PROBABLE EFFECTS OF INCREASING PUMPAGE FROM THE SCHOFIELD GROUND-WATER BODY, ISLAND OF OAHU, HAWAII

U.S. GEOLOGICAL SURVEY

WATER-RESOURCES INVESTIGATIONS 76-47

Prepared in cooperation with
Board of Water Supply
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16. Abstracts
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Increasing pumpage from the Schofield ground-water body will cause a reduction in head in the Schofield ground-water body, and a decrease in the ground-water flux to the adjacent basal-water bodies.

Recharge to the Schofield water body is estimated at 481 thousand cubic metres per day, and pumpage averages 28 thousand cubic metres per day. The difference, 453 thousand cubic metres, flows to the adjacent basal-water bodies. Of the difference, more than 80 percent flows south to the Pearl Harbor basal-water body.

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UNITS OF MEASUREMENT

Metric units (SI) have been used throughout in this report. The volumetric rate measurement unit used locally in Hawaii is million gallons per day. In this report, all reported volumetric rate measurements are followed parenthetically by the locally used unit. The following table converts measurements in the metric system to the English equivalent.

Multiply metric unit	By	To obtain English unit
metre (m)	3.281	feet (ft)
square metre (m^2)	10.76	square feet (ft^2)
cubic metre (m^3)	35.31	cubic feet (ft^3)
cubic metre (m^3)	264.2	gallons (gal)
square kilometre (km^2)	.3861	square miles (mi^2)
millimetre (mm)	.0254	inches (in)
kilometre (km)	.6214	mile (mi)

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ABSTRACT

The Schofield ground-water body underlies about 88 square kilometres near the geographic center of the island of Oahu. Ground-water dams of low-permeability rock maintain a head of 85 metres within the body, in contrast with adjacent basal-water bodies with heads of 7.3 metres or less. The low-permeability rock consists of either volcanic dikes or weathered bedrock, and is probably the latter.

Under present development, the pumpage directly from the water body is small as compared to the total flux, and most of the recharge to the body flows over and through the ground-water dams and into the adjacent basal-water bodies. Pumpage of additional ground water from the Schofield water body will cause both a reduction in recharge to the adjacent basal-water bodies and a decline in head in the Schofield water body.

Using a hydrologic budget method, it was determined that recharge to the Schofield water body averages 481 thousand cubic metres per day (127 million gallons per day). An average of 28 thousand cubic metres per day (7.4 million gallons per day) is pumped from this water body, leaving an average of 453 thousand cubic metres per day (120 million gallons per day) to be routed to the adjacent basal-water bodies. More than 80 percent of the excess ground water flows south to the Pearl Harbor basal-water body, and less than 20 percent flows north to the Waialua basal-water body.

The hydraulic characteristics of the ground-water dam were investigated using time-series techniques. From this analysis, the outflow from the water body can be considered as in part flowing through a dam and in part spilling over the top of a dam. Presently, about 130 thousand cubic metres per day (34 million gallons per day) spills over, and, thus, an average of 130 thousand cubic metres per day (34 million gallons per day) can be pumped with about 6 metres of head decline. Pumpage in excess of 130 thousand cubic metres per day (34 million gallons per day) will cause a rapid head decline.

INTRODUCTION

Location and Description of the Water Body

The Schofield high-level ground-water body underlies about 88 square kilometres of the Schofield Plateau between the Koolau and Waianae Ranges in central Oahu (fig. 1). The ground-water body was discovered in 1936 during construction of the Schofield shaft, which was planned to develop basal ground water from the Koolau aquifer with heads standing at an anticipated level of about 9 metres above sea level. The water level, however, was encountered at an altitude of 84 metres, much higher than the anticipated basal-water level but somewhat lower than the levels of dike-impounded waters in the flanking Koolau and Waianae Ranges. The water body was believed, at first, to be perched on ash or soil, but a test boring drilled to 6.4 metres below sea level demonstrated the absence of members that could cause perching and showed that there was continuous saturation of the lava flows below the depth where the water was first encountered (Stearns, 1940).

Since the completion of the Schofield shaft, wells have been drilled into the water body at seven different locations, as indicated on figure 1. The freshwater head at each site has ranged between 83.5 and 86.5 metres above sea level. No attempt has been made to construct a water-level contour map based on instantaneous head measurements, and it is assumed in this report that there is no spatial variation in head throughout the entire water body. This assumption obviously is not true, but, rather, it is a consequence of a lack of data.

Within the water body, the hydraulic conductivity is high as inferred from specific-capacity tests. On the average, the specific capacity of wells pumping from the Schofield water body is greater than 10 $(m^3/min)/m$ (cubic metres per minute per metre of drawdown) [792 (gal/min)/ft] (gallons per minute per foot of drawdown).

Wells drilled outside of the area have either penetrated a gradational region where the freshwater head is greater than that for basal-water bodies but less than that for the Schofield water body or else they have penetrated the basal-water body. Wells 2803-02 and 3203-01 penetrate the gradational region, where the head is on the order of 45 metres above sea level. Wells 2801-01 and 2703-01 penetrate the Pearl Harbor basal-water body, where the head is on the order of 7.5 metres above sea level.

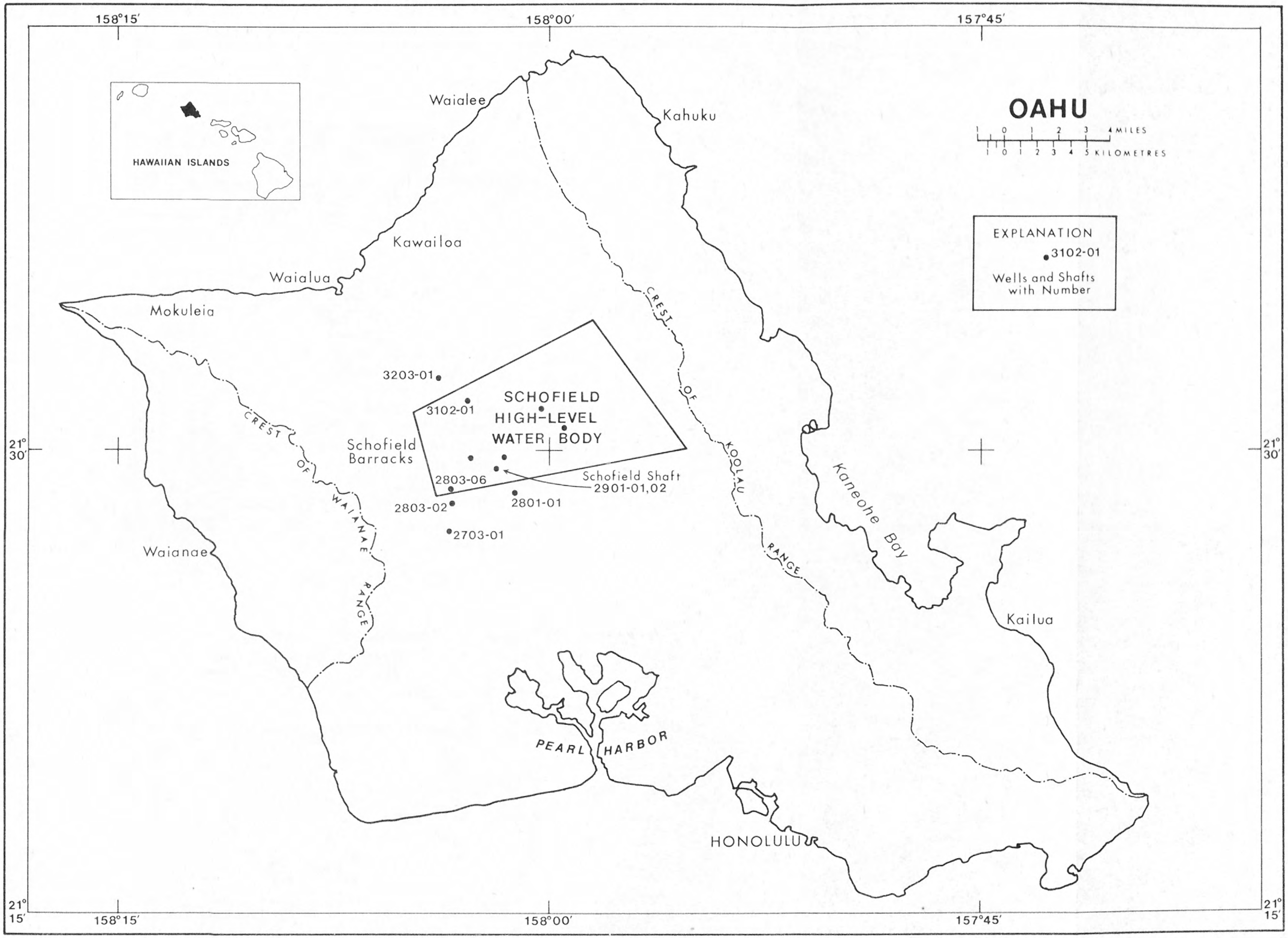

FIGURE 1. LOCATION OF SCHOFIELD HIGH-LEVEL GROUND-WATER BODY

The Development Problem

From an island-wide point of view, the Schofield water body is not an isolated water body that can be developed without affecting the adjacent basal-water bodies. Rather, this high-level water body acts as a catchment, a holding reservoir, and a conduit for some of the ground water that supplies adjacent basal-water bodies. Thus, any development of the Schofield water body is, in effect, an upstream diversion of the water.

Most of the agricultural and municipal water for the island of Oahu is presently being pumped from the adjacent basal-water bodies. Pumping from the Schofield water body would reduce the ground-water flux to the adjacent basal-water bodies. If the reduction in flux were large enough, some of the existing basal-water wells would soon produce saline water and would have to be abandoned.

There is, however, a positive factor for the development of the Schofield water body in that this is a high-level water body, and, therefore, not readily subject to saline-water intrusion. Thus, on the long term, it may be a better management scheme to develop this high-level ground-water body to its maximum, and abandon those installations in the adjacent basal-water areas that would become saline because of this upstream diversion.

Purpose and Scope

In general, the purpose of this report is to predict changes in the ground-water flow system as related to the potential development of the Schofield water body. It is desirable to know, although it is not precisely achievable, the rate at which water levels would decline in the Schofield water body, and how soon it would be before a particular well in an adjacent basal-water body became too saline for domestic use.

The work discussed in this report was begun in January 1973 in cooperation with the Board of Water Supply, City and County of Honolulu. The study was done in two phases. The first was the reconnaissance and project design phase to review what was known, to analyze the available data, and to identify needed additional effort. During this initial phase, a hydrologic model, based on existing data, was developed to describe the ground-water flux, storage, subsurface discharge from the area, and character of the boundary-flow conditions. The second was the summary analysis phase to support the initial model analysis. During this phase, specific hydrologic information was collected and used to evaluate the relative ground-water flux to the north and south from the Schofield water body.

Acknowledgments

The writers express their appreciation to the Honolulu Board of Water Supply, the U.S. Army, the U.S. Navy, and the Waialua Sugar Co., Inc., for their wholehearted cooperation and assistance.

GEOHYDROLOGIC FRAMEWORK

On the island of Oahu, ground-water bodies may be classified as either basal-water bodies or high-level water bodies. The basal-water bodies consist of freshwater that floats on underlying saline water, with the water table being only a few metres above sea level. In contrast, the water table of the high-level water bodies is commonly several hundreds of metres above sea level. On figure 2, the basal-water bodies are shown with a dotted pattern, and the high-level water bodies are shown by a crosshatch or line pattern. As with most classification systems, the contacts between the two types are gradational. The ground-water dams, although classified as high-level, actually represents the gradational region between the Schofield high-level water body and the adjacent basal-water bodies. Elsewhere on Oahu, either the contact is sharp, or else the data are not available to map the gradational region. The freshwater-head map (fig. 3) clearly shows the step-like head changes between adjacent water bodies.

