GEOLOGY AND GROUND-WATER RESOURCES OF OF THE PEARL HARBOR DISTRICT

BY

CHESTER K. WENTWORTH

BOARD OF WATER SUPPLY
HONOLULU — 1945

BOARD OF WATER SUPPLY
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GEOLOGY AND GROUND-WATER RESOURCES
OF THE
PEARL HARBOR DISTRICT

by

Chester K. Wentworth

Board of Water Supply
Honolulu, Hawaii
1945

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greatly from 250 feet per mile except on the eastern side where the over-all slope is near 500 feet to the mile. Data are insufficient to define a cliff or bench in any particular position. 63

23 - Detail of compound dike in the dike complex on the road to Waikane, windward slope. The close jointing of these dikes undoubtedly has its origin in the stresses set up at the time of cooling but at depth underground apparently does not take the form of openings capable of transmitting significant amounts of water. The release in the form of visible cracks seems to come only after the reduction of pressure near the surface. Negative No. 1372. 100

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INTRODUCTION

Location and extent

This report deals with the entire Ewa District excepting that part which lies on the eastern and southern slope of the Waianae Range immediately underlain by Waianae basalt. The report therefore overlaps the Halawa portion of the Moanalua-Halawa report and is intended to cover all that part of the leeward slope of the Koolau Range which lies northwest of the Honolulu District (Red Hill ridge) and south of the Schofield saddle divide. This divide separates the drainage of Waikakalaua Stream, which flows southward to Pearl Harbor, and that of Kaukonahua Stream, which flows northward to Waialua Bay. (See Figure 1) The Koolau portion of the Ewa District is a well-marked natural unit. It includes the whole Koolau slope which drains to Pearl Harbor and no other part, and so far as we know it includes a similar area of ground-water drainage entering Pearl Harbor. It has been conspicuous since prehistoric time for the great Pearl Harbor Springs.

The part of the Ewa District excluded from this report is the relatively small portion lying on the eastern and southern slope of the Waianae Range which was high enough so that it was not overlapped by the later Koolau lavas that form the larger part of the flatter slopes between the two ranges. Because the geologic and hydrologic conditions of the Waianae

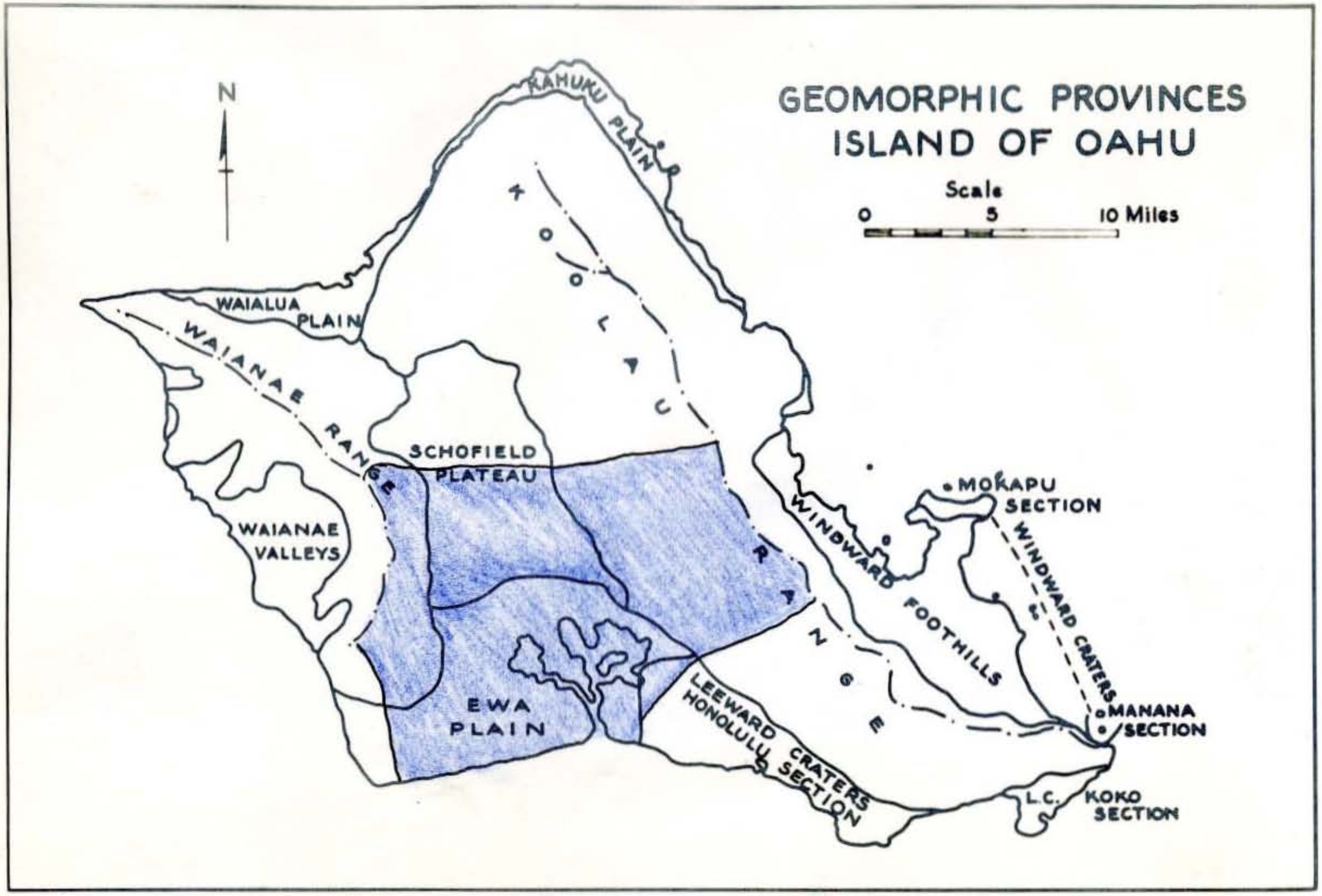

Figure 1 - Index map showing chief geomorphic provinces of the Island of Oahu. Included in each province is an area in which a similar type of topography is found and in which a somewhat uniform history of land-form development has prevailed during geologic time. The area shaded in blue is the Pearl Harbor district treated in this report.

Range are quite distinct it seems best to limit the discussion at this point. The relationship between the Koolau and Waianae Ranges is described elsewhere (1).

Included in the Pearl Harbor area are the chief leeward Koolau valleys of South and North Halawa, Kalauao, Waimalu, Waimano, Waiawa, Kipapa, and Waikakalaua. At the northwest and west are Waieli and Honouliuli valleys. Finally there are the lower dome slopes and wide, fringing reef plain adjacent to the mouths of all these streams around Pearl Harbor. The area is bounded on the southeast by the boundary of the Honolulu District, which runs from a point east of Fort Kamehameha through Puuloa Station, thence east of Makalapa Crater and northeast along the Red Hill ridge to the Koolau crest at the middle of the head of Haiku Valley. From here the boundary runs northwestward nearly 10 miles along the Koolau crest to Puu Kaaumakua beyond the head of Waikane Valley, whence it runs generally westward between the valleys of Kaukonahua and Waikakalaua streams to a point south of Wahiawa. The boundary continues westward so as to include branches of Waikeli Stream which heads near Kolekole pass. The line is then drawn approximately along the lower margin of the outcrop of Waianae basalt, as previously mapped, and thence on a southwesterly line running east of the railway station Gilbert to Barber's Point. The

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(1) Wentworth, C. K., and Winchell, H., The Koolau Basalt Series, (In course of preparation) 1945.

total land area of this hydrologic district is 131 square miles and it is thus not only much larger than any of the components of the Honolulu District on which reports have been prepared but has over twice the area of all these together.

