(200)
R290
no. 81-1119

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

✓ tu aral

U.S. GEOLOGICAL SURVEY
RESTON VA.
MAR 30 1982
LIBRARY

Prepared in cooperation with the

BOARD OF WATER SUPPLY

CITY AND COUNTY OF HONOLULU

Honolulu, Hawaii

USGS LIBRARY-RESTON
3 1818 00072129 8

UNITED STATES

DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

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

By Kiyoshi J. Takasaki

With a Section on

FLOW HYDRAULICS IN DIKE TUNNELS IN HAWAII

By John F. Mink, Consulting Hydrologist

Open-File Report 81-1119

Prepared in cooperation with the
BOARD OF WATER SUPPLY
CITY AND COUNTY OF HONOLULU
Honolulu, Hawaii

December 1981

Open-file report
(Geological Survey (U.S.))

332466

CONTENTS

Page

Conversion table ---------- xi

Abstract ---------- 1

Introduction ---------- 3

  Purpose and scope ---------- 3

  Evolution of the concept for the development of dike-impounded water ---------- 4

Geologic sketch ---------- 9

  Volcanic activity ---------- 9

  Rift-zone structures ---------- 9

    Marginal dike zone defined ---------- 13

    Attitude of dikes ---------- 13

Dikes and their effect on storage and movement of ground water ---------- 15

  Geologic framework of dike-impounded reservoirs ---------- 15

  Factors controlling recharge and discharge of dike-impounded water ---------- 19

Dikes in the Koolau Range ---------- 23

  Rift zones ---------- 23

  Data base ---------- 25

  Attitude and density of dikes ---------- 26

    Strike or trend ---------- 26

    Dip ---------- 26

    Thickness ---------- 30

    Density ---------- 30

Dike-impounded water in the Koolau Range ---------- 32

  The reservoir ---------- 32

  Development ---------- 38

CONTENTS--Continued

Page

Dike-impounded water in the Koolau Range--Continued

Dike-impounded water in selected subzones ---------------------- 38
    The northern end subzone -- 41
        Dikes -- 41
        Dike-impounded reservoirs ------------------------------------ 41
        Past and potential development ------------------------------ 48
    Waiahole-Kaluanui subzone ------------------------------------- 51
        Dikes -- 51
        Dike-impounded reservoirs ------------------------------------ 58
        Past and potential development ------------------------------ 66
    Kaneohe subzone --- 70
        Dikes -- 70
        Dike-impounded reservoirs ------------------------------------ 72
        Past and potential development ------------------------------ 78
    The southeastern end subzone --------------------------------- 81
        Dikes -- 84
        Dike-impounded reservoirs ------------------------------------ 85
        Past and potential development ------------------------------ 91
            Maunawili Valley -- 91
            Waimanalo area --- 94
            Leeward area -- 97
    Summary of dike-impounded water in the subzones ------------- 101
Dikes in the Waianae Range -- 103
    Rift zones -- 103
    Data base --- 105
    Attitude and density of dikes ---------------------------------- 106

CONTENTS--Continued

Page

Dike-impounded water in the Waianae Range ---------------------- 110
  The reservoir -- 110
  Development --- 113
  Potential development --- 114
Flow hydraulics in dike tunnels by John F. Mink ------------------ 117
  Turbulent flow -- 123
  Determination of volume of storage ------------------------------ 126
  Applications of the free-flow equations in Hawaii --------------- 127
  Flow decay and storage at Waihee and Kahana tunnels ------------- 128
  Summary --- 134
References --- 135

ILLUSTRATIONS

Figure Page

1. Map of the island of Oahu, showing rift zones and calderas of Koolau and Waianae volcanoes --------------- 10
2. Map of the island of Oahu, showing the relation of strong positive gravity anomalies to the calderas of Koolau and Waianae volcanoes -------------- 12
3. Sketch showing relation of strike and dip of a dike -- 14
4. Block diagrams showing 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 -- 16
5. Sections showing ideal and poorest conditions for recharge in the rift zone ----------------------------- 20
6. Map of island of Oahu, showing dikes, dike-intruded rocks, ground-water bodies, and subzones -------------- 24
7. Graphs showing the relation of the strike of dikes to dike frequency in selected areas generally windward (east) of the Koolau crest ------------------- 27
8. Graphs showing the relation of the strike of dikes to dike frequency in selected areas generally leeward (west) of the Koolau crest -------------------- 28
9. Profile of water level of dike-impounded ground water extending from Kahana to Waimanalo -------------- 33
10. Graph showing storage of dike-impounded water as a function of water-table altitude and specific yield of the reservoir rocks ------------------------- 35