Saturation is continuous below the water table (fig. 4), and all the ground water could be logically considered as a single water body. The subdivision of the island ground water into smaller ground-water bodies depends on a sharp contrast in rock permeability, although the nomenclature implies that the subdivision is based on the altitude of the water table. Actually, the altitude of the water table is dependent on both rock permeability and the rate of deep infiltration of rainfall to the water body.

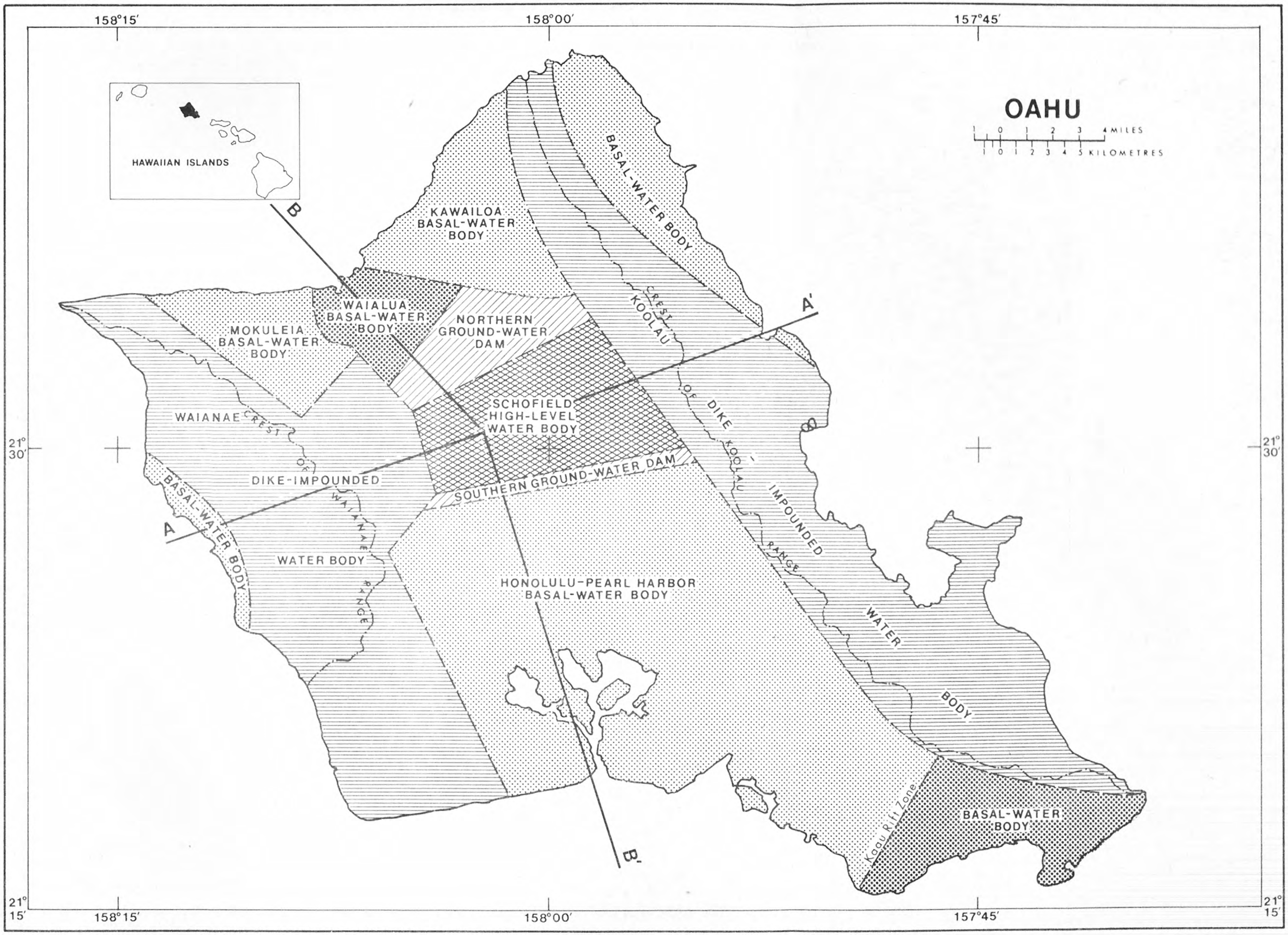

FIGURE 2. GEOHYDROLOGIC MAP OF THE ISLAND OF OAHU

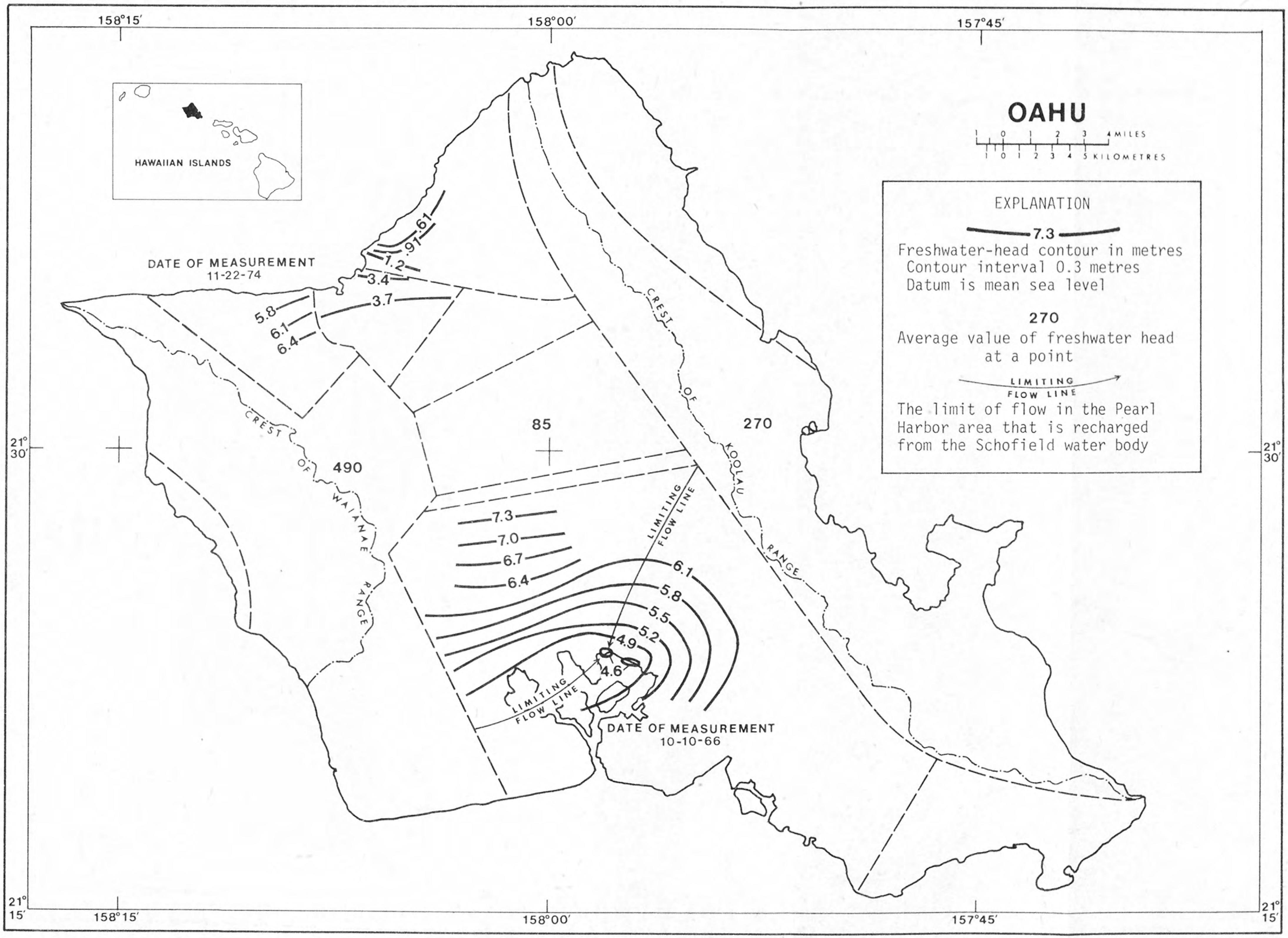

FIGURE 3. FRESHWATER-HEAD MAP

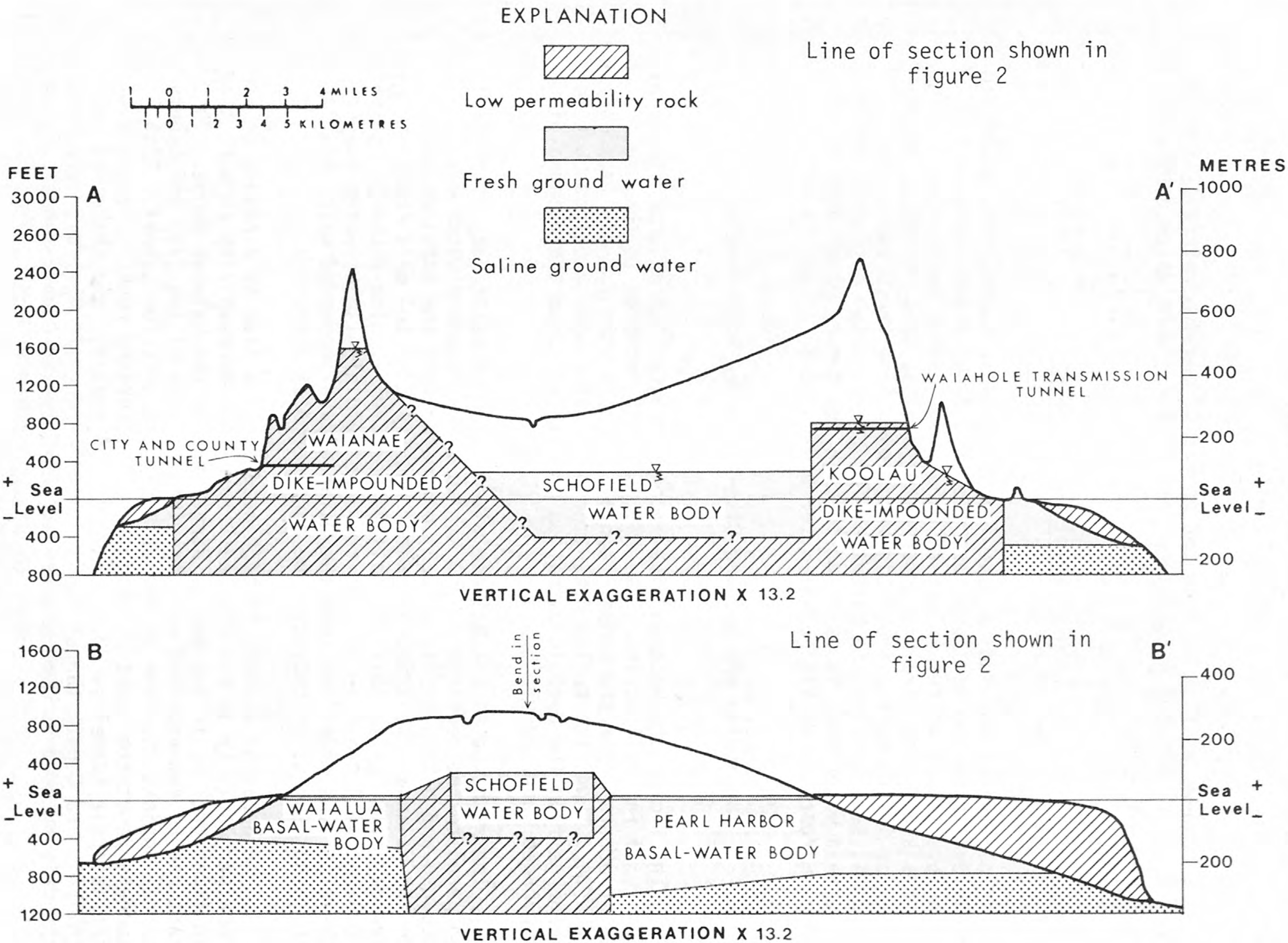

Figure 4. Geohydrologic sections A-A' and B-B'

Ground-water flow is from the points of maximum rainfall (fig. 5) to the ocean, but the actual flow path of the ground water depends on rock permeability.