Purpose, scope and methods of study

Methods used in this study were similar to those used in earlier studies and are therein described. However, the proportionate emphasis on different aspects of the work has been materially different. In the eastern part of the area, especially Halawa, a moderate amount of detailed traversing of the mountainous area was completed, as reported in the Moanalua-Halawa report. There has been increasing reason, partly because of the smaller number of dikes found and partly because of the greater length of valleys, to doubt if specific structures having critical local bearing on the water supply conditions would be found and to doubt if a traverse net on a scale comparable to that used in the central and eastern Honolulu area was likely to prove profitable.

The very much larger area involved, the greater length of valleys, and relatively greater difficulty of access as well as the curtailment of assistance during the latter part of the war period have prevented continuing the detailed mountain work described in earlier reports. Furthermore, the change in the character of the geologic structure of the valleys, with lack of post-Koolau volcanic rocks and of perched water bodies in valley fills, has reduced the expectation of finding specific high-level water bodies in the inland mountain country.

All these conditions have dovetailed with the centering of hydrologic problems around the Pearl Harbor Springs, the large number of artesian wells and heavy draft for irrigation in the Pearl Harbor area. Opportunity in the Pearl Harbor area to study, in close juxtaposition the relationship of free basal water and artesian basal water is superior to that in the Honolulu area because of the dissection of the caprock by the arms of Pearl Harbor and because the upper surface of the caprock is graded to only a few feet above sea level. The contemporary shift from development of ground water by artesian wells to development by basal shafts has been greatly accelerated at present in the eastern Pearl Harbor area. Hence understanding of these relationships is of the greatest importance and has required consideration in the present report equally of the geologic factors and of overall hydrologic data, available up to the end of 1944.

History and acknowledgments

Earlier reports of this series have set forth the history of geologic work and of this study. The Moanalua-Halawa report was completed in 1942, after the outbreak of the Pacific war, and all work for the present report has been done during war time and much of it in close proximity to many construction projects related to the war. Without insisting on any need for detailed examination of all excavations, interesting as these might be from a geologic standpoint, the writer has at no point encountered sustained objection to such observations in military areas and projects as have been deemed essential to the present study. Officers and men of the military service, as well as contractors and employees, have without exception been courteous and helpful in making necessary arrangements as to passes, or escorts, or permission in special instances to take photographs. Other than in the avoidance of military installations and shorelines in wide range and panoramic views, there has been no restriction in the taking of all geologic photographs that would ordinarily be taken.

Rijo Hori served efficiently as general laboratory assistant, draftsman and computer, as well as taking part in many field operations, until his transfer to the division of water resources, January 1, 1944. Masami Iwamura proved a very effective field assistant until his transfer on June 1, 1943 to the commercial division. Dan Cain served as field assistant during the summer of 1943. Rose Umeda and George Adachi were employed as Under Physical Science Aides commencing in June 1944, and have provided valuable assistance while learning the duties and practices of the division. Finally, the writer is especially under obligation to Ellwood Bartz, Associate Engineer, who compiled data of various sorts in the latter part of the report and took charge of much of the detail of arranging both text and illustrations. His suggestions and criticisms, at times challenging, have led to material improvement and clarification at various points.

GEOGRAPHY

Geomorphic divisions

The relationship of the Pearl Harbor district, as treated in this report, to the geomorphic divisions recognized on the Island of Oahu is shown in Figure 1. Parts of five divisions are represented. The main, inland drainage area is part of the Koolau Range, leeward slope. (See Figure 2) A part of the intermediate upland of the northern and longer stream basins is included in the Schofield Plateau, and the coastal margin includes almost the whole of the Ewa Plain, the lowland which wholly surrounds Pearl Harbor. A small section of the Leeward Craters area is included. The line between the Koolau Range province and the Ewa Plain province is much less distinct in this area than is the margin of the range in the Honolulu area, since in this Pearl Harbor bight there is no very marked cliff cut against the range. However, the spurs of the Koolau dome rise inland from the level of the plain at rates of 250 to 500 feet to the mile, so that the flats of the intervening valleys are set off by valley wall cliffs and Koolau rock is exposed in numerous low road banks where the older roads border

Figure 2 - Panorama of apron area and Koolau Range from Honolulu on the right to the Waikakalaua-Kaukonahua divide on the left. View from point north of Schofield road junction over-looking Waiawa Valley. Negatives No. 21798-9-800.

the ends of spurs.

On the other hand, the line between the Schofield Plateau and the Koolau Range, though these are two perfectly justifiable and distinct divisions, has to be drawn somewhat arbitrarily in any particular locality. Finally, the line between the western part of Ewa Plain and the Plateau is not topographically sharp but can usually be discriminated on the basis of soil color, the residual soil of the Plateau being red and the soil derived from the transported deposits of the adjacent margin of the Plain being brown.

Topography and drainage

GENERAL

The central portion of the Koolau Range trends almost exactly in a southeast to northwest direction. The leeward margin of the part included in the Koolau Range division is a line which is only slightly convex toward the southwest, facing two separate geomorphic divisions. In the area covered in this report, these are the Ewa Plain and the Schofield Plateau. The Schofield Plateau is a wide extension of the Koolau dome which extends to the southwest some six to eight miles beyond the corresponding dome margin in the Honolulu and Pearl Harbor areas. This plateau abuts on the Waianae dome at elevations of nearly 1000 feet in the central portion and it is evident that the Koolau dome slopes, in this section, are very much less than those of the southeastern part of the leeward slope. The joining of the Waianae and the Koolau domes above sea level by the building of the Schofield plateau left the well-protected bight in the coast in which Pearl Harbor and the Ewa Plain have been shaped.

THE KOOLAU MOUNTAIN AREA

The mountainous part of this district is a section of the leeward slope which has a straight line width along the crest of the range of 8 miles. The length of successive valley segments is nearly uniform at 6 miles, with variations of less than a mile caused by the slightly crenulate pattern of the crest due to alternating heads of leeward and windward valleys. At the lower margin of the mountainous section the width, measured parallel to the crest as before, is 10 miles, the increase of 2 miles being due to the slight divergence caused by the convex form of the dome.

