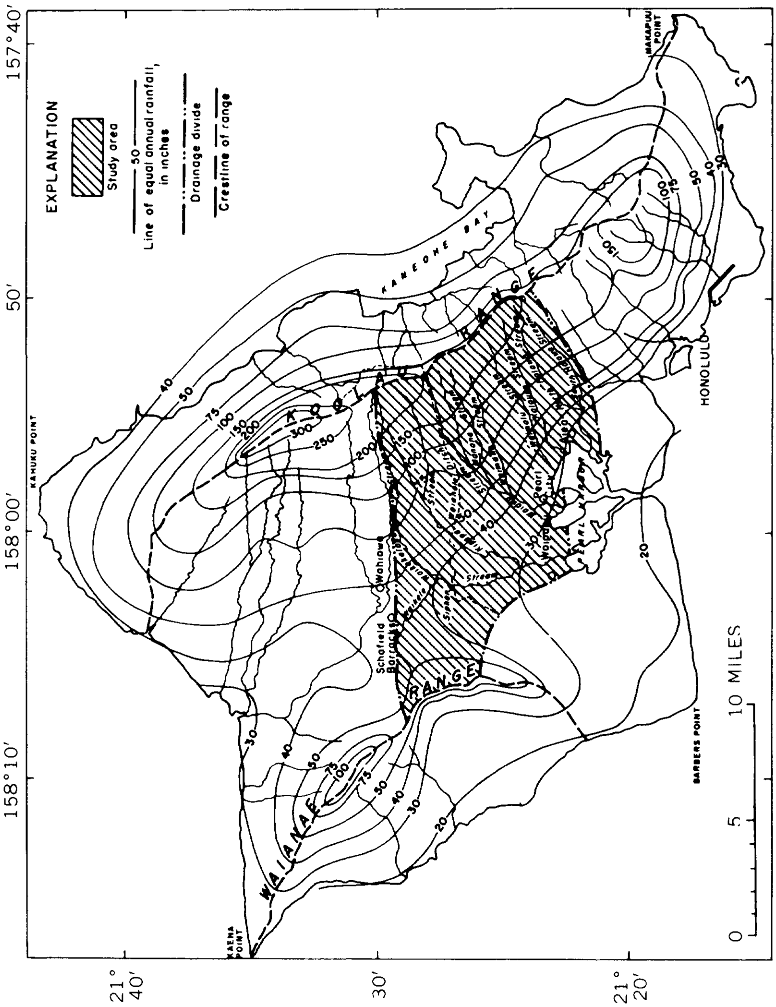

FIGURE 1. — Oahu study area, its streams, and lines of equal rainfall for the island.

RECORDS AVAILABLE

Although current-meter measurements of the flow of water into Pearl Harbor have been made since 1911, daily streamflow records are available only from 1929. In that year, a gaging station was established on North Halawa Stream. Gaging stations that are being or have been operated on streams entering Pearl Harbor are listed in table 1, and their locations are shown in figure 2.

TABLE 1.—*List of gaging stations on streams entering Pearl Harbor*

Station name	Station No.	Drainage area (sq mi)	Period of record (fiscal years)
Kipapa Stream near Wahiawa	2128	4.29	1957–67
Kipapa Stream near Waipahu	2129	13.8	1966–67
Waikele Stream near Waipahu	2130	45.7	1951–67
Waiawa Stream near Pearl City	2160	25.4	1952–67
Waimalu Stream near Aiea	2230	6.07	1952–67
Kalauao Stream at Moanalua Road at Aiea	2245	2.59	1957–67
North Halawa Stream near Aiea	2260	3.45	1929–33, 1953–67
Halawa Stream near Aiea	2270	8.78	1953–62

DESCRIPTION OF THE AREA

DRAINAGE

Five streams draining 89.5 square miles discharge into Pearl Harbor. The longest natural waterway, 14 miles long, is formed by Waikakalaua Stream and the southern part of Waikele Stream (fig. 2). Little or no water is provided to any of the streams by the high-level dike-confined ground-water bodies of the Koolau Range; the larger streams are perennial in their upper reaches because of persistent rainfall in the Koolau highlands. All streams are perennial below an altitude of about 20 feet and are intermittent between that altitude and their upper reaches. Infiltration and evaporation from the drainage basin are large; therefore, only a small fraction of the rain runs off into Pearl Harbor.

RAINFALL

The areal variation of annual rainfall on Oahu is great. Rainfall ranges from about 20 inches along the leeward coast to about 300 inches in the north-central part of the Koolau Range (fig. 1).

In the Pearl Harbor area, annual rainfall ranges from between 20 and 30 inches at Pearl Harbor to about 225 inches near the crest of the central part of the Koolau Range. Trade winds, from the northeast, blow two-thirds of the year (Yeh and others, 1951, p. 36). The warm moist air of the trade winds is cooled as it rises over the Koolau Range, and rain results. The maximum orographic rainfall occurs within 1 mile leeward, or southwest, of the crest of the range. Farther to the southwest, orographic rainfall decreases according to a geometric regression (Mink, 1962b).

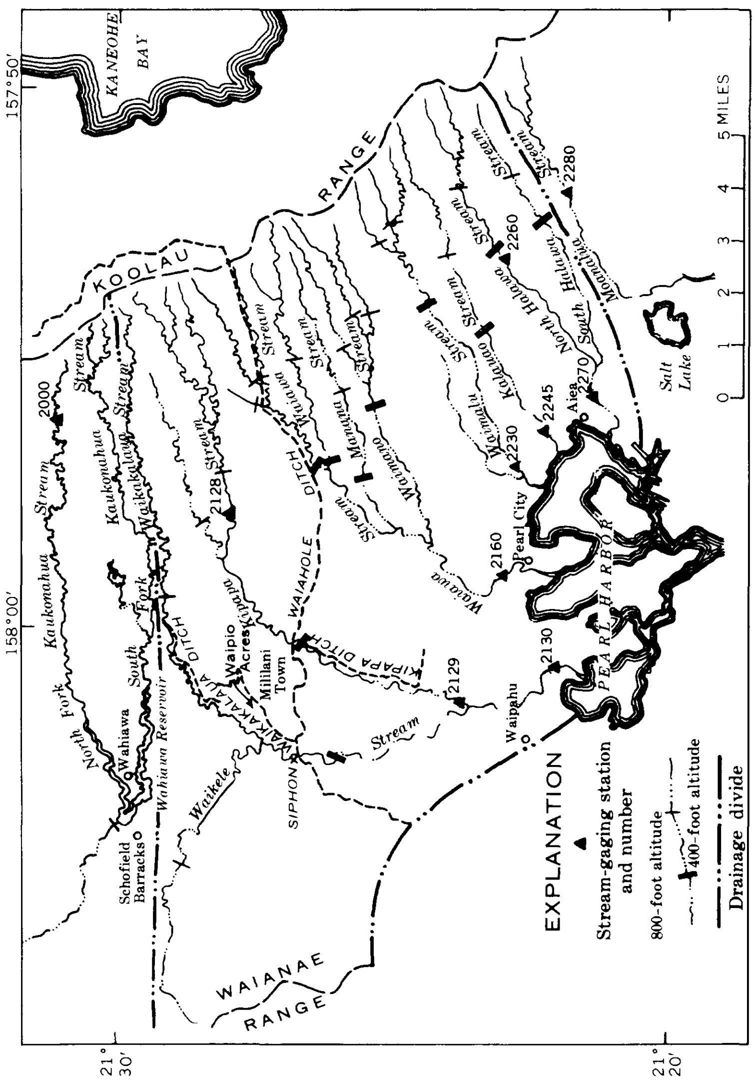

FIGURE 2. — Locations of gaging stations and the 800- and 400-foot altitudes on the streams. Data from long-term stations 2000 and 2280, both outside the report area, were used to extend the records to the 1931–60 base period in the Pearl Harbor area.