High-Level Water Bodies

The Waianae and Koolau dike-impounded water bodies, the Schofield high-level ground-water body, and the ground-water dams make up the high-level water on the island of Oahu. The higher heads occur in the Waianae and Koolau dike-impounded water bodies; thus, there is potential for inflow to the Schofield water body from these two units (fig. 4, sec. A-A'). The potential for ground-water outflow from the Schofield water body is over and through the ground-water dams to the Pearl Harbor and Waialua basal-water bodies (fig. 4, sec. B-B').

The Koolau and Waianae Dike-Impounded Water Bodies

The Koolau and Waianae dike-impounded water bodies underlie local points of rainfall maxima (fig. 5). Natural recharge to the ground water occurs where the annual rainfall is more than 1.3 m/y (metres/year) (p. 24). Thus, the Koolau dike-impounded water body receives much more recharge from the deep infiltration of rainfall than the Waianae dike-impounded water body.

The recharge to the Waianae dike-impounded water body is trivial compared to the recharge to the Koolau dike-impounded water body. Rosenau and others (1971, p. D33) estimated that the total recharge to the Waianae dike-impounded water body is 23 x 10^3 m^3/d (cubic metres per day) [6 Mgal/d (million gallons per day)]. The recharge is small, compared with the flux through the Schofield high-level water body, therefore the underflow from the Waianae dike-impounded water body to the Schofield water body will be considered as zero.

The apparent anomaly of high head and low flux is a result of low rock permeability in the Waianae Range. The permeability is more than 10 times greater in the Koolau Range than in the Waianae Range. This fact can be demonstrated by comparing the flow of the City and County tunnel against the flow of the Waiahole transmission tunnel. Both tunnels penetrate about 3,000 metres of saturated rock. The yield of the Waiahole tunnel is 28 x 10^3 m^3/d (7.4 Mgal/d), and the yield of the City and County tunnel is 2.8 x 10^3 m^3/d (0.74 Mgal/d), even though the driving head is much greater at the City and County tunnel.

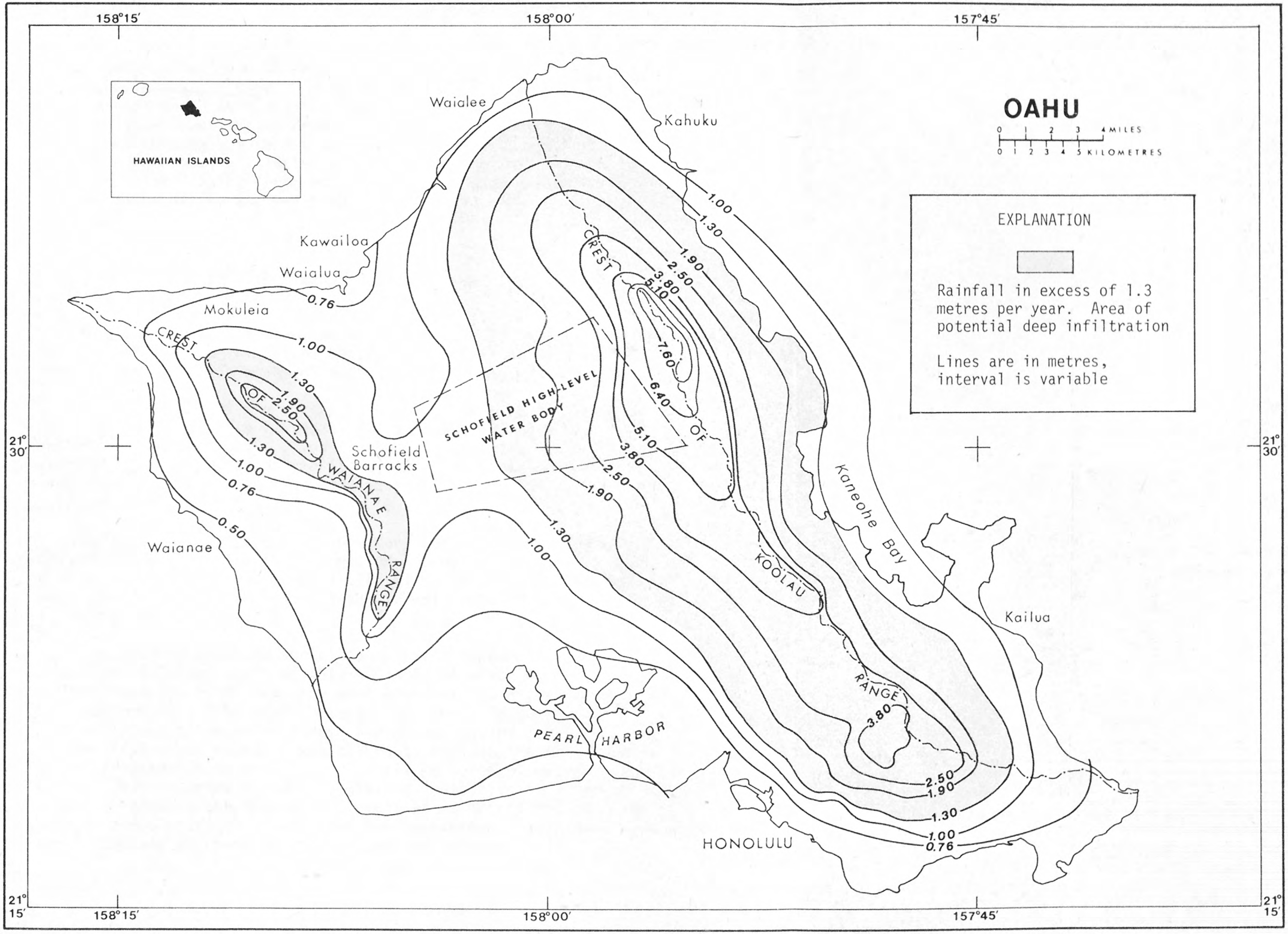

FIGURE 5. RAINFALL MAP FOR THE ISLAND OF OAHU, 1931-60

The water table in the Koolau dike-impounded water body is about 270 metres above sea level. A system of tunnels has been drilled into the mountain range at elevations between 210 and 240 metres above sea level. These tunnels have never gone dry, indicating that the head difference between the Koolau high-level water body and the Schofield water body has been a relatively constant 185 metres (fig. 4, sec. A-A'). Thus, the time-varying recharge to the Koolau dike-impounded water body appears to be stored and released at a constant rate to the Schofield water body.

The Schofield High-Level Water Body

The Schofield high-level water body (fig. 2) includes the area that is underlain by highly permeable rocks that are saturated with water to an elevation about 85 metres above sea level.

The positions of the north and south boundaries of the Schofield water body were first outlined by Swartz (1940) by means of electrical resistivity measurements, using the Lee Partitioning Method. Information from wells subsequently drilled within and outside the outlined area indicates the boundaries that were located essentially as Swartz outlined them.

North boundary.--The north boundary was placed between well 3102-01 and well 3203-01 in the same direction, as was indicated by Swartz (1940). The water level in well 3102-01 was measured at 82 metres above sea level, and the water level in well 3203-01 was measured at 45 metres above sea level.

South boundary.--The south boundary is represented by a line drawn from about 500 feet south of well 2803-06, in which water level is 85 metres above sea level near the west boundary, to and extending beyond the midpoint of a line drawn between the Schofield shaft and well 2801-01 in which the water levels are 85 metres and 7.3 metres, respectively. The south boundary was placed to exclude the well 2803-02 near the west boundary, in which water levels measured 61 metres above sea level. This intermediate water level is indicative of a narrow ground-water dam between the high-water levels at 85 metres and the basal-water levels at 7.3 metres. As with the northern ground-water dam, the structural features which comprise this dam are unknown.

East boundary.--The east boundary is a line indicating the western limit of northwest-trending dikes of the Koolau Volcanic Series. A line was drawn by extending the line of westernmost dikes mapped in the Waialee area of northwest Koolau Range, dikes mapped in the Waiahole transmission tunnel in central Koolau Range, and dikes that are exposed in stream channels within the area of the Schofield water body. This is a dike and hydrologic boundary. Water levels east of this boundary are about 185 metres higher than those of the Schofield water body.

West boundary.--The west boundary was established as a line corresponding to the subsurface slope of Waianae rocks at an altitude of 120 metres. The boundary is the inferred contact of the Koolau and Waianae rocks at this altitude.

Ground-Water Dams

The ground-water dams are formed by two parallel east-west trending ridges of low-permeability rocks. The exact nature of the geologic materials that form the dam is unknown, and the existence of the dams is based entirely on hydrologic inference.

The southern dam is about 1.6 km (kilometres) wide judging from the water levels in shaft 2901-01 and well 2801-01. Roughly 78 metres of head is dissipated as the water flows southward over and through this ground-water dam. The hydraulic gradient within the dam is 49 m/km, or more than one hundred times that of the adjacent basal-water bodies.

The width of the northern ground-water dam is unkown. It is shown on figures 3 and 4 as being wider than the southern dam, because the hydrologic analysis (p.29) indicates that most of the ground-water underflow is from the Schofield high-level water body to the Pearl Harbor basal-water body.

Basal-Water Bodies

The Honolulu-Pearl Harbor basal-water body lies to the south of the Schofield high-level water body and the Waialua basal-water body lies to the north. The potential exists for ground-water underflow to move from the Schofield high-level water body to both of these basal-water bodies.

The Honolulu-Pearl Harbor basal-water body is bounded on the east by the Kaau rift zone; thence, in a northeasterly direction by the Koolau dike swarm; thence, westerly by the southern ground-water dam of Schofield water body; and thence, southeasterly by the Waianae dike swarm. The dike-swarm boundaries are nearly vertical. The Schofield dams are assumed to be vertical also. The coastal-plain and valley-fill deposits form an irregular sloping boundary between the Waianae dike swarm and the Kaau rift zone.

Deep, poorly permeable valley-fill deposits of the Anahulu River form the northeastern boundary of the Waialua basal-water body. The boundary runs thence in a southwesterly direction along the northern ground-water dam of Schofield water body to the Waianae dike-impounded water body; thence, northwesterly along the deep valley fill of Kaukonahua Stream to the ocean. The valley-fill deposits of the Anahulu River are more than 90 metres deep, and the valley-fill deposits of Kaukonahua Stream are more than 210 metres deep. The boundaries are virtually vertical. The coastal-plain deposits form an irregular sloping boundary between Kaukonahua Stream and Anahulu River.

Some of the Schofield high-level water could leak through the ground-water dam directly to the Kawailoa basal-water body, but it is assumed for this report that the deep valley fill of the Anahulu River represents a no-flow boundary from the ocean to its intersection with the Koolau dike-impounded water body.

The Depth to Saline Water

In a humid, mountainous insular setting, the ground-water management problems usually are related to the quality of water rather than the quantity. There is, in effect, an infinite amount of water available because, below sea level, the rocks are completely saturated, and in Hawaii the rock permeability is great enough so that high-production wells are easy to construct. However, if the wells pump more water than the freshwater flux, the underlying saline ground water will eventually enter the well.

The static Ghyben-Herzberg equation states that the depth below sea level of the base of the freshwater is 40 times the freshwater-head elevation above sea level.

Two points of local maximum freshwater head are in the Waianae and Koolau dike-impounded water bodies. The maximum head in the Waianae dike-impounded water body is 490 metres; therefore, the interface should be at 19,600 metres below sea level. The maximum head in the Koolau dike-impounded water body is 270 metres, which yields an interface position of 10,800 metres below sea level. These water bodies are probably not basal, but rather, they are terminated at an unknown depth by impermeable rocks. These calculations of depth to the interfaces only indicate that there is no saltwater problem in either the Waianae or Koolau dike-impounded water bodies.

The Schofield high-level water body, with an average head of 85 metres, would have an interface at 3,400 metres below sea level. This water body is probably terminated by impermeable rock, rather than extending to this depth. However, the calculation does indicate that there is no possible saltwater problem if the head is maintained at or near its present level.

