UNITED STATES

DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

EVALUATION OF MAJOR DIKE-IMPOUNDED GROUND-WATER RESERVOIRS, ISLAND OF OAHU

With a Section on

FLOW HYDRAULICS IN DIKE TUNNELS IN HAWAII

Open-File Report 81-1119

Prepared in cooperation with the

BOARD OF WATER SUPPLY

CITY AND COUNTY OF HONOLULU

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CONVERSION TABLE

The following table may be used to convert measurements in the inch-pound system to the International System of Units (SI).

Multiply inch-pound units	By	To obtain SI units
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.0929	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
gallon (gal)	3.785	liter (L)
million gallons (10^6 gal or Mgal)	3785	cubic meters (m^3)
	Volume Per Unit Time (includes Flow)	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second-day ((ft^3/s)-d)	2447	cubic meter (m^3)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (10^6gal/d or Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Miscellaneous	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
foot per day (ft/d)	0.3048	meter per day (m/d)
gallon per minute per foot (gal/min)/ft	0.207	liter per second per meter (L/s)/m
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)

EVALUATION OF MAJOR DIKE-IMPOUNDED GROUND-WATER RESERVOIRS, ISLAND OF OAHU

By Kiyoshi J. Takasaki[1/] and John F. Mink[2/]

ABSTRACT

Ground-water reservoirs impounded by volcanic dikes receive a substantial part of the total recharge to ground water on the island of Oahu because they generally underlie the rainiest areas. They accumulate the infiltration from rainfall, store it temporarily, and steadily leak it to abutting basal reservoirs or to streams cutting into them. The dike reservoirs have high hydraulic heads and are mostly isolated from saline water.

The most important and productive of the dike-impounded reservoirs occur in an area of about 135 square miles in the main fissure zone of the Koolau volcano where the top of the dike-impounded water reaches an altitude of at least 1,000 feet. Water is impounded and stored both above and below sea level. The water stored above sea level in the area of about 135 square miles has been roughly estimated at 560 billion gallons by using a mean water level of 400 feet and a mean specific yield of 0.05. In comparison, the water stored above sea level in reservoirs with a mean water level of 300 feet and mean specific yield of 0.03 underlying a dike-intruded area of about 53 square miles in the Waianae Range has been roughly estimated at 100 billion gallons. Storage below sea level is indeterminable, owing to uncertainties in the ability of the rock to store water resulting from increasing dike density and decreasing porosity.

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Tunnels have, by breaching dike controls, reduced the water stored above sea level by at least 50 billion gallons in the Koolau Range and by 5-1/2 billion gallons in the Waianae Range, only a small part of the total water stored.

Total leakage from storage in the Koolau Range has been estimated at about 280 Mgal/d (million gallons per day). This estimated leakage from the dike-impounded reservoirs makes up a significant part of the ground-water yield of the Koolau Range, which has been estimated to range from 450 to 580 Mgal/d. The largest unused surface leakage is in the Kaneohe, Kahana, and Punaluu areas and the largest unused underflow occurs in the Waialee, Hauula-Laie, Punaluu, and Kahana areas. The unused underflow leakage is small in areas near and east of Waialae but it is an important supply because of the great need of augmenting water supplies there.

Total leakage from storage in the Waianae Range has not been estimated because underflow is difficult to determine. Much of the surface leakage, about 4 Mgal/d in the upper parts of Waianae, Makaha, and Lualualei Valleys, has been diverted by tunnels. Hence, supplies available, other than surface leakage, cannot be estimated from the discharge end of the hydrologic cycle. Infiltration in the Waianae Range to dike-intruded reservoirs in the upper part of the valleys on the west (leeward) side has been estimated at about 20 Mgal/d, and on the east (windward) side, at about 10 Mgal/d. The available supply has been estimated at about 15 Mgal/d from the infiltration on the leeward side, of which about 4 Mgal/d is now being developed. No estimate has been made for the available supply on the windward side. Dike-intruded reservoirs at shallow depths west (lee side) of the crest are in upper Makaha, Waianae, and Lualualei Valleys. They are at moderate depths in upper Haleanu and in lower Kaukonahua Gulches on the east (windward) side.

Flow hydraulics in dike tunnels is also discussed.

INTRODUCTION

Ground-water reservoirs on Oahu store a very large but only approximately estimatable quantity of freshwater. These reservoirs include interconnected water bodies that are impounded by volcanic dikes or other geologic structures, and water bodies that are floating on saline ground water in dike-free lava flows in the flanks of the volcanoes. A significant amount of water is stored above sea level, to an altitude of at least 2,000 feet in the Waianae Range, but most is stored below sea level. The depths of freshwater storage below sea level range from a few feet to 1,000 feet or more in the dike-free lavas, and probably to several thousands of feet in the compartmented lavas between dikes. Other water bodies, small in comparison, are perched above and isolated from these interconnected bodies.

This report is primarily concerned with high-head dike-impounded ground-water reservoirs that underlie interior mountainous areas where rainfall and subsequent recharge to ground water are the greatest. These reservoirs, owing to their upgradient positions, play a very important role in the recharge, storage, movement, and discharge of all ground water on the island.

The work was done by the U.S. Geological Survey in cooperation with the Board of Water Supply, City and County of Honolulu.

Purpose and Scope

The purpose of the studies discussed in this report is to explain the mode of occurrence of dike-impounded water, its development, its flow hydraulics, its role in the hydrology of the ground-water cycle, and, most importantly, its potential as a supplementary supply source during high-demand dry periods. The report delineates the principal rift-zone areas where dikes occur and outlines development of new and redevelopment of existing dike-impounded water sources.

Evolution of the Concept for the Development of Dike-Impounded Water

M. M. O'Shaughnessy (1909), in an article on irrigation works in the Hawaiian Islands, described the development of ground water at high altitudes as follows:

"The most novel development in water supply has been the discovery of water by drilling tunnels into the lava formation at high altitudes in encouraging localities."

Except for "encouraging localities," O'Shaughnessy does not mention the geologic structures that are necessary for the occurrence of ground water at these high-altitude areas. The early tunnels he describes on Oahu and Maui were dug mostly before or near the turn of the century. Stearns and Vaksvik (1935) gave a date of about 1888 for a tunnel dug in Waimanalo Valley in Oahu and about 1900 for the early tunnels dug in Iao Valley on the island of Maui.

One of the earliest reports that implies a relationship between the geologic structure and the occurrence of ground water at high altitudes was given by Lippincott (1911). His explanation for the large discharge of water above an altitude of 750 feet and his subsequent rationale for the driving of a tunnel at about this altitude from the east or windward side of the Koolau crest to the west or lee side on Oahu follows:

"There is a pronounced strata of hard and impervious bed rock, which apparently forms the floor, or bed, of the under-ground reservoir, the top of which appears on the windward side of the range, at an elevation of approximately 850 feet in the Waiahole District. This bed rock can be observed continuously from Waiahole through to the Kahana Gulch, it being perhaps 50 feet higher in the Kahana district, and lower in the districts southerly from Waiahole. This bed rock appears to be overlaid with a porous formation, which carries large quantities of water. Practically all of the spring waters, which have been measured at the 750 feet level, on the windward side of the island in connection with these investigations, are fed from the underground reservoir, and issue from the top of this stratum of bed rock."

The horizontal strata that Lippincott describes probably refers to massive lava flows or sills (tabular intrusive volcanic rocks that are generally parallel to the lava flows). Neither of these rock types is areally extensive on Oahu. There was, however, no mention, in Lippincott's report, of dikes (tabular intrusive volcanic rocks that generally cut across the lava flows) or any other vertical geological structures that could deter or impound the horizontal flow of ground water.

Martin and Pierce (1913) specifically commented on the uniformity of streamflow fed by springs at altitudes of about 1,000 feet in the Waiahole area and between 800 and 900 feet in the Kaneohe area. They offered no explanation for the uniformity of streamflow nor the similarity in the altitudes of the springs.

Jorgen Jorgensen (1916), in a report to the Honolulu Water Commission, was one of the first to associate the presence of dikes with the occurrence of ground water and the piercing of dikes by tunneling with the development of ground water. The following quotation is taken from his report:

"At a distance of 600 feet from the portal, a vertical dyke of close-grained lava rock about 8 feet thick was met and as this was pierced a heavy flow of water appeared."

Although there is a clear implication in the above quotation and in a profile of the Waiahole tunnel shown in his report regarding the ability of dikes to impound ground water, Jorgensen does not elaborate on the relation of the dikes to the occurrence or impoundment of ground water at high altitudes on the windward side of Oahu. As Lippincott did in 1911, Jorgensen believed that a hard layer of rock formed the bottom of a large perched ground-water body. According to Jorgensen, the hard layer was impervious but had many faulty spots that allowed a portion of the water to escape to form the many high-altitude springs on the windward side of Oahu.

H. S. Palmer (1921) was the first to outline the role of sills and dikes in the movement and occurrence of ground water at high altitudes. The following is a quotation from his report in 1921:

"The dikes and sills are in consequence members capable of restraining and controlling the circulation of ground water. The sills may form negative members which prevent downward movement. The dikes may form vertical restraining members which prevent horizontal escape."

Palmer continues thus: "...The best success in tunneling for water has been had where the tunnels have intersected dikes."

Also: "...Tunnels driven in through the dikes are virtually artificial leaks, so placed that water can be conveniently caught for use."

W. O. Clark was the pioneer in advancing the technology of developing dike-impounded water at high altitudes. He was early in recognizing and relating water-development possibilities of dike-impounded water to the geologic framework. Clark (1922) was the first to recognize the balance that exists between natural recharge and discharge in a ground-water reservoir formed by dikes. Although it was recognized early that a tunnel has its largest flow when newly dug and that this flow will diminish to some lower rate, it was Clark who first attributed this to depletion in reservoir storage. He explained that the quantity of water obtained initially by tunneling depends upon the position at which the reservoir is tapped; also, that it is possible to tap the reservoir to such an extent that it will be completely drained and, thereafter, will not behave as a reservoir at all in that the yield will fluctuate with climatic conditions.

W. O. Clark (1930) evaluated the existing tunnels in the upper Waianae Range in relation to the geologic framework. He was the first to recommend a tunnel siting (Uwau tunnel) on the basis of trend and density of dikes in the main rift zone (Clark, 1932). He was also the first to recommend that a bulkhead gate be placed in a water-development tunnel (Waikane No. 2) for the specific purpose of restoring storage (Clark, 1934). This was followed by a study to determine the effects of the bulkhead gate placed in that tunnel (Olstad and Clark, 1936).

C. K. Wentworth (1938, 1940) described in considerable detail the geologic framework and the occurrence of ground water in upper Palolo-Waialae and Manoa-Makiki Districts in Honolulu. His work included the mapping of hundreds of dikes and sills and subsequent description of the dike system in these areas. He made several recommendations for the additional development of dike-impounded water.

Stearns, in a report by Stearns and Vaksvik (1935), tabulated and described, in some detail, all the tunnels driven to develop high-altitude ground water in Oahu. He also delineated areas in Oahu where ground water was likely to be impounded by dikes. Stearns also proposed a system of tunnels extending from Kalihi Valley to Waiahole for the purpose of developing dike-impounded ground water. He later showed, on a geologic map (Stearns, 1939), the location and trends of dikes mapped on Oahu.

D. C. Cox (1947) described, in detail, the geology and ground-water hydrology of the Kahaluu tunnel and surroundings.

The first mathematical treatise on tunnel flow was prepared by J. B. Cox (Larrison and Cox, 1948). It included evidence that an increase in flow from a tunnel in upper Waianae Valley (tunnel 19) was caused chiefly by drawing water from underground storage. The loss of storage was manifested in reduced flows of nearby tunnels. Cox also showed there was a great lag in the relationship between antecedent rainfall and increase in tunnel flow. He also introduced the use of multiple exponential equations of head decay to approximate the flow of a tunnel that penetrates a series of dike compartments.

D. C. Cox (1949) summarized and discussed all the hydrologic investigations in upper Waianae Valley prior to 1948. The 1949 report formed the basis for Cox to predict the flow for the planned extension of the City and County tunnel from 6,000 to 10,000 feet and the possible effect on the flow of the existing tunnels.

D. C. Cox (1957) proposed a scheme to develop ground water in a tunnel at high altitude (Waiahole main tunnel). The scheme included the drilling of wells in some of the dike compartments which would be pumped during periods of low flow. During periods of high flow, the dike compartments would be allowed to recover. Cox also prepared a bibliography accompanied by abstracts of the Waiahole Water Co. system from its inception to 1946.

During the period 1957 to 1960, an extensive and systematic mapping of dikes took place in and near the tunnels of the Waiahole Water Co. system for the specific purpose of relating tunnel flow to dike intrusions and the host rocks. The principal investigators during this period were D. C. Cox, then with the Hawaiian Sugar Planters' Association; John F. Mink, then with the U.S. Geological Survey and the Honolulu Board of Water Supply; and George Yamanaga and K. J. Takasaki of the U.S. Geological Survey.

G. T. Hirashima's contribution to the evolution of the concept for the development of dike-impounded water included papers in 1962, 1963, 1965, and 1971. His studies were chiefly concerned with aspects of tunnel storage and tunnel depletion and the effects of changes in them on ground-water flow and streamflow. Hirashima, in a report by Takasaki, Hirashima, and Lubke (1969), introduced the use of an exponential equation of flow depletion to calculate storage and to compare the hydraulic conductivity of the reservoir rocks of different tunnels.

John F. Mink (1971, 1978) refined the die-away exponential expression by the addition of a recharge constant. By so doing, tunnel flow was made to equal the recharge constant after storage was depleted. This refinement made it possible to manipulate the expression to attain accurate estimates of storage.

GEOLOGIC SKETCH

Volcanic Activity

The island of Oahu was built by the coalescence of two volcanoes, the Waianae, forming the western part of the island, and the Koolau, forming the eastern part. The Waianae volcano became dormant before the Koolau, and westward-dipping lava flows of the Koolau overlapped the eroded eastern slopes of the Waianae in the central part of the island. The initial mountain-building phase of these volcanoes ended in a long period of quiescence, during which the volcanoes were deeply eroded. The rocks of the mountain-building phase belong to the Waianae Volcanics and Koolau Volcanics.

Renewed vulcanism occurred in the southeastern part of the Koolau Range and left several intravalley lava flows, cinder cones, and many tuff cones. This activity produced rocks of the Honolulu Volcanics.

Rift-Zone Structures

The Waianae and Koolau volcanoes are typical Hawaiian shield volcanoes with collapsed calderas near their summits. The trilinear pattern of the rift zones common to the volcanoes is the result of upward thrust from beneath each volcano, and the caldera is the result of the relaxing of this same upward thrust (Macdonald, 1956). Both volcanoes have two principal rift zones and a less well-developed third rift zone. The two principal rift zones of the Waianae volcano meet in the summit region at an angle of about 150 degrees and those of the Koolau volcano at an angle of about 165 degrees. The third rift zone in each volcano extends from the summit region at the apex of the exterior angle formed by the principal rift zones (fig. 1).

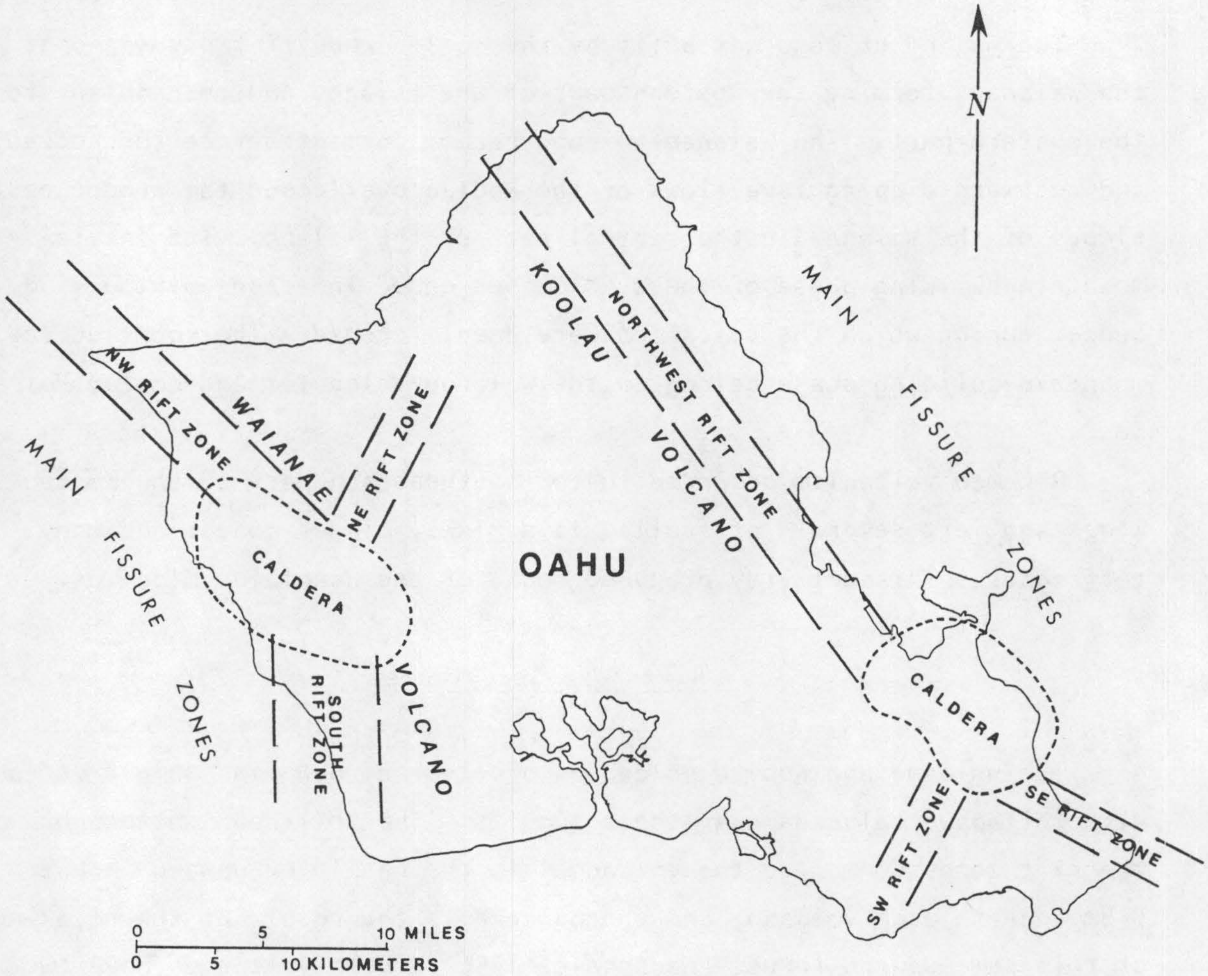


Figure 1. Rift zones and calderas of Koolau and Waianae volcanoes (after Macdonald, 1972).

The junction of the rift zones lies in a caldera whose eroded extension was about 10 miles long and 5 miles wide in the Waianae volcano and about 8 miles long and 4 miles wide in the Koolau volcano. Large parts of the caldera structures and the lavas that filled the calderas have been extensively eroded.

The presence of near-surface dense rock underlying the caldera areas is indicated by strong positive gravity anomalies. The relations of each caldera to a positive gravity anomaly and to the rift zones are shown in figures 2 and 1, respectively.

On the recently active volcanoes, the rift zones are marked at the surface by open fissures and by lines of cinder and spatter cones. In older volcanoes, such as Waianae and Koolau, where erosion has exposed the rift zone 3,000 feet or more below the original surface, these features are generally absent on the surface. The rift zones, instead, are marked by swarms of closely spaced, nearly vertical, and nearly parallel dikes. These aggregates of dikes and the rocks they intrude are known in Hawaii as "dike complexes" (Stearns and Vaksvik, 1935, p. 77).

The abundance of dikes in a dike complex is greatest in the central part of the main fissure zone, where the number of dikes can be as much as 1,000 per mile of horizontal distance across the zone. Macdonald (1956) cites a probable average of between 100 and 200 per mile. In the adjacent outer part of the complex, the number sharply decreases to between 10 and 100 per mile and at the edge the number declines abruptly (Macdonald and Abbott, 1970, p. 126-127).

The number of dikes in a dike complex is also a function of the depth of exposure below the original surface. Each lava flow that emanates at the surface needs one or more feeders, which consolidate to form dikes when the eruption ceases. It has been calculated that, in a 2-mile-wide dike complex, the number of feeders necessary is approximately 100 for each 1,000 feet of rise (Wentworth and Macdonald, 1953, p. 91). The dike complex, hence, is readily recognizable in the Waianae and Koolau volcanoes, where they have been eroded, in part, to depths of 3,000 feet or more.

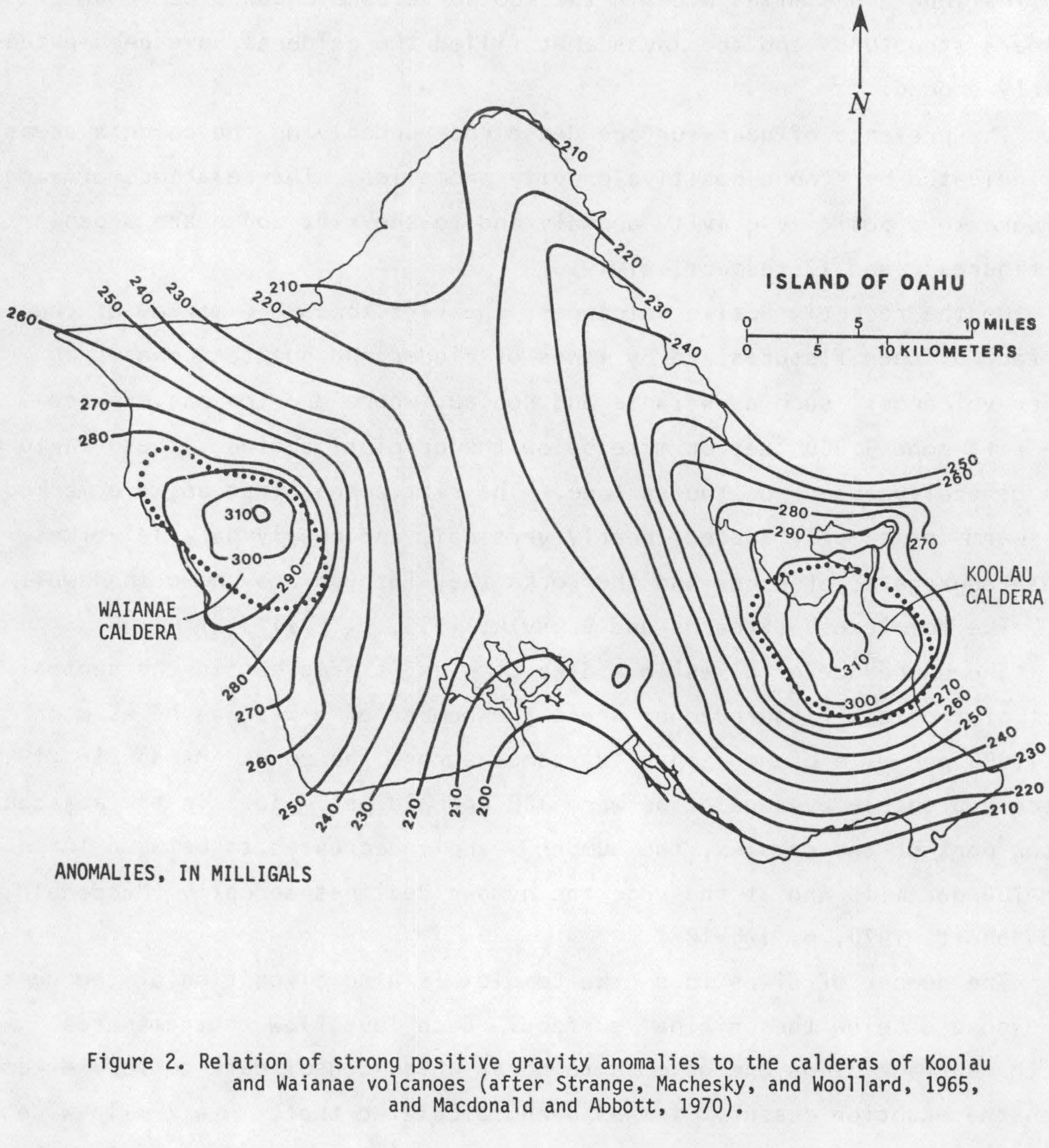


Figure 2. Relation of strong positive gravity anomalies to the calderas of Koolau and Waianae volcanoes (after Strange, Machesky, and Woollard, 1965, and Macdonald and Abbott, 1970).

Marginal Dike Zone Defined

The term "marginal dike zone" was introduced by Stearns (Stearns and Vaksvik, 1935) and has been used to describe the outer part of the dike complex, where dike intrusions are drastically reduced to single, widely scattered dikes. Dike intrusions in the marginal dike zone generally number fewer than 100 dikes per mile and constitute a percentage usually less than 5 percent of the total rock volume. Dikes in a dike complex compose at least 10 percent, or more of the total rock volume. Although the strike of the dikes is generally the same in the dike complex and in the marginal dike zone, these zones are generally distinct with little transition between them.

In general, the dike complex acts as a deterrent to ground-water flow in all directions, while the marginal dike zone is a deterrent to flow primarily in the direction normal to the dikes, therefore, the occurrence of dike-impounded water is more favorable in the marginal dike zone than in the dike complex.

Attitude of Dikes

In this report and in most geologic reports, the attitude or trend and inclination of dikes are described by their strikes and dips. A simple way to illustrate the strike and dip (of a dike) is to imagine a dike intersecting a horizontal surface from below. The compass direction of the intersection of the horizontal surface with the dike is called the strike. This gives the bearing or trend of the dike. The dip of the dike is the maximum acute angle between a horizontal plane and the dike; the maximum is 90 degrees when the dike is vertical. The dip measures the inclination of the dike. The dip is also given a compass direction, which is always perpendicular to the strike and in the direction of the angle measured (fig. 3).

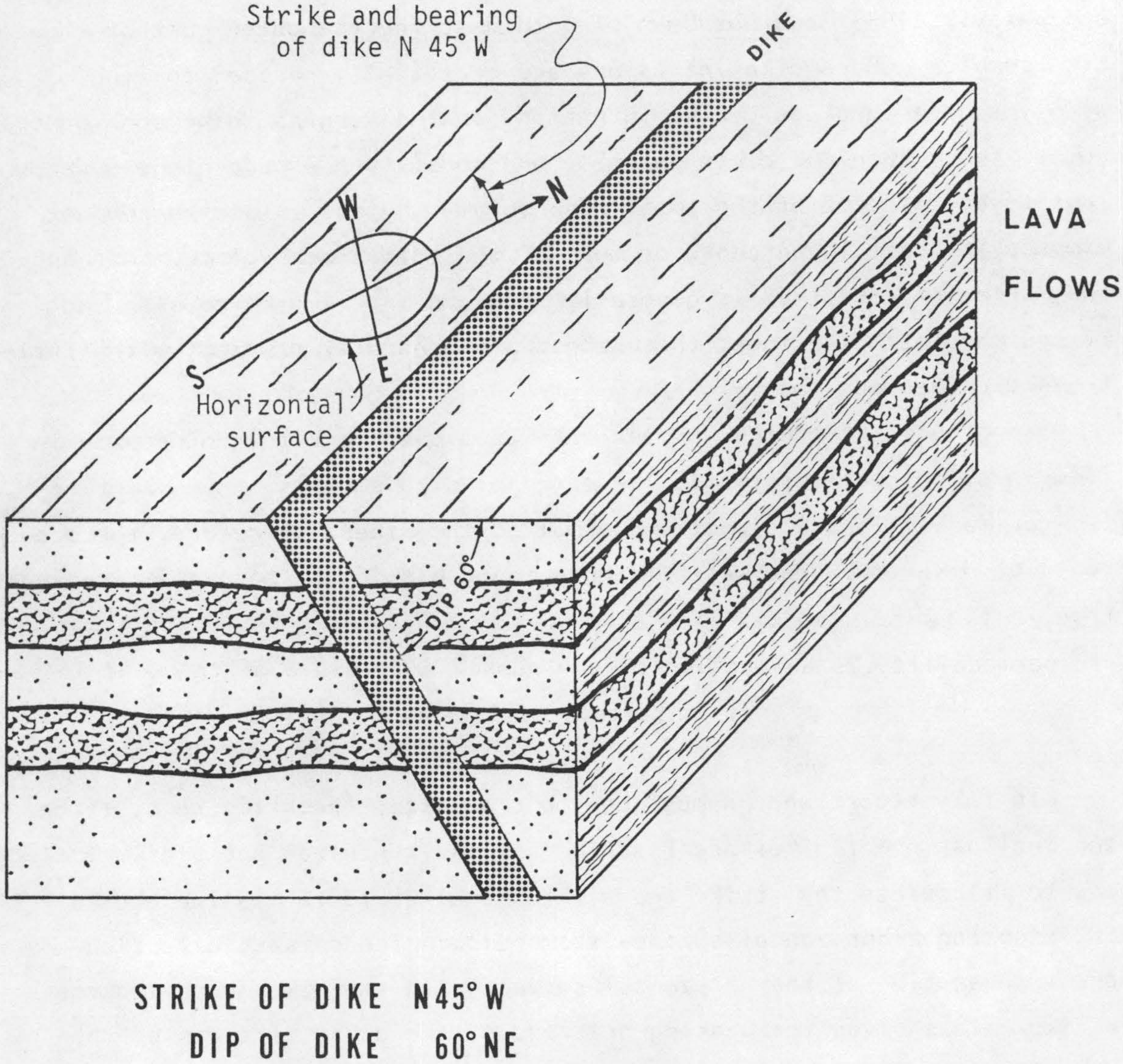


Figure 3. Relation of strike and dip of a dike.

DIKES AND THEIR EFFECT ON STORAGE AND MOVEMENT OF GROUND WATER

Geologic Framework of Dike-Impounded Reservoirs

The principal reservoirs of ground water in Oahu are in basaltic lava flows that were extruded above sea level. Because both the Waianae and Koolau volcanic domes have sunk 1,200 feet or more (Macdonald and Abbott, 1970, p. 356), these subaerial flows now extend well below sea level to provide permeable lavas at these depths. The subaerial flows generally are thinly bedded, highly clinkery, and highly permeable. In contrast, flows extruded in water are likely to be more massive, less clinkery, and less permeable. The ground water occurs in interconnected reservoirs that are impounded by dikes in the rift-zone areas or reservoirs that are dike free in the flanks of the volcano.

The regional permeability of lavas, whether high or low initially, is significantly reduced when they are intruded by dikes. The reduction in permeability is a function of the number and volume of the dike intrusions and the geometry of the dikes. Williams and Soroos (1973), in an evaluation of methods of pumping-test analyses in eight locations in Hawaii, show a transmissivity of 33,420 $(ft^3/ft)/d$ (cubic feet per foot per day) or about 250,000 (gal/d)/ft (gallons per day per foot) for a dike-intruded basaltic aquifer in Waikolu Valley on Molokai. This value, probably indicative of the transmissivity parallel to the general dike trend, is no more than one-tenth of the transmissivity of most dike-free basaltic aquifers.

Generally, the permeability of lavas is highest in the plane of the lava flows. Dike intrusions, even a single thick dike normal to this plane, would significantly retard the flow of water, and if the retardation is sufficient the principal flow of water could change to a direction parallel to the alinement of the dikes (fig. 4). If the dike intrusions become sufficiently numerous and intersect, the dike-intruded rock section could become a barrier to ground-water flow.

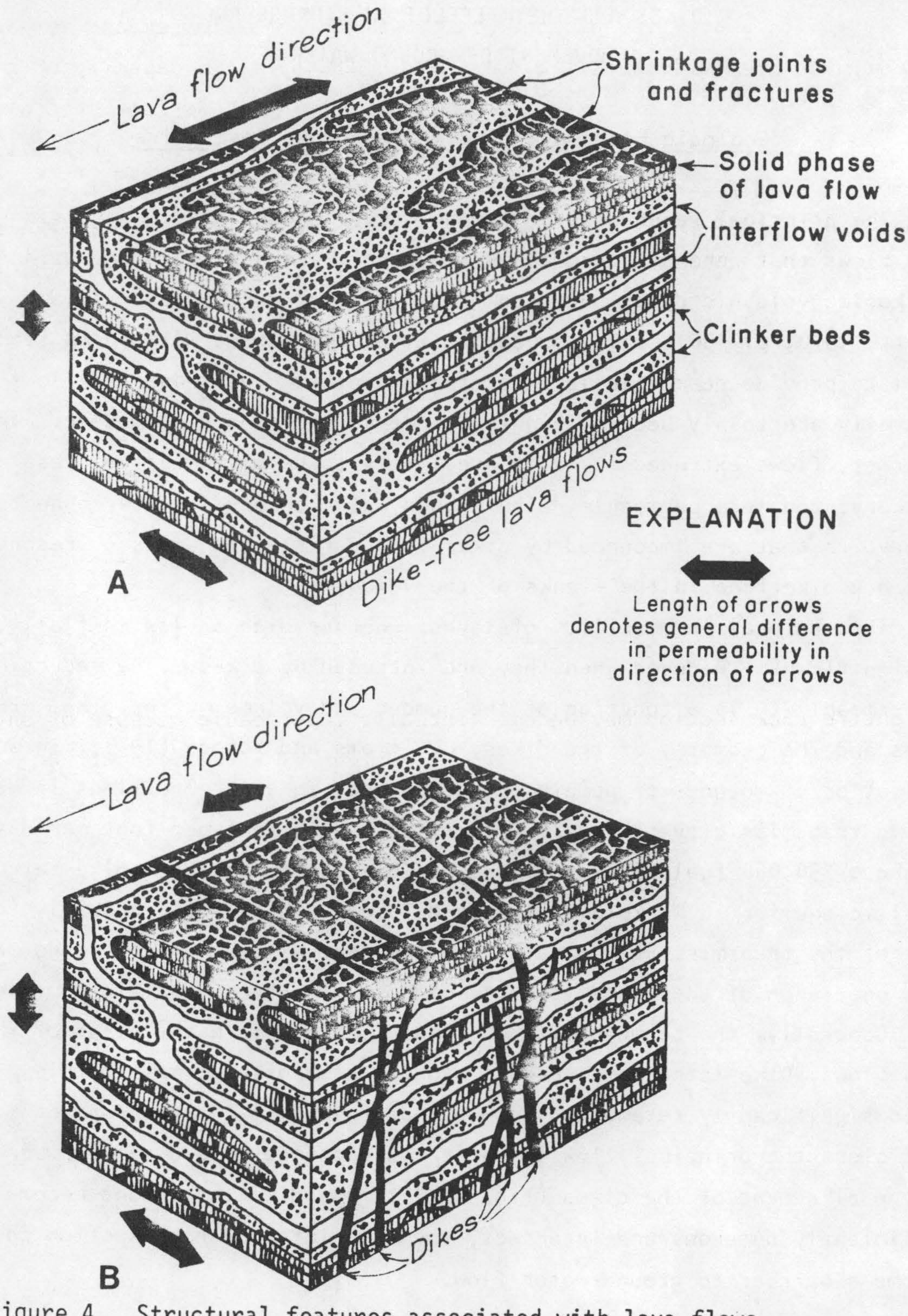


Figure 4. Structural features associated with lava flows (A) highest permeability is in the flow direction and (B) permeability is significantly lower where dikes intruded at right angles to the flow direction (after Takasaki and Valenciano, 1969).

Hydraulic properties of aquifers can often be estimated and compared by using the specific capacities of wells. The specific capacity of a well is its discharge expressed in gallons per minute per foot of drawdown. Owing to differences in the degree of penetration of aquifers by wells, which is a significant factor in using specific capacity to estimate aquifer properties, a more comparable value is obtained by dividing specific capacity by the thickness of the aquifer penetrated. Table 1 shows the specific capacity and the specific capacity per foot of aquifer penetration for wells that tap aquifers impounded by dikes.