A cyclonic pattern of air circulation, which causes a more uniformly distributed rainfall, occurs about one-fifth of the year (Yeh and others, 1951, p. 36). It occurs more frequently in winter and provides the bulk of the rain for the dry, leeward areas of the island. The summers are generally dry.

GROUND WATER

Rainfall is the source of all fresh water on Oahu. Part of the rainfall runs off directly to the sea in streams, part evaporates or transpires into the atmosphere, and part moves downward through the soil and rocks to become ground water. The ground water moves slowly through the rocks and eventually reaches points of discharge to streams, to the ocean, or to the atmosphere.

BASAL GROUND WATER

The main water table in the study area stands a few tens of feet above sea level. This is the basal water table. Above the basal aquifer is a confining layer, locally called the cap rock, composed of sedimentary material that is less permeable than the basaltic lava of the basal aquifer. The cap rock retards the seaward movement of ground water, and the water stands at a higher level in the aquifer than it would if the cap rock were absent. The upper part of the basal ground-water body is fresh — recharged principally by rainfall in the Koolau Range — and the lower part is sea water. Because the specific gravity of fresh water is slightly less than that of sea water, the fresh water floats on the sea water as a lens-shaped body. The basaltic lavas of the basal aquifer are saturated to an unknown depth below sea level. (For a more detailed discussion of basal ground water, see "Ground-water Resources in Southern Oahu, Hawaii" by Visher and Mink, 1964.)

DISCHARGE

Water from the basal ground-water body is discharged by springs near the shore of Pearl Harbor, by springs and seeps along stream channels near sea level, and by pumping from wells and shafts. The flow of springs near the shore of Pearl Harbor has been measured at gaging stations at or near mean sea level since 1931. In 1937, some of the gaging stations were discontinued because of changes in flow patterns caused by building construction. The flow of some small springs and seeps along stream channels can only be estimated; however, the amount of such unmeasured water is probably small. Dale (1967) estimated that the total discharge of water from the basal ground-water body averaged 250 mgd during the years 1931–65.

RUNOFF

Runoff from five drainage basins in the Pearl Harbor area is measured at seven stream-gaging stations (table 1). Another station was discontinued in 1962. Flow at four of the active stations and at the one discontinued station includes some discharge from the basal aquifer and some return flow from irrigation of sugarcane. The station on Kipapa Stream near Waipahu (sta. 2129) is upstream from the zone of discharge from the basal aquifer. Its record of discharge includes only excess irrigation water spilled intermittently into the stream above the station. The remaining two stations, Kipapa Stream near Wahiawa (sta. 2128) and North Halawa Stream near Aiea (sta. 2260), are also upstream from all discharges from the basal aquifer, and they record runoff from rain only.

FLOW DURATION AND REGIMEN OF FLOW

Streams in the Pearl Harbor area flow generally at right angles to the Koolau Range and cut across lines of equal rainfall, which are roughly parallel to the range. Thus, rainfall in each drainage area is greatest near the headwaters and least at the mouths of streams (fig. 1).

A typical stream in the Pearl Harbor area flows only for the time it takes for the rain in excess of infiltration capacity to collect in stream channels and drain out of the valley. Because there is little or no valley storage and because there are no perennial springs in the headwaters, streams stop flowing a few days after the rain stops.

Rainfall in the Koolau Range is most persistent — as are the trade winds — during August. This persistence is reflected in the runoff of North Halawa Stream, in the southern part of the area, and of Kipapa Stream, in the northern part.

Although North Halawa Stream may have days of no flow during any month, the percentage of time of no flow is least during August. This is shown in figure 3, where the percentage of time flow equals or exceeds 0.01 mgd is shown on the ordinate scale. North Halawa Stream is dry one-third of the time.

The graph (fig. 4) for Kipapa Stream (sta. 2128), which is near the region of highest rainfall on Oahu, shows effects of persistent trade-wind rainfall better than does the graph (fig. 3) for North Halawa Stream. As shown by the record for both streams, June is the driest month of the year.

The flow-duration curve shows the percentage of time, for a given period, that any discharge was equaled or exceeded and is a useful device for analyzing the availability and variability of streamflow.

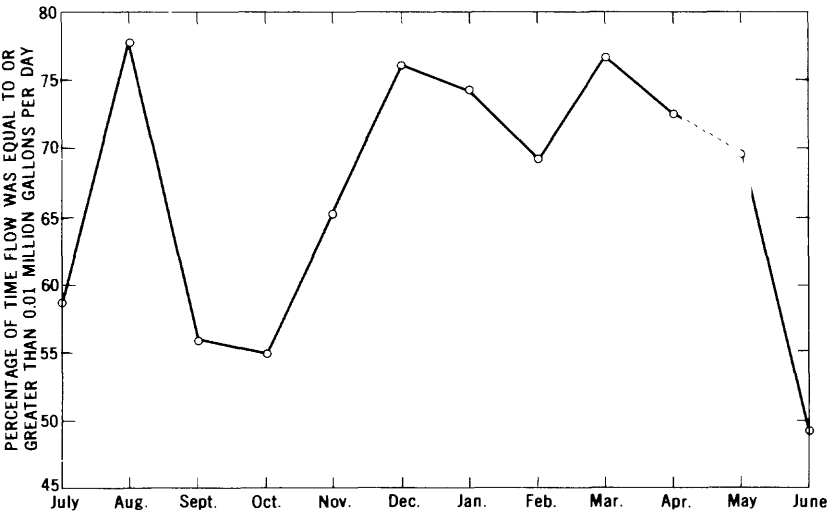

FIGURE 3. — Range in percentage of nonzero discharge days for North Halawa Stream near Aiea (sta. 2260).

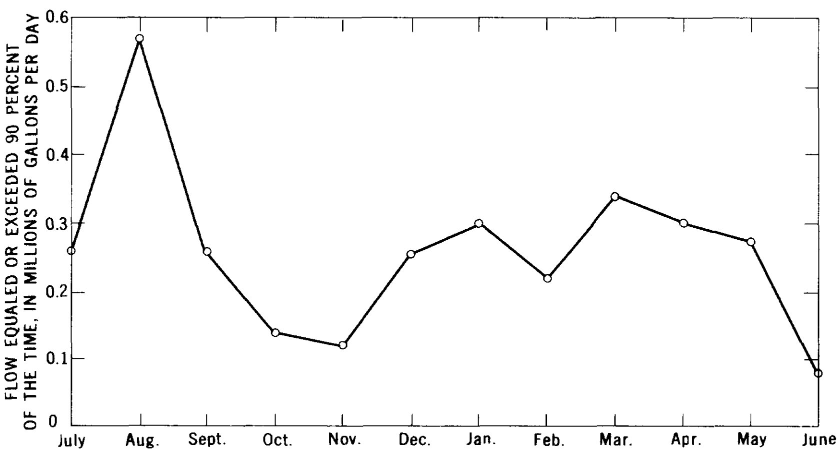

FIGURE 4. — Range in Q_{90} discharges of Kipapa Stream near Wahiawa (sta. 2128).

The flow-duration curves for North Halawa Stream near Aiea (sta. 2260, fig. 5) and for Kipapa Stream near Wahiawa (sta. 2128, fig. 6) are typical curves for streams in the Pearl Harbor area. Both curves have steep slopes throughout the range of discharges, which indicate the absence of perennial storage in the drainage areas. Kipapa Stream flows a greater percentage of time than does North Halawa Stream only because the watershed of Kipapa

Stream receives runoff-producing rains a greater percentage of time than does the watershed of North Halawa Stream.