Elevations along the crest of the range in this section vary from 2200 to 2800 feet, with the low points and high points determined more particularly by the positions of the steeper windward valleys than by the shapes of the leeward valleys. The crest of the range in this section is very slightly convex toward the leeward coast in its horizontal pattern and is marked by about four local convexities in the same direction, which are caused by the eroding heads of the major windward valleys of Haiku, Kahaluu, Waihee, and Waiahole. In the heads of these valleys, the cirque-like slope falls off 1200 to 1500 feet at overall angles of 55 degrees, with an intermediate wall, commonly 500 feet or more, at 70 to 80 degrees. Between these valleys are buttress ridges that extend toward the windward coast a mile or more before reaching the 1000-foot contour. The ensemble of these valley heads and intervening spurs, seen from the windward highway two to three miles distant, is the windward pali (cliff) and is only slightly less striking than the pali of the Nuuanu or Waimanalo sections as seen from Kailua and Lanikai.

The mountainous leeward slope of this district is made up of the drainage basins of five major stream systems which drain into Pearl Harbor. At the Forest Reserve line there are 8 major through valleys, but three of these merge with others before reaching the coast. Toward the range crest several of the valleys expand to form rather broad basin heads, separated by the slightly more distinct ridges that lie between the basins, but themselves divided by the shorter ridges that are cut off with the merging of the several head branches. Some of these features will be brought out by the following brief, valley by valley, description. (See Figure 3)

The Halawa basin in its lower portion is about 1½ miles wide and the two valleys of North and South Halawa streams are here nearly equal in width. They are separated by a flow-slope facet, somewhat cut by branches which mostly flow to

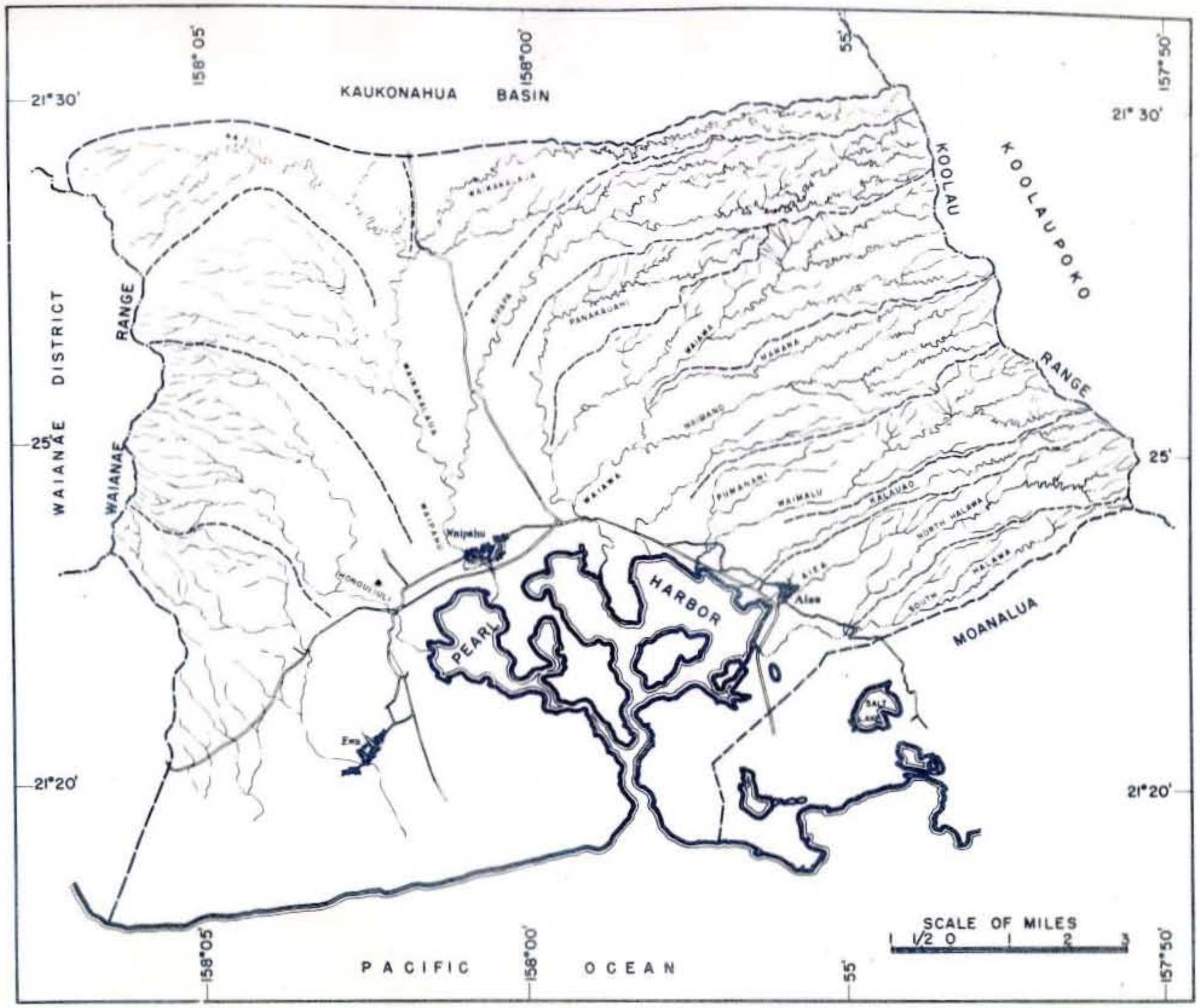

Figure 3 - Sketch map showing chief streams and drainage basins in the Pearl Harbor district. Based on U.S.G.S. map of Oahu, 1/62500.

South Halawa Stream. Farther inland the head of North Halawa basin is much expanded and is drained by several large branches, over a mile in length, which head at the Koolau crest. In the corresponding inland portion, the head of South Halawa Valley consists of a single, unbranched channel. This is one or two hundred feet higher than adjacent branches of North Halawa and at one point comes within less than 75 feet of spilling over into the North Halawa drainage. It is probable, though perhaps not susceptible of proof, that the North Halawa head drainage has grown by piracy of branches from South Halawa in earlier erosional stages.

Kalauao Stream drains a single, unbranched valley which heads at the Koolau crest. The basin is 1/3 to 1/2 mile wide and about 6½ miles long. For nearly 3 miles of the inland portion it is separated from North Halawa by a typical knife-edge ridge and in the seaward portion the large Aiea facet intervenes.

Waimalu Stream drains a basin that is 1¼ to 1½ miles wide from the Koolau crest to the coast. The stream has several branches on each side and its head is composed of four branches a mile or more in length, which reach the crest. These branches converge successively and the combined main channel starts at a junction about 1½ miles from the crest and less than 700 feet above sea level. A large branch, Punanani, drains much of the facet on the north side and joins

Waimalu channel near the margin of the coastal plain.

The next stream system to the northwest is Waimano, which consists of three long head branches, 2¾ to 3½ miles in length, and several other small branches farther seaward. The basin is 1¼ to 1½ miles wide and the main channel is formed by convergence of the long head branches at nearly 3½ miles from the crest and only 500 feet in elevation. Waimano Stream joins Waiawa Stream at the margin of the range and has no separate mouth. Waiawa Stream has two chief long branches which receive seven or eight short tributaries from the Koolau crest over a width of about 2 miles. The junction of the two chief branches is just outside the Forest Boundary and Manana, a less deeply eroded third branch drains a narrow basin to the south and fails by a half mile to reach the Koolau crest.