The dikes, because they retard the flow of water, impound and store water behind them. The limiting height and depth to which water can be stored behind them depend on the geometry of the dike intrusions, the hydraulic properties of the dike materials to retain the impounded water, and the water-bearing properties of the reservoir rocks. At equilibrium conditions, the water will rise in the reservoir to a level where the leakage through or over the dikes equals the inflow into the reservoir. The effective storage of the reservoir will be limited to depths where the entire rock section may become virtually impermeable because of an increasing number of dike intrusions or because of lava flow extruded below sea level so that the high hydraulic pressure of the seawater caused the reduction of the hydraulic conductivity of the lava flow.

Ground-water reservoirs impounded behind dikes provide storage and opportunities for development. Ideal conditions for ground-water storage and development are provided where permeable flank lava flows are intruded by widely scattered dikes and where the strike of the dikes is normal to the direction of the regional ground-water flow. Conditions become less favorable as the number of dike intrusions and intersections increases, where the rocks intruded are of low hydraulic conductivity, or where the dikes are parallel to the direction of the regional ground-water flow. The least favorable conditions occur where dikes are so numerous with mixed orientations that they form a network of dense rock and where the hydraulic conductivity of the intruded rocks is so low due to massive structure, deep weathering, or secondary mineralization.

Table 1. Specific capacities and specific capacities per foot of aquifer penetration for wells tapping dike-impounded aquifers in Koolau Range

Aquifer setting	Specific capacity (gal/min)/ft	Specific capacity per uncased foot of aquifer $(gal/min)/ft^2$
Caldera area (highly mineralized) -----	< 1	0.001-0.005
Dike complex --------------------------	< 10	.005- .05
Marginal dike zone --------------------	10-50	.05 - .5
Marginal dike zone open to saline ground water -----------------	> 50	.5 -2

Factors Controlling Recharge and Discharge of Dike-Impounded Water

Most of the rainfall is orographic and occurs when warm, moisture-laden trade winds blowing from the northeast are rapidly cooled as they rise along the steep slopes of the mountains. The rainfall resulting from this rapid cooling is heaviest near the crest. The trade winds, blowing from the general northeast direction, are approximately normal to the trend of both the Koolau and Waianae Ranges; hence, the commonly used terms are windward (east of the crest) and leeward (west of the crest) to denote directions. Except near the crest, the windward areas are generally rainier than the leeward areas.

Dike-impounded reservoirs receive a substantial part of recharge to ground water on the island of Oahu because they generally underlie the heavy rainfall areas. These reservoirs accumulate the infiltration from rainfall, store it temporarily, and leak it steadily to abutting basal reservoirs or to streams cutting into the dike-impounded reservoirs. In areas where the dike-impounded reservoirs are near the land surface, some discharge is directly to evaporation and transpiration. The reservoirs, owing generally to the high capacity of the surface rocks to absorb rainfall and their own large capacity to store water, serve as holding tanks that effectively dampen the great variability in rainfall recharge.

The factors controlling recharge in the rift-zone areas include the rate and persistency of rainfall, absorptive characteristics of the land surface, permeability of the reservoir rocks, dike pattern and dike density, slope of land surface, forest cover, and evapotranspiration. The ideal is for the potential recharge rate to be fully achieved under the most favorable conditions of the factors mentioned above. A manifestation of such a condition would be a low runoff-to-rainfall ratio and deep ground-water levels (fig. 5). A significant part of the rift-zone areas in the Koolau Range falls into the category approaching the more nearly optimal conditions, and a significant part of the rift-zone areas in the Waianae Range is in the opposite extreme, approaching the poorest of conditions.

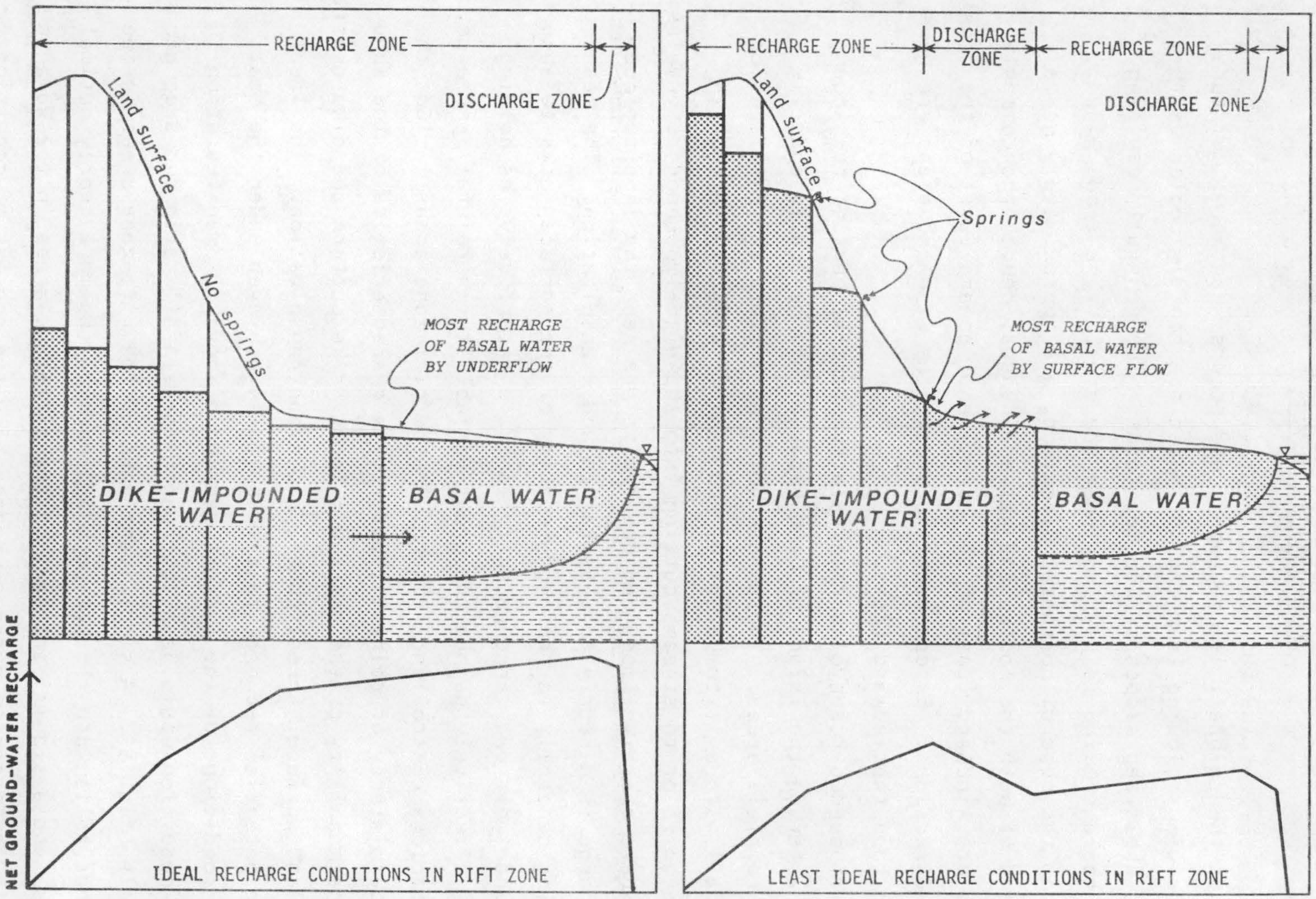


Figure 5. Ideal and poorest conditions for recharge in the rift zone. (Extreme vertical exaggeration.)

The factors that control recharge also control discharge in the rift-zone areas. Where the conditions are ideal for recharge, discharge of ground water to the surface is nonexistent. Where the conditions are least ideal, recharge is limited and most of the ground water is discharged to the surface as springs.

The discharge of dike-impounded water, either below the ground or on the surface, becomes potential recharge to down-gradient water bodies. The ideal would be a total transfer as underflow with no opportunity for evapotranspiration loss or surface flow to the sea. The least ideal would be where all discharge of dike-impounded to down-gradient water bodies is on the surface where maximum opportunity for evapotranspiration and surface loss to the sea prevails (fig. 5).

Where the rift-zone extends to the sea, the mode of discharge to the sea depends largely on the density and trend of the dikes and the permeability of the rocks at depth. The surface discharge would probably be high and the underflow low where dikes are numerous and parallel the shore or where the permeability of the near-shore rocks are low, or both. The discharge mode would be reversed if dikes were sparse and normal to the shore and the permeability of the rocks high. The Kaneohe area is one in which surface discharge to the sea is high and underflow discharge low because dikes are parallel to the shore and near-shore rocks are poorly permeable. The reverse condition probably exists in the Waialee area in the north end of the Koolau Range where dikes are sparse and normal to the shore.

An understanding of the factors controlling the recharge and discharge of dike-impounded reservoirs provides a basis for enhancing the natural recharge and controlling of the rate of discharge from a reservoir.

Although intrinsic physical characteristics of the dikes and host rocks cannot be altered, water levels in the reservoirs can be controlled. Water levels can be lowered by piercing the dike dams or by pumping the dike-impounded reservoir. Lowered water levels, in many instances, would make more space for recharge than that under natural conditions. If water levels were lowered sufficiently, losses to evapotranspiration could become significantly less, thereby further decreasing discharge. In reservoirs where tunneling has lowered water levels to new equilibrium levels, bulkheads can patch the pierced dikes and permit restoration of water levels to the old equilibrium levels. The discharge can then be permitted at higher rates than at the new equilibrium rates for short periods of time as needed.

Without insight as to the modes of recharge and discharge of the dike-impounded reservoirs, it becomes difficult to account for the ground-water flow, which is essential in meaningful water-budget studies. Much of the current difficulty in arriving at comparable figures for the ground-water component in water-budget studies in Hawaii stems from improper evaluation of dissimilar zones of recharge and discharge of dike-impounded and basal reservoirs.

DIKES IN THE KOOLAU RANGE

Rift Zones

The main fissure zone from which the lavas erupted to form the bulk of the Koolau volcano extends in an arc about 30 miles in length from the Waimanalo area to Waialee on the north coast. This zone, where exposed at depth by erosion, is marked by dikes that strike nearly east-west in the southernmost part and nearly north-south in the northernmost part (fig. 6). A minor rift, in which the dikes trend northeasterly and generally normal to the dikes in the main rift, intersects the main rift in the southern part. This minor rift is called the southwest or Kaau rift; the segment of the main rift north of the intersection of the minor rift is called the northwest rift; and the segment south of this intersection is called the southeast rift (fig. 1). One or more minor rift zones manifested by many north- and northeast-trending dikes lie in the area east of the Kaau rift zone.

The south end of the main rift lies to windward of the present crest of the Koolau Range, and the north end straddles the crest.

The junction of the northwest, southeast, and southwest rifts lies in a caldera, which was about 8 miles long and 4 miles wide (fig. 1). Much of the caldera structure and the lavas that ponded in the caldera have been extensively eroded. This erosion may have been the result of the weakened condition of the rock because of their alteration by rising volcanic gases in the caldera (Macdonald and Abbott, 1970, p. 179). The most notable remnant of the caldera-filling lavas is Olomana Peak.

Figure 6. Dikes, dike-intruded rocks, ground-water bodies and subzones, island of Oahu. (Illustration is oversized; attached at back of report.)

Data Base

The ensuing discussion of dikes and dike-related structures in the Koolau Range is based largely on data collected in four periods.

Period	Investigator	Remarks
1930-33	T. F. Harris and H. T. Stearns, U.S. Geological Survey	Field investigations in preparing report on the geology and ground-water resources of Oahu (Stearns and Vaksvik, 1935).
1934-43	C. K. Wentworth, Honolulu Board of Water Supply	Field investigations in preparing manuscript reports on geology and ground-water resources of areas in Honolulu (Wentworth, 1938, 1940).
1957-61	D. C. Cox, University of Hawaii; J. F. Mink, then of Honolulu Board of Water Supply; and K. J. Takasaki, U.S. Geological Survey	Field investigations related to study of Waiahole tunnel system and water resources of windward Oahu (Cox, 1947, 1957; Mink, 1971; Takasaki, Hirashima, and Lubke, 1969).
1962-63	K. J. Takasaki, U.S. Geological Survey	Field investigations in preparing report of water in the Kahuku area (Takasaki and Valenciano 1969).

Many other investigators have also collected dike data. However, much is buried in files and field notebooks and generally is difficult to compile.

Generally, the data given in this report were systematically collected in the periods mentioned above and include information on strike, thickness, and dip of the dikes and, often, descriptions of the host rock. The data include descriptions of about 1,000 discrete dike locations.

Attitude and Density of Dikes

Strike or Trend

The northwest-striking dikes in the main fissure zone of the Koolau Range show a gradual shift in their trends from nearly east-west at the south end to nearly north-south at the north end. The shift in trend suggests an arcuate fissure zone that is concave to the northeast. A plot of the dikes that were mapped in the field is shown in figure 6. The relation of the strike of the dikes to dike frequency by selected areas is shown in figures 7 and 8.

The dikes in the minor rift zones show a shift in trend from northerly to northeasterly away from the south end of the main fissure.

Dip

Dip measurements were made on about a third of the dikes recorded in the study. Table 2 shows a list of these dip measurements by selected areas.

According to these measurements, approximately 50 percent of the dikes mapped are vertical, and approximately 80 percent dip less than 30 degrees from the vertical.

The data available for direction of the dips were not sufficient to make any conclusions and are included merely as part of the data base.

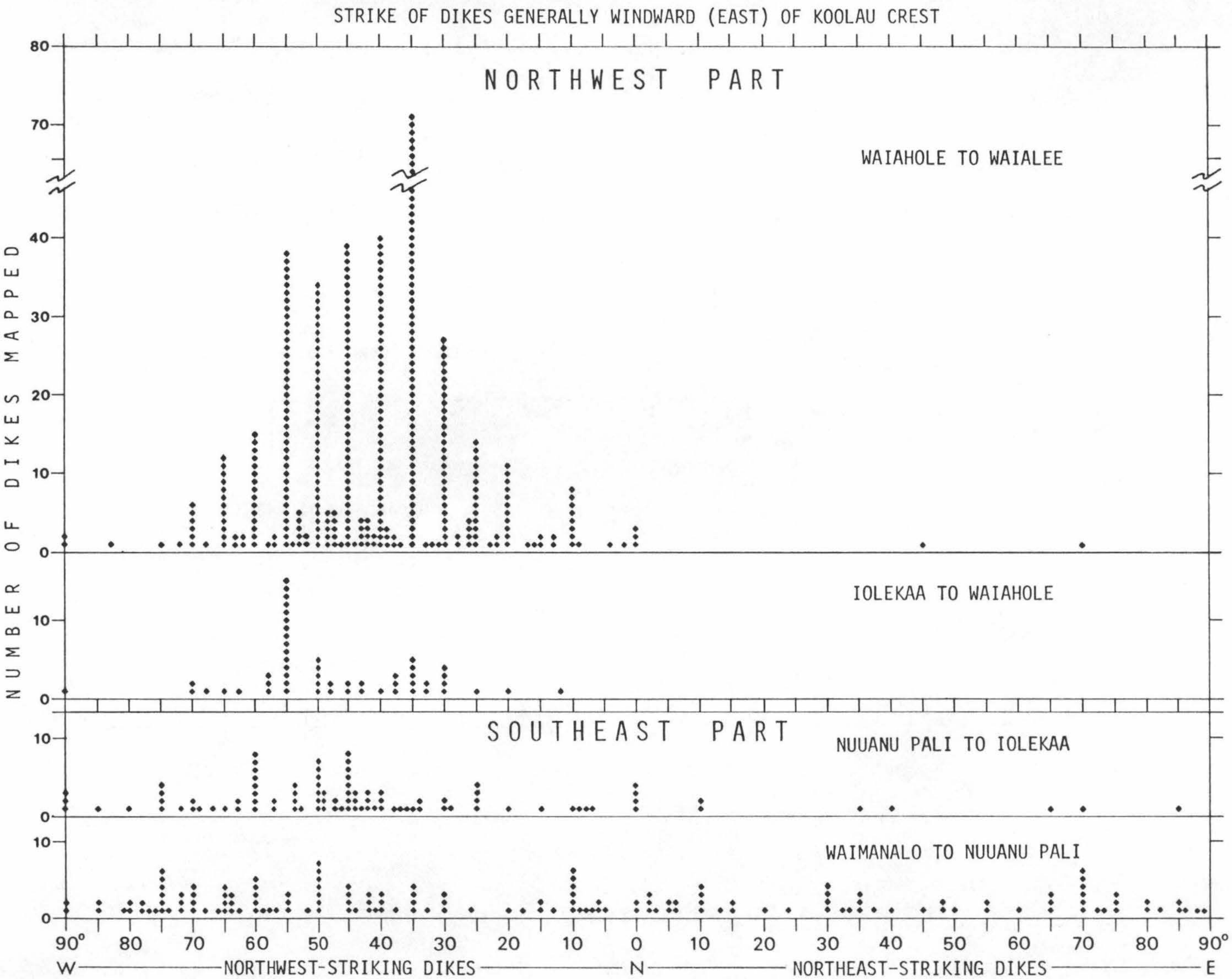


Figure 7. Relation of the strike of dikes to dike frequency in selected areas generally windward (east) of the Koolau crest.

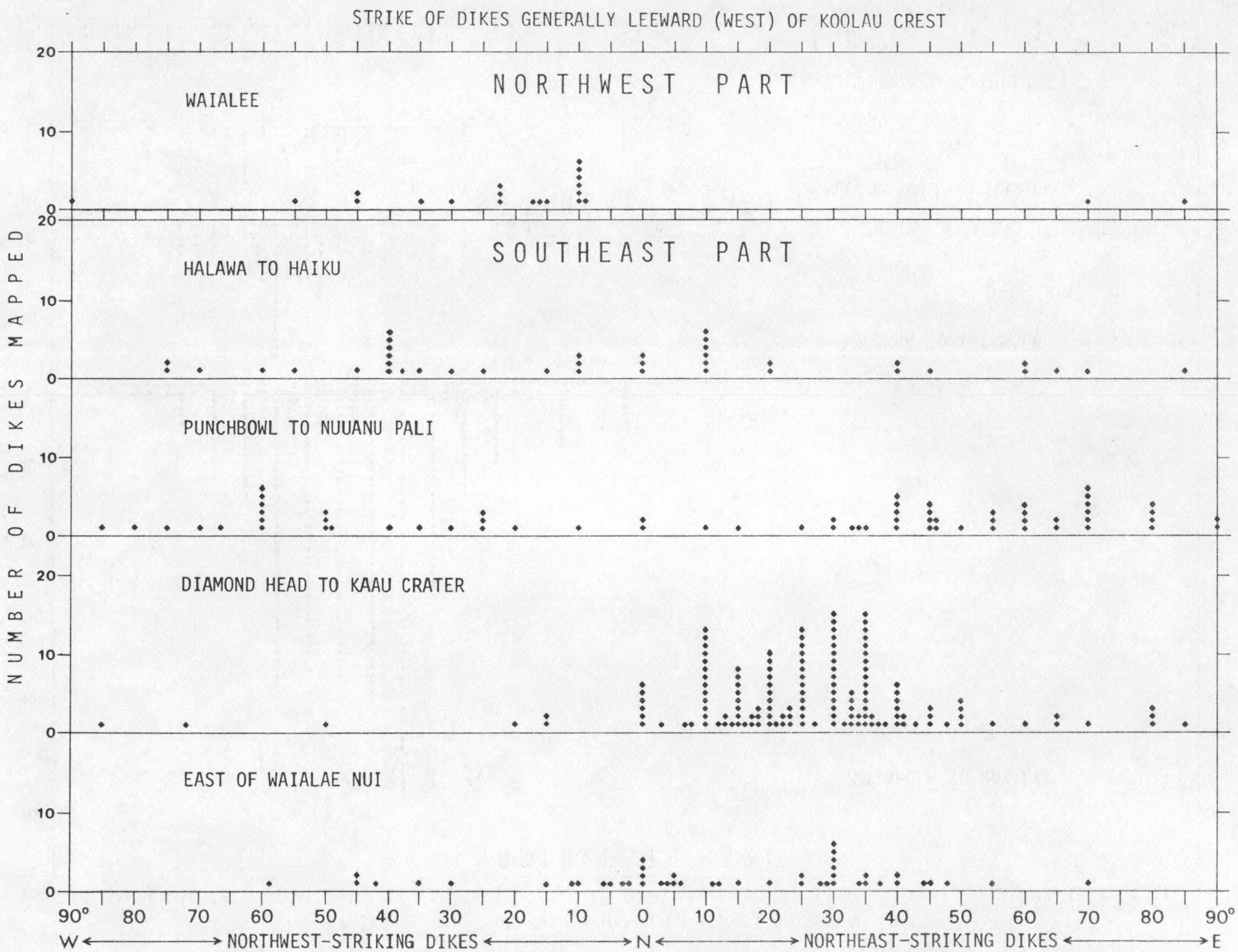


Figure 8. Relation of the strike of dikes to dike frequency in selected areas generally leeward (west) of the Koolau crest.

Table 2. Dips of dikes mapped in Koolau Range

Southeast part from Waimanalo to Halawa-Iolekaa

Generally windward of crest

	Degrees	N	S	E	W	NE	NW	SE	SW	90°	All
Waimanalo to Nuuanu Pali	90									26	26
	89-81	3	2	-	-	5	-	-	3	-	13
	80-71	6	2	4	-	2	-	2	4	-	20
	70-61	3	4	3	1	1	1	1	2	-	16
	60-51	2	1	3	-	-	1	-	2	-	9
	< 50	-	-	-	1	2	1	1	-	-	5
Subtotal		14	9	10	2	10	3	4	11	26	89
Nuuanu Pali to Iolekaa	90									14	14
	89-81	3	1	-	-	3	-	-	2	-	9
	80-71	-	-	1	1	3	-	-	2	-	7
	70-61	-	-	-	1	2	1	1	1	-	6
	60-51	1	-	-	-	-	-	-	1	-	2
	< 50	-	1	-	-	-	-	1	1	-	3
Subtotal		4	2	1	2	8	1	2	7	14	41
Total		18	11	11	4	18	4	6	18	40	130

Generally leeward of crest

	Degrees	N	S	E	W	NE	NW	SE	SW	90°	All
East of Waialae Nui										4	4
	89-81	-	-	1	1	-	-	1	-	-	3
	80-71	1	1	3	1	1	-	5	2	-	14
	71-60	-	-	2	-	-	-	2	-	-	4
	60-51	-	-	-	-	-	-	3	-	-	3
	< 50	-	-	-	-	-	-	2	1	-	3
Subtotal		1	1	6	2	1	-	13	3	4	31
Diamond Head to Kaau Crater	90									26	26
	89-81	-	-	-	1	-	1	4	-	-	6
	80-71	-	-	5	4	-	-	5	-	-	14
	70-61	1	1	2	1	-	2	3	-	-	10
	60-51	-	-	-	-	-	2	2	-	-	4
	< 50	-	-	2	1	-	1	3	-	-	7
Subtotal		1	1	9	7	-	6	17	-	26	67
Punchbowl to Nuuanu Pali	90									10	10
	89-81	-	-	1	-	1	-	-	-	-	2
	80-71	-	-	1	-	2	-	-	1	-	4
	70-61	-	-	-	-	2	-	-	1	-	3
	60-51	-	-	-	-	-	-	1	1	-	2
	< 50	-	2	-	-	-	1	1	1	-	5
Subtotal		-	2	2	-	5	1	2	4	10	26
Halawa to Haiku	90									5	5
	89-81	1	1	-	-	-	-	-	-	-	2
	80-71	-	-	1	2	-	-	-	-	-	3
	70-61	-	-	1	1	-	1	-	-	-	3
	60-51	1	-	-	-	-	-	-	-	-	1
	< 50	-	-	1	-	-	-	-	-	-	1
Subtotal		2	1	3	3	-	1	-	-	5	15
Total		4	5	20	12	6	8	32	7	45	139

Northwest part from Halawa-Iolekaa to Waialee

	Degrees	N	S	E	W	NE	NW	SE	SW	90°	All
Iolekaa to Waiahole	90									19	19
	89-81	-	1	-	-	-	-	-	-	-	1
	80-71	1	1	-	-	-	-	-	3	-	5
	< 70	-	-	-	-	-	-	-	-	-	-
Subtotal		1	2	-	-	-	-	-	3	19	25
Waiahole to Waialee	90	-	-	-	-	-	-	-	-	72	72
	89-81	-	-	-	-	2	-	-	5	-	7
	80-71	1	-	-	1	9	-	-	11	-	22
	70-61	-	-	-	1	2	-	-	3	-	6
	< 60	-	-	-	-	2	-	-	1	-	3
Subtotal		1	-	-	2	15	-	-	20	72	110
Total		2	2	-	2	15	-	-	23	91	135
Grand total		19	13	11	6	32	4	6	41	131	265

	Degrees	N	S	E	W	NE	NW	SE	SW	90°	All
Waialee	90									16	16
	89-81	-	-	-	-	-	-	-	1	-	1
	< 80	-	-	-	-	-	-	-	-	-	-
		-	-	-	-	-	-	-	1	16	17
Total		-	-	-	-	-	-	-	1	16	17
Grand total		4	5	20	12	6	8	32	8	61	156

Thickness

The thickest dikes mapped are in the northwestern half of the main fissure zone. Most of the dikes strike northwest and are between 3 and 7 feet in thickness, but dikes thicker than 10 feet are common. Dikes in the southern part of the Koolau Range generally range in thickness from 1 to 3 feet.

The thickness of dikes mapped in the minor rift zones are generally more uniform. Most of the dikes are between 1 and 3 feet in thickness, and dikes thicker than 5 feet are sparse. Dikes in the Kaau rift zone are generally the thickest in the minor rift zones.

Table 3 shows the distribution and thickness of dikes in the Koolau Range. The measurements tabulated indicate that the dikes in the main fissure zone are thicker at higher altitudes in the northern part of the range and thinner at lower altitudes in the southern part.

Density

A dike complex, an area where dike intrusions exceed 100 per mile, has been delineated in the southern part of the main fissure zone. This delineation was made on the basis of the available data. The dike complex is shown as the shaded area in figure 6. It includes the caldera area and the central part of the main fissure zone. Data are sparse near the crest in the northern part of the range; thus, delineation of the dike complex in this area was not made. A dike complex for the minor rift-zone areas was also not delineated, for the same reason.

The area adjacent to and straddling the dike complex to the margins of the outermost dikes has been designated as the marginal dike zone. Much of the dike-intruded area in the minor rift zone would probably fall into the category of marginal dike zone. The marginal dike zone and the dike complex constitute the limits of the areas underlain by dike-impounded water.

Table 3. Thickness and distribution of dikes mapped in the Koolau Range

Location/thickness (ft)	< 1	1	1-1/2	2	2-1/2	3	4	5	6	7	8	9	> 10	All
						Number of dikes								
Southeast part														
Leeward (West side)														
East of Waialae Nui -----	1	5	9	8	1	10							1	35
Diamond Head-Kaau Crater ----------------	5	20	17	28	8	15	9	6	1	1	2		3	115
Punchbowl-Nuuanu Pali ---	3	4	5	6	6	10	7	2		1		1	2	47
Halawa-Haiku ------------	8	1		2	3	4	1	1	1					21
Windward (East side)														
Waimanalo-Maunawili -----	6	13	10	14	4	9	5	8			2			71
Nuuanu Pali-Iolekaa -----	6	4		4	2	7	3	6		1	1		1	35
Southeast total ----------	29	47	41	62	24	55	25	23	2	3	5	1	7	324
Northwest part														
Leeward ------------------		2		3		3		4	5				2	19
Windward														
Iolekaa-Waiahole -------	2	6		6		4	1	4	7	9	5	1	3	48
Waiahole-Waialee -------	3	10	2	10		25	11	30	18	5	7	7	45	173
Northwest total ---------	5	18	2	19		32	12	38	30	14	12	8	50	240
Grand total ----------------	34	65	43	81	24	87	37	61	32	17	17	9	57	564

DIKE-IMPOUNDED WATER IN THE KOOLAU RANGE

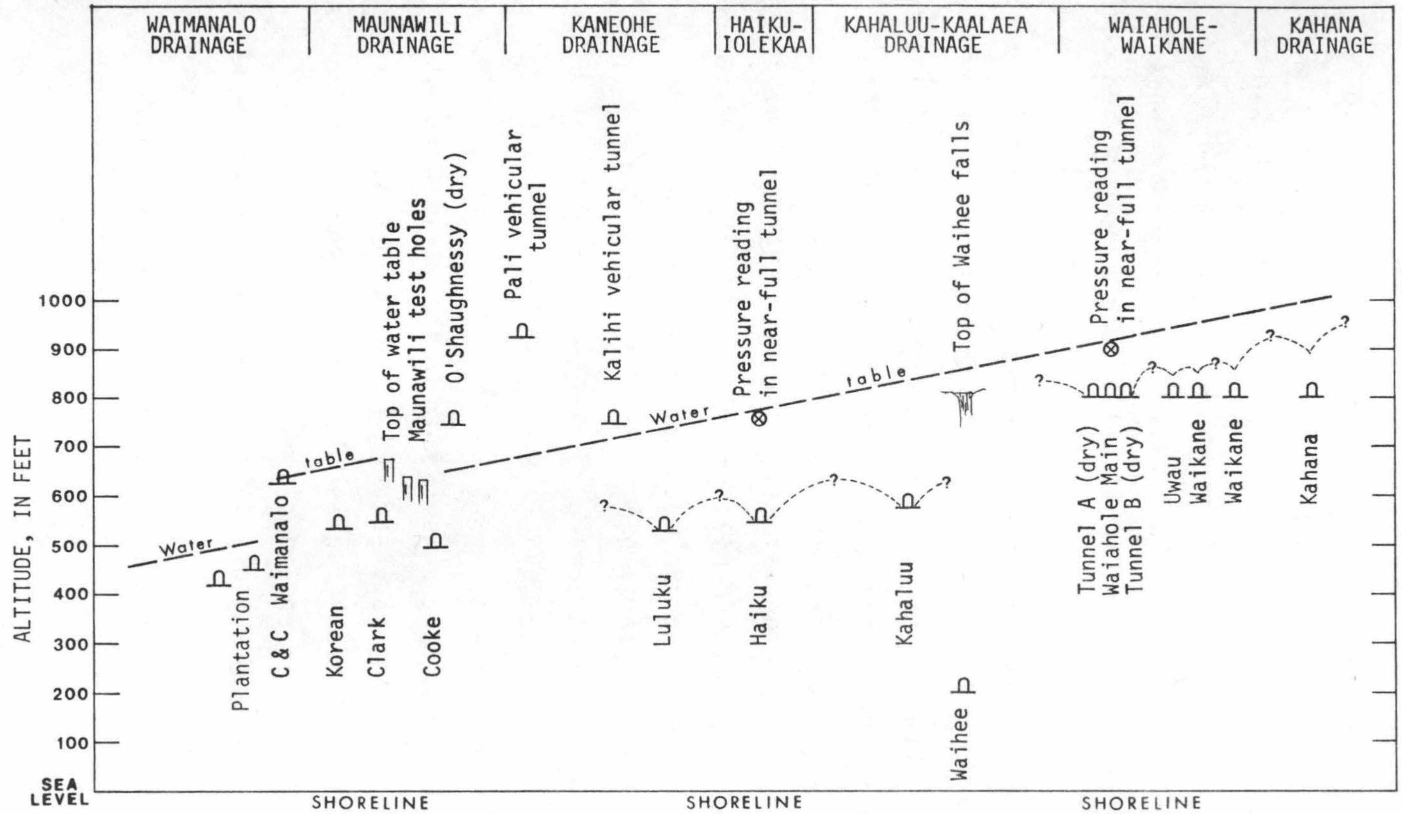
The Reservoir

The main Koolau fissure zone extends in an arcuate zone, approximately 30 miles long and 2 to 6 miles wide, and has an area of about 135 square miles. The Kaau rift and other minor rift zones outside this area add an additional 10 square miles of dike-intruded rocks (fig. 6).

The main fissure zone lies in an area of the heaviest rainfall in the Koolau Range. Mean annual rainfall in the zone ranges from about 40 inches at the north and southern ends to more than 250 inches in the northwest part. Average rainfall is about 110 inches per year, which is equivalent to 260 billion gallons or about 720 Mgal/d. This rainfall input is about a third of the island's total rainfall.

The rocks underlying the main fissure zone store a very large quantity of water impounded by dikes. The limiting height and depth to which water is stored and the movement of the stored water depend on the geometry of the dike pattern and the hydraulic conductivity of the dikes and lavas intruded. At some great depths, movement of the stored water may cease where the increased number of dikes greatly restricts the ground-water flow. Also, at great depths the ability of the reservoir rocks to store water is greatly reduced because of the absence of voids in the lavas extruded at great depths below sea level.

Near the crest of the Koolau Range, water is stored at altitudes as high as 1,000 feet in the northwest part and about 400 feet in the southeast part. A profile of the water level extending from Kahana to Waimanalo is shown in figure 9. The profile was drawn from data available for water-development tunnels, springs, test borings, and vehicular tunnels. In the coastal areas and deep valleys, the dike-impounded water is largely confined below an apron of poorly permeable alluvium or weathered bedrock.



EXPLANATION

Water-development tunnel

Pressure reading

Free-flow tunnel drawdown
Most flow from tunnel floor

Free-flow tunnel drawdown
Most flow from tunnel ceiling and sides

Figure 9. Water level of dike-impounded ground water extending from Kahana to Waimanalo.

Storage of dike-impounded water, especially that part below sea level, is indeterminable owing to the unmeasurable parameters mentioned below which are needed for storage estimation. It is possible, however, to estimate the storage above sea level because some of the parameters required can be measured or reasonably estimated. Among them are the altitude of the dike-impounded water table, the geometry and density of the dike pattern, yield and storage-depletion characteristics of water-development tunnels, hydraulic behavior during pumping of wells, and extent of bedrock weathering.

Figure 10 shows the relationship between the mean water-table altitude and the mean specific yield of the reservoir rocks underlying the main fissure zone covering 135 square miles. The figure covers ranges of water-table altitudes from 100 to 500 feet and of specific yield from 0.02 to 0.10. The storage resulting from any combination of these two parameters within the assumed limits is given by a family of curves. The "X" in the figure, which represents about 560 billion gallons, is then the storage above sea level computed by assuming the mean water-table altitude of 400 feet and the mean specific yield of 0.05.

Tunnels have, by breaching dike controls, reduced storage by at least 50 billion gallons (estimate by Takasaki and Mink), which is only a small part of the initial total storage.

Water in parts of the minor rift zone (Kaau) in the southeast part is stored to higher altitudes than water stored in the main fissure zone. Tunnels in Palolo and Manoa Valleys indicate altitudes of the water levels of at least 990 and 760 feet, respectively.

Rainfall, which averages about 720 Mgal/d on the main fissure zone, is the principal source of recharge. The crest of the range lies within the fissure zone, so there is no surface inflow of water from outside the zone.