The flow-duration curve for Waikele Stream near Waipahu (sta. 2130; solid line in fig. 7) for the 1958–59 and 1961–67 fiscal years has a steep slope over the range of discharges that are equaled or exceeded less than 7 percent of the time and has a flatter slope over the range of discharges that are equaled or exceeded more than 7 percent of the time. The flatter slope indicates perennial storage in the drainage basin. However, that storage is in the basal ground-water body and contributes to streamflow only below an altitude of about 30 feet.

Duration curves for other streams that are gaged near sea level also show the effect of leakage from the basal ground-water body but to a lesser degree than curves for Waikele Stream, because these streams receive less discharge of ground water. In addition to discharge from the basal ground-water body, the flow of all streams at low altitudes includes irrigation return flows. Some of the streams receive effluent from sewage-treatment plants also.

MEAN ANNUAL DIRECT RUNOFF

Watersheds of all streams in the Pearl Harbor area have similar rainfall-distribution patterns (fig. 1) and similar geology. All streams are dry in the middle and lower reaches during periods of little or no rain. Rainfall can be correlated with runoff where the streamflow data are collected at altitudes above all inflows from sources other than rain. At stations where the streamflow includes water from other sources, the records were adjusted by eliminating all flow except direct runoff from rain. To do this, relation curves were constructed from the discharges measured at the gaging stations and the discharges measured concurrently at sites above the spring-inflow zones. The curves were used to estimate the shape of the flow-duration curve for direct runoff only. (See fig. 7, dashed line.) The area between the curve for total flow and the curve for estimated direct runoff was integrated to determine the flow contributed by springs and seeps, irrigation return, and sewage effluent during the periods of record. This estimated flow was then adjusted to the 1931–60 period.

The estimated long-term (1931–60) mean annual direct runoffs and long-term mean annual runoffs of total flow are given in table 2. The long-term mean annual runoffs of total flow were determined by a series of runoff correlations involving the short-term records for the stations in the area and the long-term records for North Fork Kaukonahua Stream above Right Branch (sta. 2000, fig. 2) and Moanalua Stream near Honolulu (sta. 2280, fig. 2).

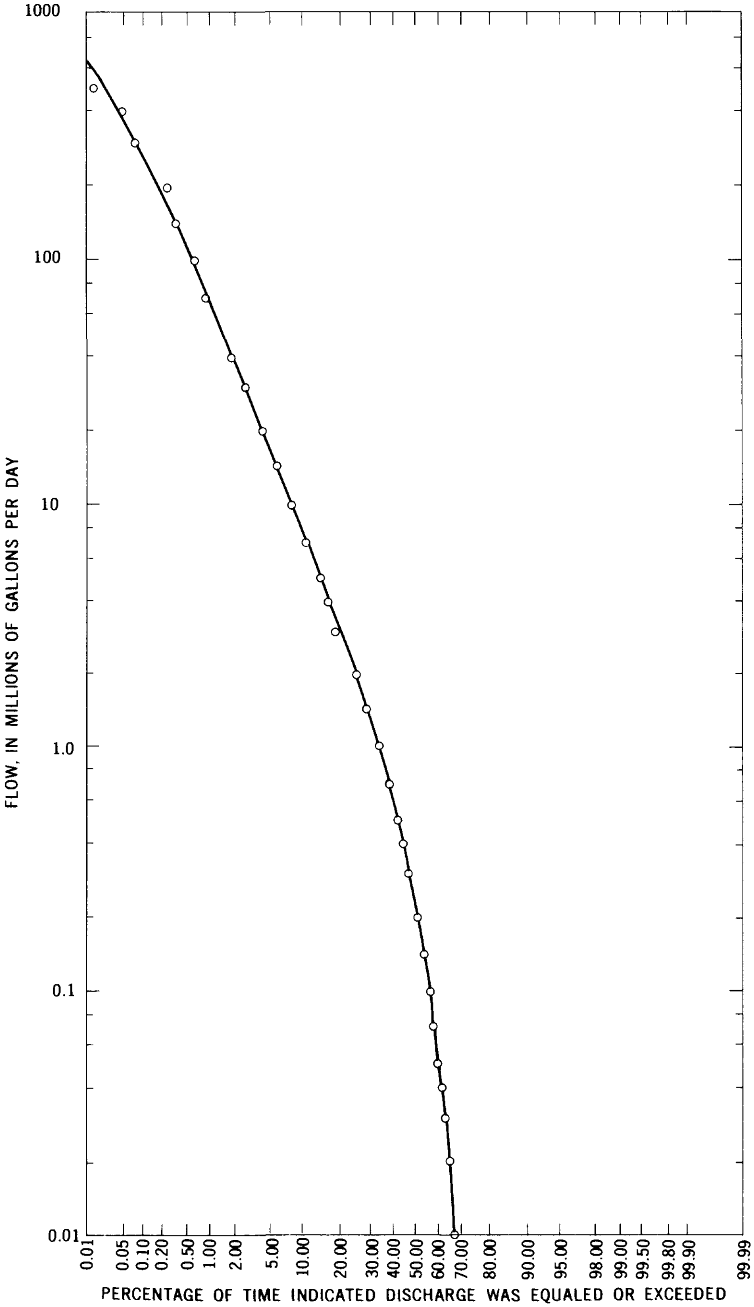

FIGURE 5. — Flow-duration curve for North Halawa Stream near Aiea (sta. 2260), 1930–33, 1954–66 fiscal years.

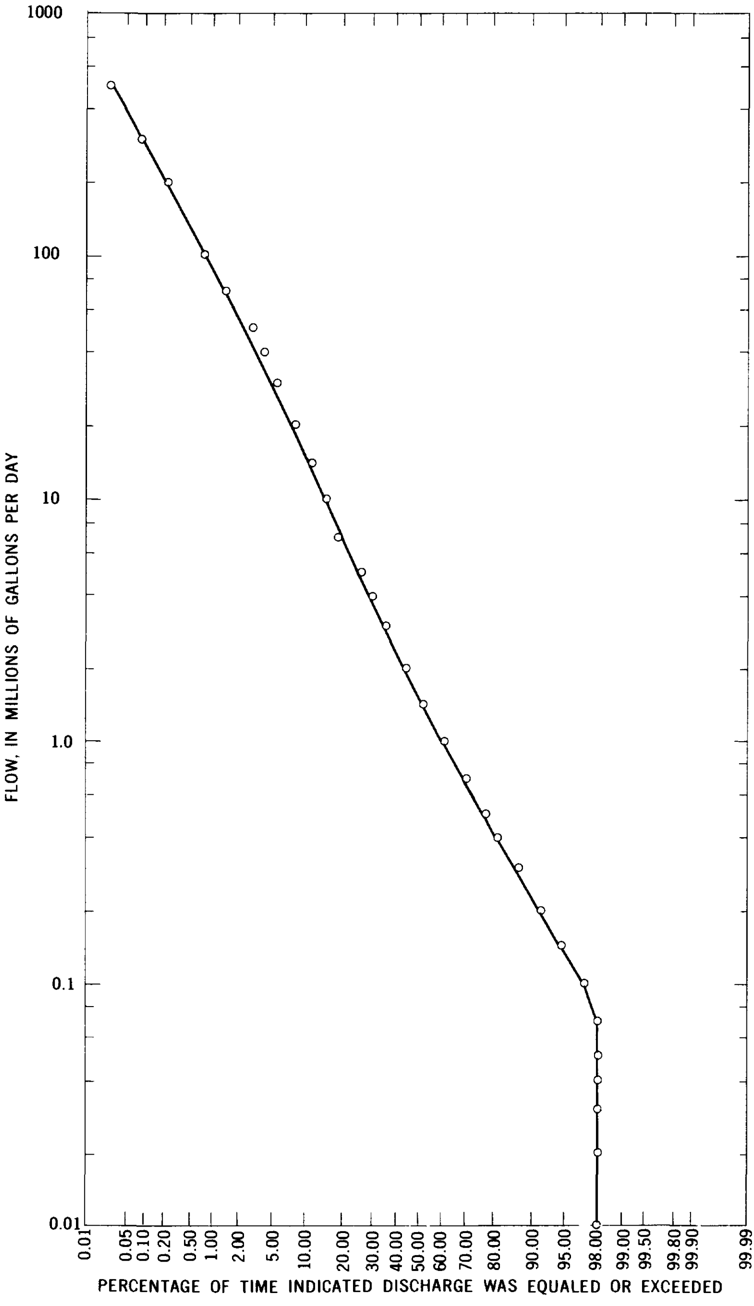

FIGURE 6.—Flow-duration curve for Kipapa Stream near Wahiawa (sta. 2128), 1958–59, 1961–67 fiscal years.