On October 10, 1966, the head for the Pearl Harbor basal-water body ranged between 4.6 and 7.3 metres. These head contours are reasonably close to the average conditions over the past 30 years. Near the shore of Pearl Harbor, where the head was 4.6 metres, the interface depth would be 184 metres below sea level, and near the northern ground-water dam, where the head was 7.3 metres, the interface would be 292 metres below sea level. There are wells in the Pearl Harbor area that have been drilled to depths of more than 200 metres below sea level that produce brackish water, and, therefore, there is definitely a saltwater problem in this area.

On November 22, 1974, the head for the Waialua basal-water body ranged between 3.4 and 3.7 metres; thus, the interface depth would be between 136 and 148 metres below sea level. Many of the wells in the Waialua area have been drilled to depths of 130 metres below sea level that have produced brackish water, and, therefore, there is also a saltwater problem in this area.

BRIEF HYDROLOGIC SETTING AND SUMMARY OF RECORDS AVAILABLE

Climate

Mean annual rainfall in the Schofield area ranges from less than 1000 mm (millimetres) to more than 7600 mm. That part of the study area near the Koolau crest receives the highest annual rainfall on Oahu. In general, rainfall records are good, except in rainy, interior mountain areas.

Rainfall records are available for 45 rain-gage stations in the area upgradient to or underlain by the Schofield water body (fig. 6). The earliest record available is that for rain-gage station 872 in Wahiawa located at an altitude of 280 metres. This gage was established in 1900 and is still being used. The lines of equal rainfall shown in figure 6 were drawn from an unpublished rainfall map prepared by the Honolulu Board of Water Supply in 1960, based on rainfall averages for the 30-year period, 1931-60.

Streamflow

Streams draining the leeward slopes of the Koolau Range are flashy, and their flows depend primarily on the intensity and persistence of rainfall. Except below diversions, these streams are generally perennial and their flow may be sustained by leakage of ground water impounded in the Koolau dike system, but the contribution from ground water represents only a small part of the total flow of the streams. The flow characteristics of some of the streams in the study area are included in a report by Hirashima (1965).

In the upper reaches of Kaukonahua Stream, about 60 percent of the rainfall runs off as streamflow. The ratio of runoff to rainfall for gaging station 2000 (fig. 7) was 0.69 for the period 1913-24, 1926-52, 1960-74, and the ratio for gaging station 2010 was 0.53 for the period 1913-24, 1926-32, 1934-53. This is a relatively high ratio, and is probably caused by high head and the rejection of recharge, as well as low rock permeability in the Koolau dike-impounded water body.

Where the stream basin overlies the Schofield high-level water body, the rocks are more permeable and the head is lower. In this area, the runoff-to-rainfall ratio is close to 20 percent.

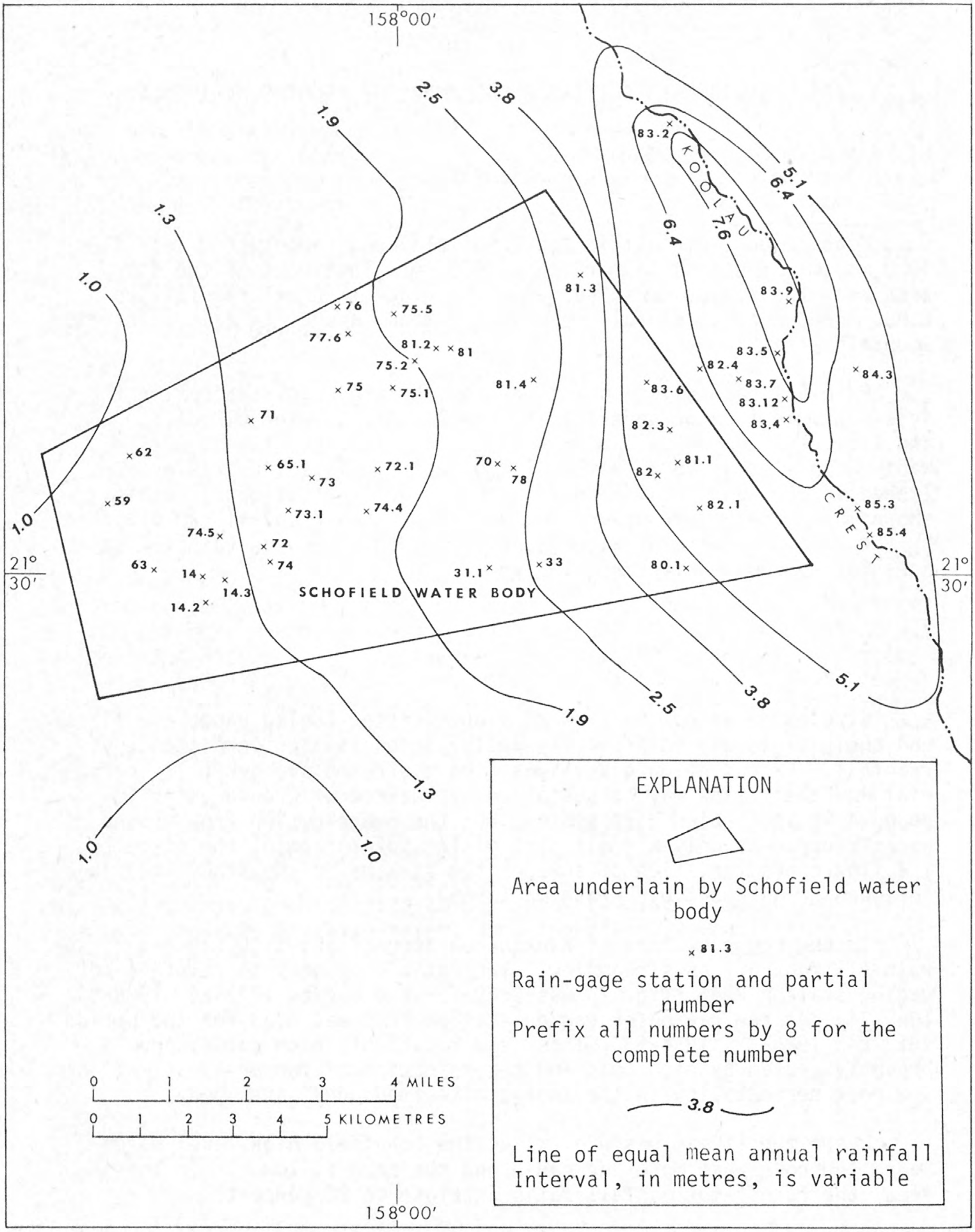

Figure 6. Mean annual rainfall, 1931-60, and rain-gage station locations in Schofield area

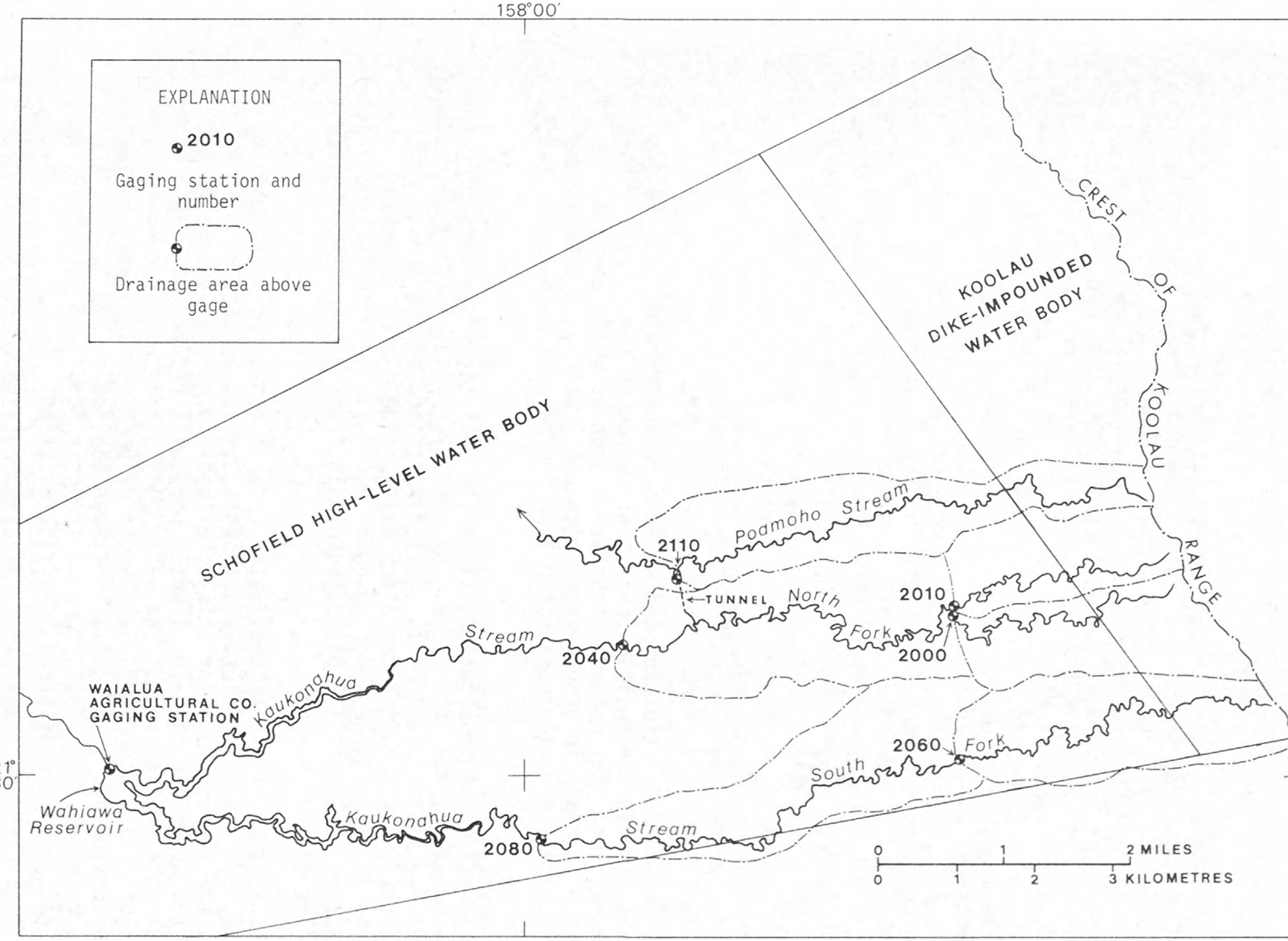

FIGURE 7. LOCATION OF STREAM-GAGING STATIONS IN THE SCHOFIELD AREA

Kaukonahua Stream has been dammed just below the confluence of the North and South Forks of the stream. Poamoho Stream, just above gaging station 2110, has been diverted through a tunnel into the Kaukonahua basin and into Wahiawa Reservoir. The combined inflow into Wahiawa Reservoir, as measured at gaging stations 2040 and 2080, averaged slightly over 143×10^3 m^3/d (38 Mgal/d) for the period 1953 to 1967. Effluent discharge of two sewage-treatment plants adds slightly over 3×10^3 m^3/d (1 Mgal/d). For the period 1953 to 1967, the reservoir outflow, made up discharge of the delivery tunnel, spillway overflow, and leakage, was determined to average slightly less than 143×10^3 m^3/d (38 Mgal/d). The net change in storage for this period was also measured. The apparent difference for the 15-year period is less than 7×10^3 m^3/d (2 Mgal/d). Rainfall in the reservoir area is estimated to be about 1270 mm and evaporation from the reservoir about 1780 mm. Thus, it appears that leakage from Wahiawa Reservoir to the ground-water body is small.

HYDROLOGIC ANALYSIS

The source of fresh ground water on Oahu is rainfall, and the natural sink is the Pacific Ocean that surrounds the island. There is no evidence that manmade structures, such as wells and shafts, cause an increase in ground-water recharge. Rather, the wells and shafts merely divert ground water from its natural path to the Pacific Ocean.