ILLUSTRATIONS--Continued

Figure Page

11. Hydrograph showing base-flow discharge of Waihee Stream and water levels of the Kahana well, Schofield shaft, and well 2153-02 ---------------------- 37
12. Map of the northern end subzone, showing dikes, rift zone, and location of wells and gaging stations -------- 42
13. Duration curves of daily flows for windward stream, Malaekahana, (sta. 3089.9) and leeward streams, Kamananui (sta. 3250), and Opaeula (sta. 3450) --------- 44
14. Graph showing the relation between pumping rate and drawdown in tests of Opana and Waialee wells ----------- 52
15. Map of Waiahole-Kaluanui subzone showing dikes, dike-intruded rocks in dike complex and marginal dike zone, and location of tunnels, wells, and gaging stations -- 53
16. Logs showing position and orientation of the dikes and flow measurements in the Waiahole main bore, Waikane tunnel 1, and Waikane tunnel 2 ------------------------- 56
17. Logs showing position and orientation of the dikes and flow measurements in the Uwau and Kahana tunnels --- 57
18. Duration curves of daily flows for windward stream, Kahana (sta. 2965) and leeward stream, North Fork Kaukonahua (sta. 2000) --------------------------------- 67
19. Relative altitudes of base-flow measuring points in streams in Waiahole and Hakipuu areas ------------------ 69
20. Map of Kaneohe subzone, showing dikes, dike-intruded rocks in dike complex and marginal dike zone, and location of tunnels, wells, and gaging stations ------- 71

Figure Page

21. Sketch showing directions of ground-water movement between parallel dikes above an altitude of 600 feet in the area between Luluku and Kaalaea Streams --- 74
22. Duration curves of daily flows for windward stream, Kamooalii (sta. 2739) and leeward stream, North Halawa (sta. 2260) ------------------------------------ 75
23. Section showing zones of discharge in Kaneohe subzone ---- 77
24. Graph relating pumping rate versus drawdown for selected wells in the marginal dike zone and the dike complex -- 82
25. Map of the southeastern end subzone, showing dikes, dike-intruded rocks in dike complex, marginal dike zone, minor rift zone and location of tunnels, wells, and gaging stations --------------------------- 83
26. Map of Palolo-Waialae District, showing frequency and distribution of dikes and sills ---------------------- 86
27. Hydrograph showing water levels in test holes 2046-01,-02, and 2047-02 ----------------------------- 87
28. Hydrograph showing water levels during drilling of test hole 2047-02 ------------------------------------- 88
29. Section showing possible water-level gradient across the Koolau crest from Manoa tunnel No. 3 to Clark tunnel -- 90
30. Relative altitudes of water levels in wells, water-level gradient of dike-impounded water, tunnels, and base-flow measuring points in streams in Maunawili Valley ---------------------------- 93
31. Relative altitudes of water-level gradient of dike-impounded water, tunnels, and base-flow measuring points in streams in the Waimanalo area ------ 96

ILLUSTRATIONS--Continued

Figure | Page

32. Duration curves of daily flows at Waiakeakua (sta. 2405) and Waihi (sta. 2385) Streams -------------- 98
33. Duration curves of daily flows of Waiakeakua Stream (sta. 2405) before and after tunnel construction ------- 100
34. Geologic map of Waianae Range ---------------------------- 104
35. Map of part of Waianae Range, showing dikes, rift zones, and principal tunnels -------------------------- 107
36. Graph showing the relation of the strike of dikes to dike frequency in Waianae Range -------------------- 108
37. Section showing the distribution of dikes in the Kunesh tunnel and other upper Waianae tunnels ---------- 109
38. Idealized sketch of flow to dike-impounded high-head tunnel -- 122
39. Graph showing Waihee tunnel free-flow decay --------------- 130
40. Graph showing Kahana tunnel free-flow decay --------------- 131