Diversions of surface water for irrigation also affected the runoff record. Because the diverted water was used for irrigation upstream from the gaging stations, the streamflow past the sta-

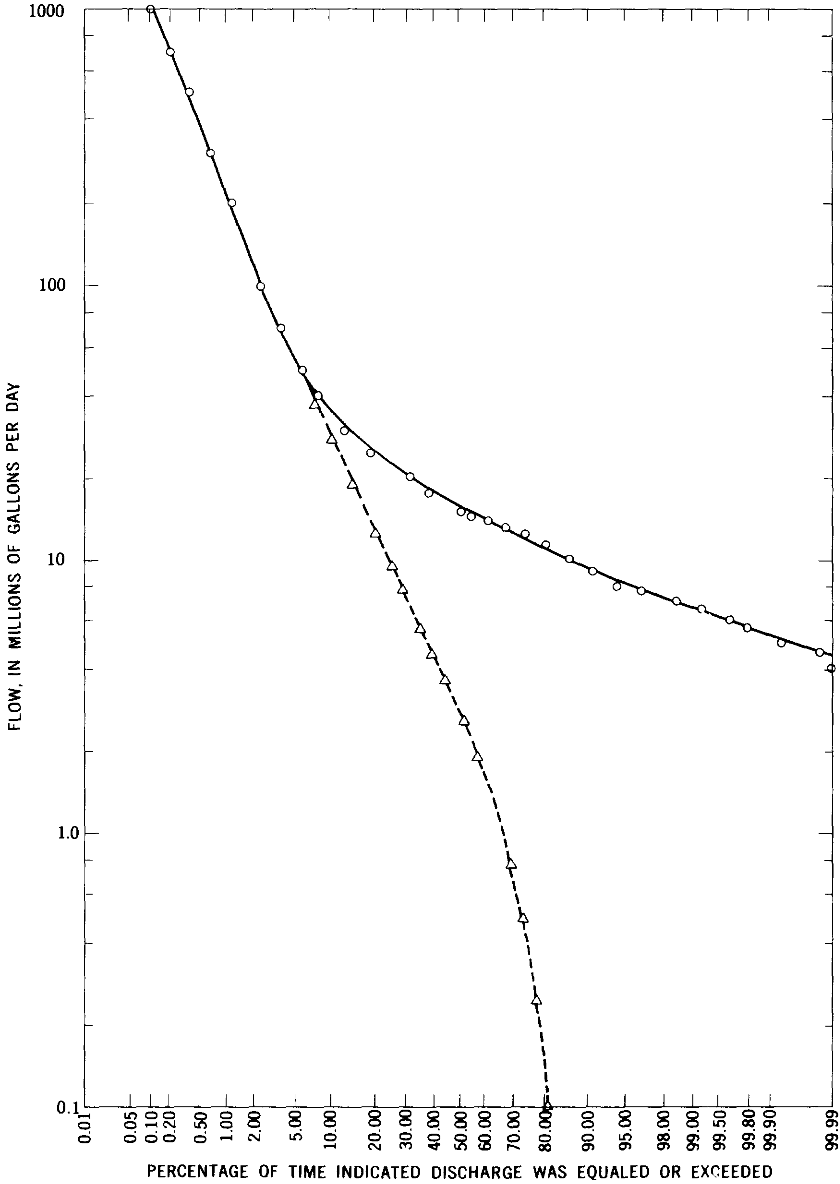

FIGURE 7.—Flow-duration curves for Waikele Stream near Waipahu (sta. 2130), 1958–59, 1961–67 fiscal years. Solid line is curve for total flow; dashed line is curve for direct runoff only.

TABLE 2. — *Hydrologic budget (mean annual runoff) for watersheds above selected gaging stations for 1931–60*

[mgd, million gallons per day]

Station No.	Stream	Drainage area (sq mi)	Rainfall		Total flow (mgd)	Spring inflow, irrigation return, or sewage flow (mgd)	Direct runoff (mgd)	Adjustment for diversion (mgd)	Total direct runoff		Water loss	
			in.	mgd					mgd	in.	in.	mgd
2270	Halawa	8.78	92	....	7.55	1.19	6.36	....	6.36	15.2	76.8	....
2245	Kalauao	2.59	96	....	1.81	.07	1.74	....	1.74	14.1	81.9	....
2230	Waimalu	6.07	116	....	5.27	.60	4.67	[1]1.0	5.67	19.6	96.4	....
2160	Waiawa	26.4	98	....	17.0	2.60	14.4	[2].6	15.0	11.9	86.1	....
2130	Waikele	45.7	68	....	25.9	10.6	15.3	[2]3.2	18.5	8.50	59.5	....
	Total or average	89.54	83.3	355	57.53	15.06	42.47	4.8	47.27	11.1	72.2	308
2260	North Halawa	3.45	127	....	3.72	....	3.72	....	3.72	22.6	104.4	....
2128	Kipapa	4.29	170	....	6.42	....	6.42	....	6.42	31.4	138.6	....
2280	Moanalua	2.73	125	....	2.01	....	2.01	....	2.01	15.5	109.5	....

[1]No long-term data on diversion available. Average for 1947–62 used.

[2]Adjustments for diversion are only one-half of long-term diversion because estimated long-term runoff is based on short-term records that were affected by reduced diversions.

tions included some return irrigation water. However, this return irrigation water is probably a small part of the total quantity measured at the gaging station and was neglected.

Since 1953, diversion of streamflow for irrigation has been decreasing, owing to the increased cost of maintenance of ditches and diversion works. This decrease in diversion of streamflow has been offset by increased pumping of ground water, a less variable supply. Adjustment in the computations for diversion was less than the long-term average diversion because the decrease in diversion was occurring during the 1931–60 base period.

AVERAGE ANNUAL WATER LOSS

Water loss from a drainage basin, defined in terms of surface flow, occurs (1) when rain infiltrates the ground and percolates to the water table, (2) when water seeps to the water table through the streambeds, and (3) when water is evaporated or transpired. In this report, the average annual water loss from the drainage basins of streams entering Pearl Harbor is defined as the difference between the 30-year (1931–60) mean annual rainfall over the basins and the 30-year mean annual direct runoff.

The long-term average annual rainfall over the 90 square miles of drainage area, as determined from the precipitation map (fig. 1), was 83.3 inches, or 355 mgd. Direct runoff (exclusive of runoff from basal springs, irrigation return water, and sewage effluent) averaged 11.1 inches. Water loss, therefore, was 72.2 inches, or 308 mgd (table 2). However, it is not known what part of the loss is attributable to evapotranspiration and what part to infiltration and deep percolation.