The next large drainage system in the mountainous area is that of Kipapa Stream, which at the crest of the range has at least 4 large branches and farther downstream has various others. This system in the inland mountainous area has about the same length as other streams but also follows a long curving course on the gentler surface of the Schofield Plateau province. The main channel of Kipapa is formed by confluence of head branches at about 3 miles from the crest of the range and at an elevation of about 1000 feet. At its lower end, at a point about 2 miles north of the end of West Loch of Pearl Harbor, Kipapa Stream joins with Waikakalaua Stream to form Waipahu Stream (generally called Waikele Stream) which flows into Pearl Harbor west of

Waipahu.

Between the well defined valleys of Kipapa and Waiawa, owing to the wide bend of the former on the Schofield Plateau, there is a stream system consisting of the trunk and several branches of Panakauahi Stream, which drains an area of several square miles. This stream at present enters the lower channel of Waiawa but topographic relations indicate that it once had a separate outlet to the head of Middle Loch. The system reaches only a short distance inside the Forest Reserve line to about 1500 feet and is comparable to the basin of Aiea Stream which drains the Aiea facet.

Waikakalaua Stream is the last and longest of the streams that drain from the Koolau crest to Pearl Harbor. Measured to the mouth of Waipahu Stream the minimum length of the valley is more than 20 miles and there is little doubt that the channel length by detailed tape measurements would be well above 30 miles. The whole mountain section of the basin is narrow, being but little over a half mile wide on the average, and there are few tributaries. The divide between this basin and that of Kaukonahua Stream is the northern limit of the territory covered in this report, since Kaukonahua Stream drains to the north coast.

Waikakalaua Stream swings to the westward in a bend still wider than that of Kipapa Stream, both being fundamentally determined by the slope of lava flows on the broad apron of the Koolau dome. Waikakalaua Stream at a point about 5¼ miles

Waikele

north of Pearl Harbor, West Loch, is joined by Waieli Stream which comes down the slope of the Waianae dome from a point near Kolekole Pass. The main channel of Waikakalaua is joined 3½ miles farther south by the water from Kipapa Stream, and from that point seaward is designated Waipahu Stream by recent decision of the Advisory Committee on Geographic Names, in accordance with the best evidence as to past usage. (1) Some four miles of the eastern slope of the Waianae Range south of Kolekole Pass drains into this Waipahu system making it a large triangular area, one of the two largest drainage basins

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(1) The Sixth Report of the U.S. Geographic Board, 1890 to 1932, gives the following pertinent decisions:

Waikele: land division, Ewa District, Oahu, T. H.

Waieli: stream tributary to Waikakalaua Stream from the west, Ewa District, Oahu, T. H.

Waikakalaua: stream, rising in Koolau Mountains, flowing southward, joining Kipapa Stream from the west to form Waipahu Stream, Ewa District, Oahu, T. H.

Kipapa: stream, rising in Koolau Mountains, flowing southward, joining Waikakalaua Stream to form Waipahu Stream, Ewa District, Oahu, T. H.

Waipahu: stream, formed by junction of Kipapa and Waikakalaua streams, flowing southward into West Loch of Pearl Harbor, Ewa District, Oahu, T. H.

Excerpt from letter written by Max H. Carson, Chief Hydrographer to R. D. King, Advisory Committee on Geographic Names, Oct. 22, 1943.

on Oahu. (See Figure 4)

South of the head of the Waipahu drainage basin is a section drained by head branches of Honouliuli Stream, which enters Pearl Harbor, and by other streams flowing directly to the margin of the Ewa Plain east of Barber's Point. For the most part, the head portions of the basins from Halawa to Waikakalaua, inland from the points of the flow-slope facets, constitute a mountainous terrane of maximum ruggedness, with practically no flat land and chiefly in heavily wooded slopes of 35 to 80 degrees. This is an area of nearly 40 square miles, with a prevailing relief from valley bottom to ridge crest of 700 to 1200 feet. Seaward from this belt is one in which the ridges widen to triangular flow-slope facets, commencing at elevations ranging from 1600 to 1000 feet, and sloping thence down to less than 100 feet where the surface of the dome merges with surrounding terrace surfaces. Between the flow-slope facets each of the major valleys is a steep-walled canyon, with walls increasing in height progressively inland, and commonly having a moderately flat bottom 500 to 1500 feet wide. In this section because of lower annual rainfall the valley walls are less fully covered by vegetation and the stratification of the sloping lava flows is more clearly and continuously shown than in the mountain section where rock exposures are few and only rarely visible from a distance. (See Figures 5, 6, and 7)

Fig. 4 - View across part of surface of Koolau apron to southern half of Waianae Range, from point east of Honouliuli Valley at elevation about 360 feet. Negatives No. 21626-7.

Figure 5 - Panorama looking inland in South Halawa Valley from point on boundary of Honolulu and Ewa Districts. At left is view of sliver spur and small valley beyond it. In the bottom of the main valley is a characteristic meandering of the stream channel and alternation of talus spurs. Negatives No. 21240-1.

Figure 6 - Panorama looking inland from ridge west of Waimalu, showing mountain topography and crest of the Koolau Range. Negatives No. 21576-77-78.

Figure 7 - View of Kipapa Gulch at main highway crossing in Longitude 158-01. The horizon is the profile of the apron surface and the north end of the Waianae Range shows at the left. Negatives No. 21790-91.

THE FLOW SLOPE SURFACE

The general character of the triangular remnants of the original dome slopes that are called flow-slope facets has been set forth in other reports in the Honolulu area. In the Pearl Harbor area, well marked facets are found all the way northward to the Schofield divide. The inland apexes and the margins overlooking the valleys on either side are typical but at the north the seaward portions are not sharply limited and become elongated into a nearly continuous apron with slopes generally as low as 150 feet or less to the mile. These are to be compared with the slopes of the inland portions of facets which amount to 300 or 400 feet per mile in this area and approach 500 feet in parts of the Honolulu area. (See Figure 8)

The inner apex of a facet is the point where the facet gives way to a single sharp ridge directly overlooking two major valleys. We find that some of the facets of the Pearl Harbor area, especially those having apexes at elevations of over 1200 feet, are much dissected in the inland portion, and have surfaces that are not wholly mantled by basaltic residuum. A good example is the Aiea facet which is cut into several sub-areas by the branches of Aiea Stream. This facet has an apex at Puu Uau, at elevation 1656. However, seaward from this point is a maze of ridges and moderately deep valleys and the inland limit of fairly unbroken surface mantled by residuum could be drawn through several subordinate apexes such as that inland from the Navy Hospital at about 1000 feet. This is purely

of Waimalu Valley at about 700 feet, showing head of small,
aianae Range to the left. Negatives No. 21571-75.

Figure 8 - Panoramic view from point on facet west of Waimalu Valley at about 700 feet, showing head of small, branching valley on facet, with apron surface and Waianae Range to the left. Negatives No. 21571-75.

a matter of definitions; from a distance the triangular, tabular unity of the larger facet ending at Puu Uau, is well indicated, but to an observer on the facet itself the separation of the unbroken units of arable land by the intervening forest or scrub terrane is equally evident.