As a first approximation, all wells and shafts are competing for the same water, and, therefore, any new well field, located upgradient from the existing older wells, will divert some of the ground water that previously supplied the older wells. The degree to which a new well field affects the older downgradient wells depends on the location of the new wells within the geohydrologic framework and the magnitude of withdrawal of water.

The Schofield high-level water body is contained in highly permeable rock and is completely surrounded by low-permeability rock. Thus, the head surface for this water body is nearly level. Pumpage from the Schofield high-level water body will reduce the head uniformly over the entire area of the water body. This will reduce the ground-water underflow along the full length of both dams, as well as increase the underflow along the contact between the Koolau and Schofield high-level water bodies. Thus, pumpage from the Schofield high-level water body will have a widespread, distributed effect.

The basal-water bodies are also contained in highly permeable rock, surrounded by low-permeability rock, but these water bodies are hydraulically connected to the ocean. Therefore, it is impossible to induce large changes in water levels without causing saltwater upconing at wells. Thus, the head and hydraulic gradients cannot be changed appreciably in a basal-water body, and the effects of additional pumping are localized to the basal-water body.

In summary, it is possible to reduce the underflow over and through the ground-water dams by pumping from the Schofield high-level water body, but is is not possible to increase underflow from adjacent high-level water bodies by increasing the pumping from basal-water bodies.

The pumping of additional ground water from the Schofield high-level water body will cause the freshwater head to decline in the Schofield water body, and will cause a reduction in ground-water flux to the adjacent basal-water bodies. The reduction in flux will be the most critical change in the ground-water system, because some of the wells in the basal-water body would eventually pump saline water as a result of the flux change. In the following section, the ground-water flux is computed.

Ground-Water Flux

Ground-water flux is the volume rate of flow passing through a cross-sectional area that is perpendicular to the flow path. Figure 8 shows the alinement of the cross sections that are pertinent to this report. Ground-water inflow to the Schofield computational unit is the deep infiltration of rainfall directly on the computational unit plus the flux across boundary A from the Koolau computational unit. Ground-water outflow from the Schofield computational unit is pumpage from the Schofield water body plus the flux across boundaries B and C.

The inflow to the Schofield computational unit can be computed as rainfall minus evapotranspiration and runoff for both the Koolau and Schofield computational units. The outflow from the Schofield computational unit is the flux across boundaries B and C plus pumpage from the Schofield water body. Under steady-state conditions the outflow must equal the inflow; therefore, the sum of the flux across boundaries B and C can be readily computed. The flux across boundaries B and C is part of the inflow to the Pearl Harbor and Waialua computational areas, respectively. Therefore, the flux across boundaries B and C can be determined by an inflow-outflow analysis of the Pearl Harbor and Waialua computational areas.

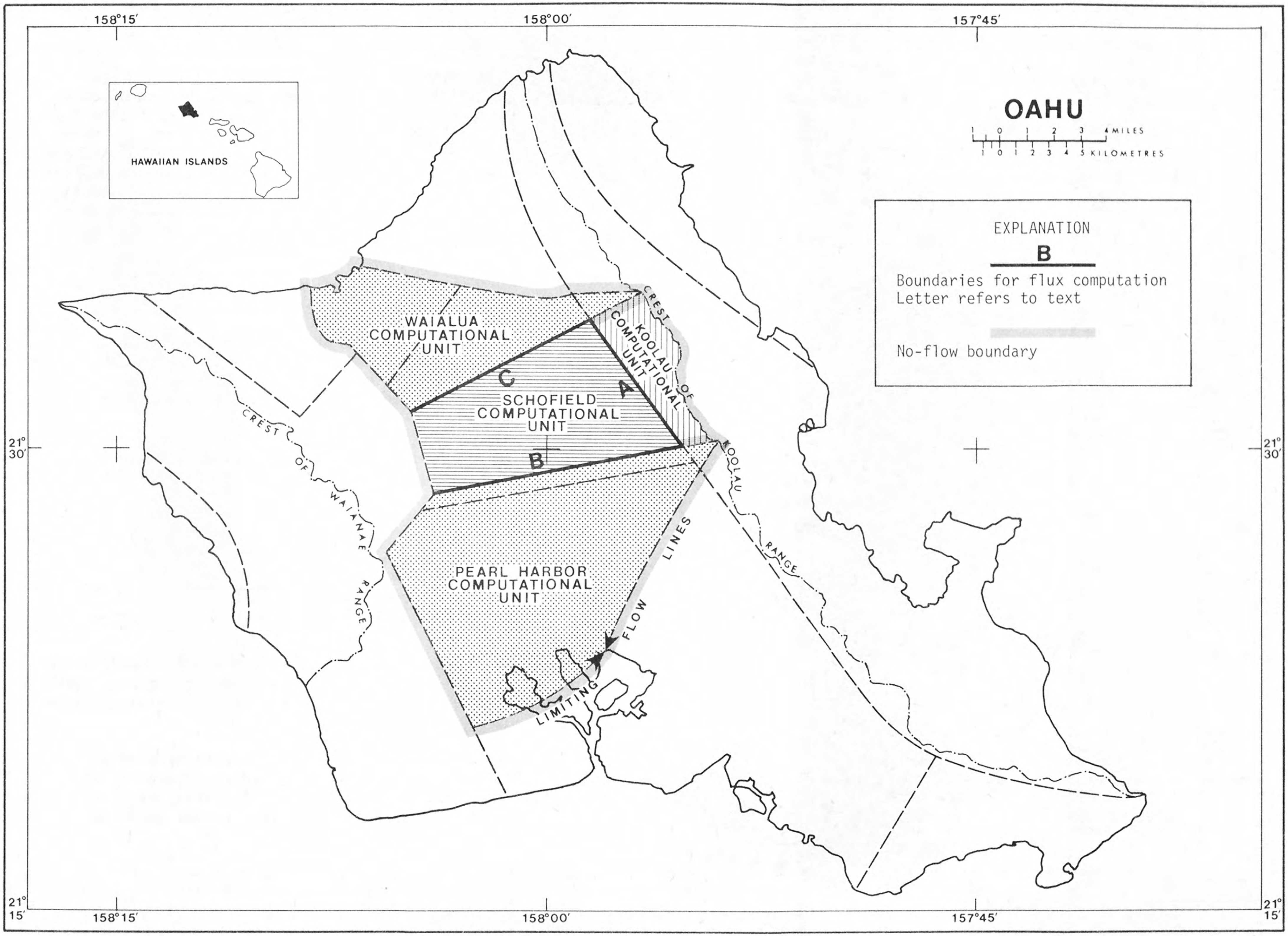

FIGURE 8. COMPUTATIONAL UNITS FOR DETERMINING GROUND-WATER RECHARGE AND DISCHARGE

The procedure for computing the flux across boundaries B and C is to compute an inflow-outflow budget for the computational units assuming that all the boundaries of the computational units are no-flow boundaries, including boundaries A, B, and C (fig. 8). Long-term averages were used, during which the heads in the various water bodies remained virtually constant with time. Under these conditions, inflow balances outflow, and no change occurs in ground-water storage. The flux across boundaries A, B, and C is computed as the quantity required to obtain an inflow-outflow balance for each separate computational unit.

Ground-Water Recharge

Assuming that boundaries A, B, and C are no-flow boundaries, nearly all of the inflow to each computational unit is ground-water recharge. This quantity was estimated as the mean annual rainfall minus the mean direct stream runoff minus the mean potential evapotranspiration.

Mean direct stream runoff varies with the mean annual rainfall. Where the rainfall is less than 5 metres per year,

$$R = 0.22P - 0.18 \qquad (1)$$

where R = runoff in metres
P = rainfall in metres.

When the rainfall exceeds 7 metres per year,

$$R = 0.6P. \qquad (2)$$

The relationship for equation 1 is based on data and work by Hirashima (1971, p. B13), and the relationship for equation 2 is based on the runoff-to-rainfall ratio as determined for gaging stations 2000 and 2010.

The evapotranspiration is estimated as being equal to the potential evapotranspiration. Potential evapotranspiration is inversely related to the rainfall. Takasaki, Hirashima, and Lubke (1969, p. 22) found that for the windward Oahu area

$$\mathrm{Log}_{10}E = 0.3438 - 0.1378P \qquad (3)$$

where E = median annual pan evaporation in metres
P = mean annual rainfall in metres.

With both direct runoff and potential evapotranspiration estimated from the rainfall, it is convenient to estimate deep infiltration directly from the rainfall map. Figure 9 is the graph of the deep infiltration for the rainfall intervals of the rainfall map. If the rainfall is less than 1.3 metres, all the rainfall is consumed by evapotranspiration. Above 1.3 metres, the deep infiltration increases reaching a maximum of 4.05 metres in the 5.1- to 6.4-metre rainfall range.

The sum of the ground-water recharge from the deep infiltration of rainfall averages 610 x 10^3 m^3/d (589 Mgal/d). This figure was determined by planimetering a 1:62,500-scale rainfall map for each of the computational units (table 1).

In addition to the deep infiltration of rainfall, about 84 x 10^3 m^3/d (22 Mgal/d) of irrigation water, which has been applied in excess of plant requirements, infiltrates to the basal-water bodies. Twenty-one thousand m^3/d (5.5 Mgal/d) infiltrates in the Pearl Harbor computational area (Dale, 1967), and 43 x 10^3 m^3/d (11.4 Mgal/d), in the Waialua area (Rosenau and others, 1971).

The sum of the ground-water recharge for the computational units is 674 x 10^3 m^3/d (178 Mgal/d) (table 2). This includes the deep infiltration of rainfall plus the irrigation water applied in excess of plant requirements.

Ground-Water Discharge

Ground-water discharge is from wells and shafts, and to a lesser degree, by coastal-plain leakage. Most of the discharges from wells and shafts have been measured for many years. The leakage in the Pearl Harbor area where it occurs as distinct springs has been measured, but diffuse seeps that occur in the Pearl Harbor area have not been measured. No coastal-plain leakage measurements have been made in the Waialua area.

Ground-water discharge for the indicated periods of record (table 3) has averaged 730 x 10^3 m^3/d (193 Mgal/d). The 56 x 10^3 m^3/d (15 Mgal/d) difference between recharge qnd discharge is related to computation techniques, and is not related to change in storage. The discharge of 560 x 10^3 m^3/d (148 Mgal/d) from the Pearl Harbor unit includes both springflow as well as discharge from wells and shafts. There is no springflow from the Schofield unit; therefore, the 28 x 10^3 m^3/d (7.4 Mgal/d) discharge rate is the average for shaft 2901-01. There are no wells in the Koolau unit, and, therefore, there is zero ground-water discharge to the surface. The 140 x 10^3 m^3/d (37 Mgal/d) discharge rate for the Waialua area is pumpage from irrigation wells and does not include the unknown quantity of coastal-plain leakage.