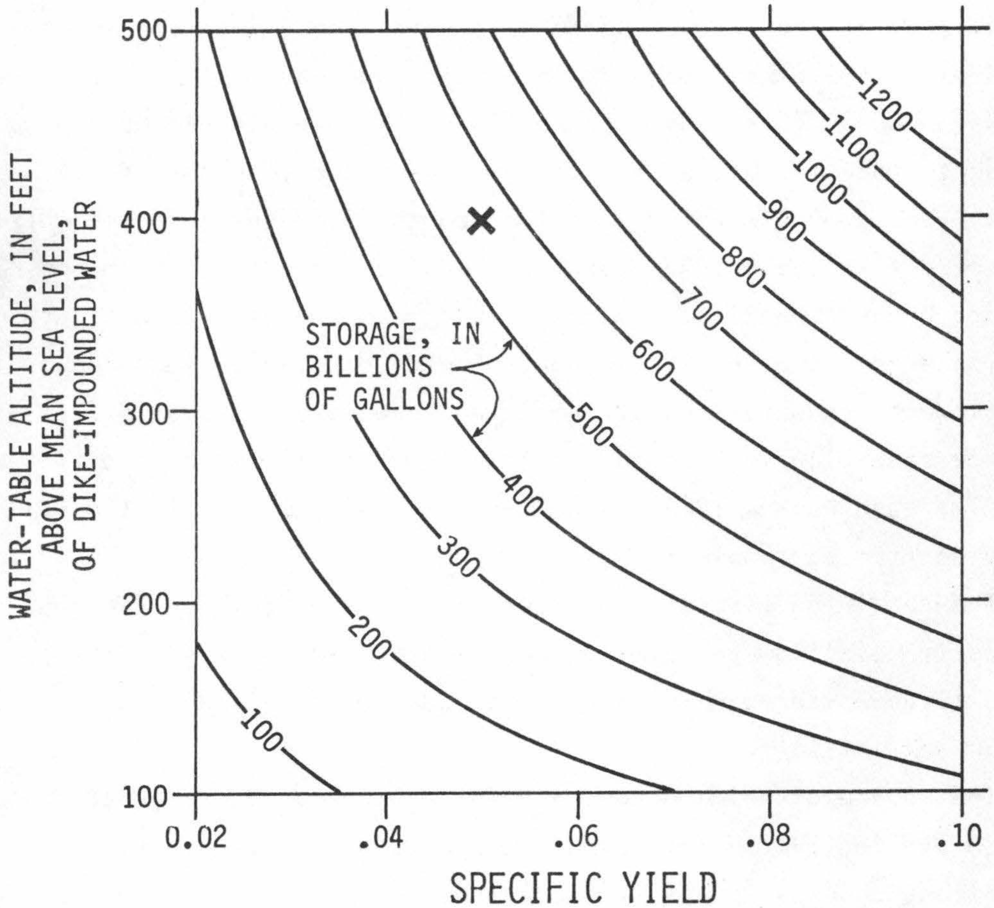


Figure 10. Storage of dike-impounded water as a function of water-table altitude and specific yield of the reservoir rocks.

Valleys on the windward side penetrate deeply into the mountains and cut into the dike-impounded reservoir, whereas most of the leeward valleys do not. This causes proportionately more dike-impounded water to leak to the windward side from the area underlying the crest. Consequently, the ground-water divide lies to the leeward along most of the crest except in the southern part where water levels in the minor Kaau rift are higher than in the main fissure zone. A significant part of the discharge from the dike-impounded reservoir can be measured as the base flow of windward-side streams. An inventory of these streams indicates that the base flow in them ranges from about 80 to 150 Mgal/d (Takasaki, Hirashima, and Lubke, 1969). The perennial streams are in the valleys extending from Waimanalo to Kaluanui.

The remaining discharge or leaks from the dike-impounded reservoir are mostly underflow to abutting basal-water reservoirs, to the Schofield high-altitude reservoir in the central part of the island, or to sea (Dale and Takasaki, 1976).

The Koolau dike-impounded reservoir, because of its great storage, is highly effective in dampening the great variability in rainfall recharge. Significant changes in its storage result only after prolonged periods of high or low rainfall. The quantity of discharge from the reservoir at any given time, therefore, is not predominantly a function of the rainfall but of the quantity of water in storage, or, more precisely, the head of the stored water.

Leakage at the land surface, as indicated previously, can be directly measured as the base flow in streams. The magnitude of the leakage as underflow to other downgradient water bodies is not directly measurable, but its variation is manifested as changes in the water levels of the recipient water bodies. Figure 11 shows the base-flow discharge of Waihee Stream, the water levels of Kahana well 3352-01 on the windward side, and the water levels of the Schofield Shaft (2901-07) and well 2153-02 on the leeward side. The good correlation between the base flow of the stream and the water levels in wells indicates that recharge to downgradient water bodies from the dike-impounded water bodies is significant.

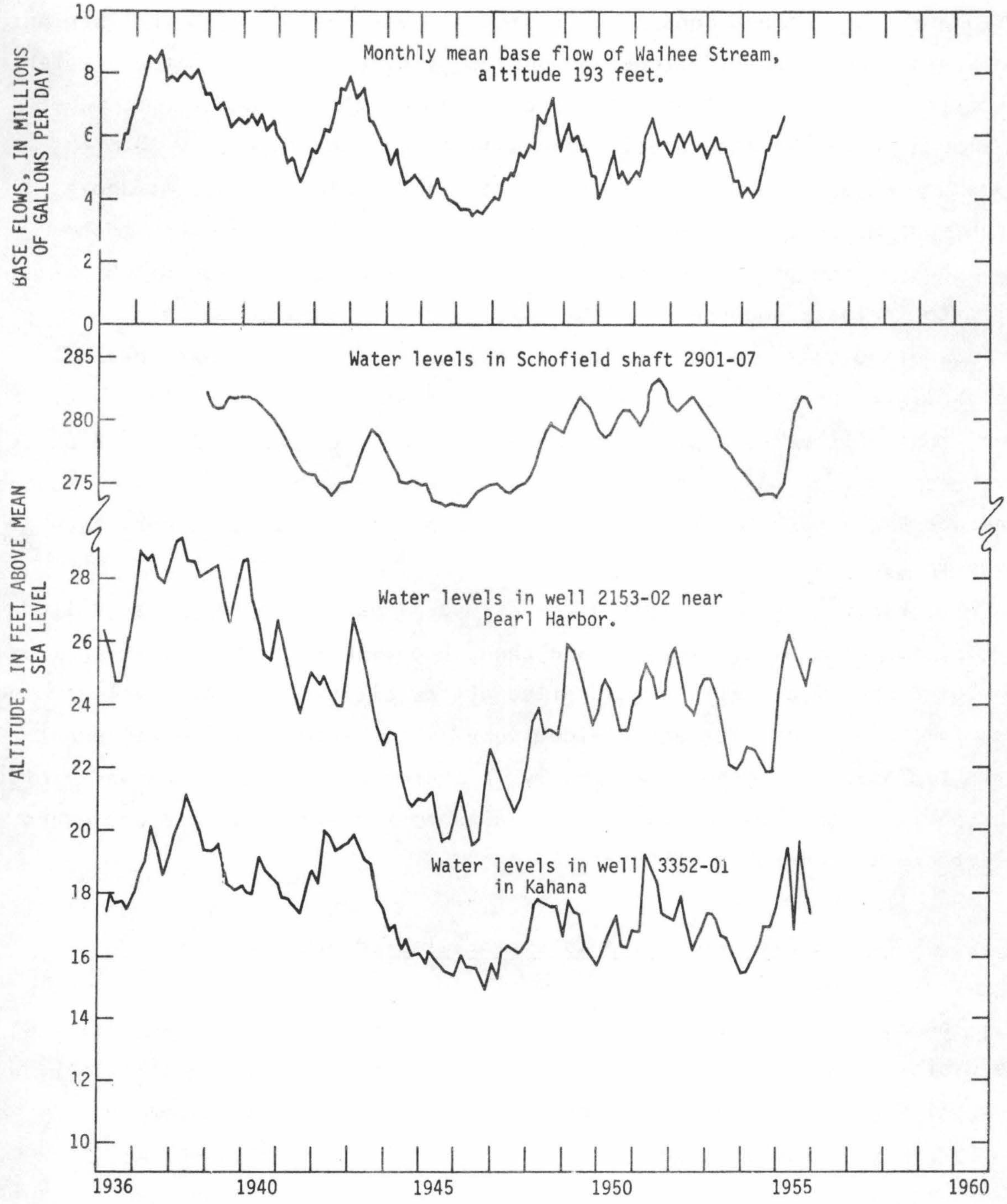


Figure 11. Base-flow discharge of Waihee Stream and water levels of the Kahana well, Schofield shaft, and well 2153-02.

Development

Early development consisted of simple diversion of water from springs and spring-fed streams that were supplied by dike-impounded water. Later, diversions consisting of an extensive system of ditches and flumes were developed in the Kaneohe area. Maunawili ditch was started in 1878 to transport water from Maunawili Valley to the Waimanalo area. Waiahole ditch system, completed in 1915, transports water from the windward to the leeward side of the Koolau Range. In the 1920's, Punaluu ditch was built to irrigate sugarcane on the coast north of Punaluu Valley.

Simple diversions gave way to tunneling mostly at or near springs. The earliest tunnel reportedly was dug in Waimanalo Valley in 1888. Since then, most of the development has been by tunneling. About 25 tunnels have been dug, of which at least 21 tap water impounded in the main fissure zone and 4 tap water in the minor rift zones. The data for tunnels are given in table 4.

The first well to exploit dike-intruded lavas reportedly was drilled in 1892 in Waimanalo Valley. Since then, about 40 wells have been drilled. Many of the earlier wells were drilled at low altitudes in highly weathered rock in the dike complex and yielded very little water. The more recent wells tap less weathered rock, mostly in the marginal dike zone, and yield substantial quantities of water. The data for the wells in use and other selected wells are given in table 5.

Dike-Impounded Water in Selected Subzones

The main fissure zone was divided into four subzones to facilitate discussion. The subzones, as delineated in figure 6 are: (1) the northern end; (2) Waiahole-Kaluanui; (3) Kaneohe; and (4) the southeastern end.

Table 4. Chronologic record of tunneling to develop dike-impounded ground water in the Koolau Range

Constructed year	Name	Location	Owner	Altitude, feet	Total length, feet	Use	Remarks
About 1888	Plantation 1	Waimanalo	Board of Water Supply	415	125	Municipal	Purchased from Waimanalo Development Co. in 1951.
About 1893	O'Shaughnessy	Maunawili	Castle Estate	750	449	None	Dry.
About 1900	Fault	do.	do.	450	350	Irrigation	Ditched to Waimanalo.
1913 to 1916	Waiahole (main bore)	Waiahole	Waiahole Water Co.	724	14,567	do.	Ditched to Oahu Sugar Co.
1915	Tunnel A	do.	do.	790	1,011	None	Dry.
Do.	Tunnel B	do.	do.	800	1,260	do.	Do.
Before 1916	Henry	Kaneohe	Unknown	250	50	do.	
Do.	Luluku (old)	do.	Castle Estate	598	20	do.	Severed as supply source, 1941.
Do.	do.	do.	do.	597	90	do.	Do.
1920	Palolo	Palolo	Board of Water Supply	987	180	Municipal	
1922-26	Clark	Maunawili	Castle Estate	550	1,117	Irrigation	Ditched to Waimanalo.
Do.	Plantation 2	Waimanalo	Board of Water Supply	425	50	Municipal	Purchased from Waimanalo Development Co. in 1951.
1923	Korean	Maunawili	Castle Estate	535	160	Irrigation	Ditched to Waimanalo.
About 1923	Manoa 1	Manoa	Board of Water Supply	550	72	None	
Do.	Manoa 2	do.	do.	550±	9	do.	
Do.	Manoa 3	do.	do.	760	189	Municipal	
Do.	Manoa 4	do.	do.	850	100	None	
Do.	Manoa 5	do.	do.	---	25	do.	
1925-27	Waikane 1	Waikane	Waiahole Water Co.	800±	2,635	Irrigation	Ditched to Oahu Sugar Co.
1933-34	do.	do.	do.	800±	3,445	do.	Tunnel extended 810 feet.
1926	Cooke	Maunawili	Castle Estate	500	130	do.	Ditched to Waimanalo.
1927-29	Waikane 2	Waikane	Waiahole Water Co.	800±	2,341	do.	Ditched to Oahu Sugar Co.
1929-31	Kahana	Kahana	do.	800±	1,975	do.	Do.
About 1929	C and C 1	Waimanalo	Board of Water Supply	462	---	Municipal	
1932-35	Uwau	Uwau	Waiahole Water Co.	800±	2,275	Irrigation	Ditched to Oahu Sugar Co.
1963	do.	do.	do.	800±	2,503	do.	Tunnel extended 228 feet.
1940	C and C 2	Waimanalo	Board of Water Supply	620	499	Municipal	Tunneling cost, $8,152.
Do.	Haiku	Haiku	do.	550	1,320	do.	Tunneling cost, $47,854.
1946	Kahaluu	Kahaluu	do.	585	383	do.	Tunneling cost, $282,571; total project, $500,000.
1945-48	Luluku	Kaneohe	do.	530	481	do.	Tunnel bid, $26,248.
1955	Waihee	Waihee	do.	218	1,795	do.	Entire project cost, including tunnel, 1 Mgal reservoir, 2 boosters, transmission mains, etc., $1,200,000.

Table 5. Selected drilled wells tapping dike-impounded ground water in the Koolau Range

Well number						Water-level measurement alt., ft		1978 draft	
New	Old	Subzone	Owner	Alt., in ft	Use	High-est	Low-est	Mgal	Remarks
1847-01	-	Southeastern end	BWS[1/]	385	Municipal	22		490	Specific capacity, about 100.
1947-01	-	do.	Private	900±	Irrigation	790			Depth of well, 246 feet.
2043-02	420	do.	BWS[1/]	142	Municipal	31	29	10	Specific capacity, about 2.
2044-01	409	do.	State	310	Unused	308	273		
2044-02	423	do.	do.	150	Abandoned				Well collapse.
2046-01	T 49	do.	BWS[1/]	777	Test bore	636	625		Exploration in Maunawili Valley.
2046-02	T 50	do.	do.	1,008	do.	676	667		Do.
2047-01	T 48	do.	do.	1,272	do.	1,170	1,013		Do.
2047-02	T 48A	do.	do.	1,272	do.	624	613		Do.
2047-03	T 86-1	do.	do.	549	do.	426			Specific capacity, about 50.
2047-04	T 86-2	do.	do.	526	do.	541			Probably perched water.
2047-05	36-1	do.	do.	528	Unused	426			Specific capacity, about 30.
2246-01	422	do.	do.	92	Sealed	78	75		Specific capacity, less than 2.
2348-01	T 54	Kaneohe	do.	290	Test bore	306	293		Kuou test bore.
2348-02	416-1	do.	do.	274	Municipal	301	277	653	Specific capacity, about 4.
2348-03	416-2	do.	do.	293	do.	293	288		Specific capacity, about 250.
2348-04	T 55	do.	do.	309	Test bore	321	295		
2446-02	413	Southeastern end	Private	29	Unused	20	15		
2446-03	414	do.	do.	47	do.	27	25		
2448-01	416	Kaneohe	State	252	Domestic	249		32	
2448-02	416-3	do.	Private	216	do.	212	201		Specific capacity, less than 1.
2548-01	T 71	do.	County	179	Test bore	126	124		Well drilled into 20 feet of coral at bottom.
2549-01	407-17	do.	BWS[1/]	485	Unused	325			Specific capacity, about 4.
2550-01	407-16	do.	Private	190	Irrigation	180			Specific capacity, about 14.
2550-02	T 65	do.	do.	250	Test bore	242	231		Specific capacity, about 20.
2550-03	T 65A	do.	do.	250	do.	241	230		
2649-01	T 66	do.	do.	90	Sealed	75	72		Specific capacity, less than 1.
650-01	407-3	do.	do.	109	Unused	73	69		
2650-02	T 63	do.	do.	160	Test bore	151	149		Specific capacity, less than 2.
2652-01		Kaneohe	BWS[1/]	690	Test bore				Free-flowing inclined holes.
2652-02		do.	do.	690	do.				Do.
2652-03		do.	do.	690	do.				Do.
2652-04		do.	do.		do.				Do.
2750-01	407	do.	Private	3	Domestic	7	6	1	Flowing well.
2750-03	407-5	do.	do.	40	do.	33			
2751-02	T-114	do.	BWS[1/]	192	Municipal	185			Specific capacity, about 30.
2751-03	T-115	do.	do.	198	do.	191			Specific capacity, about 25.
2850-04	407-9	do.	Private	19	Domestic	10	8		Specific capacity, less than 1.
3352-01	405	Waiahole-Kaluanui	do.	10	do.	21	14		
3353-01		do.	BWS[1/]	35	Municipal	18			Specific capacity, about 10.
3353-02		do.	do.	93	do.	25			Specific capacity, about 9.
3353-03		do.	do.	174	Unused	124			Specific capacity, about 4.
3353-04		do.	do.	101	do.	88			Specific capacity, about 4.
3453-06		do.	do.	66	Municipal	57	18	386	Specific capacity, about 15.
3453-07		do.	do.	62	do.		18		Specific capacity, about 40.
4100-01	338	Northern end	Private	15	Irrigation	11	9		Underlain by saline ground water at shallow depths.
4100-02	338-1	do.	do.	37					
4100-03	338-2	do.	BWS[1/]	140	Unused	10			See text for pump-test data.
4101-03	337	do.	State	22	Observation	16	11		Underlain by saline ground water at shallow depth.
4101-04	337-1	do.	do.	67	Sealed	21	18		Sealed, 1960.
4101-05	337-2	do.	do.	75	Unused	22	18		Head recording gage from 1963 to 1965.
4101-06	337-3	do.	do.	86	do.	19	17		Head recording gage from 1962 to 1963.
4101-08	337-6	do.	do.	63	do.	20	19	151	Airline head measurement, 14 feet.
4101-09	337-5	do.	Private	19	Irrigation	9	7		Underlain by saline ground water at shallow depths.
4101-11	335-10	do.	State	58	Stock	3	1	2	Basal-water well abutted by dike water.
4101-11	337-4A	do.	BWS[1/]	82	Municipal	19			Underlain by saline ground water at shallow depths.

1/ Board of Water Supply.

The Northern End Subzone

The subzone at the northern end comprises that part of the main fissure zone that abuts the area from Hauula to Kahuku and terminates at the shore in the Waialee area (fig. 12). It includes the rainiest part of the fissure zone and receives about a third of the rainfall that falls on the fissure zone.

Dikes

The subzone is about 5 miles wide in the southern part near Hauula and tapers to a width of about 2 miles at the Waialee end. Nearly all the dikes mapped are vertical or nearly so and have strikes of N. 30° - 40° W. dominating in the southern part and N. 10° - 20° W. dominating near Waialee. Most are 3 to 7 feet thick, with few less than 2 feet or more than 10 feet thick.

Dike-impounded reservoirs

The largest storage of dike-impounded water is in the northern end subzone. The top of the reservoir is at high altitude. Owing to the uneroded nature of both the windward and leeward slopes, none of the valleys are cut deep enough into the reservoir to allow much surface leakage. The only apparent leakage is the small but persistent discharge to the middle reaches of Maakua Gulch and Kaipapau Streams between altitudes of 1,100 and 600 feet (Takasaki and Valenciano, 1969, p. 44). Above and below these altitudes, the streams lose water and recharge the dike-impounded reservoir. The highest water levels in the main fissure zone, inferred from these observations, probably occur in this subzone and are at an altitude of at least 1,000 feet. The altitude of the water level at the Waialee end, where dike-impounded water discharges to sea, is less than 10 feet.

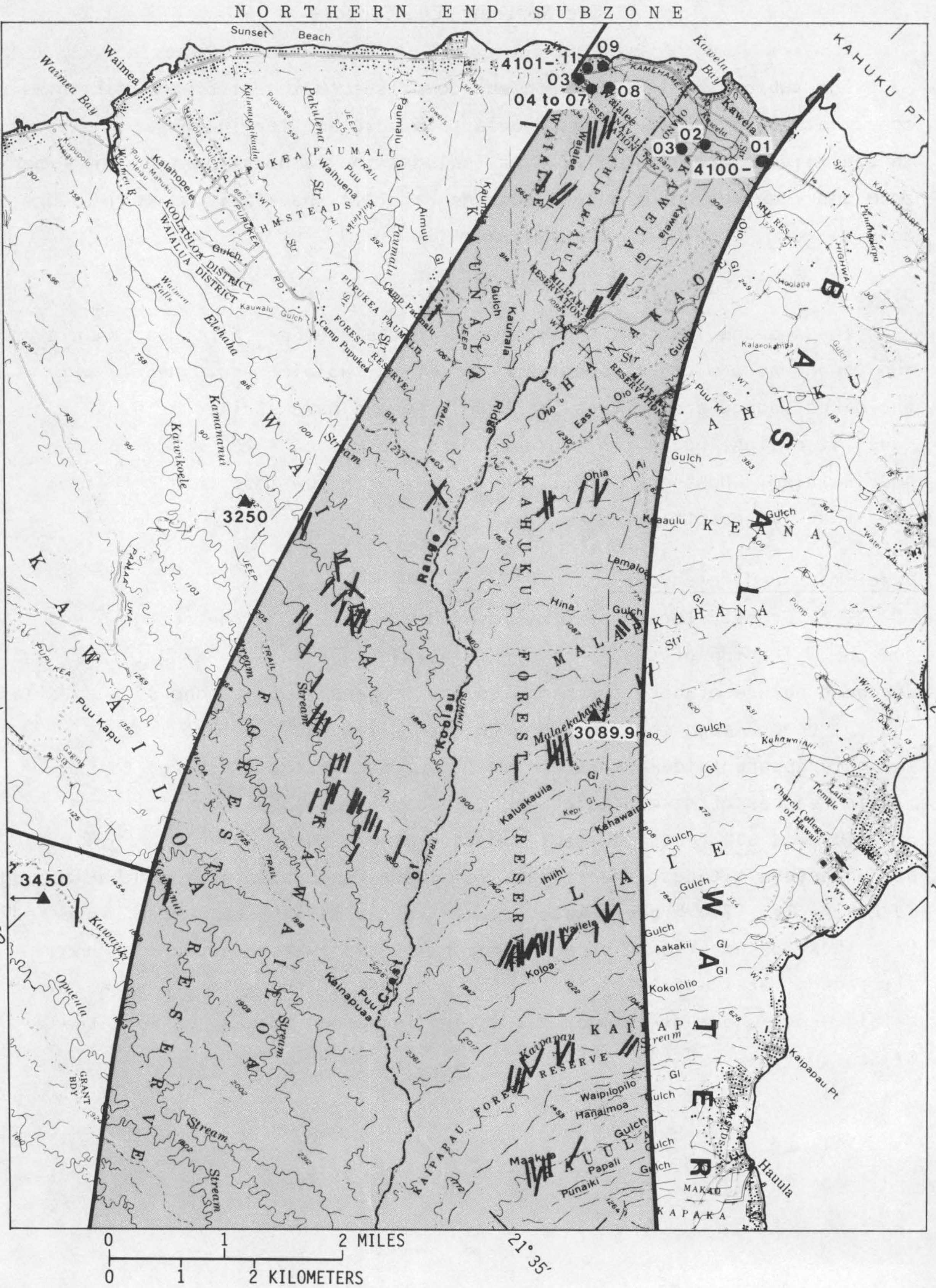


Figure 12. Dikes, rift zone, and location of wells and gaging stations, northern end subzone.

The steep nature of the flow-duration curves of Malaekahana Stream on the windward side and Kamananui and Opaeula Streams on the leeward side, shown in figure 13, is another indication that leakage of dike-impounded water to the surface is small.

The part of the rainfall that infiltrates and recharges the dike-impounded reservoir is large. Subsequent discharge of water from the reservoir is also large, but, as indicated previously, only a small part of it occurs at the land surface. It follows, then, that most of the inferred discharge of the dike-impounded water must be by underflow to downgradient basal-water bodies, the Schofield water body, the Waiahole-Kaluanui subzone, and to sea at the Waialee end (fig. 6).

The underflow or ground-water flow can be estimated by Darcy's law in the form of Q = TIL, as defined by Ferris, Knowles, Brown, and Stallman (1962, p. 73), provided the necessary parameters are available or can be adequately estimated. In the equation, Q is ground-water flow, in gallons or cubic feet per day; T is transmissivity, in gallons or cubic feet per foot per day; I is hydraulic gradient, in feet per mile; and L is width in miles, of the cross section through which the discharge occurs.

The following estimates of the underflow out of the subzone were thus made by using available data and computations from previous studies.

A. Northward to sea in the Waialee area.
   1. Assumptions.
      a. Underflow from the rift zone is northward to sea.
   2. Data available in U.S. Geological Survey files and in Takasaki and Valenciano (1969).
      a. The hydraulic gradient (I) was determined from water-level measurements to be 50 ft/mi (feet per mile) in the rift zone perpendicular to the shore.
      b. The width (L) of the rift zone was estimated from geologic information to be 2 miles.
      c. A transmissivity (T) of 26,738 $(ft^3/ft)/d$ or 200,000 (gal/d)/ft was estimated from analysis of pumping-capacity test data.

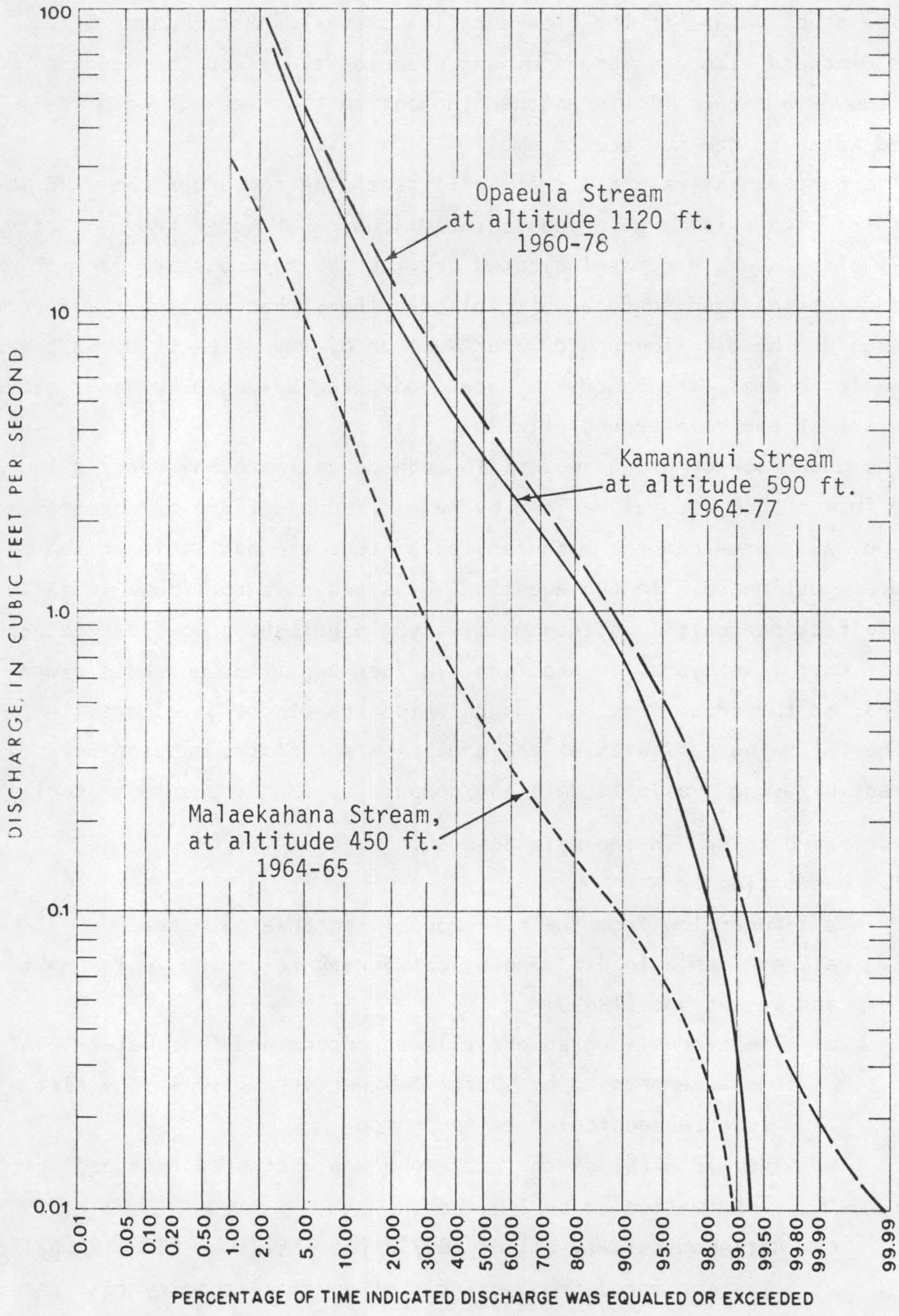


Figure 13. Duration curves of daily flows for windward stream, Malaekahana (sta. 3089.9) and leeward streams, Kamananui (sta. 3250) and Opaeula (sta. 3450).

3. Calculation

   a. $Q = TIL$

   $Q = (26,738)\ (50)\ (2)$

   $Q = 2,673,800\ (ft^3/ft)/d$ or 20 Mgal/d.

B. Northeastward to the windward basal reservoir from Hauula to Laie.

1. Assumptions.

   a. Nearly all the recharge to the basal reservoir is from underflow of dike-impounded water, so that an estimate of the basal-water flow is also an estimate of the underflow.

2. Data available in U.S. Geological Survey files and in Takasaki and Valenciano (1969).

   a. The hydraulic gradient (I) in the basal reservoir perpendicular to the edge of the rift zone was estimated to be 2.5 ft/mi.

   b. Geologic information shows that the edge of the rift zone is nearly perpendicular to the flow in the basal reservoir, so that the distance of 4.5 miles along the edge of the rift zone is probably equal to the width of flow (L) in the basal reservoir.

   c. Transmissivity (T) of 401,070 $(ft^3/ft)/d$ or 3,000,000 (gal/d)/ft was estimated from pumping tests (Takasaki, Hirashima, and Lubke, 1969).

3. Calculations.

   a. $Q = TIL$

   $Q = (401,070)\ (2.5)\ (4.5)$

   $Q = 4,512,038\ (ft^3/ft)/d$ or about 34 Mgal/d.

   b. A weighted average flow was derived by using the natural flow of 10 and 7 Mgal/d per coastline mile for Hauula and Laie, respectively, as given in Takasaki and Valenciano (1969). If a weighted average flow of 8 Mgal/d per coastline mile is used, then the total underflow along a 4.5-mi coastline is 36 Mgal/d which is very close to the calculated underflow of 34 Mgal/d obtained by Darcy's law.

C. Northeastward to the windward basal reservoir in the Kahuku area.

1. Assumptions.

   a. The basal ground-water flow is nearly equal to the underflow of dike-impounded water.

2. Data available in U.S. Geological Survey files and Takasaki and Valenciano (1969).

   a. The hydraulic gradient (I) in the basal reservoir perpendicular to the edge of the rift zone was estimated to be 3 ft/mi.

   b. Geologic information shows that the edge of the rift zone is nearly perpendicular to the flow in the basal reservoir, so that the distance of 4.5 miles along the edge of the rift zone is probably equal to the width of flow (L) in the basal reservoir.

   c. A weighted average flow of 3 Mgal/d per coastline mile for Kahuku was used (Takasaki and Valenciano, 1969).

3. Calculations.

   a. The transmissivity (T) was calculated by using the following ratio:

$$\frac{\text{Kahuku basal flow per coastline mile}}{\text{Hauula-Laie basal per coastline mile}} = \frac{\text{Kahuku (T)}}{\text{Hauula-Laie (T)}}$$

$$\frac{3\ \text{(Mgal/d)/mi}}{8\ \text{(Mgal/d)/mi}} = \frac{\text{Kahuku (T)}}{401{,}070\ (\text{ft}^3/\text{ft})/\text{d}}$$

Kahuku (T) = 150,400 $(\text{ft}^3/\text{ft})/\text{d}$ or 1,125,000 (gal/d)/ft.

   b. Q = TIL

Q = (150,400) (3) (4.5)

Q = 2,030,400 $(\text{ft}^3/\text{ft})/\text{d}$ or about 15 (Mgal)/d.

   c. Q of 15 Mgal/d compares with 13.5 Mgal/d calculated by multiplying 3 (Mgal/d)/mi by 4.5 miles of coastline.

   d. An average Q of 14 Mgal/d was used.

D. Southwestward to the leeward basal reservoir and the Schofield water body.

1. Assumptions.

a. The underflow to the leeward basal reservoir and the Schofield water body is equal to the underflow in the windward area from Hauula to Laie (34 Mgal/d) and to Kahuku (14 Mgal/d), or a total of 48 Mgal/d.

E. Southeastward to the Waiahole-Kaluanui subzone.

1. Assumptions.

a. The underflow is significant and contributes to the base flow of Punaluu Stream (Takasaki, Hirashima, and Lubke, 1969). The underflow is not determinable.

The total of all the underflow out of the main fissure zone, except to the Waiahole-Kaluanui subzone, is summarized thus:

Northward to sea in the Waialee area	20 Mgal/d
Northeastward to the basal reservoir from Hauula to Laie	34 Mgal/d
Northeastward to the basal reservoir in the Kahuku area	14 Mgal/d
Southwestward to leeward areas	48 Mgal/d
Total	116 Mgal/d

This total underflow of 116 Mgal/d represents roughly 50 percent of the rainfall input.

The estimated underflow thus derived should not be taken as or substituted for the sustainable yield from the subzone. The sustainable yield of an area is defined as the yield that can be developed and sustained indefinitely under current development techniques and economic constraints.

Past and potential development

At least 11 wells have been drilled in the subzone to tap the dike-impounded reservoir. Of the wells drilled, 3 are used for municipal supply, 1 for private domestic supply, 1 for golf-course irrigation, 1 for truck-farm irrigation, and 1 for observation; 3 wells are unused and 1 has been sealed. The reported municipal pumpage in 1978 was about 250 million gallons or 0.7 Mgal/d. In addition, about 1 Mgal/d, which is not reported, is pumped for irrigation, mostly at the golf course. All wells are in the Waialee area.

The most promising area for the development of dike-impounded water in the subzone is near Waialee because of (1) the current low draft of less than 2 Mgal/d, which is well below the estimated underflow discharge; (2) the water that is developed will be water now being discharged to sea; and (3) the proximity and easy access to promising well sites from existing roads.

Development near the shore should be avoided because the dikes which strike normal to the shore do not effectively prevent the near-shore ground water from being intruded by saline ground water. Another significant salinity source is the return irrigation water of high salinity that was applied to sugarcane fields for a period of about 50 years prior to 1971.

Assuming that the ground-water flow is uniform across the 2-mile width of the fissure zone and the probability of intrusion of saline water near the shore, wells drilled at about an altitude of 400 feet would be the most efficient means of developing ground water in the Waialee area.

An array of wells could be spaced roughly equidistant from one another across the width of the fissure zone. The sustainable yield and performance of such wells in the eastern half of the fissure zone would probably be similar to the Opana well, 4100-03, drilled in 1969 (see table 6). The sustainable yield of such wells in the western half would probably be somewhat lower, judging by the performance of Waialee well, 4101-11 (see table 7).

Table 6. Pumping test, Opana well, 4100-03

Date 1969	Time	Duration (min)	Pumping rate (gal/min)	Drawdown[a] (ft)	Remarks
Aug. 18 ---	10:30-10:35 ---	5	370	1.3	Start pump 10:30.
	10:35-11:25 ---	50	420	1.7	
	11:25-12:10 ---	45	500	2.4	
	12:10-13:25 ---	75	793	4.5	
	13:25-13:55 ---	30	1,135	9.8	
	13:55-14:20 ---	25	1,175	10.3	
	14:20-14:50 ---	30	1,425	13.7	
	14:50-15:10 ---	20	1,440	14.4	
	15:10-15:25 ---	15	1,780	21.6	Stop pump 15:25.
	15:26 ---	1	0	12.6	
	15:27 ---	1	0	6.8	
	15:28 ---	1	0	.4	
	15:30 ---	2	0	.2	
	15:35 ---	5	0	.1	
	(Water sampled at 10:40 and several times throughout test; no change in chloride concentration of 32 mg/L, hardness of 58 mg/L, and alkalinity of 48 mg/L.)				
Aug. 20 to 25 -------	Pumped steadily for 5 days at 800 gal/min. Drawdown remained at 5.5 feet during test; chloride concentration remained at 32 mg/L; and nitrate at 0.5 mg/L.				

[a] Airline measurements.