TABLES

Table Page

1. Specific capacities and specific capacities per foot of aquifer penetration for wells tapping dike-impounded aquifers in the Koolau Range ----------- 18
2. Dips of dikes mapped in Koolau Range --------------------- 29
3. Thickness and distribution of dikes mapped in Koolau Range -- 31
4. Chronologic record of tunneling to develop dike-impounded ground water in the Koolau Range ------------ 39
5. Selected drilled wells tapping dike-impounded ground water in the Koolau Range ---------------------- 40
6. Pumping test, Opana well 4100-03 ------------------------ 49
7. Pumping test, Waialee well 4104-11 ----------------------- 50
8. Dikes in the Waiahole tunnel system --------------------- 55
9. Volume of storage depleted in tunnels at the Waiahole tunnel system -------------------------------- 60
10. Statistics of Waiahole tunnel system base flows ---------- 63
11. Summary of discharges from dike-impounded reservoirs in the subzones --------------------------- 102
12. Summary of hydrologic budgets and supplies available, used and unused, in areas underlain by dike-intruded ground-water reservoirs ------------- 115

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.

---

[1] Hydrologist, U.S. Geological Survey.

[2] Consulting hydrologist, Honolulu, Hawaii.

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).

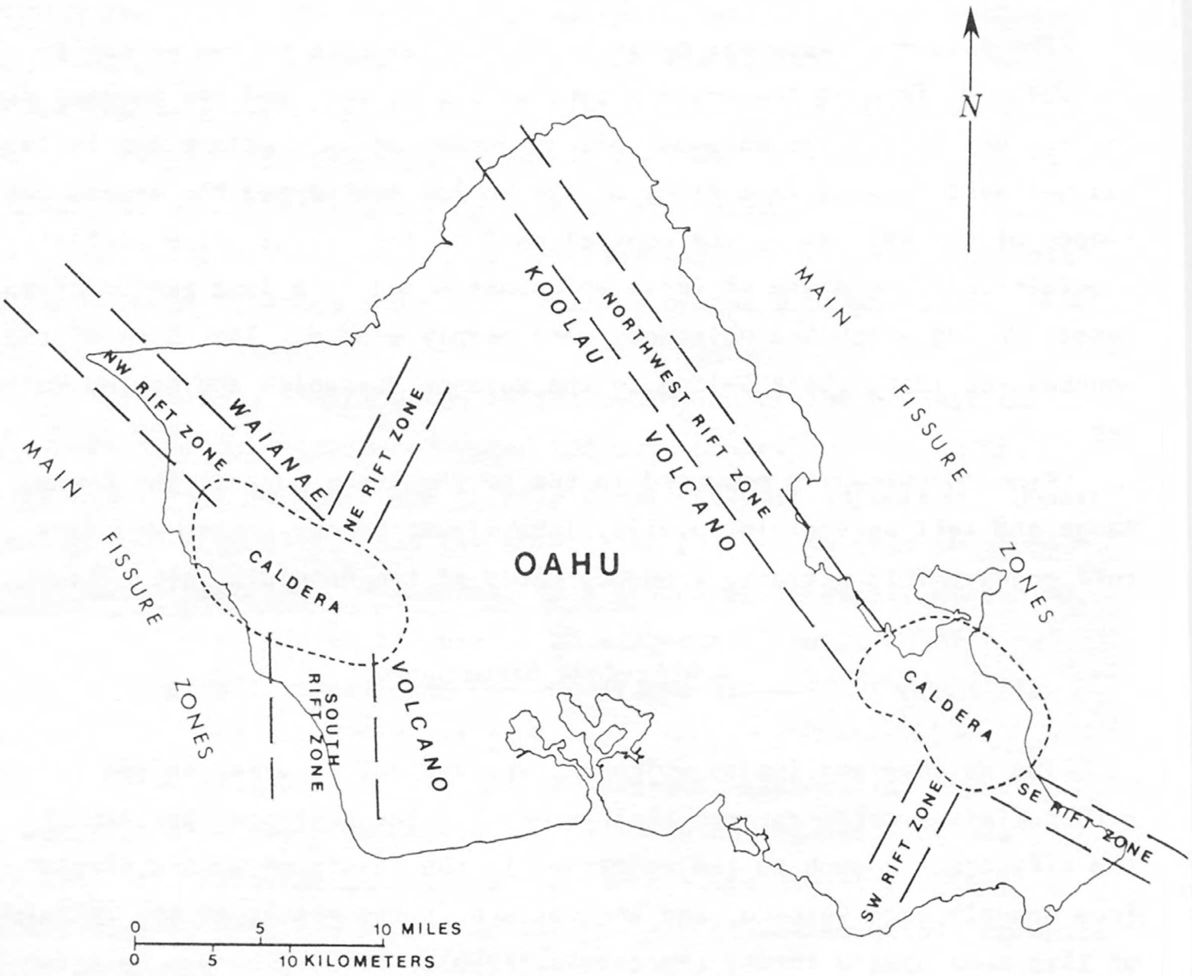
N
MAIN FISSURE ZONES
MAIN FISSURE ZONES
NW RIFT ZONE
WAIANAE
NE RIFT ZONE
CALDERA
SOUTH RIFT ZONE
VOLCANO
OAHU
KOOLAU
NORTHWEST RIFT ZONE
VOLCANO
CALDERA
SW RIFT ZONE
SE RIFT ZONE
0 5 10 MILES
0 5 10 KILOMETERS