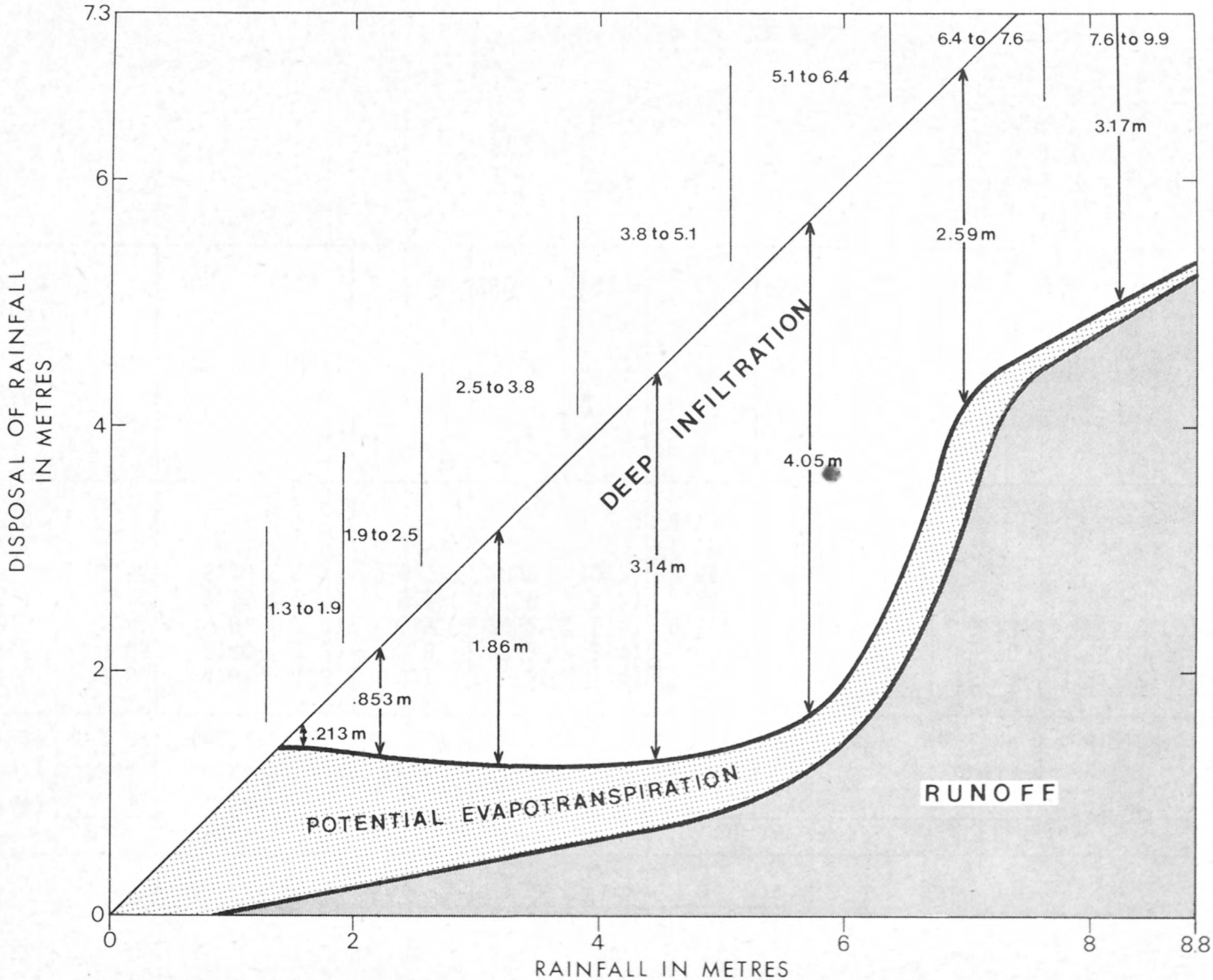

Figure 9. Disposal of rainfall as related to rainfall range

Table 1. Mean annual deep infiltration of rainfall

Rainfall interval (metres)	Pearl Harbor		Schofield		Koolau		Waialua	
	Area $m^2 x 10^6$	Volume $m^3 x 10^6$ ($gal x 10^9$)	Area $m^2 x 10^6$	Volume $m^3 x 10^6$ ($gal x 10^9$)	Area $m^2 x 10^6$	Volume $m^3 x 10^6$ ($gal x 10^9$)	Area $m^2 x 10^6$	Volume $m^3 x 10^6$ ($gal x 10^9$)
1.3-1.9	22.8	4.87 (1.3)	25.1	5.35 (1.4)			18.0	3.84 (1.0)
1.9-2.5	9.85	8.40 (2.2)	23.8	20.3 (5.4)			3.90	3.33 (0.9)
2.5-3.8	5.67	10.5 (2.8)	10.9	20.2 (5.4)	0.557	1.03 (0.3)	0.185	.345(0.09)
3.8-5.1	2.60	8.16 (2.2)	5.67	17.8 (4.7)	1.21	3.79 (1.0)		
5.1-6.4	1.58	6.40 (1.7)	9.57	38.8 (10.2)	8.55	34.6 (9.1)		
6.4-7.6					7.99	20.7 (5.5)		
7.6-8.9					3.72	11.8 (3.1)		
Sum								
$m^3 x 10^6$/yr ($gal x 10^9$/yr)		38.3 (10.1)		102.4 (27.0)		71.9 (19.0)		10.6 (2.8)
$m^3 x 10^3$/d (Mgal/d)		105 (27)		280 (74)		196 (52)		29 (8)

Table 2. Ground-water recharge

Computational area	Recharge $m^3 \times 10^3/d$ (Mgal/d)
Pearl Harbor	126 (33)
Schofield	280 (74)
Koolau	196 (52)
Waialua	72 (19)
Sum	674 (178)

Table 3. Ground-water discharge

Computational unit	Discharge $m^3 \times 10^3/d$	(Mgal/d)	Period of record
Pearl Harbor	560	(148)	1960-1970
Schofield	28	(7.4)	1942-1970
Koolau	0	(0)	--
Waialua	140	(37)	1955-1969
Sum	730	(192)	

The Computation of Flux

The flux is computed across one inflow boundary (A) and two outflow boundaries (B and C), with respect to the Schofield computational unit (fig. 8).

It is assumed for the Koolau computational unit that all boundaries, with the exception of boundary A, are no-flow boundaries. There is no surface discharge from the Koolau unit; therefore, the flux to the Schofield computational unit through boundary A must be equal to the 196 x 10^3 m^3/d (52 Mgal/d) recharge to the Koolau computational unit.

The flux through boundaries B and C must be equal to the incoming flux through boundary A, plus the deep infiltration of rainfall, minus the discharge from the Schofield water body. Thus, there is 448 x 10^3 m^3/d (118 Mgal/d) that must be routed through boundaries B and C, in order to balance inflow and outflow for the Schofield unit. The Pearl Harbor unit requires routing of 434 x 10^3 m^3/d (115 Mgal/d) through boundary B to balance the difference between the 560 x 10^3 m^3/d (148 Mgal/d) discharge rate and the 126 x 10^3 m^3/d (33 Mgal/d) recharge rate, and the Waialua unit requires the routing of 68 x 10^3 m^3/d (18 Mgal/d) through boundary C to balance the difference between the 140 x 10^3 m^3/d (37 Mgal/d) discharge rate and the 72 x 10^3 m^3/d (19 Mgal/d) recharge rate.

It requires 502 x 10^3 m^3/d (133 Mgal/d) to balance the inflow and outflow from the point of view of the basal units and 476 x 10^3 m^3/d (126 Mgal/d) from the point of view of the Schofield unit. These figures should obviously be equal, the difference being caused by measurement errors or faulty assumptions. It is possible to pump the entire flux presently passing through boundaries A and B from the Schofield water body, but this location is upgradient with respect to the Pearl Harbor and Waialua units. Therefore, any increase in pumpage from the Schofield unit will ultimately require reductions in discharge primarily from the Pearl Harbor unit.

Probable Water-Level Changes in Schofield Water Body

Up to this point, the hydrologic analysis has been based on steady-state conditions and long-term averages. The analysis indicated that the Schofield water body receives 476 x 10^3 m^3/d (126 Mgal/d) in groundwater recharge and inflow across boundary A. Of this total, it was estimated that 434 x 10^3 m^3/d (115 Mgal/d) flows toward Pearl Harbor and 68 x 10^3 m^3/d (18 Mgal/d) flows toward Waialua.

Only about 28×10^3 m^3/d (7 Mgal/d) is pumped presently from the Schofield water body. Additional ground-water withdrawals from the Schofield water body will cause declines in the water levels in the Schofield water body and reduce the ground-water flow primarily to the Pearl Harbor area. The present analysis is confined to estimating the probable water-level changes that will result from increasing pumpage from the Schofield water body. Additional questions of how much and how soon the Pearl Harbor and Waialua aquifers will be affected by the increased pumpage cannot be answered at this time.

The change in water levels is dependent on not only the rate of pumpage but also on how the ground water flows past the ground-water dams that bound the Schofield water body on the north and south. It has been previously shown that the majority of the flux is through the southern boundary (B); therefore, to simplify the problem the northern boundary (C) will be assumed to be no-flow, and the problem is cast using a hypothetical single dam. It is possible that the ground water could flow (1) entirely through the ground-water dam; (2) entirely over the top of the dam; or (3) a combination of the two modes (fig. 10). The three modes of flow were analyzed using the mass-balance equation where the inflow to Schofield water body is equal to outflow plus the change in storage.

In evaluating the mass-balance equation, monthly time increments were used over a period of 36 years, 1937-72, when concurrent rainfall and water-level records were available in the Schofield area. The rainfall records at Wahiawa (rain gage 882) were considered to be representative of the time variation in recharge to the Schofield water body and water-level records at well 2901-02 to be an index of the change in storage.

Because the recharge rate (476×10^3 m^3/d) (126 Mgal/d) under steady-state conditions is large in comparison to pumpage (28×10^3 m^3/d)(7 Mgal/d) from the water body, it was assumed that the water-level fluctuations are caused exclusively by the varying recharge rate. The rainfall is highly variable, and the rate at which rainfall affects the ground-water body is attenuated depending upon the infiltration capabilities of the rocks. Therefore, the rainfall records at Wahiawa were smoothed by an arbitrary method using a weighted 12-month moving average. A comparison of the smoothed rainfall records with the water-level records indicates general agreement showing the same major fluctuations as well as many of the minor fluctuations (fig. 11).