Table 7. Pumping test, Waialee well, 4101-11

Date 1970	Time	Duration (min)	Pumping rate (gal/min)	Draw-down[a/] (ft)	Chloride concentration (mg/L)
March 19 ----	9:40-11:40 ----	120	714	1.2	380
	11:35-12:43 ----	68	938	1.6	360
	12:43-13:20 ----	37	1,111	1.9	355
	13:20-13:56 ----	36	1,364	2.3	345
	13:56-14:40 ----	44	1,759	3.5	340
	14:40 (Stop pump)				
	14:41 ------------		0	2.5	
	14:42 ------------		0	1.4	
	14:44 ------------		0	.5	
	14:45 ------------		0	0	
	(Depth of well, 181 feet below mean sea level.)				
May 14 ----	9:50-10:50 ----	60	260	11.6	260
	10:50-11:20 ----	30	302	13.6	
	11:20-12:20 ----	60	414	23.6	260
	12:20-13:50 ----	90	577	26.8	252
	13:50 (Stop pump)				
	13:51 ------------		0	.7	
	13.52 ------------		0	.5	
	13.54 ------------		0	.5	
	(Depth of well, backfilled 132 feet with cement to depth of 49 feet below mean sea level.)				

a/ Airline measurements.

The results of two pumping tests on the Opana well, one a 5-hour step-drawdown test and the other a 5-day constant discharge test, are given in table 6. The results of two pumping tests on the Waialee well are given in table 7. Figure 14 shows the relation between the pumping rate and the drawdown in wells during the tests.

Development elsewhere in the northern end subzone is not feasible, owing to the difficult access and terrain. The development of downgradient basal-water bodies, which receive most of their recharge as underflow from the subzone, appears more feasible.

Waiahole-Kaluanui Subzone

This subzone extends from Waiahole to Kaluanui. The southern part of the subzone, between Waiahole and Kahana, includes the Waiahole tunnel and transmission system (fig. 15).

Dikes

The southern part of the subzone between Waiahole and Kahana exhibits the finest example in the Koolau Range of the components of the rift zone and how they control the characteristics of ground-water behavior. The limits of the dike complex and of the marginal dike zone have been established by surface mapping and the logging of water-development tunnels driven into the rift zone. In Waiahole Valley, for instance, the dike complex is 2 miles wide, extending from the coast to within a half mile of the Koolau crest. The marginal dike zone on the mountain side of the rift zone is a mile wide and is about equally apportioned on either side of the crest of the range (fig. 15).

Northward, the dike complex narrows to about a mile in width in upper Kahana Valley. To the east, the marginal dike zone, extending down Kahana Valley to Kahana Bay, is 3 miles wide. West of the dike-complex boundary, the width of the marginal zone has been projected to be about a mile.

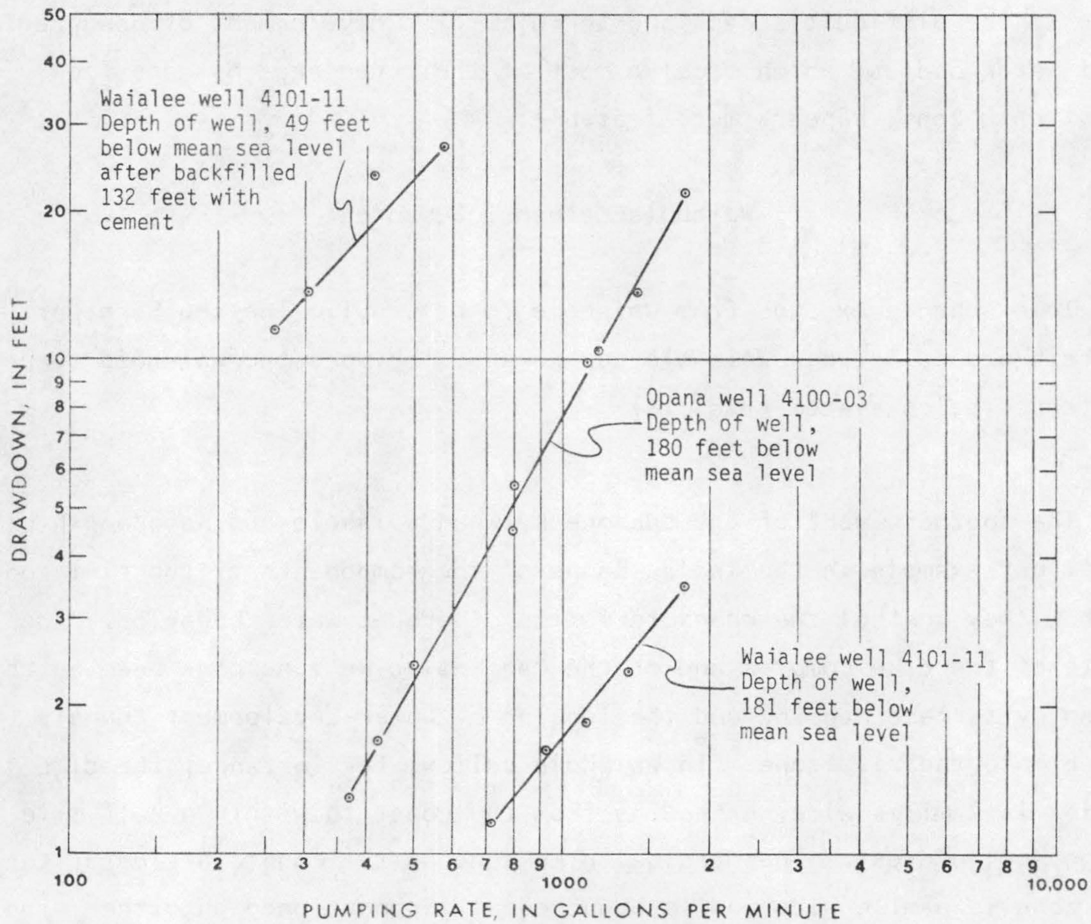


Figure 14. Relation between pumping rate and drawdown in tests of Opana and Waialee wells.

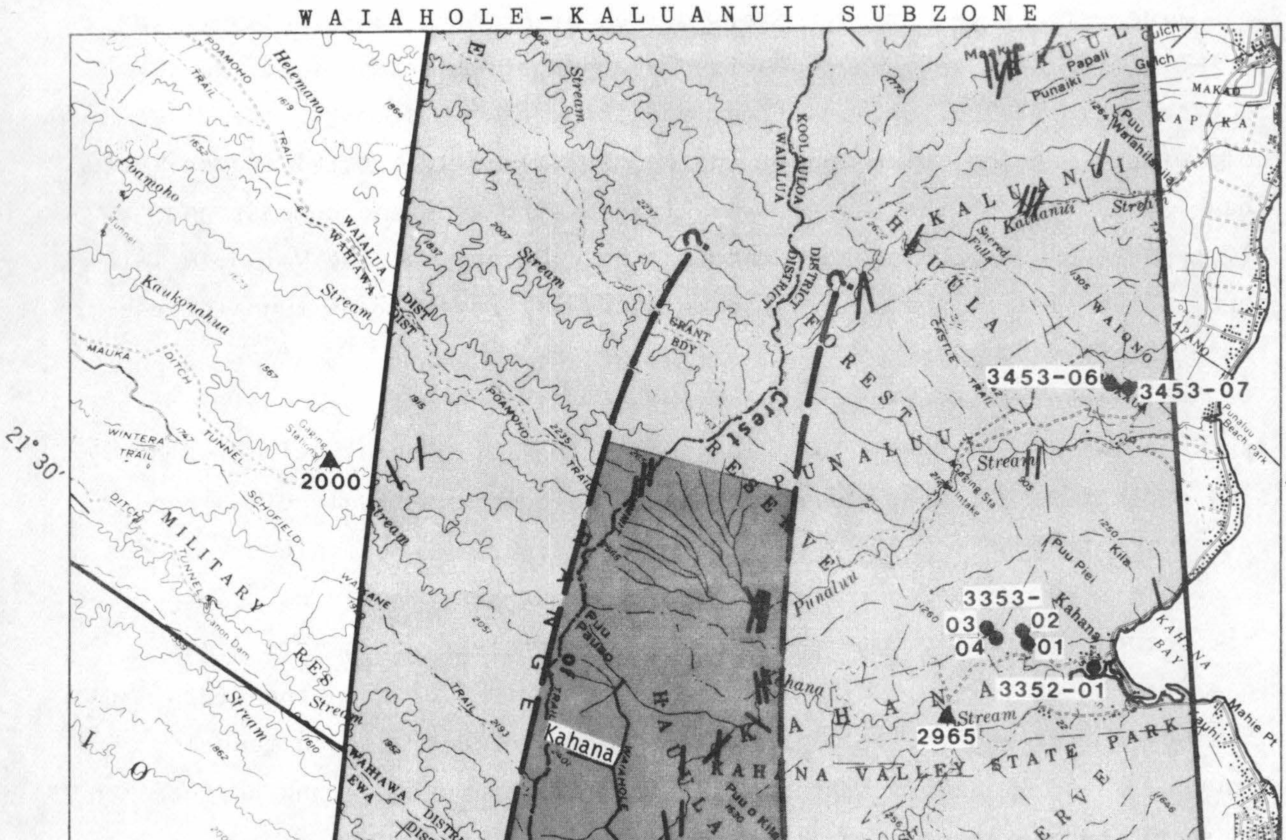


Figure 15. Dikes, dike-intruded rocks in dike complex and marginal dike zone, and location of tunnels, wells, and gaging stations, Waiahole-Kaluanui subzone.

Five water-development tunnels driven at nearly right angles to the strike of the rift zone have provided an unusual opportunity to map the occurrence, distribution, position, and thickness of dikes in the dike complex and marginal dike zone. In the early 1960's, a total of more than 13,000 feet of the tunnels were logged with tape and compass and all exposed dikes were measured and mapped. Except for the Waiahole main bore, which lies in the marginal dike zone, all development tunnels penetrate the dike complex.

As a general rule, the dikes are vertical or nearly vertical and strike between N. 35° - 55° W. In the marginal dike zone, only distinctly single dikes were found, whereas in the dike complex, single dikes and extensive stretches of "multiple" dikes are typical. Multiple dikes consist of single dikes emplaced so close together that practically no country rock occurs. Normally, it is difficult to differentiate single dikes in a stretch of multiple dikes. Table 8 summarizes data on the width of single dikes and the total proportion of dike rock in each tunnel. Figures 16 and 17 are logs of the tunnels showing position and orientation of the dikes and associated flow measurements.

Dikes in the northern part were more difficult to map than those in the southern part owing to the absence of tunnels, the steep terrain, and the shattered nature of dikes in the area containing the dike complex. The dike complex probably extends slightly beyond the Koolau crest at the head of Punaluu Valley where numerous northwest striking dikes cut across the crest. Starting at the head of Kaluanui Valley and continuing north for some distance, the dike complex probably narrows and lies astride the Koolau crest. A marginal dike zone probably exists on both the leeward and windward sides of such a dike complex (fig. 6).

Table 8. Dikes in the Waiahole Tunnel System

Development tunnel	Number of single dikes mapped	Average width of single dikes, (feet)	Total footage of dike rock	Total footage mapped	Footage of dike rock per total footage mapped (percent)	Rift zone component
Waiahole Main Bore -	16	5.8	92	3,825	2.4	Marginal.
Uwau --------	54	5.7	530	2,245	24	Complex.
Waikane 2 ---	37	5.2	1,219	2,341	52	Do.
Waikane 1 ---	81	5.5	1,414	2,945	48	Do.
Kahana ------	28	5.3	578	1,900	30	Do.

The average width of single dikes in the Waiahole-Kahana subzone is 5.5 feet, nearly 3 feet wider than the dikes in the Kailua Waimanalo-Honolulu region south and east of Nuuanu Pali.

Figure 16. Position and orientation of the dikes and flow measurements in the Waiahole main bore, Waikane tunnel 1, and Waikane tunnel 2. Location of dikes and tunnels shown in figure 15. (Illustration is oversized; attached at back of report.)

Figure 17. Position and orientation of the dikes and flow measurements in the Uwau and Kahana tunnels. Location of dikes and tunnels shown in figure 15. (Illustration is oversized; attached at back of report.)

Dike-impounded reservoirs

The high-altitude, dike-impounded reservoirs, above an altitude of 800 feet between Waiahole and Kahana Valleys, now yield an average flow of 28 Mgal/d to the Waiahole tunnel system. Because the tunnel system and the dike-impounded reservoirs are under steady-state conditions, there is no further depletion of ground-water storage in the aquifers.

The essential part of the system, the main bore of the Waiahole transmission-development tunnel driven from Waiahole Valley on the windward side of the Koolau Range to Waiawa Valley on the leeward side, was started in 1913 and completed in 1915. Four other tunnels were started between 1915 and 1929. Uwau tunnel was further extended, as recently as 1963.

An enormous volume of stored ground water drained from the dike aquifers during and after construction, some of it wasted owing to the resulting large flows that could not be utilized. The final equilibrium or base flow of the tunnel system is not appreciably different from the sum of the base flows of streams on the windward side before the tunnels were constructed. In fact, the only parts of the system that were truly needed to take advantage of the base flows and their transmittal to leeward Oahu are the main trans-Koolau Waiahole bore and the ditch transmission tunnel that parallels the Koolau Range on the windward side.

Two components of storage volume have been computed by simple addition of flows, all of which were measured. The first component, the largest, is that volume which discharges from a maximum initial flow, which is normally coincident with the cessation of tunneling. This volume originates from compartments breached by a short stretch of tunnel. It is the most exploitable component of storage and can be called the "principal storage". Decay of principal storage is monotonic.

The second component is that which drains away while the tunnel is being driven to the point where the principal storage is encountered. This storage component is usually dispersed over a long stretch of tunnel and is, therefore, not as readily exploitable as the principal storage. This second component can be termed "secondary storage". Discharge increases during this stage of tunneling.

The grand total of principal storage in the Waiahole tunnel system amounted to 33,230 Mgal, all of which has been dissipated. Kahana tunnel emptied the largest volume of principal storage, about 10,265 Mgal.

The grand total of secondary storage amounted to 12,965 Mgal, all lost also. The main bore of Waiahole discharged the largest combined volume of principal and secondary storage, about 15,175 Mgal.

The total storage (principal plus secondary) discharged by the Waiahole tunnel system was 46,195 Mgal. The detailed computation of this storage depletion is shown in table 9.

Table 10 summarizes data on the base flow of each development tunnel. The base flows given for Uwau, Waikane 1, Waikane 2, Kahana and the main Waiahole bore, which was measured west or leeward of the Koolau crest, consist exclusively of ground water; for the main Waiahole bore, which was measured east or windward of the crest, a surface-water component plus water pumped from a stream below the tunnel portal is combined with ground-water flow. The recording flow-gage locations do not permit an accurate determination of base flow in the windward section of the main bore, but of the average 5.65 Mgal/d noted in the table, approximately 1 Mgal/d consists of tunnel ground-water seepage.

The Waiahole system, along with Waihee tunnel, offers unusually favorable conditions for manipulating the storage features of dike-impounded reservoirs. The vast initial storage that has been depleted could not likely be returned to its original state because of disruption to the integrity of the reservoir caused by tunnel construction. Significant portions of it, however, can be restored and manipulated economically in each of the development tunnels in a manner similar to that employed in Waihee tunnel. Correctly located and properly built bulkheads in the tunnels could provide the means for improved management of the water resource.

Table 9. Volume of storage depleted, Waiahole tunnel system
(Volumes in millions of gallons)

Tunnel	Monotonic decay Q_0 (stop tunneling) to $\bar{R}$					Pre-monotonic decay for condition, $Q > \bar{R}$					Pre-monotonic decay for condition, $Q < \bar{R}$				Long-term average base-flow rate	Period during which base-flow established
	Q_0	R	(Days) t	V_T	V_S	Q_0	Q_M	(Days) t	V_T	V_S	Q_0	Q_M	(Days) t	V_T	$\bar{R}$	
Waikane 1																
Phase 1 (Aug. 1925-Dec. 1931)	9.10	3.0	1,674	8,959	3,937	3.46	9.04	304	1,462	551	0.50	2.50	365	553		
Phase 2 (Nov. 1933-June 1936)	10.25	4.33	668	4,822	1,930	5.72	9.25	184	1,236	439					4.55	1938-78.
Totals					5,867					990						
Waikane 2 (Aug. 1927-Feb. 1936)	6.39	1.12	2,555	11,121	8,259	1.29	4.40	455	983	473	.08	.90	122	71	1.12	1938-78.
Kahana (Aug. 1929-Apr. 1936)	15.10	4.04	1,914	17,998	10,265	5.80	13.30	396	3,269	1,669	.57	2.62	153	205	3.59	1938-78.
Uwau[1/]																
Phase 1 (Aug. 1932-Nov. 1934)	10.73	5.60	518	3,671	770[1/]					458	.25	7.49	153	906[2/]		
Phase 2 (Dec. 1934-Aug. 1936)	16.83	10.84	243	3,565	931[1/]					796	5.85	14.79	365	3,844[2/]	10.20	1938-62.
Phase 3 (July 1963-May 1964)	6.93	13.39	212	3,141	302[1/]					239	11.96	6.71	123	1,798[2/]	12.97	1967-78.
Totals					2,003[1/]					1,493						
Main[3/] (Aug. 1913-May 1916)	40	8.6	457	10,767	6,836	16	16	275	4,514	2,149					4.79	Ground water leeward of crest 1938-78.
						20	28	305	8,815	6,192					5.65	Ground water windward of crest + surface + pump water.
Totals					6,836					8,341						
					33,230					12,966						

Explanation--table 9

Q_0 Flow rate at the start of the period of interest.

Q_M Maximum flow rate during pre-monotonic decay period.

Q Transient flow rate.

R Base flow rate.

$\overline{R}$ Long-term average base-flow rate.

t Time (days).

V_T Total volume discharged.

V_S Volume discharged from storage (principal storage).

1/ Uwau tunnel: Base flow was not reached by the end of phase 1, the start of phase 2, for the Monotonic decay. V_S computed by assuming R = 5.60 Mgal/d. The V_S may be understated by as much as 700 Mgal. V_S for the pre-monotonic period (Q > R) was computed by assuming R = 2.93.

For phase 2, pre-monotonic decay, V_S, computed by using R = 8.35.

For phase 3, pre-monotonic decay, V_S computed by using R = 12.68.

Uwau is the most difficult of the tunnels for making an accurate accounting of storage. However, the possible error in storage estimate would give values that would affect the grand total of storage by less than 5 percent.

2/ Uwau tunnel: Includes both V_T (Q > R) and V_T (Q < R).

3/ Main tunnel: For the period August 1913 through December 1916, Olstad reported total outflow as 27,088 Mgal. Based on flow data given in Stearns and Vaksvik (1935), a computation for this study gives a total outflow of 25,936 Mgal for the same period. The values of V_S are based on the latter figure and a base flow R = 8.6 Mgal/d, applicable during the period of decay.

Long-term (1938-78) ground-water flow from within the main bore is approximately 7.2 Mgal/d, of which about 5 Mgal/d originates leeward of the crest of the range and the remainder windward of the crest.

Storage volume is computed as the excess of flow over base flow. The data from which the calculations were made is the set of monthly flows reduced to average daily flow for each month of record. The following terms were used in computation of storage depletion and are defined as:

Monotonic decay: This is the period of decay following achievement of maximum discharge, which ordinarily is coincident with cessation of tunneling. Flow decays continuously until base flow is reached. This storage is the component most readily exploitable.

Pre-monotonic decay for condition, ($Q > R$): This refers to the tunneling period when flow exceeds final base flow but before maximum discharge is achieved. Storage lost in this period does not follow a monotonic decay pattern. Some of this storage could be exploited.

Pre-monotonic decay for condition, ($Q < R$): This period is coincident with the initial phase of tunneling during which discharge is relatively small and never exceeds final base flow. Both recharge and storage are discharged, but storage is not easily exploitable.

Table 10. Statistics of Waiahole tunnel system base flows

(Flows in million gallons per day)

Tunnel	Base flow equilibrium period	No. years	Average base flow	Standard deviation	Coefficient of variation
Waikane 1 --------	1938-78	41	4.55	0.97	0.21
Waikane 2 --------	1938-78	41	1.12	.16	.14
Kahana -----------	1938-78	41	3.59	.73	.20
Uwau -------------	1938-62	25	10.20	2.01	.20
Uwau[1/] -----------	1967-78	12	12.97	1.77	.14
Main Waiahole, ground water leeward of crest -----------	1938-78	41	4.79	.98	.20
Main Waiahole, ground water windward of crest + surface water + pump water ------	1938-78	41	5.65	2.73	.48

[1/] Uwau tunnel was lengthened by 228 feet in 1963-64.

The hydraulics of drainage from storage in development tunnels and outlines of the data base that is required to establish a rule of operation for each bulkheaded tunnel are discussed in the section on flow hydraulics by John F. Mink. In general, maximum ground-water flow occurs toward the deepest penetration of the tunnels, and it is here that optimal locations for bulkheading occur. This was the case for Waihee tunnel, where the only successful bulkhead was emplaced. In other instances where bulkheads were attempted, they were set too far away from the principal dike section controlling storage. As a result, restored storage was small and the use of bulkheads was abandoned.

In the Waiahole system, the prime candidate for restoration of storage is Kahana tunnel. Access to more than 10 billion gallons of principal storage was attained near the head of the tunnel. The optimal location for a bulkhead lies somewhere in the final 300 feet of the tunnel. Because it would take many years to restore the initially large storage, even if indeed such restoration could be accomplished, lesser storage volume could be allowed to accumulate in shorter time periods and then manipulated.

Each development tunnel offers storage opportunities, although bulkheading of the main bore would have to be designed to allow transmission of water collected from the entire system. The attempt to bulkhead Waikane tunnel 2 in 1934-35 failed because the bulkhead was too close to the portal and not close enough to the head of the tunnel where the main storage was encountered. A similarly unsuccessful bulkhead was emplaced in Uwau tunnel of the Waiahole system. On the other hand, the bulkhead in the Waihee tunnel has been spectacularly successful.

Leakage and overflow from the dike-impounded water bodies, not exploited by tunnels, continues to provide flow in all streams at the lower levels. Exceptions are the lower parts of Hakipuu and Kaaawa Streams, which are somewhat isolated from the main Koolau mass.

G. T. Hirashima (in Takasaki, Hirashima, and Lubke, 1969) has determined the average flow ($Q_{average}$) and the base flow (Q_{90} percentile) of the streams below tunnel level. Hirashima's inventory is given below.

Computed discharges in million gallons per day

Stream	$Q_{(average)}$	$Q_{(90 \text{ percentile})}$
Waiahole -----------------	6.9	3.9
Waianu -------------------	1.2	.5
Waikane, (alt. 75 ft) ----	4.2	1.4
Hakipuu ------------------	1.1	.38
Kaaawa -------------------	1.0	.14
Kahana -------------------	29.5	11.2
Total -----------------	43.9	17.5

Waiahole, Waianu, and Waikane Streams, downgradient from Uwau tunnel and Waikane tunnels 1 and 2, lie entirely in the dike complex. The total base flow of the streams below tunnel level is 5.8 Mgal/d or only about a third of the flow of the upgradient tunnels. Kahana Stream, in contrast, downgradient from Kahana tunnel lies only partly in the dike complex and mostly in the marginal dike zone. Its base flow below tunnel level is 11.2 Mgal/d, or about three times the flow of the tunnel.

Hakipuu and Kaaawa Valleys, which lie mostly and entirely in the marginal dike zone, respectively, are losing streams in part of their reach.

The valleys to the lee or east of the Koolau crest are not cut deep enough to tap the dike-impounded reservoirs. This is indicated by the steep nature of the flow-duration curve of North Fork Kaukonahua Stream compared to the flatness for that of Kahana Stream on the windward or west side of the crest (fig. 18).

Past and potential development

Major development of dike-impounded water is by the Waiahole tunnel and transmission system constructed at an altitude of about 800 feet from Kahana to Waiahole Valley and leeward Oahu. Optimal opportunities for manipulating storage and managing these impounded aquifers are discussed in the section on the dike-impounded reservoirs and in the section on flow hydraulics.

Downgradient from the tunnel system, water in streams fed by dike-impounded water is diverted by pumping in Waiahole Stream, at an altitude of about 500 feet, by intakes in Waianu Stream at 460 feet, in Waikane Stream at 120 feet, and in Hakipuu Stream at 150 feet. Most significant of these diversions is the pumping of about 1 Mgal/d from Waiahole Stream into the main Waiahole transmission tunnel. Water is diverted from the other streams for domestic and agricultural use. Two municipal wells and an artesian well (3352-01), which supplies several families in Kahana, tap the dike-intruded aquifer in which ground water is only partially impounded.

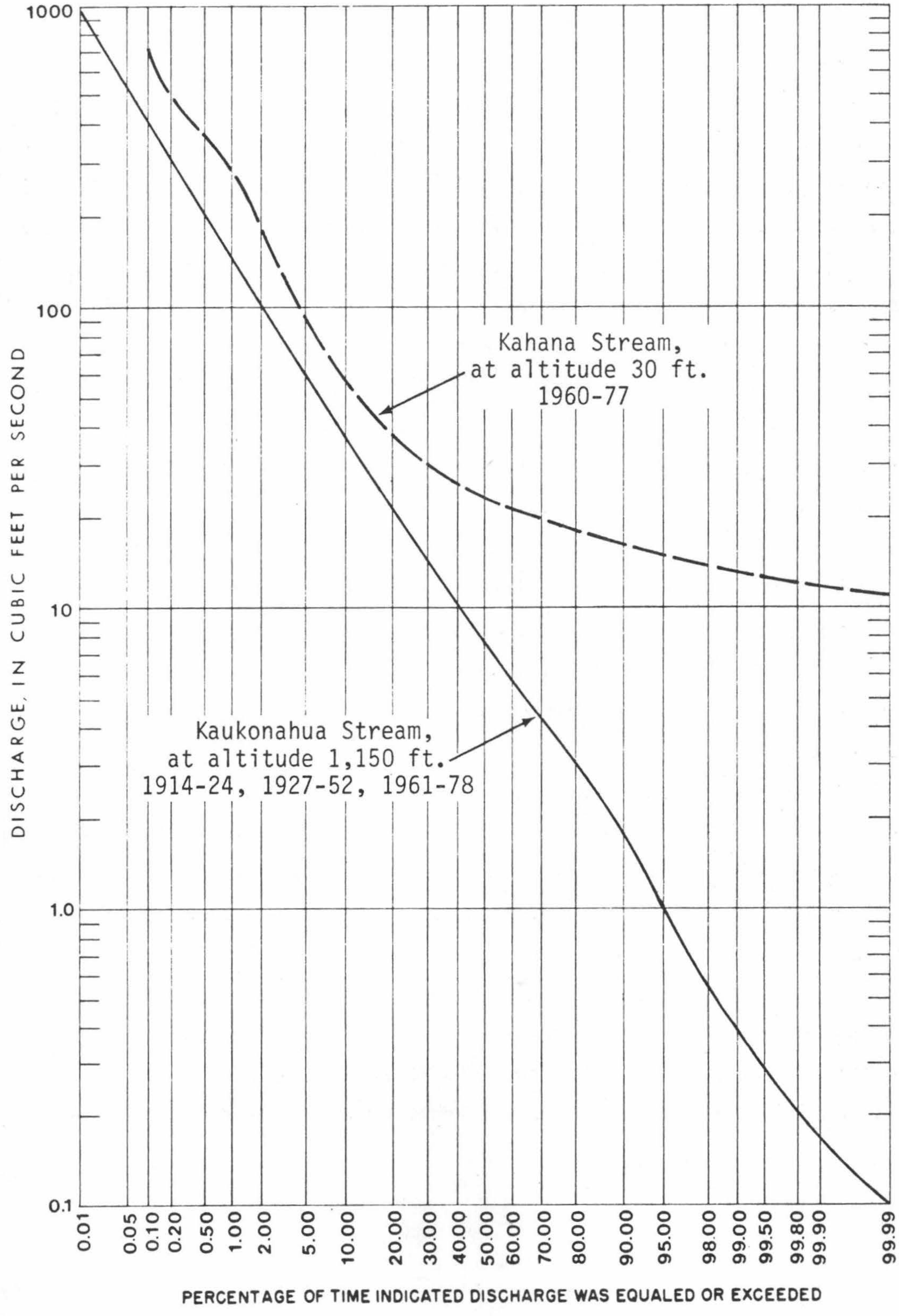
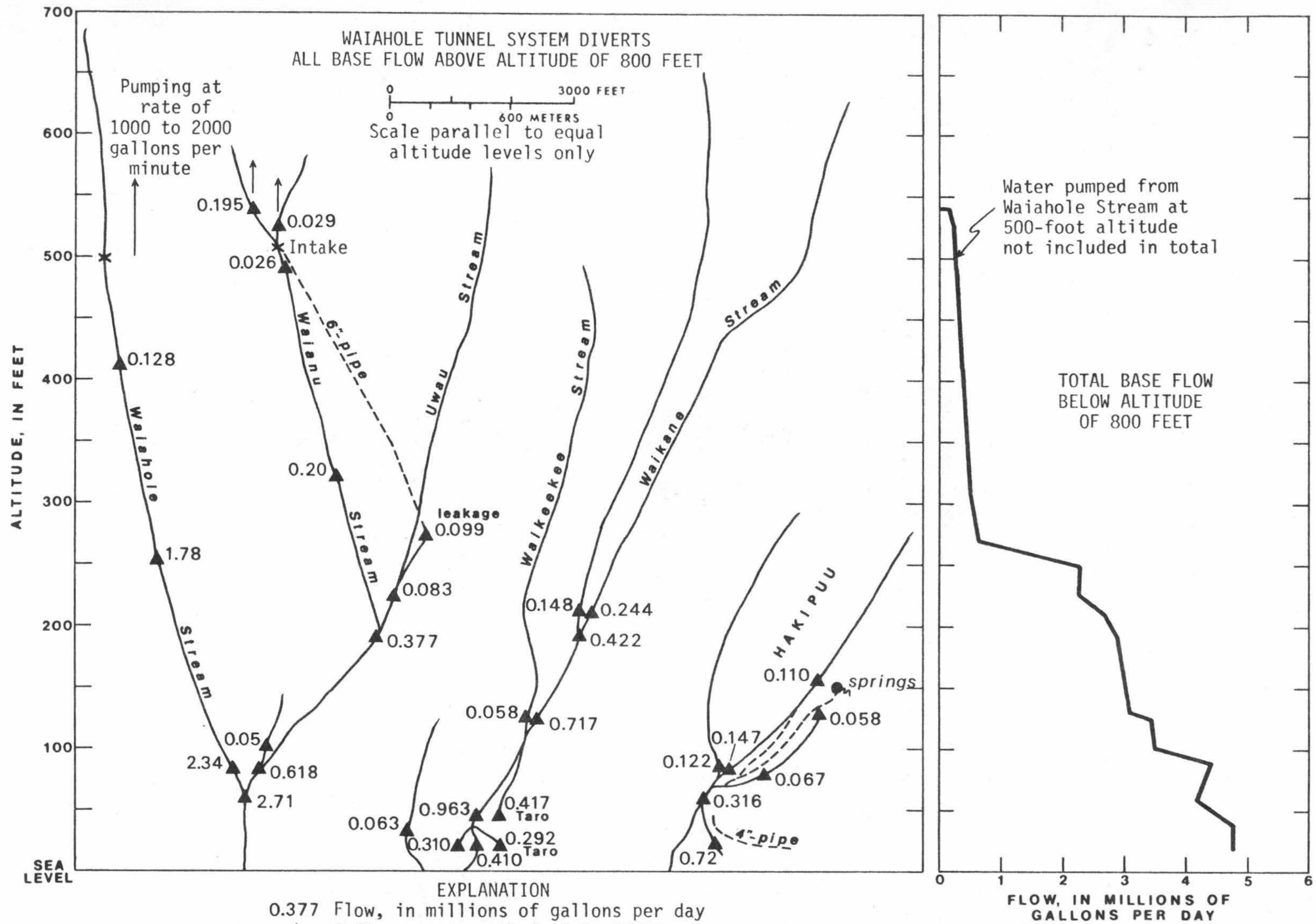


Figure 18. Duration curves of daily flows for windward stream, Kahana (sta. 2965) and leeward stream, North Fork Kaukonahua (sta. 2000).

Much of the base flow of Punaluu Stream was diverted to irrigate sugar in the Punaluu-Kaluanui area until the end of 1971 when Kahuku Sugar Co. ceased operations. Two wells (3543-06, -07), which tap a dike-intruded aquifer, supply about 1 Mgal/d to the municipal supply. These wells are in the marginal dike zone, as mapped in this report, and like well 3352-01 in Kahana, ground water is only partially impounded.

The base flow remaining in streams between Waiahole and Hakipuu is shown figure 19. All discharge measurements were made in July 1959 during a prolonged period of low rainfall. More than a third of the total flow measured is accounted for by the gain of 1.65 Mgal/d in Waiahole Stream between altitudes of 400 and 250 feet. A subsequent measurement, a year later, indicated a gain of 2.4 Mgal/d for the same reach in the stream. A plausible explanation is that Waiahole Stream, in this reach, cuts deeper both horizontally and vertically into saturated rock than the other valleys, resulting in more leakage. The gains in the other valleys are steady in the downstream direction and seem to indicate slow and uniform drainage by the streams cutting into saturated rock. The possible future use of these gains in streamflow which represent ground-water discharge should be investigated.

Ordinarily a well drilled in the dike complex, such as the Waiahole-Waikane area, cannot be expected to yield large quantities of water, owing to low permeability of the rocks. The specific capacity of such a well would be likely to fall in the range between 10 and 1 (gal/min)/ft (gallons per minute per foot) of drawdown for a well drilled about 200 feet into saturated rock. This means that a well pumped at a rate of 200 gal/min would induce a drawdown in the pumped well of 20 to 200 feet. A higher pumping rate would probably require a deeper well, if the capacity were close to 1. An alternative to deeper wells would be numerous shallow wells.



EXPLANATION

0.377 Flow, in millions of gallons per day

▲ A flow measurement in July 1959

↑ Diverted by pipeline

Figure 19. Relative altitudes of base-flow measuring points in streams in Waiahole and Hakipuu areas.

The possibilities of developing water in the marginal dike zone in the middle and lower reaches of Punaluu and Kahana Valleys are excellent. If the development is in the rapidly gaining reaches of the stream channel, which are between an altitude of 400 and 200 feet in Punaluu Stream and between 200 and 100 feet in Kahana Stream (Takasaki, Hirashima, and Lubke, 1969), the north bank of the stream would be a better choice than the south bank in both valleys because the dominant ground-water flow is in the direction of the strike of the dikes, from northwest to southeast. The gaining nature of the streams below these channel altitudes is greatly reduced owing to the thickening of sedimentary overburden and depth of weathering. Much of the discharge of dike-impounded water then shifts from the stream channel as underflow to the sedimentary overburden or directly to sea. This underflow has been estimated as 10 Mgal/d in the Kahana area and about 25 Mgal/d in the Punaluu-Kaluanui area (Takasaki, Hirashima, and Lubke, 1969). Successful development by wells would depend largely on well siting, taking into account the depth of the sedimentary overburden, and the depth of weathering of the aquifer rock.

Kaneohe Subzone

This subzone comprises that part of the main fissure zone which parallels and includes Kaneohe Bay only as far north as Kaalaea Valley (fig. 20). It was purposely subzoned in this way so that the subzone did not include the Waiahole tunnel and ditch system, which is discussed in the Waiahole-Kaluanui subzone.