Preservation of the facet areas from erosion is partly a matter of geometry; the lower gorges of major streams are farther apart, and cut less deeply, hence invade the facet slopes less than in the inland area where the heads of expanded tributaries merge at the knife-edge ridge. The difference is due in part to the lower rainfall of the lower leeward slope, which induces a less active erosion and development of tributaries. We can conclude that if the geometric arrangement of major valleys is such as to leave a large and long facet, such as that at Aiea, then it is likely because of its relation to increased rainfall that the inland portion will be considerably dissected.

THE SOUTH SCHOFIELD APRON

This is the southern half of what has been called the Schofield Plateau, or which might be called the Schofield saddle. Morphologically, this is only one of the typical saddle areas in Hawaii; others occur on other islands where the lavas of a later cone form a gently sloping saddle enveloping the steeper slopes of an earlier cone. (Cf. the isthmus of Maui or the Humuula saddle of Hawaii) It is often said that the lavas of the later cone "ponded against the slope of the earlier cone". Though this is somewhat vivid and suggestive, it cannot be literally true since no saddle area has ever been at one time flooded by such volumes of lava as to assume a widespread level or unit hydraulic surface. The appearance of lowered gradient must be explained by recurrent retardation of successive flows under a more complex set of both hydraulic and thermal conditions. Discussion of the possible mechanics of saddle and apron formation is beyond the scope of this report. We here only emphasize the fact that an area of nearly 50 square miles south of the Schofield divide is underlain by lava flows at slopes as low as 150 feet to the mile and that the upper surface of these flows is as much a part of the Koolau dome slope as any of the steeper parts. Because of these low slopes and the limited rainfall of the area, erosion is slight and there is only a very moderate dissection by streams arising locally. The area is crossed by the channels of the major streams flowing in valleys that are commonly 200 feet deep and 1000 to 1500 feet wide, rim to rim. Between these valleys are areas a few square miles in extent that are not broken by any irregularity other than the prevailing slope of about 150 feet to the mile.

THE TERRACE FRINGE

Seaward from the margin of exposed Koolau surface there are two chief morphologic units, the coastal terrace which has been called the Fort Shafter terrace and the reef flat known in its chief area as the Ewa Coral Plain. The terrace formations will be described in the section, FORT SHAFTER TERRACE FORMATION. The topographic surface is not readily distinguished from that of the apron of Koolau residuum with which it merges. Mapping of its inner margin in the western area, where the apron has such low slopes, relies chiefly on distinctions of soil color plus relationship to Koolau bedrock. In the eastern part of the area and locally in the central part around Waipahu, where erosion exposes the edge of the terrace and its formations, it can be more easily recognized. In certain areas both the Ewa Plain and the terrace have gained considerable contributions from the tuff thrown out during Salt Lake eruptions. However, except at the eastern margin of the area, in the craters Makalapa and Aliamanu, the tuff of secondary eruptions cannot be regarded as a major topographic element and will in this section be treated simply as a component of the formations which underlie the terrace or reef flat surfaces.

THE EWA CORAL PLAIN

Both east and west of the entrance to Pearl Harbor the rock structure underlying the coastal flats consists chiefly of coral, as stated in the section, EWA CORAL REEF FORMATION. On the east side all but the seaward parts of the coral reef formation are thinly covered by tuff from the Salt Lake vents. At various points around the landward margin of the harbor there are scattered masses of coral reef. However, it is on the west side in a belt 3 or 4 miles wide and extending from the harbor entrance to Barber's Point, that the coral plain is most conspicuous. Much of this surface has no other soil than coral sand, or clay soils derived from marine formations. There is practically no fertile soil and a good share of the surface shows solution-pitted, rugged, coral reef rock, on which grows chiefly algaroba scrub, scattered desert grasses and other thorny plants.

DRAINAGE PATTERN

The drainage pattern of the Pearl Harbor area is the product of several factors and shows the effect of these in its different parts. Originally there was a series of radial streams, consequent on the leeward slope of the Koolau dome. The head portions of the major streams from Halawa to Waikakalaua are of this type. Most primitive of these streams is Kalauao, which has practically no tributaries. Others in some degree have responded to the tendency toward integration and have developed a more complex pattern, with head tributaries, or mid-channel branches, or even second or third order tributaries. In the mountainous section, the Kipapa system is the most mature, with a rather complex, semi-dendritic, though elongated pattern.

The second factor in determining pattern of streams in this area is the saddle and apron form of the south slope of the Schofield Saddle. Here the detailed courses of lava flows are no longer traceable but there is little doubt that the pattern was closely similar to that of the present channels of Waiawa, Kipapa, and Waikakalaua streams.

Downhill has for many thousands of years been the same direction for streams as it was for the later lava flows in the course of their building against the Waianae dome. The only important difference is that in the case of the lava flows there was no concurrent extension of lava to pour down the Waianae slopes, whereas in the subsequent history of erosion and deposition there has been drainage off the Waianae slope. This has resulted in cutting of channels from that side, and particularly the building of a detrital fan cover that is one to two miles wide and overlaps the Koolau lava flows that lie against the Waianae slope. Hence the long bend of Koolau streams does not extend as far west as the long bend of the westernmost Koolau flows toward the end of Koolau activity.