SEEPAGE LOSSES

Most deep percolation probably occurs in the upland areas of heavy rainfall before water collects in the middle and lower reaches of stream channels. The alluvial streambeds are poorly permeable. Thus, once water collects in the channels and fills all the pools and interstices of the alluvium, additional inflow of water will flow out to sea, only slightly decreased by seepage.

The discharge records for the gaging station on North Halawa Stream near Aiea (sta. 2260) and observations of no flow at the confluence of North Halawa Stream with South Halawa Stream indicate that at least 5.3 million gallons of water is required to fill all the pools and saturate the streambed in the reach between the two sites. It is not known how much of the 5.3 million gallons is lost in deep percolation during the initial wetting, but measurements made at other times indicate that once the streambed is saturated, only small amounts of water seep through the bed of North Halawa Stream.

Measurements of Kipapa and Waikakalaua Streams show that seepage from these streambeds also is small. Because continuous records of discharge are more reliable than individual current-meter measurements, the concurrent records of stations 2128 and 2129 on Kipapa Stream are used to show the magnitude of seepage. Duration curves for the two stations are plotted for the period of concurrent record, December 14, 1966–March 31, 1968, in figure 8. The maximum difference between the two curves at low flow, which is indicative of the maximum dry-weather seepage between the two stations, is about 0.35 mgd. The distance between the two stations is 8.2 miles; therefore, seepage through the bed of Kipapa Stream is about 0.04 mgd per mile of stream.

RECHARGE

Dale (1967) estimated that throughout the years 1931–65 the discharge of ground water in the Pearl Harbor area averaged 250 mgd. This large discharge without a progressive lowering of the water level in the basal ground-water body suggests that recharge to the ground-water body was approximately equal to discharge from it.

The basal ground-water body is recharged by direct infiltration of rain, principally in the high forested area, by infiltration of irrigation water applied in excess of plant requirements, by seepage of water through streambeds, and by possible ground-water inflow from outside the area. Estimates of the amount of recharge provided by each of the items are beyond the scope of this report. Of importance, however, is the amount of the potential infiltration.

The land overlying the basaltic aquifer intake area has a loose and porous structure and a high capacity to absorb water. Mink (1962a) estimated that 50 to 60 percent of the aggregate rainfall and the water applied in the irrigation of sugarcane in the Pearl Harbor area returns to the ground-water body.

EFFECT OF CHANGES IN WATER USE

Before 1953, streams supplied an average of 8.6 mgd of the irrigation water; and before 1963, the Waiahole Ditch (fig. 2) supplied an average of 26.1 mgd of surface water and ground water imported from the east side of the Koolau Range. The basal aquifer supplied the rest of the irrigation water.

After 1953, diversion of surface water for irrigation decreased until, in 1963, only about 1 mgd was diverted. This resulted in a decrease of about 4 mgd [$0.5\times(8.6-1.0)$] in recharge. However, since 1963, there has been an increase of 5 to 6 mgd of water imported from eastern Oahu by way of the Waiahole Ditch. In

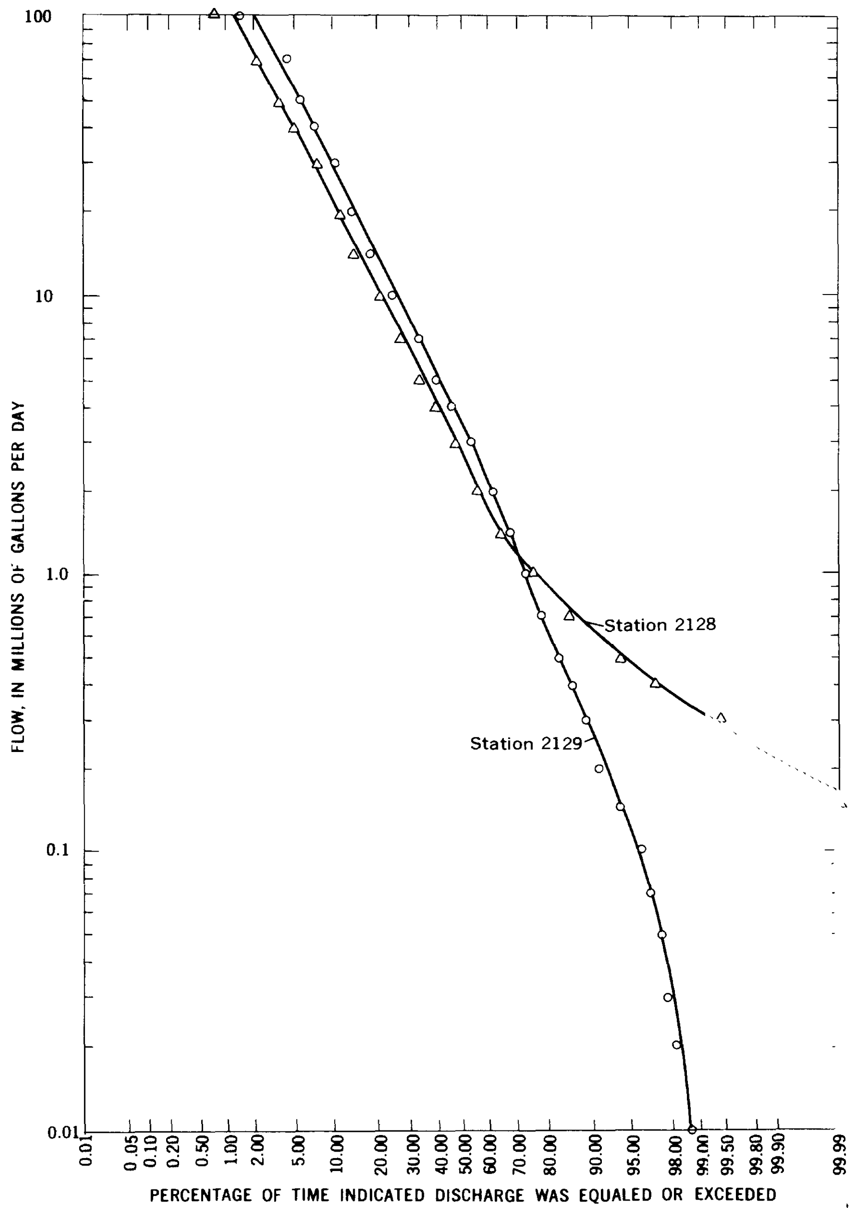

FIGURE 8. — Flow-duration curves for Kipapa Stream stations 2128 and 2129, December 14, 1966–March 31, 1968.

addition, about 2.2 mgd of the water available in Waikele Stream, at the Waiahole Ditch siphon, is pumped into Waiahole Ditch for irrigation. The water available at the siphon is the effluent from sewage treatment plants at Schofield Barracks and Waipio Acres and the ground water returned to the stream after being used for air conditioning by the U.S. Navy. At the present time (1968), ground water constitutes the largest part of the water used; however, sewage effluent may be used for irrigation in greater amounts in the future. The capacity of the pumps at the siphon is 2,975 gallons per minute, or 4.3 mgd.

Dale (1967) estimated that, owing to a decrease in pumping for agricultural use and an increase in pumping for urban use, infiltrated irrigation water decreased by 10 mgd. The result has been a net increase in ground-water discharge. The development of Mililani Town in the northern part of the area will eventually increase ground-water discharge by an additional 10 mgd or more.

AVAILABILITY OF STREAMFLOW AT LOW ALTITUDES

The decrease in the use of surface water for irrigation mentioned previously will be partly offset by the planned use of part of the perennial flow of Waikele Stream at the gaging station near Waipahu (sta. 2130). The perennial flow, which is contributed mainly by the basal ground-water body, averages about 10.6 mgd. However, the lowest daily flow recorded during the periods of record (1958–59, 1961–67) was 4.4 mgd in 1963.