Dikes

The subzone includes part of the caldera, most of which lies in the subzone to the southeast (fig. 1). A dike complex, 3 to 5 miles wide and manifested by many multiple dike exposures, runs through the center of the subzone and lies entirely on the east or windward side of the Koolau crest. The marginal dike zone that abuts and parallels the dike complex

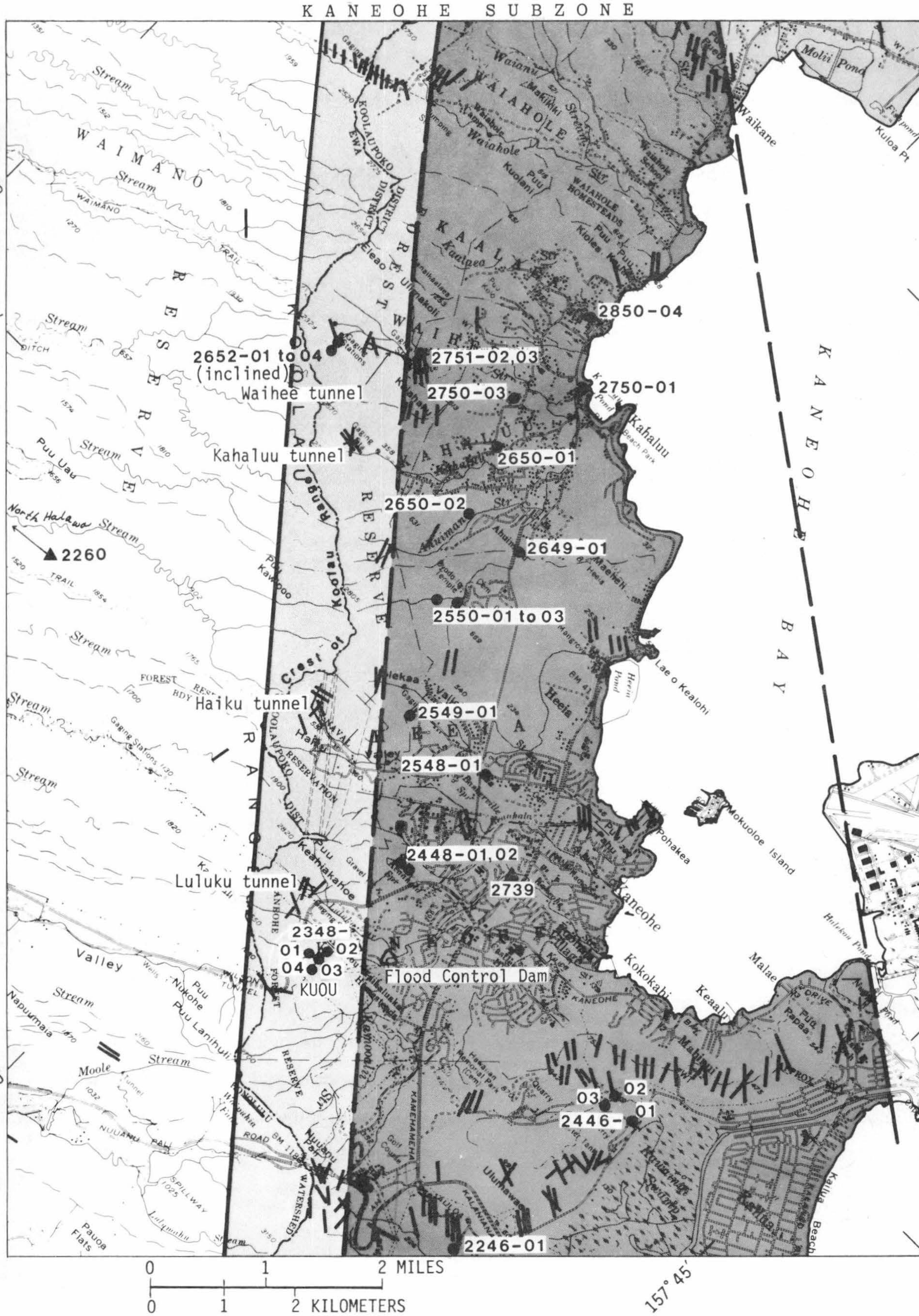


Figure 20. Dikes, dike-intruded rocks in dike complex and marginal dike zone, and location of tunnels, wells, and gaging stations, Kaneohe subzone.

on the west is about a mile wide. The width of the marginal zone east of the dike complex is not known because it lies largely below the surface of the sea. Most of the marginal dike zone west of the dike complex lies on the windward side of the crest.

Numerous dikes in the dike complex with strikes ranging from N. 55° - 75° W. are exposed along the ridge projecting northeastward from Nuuanu Pali. The strike of the dikes shows an apparent shift in direction to the north in the rift zone in the northwest direction. Dikes striking close to N. 55° W. are most frequent in the southeast part and those striking N. 35° W. become increasingly more frequent with distance away from the southeast part. The trend of the dikes roughly parallels the trend of the Koolau crest. A few north- to northeast-striking dikes have been mapped in upper Haiku Valley.

Most of the dikes mapped are vertical or nearly so. Dikes are generally less than 5 feet thick in the southeast part and more than 5 feet thick in the northwest part of the subzone.

Dike-impounded reservoirs

Dike-impounded water occurs at or near the surface in much of the subzone. The exception is near the crest where steep cliffs forming the heads of valleys on the windward side have cut deeply into the reservoirs and have nearly drained them down to the base of the cliffs at an altitude of about 600 feet. The impounded water is generally unconfined in the mountainous areas in unweathered rock and confined to partly confined in low-lying areas under an alluvial apron or a mantle of highly weathered rock. The rocks in the coastal areas, although saturated, are highly weathered to great depths, and movement of water in them or through them is very small.

The top of the dike-impounded reservoir in the mountains ranges from an altitude of about 900 feet near Kaalaea to about 650 feet near the Nuuanu Pali. The altitudes of the water surface shown in figure 9 were estimated from pressure readings in tunnels, altitudes of springs, and the absence of saturated rock in vehicular tunnels.

Figure 21 is a diagrammatic sketch showing the likely directions of ground-water movement between parallel dikes above an altitude of 600 feet in the subzone. Although water levels are high, they were higher in past geologic times before water impounded in them was progressively lowered as eroding valleys penetrated deeper into the reservoirs. As each dike in the reservoir was breached by deepening valleys, especially in the marginal zone, water in the reservoir moved toward the breached area much more freely along the dike than through it, and the water level in the reservoir was subsequently lowered. Thus, a valley that penetrates deeper into the mountains cuts more dikes and is able to divert water from behind dikes not yet breached in a less deeply penetrating valley. This capturing or pirating of ground water can be likened to "stream piracy" where the upper part of a stream is diverted by another stream. Since ground water moves freely along dikes that traverse drainage divides, including the Koolau crest, water impounded on the leeward side can easily be diverted to lower points of discharge in windward stream valleys.

Hirashima (1963) concluded that lowering of the water level by the construction of Haiku tunnel has pirated 1 Mgal/d of ground water that normally discharged into Kahaluu Stream, 2-1/2 miles away, and now flows toward and into Haiku tunnel.

Owing to the deep penetration of the subzone by windward valleys, most water impounded above the level of the valley floors moves toward the windward side. Hence, in this subzone, tunnels less than 1,000 feet in length, which are simply extensions of the valley floors at tunnel level, cannot be expected to intercept much water now moving toward the leeward side.

The flat nature of the flow-duration curve of Kamooalii Stream compared to the steepness for that of North Halawa Stream, shown in figure 22, indicates the typical contrast in the flow regimes of streams east of the crest (windward) and those west of the crest (leeward). The flatness of the Kamooalii Stream curve is typical of perennial streams in the subzone (Takasaki, Hirashima, and Lubke, 1969, p. 41 to 44). Most of the flow

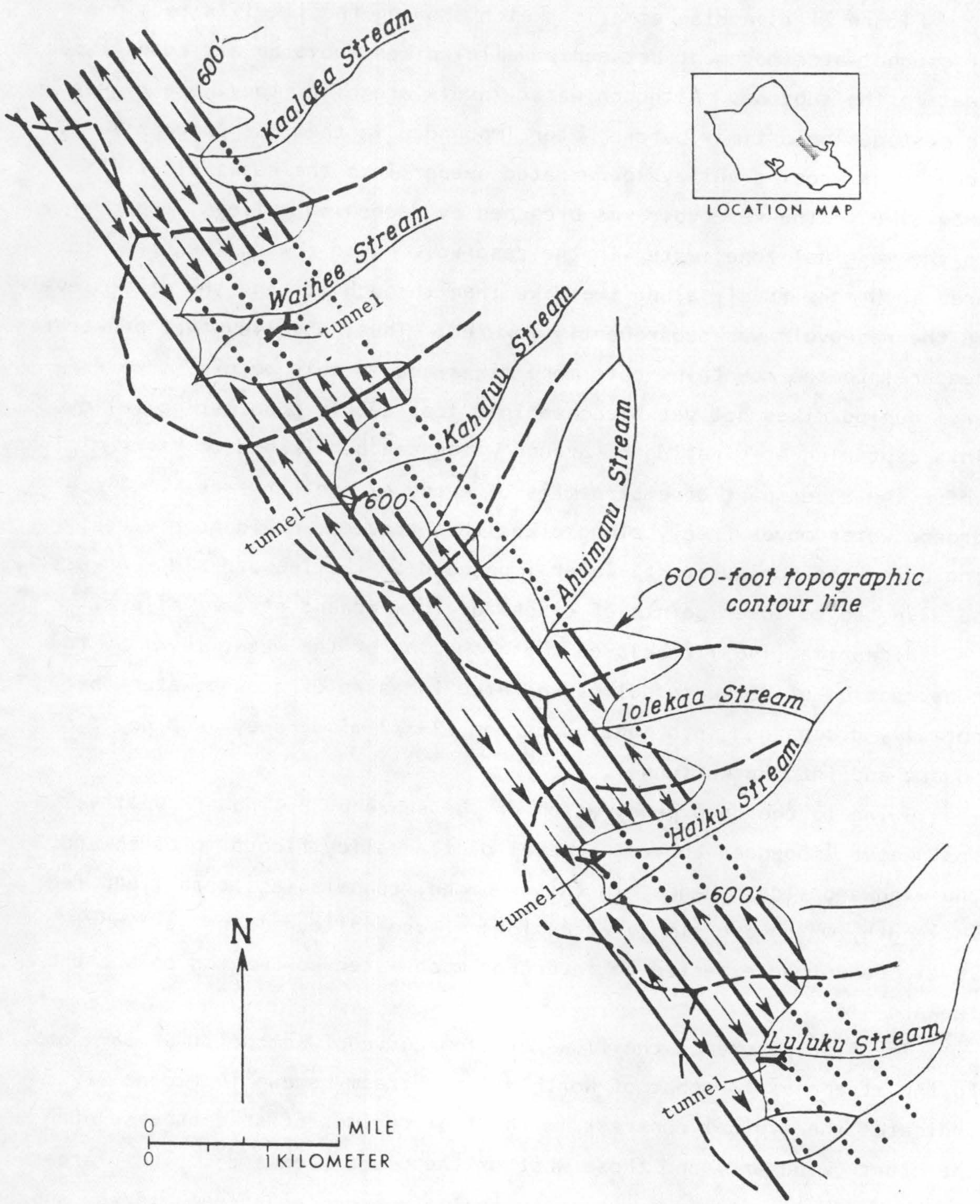


Figure 21. Sketch showing by arrows the probable directions of movement of ground water between parallel dikes above an altitude of 600 feet in the area between Luluku and Kaalaea Streams. Solid and dotted lines show the general trend of the dikes. Dashed lines mark the crests of ridges.

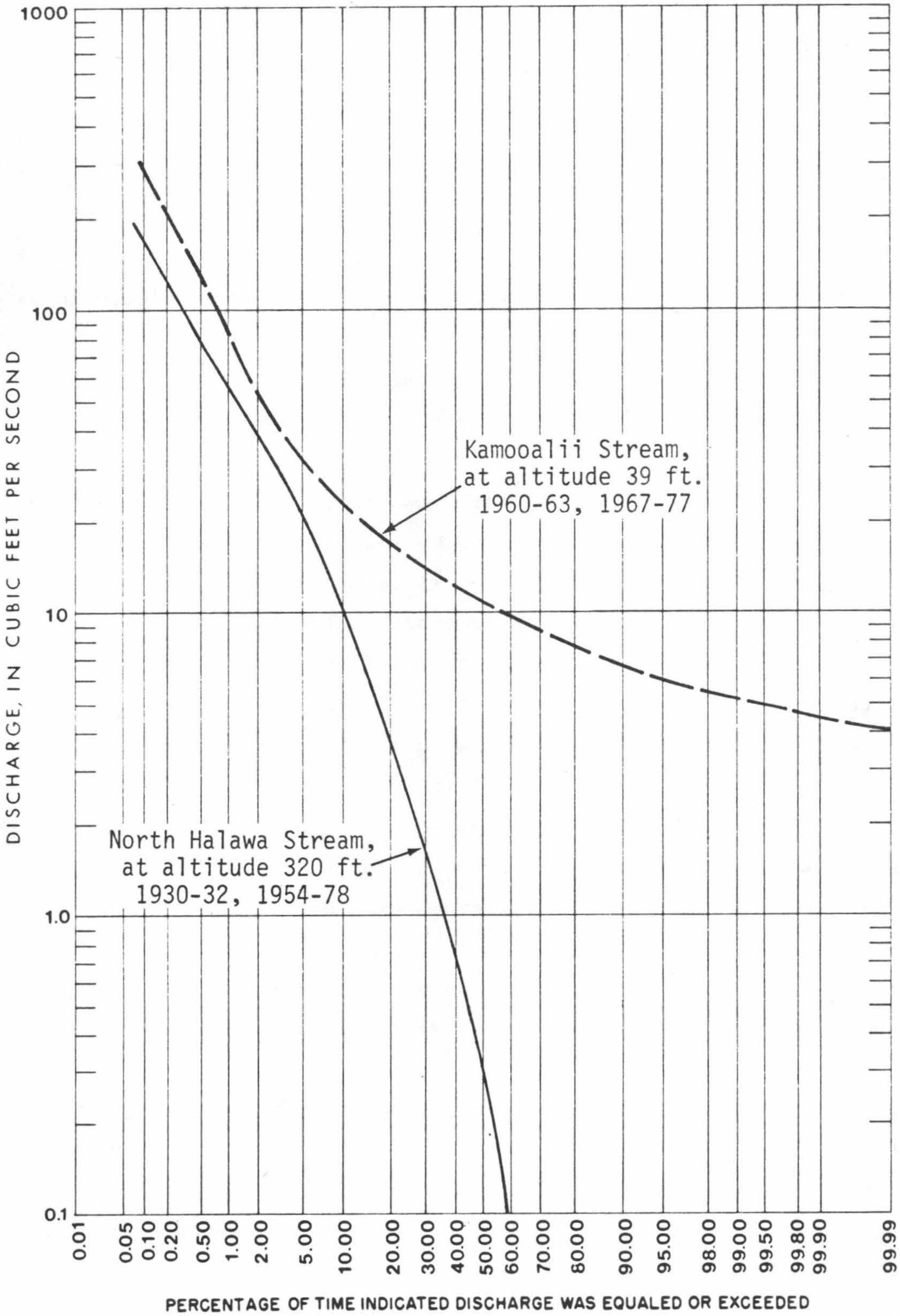


Figure 22. Duration curves of daily flows for windward stream, Kamooalii (sta. 2739) and leeward stream, North Halawa (sta. 2260).

of the windward streams represents effluent discharge from the dike reservoir situated above the valley floors; a part of this flow is diverted from the lee of the crest. There is no indication that the leeward valleys are cut deep enough to tap the dike-impounded reservoir in this subzone.

There are two major zones of ground-water discharge in the stream valleys. The higher zone between altitudes of about 700 and 500 feet is near the base of the cliffs and the lower is between altitudes of 225 and 150 feet (fig. 23). A previous investigation, which included an extensive Lubke, 1969), indicated that about a third of the total visible base flow is from the upper zone and slightly more than half is from the lower. Between these two zones, the streams are gaining and account for the remainder of the base flow, or about a sixth of the total. An undetermined quantity of ground water discharges as underflow directly to sea. Judging by the weathered nature of the surface rocks and rocks at depths as indicated in well logs, the underflow to the sea is deemed small.

The two major zones of discharge separate three rather distinctive ground-water reservoirs. These are an unconfined reservoir above the discharge zone whose leakage and overflow discharges at the upper discharge zone; a partly confined reservoir between the discharge zones in which most of the water discharges at the lower discharge zone near the edge of the dike complex, owing to the damming effect of the dike complex and the presence of less consolidated alluvium in the stream channels; and a nearly saturated but very low-yielding reservoir in the dike complex below the lower discharge zone.

The mean flow ($Q_{average}$) of all perennial streams in the subzone is about 40 Mgal/d, and flow that is sustained 90 percent of the time (Q_{90}) is about 22 Mgal/d (Takasaki, Hirashima, and Lubke, 1969, p. 40). This range is probably a good measure of the range of total visible leakage from the dike-impounded reservoir. Average base flow is about 30 Mgal/d. This flow includes withdrawal by tunnels and wells, which averages about 8 and 3 Mgal/d, respectively. Under these prevailing conditions, any change in the withdrawal rate is manifested by a change in the base flow.

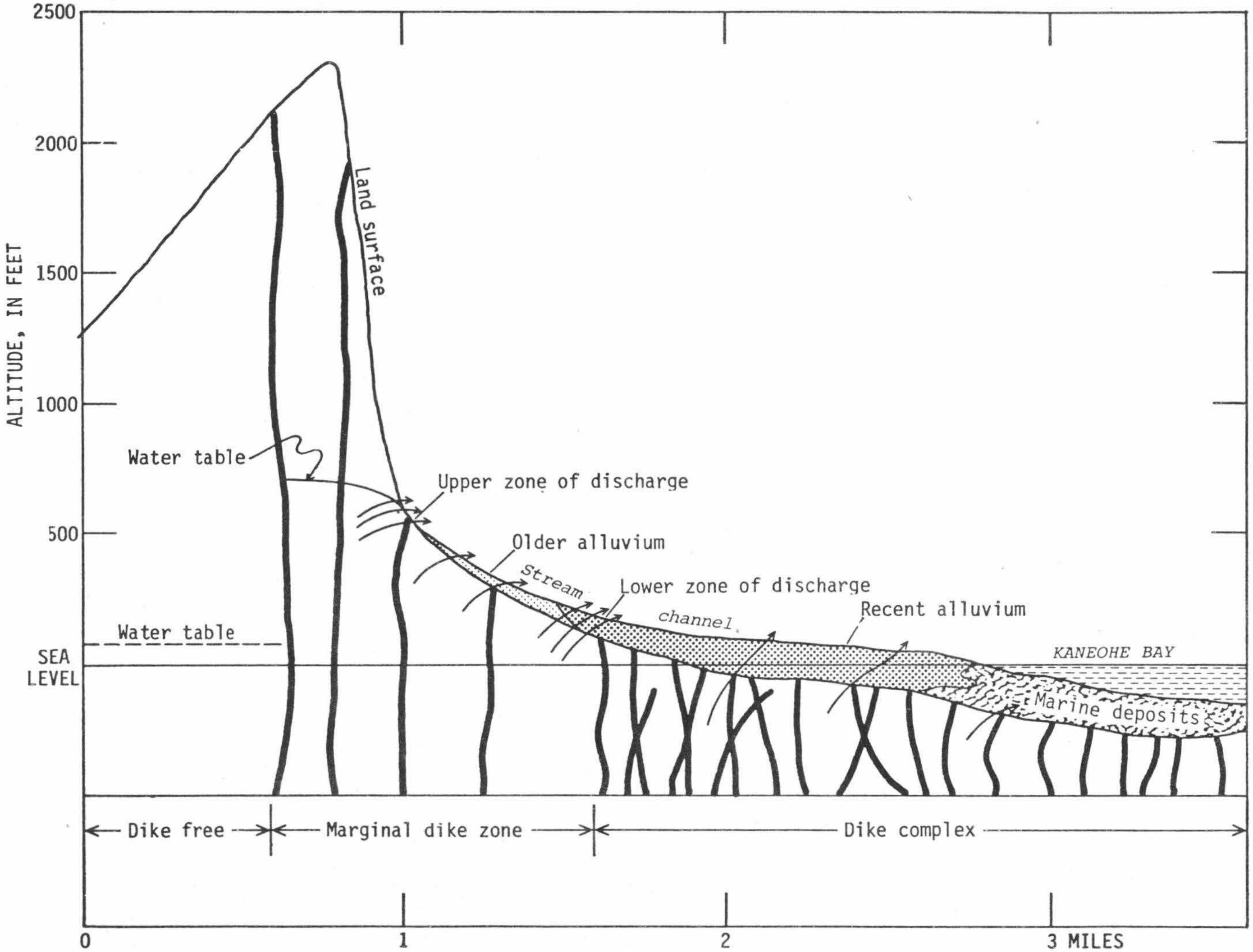


Figure 23. Zones of discharge, Kaneohe subzone.

The rapidity with which a change in the base flow would follow a change in the withdrawal rate, and the severity of the change, are generally functions of the distance between the withdrawal site and the stream.

Past and potential development

At the turn of the century, water was principally used to irrigate taro and rice in the Kaneohe subzone. A network of ditches and flumes was constructed to divert the water from spring-fed streams. By 1940, cultivation of rice and taro had diminished considerably, having given way to truck farming.

After 1940, principal water use shifted from irrigation to municipal supply because of demands of rapidly growing communities in the subzone. The development of municipal water supplies in the subzone had increased from less than 1 Mgal/d in 1940 to more than 7 Mgal/d in 1962 when it became apparent that the development of water in the subzone was not keeping pace with the demand. Beginning in 1965, wells tapping basal-water supplies were drilled in the Waiahole-Kaluanui subzone to augment the supply being developed in the Kaneohe subzone. By 1979, development from wells and tunnels tapping dike-impounded reservoirs in the Kaneohe subzone reached about 11 Mgal/d.

Nearly all present development is for municipal supply. Depending on the available supply, 3 Mgal/d or more of the flow of Waihee Stream is used for taro irrigation. Of this quanity, a recent court ruling decreed that 2.7 Mgal/d be retained and committed for taro irrigation.

About 30 wells have been drilled, most of them for domestic use in the middle 1940's and early 1950's before the availability of municipal water in the then newly developing central part of the subzone. Nearly all these earlier wells, now mostly abandoned, were drilled in the dike complex, where yield from the wells was generally poor. Much of the drilling activity ceased as soon as municipal water was made available. In recent years, there has been some renewed drilling, but, unlike the earlier period, most of the drilling has been in the marginal dike zone.

The upper unconfined reservoir is now tapped for about 5 Mgal/d by tunnels near the heads of Luluku, Haiku, and Kahaluu Valleys and by four inclined drilled wells in upper Waihee Valley. The partly confined reservoir is tapped for about 6 Mgal, of which 4 Mgal/d is developed by Waihee tunnel and 2 Mgal/d by a well in Kuou Valley.

The prevailing practice of maintaining maximum yields from free-flowing tunnels in the upper unconfined reservoir for the principal supply source and pumping from wells in the partly confined reservoir for the supplementary source is hydrologically inefficient. If, instead, the upper reservoir were maintained nearly full, so that flow can be regulated at higher rates when needed, and the lower reservoir at maximum depletable levels, water use would be more efficient. This method would also take fullest advantage of the development possibilities as manifested by the base flow, which discharges only about a third of its flow at the upper discharge zone and the rest between there and the lower discharge zone.

Additional wells between the upper and lower discharge zones would tap the potential supply, which is at least two thirds of the base-flow discharge. The southern half of the subzone appears to be more attractive for new development because prevailing draft and streamflow commitments are less than in the northern half.

With properly placed bulkheads in Haiku, Kahaluu, and Luluku tunnels, restoration of storage of 1 billion gallons or more is possible. At these restored reservoir levels, a combined flow rate of twice or more the average flow rate of 4 Mgal/d of these tunnels would be available for summer or shorter term peaking. A more precise sustainable peaking flow for the summer could be determined after the bulkheads are placed and flow tests conducted. The day-to-day average demands for water could then be supplied by development in the partly confined reservoir instead of by the perennial free flow of tunnels.

The method of development outlined above would result in permanent lowering of water levels between the upper and lower discharge zones. A subsequent increase in recharge would probably result by making more reservoir space available for infiltration during heavy rainfall periods and, also, by making less water available for evapotranspiration. Whether the contemplated increase in recharge would increase in a significant amount, the yield of the reservoir is not known. On the other hand, there would probably be little or no decrease in recharge in the upper unconfined reservoir, because prevailing water levels are deep and would remain deep even after full restoration of storage in it.

The contemplated increase in reservoir yield would partially compensate for the reduction in the visible base-flow discharge. As outlined previously, the effect on the base-flow discharge at or above the upper discharge zone by development would be small. Likewise, water downgradient in storage in the dike complex would be little affected, owing mostly to the low permeability of the rocks in the dike complex.

Any new development scheme must take into account that any change in the withdrawal rate by development is manifested by a change in the base flow. The following denotes the prospect for development and the probable degree of base-flow reduction by the development.

Well or tunnel site	Development prospect	Degree of base-flow reduction by development
At or above upper discharge zone	Good	Severe: Locally in upper discharge zone; lateral extent may be significant. Significant: In down-gradient marginal dike zone. Small: Lower discharge zone.
In marginal dike zone between upper and lower discharge zone	Fair to good	Severe: Locally in marginal dike zone; lateral extent is limited. Significant: Lower discharge zone. Small: At or above upper discharge zone.
Lower zone of discharge	Fair	Severe: Locally in lower zone of discharge; lateral extent is very limited. Small: Marginal dike zone between upper and lower discharge zone. Insignificant: At or above upper discharge zone.
In dike complex, down gradient of lower zone of discharge	Poor	Small: Locally in dike complex; lateral extent is very limited.

The specific capacity of a well, which is a measure of the yield in an individual well should also be considered in any development scheme. Figure 24 shows the specific capacity of several selected wells in the Kaneohe subzone, 4 in the marginal dike zone and 9 in the dike complex. As shown, the specific capacity of most of the wells in the dike complex is less than 10, and those in the marginal dike zone is greater than 10.

Of possible significance to change in the hydrology and subsequent water development in the subzone is the U.S. Army Corps of Engineers "Flood Control and Allied Purposes" project. This project is in its final construction stages in the southern part of Kaneohe and features (1) a 2,200-foot-long, 76-foot-high, and 20-foot-wide (top) earthfill embankment on Kamooalii Stream at an altitude of 125 feet and (2) a reservoir that will be maintained at an altitude of 160 feet to create a 26-acre permanent pool. The embankment is below the lower zone of natural discharge and the reservoir is partly in it. Owing to the embankment's position below the lower discharge and the small acreage of the permanent pool, its effect on the baseflow discharge pattern in the area will probably be small. The contemplated evaporation from the surface of the permanent pool will probably not be significantly greater than the natural evapotranspiration it replaces. Natural seepage into the pool area will be reduced by upgradient ground-water withdrawal, but this reduction will probably be replaced and replenished by overland flow to be impounded by the embankment.

The Southeastern End Subzone

This subzone at the southeastern end comprises that part of the main fissure that lies east of Nuuanu Pali (fig. 25). It also includes Kaau and other minor rifts, which lie outside the main fissure zone.

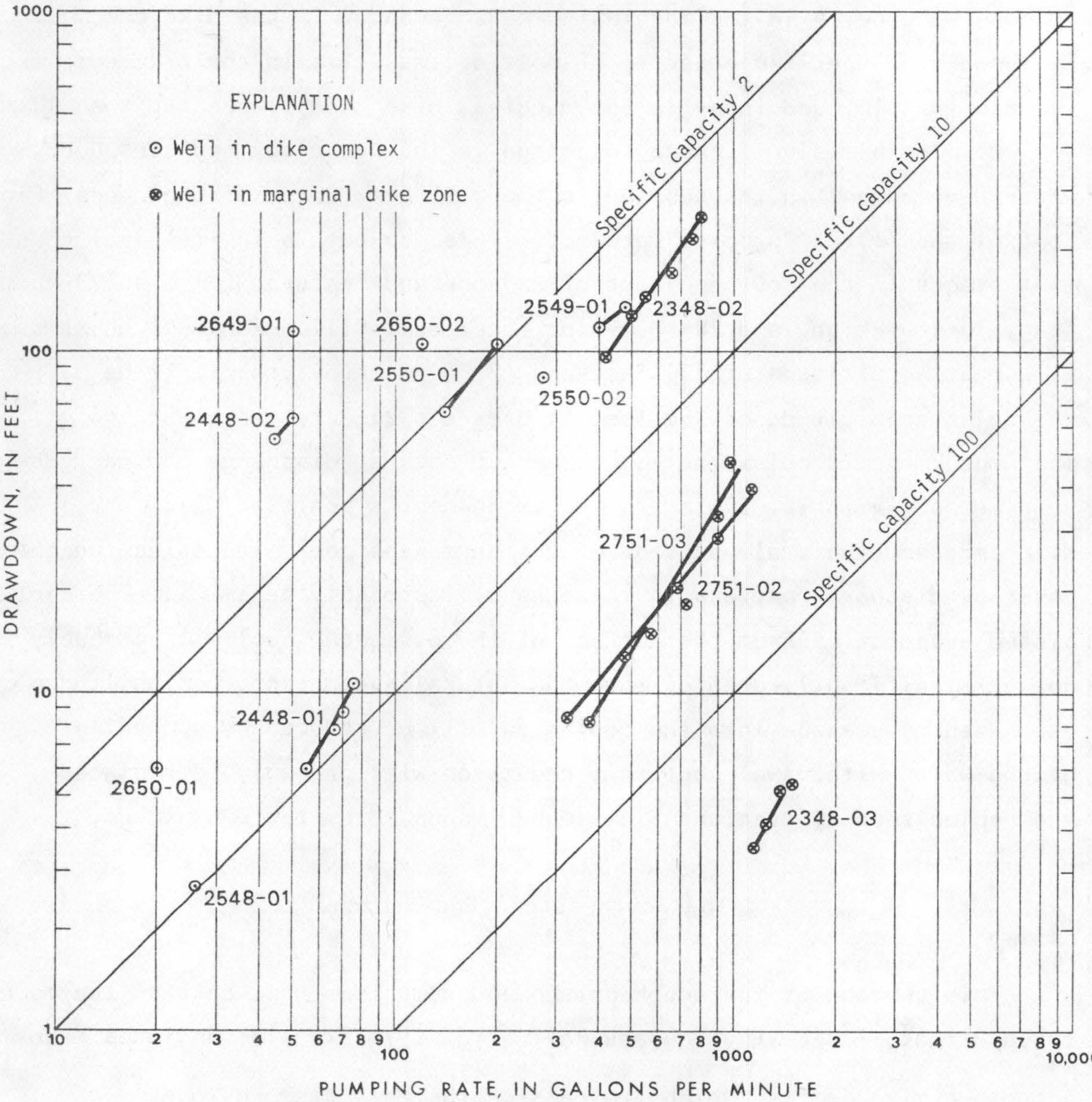


Figure 24. Pumping rate versus drawdown for selected wells in the marginal dike zone and dike complex of the Kaneohe subzone.

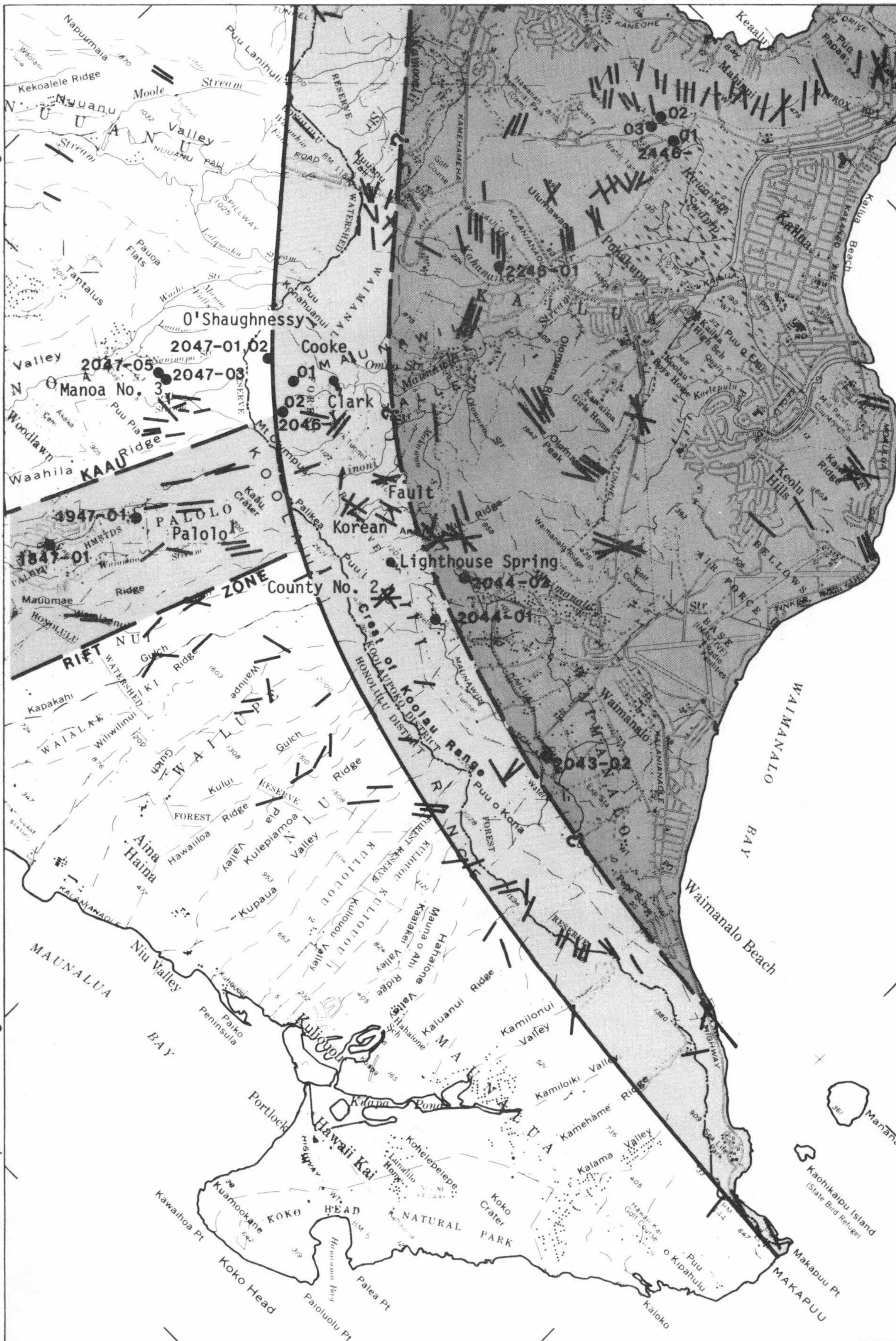


Figure 25. Dikes, dike-intruded rocks in dike complex, marginal dike zone, minor rift zone and location of tunnels, wells, and gaging stations, southeastern end subzone.

Dikes

The subzone includes the major part of the caldera, which is centered in or near Kawainui Swamp at the junction of the northwest, southeast, and southwest (Kaau) rifts (fig. 1). The main fissure zone is widest in the caldera area, and dikes in this area criss- cross and strike mostly in the direction of the northwest and southeast rifts. Dikes of the Kaau rift are less frequent. The strike of the dikes in the three converging rift zones are predominantly N. 55° W. in the northwest rift, N. 75° W. in the southeast rift, and N. 30° E. in the southwest rift.

Away from the caldera area, the dikes in the southeast rift show a gradual shift from about N. 75° W. near the caldera to nearly east-west at the eastern end. Dikes in the northwest rift are predominantly N. 55° W. in this subzone. The dikes in the southwest rift are predominantly N. 30° E. and show a shift in trend from northeasterly to northerly, going from west to east.

The exposures of dikes of the main fissure zone are somewhat obscured by scattered outcrops of breccia, caldera-filling lavas, and rocks of the Honolulu Volcanics. Owing to these outcrops and to deep weathering, there is no evidence of an apparent demarcation between the dike complex and the marginal dike zone as in the Kaneohe subzone. The marginal dike zone, as mapped in the Kaneohe subzone, was projected into this subzone by following the outer edge of the main fissure. This marginal dike zone, thus projected, includes the areas of numerous springs and seeps, the larger of which led to their development by tunnels. The inferred dike complex, in contrast, is characterized by shallow water levels, poor-yielding wells, and slow drainage of ground water into stream channels.

The dikes of the Kaau rift and other minor rifts in the leeward slopes of the Koolau Range were mapped and discussed in considerable detail by C. K. Wentworth (1938, 1940). According to Wentworth, there are concentrations of dikes along zones extending down the leeward slopes, which trend transverse to dikes in the main fissure zone. The lower leeward slopes are comparatively free from dikes and sills whose frequency systematically increases toward the main fissure zone. The most notable concentration of dikes is along a zone in Palolo Valley extending from Diamond Head to Kaau Crater. Other notable zones of dike concentration are in Manoa Valley and other valleys to the east of Palolo Valley. Figure 26 shows the frequency distribution of dikes and sills in the Palolo-Waialae area.