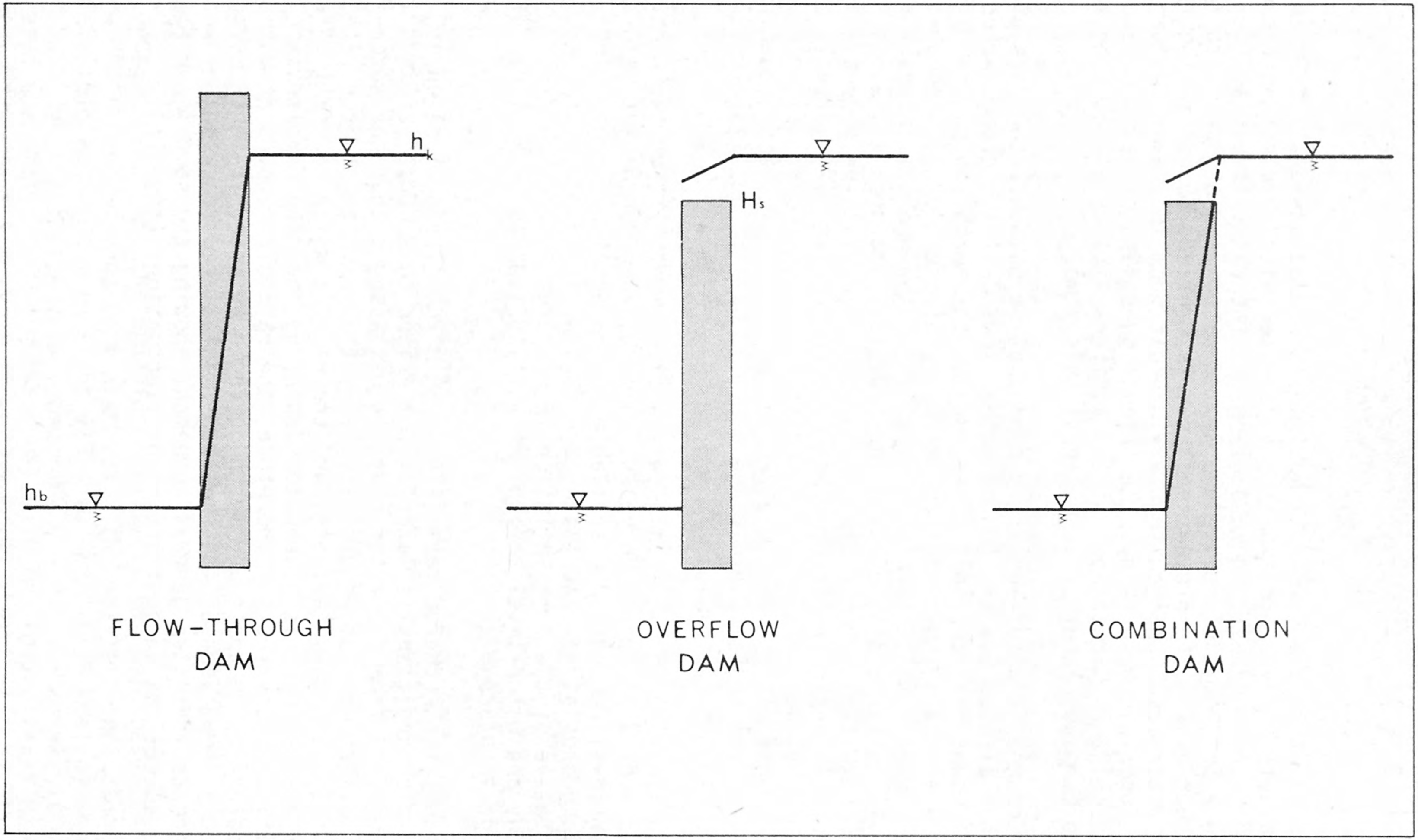

Figure 10. Possible outflow modes for the Schofield water body

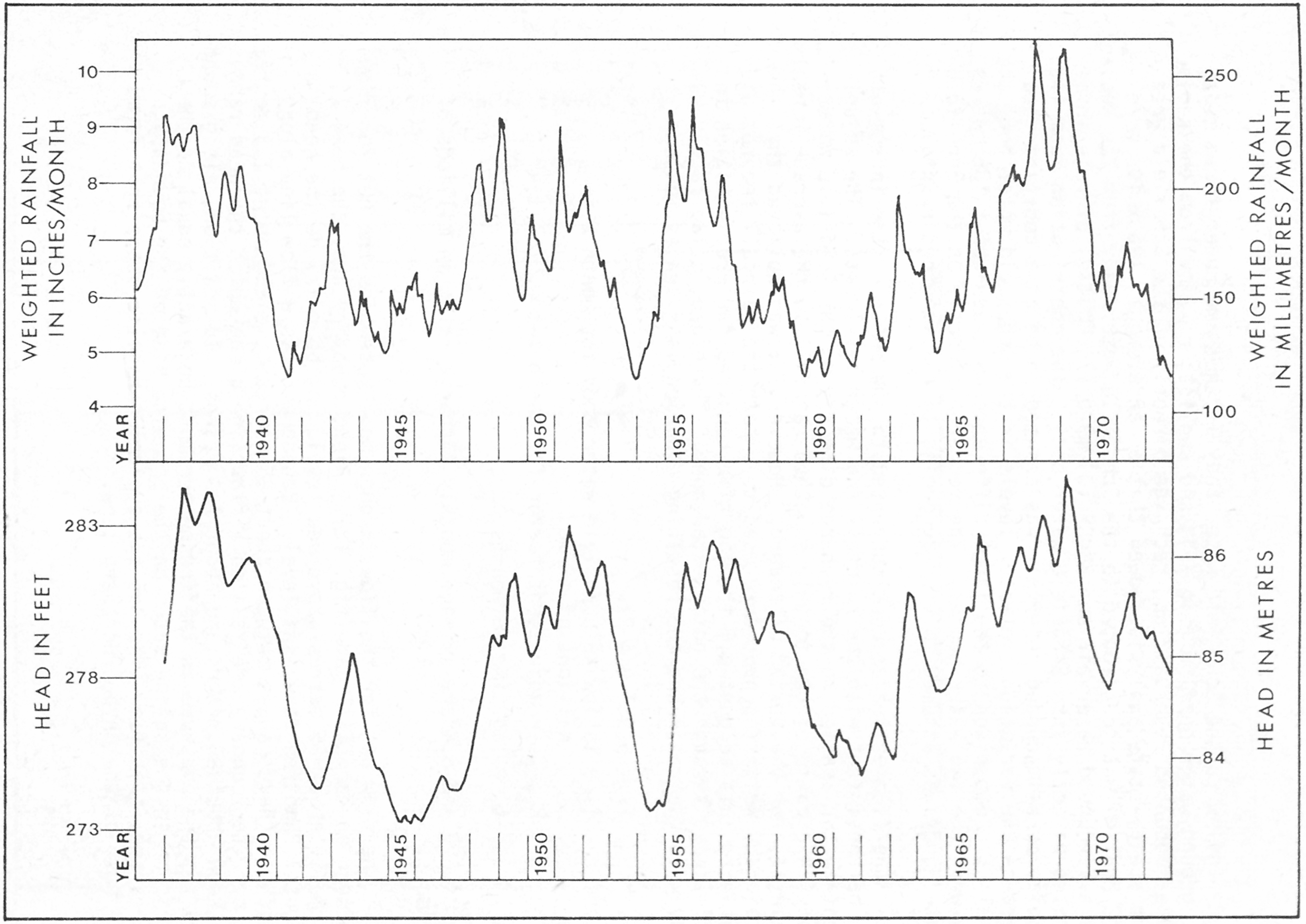

Figure 11. Smoothed rainfall for Wahiawa station 882 and ground-water head at well 2901-02

Inflow to the Schofield water body is the same under three modes of ground-water outflow (fig. 9), and consists of flow from the Koolau dike-impounded reservoir and recharge directly on the Schofield area. The steady-state analysis showed that on an average, 196 x 10^3 m^3/d (52 Mgal/d) was contributed to the Schofield water body from the Koolau dike-impounded reservoir and 280 x 10^3 m^3/d (74 Mgal/d) of rain infiltrates directly into Schofield water body. The contribution from the Koolau dike-impounded reservoir was assumed to be at a constant rate because the variations in water levels in the Schofield water body are small in comparison to the large difference in head--about 185 metres between the two water bodies. The recharge directly on the Schofield water body was assumed to vary according to the smoothed rainfall.

The flow estimates were converted to the monthly time increments to be consistent with the rainfall and water-level data. The adjustment factor applied to the recharge directly on the Schofield water body is a ratio of the monthly smoothed rainfall to the average monthly rainfall for the period of record. However, it was believed that the arbitrary weighting procedure used to smooth the rainfall records did not take into account all the lag time required for precipitation to infiltrate through the unsaturated zone. Therefore, a lag factor was added to the ratio and the resulting equation is given as follows:

$$I_t = 5.9 + 8.4\, R_{(t-\ell)} \qquad (4)$$

where I_t = inflow to Schofield water body for month t in millions of m^3/mo

$R_{(t-\ell)}$ = adjustment factor for month $t-\ell$

ℓ = lag time in months.

Terms 5.9 and 8.4 are average monthly recharge rates in millions of m^3/mo.

The flow net for the flow-through mode resembles the net for flow through an earthfill dam (fig. 12). Along boundary abc, the head is normally about 85 metres above sea level. At boundary de the head is about 7.3 metres above sea level. Boundary cd is a flow line along which the head ranges between about 85 metres at c and about 7.3 metres at d. The boundary afe is also a flow line along which the head ranges between about 85 metres and about 7.3 metres. In addition, along boundary fe, the pressure in the freshwater must be exactly equal to the pressure in the saline water on the opposite side of the boundary; therefore, this flow line has the typical parabolic shape that forms the base of the Ghyben-Herzberg lens.

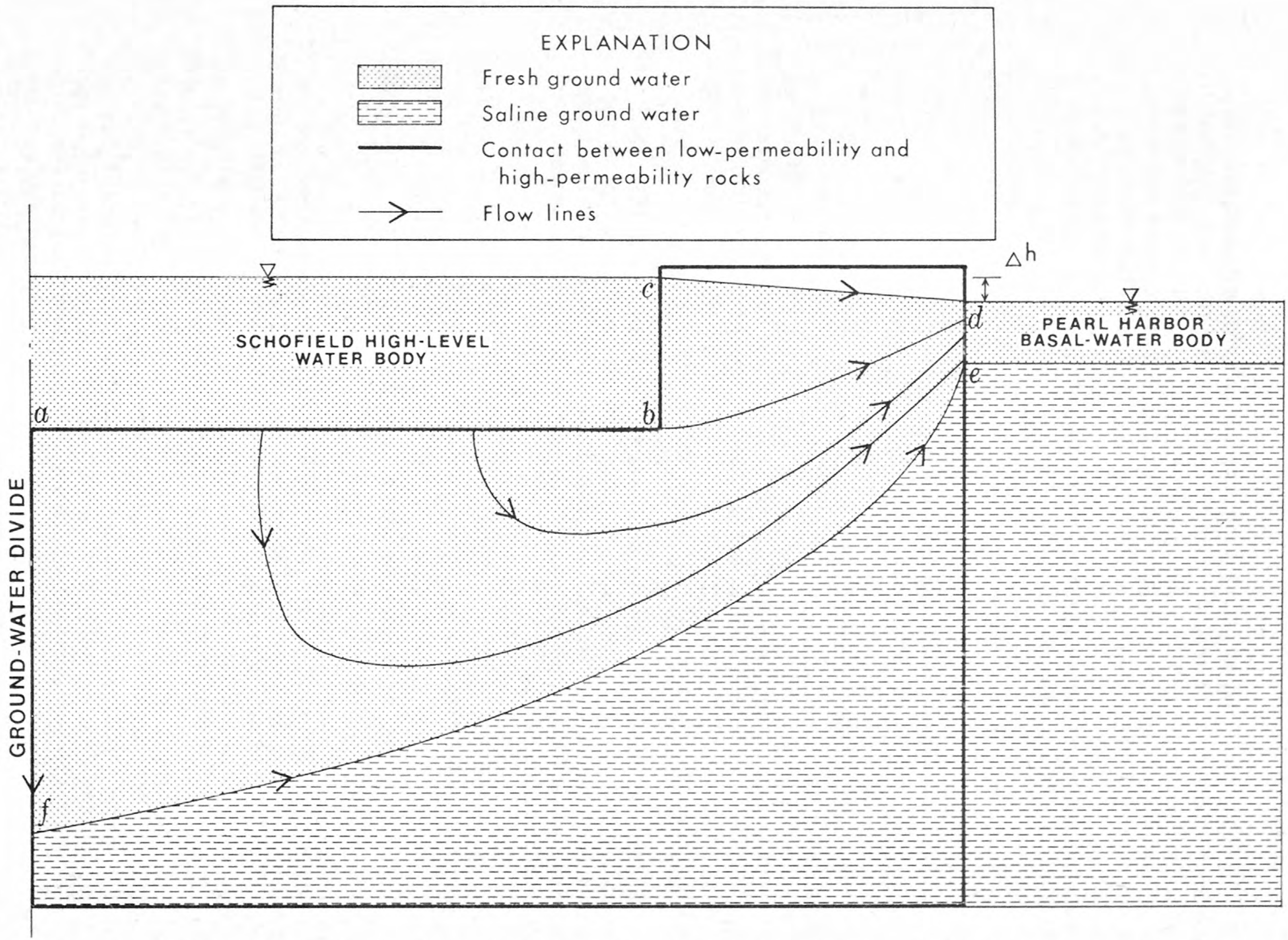

Figure 12. Schematic hydrologic section for the flow region between the Schofield high-level water body and the Pearl Harbor basal-water body

The head along boundary abc has varied between 83 metres during 1945 and 1954 and 86 metres during 1938 and 1969 (fig. 11), and the head along boundary de has remained a relatively constant 7.3 metres. For this small range of variation in head, the flux through any arbitrary control surface placed within the low-permeability rocks is linearly related to the head difference as measured at boundary abc and as measured at boundary de. Thus, the outflow under the flow-through mode is represented by

$$Q_t = A\,(h_t - 7.3) \qquad (5)$$

where Q_t = outflow for month t

A = flow-through coefficient

h_t = head of Schofield water body in month t.

The coefficient A cannot be reduced to the common terms used in ground-water mechanics, because the hydraulic gradient is not measured at all points on a control surface. In this case, the head difference is measured over a finite length, and this length varies depending on the flow line. Therefore, the coefficient A should be considered merely as a relating coefficient that relates flow through the dam to the head difference.

If the ground-water dam is virtually impermeable and all the ground water flows over the dam, the outflow is considered to be the product of a spill coefficient and the difference in head between the Schofield water body and the top of the dam. The outflow, under this mode, is represented by

$$Q_t = B\,(h_t - H) \qquad (6)$$

where Q_t = outflow for month t

B = spill coefficient

h_t = head of Schofield water body in month t

H = altitude of top of dam.