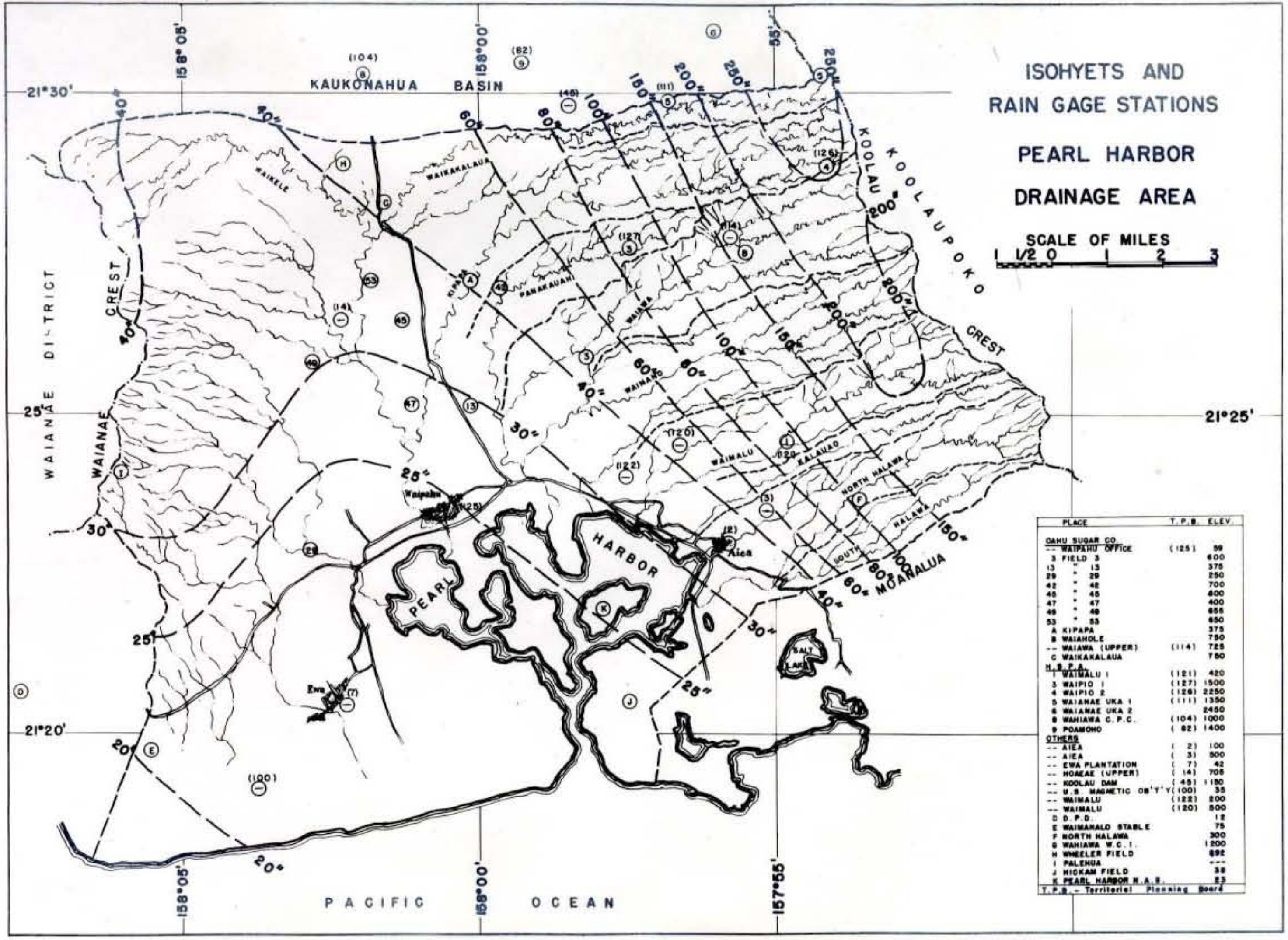
Finally, the leeward drainage of the Koolau Range, north of the Salt Lake craters and east of the Waianae Range, which is now combined in the outlet from Pearl Harbor, has been greatly modified in the course of strand line and shore pattern changes throughout Pleistocene time. It is not essential to detail these here, but they are mentioned as the last of the four chief factors in bringing about the integration of drainage lines from a total of about ten major channels which come off the range slope to five channels that enter Pearl Harbor, and thence to the one channel that leaves Pearl Harbor. These shore changes are:

(1) the excessive accumulation of sediments from the land in the sheltered reentrant which lies between the Koolau and Waianae ranges, (2) the effect of volcanic building by explosion products that came from the Salt Lake vents and produced several square miles of new land in the area between the Kalihi channel and the present Pearl Harbor, (3) the growth of coral and formation of coral reef at all suitable points on this lee shore, and (4) the sea level changes which have set the immediate relationships under which each phase of the evolution of the shore line has taken place.

In the course of these drainage changes, the parallel building of the coastal plain took place. The coastal plain is the upper surface of what hydrologists call the cap rock. This is the controlling structural element in the artesian condition that prevails both in the Honolulu and Pearl Harbor regions.

Rainfall

In Figure 9 is shown an isohyetal map of the Pearl Harbor district. The portion of this district which lies in the mountainous part of the Koolau Range has a distribution of annual rainfall which is similar to that of the several districts already discussed in this series of reports. Unfortuna-



PLACE	T.P.B.	ELEV.
OAHU SUGAR CO.		
-- WAIPAHU OFFICE	(125)	59
3 FIELD 3		600
13 " 13		375
29 " 29		250
42 " 42		700
45 " 45		600
47 " 47		400
49 " 49		655
53 " 53		650
A KIPAPA		375
B WAIAHOLE		750
-- WAIAWA (UPPER)	(114)	725
C WAIKAKALAUA		760
H.S.P.A.		
1 WAIMALU 1	(121)	420
3 WAIPIO 1	(127)	1500
4 WAIPIO 2	(126)	2250
5 WAIANAE UKA 1	(111)	1350
6 WAIANAE UKA 2		2450
8 WAHIAWA C.P.C.	(104)	1000
9 POAMOHO	(82)	1400
OTHERS		
-- AIEA	(2)	100
-- AIEA	(3)	500
-- EWA PLANTATION	(7)	42
-- HOAEAE (UPPER)	(14)	705
-- KOOLAU DAM	(45)	1150
-- U.S. MAGNETIC OB'T'Y	(100)	35
-- WAIMALU	(122)	200
-- WAIMALU	(120)	500
D D.P.D.		12
E WAIMANALO STABLE		75
F NORTH HALAWA		300
G WAHIAWA W.C.I.		1200
H WHEELER FIELD		892
I PALEHUA		---
J HICKAM FIELD		38
K PEARL HARBOR N.A.S.		23

T.P.B. - Territorial Planning Board

Figure 9 - Isohyetal map of Pearl Harbor district showing numbers and locations of rain gages. Rainfall data from U. S. Weather Bureau, Territorial Planning Board, Oahu Sugar Company, and U. S. Geol. Survey.

tely we do not have a sufficient number of raingage records over adequate periods to support a detailed contouring with a small contour interval. However, the broader outlines are very clear and the position of the zone of maximum rainfall can be drawn with confidence on the basis of both local stations and the pattern in other parts of the high summit area.

The maximum rainfall increases along a line parallel to the crest of the range and about a mile leeward of it. The lowest value of the maximum is just over 150 inches near the head of South Halawa Valley and the highest value approximately 240 inches near the head of Waikakalaua Valley. Along the crest of the range the annual rainfall is 30 to 40 inches less than that in the zone of the maximum in a corresponding position. From the maximum, the annual rainfall reduces rapidly to leeward, to reach about 35 inches near Aiea and about 50 inches near Wahiawa. The broad apron south of Schofield Saddle nowhere gets over 50 inches and probably does not average much in excess of 30 inches. It is readily seen that by far the largest contribution to total ground water supply is made by the inland mountainous area, especially since the intake conditions on the apron area are relatively less favorable.