Dike-impounded reservoirs

Dike-impounded water occurs at or near the surface in much of the low-lying area on the windward, or east, side of the crest. The high volcanic ridges in the dike complex and the coastal areas of the Koolau Range in the marginal dike zone are generally unsaturated to some level above abutting low-lying saturated areas. Water levels in a test hole in upper Maunawili Valley indicate the occurrence of some water perched above the dike-impounded water at an altitude of about 1,100 feet. Subsequent observations of the water level in this test hole and in other test holes nearby indicate that the perched water body is very small. As in the Kaneohe subzone, the dike-impounded water is generally unconfined in the mountainous areas and confined to partly confined in low-lying areas under a mantle of alluvium, recent lavas of the Honolulu Volcanics, or highly weathered rock.

The top of the dike-impounded water in the mountainous areas on the windward side is highest along a 2-mile stretch between upper Maunawili and Waimanalo Valleys. Water levels in this stretch appear independent of and about 100 feet higher than water levels of an apparently continuous water-level gradient from Kahana to Waimanalo Valley (fig. 9). Periodic water-level measurements in and near this stretch in test holes (2046-01, -02; 2047-02) are shown in figure 27. The perched-water body, as detected during the drilling of test hole 2047-02 in upper Maunawili Valley, is shown in figure 28.

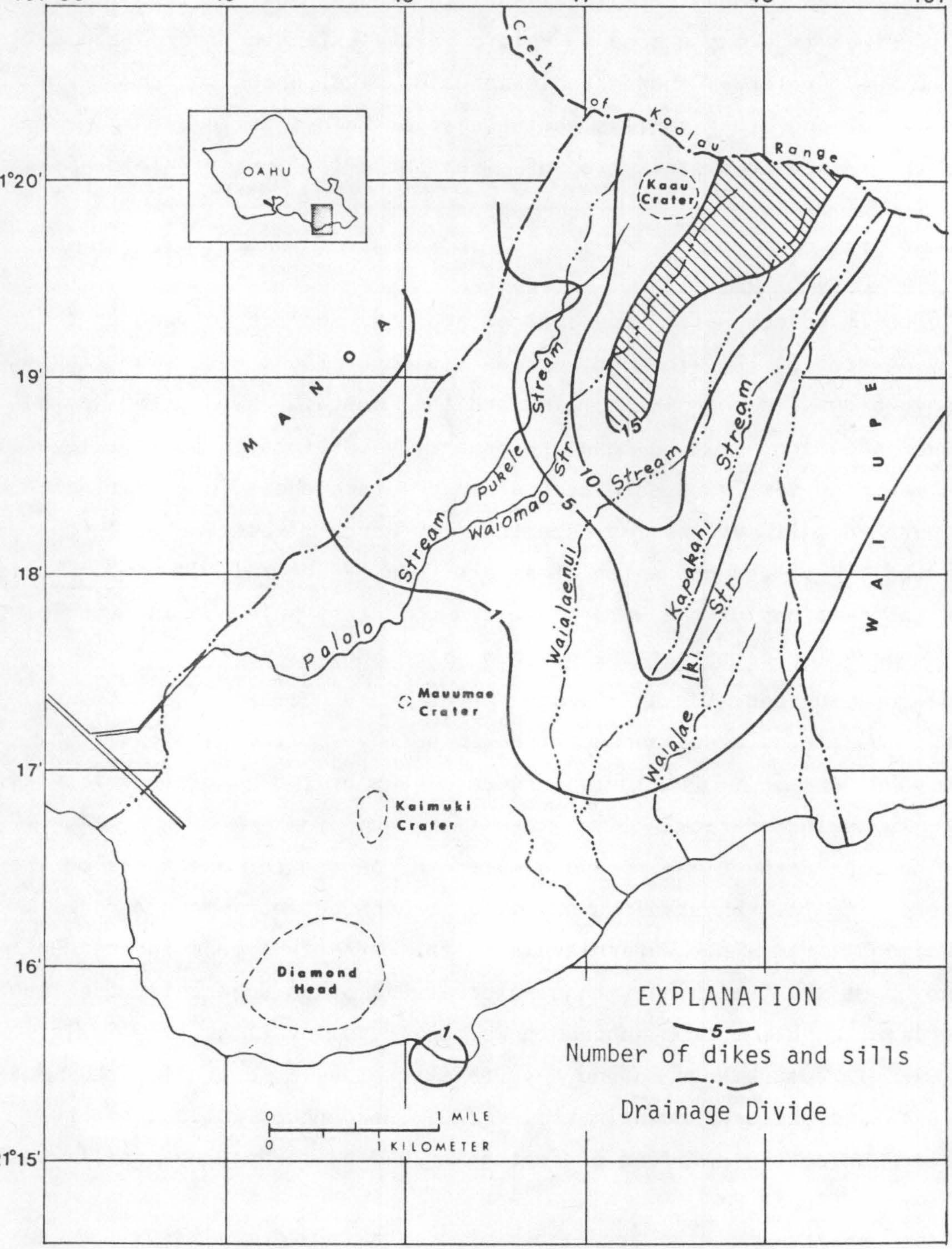


Figure 26. Frequency and distribution of dikes and sills, Palolo-Waialae District (after Wentworth, 1938).

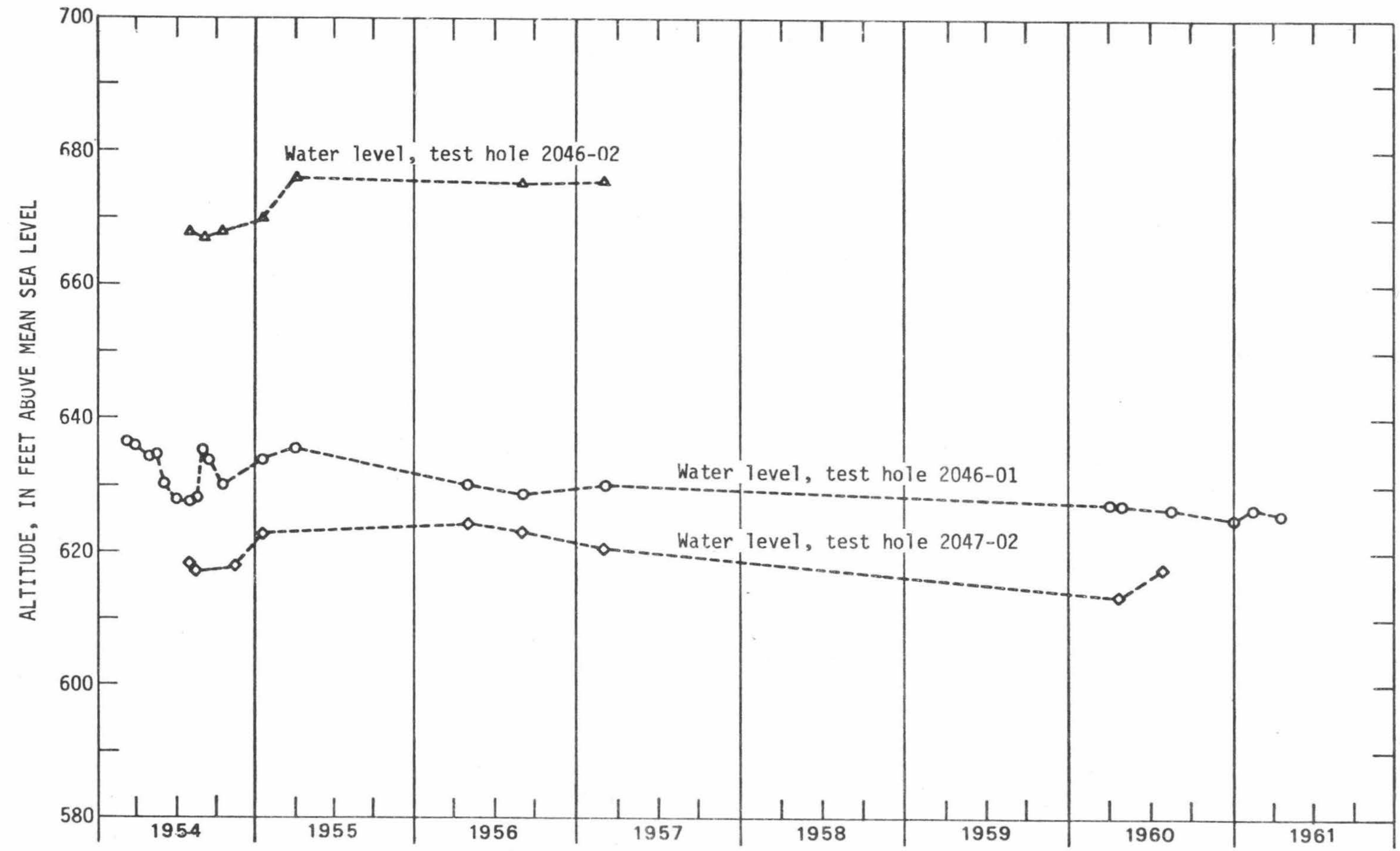


Figure 27. Water levels in test holes 2046-01, 02, and 2047-02.

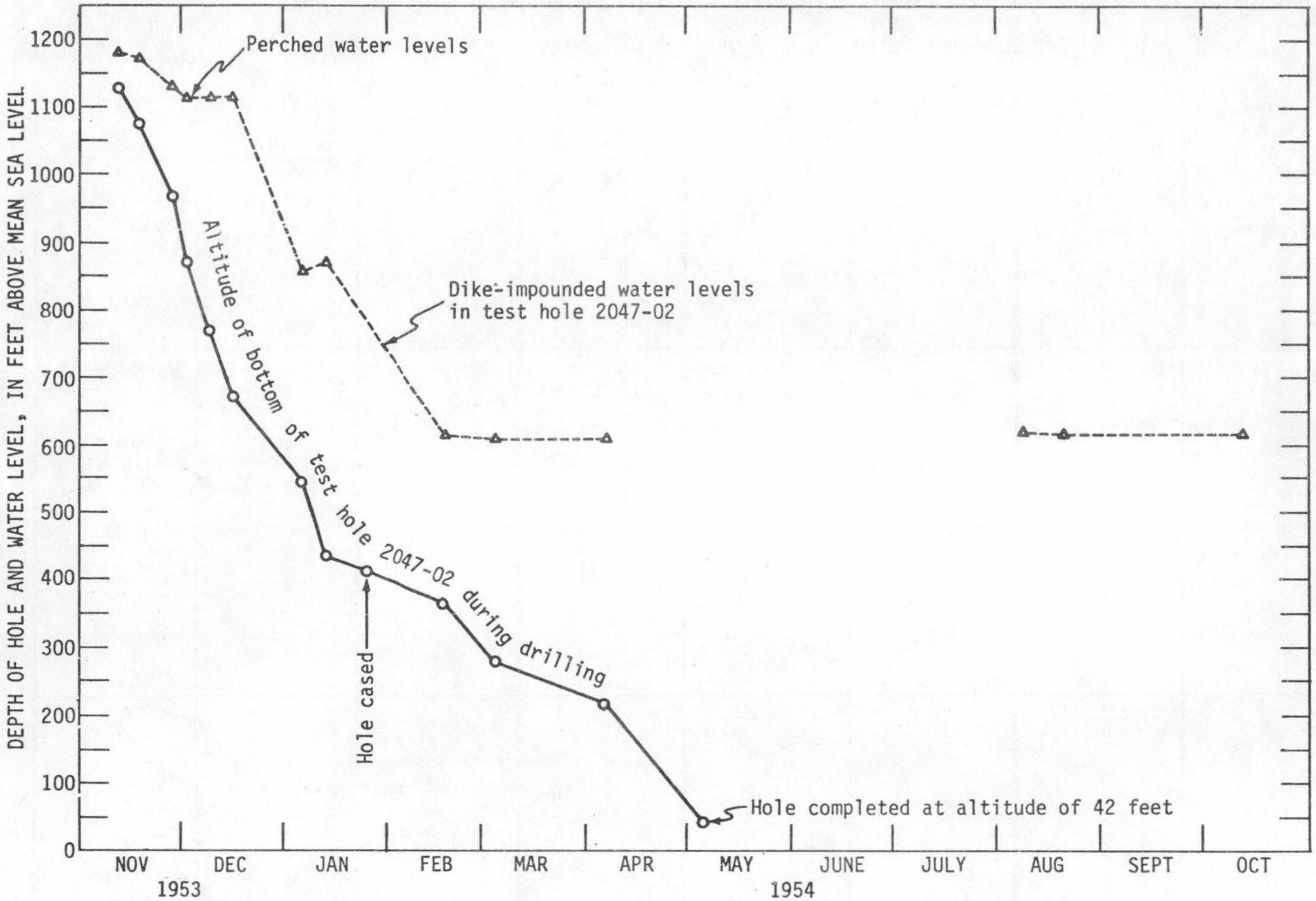


Figure 28. Water levels during drilling of test hole 2047-02.

A plausible explanation for this isolated high water-level anomaly is that northeast-trending dikes of the Kaau rift intersect and criss-cross northwest-trending dikes of the main fissure zone and locally impound ground water in small rectangular-shaped compartments. The smaller water bodies in these rectangular compartments would be slower draining than the abutting water bodies in linear-shaped compartments, which are impounded by mostly parallel dikes. The higher water levels in the area occupied by the rectangular compartments thus result from the large difference in rates of drainage.

Another explanation is that the higher water levels are part of the ground-water body impounded by dikes of the Kaau rift, the top of which stands at an altitude of 990 and 835 feet in upper Palolo and Manoa Valleys, respectively. This situation would imply movement of ground water from the leeward to the windward side of the Koolau Range, from at least 0.75 mile leeward of the crest. A possible water-level gradient drawn across the Koolau crest from the Manoa tunnel No. 3 to Clark tunnel is shown in figure 29.

Palolo and Manoa tunnels tap water impounded by near-parallel northeast-striking dikes about 3/4 mile leeward of the Koolau crest. It is likely that water impounded by dikes extends both eastward and southward of these tunnels. These water bodies are probably less extensive individually and areally than similar water bodies on the other side of the crest because water bodies in Palolo and Manoa Valleys are impounded by dikes that parallel rather than cut across the natural lava slopes and the common direction of the preferred ground-water flow from mountain to sea. Also, Palolo and Manoa Valleys are wide and are nearly parallel to the dikes and afford additional escape for the impounded water bodies. The opposite is the case in the main fissure zone.

Dike-impounded water levels in Palolo and Manoa Valleys stand about 400 feet higher than water levels on the other side of the crest. According to Wentworth (1938, p. 232), storage depletion in the Palolo tunnel was about 100 million gallons. There is no supporting evidence to show that

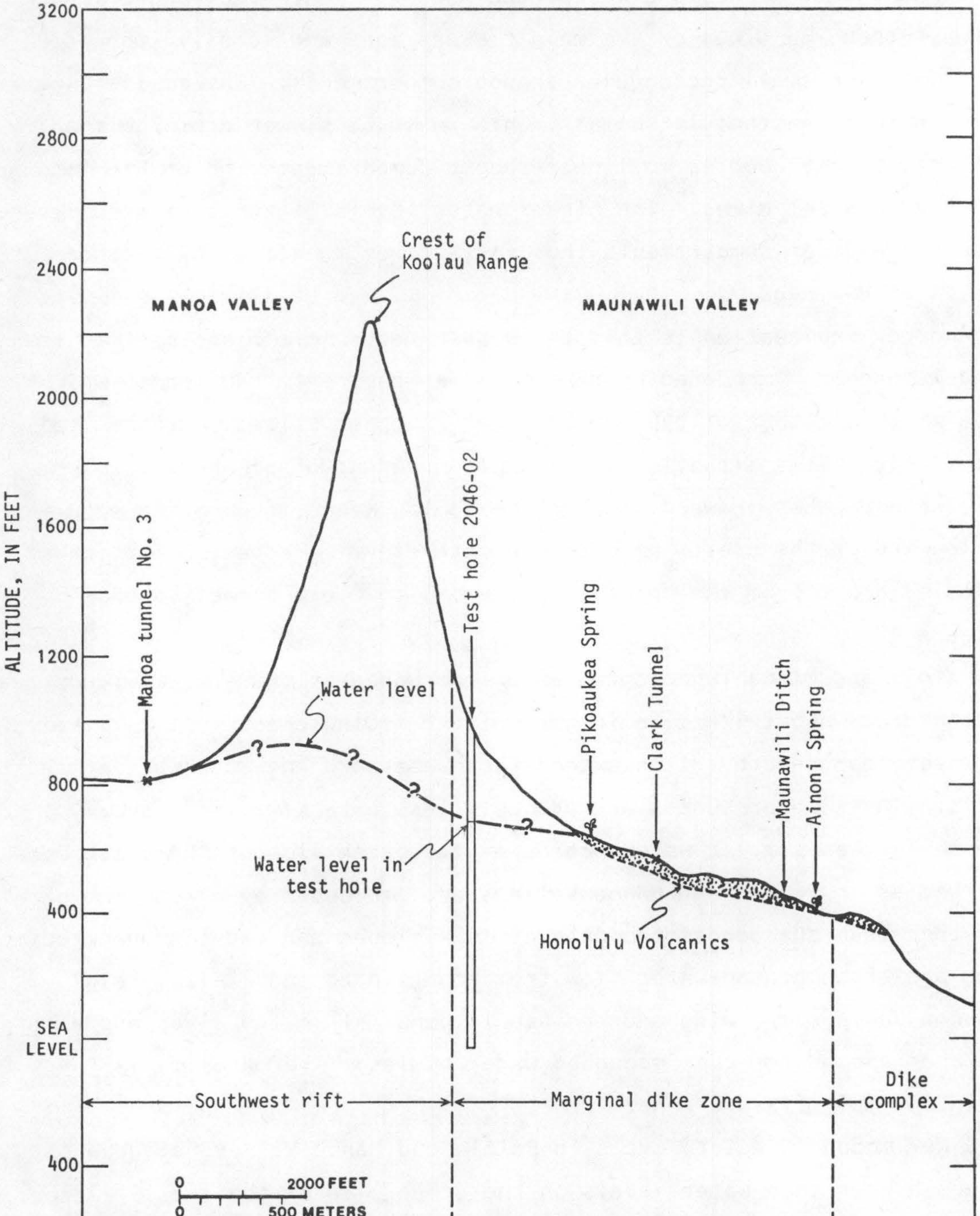


Figure 29. Possible water-level gradient across the Koolau crest from Manoa tunnel No. 3 to Clark tunnel.

storage depleted by Manoa tunnel was significantly greater or smaller. This depletion of 100 million gallons is only a tenth that of tunnels in the main fissure zone.

Unlike water bodies in the main fissure zone where impoundment is almost solely by dikes that restrain horizontal flow of water, there is some evidence indicating that flow in water bodies in upper Palolo and Manoa Valleys may also be restrained in the downward direction. The water may be perched, in addition to being restrained horizontally by dikes. The supporting evidence is the many outcrops of sills and tuffs reported by C. K. Wentworth (1938), the known occurrence of perched water as shown by the drilling of well 2047-05 in Manoa Valley, the small storage of the impounded water bodies, and the apparent absence of a smooth water-level gradient.

A traverse into Waialaenui Valley, just east of Palolo Valley, was made by H. S. Palmer (1921) in September 1920, after a moderately rainy period. Palmer describes the stream as being dry up to an altitude of 1,000 feet, the extent of his traverse. The authors, in a traverse in October 1979, found the stream to be perennial, beginning at about an altitude of 1,000 feet. Their traverse extended to an altitude of about 1,300 feet.

Except for some stagnant water in alluvium at about an altitude of 800 feet in the east branch of Wailupe Gulch, H. S. Palmer (1921) found no evidence of ground-water discharge at the surface, up to this level.

Past and potential development

Maunawili Valley.--Maunawili Valley is drained by Maunawili and Kahana-iki Streams and their tributaries. Nearly all of the water development, an average of about 2 Mgal/d, is from the drainage of Maunawili Stream above an altitude of about 400 feet in the stream channels and above the level of Maunawili Ditch. The water is developed from three tunnels, a spring, and streamflow above ditch level, and is exported to Waimanalo Valley. Development below the ditch level is less than 0.1 Mgal/d from two springs and two wells.

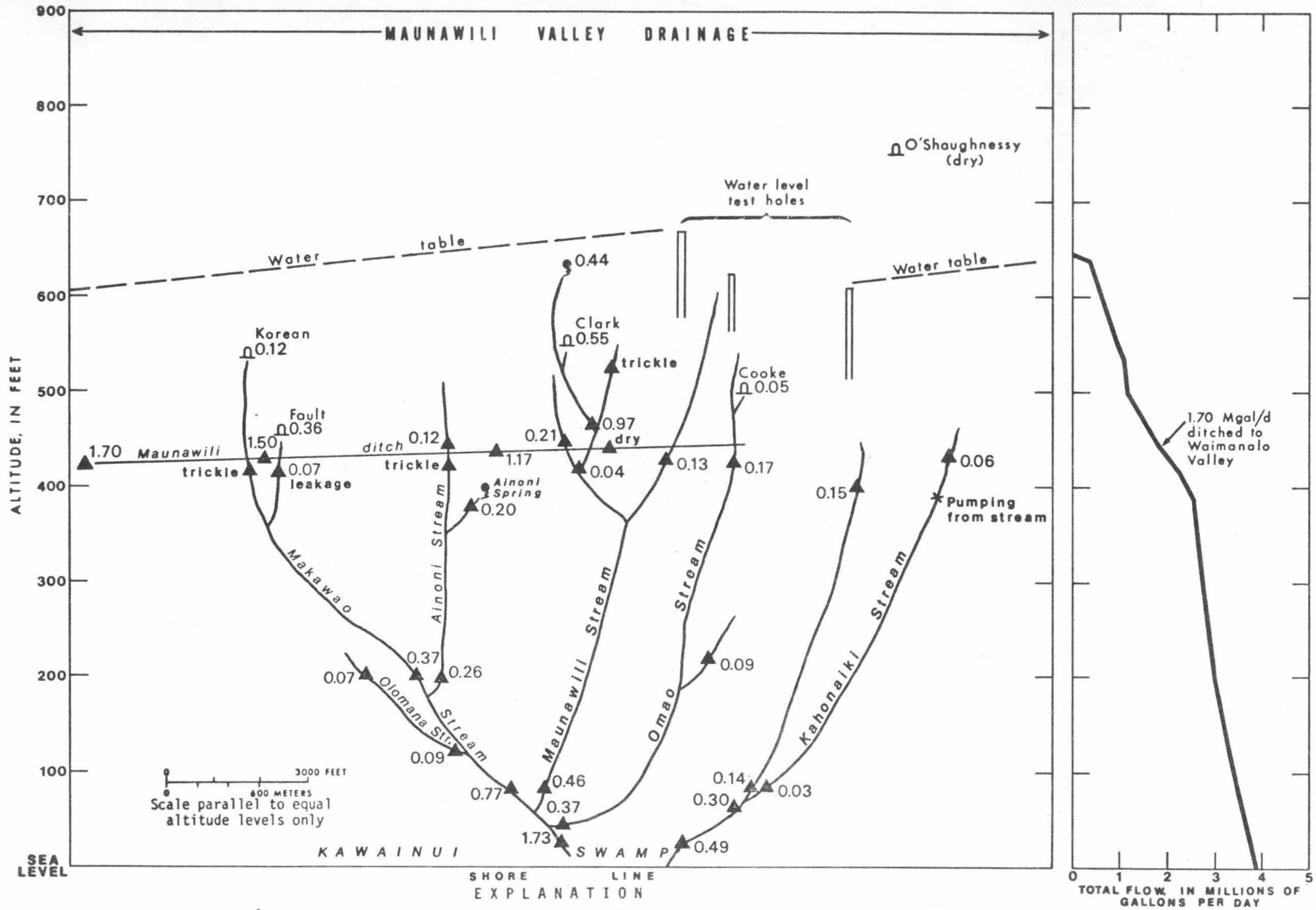
Maunawili Ditch roughly follows the 400-foot contour and extends across the drainage of Maunawili Stream; from there it follows a tunnel under Aniani Nui Ridge into Waimanalo Valley, where it terminates in the eastern part of the subzone at an altitude of about 200 feet. The first 1,000 feet of the ditch in Maunawili Valley was detached several years ago when the wooden flume across the stream channel was destroyed.

A systematic measurement of the base-flow discharge in Maunawili Valley was made by the U.S. Geological Survey in July 1959, during a prolonged period of low rainfall (fig. 30). The measurements, as shown in figure 30, totaled slightly less than 4 Mgal/d. All the discharge measurements were of free flow. As shown, more than 60 percent of the total base flow was measured above an altitude of about 400 feet in the stream channels. A line connecting these measuring points roughly coincides with the demarcation of the marginal zone and dike complex. Effluent flow below this level in the dike complex is highly diffused. In the Kaneohe subzone, effluent flow increased at lower levels in the stream channels, between altitudes of 225 to 150 feet, which, in the Kaneohe subzone, coincides with the inner edge of the marginal dike zone.

The Honolulu Board of Water Supply made a similar survey of the water sources that flow into Maunawili Ditch and other supply developments in the valley in November 1960 (H. K. Lee, 1960). These measurements were similar to the measurements of the U.S. Geological Survey.

W. O. Clark (1922) and H. S. Palmer (1957), among others, have described the geologic structures and the occurrence of dike-impounded water in Maunawili Valley and have recommended methods of developing and managing the base-flow supply by tunnels, some with bulkheads in them.

C. K. Wentworth (1953) investigated the possibility of basal ground water extending across the Koolau Range from the lee side by the drilling of test holes in upper Maunawili Valley. D. C. Cox (1954) summarized and interpreted the results of this drilling and concluded that basal water from the lee side did not extend into upper Maunawili Valley.



EXPLANATION

▲	0.36	⩍
Flow measurement on July 22-23 and 29-30, 1959	Flow, in millions of gallons per day	Water-development tunnel

Figure 30. Relative altitudes of water levels in wells, water-level gradient of dike-impounded water, tunnels, and base-flow measuring points in streams.

Further development, aimed solely at the base-flow discharge by horizontal tunneling in the marginal dike zone or anywhere in Maunawili Valley, would not enhance the existing net water supply. The principal reason is that the base-flow discharge is too small and that the present tunnels are already effective in channeling nearly all base flow available above Maunawili Ditch. The base-flow discharge in the dike complex below the ditch level appears too diffused and probably not easily developable by wells or tunnels. If or when the principal use of the water changes from agricultural to municipal, the extension, modification, and bulkheading of some of the tunnels or even the construction of new tunnels, may become feasible for better management and quality control.

The drilling of two large-diameter wells in the marginal dike zone, one in the stretch of the high water levels and one out of it to the west would be more favorable. The wells would need to be drilled at least 200 feet into unweathered saturated rock. Overburden of weathered or other low-permeable rock may be more than 100 feet thick.

An array of wells, if proven to be successful, could then be pumped at rates in excess of the base-flow discharge by mining water from storage for utilization during the heavy-demand summer months or for short-term peaking. It is likely that mining from storage would sufficiently lower water levels in the marginal dike zone that less water would be available for evapotranspiration, less water would be rejected during ensuing rainier periods, and more space would be available for infiltration. The consequent price for such a development scheme would be reduction in the base-flow discharge during the pumping period and for some time after, the magnitude and duration of which would depend on the pumping rate. This reduction in base-flow discharge would generally coincide with a period of low agricultural water demand.

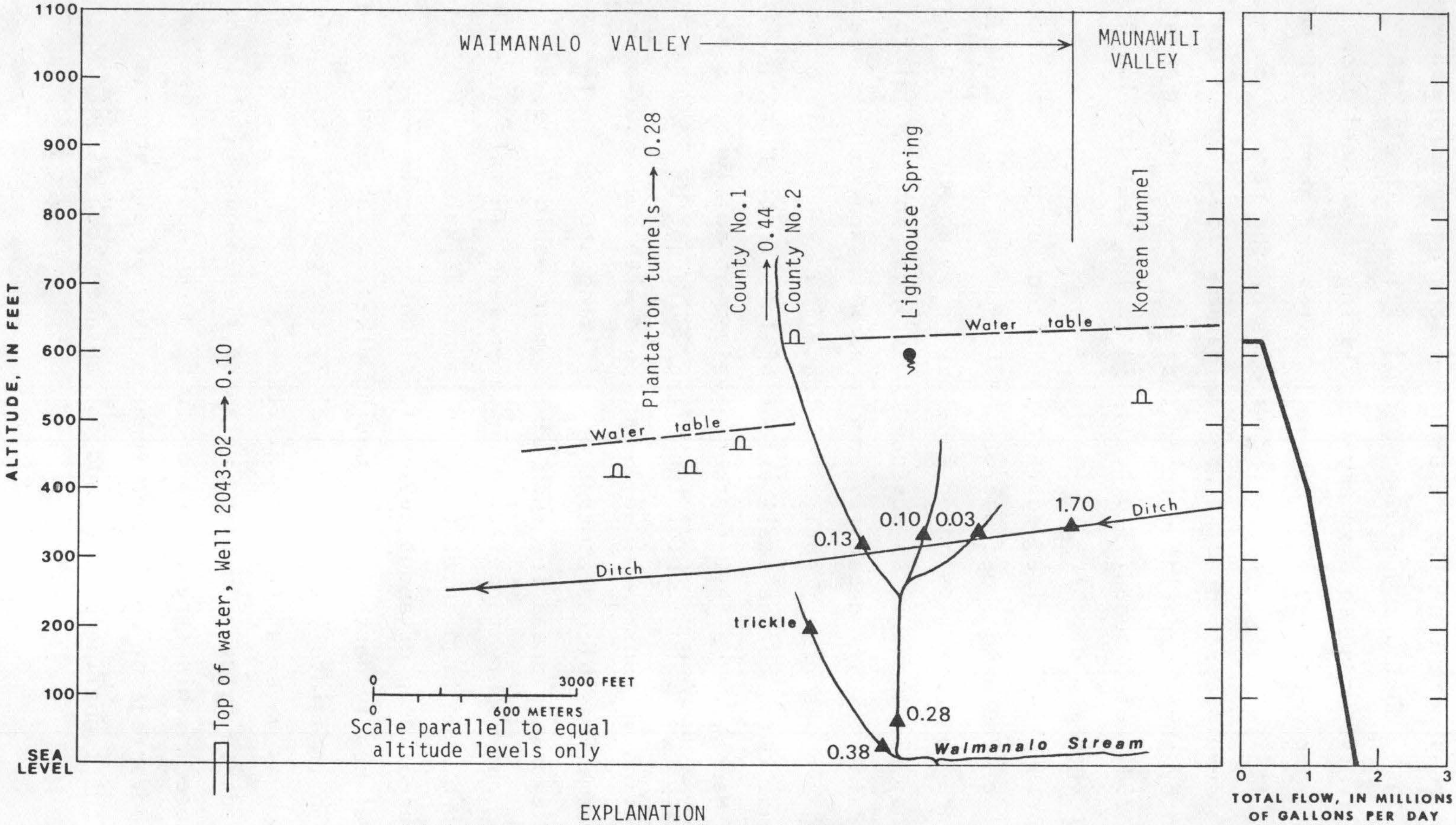
Waimanalo area.--Dike-impounded water in the Waimanalo area is developed by five tunnels located above the level of Maunawili Ditch. Total draft, in 1978, averaged 0.55 Mgal/d.

A systematic measurement of the base-flow discharge in the area was made on July 31, 1959, during a prolonged period of low rainfall. As shown in figure 31, the measured discharge, including the tunnel flow, was about 1 Mgal/d above the level of Maunawili Ditch and about 0.70 Mgal/d below the ditch. It is likely, however, that much of the streamflow measured below ditch level represented return irrigation flow. Water for irrigation is fed by three parallel ditches that cut across the area at altitudes 360 to 200 feet (Maunawili Ditch), 150 to 100 feet (Kailua Ditch), and 80 to 40 feet (unnamed ditch).

C. K. Wentworth (1943) advised against tunneling for dike-impounded water to the east of Puu O Kona because of the following: (1) the dikes of the main fissure zone are missing or fade out or swing northward away from the mountains; (2) there is an absence of springs; and (3) rainfall is low. H. S. Palmer (1957) generally concurred with Wentworth's reasoning for not tunneling and was also skeptical of tunneling even a mile or more west of Puu O Kona, owing to the small extent of infiltration area.

As in upper Maunawili Valley, further development solely aimed at the base-flow discharge by horizontal tunneling would not be advantageous. However, if tunneling or horizontal wells equipped with bulkheads or other controls later seems feasible as a means of utilizing storage in the mountains, the most favorable areas for such development would be between Lighthouse Spring and County tunnel 2. The water level in this stretch is a continuation of the high level found in Maunawili Valley. The water level has an apparent drop of about 100 feet, slightly to the west of tunnel 2. Several nearly north-south trending dikes, which were mapped in the small drain immediately east of tunnel 2, are part of the apparent controls that impound water at the high altitudes.

For the immediate future, instead, wells drilled above an altitude of 400 feet or more in this stretch appear to be more feasible than tunneling. The chief advantage of wells over tunnels is that all storage is depleted during the tunneling period, and for an area such as this where



EXPLANATION

0.28 Stream flow, in millions of gallons per day

▲ Flow measurement on July 31, 1959

Ո Water-development tunnel

↑ Discharge, in millions of gallons per day

Figure 31. Relative altitudes of water-level gradient of dike-impounded water, tunnels, and base-flow measuring points in streams.

the base flow is so small, this would be highly undesirable. As in Maunawili Valley, such wells would, for optimum usefulness, be pumped only in the high-demand summer months or for short-term peaking.

Owing to the weathered nature of the rocks to high altitudes west of County tunnel 2, the most favorable area for wells would be deep inside the existing tunnels. The rocks in the tunnels are saturated below the floor, and the chances of tapping unweathered rock at shallow depths are much greater than in the lower weathered slopes.

Leeward area.--Dike-impounded water west and lee of the Koolau crest is developed by Manoa tunnel No. 3 and Palolo tunnel. Manoa tunnel No. 3 is one of five tunnels dug in Manoa Valley and is the only one still in use. In addition to the tunnels, dike-impounded water in Manoa Valley is tapped by a well drilled in 1970 and never used. The well, 2047-03, was drilled at the site of Waaloa Springs about 1,500 feet to the west of Manoa tunnel No. 3. The results obtained from the drilling of two test holes and well 2047-03 near the springs defined the source of the springs to be a water body perched in alluvium about 100 feet above the dike-impounded body.

Palolo tunnel, dug at an altitude of about 990 feet, is located in the valley of Waiomao Stream, the east branch of Palolo Stream. There are two wells drilled at high altitudes in Palolo Valley. One well, at an altitude of about 900 feet and 200 feet in depth, apparently taps a small perched water body. The other, well 2047-05 at an altitude of 385 feet, is drilled in the vicinity of dike-intruded rocks but the water body tapped is apparently only partially impounded. The water level in the well stands at an altitude of about 22 feet. The specific capacity of the well is about 100; the specific capacity per foot of aquifer is 0.7, or about in the range of values found for water bodies in the marginal dike zone of the northern end subzone.