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.

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 $b = p^2 D$ 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:

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

and for constant recharge it is:

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

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:

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

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).

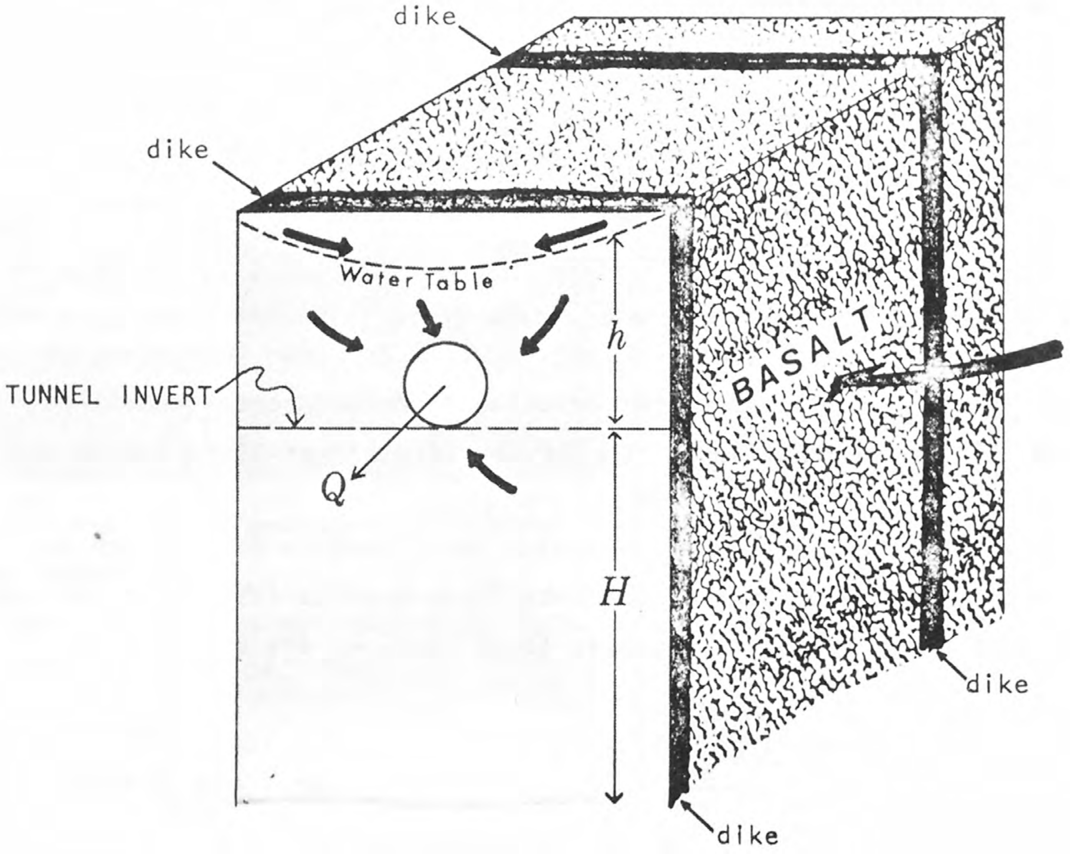
dike
dike
Water Table
h
TUNNEL INVERT
Q
H
BASALT
dike
dike

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,

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

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 $\frac{Q - Q_R}{Q_o - Q_R} = \exp\ (-at)$,

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

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:

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

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

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

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,

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

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

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

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,

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

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,

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

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),

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

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,

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

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

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

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

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

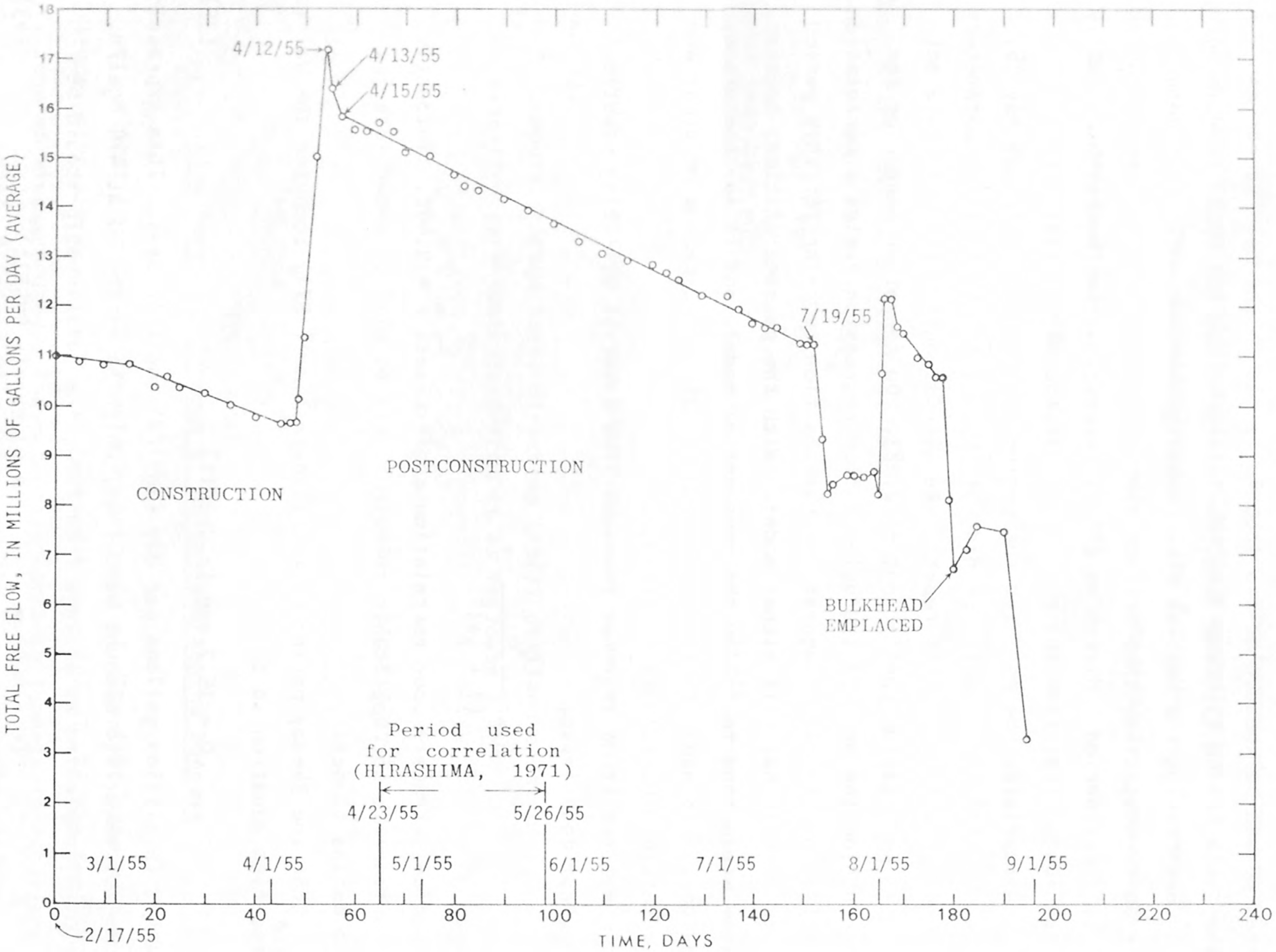

Figure 39. Waihee tunnel free-flow decay.