An analysis of areas and rainfall quantities which is developed later in this report leads to infiltration quantities which are smaller than the quantities that are indicated by year by year known discharge. (Figure 10) This raises the question as to the estimated rainfall quantities. It would be useful to have several more raingages in this area, but

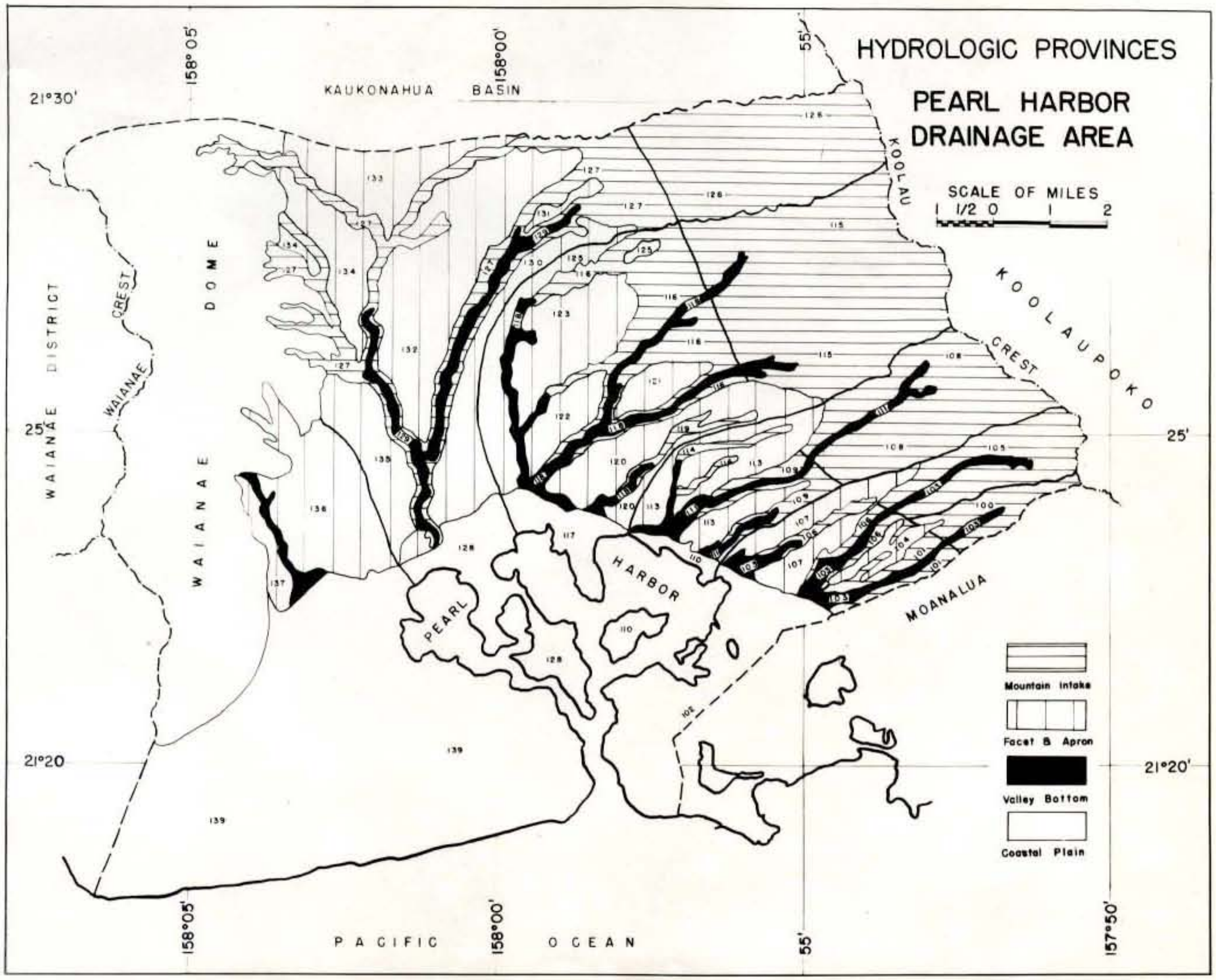


Figure 10 - Hydrologic provinces of Pearl Harbor district.
(Table I, p. 83)

there is no reason to believe that mean rainfall would be shown to be greater in an amount sufficient to resolve this discrepancy. (Figure 11) It is believed that the general mean of annual rainfall for any large area is indicated within 10% by the existing data.

Vegetation and soils, settlement, etc.

The soils of this area vary with parent rock, rainfall, and elevation. They have been mapped by Z. C. Foster of the Federal Soil Survey. (Figure 12) (1) The following table taken from Foster's report gives the chief characteristics of the soils found in this area.

"Abbreviated Outline of Soil Characteristics"

I Barber's Point-Sand Hill Association (Sands and Rock of Marine Origin)

Loose coral sands and sand dunes, soils with heavy clay topsoils over solid coral rock, and shallow reddish-brown loamy soils. Vegetatign dominantly of kiawe, sandbur, ilima and species of Chlois.

II Ewa-Mana-Wailuku-Waialua Association (Soils from alluvium and Marine Sediments)

These soils are derived from alluvial, colluvial and marine deposits. They are inherently fertile,

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(1) Zera C. Foster, Soils of Hawaii, Territorial Planning Board, First Progress Report, pp. 57-81, Plates 20-23, 1939.

Figure 11 - Raingage as installed on a low, interstream ridge in North Halawa Valley. Negative No. 21419.