Figure 32 shows the flow-duration curves of Waiakeakua and Waihi Streams in upper Manoa Valley. Waiakeakua Stream drains the eastern and central parts of the valley and Waihi Stream the western part. The flatter

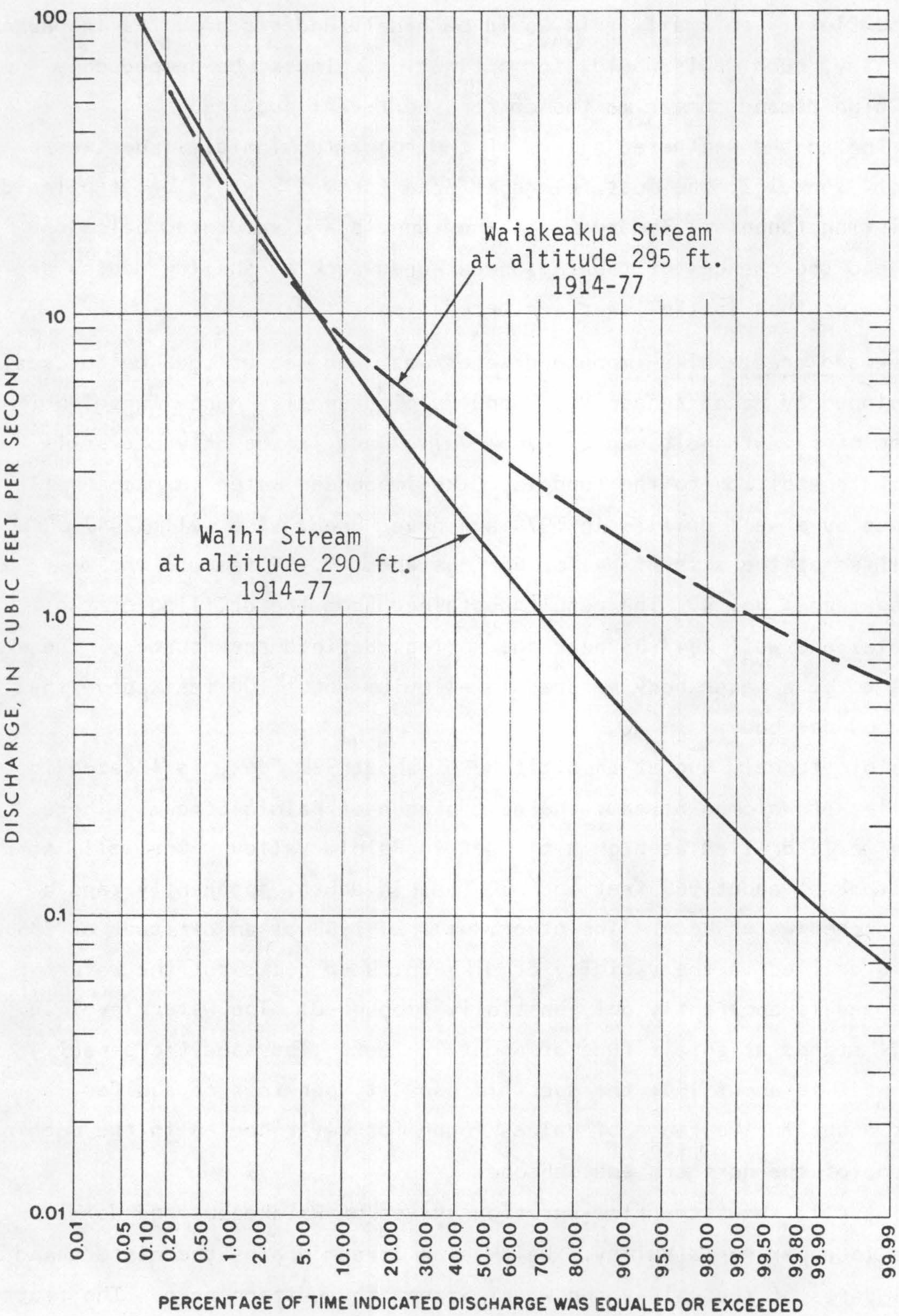


Figure 32. Duration curves of daily flows at Waiakeakua (sta. 2405) and Waihi (2385) Streams.

sloped flow-duration curve of Waiakeakua Stream indicates that ground-water storage and leakage from storage are greater in the eastern part of the valley than the western part above an altitude of the stream gages, or about 300 feet.

According to Wentworth (1936), all water derived from tunnel No. 3, at an altitude of about 760 feet near Waiakeakua Stream, was newly developed water and the effect on the flow of the stream was nil. His reasoning was that the impounding dikes are parallel to Waiakeakua Stream and were effective water barriers against significant leakage into the stream. Wentworth's reasoning is substantiated, in part, by comparing the flow-duration curves of Waiakeakua Stream before tunnel construction from 1914 to 1920 and the period before and after construction from 1914 to 1977 (fig. 33).

Owing to the apparent small leakage of dike-impounded water into the upper and middle reaches of streams in Manoa Valley, ground-water development above an altitude of 300 feet for the purpose of increasing perennial supply needs would not be advantageous. Development would reduce recharge to down-gradient basal-water bodies.

Other sources designed primarily to satisfy the needs of high-demand periods or for short-term peaking would allow more efficient use of the water in upper Manoa Valley. Well 2047-05, drilled near Waaloa Springs, could be utilized in this manner.

Owing to the the absence of significant leakage of dike-impounded water, development of the ground water at high altitudes in Palolo Valley and in valleys to its east would not be feasible. However, wells drilled to water bodies being fed by dike-impounded water in areas sufficiently far inland that natural saline ground-water intrusion is minimal would enhance supplies. This would be especially favorable in areas where down-gradient water bodies are undeveloped and being discharged unused to sea, as in many of the valleys east of Palolo Valley.

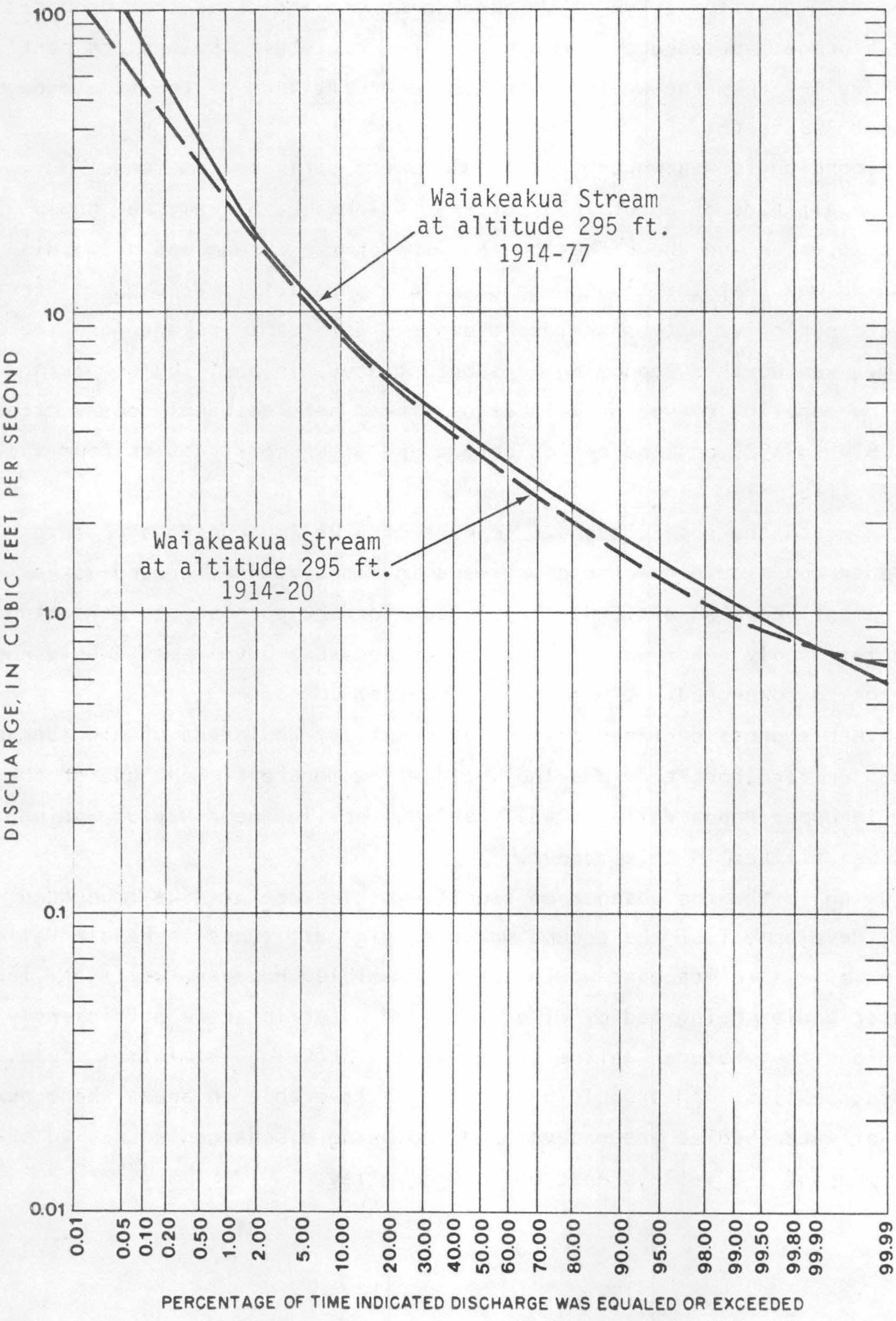


Figure 33. Duration curves of daily flows of Waiakeakua Stream (sta. 2405) before and after tunnel construction.

Summary of Dike-Impounded Water in the Subzones of the Koolau Range

The measured and estimated discharge from the dike-impounded reservoirs in the Koolau Range totals 263 Mgal/d. Of this quantity, the measured discharge is 86 Mgal/d, which consists of the visible flow of streams and springs, tunnel and well discharges, and diversions in areas underlain by dike-impounded water. The remainder, or 177 Mgal/d, is the estimated underflow to downgradient water bodies. Owing to the uncertainty in the location of the ground-water divide west or in the lee of the Koolau crest in the Kaneohe area and of the limits of the minor rift zones in southeastern Oahu, the underflow discharges from these areas were not determined. The figures and references from which the above estimates were made are given in the subzone discussions and summarized in table 11.

The underflow discharges west or in the lee of the Koolau crest into the Schofield water body and the Waialua basal-water body have been estimated at 52 and 22 Mgal/d (table 11), respectively, for a total of 74 Mgal/d. The underflow discharge, south of these areas, is probably no greater than a third of this quantity, say 20 Mgal/d. This rough estimate, added to the previous total of 263 Mgal/d, gives 283 Mgal/d.

The value of 283 Mgal/d makes up a significant part of the sustainable ground-water yield of the Koolau Range, which has been estimated to range from about 450 to 580 Mgal/d by the State Water Commission, in its report to the Governor in January of 1979.

On the basis of the values given in table 11, the most promising areas for the development of the visible discharge from the dike-impounded reservoirs are the Kaneohe, Kahana, and Punaluu areas. Likewise, the most promising areas for the development of the underflow discharge are in the Waialee, Hauula-Laie, Punaluu-Kaluanui, and Kahana areas.

Table 11. Summary of discharges from dike-impounded reservoirs in the subzones

(Millions of gallons per day)

Subzone	Measured flow from high-altitude dike-impounded reservoirs: Total	Used[a/]	Unused[b/]	Estimated average underflow from high-altitude dike-impounded reservoirs: Total	Receiving water bodies; Remarks
The northern end					
Waialee area ----------------	Small	0		20	Sea; draft about 2 from dike-impounded reservoir.
Kahuku area -----------------	Small	0		14	Basal body in which draft is about 2.
Hauula-Laie area ------------	Small	0		34	Basal body in which draft is about 3.
Leeward areas -----------------	Small	0			
Abutting Waialua ------------				22	Basal body in which draft is about 60.
Abutting Schofield ----------				26[c/]	Schofield body in which draft is about 17.
Waiahole-Kaluanui					
Punaluu-Kaluanui ------------	11	1	10	25[d/]	Basal body in which draft is about 7.
Waiahole-Kahana -------------	-	-	-	-	
Above tunnel level --------	28	28	0	-	
Below tunnel level --------	-	-	-	-	
Waiahole-Waikane --------	6	2	4	-	Sea; underflow is small.
Kahana ------------------	11	0.1	11	10	Sea; Takasaki and others (1969).
Leeward ---------------------	-	-	-	-	
Abutting Schofield --------	Small	0		26[c/]	Schofield body with leeward Hauula-Laie.
Abutting Pearl Harbor -----	Small	0		Not determined	Basal body in which draft is about 240.
Kaneohe					
Windward (east of crest) ---	22	15	7	-	Sea; underflow is small.
Leeward (west of crest) ----	Small	0		Not determined	Basal body in which draft is about 240.
The southeastern end					
Maunawili Valley					
Above ditch level --------	2.2	1.8	0.4	-	
Below ditch level --------	2.0	0.1	2.0	-	Sea; underflow is small.
Waimanalo area					
Above ditch level --------	1.0	0.7	0.3	-	
Below ditch level --------	Small	0.1		Small	Effluent streamflow is mostly return irrigation.
Leeward area					
Manoa -------------------	1.8	0.3	1.5	Not determined	Basal body in which draft is about 14.
Palolo -------------------	0.8	0.3	0.5	do.	Basal body in which draft is about 5.
Waialae-Hawaii Kai -------	Small	0		do.	Basal body in which draft is about 1.
Total ------------------------	86	49	37	177	Underflow to water bodies; exclusive of that not yet determined.

[a/] Average draft or flow from tunnels, wells, or diversions.

[b/] Ground-water component of streamflow taken as Q_{90}.

[c/] One-half of estimated underflow to Schofield water body; estimate from Dale and Takasaki (1976).

[d/] Prorated from Takasaki and others (1969).

DIKES IN THE WAIANAE RANGE

Rift Zones

The rocks of the Waianae Volcanics have been divided into the lower, middle, and upper members (Stearns and Vaksvik, 1935). The lower member comprises the rocks that built the bulk of the volcano. The middle member largely consists of rocks that accumulated in and gradually filled the caldera. The upper member is the thin andesitic capping that covered most of the volcano late in its building phase (Macdonald and Abbott, 1970, p. 358). The distribution of these rocks is shown in figure 34.

The main fissure zone, from which the lavas erupted, consists of two principal rifts, the northwest and south (fig. 1). A minor rift, in which the dikes trend northeasterly, intersects the juncture of the main fissure in the central part of the range hereafter named as northeast rift zone. Most of the dikes in the northeast rift are overlain by the sparsely dike-intruded upper member, although in the channel of Kaukonahua Stream dikes are exposed where the upper member has been eroded. The junction of the northwest, south, and northeast rifts lies in a caldera, the outer limits of which are about 10 miles long and 5 miles wide. Much of the caldera structure and the lavas that ponded in the caldera in Makaha, Waianae, and Lualualei Valleys have been extensively eroded.

Deep erosion has removed most of the western slope of the volcano. Dikes are sparse in the poorly permeable, massive upper member and significantly more numerous in the more permeable lower and middle members.

The deeply eroded main fissure zone lies to the lee of the crest in most of the Waianae Range. The minor northeast rift lies entirely in the windward side of the crest. It is capped by the upper member in the less eroded areas and overlain by sediments in deeply eroded areas.

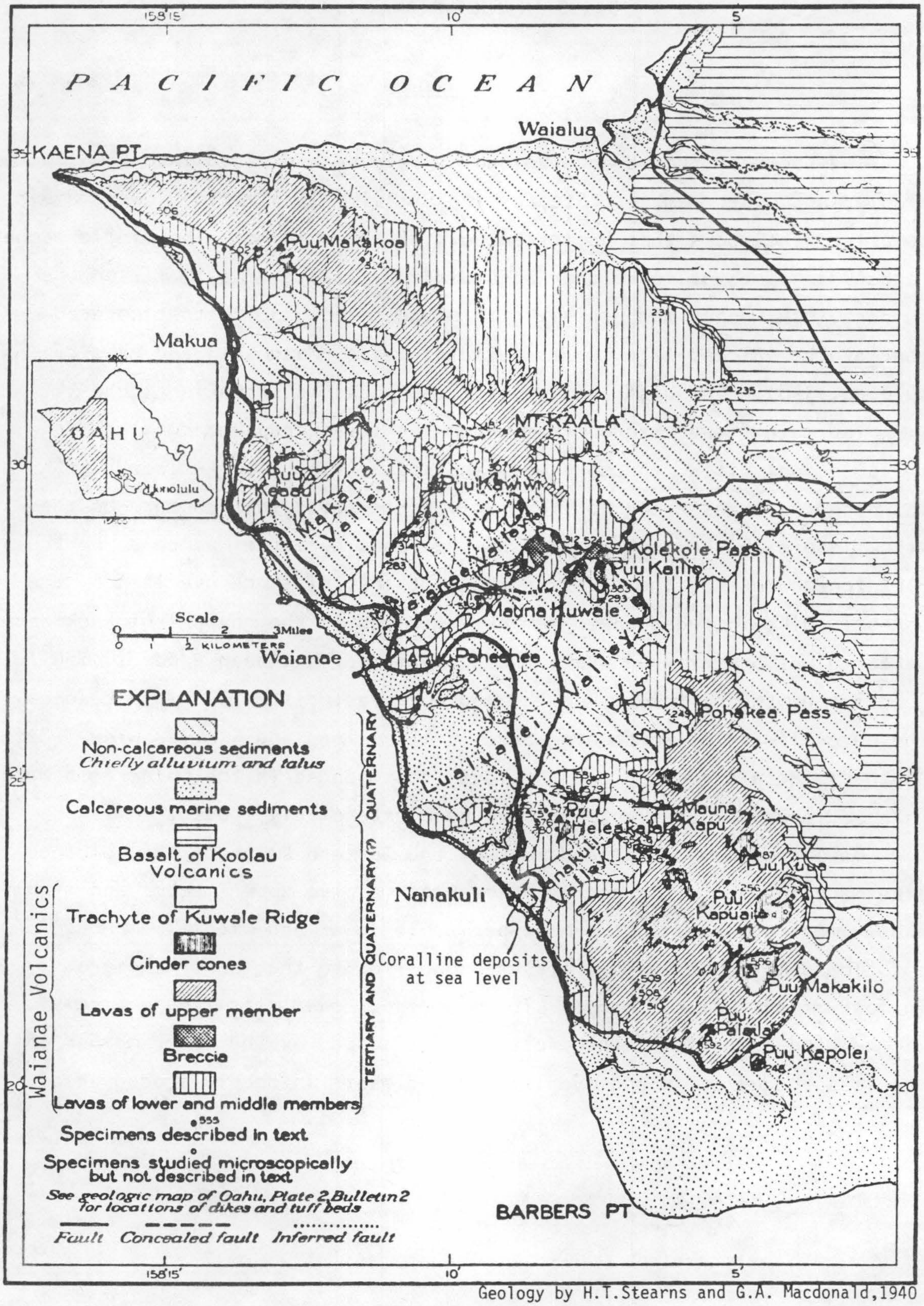


Figure 34. Geologic map of Waianae Range.
(Modified from Stearns and Macdonald, 1940.)

Data Base

Information on dikes was largely taken from reports and field notes. The data thus used include descriptions of about 250 discrete dike locations.

Period	Investigator	Remarks
1930	W. O. Clark, Hawaiian Sugar Planters' Assn.	Field investigations in preparing report on ground water of a portion of Waianae (Clark, 1930).
1930-33	T. F. Harris and H. T. Stearns, U.S. Geological Survey	Field investigations in preparing report on the geology and ground-water resources of Oahu (Stearns and Vaksvik, 1935).
1948-50	C. K. Wentworth, Honolulu Board of Water Supply and Dan A. Davis, U.S. Geological Survey	Field Investigations for Suburban Water Systems, City and County of Honolulu.
1949	D. C. Cox, Hawaiian Sugar Planters' Assn.	Unpublished report of Suburban Water Systems, City and County of Honolulu (Cox, 1949).
1967-68	K. J. Takasaki, U.S. Geological Survey	Field investigations in preparing ground-water report of Waianae District (Takasaki, 1971).
1977-78	J. F. Mink, consultant	Honolulu Board of Water Supply Waianae Study (Mink, 1978).

Attitude and Density of Dikes

The dikes usually trend in the same direction as the rift zones in which they occur. The trends normally are about N. 45° W. in the northwest rift; about S. 10° E. in the south rift; and about N. 25° E. in the northeast rift. In the caldera area where the rift zones intersect, the dikes likewise intersect in a criss-cross pattern (fig. 35).

The outer limits of the caldera occupy much of the main fissure zone in Makaha, Waianae, and Lualualei Valleys where dikes are mostly thin and few in number and not typical of dike outcrops in a deeply eroded dike complex. It is likely that subsidence has buried the mountain-building feeder dikes below the caldera-filling lavas that now crop out in these valleys. Hence, a dike complex that results from the deep erosion of the principal feeder dikes is not readily apparent in the Waianae Range.

The relation of the strike of the dikes to the dike frequency in the Waianae Range is shown in figure 36. Most of the dikes were mapped in the deeply eroded caldera area in the Makaha, Waianae, and Lualualei areas. The dikes thus mapped are mostly less than 2 feet thick.

Mink (1978), using the criterion of one or more 2-foot-thick dikes per 100 feet of country rock for identifying a dike complex, describes a dike complex of the northwest rift zone extending to about Puu Kolealiilii in upper Waianae and that of the south rift zone to near Puu o Hulu. Figure 37, after Mink, shows the distribution of dikes in the Kunesh tunnel and in some of the other tunnels in Waianae Valley. According to Mink (1978), it is possible that Kunesh tunnel penetrates the periphery of the main caldera in addition to a narrow dike complex.

Figure 35. Part of Waianae Range showing dikes, rift zones, and principal tunnels. (Illustration is oversized; attached at back of report.)

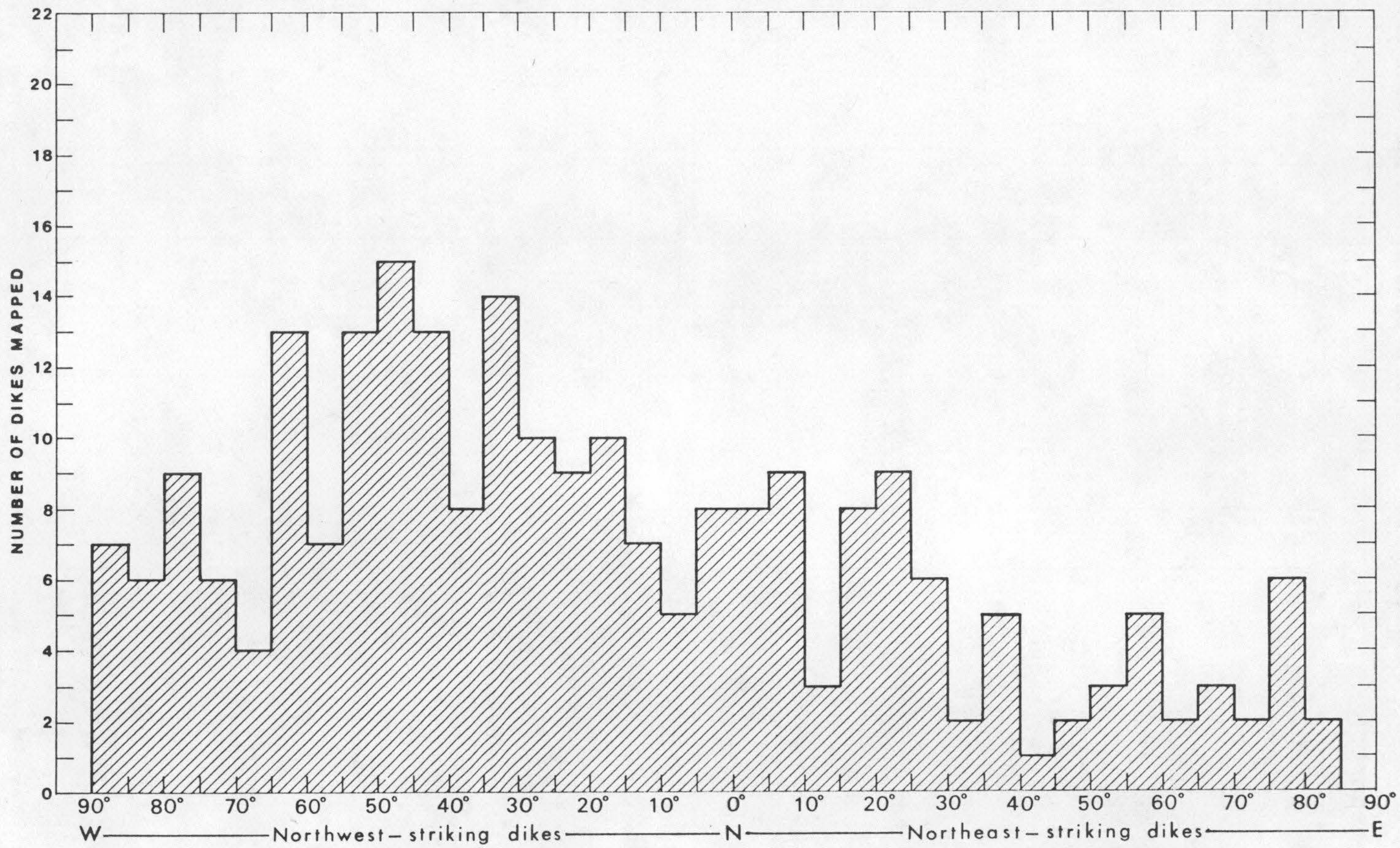


Figure 36. Relation of the strike of dikes to dike frequency in Waianae Range.

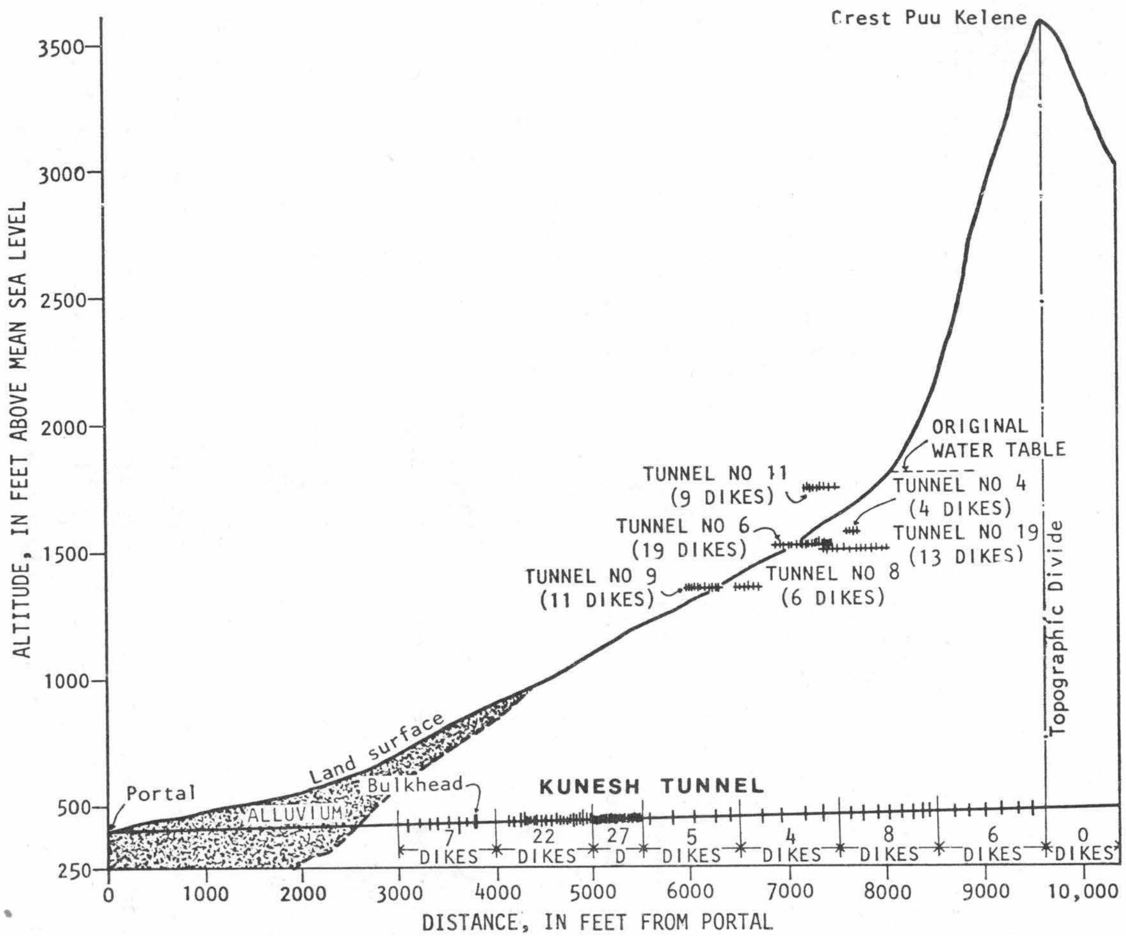


Figure 37. Distribution of dikes in the Kunesh tunnel and other upper Waianae tunnels. (Modified from Mink, 1978.)

DIKE-IMPOUNDED WATER IN THE WAIANAE RANGE

The Reservoir

Most of the reservoir underlies the northwest and south rift zones that make up the main fissure zone, about 4 miles wide, which lies in and occupies much of the area west or in the lee of the Waianae crest. The rest of the reservoir underlies the northeast rift, which is entirely in the windward area. The northeast rift is about 2 miles wide. The total area underlain by dike-intruded rocks is roughly 53 square miles, of which about 8 square miles comprises the northeast rift.

Although dike-impounded rocks underlie most of the leeward area, not all the rocks contain water of suitable quality for development. The geologic framework necessary to contain such a reservoir has been significantly reduced by erosion which has cut deeply into the range in Lualualei Valley and less deeply in Waianae and Makaha Valleys.

As a result of erosion, dike-impounded rocks above and to some distance below sea level have been replaced, in part, by deposition of permeable coralline material in the deeply eroded areas (fig. 34). The coralline deposits, because of their easy access to seawater, are nearly everywhere saturated with near-brackish to brackish water ranging in chloride concentration from 500 to more than 10,000 mg/L. Where brackish water overlies the dike-impounded reservoir, development is not feasible. The coralline deposits also act as sinks for abutting dike-impounded water bodies deep in valleys and have the effect of short-circuiting ground-water flow in the volcanic aquifer. Once short-circuited, the water becomes less fresh and, in most areas, much more available to the transpiring vegetation in the valley flats such as the phreatophyte kiawe (Prosopis chilensis), which is a close relative of the mesquite common to the southwestern part of the continental United States. The reservoir suitable for development is thus reduced by the above constraints by about 10 square miles and is further reduced in the coastal areas where dike-impounded bodies abut the sea.

The top of the dike-impounded reservoirs, west or in the lee of the crest, extends from an altitude of a few feet near the coast to more than 1,800 feet near the crest at Kaala. Although interconnected, these reservoirs show steep step-like gradients toward the valley floors, which cut deeply into the range and form the major sinks. The lack of homogeneity in the water-level gradient can be attributed to damming effects, due to changes in permeability caused by variations in dike density, dike trends, and brecciation.

The reservoirs on the windward side are probably at lower levels with more uniform water-level gradients, because of the sparseness of the above-mentioned damming effects. The movement of the dike-impounded water is difficult to determine with the data available. The streams windward of the crest apparently do not cut deeply enough to tap the dike-impounded reservoirs.

There is little water-level information east or windward of the crest except for test hole 3205-01 in Kaukonahua Gulch. Three tunnels, now abandoned, have been dug in the windward side; two in the northeast rift zone at altitudes of 1,040 feet near Schofield (North Schofield tunnel) and at 2,700 feet in the southeast slope of Kaala (Kaala tunnel), and one in the northwest rift at about 1,200 feet, 3 miles east of Kaena Point (Andrews tunnel). No dikes were reported pierced by these tunnels.

Mean annual rainfall of the reservoir area ranges generally from 25 to 80 inches and is about 40 inches on the leeward side and about 60 inches on the windward side. These means are equivalent to rainfall of 68 Mgal/d and 22 Mgal/d on the leeward and windward areas, respectively.

Mink (1978, p. 57) showed a similar rainfall on the leeward areas underlain by basalt and talus. The areas considered were nearly identical in both cases. Mink divided the rainfall input into two areas; where annual rainfall is greater than 40 inches and where it is less. The equivalent rainfall input thus computed was 38 and 30 Mgal/d, respectively, or a total of 68 Mgal/d for the leeward side.

Owing largely to evapotranspiration demand, which potentially exceeds the rainfall input and the surface and subsurface inflows, the input from areas receiving an annual rainfall of less than 40 inches will not be considered as contributing recharge to the area where domestic water supplies can be developed. Even though the recharge may be of some significance, the low-rainfall areas, mostly near the coast, generally abut the sea or coralline deposits saturated with brackish water, which makes development of domestic water supplies difficult. Large future developments of water are not likely to occur or be recommended in these areas, so including the rainfall therein as recharge to the potential developable supply would not be realistic.

The infiltration rates for the reservoir area have been estimated at 20 Mgal/d (Mink, 1978, p. 57) for the leeward side and 10 Mgal/d for the windward side or a total infiltration of 30 Mgal/d.

Owing to the position of the rift zones relative to the crest and the valleys that cut into them, the likelihood is that underflow from the windward side of the crest to the lee or vice versa is small and not significant. The dike-impounded water bodies on each side of the crest are then nearly distinct and independent relative to the hydrologic cycle. The movement of dike-impounded water leeward of the crest is discussed by Takasaki (1971).

Storage of dike-impounded water above sea level can only be very roughly estimated in the Waianae Range. Part of the uncertainty is caused by the steep step-like water gradient where even an estimate of the mean top of the storage water is highly conjectural on the leeward side. There is very little information on the windward side of the crest.

For the sake of comparison with the Koolau storage, an idea of the magnitude of the Waianae storage is given by using the following estimated parameters.

Parameter	Leeward	Windward
Area underlain by dike-impounded water (square mile) ----------------------------------	35	8
Mean top of stored water above sea level (feet) ----	300	400
Mean specific yield -------------------------------	.03	.05
Computed storage (billion gallons) ----------------	66	34
Total storage (leeward and windward) --------------	100 billion gallons	

This estimated storage of 100 billion gallons in the Waianae Range compares with an estimate of 550 billion gallons in the Koolau Range. Tunnels in the Waianae Range have, by breaching dike controls, reduced storage by about 5-1/2 billion gallons (Mink, 1978, p. 1-4). The reduction in the Koolau Range was estimated at about 50 billion gallons.

Development

The history of water development and a chronologic review of reports covering the development were given by Mink (1978). The first wells were drilled in lower Waianae Valley by the McCandless brothers in 1882-83. Since then, about 65 wells have been drilled or dug to tap the volcanic aquifer. The dates of the early tunneling are not available, but 26 tunnels, 15 in upper Waianae Valley and 11 in upper Makaha Valley, were already supplying water for the irrigation of sugarcane by 1930. The tunnels were probably dug before or around the turn of the century. Since 1930, tunnels were dug in Waianae Valley in 1933 and in 1948-50; one in Makaha Valley in 1947, and one in Lualualei Valley in two increments, 1934 and 1946. The records of the wells and tunnels were tabulated by Mink (1978).

All development of dike-impounded water has been on the leeward side. The low water level indicated by test hole 3205-01 in Kaukonahua Gulch probably stifled plans of the Waialua Sugar Co. to develop dike-impounded water at high levels.

Potential Development

Synopses of water-development proposals by past investigators and a follow-through of their disposition were given by Mink (1978) in tables covering the valleys of Nanakuli, Lualualei, Waianae, and Makaha. Mink concluded that every investigator has arrived at the same order of magnitude, 10 to 15 Mgal/d, for the feasible exploitable supply or roughly the undeveloped sustainable yield, of which only 2 to 4 Mgal/d could be obtained from any one locality.

A summary of Mink's principal recommendations, resulting from his Waianae Water Development Study, is abstracted from his report and given as follows:

1. Utilize Makaha shaft at a steady rate of 0.4 Mgal/d.
2. Complete the mid-Makaha well for an average output of 0.5 Mgal/d. (Completed and on stream.)
3. Complete the Kamaile well field for a sustainable yield of 0.5 Mgal/d. (Completed and on stream.)
4. Drill one exploratory-development well in upper Makaha Valley at an altitude of 1,000 feet and one in upper Waianae Valley at an altitude of 1,000 feet.
5. Upon successful completion of the exploratory wells, proceed to develop an average of 2 Mgal/d in upper Waianae Valley and an average of 4 Mgal/d in upper Makaha Valley.
6. Drill exploratory-development wells in mid-Waianae, upper Nanakuli, upper Keaau, and upper Makua Valleys, when circumstances are favorable.