As with the coefficient A, the coefficient B cannot be reduced to the common terms used in ground-water mechanics, and B should be considered merely as a relating coefficient.

If the ground-water outflow is considered as occurring by both flow through and over the top of the dam, then equations 5 and 6 can be combined to yield

$$Q_t = A\ (h_t - 7.3) + B\ (h_t - H). \qquad (7)$$

The volume change in storage per unit change in time is given by

$$\Delta V_w = S\ A_{swt}\ (h_t - h_{t-1}) \qquad (8)$$

where ΔV_w = volume change in storage
S = the storage coefficient
A_{swt} = area of the water table for the Schofield water body
$(h_t - h_{t-1})$ = monthly change in water levels at shaft 2901-01.

The water-table area of the Schofield water body is 88 x 10^6 m^2 as planimetered from a 1:62,500 scale map. Therefore, the storage change in millions of cubic metres can be expressed as

$$\Delta V_w = 88\ S\ (h_t - h_{t-1}). \qquad (9)$$

Based on equations 5, 6, 7, and 9, the mass-balance equations for the three modes are shown below:

Flow-through mode

$$5.9 + 8.4\ R_{t-\ell} - A\ (h_t - 7.3) - 88S\ (h_t - h_{t-1}) = 0 \qquad (10)$$

Flow-over mode

$$5.9 + 8.4\ R_{t-\ell} - B\ (h_t - H) - 88S\ (h_t - h_{t-1}) = 0 \qquad (11)$$

Combination mode

$$5.9 + 8.4\ R_{t-\ell} - A(h_t - 7.3) - B(h_t - H) - 88S\ (h_t - h_{t-1}) = 0. \qquad (12)$$

In the above equations, data are available for only h_t and h_{t-1}, the monthly water levels at well 2901-2 in the Schofield water body, and R_t, the monthly rainfall adjustment factor computed from the Wahiawa rain-gage records. Values for the remaining parameters (ℓ, A, B, H, and S) are unknown, and these values were obtained from a computer analysis of more than 400 equations using monthly water-level and rainfall data. By use of an iteration process and substituting values for the unknowns, the absolute value for the equation error was minimized.

The three modes of ground-water flow were analyzed using the above procedure and the best-fit values for the unknown parameters were determined. Using these values and the historical rainfall records, monthly values of water levels were computed and compared to the actual records. On the basis of this comparison, the combination mode provided the best fit. The computed values of the unknown parameters for the combination mode are shown in table 4 and the comparison of the computed and actual water-level records is shown graphically in figure 13.

The probable water-level changes in the Schofield water body resulting from increased pumpage can be estimated using the computed values of the parameters. Outflow from the water body is the recharge less the pumpage and is dependent upon the head. Therefore, the head in the water body is a function of pumpage, and a relationship (fig. 14) was developed from pumpage and the mode equations. This relationship shows that almost 130 x 10^3 m^3/d (34 Mgal/d) can be pumped from the Schofield ground-water body before the head is reduced to the crest of the ground-water dam (79 metres). Pumpage in excess of this amount will cause the head to drop much more rapidly.

SUMMARY

The Schofield high-level water body is part of a complex ground-water flow system resulting from an impoundment by ground-water dams. An estimated 481 x 10^3 m^3/d (127 Mgal/d) of ground water flows through this water body, with most of this flux passing through the southern ground-water dam to replenish the Pearl Harbor basal-water body. Therefore, any additional withdrawals from the Schofield water body would divert recharge from the Pearl Harbor basal-water body.

The decline in ground-water levels in the Schofield area would be limited to less than 6 metres until pumpage exceeds 139 x 10^3 m^3/d (34 Mgal/d), which is equal to the average amount of water being spilled over the top of the southern ground-water dam. Pumpage in excess of 130 x 10^3 m^3/d (34 Mgal/d) would cause a much larger decline in ground-water levels.

Because of the high head in the Schofield water body, it is extremely unlikely that saltwater would ever become a problem in the Schofield area, but pumpage from the Schofield area will in time intensify the saltwater problem in the Pearl Harbor area.

Table 4. Schofield ground-water reservoir parameters

Parameter	Description	Combination mode
ℓ	Lag time for infiltration of rainfall to the water table, adjusted for lag introduced by rainfall smoothing ----------	6 mo
A	Relating coefficient for flow through the dam -----------------------------------	.0042 m^2/mo
B	Relating coefficient for spill over the top of the dam -----------------------	.023 m^2/mo
H	Height of the top of the dam --------------	79 m
S	Ground-water storage coefficient ----------	0.064

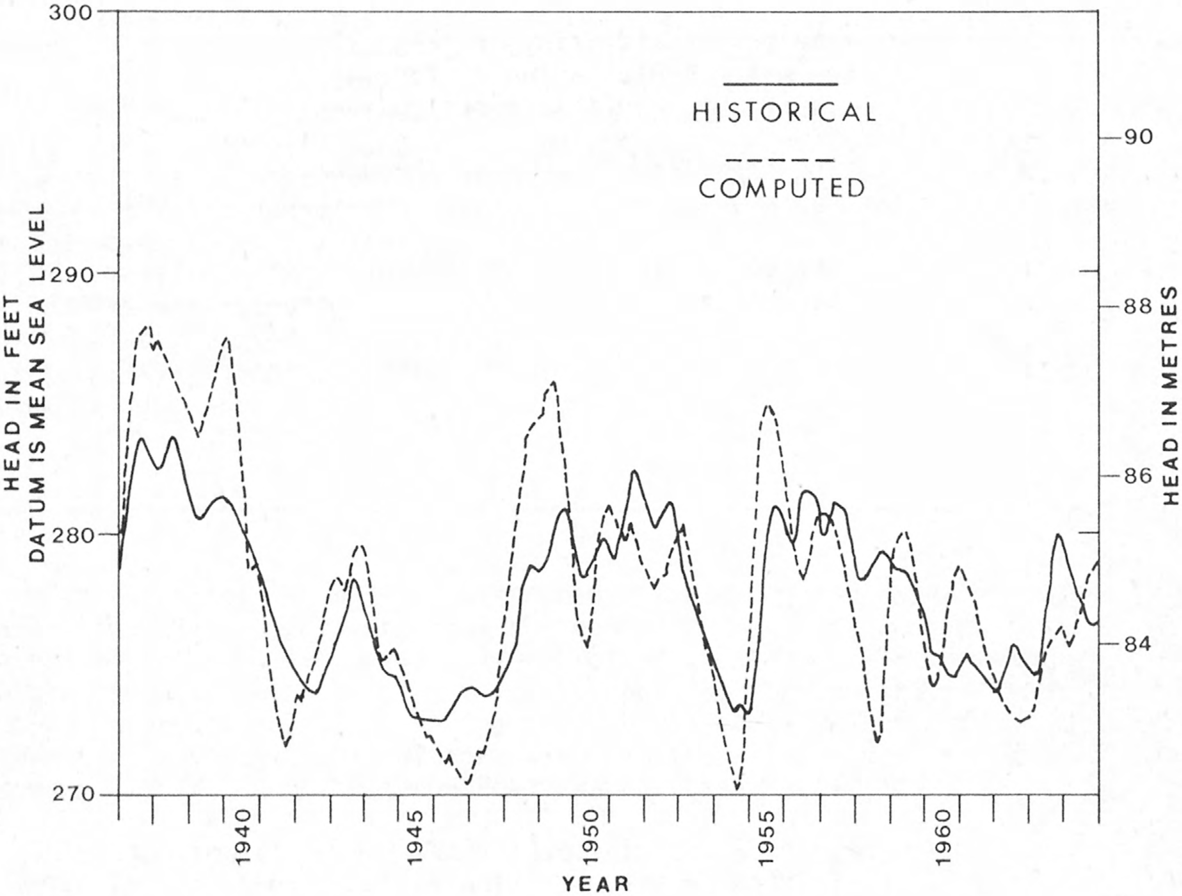

Figure 13. Comparison of the historical head with the computed head

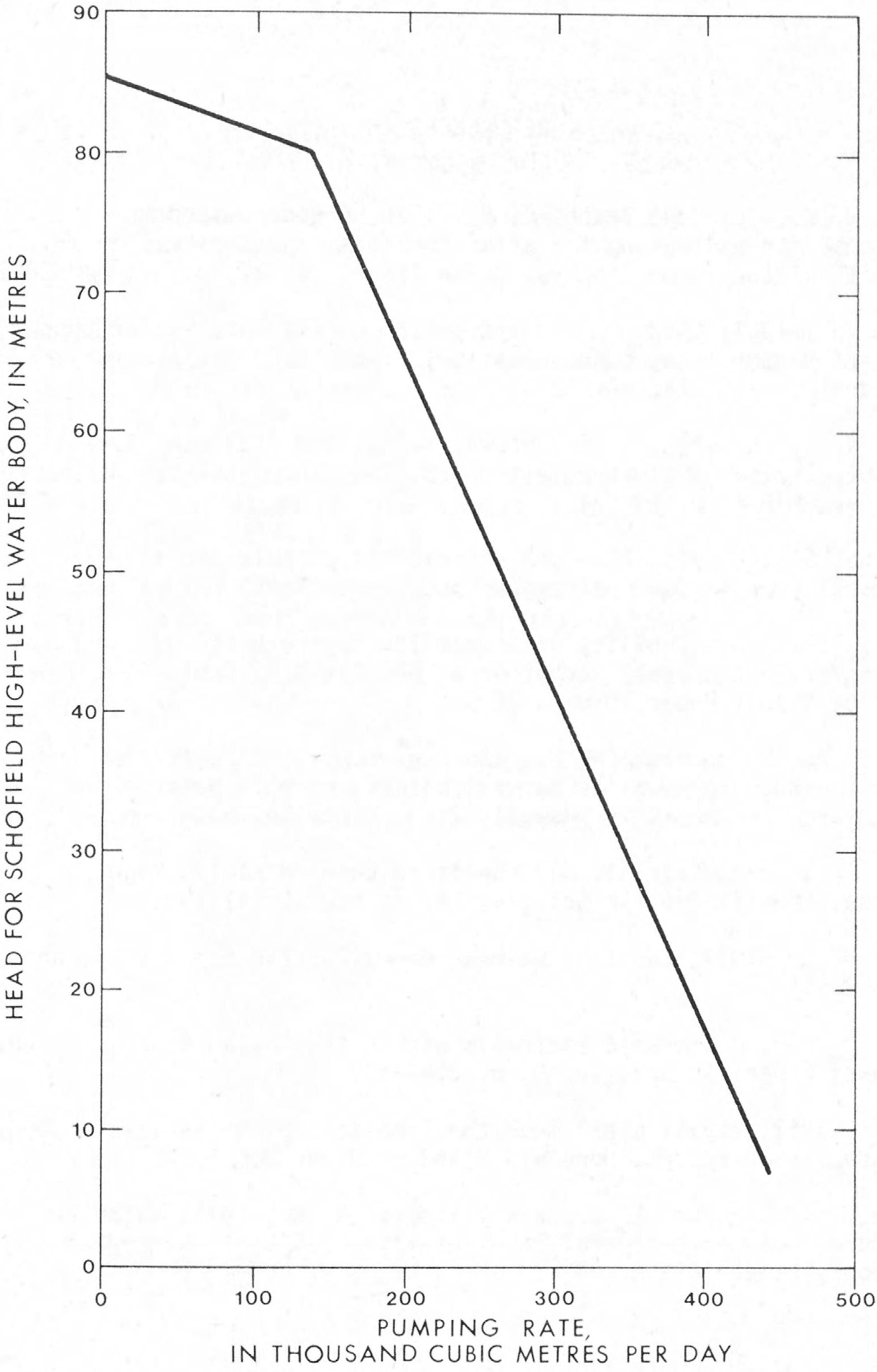

Figure 14. Predicted steady-state head as related to pumping rate for the Schofield ground-water body

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