To show how much water is available for use, low-flow frequency curves for Waikele Stream (sta. 2130) were prepared (fig. 9). The curves show the lowest mean discharge for 1 day and for 7 consecutive days. The 3-day minimum is not shown because it is nearly the same as the 1-day minimum. Curves for periods

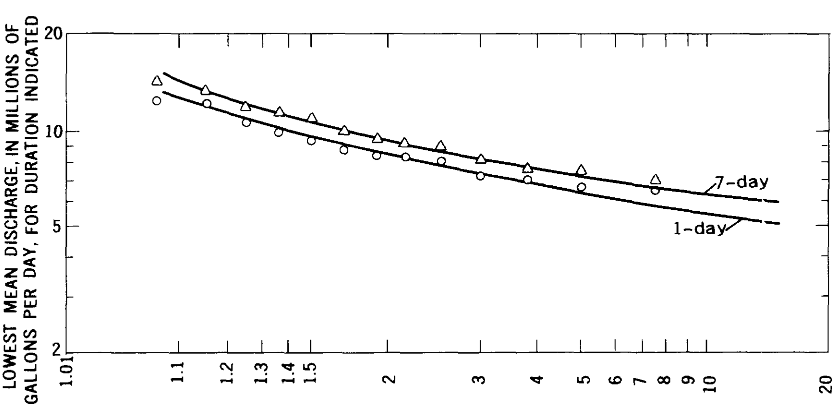

FIGURE 9. — Magnitude and frequency of low flows on Waikele Stream near Waipahu (sta. 2130), 1953–59, 1961–67 fiscal years.

longer than 7 days were not drawn because they would be affected by direct runoff from rain during such periods.

The 1-day-minimum curve, which represents the run-of-river flow, shows the flow available without storage. The 7-day-minimum curve shows the flow available if some storage is provided.

There is perennial flow also at the gaging station on Waiawa Stream (sta. 2160), which can provide an average of 2.6 mgd of irrigation water. Figure 10 shows the magnitude and frequency of the 1-day- and 7-day-minimum flows at the gaging station. Measurements made in 1967 and 1968 show that flow increased by about 1.5 mgd in the 1,000-foot reach of channel below the gaging station. This gain was equivalent to 47 percent of that from seeps and springs upstream from the gaging station. (See table 3.)

AVAILABILITY OF STREAMFLOW AT HIGHER ALTITUDES

Estimated runoff figures for altitudes of 800 and 400 feet are given in table 4. They were estimated from a regression equation

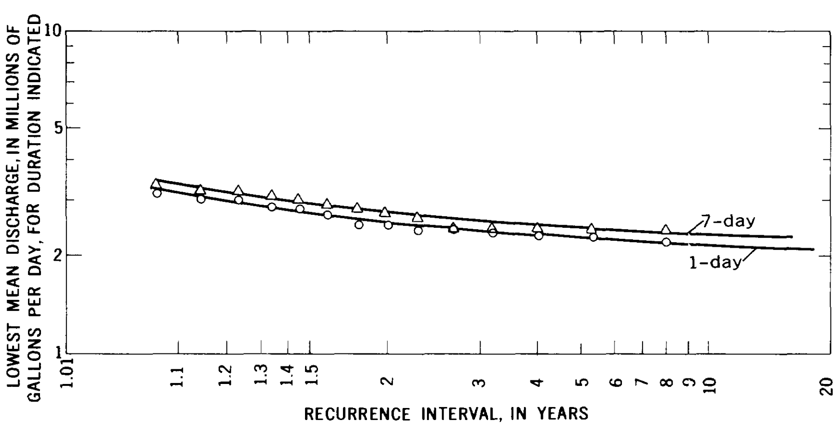

FIGURE 10. — Magnitude and frequency of low flows on Waiawa Stream near Pearl City (sta. 2160), 1953–67 fiscal years.

TABLE 3. — *Ground-water inflow to Waiawa Stream below gaging station 2160*

[Results in million gallons per day]

Date	Discharge above spring-inflow zone	Discharge at station	Ground-water gain above station[1]	Irrigation-well discharge	Discharge 1,000 feet below station	Ground-water gain below station[2]
May 12, 1967	0.81	4.49	3.68	0.79	6.78	1.50
July 10, 1967	3.28	6.19	2.91	.76	8.08	1.13
Oct. 16, 1967	.75	4.06	3.31	.63	6.59	1.90
Feb. 28, 1968	1.46	4.64	3.18	.97	7.21	1.60
Average			3.24	.79	—	1.53

[1]Discharge at station minus discharge above spring-inflow zone.
[2]Discharge 1,000 ft below station minus discharge at station minus irrigation-well discharge.

TABLE 4. — *Estimated average annual runoff at selected altitudes on streams in the Pearl Harbor area, 1931–60*

[mgd, million gallons per day]

Stream	Tributary to	800-foot altitude: Drainage area (sq mi)	800-foot altitude: Rainfall (in.)	800-foot altitude: Direct runoff in.	800-foot altitude: Direct runoff mgd	400-foot altitude: Drainage area (sq mi)	400-foot altitude: Rainfall (in.)	400-foot altitude: Direct runoff in.	400-foot altitude: Direct runoff mgd
Waikakalaua	Waikele	2.60	158	27.4	3.39	....	....	....	....
Waikele	Pacific Ocean	5.30	51	5.8	1.47	17.9	65	8.1	[1]6.92
(Unnamed)	Kipapa	1.91	127	20.2	1.84	....	....	....	....
Kipapa	Waikele	3.83	180	32.6	5.95	9.85	123	19.4	9.11
(Unnamed)	Waiawa	.31	140	23.1	.34	....	....	....	....
(Unnamed)	do	1.23	190	35.2	2.07	....	....	....	....
Waiawa	Pacific Ocean	.98	180	32.6	1.53	3.88	144	24.0	4.44
(Unnamed)	Waiawa	1.71	167	29.5	2.40	2.64	147	24.7	3.10
Manana	do	.83	140	23.1	.91	1.59	114	17.5	1.33
Waimano[2]	do	2.36	158	27.4	3.08	4.11	133	21.6	4.23
Waimalu[2]	Pacific Ocean	1.92	164	28.8	2.64	3.31	147	24.7	3.90
Kalauao	do	1.12	141	23.3	1.25	1.76	120	18.7	1.57
North Halawa	Halawa	1.56	146	24.5	1.81	2.54	135	22.0	2.66
South Halawa	do	.82	124	19.5	.76	1.43	111	16.8	1.14
Total		....	....	....	29.44	....	....	....	38.40

[1]Does not include the estimated difference of 0.5 mgd between the amount available at the Waiahole Ditch siphon and the amount pumped out of the stream.
[2]Values for 800-foot altitude represent total of the three headwater streams.

computed from the rainfall and direct-runoff figures in table 2. The equation is $\log y = 1.37 \log x - 1.576$, where y = direct runoff, in inches, and x = rainfall, in inches. The standard error of the estimate is 0.067 log units, or 16.8 percent.

Table 4 shows that at the 800- and 400-foot altitudes the mean annual direct runoff is 29 and 38 mgd, respectively. However, the runoff available in any single stream is small, the largest being 6 and 9 mgd at the 800- and 400-foot altitudes, respectively, in Kipapa Stream.

Because the direct runoffs shown in table 4 are average annual figures, they may be fully utilized only if all the flows — from low flow to flood flow — are diverted for use. To show how much of the average flow of Kipapa Stream is available if diversion is less than total, figure 11 was prepared from the record for Kipapa Stream near Wahiawa (sta. 2128). The average flow (6.4 mgd) at the gaging station at an altitude of 690 feet is nearly equal to that of the stream at 800 feet (6.0 mgd).