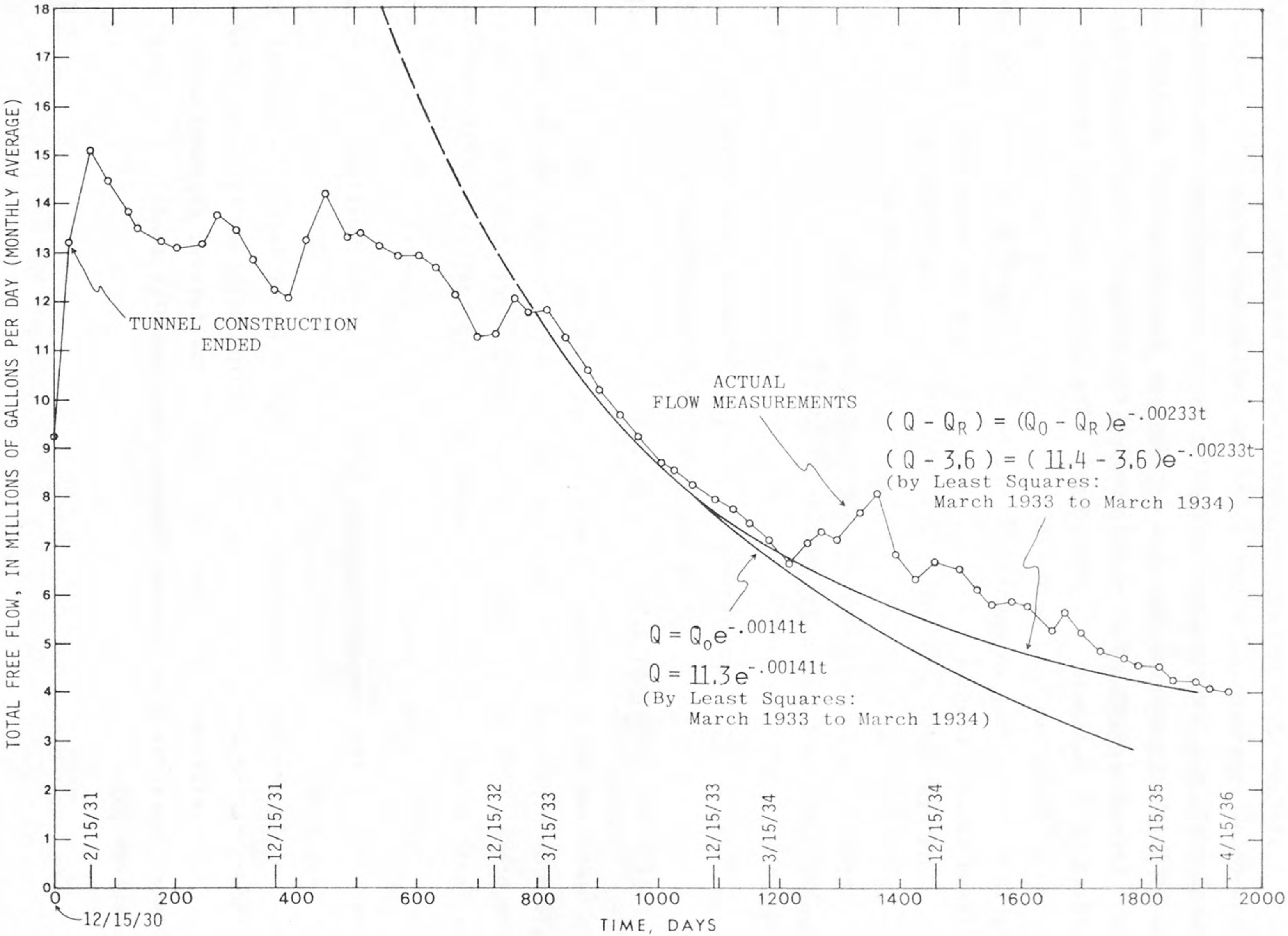

Figure 40. Kahana tunnel free-flow decay.

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 $r = 0.990$),

$$Q = 11.3 \exp(-.00141t), \qquad (41)$$

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:

$$(Q - 3.6) = (11.4 - 3.6) \exp(-.00233t), \qquad (42)$$

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.

REFERENCES

Akinaka and Associates, Ltd., Bowles, S. P., and Mink, J. F., 1975, Kohala water resources management and development plant phase III: Report to Hawaii State Department of Agriculture, Honolulu, Hawaii.

Bowles, S. P., Haiku Tunnel study: Honolulu Board of Water Supply unpublished report[1/], 9 p.