The data shown in table 12 are taken from Mink (1978). In this table table the area designated as receiving an annual rainfall greater than 40 inches is synonymous with the area designated as upper Waianae and upper Makaha. Most of upper Lualualei falls in this category. Part of the area designated as upper Makua and westward and most of upper Nanakuli and upper Keaau receives an annual rainfall of less than 40 inches. This information is important in the interpretation of the table.

Table 12. Summary of hydrologic budgets and supplies available, used and unused in areas underlain by dike-intruded ground-water reservoirs (data from Mink, 1978)

	Areas where annual rainfall is greater than 40 inches						
	Nanakuli	Lualualei	Waianae	Makaha	Keaau	Makua and westward	Total
Area (mi^2) ---	0.1	4.7	3.8	3.7	0.2	3.0	15.5
Rainfall (Mgal/d) -----	0.2	10.6	10.0	10.0	0.5	7.2	38.5
Infiltration (Mgal/d) -----	0.1	5.3	5.4	5.4	0.3	3.8	20.3
	Upper Nanakuli[a/]	Upper Lualualei[b/]	Upper Waianae	Upper Makaha	Upper Keaau[a/]	Upper Makua and westward[b/]	
Supply available (Mgal/d) ----	0.5	2.4	4.9	4.7	0.5	1.5	14.5
Supply used --------	0	0.4	2.6	0.7	0	0	3.7
Supply unused ------	0.5	2.0	2.3	4.0	0.5	1.5	10.8
	Lower Nanakuli	Lower Lualualei	Lower Waianae	Lower Makaha	Lower Keaau	Lower Makua and westward	
Supply available (Mgal/d) ----	0	0	0.5	1.1	0	0.1	1.7
Supply used --------	0	0	0	0.6	0	0.1	0.7
Supply unused ------	0	0	0.5	0.5	0	0	1.0

[a/] Annual rainfall in most of upper valley is less than 40 inches.

[b/] Annual rainfall in part of upper valley is less than 40 inches.

Table 12 shows that most ground water is available for development in upper Makaha, followed by upper Waianae, upper Lualualei, and upper Makua and westward. The drilling of exploratory-development wells in all the above-mentioned areas in the order given or in the order dictated by other circumstances, such as proximity to utilization and hydraulics, would provide additional supplies. The areas most favorable, relative to the hydraulic conductivity of the rocks due to dike intrusions, were discussed by Mink (1978).

A favorable location for an exploratory-development well would be in the northeast rift in the upper part of Haleanau Gulch. The dike-impounded water in this rift zone discharges naturally to the northwest instead of to the Pearl Harbor area in central Oahu. Another favorable location is near but upgradient from test hole 3205-01 near Kaukonahua Gulch.

FLOW HYDRAULICS IN DIKE TUNNELS

By John F. Mink

Little consideration was given to the storage potential of dike compartments tapped and dewatered by water-development tunnels until W. O. Clark recommended that a bulkhead be placed in the Waikane No. 2 tunnel of the Waiahole system in 1934, about 40 years after high-altitude water-development tunnels were first constructed in Hawaii. The bulkhead in Waikane 2 held back some water in storage, but not in sufficient volume to be considered successful. Use of the bulkhead was discontinued, but other attempts at bulkheading were tried elsewhere, also without much success, until the construction of Waihee tunnel in 1955. The concept of inducing and controlling storage was resoundingly proved with the bulkheading of Waihee tunnel.

Good flow data had been collected during excavation of the Waiahole system tunnels, but, initially, little use was made of it to evaluate storage. The daily flow measurements taken at Waihee tunnel made it clear that free-flow decay from an initial maximum followed a smooth analytic curve. The recession for Waihee appeared to be exponential, and this was the model selected by the U.S. Geological Survey and the Honolulu Board of Water Supply in their investigations starting early in the 1960's. Before then, no documented attempts had been made to express flow characteristics of high-altitude dike tunnels within an analytic framework.

The U.S. Geological Survey (Hirashima, 1971) used a laminar-flow exponential model to describe storage depletion in dike tunnels of the Koolau Range of Oahu. The Honolulu Board of Water Supply (Mink, 1962) also used the exponential model while concentrating on developing quantitative algorithms for predicting the flow behavior of Waihee tunnel. Later Mink (1975, 1977, 1978) utilized this model to evaluate dike tunnels in the Kohala region of the island of Hawaii, in West Maui, and in the Waianae Range of Oahu.

The typical sequence of events during the excavation of a high-altitude tunnel in a rift zone starts with the removal of a zone of weathered rocks, either by tunnelling or trenching, followed by penetration of more coherent fresh basalt and dikes. The weathered section is usually dry whereas the first fresh dike-basalt association may yield a measurable flow of stored water. Generally, considerable penetration into the unweathered zone is the rule before significant volumes of storage water are released.

As tunnelling advances farther and farther through the pristine dikes and basalts, flow increases, often in instantaneous jumps when key restraining dikes are punctured, until either a single dike, as in Waihee tunnel, or a series of them, as in the development tunnels of the Waiahole system, release such a large volume of stored water that excavation must be halted, most often not to resume again, if ever, until a much later time after storage has been depleted.

When the pressure of the stored water is high, the water gushes from the permeability features of the basalt as from orifices, while later, when the pressure has decreased, it oozes and trickles from the fissures, cracks, lava tubes, and clinker voids. Driven by a high pressure gradient, the flow regime is likely to be turbulent; the more gentle seepage reflects laminar flow. In most productive tunnels showing great initial storage, free flow from the rock into the tunnel at the beginning probably is turbulent, even though the aquifer flow is laminar at some distance from the tunnel face. Transition to the laminar regime at the tunnel face follows some time later, although in some cases laminar flow may dominate from the very start. The Kahana tunnel of the Waiahole system is the best example on record of the occurrence of the two flow regimes in sequence. The Waihee tunnel, on the other hand, may have exhibited laminar flow from the moment the great restraining dike was punctured.

Field evidence suggests that laminar flow accounts for much, if not all, of the period of storage recession, and in the literature describing Hawaiian high-altitude tunnels, the empirical formula of exponential decay of free flow with time, implicit to laminar flow, is used without either equivocation or consideration of other models. Nevertheless, based upon available flow decay data, this formula has proven to be the most reasonable choice.

The governing equation (in one dimension) of laminar flow in porous media without recharge is:

$$\frac{\partial\, kh \frac{\partial h}{x}}{\partial x} = S \frac{\partial h}{\partial t}, \qquad (1)$$

in which k is hydraulic conductivity, h is head, t is time, x is the coordinate parallel to the flow direction, and S is storage coefficient. The above equation can be expanded to three dimensions by treating the y and z coordinates in the same fashion as the x coordinate. Equation (1) is nonlinear and not analytically solvable. However, if k is constant and the change in head is kept small relative to the effective depth of flow, and allowing the transmissivity T = kh to be treated as if constant, the equation is linearized to:

$$\frac{\partial^2 h}{\partial x^2} = \frac{S}{T} \frac{\partial h}{\partial t}, \qquad (2)$$

a parabolic partial differential equation that can be solved analytically by separation of variables.

Let us assume that linearization is applicable to high-altitude dike-compartment tunnels. It may be reasoned that the effective depth of flow in a compartment (or a series of compartments) is much greater than the head above the free-flow point, as suggested in figure 38, and, therefore, that T = k (h + H), where H is depth of flow below the tunnel invert, is unvarying. Writing equation (2) as:

$$\frac{\partial^2 h}{\partial x^2} = \frac{1}{D} \frac{\partial h}{\partial t}, \qquad (3)$$

in which $D = \frac{T}{S}$, is the diffusivity, and solving by separation of variables, the following solution is obtained:

$$h = (A \cos px + B \sin px) \exp^{(-p^2 t)D}, \qquad (4)$$

in which p, A and B are constants. If we are not concerned with the distribution of head along the x axis but are interested only with how head decays at a fixed location, then the above equation may be stated simply as,

$$h = C \exp(-bt), \tag{5}$$

where C and $b = p^2D$ are constants. For the initial condition, $h\ (t = o) = h_o$, the constant C is equal to h_o, and:

$$h = h_o \exp(-bt), \tag{6}$$

which is the exponential decay equation of head during laminar free flow.

In equation (6), b is called the recession or decay constant and incorporates the diffusivity along with a distance parameter. According to Schoeller (1962),

$$b = \frac{\pi^2 T}{4L^2 S},$$

in which the length parameter, L, is the distance to the boundary of the ground-water regime.

Equation (6) can be transformed into a relationship between total free flow, Q, and time. From the initial condition $Q\ (t = o) = Q_o$,

$$Q = Q_o \exp(-bt), \tag{7}$$

which is the die-away equation of free flow with time commonly employed in evaluating characteristics of flow in Hawaiian high-altitude tunnels. Equation (7) does not incorporate a recharge (also called base flow) component, a feature of every tunnel. This constant recharge component, which is the same as baseflow as used in Hawaiian hydrologic terminology, is the average recharge that finds its way into the tunnel bore. It may be expanded to include a constant base flow, Q_R, by rewriting it as,

$$(Q - Q_R) = (Q_o - Q_R) \exp(-at). \tag{8}$$

The recession constant, a, in this equation is not numerically equal to b in equation (7).

Equations (7) and (8) were first derived nearly a century ago by Boussinesq (Schoeller, H., 1962) and have been widely used since then to describe flow characteristics of springs emanating from limestones and other fissured rocks (Schoeller, H., 1962 and 1965; Castany, G., 1967) and to quantify base-flow recession curves of streams (Hall, F. R., 1968). Boussinesq, according to Schoeller (1962), also derived a decay expression by solving the nonlinearized laminar flow equation, equation (1), for the case where h > H (fig. 38), which, for the extreme case, is equivalent to assuming an impermeable lower boundary with the discharge point on that boundary. This Boussinesq equation for the case of no recharge is:

$$Q = \frac{Q_o}{(1 + C_1 t)^2}, \tag{9}$$

and for constant recharge it is:

$$(Q - Q_R) = \frac{Q_o - Q_R}{(1 + C_2 t)^2}, \tag{10}$$

in which C_1, C_2 are constants. Later, it will be shown that these equations do not fit the free-flow data for Hawaiian tunnels, whereas equations (7) and (8) provide excellent fits for the decay interval following the initial period of turbulent flow.

Many other derivations of free-flow decay equations are given in the hydrological literature. In Polubarinova-Kochina (1962) the decrease of head for a freely declining water table is given as:

$$h = h_o \left\{ \operatorname{erf} \left[\frac{X}{2 \left(\frac{k h_o t}{n} \right)^{1/2}} \right] \right\}^{1/2}, \tag{11}$$

in which n is porosity. Interesting derivations of equation (7) were made by Youngs (1960) and later by Youngs and Aggelides (1976). In his 1960 paper, Youngs treated drainage of liquids from porous media by equating the media to bundles of capillary tubes. In the 1976 paper, he and Aggelides employed the Green-Ampt approach. In both instances the derived equations can be reduced to exactly the same form as equation (7).

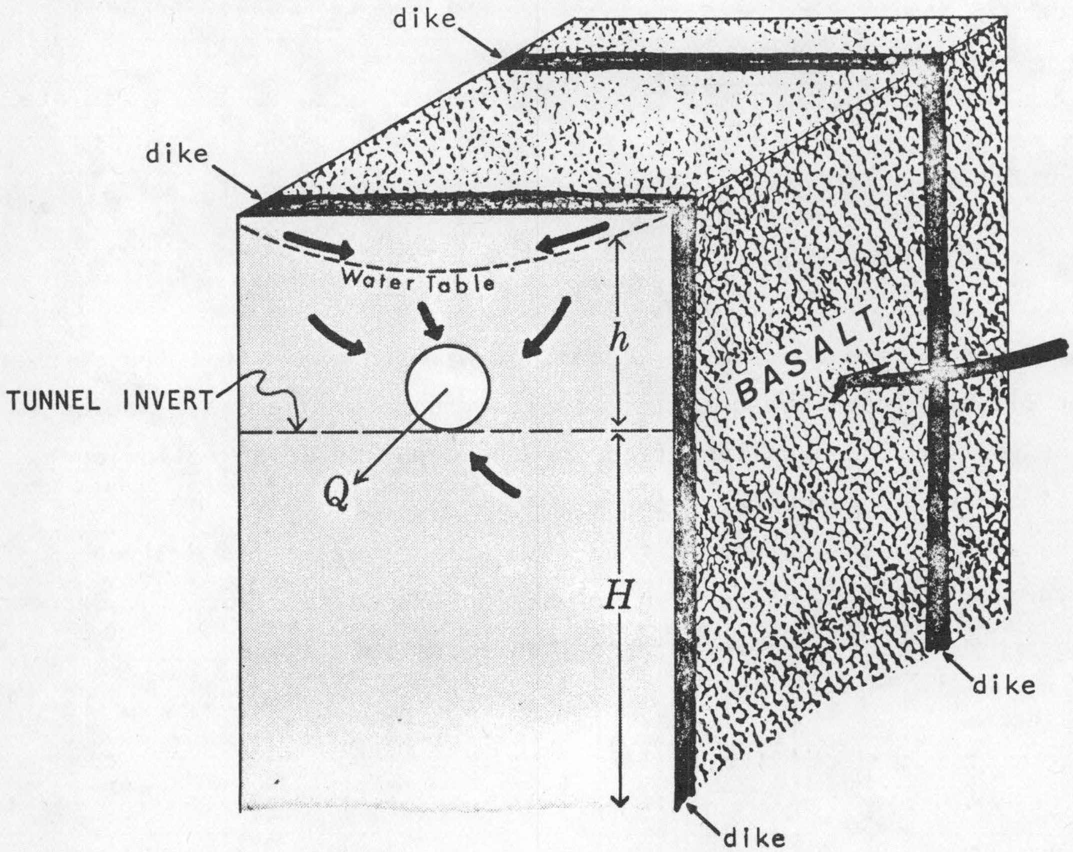


Figure 38. Idealized sketch of flow to dike-impounded high-head tunnel.

Turbulent Flow

If pressure behind a restraining dike is high and the stored water forces its way through a limited array of voids and cracks, the free discharge in the vicinity of the tunnel is likely to be governed by turbulent flow laws. Because the flow converges toward the tunnel, the velocities through the orifices are much greater than the velocities distant from the tunnel. Hence, Reynolds' numbers are much higher in the immediate vicinity of the tunnel than at a distance. Hence, turbulent flow is wholly restricted to the vicinity of the tunnel, as is the applicability of equation (26), which follows later. Discharge into the tunnel bore through voids and cracks in the basalt is analogous to flow through orifices, the basic equation for which is:

$$Q_v = C\ (\Delta h)^{1/2}, \tag{12}$$

wherein the subscript v refers to storage, C is a constant that includes the area of the orifice and Δh is the difference between the storage head and the head against which flow moves. If discharge is to the open atmosphere, equation (12) is written as:

$$Q_v = Ch^{1/2}, \tag{13}$$

in which h is storage head.

Equation (13) is converted to the nonsteady form by relating the change in storage, dV_v, to flow from storage over an elemental increment of time,

$$dV_v = -mdh = Q_v dt, \tag{14}$$

in which m is treated as a constant that represents the cross-sectional area of the dike aquifer. Substituting for Q_v,

$$Ch^{1/2}\ dt = -mdh, \tag{15}$$

which, on integration with $t_o = 0$, gives,

$$h^{1/2} = h_o^{1/2} - \frac{C}{2m}\ t. \tag{16}$$

The constants C and m may be replaced with their system values by employing initial conditions as follows:

$$Q_{vo} = Ch_o^{1/2} \tag{17}$$

$$C = Q_{vo}/h_o^{1/2} \tag{18}$$

$$V_{vo} = mh_o \tag{19}$$

$$m = \frac{V_{vo}}{h_o} . \tag{20}$$

Equation (16) now becomes,

$$h = h_o \left(1 - \frac{Q_{vo} t}{2V_{vo}}\right)^2 \tag{21}$$

Also, from equations (13) and (18),

$$Q_v = Q_{vo} \left[\frac{h}{h_o} \right]^{1/2} , \tag{22}$$

and by substituting for h, flow as a function of time is obtained as,

$$Q_v = Q_{vo} \left(1 - \frac{Q_{vo} t}{2V_{vo}}\right) \tag{23}$$

therefore,

$$V_{vo} = \frac{Q_{vo}^2 t}{2(Q_{vo} - Q_v)} .$$

Thus, for orifice flow head decays parabolically with time, while discharge decays linearly. It will be recalled that for free discharge under laminar flow conditions both the head and discharge decay exponentially with time.

Equation (23) may be altered to incorporate constant base flow by using the identities,

$$Q_v = Q - Q_R \tag{24}$$

$$Q_{vo} = Q_o - Q_R \tag{25},$$

for which Q is total flow, Q_v is flow from storage and Q_R is the constant base flow. In terms of measured or total flow, equation (23) becomes:

$$Q = Q_o - \frac{(Q_o - Q_R)^2 t}{2V_{vo}} , \tag{26}$$

or,

$$V_{vo} = \frac{(Q_o - Q_R)^2 t}{2(Q_o - Q)} ,$$

and equation (21) becomes:

$$h = h_o \left(1 - \frac{(Q_o - Q_R)t}{2V_{vo}}\right)^2 . \tag{27}$$

During and following the construction of tunnels, the most easily measured variable is total flow, and because every tunnel has a base-flow component, the most readily usable nonsteady relationships are equation (8), describing free laminar flow with recharge, and equation (26), describing orifice flow with recharge. Few data on heads during free flow have been recorded.

The initial interval of turbulent flow is easily discriminated from the laminar flow decay period by the nature of the $Q = f(t)$ plot, which is exponential for laminar and linear for orifice flow. The exponential decay phenomenon occurs only during the period of dewatering following tunnel construction; once a bulkhead and receiving pipe are emplaced in the tunnel, the orifice equations apply until the laminar flux is less than the flow that could be removed by the full pipe. However, it is from the laminar free-flow equations obtained before a bulkhead and pipe is emplaced that important information about the volume of stored water can be deduced.

Determination of Volume of Storage

Change in storage volume with time for laminar free flow having a base-flow component is expressed differentially as:

$$-dV_v = (Q - Q_R)\ dt = (Q_o - Q_R)\ \exp(-at)\ dt, \tag{28}$$

which, for prescribed limits, form the integrals,

$$-\int_{V_o}^{V_v} dV_v = (Q - Q_R) \int_{t_o}^{t} \exp(-at)\ dt. \tag{29}$$

For $t_o = 0$, V_{vo} = initial storage,

$$V_{vo} - V_v = \frac{Q_o - Q_R}{a}\,[1 - \exp(-at)], \tag{30}$$

and by the substitution $\dfrac{Q - Q_R}{Q_o - Q_R} = \exp(-at)$,

$$V_{vo} - V_v = \frac{Q_o - Q}{a}\ , \tag{31}$$

which is loss in storage for the interval between initial total flow and measured total flow sometime later.

By allowing t to go to infinity in equation (30), at which time the remaining available volume V_v would be zero, the total available initial volume in storage is given by:

$$V_{vo} = \frac{Q_o - Q_R}{a}\ , \tag{32}$$

a useful relationship, indeed.

During free-flow decay the total outflow volume, V, rather than storage volume, V_v, is measured. The relationship between changes in total and storage volumes is:

$$V = (V_{vo} - V_v) + V_R\ , \tag{33}$$

where $V_R = Q_R t$, the volume outflow due to constant recharge over the given time interval.

The total initial volume in storage is neatly obtained by equation (32) for free laminar flow conditions when easily obtained items of data are known. Q_o is generally recorded, or can be closely estimated from subsequent flow values; Q can be measured at anytime, t, after initiation of the interval of decay; and the recession constant, a, may be obtained graphically. Manipulation of the orifice equations does not yield a simple storage-volume expression like equation (32) that is free of the time variable. The orifice volume equation, without recharge, analogous to equation (31) is:

$$V_{vo} = \frac{Q_{vo}^{2} t}{2(Q_{vo} - Q_v)} , \qquad (34)$$

which is an alternative form of equation (23).
For constant recharge, the volume equation is:

$$V_{vo} = \frac{(Q_o - Q_R)^2 t}{2(Q_o - Q)} , \qquad (35)$$

which is identical to equation (26).

Applications of the Free-Flow Equations in Hawaii

The chief advantage of employing the laminar free-flow equation is to obtain a good estimate of the volume of water initially held in storage. The parameter in the equation may be ascertained graphically or computed from the flow-time record. The form of the equation used by Hirashima (1971; also given in Takasaki, et al, 1969) is identical to equation (7), in which the base-flow component is ignored,

$$Q = Q_o \exp(-bt) . \qquad (7)$$

This equation does not yield correct values of changes in storage volume. The proper relationship is that of equation (8),

$$(Q - Q_R) = (Q_o - Q_R) \exp(-at) . \qquad (8)$$

The use of equation (7) rather than (8) leads to smaller storage volumes.

The recession constants a and b have different values but can be related to each other. Ordinarily when controlling storage dikes are breached and free-flow decays from a maximum, the base-flow component is not known so that total flow, Q, is plotted against time to extract the value for b. Upon ascertaining base flow following nearly complete loss of storage, the recession constant, a, is obtained from equations (7) and (8) by the transformation,

$$a = b \frac{\ln\left\{\dfrac{Q_o - Q_R}{Q - Q_R}\right\}}{\ln\left\{\dfrac{Q_o}{Q}\right\}} \; . \tag{36}$$

The correct initial available volume of storage is given by equation (32),

$$V_{vo} = \frac{Q_o - Q_R}{a} \tag{32}$$

rather than by,

$$V_{vo} = \frac{Q_o}{b} \; , \tag{37}$$

which would be the case if the governing decay equation was taken as equation (7).

To compute storage loss, Hirashima (1971) utilized equation (37) with a base-flow term subtracted from it as follows:

$$V_{vo} - V_v = \frac{Q_o}{b} - Q_R t \; . \tag{38}$$

The proper way of obtaining storage loss is actually by equation (31),

$$V_{vo} - V_v = \frac{Q_o - Q}{a} \; . \tag{31}$$

Flow Decay and Storage at Waihee and Kahana Tunnels

The finest examples of free-flow phenomena of dike-impounded high-altitude water are shown by the Waihee and Kahana tunnels in the Koolau rift zone of windward Oahu. The data base for both tunnels is excellent. For Kahana tunnel, a record of average monthly flows from the maximum initial flow following cessation of construction is available, and for Waihee, daily measurements during the decay interval were recorded. Figure 39 is the flow decay plot for Waihee, and figure 40 is the same for Kahana.

In the Waihee tunnel storage was released upon penetrating a single 12-foot-thick dike and excavating 18 feet beyond. Actually the dike was breached and bulkheaded at two locations, one in the main tunnel and the other in a branch 137 feet long, deviating 45 degrees from the main bore. Upon penetrating the massive dike, water gushed out under considerable pressure, suggesting that orifice-type flow may have dominated in the early decay period. Hirashima (1971) correlated the logarithms of daily free flow against time and concluded that the exponential decay equation was appropriate. He analyzed the period from April 23 through May 26, 1955, a total of 34 days, but did not include the statistical parameters of the correlation in his report. Recalculating for the same data set gives a correlation coefficient of 0.983. On the other hand, for the same period the orifice (turbulent) flow regression yields a correlation coefficient of 0.975, suggesting that the flow behavior for this period of time could have fit either model. With the passage of time, however, decay would tend to follow the exponential model, and it is, therefore, reasonable to apply this relationship for the whole period of decay and for determining volumes of storage.

A correlation test for the same time interval utilizing equation (9) from Boussinesq,

$$Q = \frac{Q_o}{(1 + Ct)^2} \quad , \tag{9}$$

gives an extremely poor correlation coefficient, $r = 0.400$. Evidently this model is not applicable to Waihee nor, as will be shown later, to the Kahana tunnel.

For the 34-day period of decay, Hirashima (1971) computed the Waihee free-flow equation to be

$$Q = 15.7 \exp(-.00401t) \quad , \tag{39}$$

with Q in million gallons per day (Mgal/d) and t in days. This expression does not take into account base flow, which he estimated at 4.0 Mgal/d. Properly expressed as storage free flow, the relationship should be

$$(Q - 4.0) = (15.7 - 4.0) \exp(-.00552t) \quad . \tag{43}$$

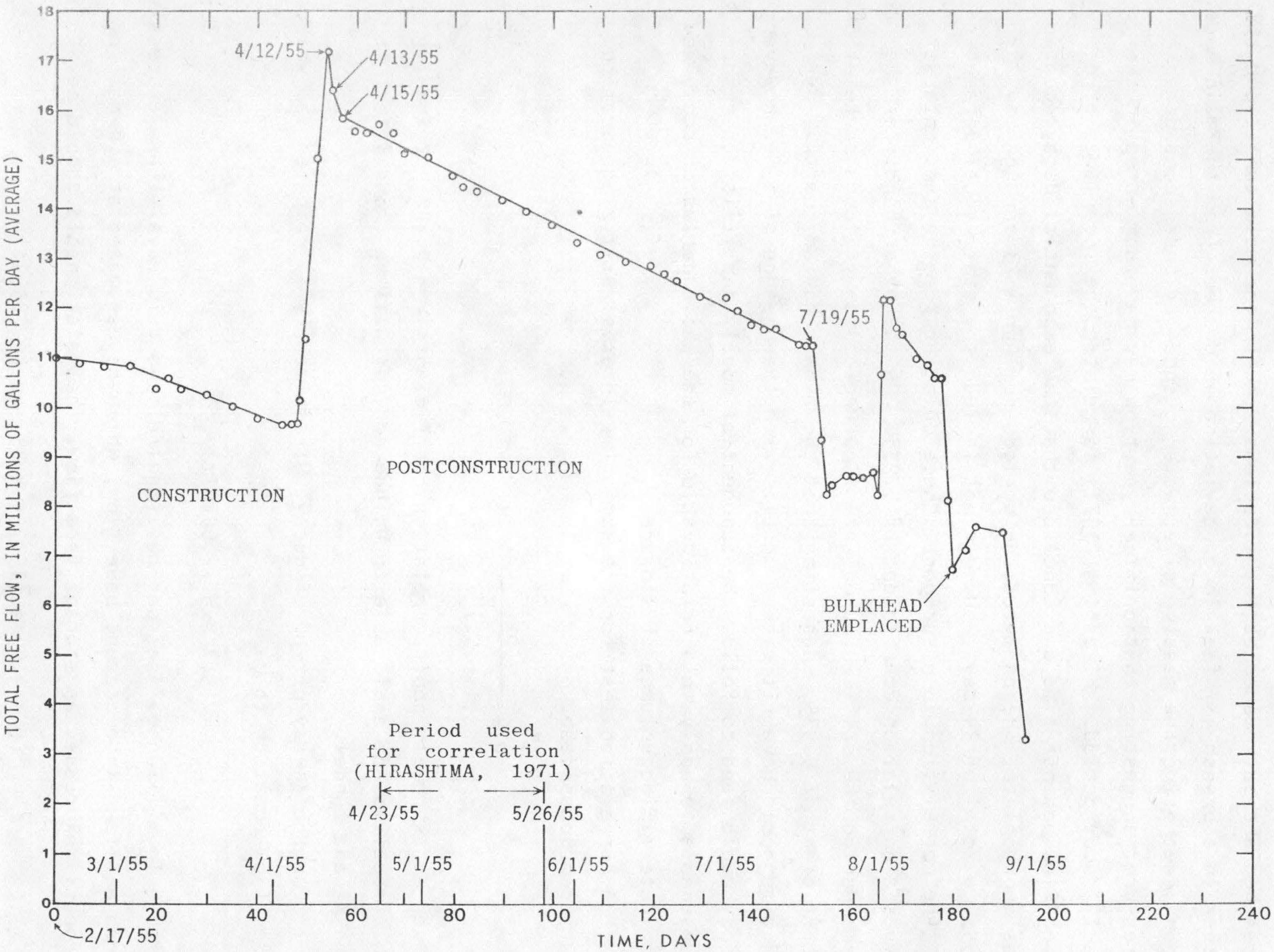


Figure 39. Waihee tunnel free-flow decay.

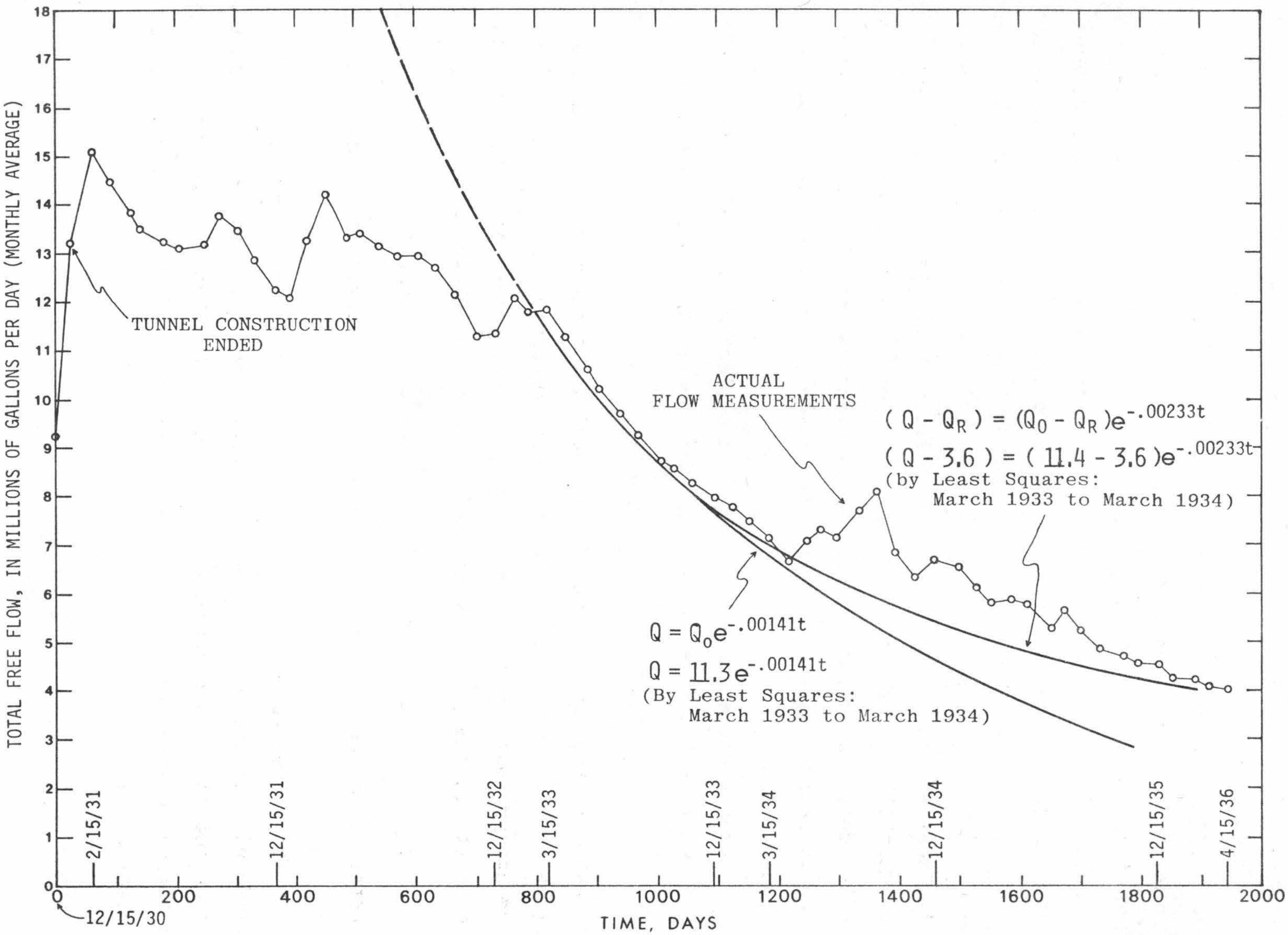


Figure 40. Kahana tunnel free-flow decay.

Figure 40, showing free-flow decay at Kahana tunnel from its maximum upon cessation of tunneling, illustrates both turbulent and laminar free-flow decay phenomena. Evidently for the period February 1931 through March 1933, the pressure gradient relative to available permeability features in the tunnel was too high for laminar flow to prevail so that turbulent flow dominated. During this period the change in flow can be interpreted to be following a linear decay. The deviations from a straight line, which is required by $Q = f(t)$ for orifice flow, were probably attributable to variations in recharge. Exponential free-flow decay became established about 2 years after tunnel completion and persisted until base flow was reached another 3-1/2 years later. For the interval, March 1933 to March 1934, a relatively dry year, exponential decay was only minimally affected by variations in recharge. Beyond March 1934, wet weather evidently enhanced base flow, but, nevertheless, the trend of decay was still exponential.

Least squares correlation for the period March 1933 to March 1934 of total free-flow yields the equation (correlation coefficient $r = 0.990$),

$$Q = 11.3 \exp(-.00141t), \tag{41}$$

in which the decay constant, fortuitously, is nearly the same as that given by Hirashima (1971), derived for the period January-March 1959. The proper form of the equation, which incorporates base flow, as obtained by least squares (correlation coefficient $r = 0.994$) is:

$$(Q - 3.6) = (11.4 - 3.6) \exp(-.00233t), \tag{42}$$

where 3.6 is the long-term average base flow. Both equations are plotted on figure 40.

As in the case of Waihee tunnel, regression of free flow against time using the second Boussinesq relationship, equation (9), is relatively poor (correlation coefficient $r = 0.660$). Manifestly, exponential decay better expresses free laminar flow in Hawaiian dike tunnels than does equation (9).

The validity of equation (42) can be shown by comparing the measured volume of released storage with that computed from the equation. For the period employed in the correlation, the actual measured outflow from the tunnel was 3,642 Mgal, of which 2,216 Mgal came from storage, assuming a base flow of 3.6 Mgal/d over the 396-day interval. Utilizing equation (31) with numerical values substituted, the storage outflow volume for this period is computed as,

$$V_{vo} - V_v = \frac{11.4 - 6.7}{.00233} = 2{,}017 \text{ Mgal}, \tag{43}$$

only 199 Mgal (9 percent) less than the measured storage loss volume.

For the entire period of monotonic flow decay commencing February 1931 (see fig. 40) and continuing until April 1936 when base flow became established, the total measured outflow volume was 17,998 Mgal, of which an estimated 10,265 Mgal drained from storage. The theoretical initial flow at the start of the monotonic decay period, assuming that laminar flow prevailed throughout the decay period, would have been,

$$Q_o = aV_{vo} + Q_R = (.00233)\ (10{,}265) + 3.6 = 27.5 \text{ Mgal/d}. \tag{44}$$

The actual maximum initial flow at the end of construction was only 15.2 Mgal/d because the outflow face of the tunnel could not accommodate higher flows. Orifice flow predominated until head decreased to a level where the laminar free-flow regime prevailed.

Summary

Free storage flow from tunnels driven in dike compartments of rift zones in Hawaii are adequately describable for practical engineering purposes by orifice (turbulent-flow) and Darcy (laminar-flow) relationships. The applicable equations depend upon the height of the water table in the dike compartments and the discharge capabilities of the tunnel-outflow faces. At high heads and limited-outflow capability, free flow initially reflects the orifice law, but eventually laminar flow prevails. Undoubtedly, complex flow phenomena exist during transition from the turbulent to the laminar states. In some cases laminar flow occurs from the very start of monotonic decay.

Once a tunnel is bulkheaded in order to conserve and control storage, free-flow laws no longer directly apply to the functional relationships among flow, head, and time. Outflow characteristics depend significantly on pipe size and pipe configuration in the tunnel cavity behind the bulkhead. Heads measured in the exit pipe during flow are not true representations of head in the aquifer; however, aquifer head can be determined by applying correction for pipe entrance and flow losses. To correctly monitor aquifer behavior, it would be best to place a measuring device directly through the restraining dike or bulkhead into the aquifer.

The hydraulic-flow laws governing discharge at the bulkhead for a completed tunnel depend on how much of the available flow the exit structure (e.g., pipe) could handle. If the laminar flux of the aquifer exceeds the pipe capacity, then turbulent-flow laws are applicable. If it is less than what can be discharged at the bulkhead, the laminar laws describe the decay phenomena. For laminar flow, both head and discharge decay exponentially; for turbulent flow, head decays parabolically and discharge decays linearly.

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