The estimated long-term flow-duration curve and the duration-area curve for Kipapa Stream (sta. 2128) are shown in figure 11. The flow-duration curve shows the percentage of time a given discharge is equaled or exceeded. The duration-area curve is the integral of the flow-duration curve along the flow axis (side scale) and shows the average flow available below a given discharge. Figure 11 may be used in the following manner. Enter the graph at the side scale — for example, at 60 mgd. The intersection of the 60-mgd line and the flow-duration curve indicates that 60-mgd flow was equaled or exceeded 1.5 percent of the time, as read on the bottom scale. Follow the 60-mgd line across the graph to where it intersects the duration-area curve. This intersection is read on the top scale and indicates that 5.6 mgd is the average of all flows less than 60 mgd. The average discharge for the stream at the gaging station is 6.42 mgd; therefore, if all flows at and below 60 mgd are diverted, about 87 percent of the average flow of the stream is available. If all flows below 40 mgd are diverted, an average of 5.2 mgd, or 81 percent of the average flow of the stream, is available.

The foregoing average flows of 5.6 and 5.2 mgd are available only if the diversion ditch is large enough to take all daily flows of 60 and 40 million gallons. Such a ditch must have a capacity much larger than 60 mgd (or 40 mgd) because of the large range in discharge in a day. If capacity is limited to 60 mgd (or 40 mgd) the average of the flows diverted will be less than 87 (or less than 81) percent of the mean annual discharge of the stream.

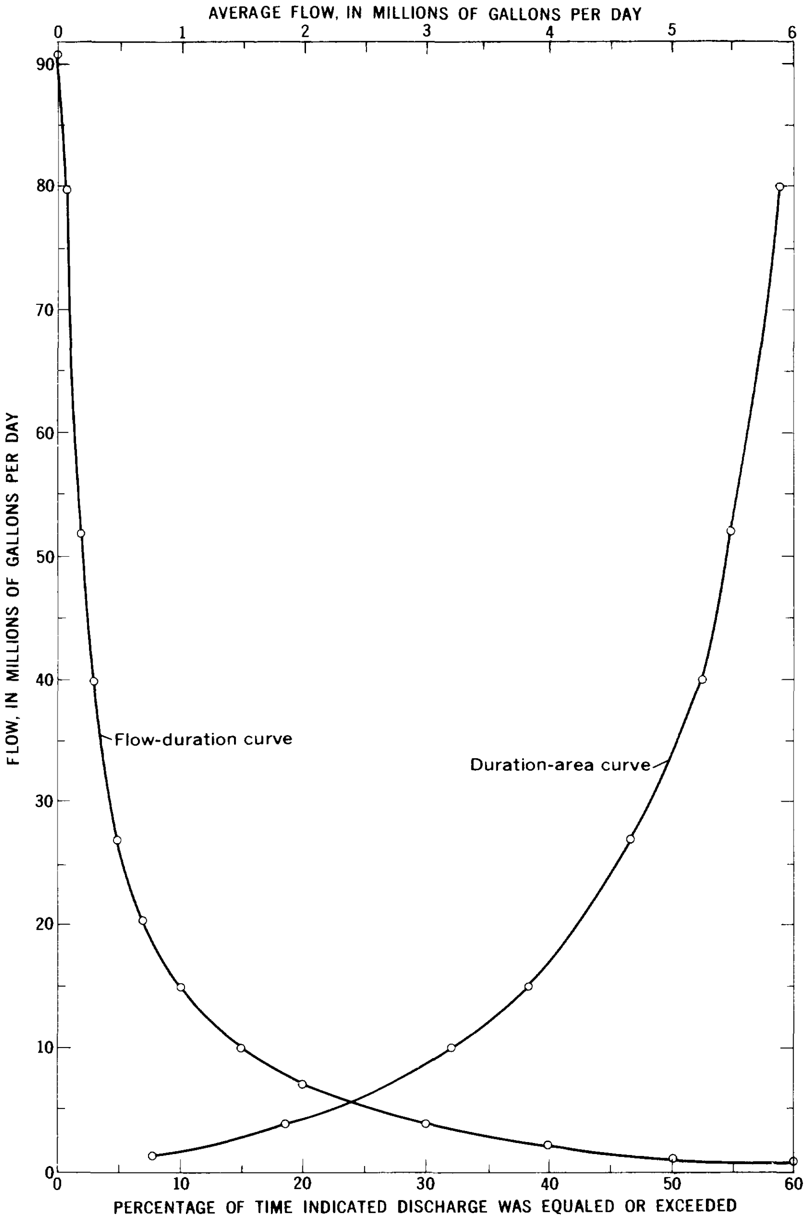

FIGURE 11. — Estimated long-term flow-duration and duration-area curves for Kipapa Stream near Wahiawa (sta. 2128). Flow-duration-curve values are read from the bottom and side scales. Duration-area-curve values are read from the top and side scales.

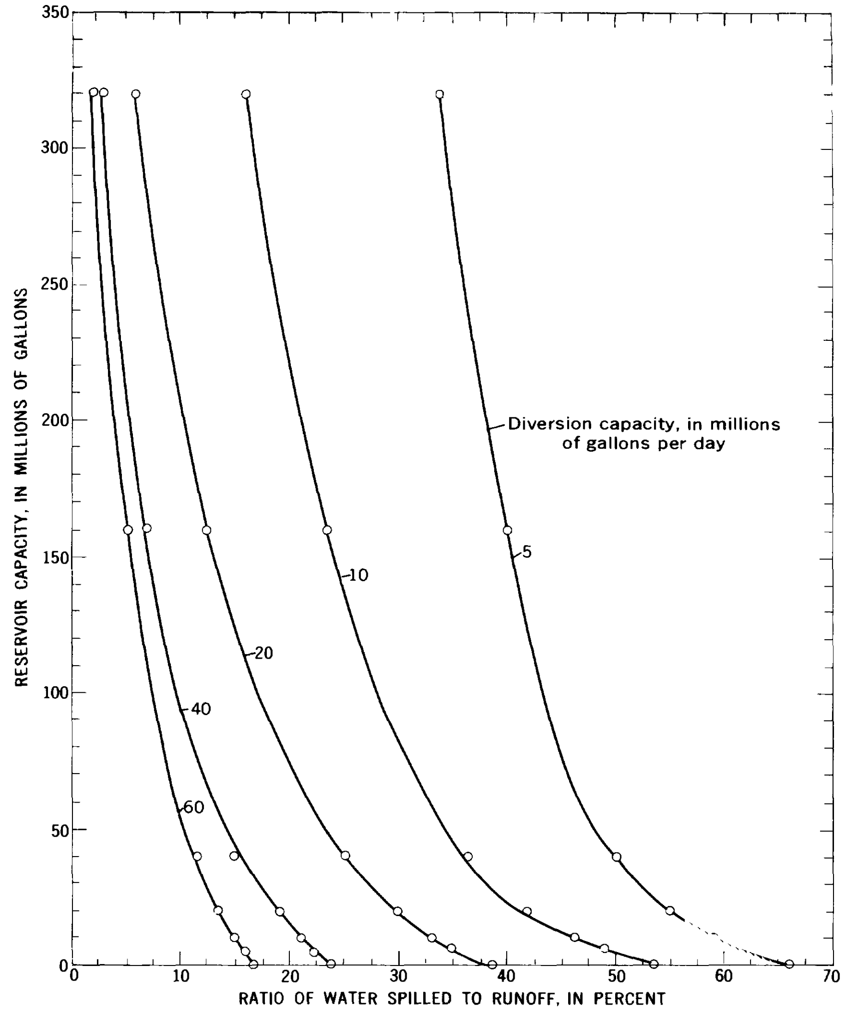

FIGURE 12. — Family of curves showing percentage of streamflow in excess of reservoir and diversion capacity for Kipapa Stream near Wahiawa (sta. 2128).