Castany, George, 1967, Traite pratique les eaux southerraines: Dunod, Paris.

Clark, W. O., 1922, Preliminary report on the geologic structures favorable to the occurrence of high-level ground water on Maunawili Range, island of Oahu, Territory of Hawaii, and the probable effect development of this water would have on the present supply: Unpublished report of C. Brewer and Co., Ltd., dated February 28[1/], 1922, 12 p.

__________1930, Ground water of a portion of Waianae: Unpublished report to the Attorney General of the Territory of Hawaii, dated September 1930[1/], 28 p.

__________1932, Uwau tunnel recommendation: Unpublished report to Oahu Sugar Co., dated May 5, 1932[1/], 3 p.

__________1934, Reasons for recommending that a gate be placed in Waikane Tunnel No. 2 of Oahu Sugar Co., Ltd.: Unpublished report to American Factors, Ltd., dated May 5, 1934[1/], 9 p.

Cox, D. C., 1947, Geology and ground-water hydrology of the Kahaluu tunnel, Oahu: Unpublished report to Suburban Water System, dated January 1947[1/], 10 p.

__________1949, Notes on the geology of the upper part of Waianae Valley, Oahu, and its relation to the yield of tunnels: Unpublished report to the Suburban Water System, dated June 1949[1/], 34 p.

__________1954, Notes on test drilling in upper Maunawili Valley: Honolulu Board of Water Supply, unpublished report[1/], 21 p.

Cox, D. C., 1957, Potential additional water development in the Waiahole Tunnel: Unpublished report to American Factors, Ltd., dated April 3, 1957[1/].

Dale, R. H., and Takasaki, K. J., 1976, Probable effects of increasing pumpage from the Schofield ground-water body, island of Oahu, Hawaii: U.S. Geological Survey Water-Resources Investigations 76-47, 45 p.

Hall, F. R., 1968, Base-flow recession, a review: Water Resources Research, vol. 4, p. 973-983.

Hawaii Division of Water and Land Development, 1977, Kahakuloa water study: Report R54, 84 p., App. A-G.

Hirashima, G. T., 1962, Effect of the Haiku Tunnel on Kahaluu Stream, Oahu, Hawaii: U.S. Geological Survey Professional Paper 450-C, p. 118-120.

__________1963a, Aspects of ground-water storage and depletion along the Molokai Irrigation Tunnel, Molokai, Hawaii: Hawaii Division of Water and Land Development Circular C20, 21 p.

__________1963b, Influence of water-development tunnels on streamflow-groundwater relations in Haiku-Kahaluu area, Oahu, Hawaii: Hawaii Division of Water and Land Development Circular C21, 11 p.

__________1965, Effects of water withdrawals by tunnels, Waihee Valley, Oahu, Hawaii: Hawaii Division of Water Land and Development Report R28, 38 p.

__________1971, Tunnels and dikes of the Koolau Range, Oahu, Hawaii, and their effect on storage depletion and movement of ground water: U.S. Geological Survey Water-Supply Paper 1999-M, 21 p.

Jorgensen, Jorgen, 1916, Development of water by tunneling in Oahu: in Honolulu Water Commission report to the Honorable Mayor and Board of Supervisors of the City and County of Honolulu on the available water supply for the city of Honolulu, 1917, p. 92-97.

Larrison, G. K., and Cox, J. B., 1948, A study and appraisal of the waters of upper Waianae: Unpublished report to Waianae Development Co., Ltd., dated August 1948[1/].

Lee, H. K., 1960, A survey of Maunawili Ditch and other water supply development in Maunawili Valley: Honolulu Board of Water Supply unpublished report, dated December 1960[1/].

Lippincott, J. B., 1911, Report on the feasibility of bringing the waters of the Waiahole, Waikane and Kahana Streams through the Koolau Range to the lands of Oahu Sugar: Unpublished report to the Board of Directors of Oahu Sugar Co., Ltd., Honolulu, Hawaii, dated August 19, 1911[1/], 29 p.

Macdonald, G. A., 1956, The structure of Hawaiian volcanoes: Koninklijk Nederlandsch Geologisch--Mijnbouwkundig Genootschap, Verhandelingen, vol. 16, p. 274-295.

__________1972, Volcanoes: Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 510 p.

Macdonald, G. A., and Abbott, A. T., 1970, Volcanoes in the sea: University of Hawaii Press, Honolulu, Hawaii, 441 p.

Martin, W. F., and Pierce, C. H., 1913, Water resources of Hawaii, 1909-1911: U.S. Geological Survey Water-Supply Paper 318, 552 p.

Mink, J. F., 1962, The hydrology of Waihee Tunnel and upper Waihee Valley: Board of Water Supply manuscript report[1/].

__________1971, A primer on dike water development: Honolulu Board of Water Supply unpublished report[1/], 12 p.

__________1978, Waianae water development study: Honolulu Board of Water Supply unpublished report[1/], 109 p., 6 appendices.

Olstad, Hans, and Clark, W. O., 1936, A study to determine the effects of the gate placed in Waikane Tunnel No. 2: Unpublished progress report to American Factors, Ltd.,[1/] 11 p.

O'Shaughnessy, M. M., 1909, Irrigation works in the Hawaiian Islands: Engineering News, vol. 61, no. 15, p. 399-403.

Palmer, H. S., 1921, Report on the possible occurrence of high-level ground water in the Honolulu region: Unpublished report to Mayor and Board of Supervisors, City and County of Honolulu, 1921[1/], 84 p.

Palmer, H. S., 1957, Waimanalo and Maunawili: Honolulu Board of Water Supply unpublished report[1/], 26 p.

Polybarinova, Kochina, 1962, Theory of ground-water movement: Princeton University Press.

Schoeller, Henri, 1962, Les eaux souterraines: Masson et cie, Paris.

__________1965, Hydrodynamique dans le karst: United Nations Educational, Scientific, and Cultural Organization, Hydrology of fractured rocks, Proceedings of Dubrovnik Symposium, vol. 1, p. 3-20.

Stearns, H. T., 1939, Geologic map and guide of Oahu, Hawaii: Hawaii Division of Hydrography Bulletin 2, 75 p., 6 pl.

Stearns, H. T., and Vaksvik, K. N., 1935, Geology and ground-water resources of the island of Oahu, Hawaii: Hawaii Division of Hydrography Bulletin 1, 479 p.

Strange, W. E., Machesky, L. F., and Woollard, G. P., 1965, A gravity survey of the island of Oahu, Hawaii: Pacific Science, vol. XIX, July 1965, p. 350-353.

Takasaki, K. J., 1971, Ground water in the Waianae District, Oahu, Hawaii: U.S. Geological Survey Hydrologic Investigations Atlas HA-358.

Takasaki, K. J., Hirashima, G. T., and Lubke, E. R., 1969, Water resources of windward Oahu, Hawaii: U.S. Geological Survey Water-Supply Paper 1894, 119 p.

Takasaki, K. J., and Valenciano, Santos, 1969, Water in the Kahuku area, Oahu, Hawaii: U.S. Geological Survey Water-Supply Paper 1874, 59 p.

Wentworth, C. K., 1936, Geology and ground-water conditions in the vicinity of the Manoa Tunnels, Waiakeakua Gulch, Oahu: Honolulu Board of Water Supply unpublished report[1/].

__________1938, Geology and ground-water resources of Palolo-Waialae District: Honolulu Board of Water Supply unpublished report[1/], 274 p.

__________1940, Geology and ground-water resources of Manoa-Makiki District: Honolulu Board of Water Supply unpublished report[1/], 145 p.

Wentworth, C. K., 1943, The problem of additional water supply for Waimanalo: Unpublished report to Suburban Water System, dated December 14, 1943[1].

__________1953, Underground water resources of the Koolaupoko District of Oahu: Honolulu Board of Water Supply unpublished report[1], 22 p.

Williams, J. A., and Soroos, R. L., 1973, Evaluation of methods of pumping test analyses for application to Hawaiian aquifers: Water Resources Research Center, University of Hawaii, Honolulu, Technical Report No. 70, 159 p.

Youngs, E. G., 1960, The drainage of liquids from porous materials: Journal of Geophysical Research, vol. 65, p. 4025-4030.

Youngs, E. G., and Aggelides, S., 1967, Drainage to a water table analyzed by the Green-Ampt approach: Journal of Hydrology, vol. 31, p. 67-79.

---

[1] Unpublished reports are available at the U.S. Geological Survey, Honolulu, Hawaii.

(200)

POCKET CONTA
4 ITEM

USGS LIBRARY-RESTON
3 1818 00072129 8