The family of curves shown in figure 12 is based on the 3,468 daily discharges of Kipapa Stream (sta. 2128) from January 1, 1957, through June 30, 1966. The curves were computer developed for the author by R. H. Dale. They show that the ratio of water spilled (water in excess of system capacity) to stream runoff can be obtained by combining various reservoir and diversion capacities. For example, the following reservoir-diversion combinations will capture all but 19 percent (amount of water spilled) of the average runoff (6.78 mgd) of Kipapa Stream (sta. 2128). The average runoff in this example differs slightly from the previous example because of a different base period.

Reservoir capacity (million gallons)	*Diversion capacity (mgd)*
250	10
80	20
20	40
0	>55

Records of Kipapa Ditch diversions show that before diversions were reduced in 1954, 51 percent of the average annual flow (9.2 mgd) of Kipapa Stream was diverted at the ditch intake. Waikakalaua Ditch diverted 65 percent of the average flow (3.5 mgd) available in Waikakalaua Stream at the ditch intake. The average of the two percentages is about 60 percent.

If only 60 percent of the streamflow available in a stream can be diverted by a practical ditch under operating conditions, the figures of runoff in table 4 should be reduced by 40 percent. The water available for recharge then becomes 17.7 and 23.0 mgd at the 800- and 400-foot altitudes, respectively.

SEDIMENTATION

Data collected on Kipapa Stream near Waipahu (sta. 2129) indicate that the suspended-sediment load is mostly silt and clay (table 5). Although the maximum discharge for which samples were taken was only 158 mgd, or 245 cubic feet per second, the suspended-sediment load for greater flows probably will be composed predominantly of silt and clay.

The desirability of maximum use of flows and minimal clogging of facilities poses a dilemma. As figure 11 shows, to obtain an average of 3.0 mgd of recharge water from Kipapa Stream, all daily flows below 9.0 mgd must be diverted; to obtain an average of 4.0 mgd, all flows below 17 mgd must be diverted. The increase of 1 mgd (from 3 to 4 mgd) in the average diversion is accompanied by a doubling (from 9 to 17 mgd) of the magnitude of the daily discharge below which all flows must be diverted. To obtain an additional 1 mgd (from 4 to 5 mgd) requires that all flows below 34 mgd be diverted. Thus, the magnitude of the daily discharge, below which all flows must be diverted, roughly doubles for each increase of 1 mgd in the amount diverted for diversions between 1 and 5 mgd.

However, as figure 13 shows, sediment discharge increases rapidly with increased water discharge. Thus, the use of surface water of the area for recharge poses a conflict. The flashiness of streamflow, on the one hand, requires that the flows diverted for

TABLE 5. — *Suspended-sediment load for Kipapa Stream near Waipahu (sta. 2129)*

[Methods of analysis: C, chemically dispersed; P, pipet; V, visual accumulation tube; W, in distilled water. T, less than 0.05 ton]

Date of collection	Time (24-hour)	Water temperature (°C)	Discharge		Sediment concentration (mg/l)	Sediment discharge (tons per day)	Percent of suspended sediment finer than indicated size, in millimeters							Method of analysis
			mgd	cfs			0.002	0.004	0.016	0.062	0.125	0.250	0.500	
Feb. 17, 1967	1030	20	9	14	8	0.3								
May 18, 1967	1400	26	3.4	5.3	16	.2								
June 30, 1967	1045	24	4.6	7.1	13	.2								
July 31, 1967	0945	24	2.8	4.3	11	.1								
Aug. 8, 1967	1145	24	25	39	24	2.5								
Dec. 18, 1967	1005	22	158	245	585	387	34	48	78	93	98	99	100	VPWC
Dec. 18, 1967	1240	22	85	132	300	107	39	56	88	97	100	...	....	VPWC
Dec. 19, 1967	1025	....	16	24	27	1.7								
Jan. 5, 1968	1225	21	[1]130	[1]200	283	[1]160								
Mar. 25, 1968	1510	22	19	30	18	1.5								
May 8, 1968	1105	23	1.2	1.8	3	T								

[1]Estimated.

recharge be high enough so that the average volume of recharge water will be enough to justify the costs of a recharge project. On the other hand, lower flows are desirable to prevent clogging of recharge facilities by suspended sediment.

The flow of Kipapa Stream is used for irrigation of sugarcane, but the concentration of suspended sediment must be considered if the flow is to be used in recharge tunnels, wells, or basins.

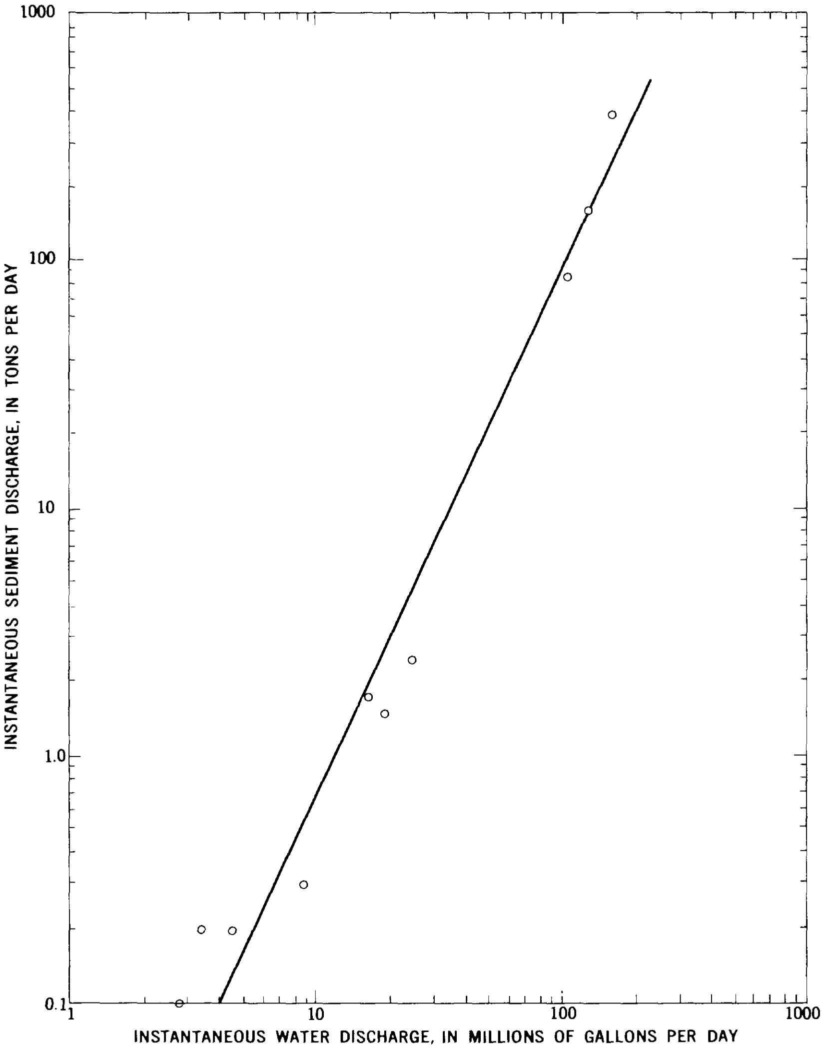

FIGURE 13. — Relationship of instantaneous sediment discharge to instantaneous water discharge for Kipapa Stream near Waipahu (sta. 2129).

Artificial recharge of Hawaiian aquifers from streamflow has not been attempted but appears to be an obtainable and desirable goal. Practical tests must be made to provide some of the answers needed to design efficient recharge facilities. Unused ditches or reservoirs might be excavated or large-diameter shafts or wells might be dug to bedrock for recharge testing.

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