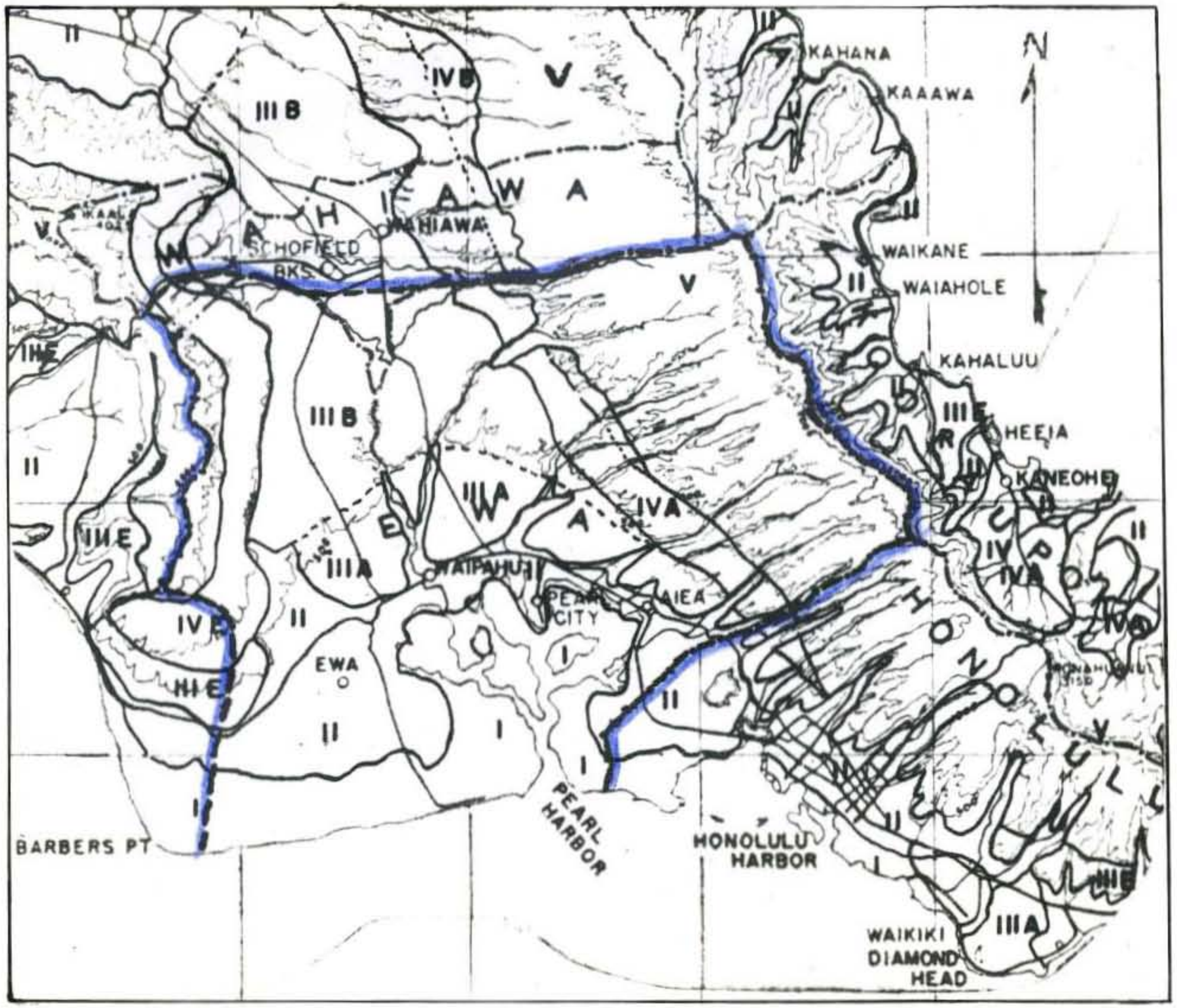

Figure 12 - Map showing types of soils in the Pearl Harbor district. The soil types and pattern are important not only because of their agricultural possibilities, but because their types may indicate the effectiveness of infiltration and is a result of long-standing climatic conditions which are closely similar to those of today. (From map and report on soils by Z. C. Foster, U.S. Soil Survey, printed in First Progress Report of the Territorial Planning Board. 1939)

show great diversity of texture and are largely used for sugar cane, with some of the highest yields of any soils in the territory.

III Makaweli-Molokai-Wahiawa Association (Red-brown loams)

These soils are residual from basaltic and andesitic lava flows. They generally have good tillage properties and moisture-retaining qualities and are among the most desired soils of the territory, used for sugar cane growth where rainfall or water are available and for pineapples otherwise. Destructive erosion is felt in some areas. Division III-A is where rainfall exceeds evaporation only during brief downpours, and Division III-B is where monthly rainfall exceeds evaporation at least two or three months of the year, with appropriate effect on both crops and soils. Division III-E is where the soils are generally too shallow, stony and dry to be used other than for pasture.

IV Haiku-Puhi-Paalaa Association (Yellow-brown, Reddish-brown, Brownish-yellow Lateritic Soils, Residual)

These are residual soils occurring topographically above the red-brown loams and the surface layer has a different color from the underlying material. These soils occur in rainfall from 60 to 125 inches and in a zone having annual temperatures two or more degrees lower than the preceding group. This belt supports cane growth only in places where very favorable relief facilitates cultivation, or pineapple growth only when market prices are high. Division IV-A has soils that are pale-brown to gray-brown, and with soft rock at 40 inches or less. Division IV-B has more clayey grayer surface soils. The latter has more difficulties in cultivation. Unless systematic program of management and improvement is adopted these are best as forest areas. Division IV-E includes badly eroded areas.

V Koolau-Kohala Association (Forested Soils)

These soils occupy areas of high rainfall and deep gullied mountain ranges and slopes. Developed under conditions of high rainfall and low temperatures, oxidation is retarded and leaching by water removes iron. Adapted to rain forest vegetation.

VI Alakai-Kawela-Puu Kukui Association

These soils occupy more or less flat-topped areas in high rainfall belt, where conditions permit development of peat. Open areas of grasses, sedge, shrub ohia surrounded by taller ohia. These are the areas of potential ceramic soil and are so limited on Oahu that they were not mapped separately from V.

As might be expected from the map of Figure 12 and the foregoing description of soil types, the larger part of the Ewa coral plain near the coast is useful chiefly for grazing. Farther inland and extending over soil areas II, III-A, and III-B is a wide belt around the shores of Pearl Harbor devoted to the growth of sugar cane. (Figure 13) Higher up on the Schofield saddle area are extensive areas of pineapples, above the level of the Waiahole ditch, while inland toward the Koolau forest area is a belt suitable for grazing. (Figure 14) (See Plate 33, Territorial Planning Board, First Progress Report, p. 74) There are several large areas and many small areas around the Pearl Harbor shore devoted to wet garden patches planted in taro, cress and other such crops. (Figure 15) Hickam Field lies to the east of Pearl Harbor and much of the housing and earlier land utilization connected with the naval base is also on the Puuloa Peninsula. No attempt is made here to treat of the greatly expanded pattern of federal and military land use, since description is neither essential nor appropriate at this time.

The three chief towns in this area are Aiea, Waipahu and Ewa, identified respectively with the three major sugar plantations, Honolulu Plantation Company, Oahu Sugar Company

Figure 13 - Sugar cane in the apron area west of Kipapa Gulch at about 600 feet, showing a field road and parallel main contour ditch with diversion gates at a road intersection. Negative No. 21780.

Figure 14 - Pineapples at the edge of a pineapple field at about 700 feet, above the Waiahole ditch, west of Waikakalaua Gulch. Negative No. 21761.

Figure 15 - Taro growing in terraced wet gardens at Waiau Springs. Negative No. 21478.

and Ewa Plantation Company. Aiea and Waipahu are situated on the main highway from Honolulu around the Pearl Harbor shore and are not exclusively sugar plantation towns. Ewa is built wholly around Ewa plantation business and employees. Wahiawa lies between the forks of Kaukonahua Stream on the Waialua side of the Schofield Divide and hence is not in this district. Parts of Schofield Barracks and Wheeler Field army posts are inside the area here discussed. There are several other small settlements, and a large and changing service and construction population having to do with the present war condition. On the Aiea facet there is some settlement, with a growing number of permanent homes of persons employed in Honolulu or at Pearl Harbor, up to an elevation of about 800 feet. The Waimano Home, a territorial institution for the feeble minded, is located on the facet south of Waimano Valley at about 800 feet elevation.

In Waimalu, Waiawa, and Waikele valleys, there are small pump station settlements of a few houses at points not over two miles from the coast. There are also at various reservoirs, which are part of the irrigation system for sugar growth on the apron slope between elevations 200 and 800 feet, several small plantation camps of a few houses. It appears that in recent years, with increasing use of the automobile there has been less and less use of these smaller camps and more of the plantation employees live in the larger towns and closer to the main highways. No permanent residence is known above 1000 feet.

A part of the mountainous, leeward slope of the Koolau Range is government land in the Forest Reserve, but most is privately owned and administered under the rules of the Department of Forestry so far as access by hunters and hikers is concerned. (See Figure 16) At certain points passage on trails may at present be restricted owing to proximity of some sort of outpost military installation but on the other hand there has been no general exclusion order with reference to the inland mountain country in this area.

Hunting with firearms is at present prohibited for civilians. There remains a moderate amount of hunting of wild pigs with dogs and a knife, but this is an insufficient control and there has been an increase in the pig population in the past three years.

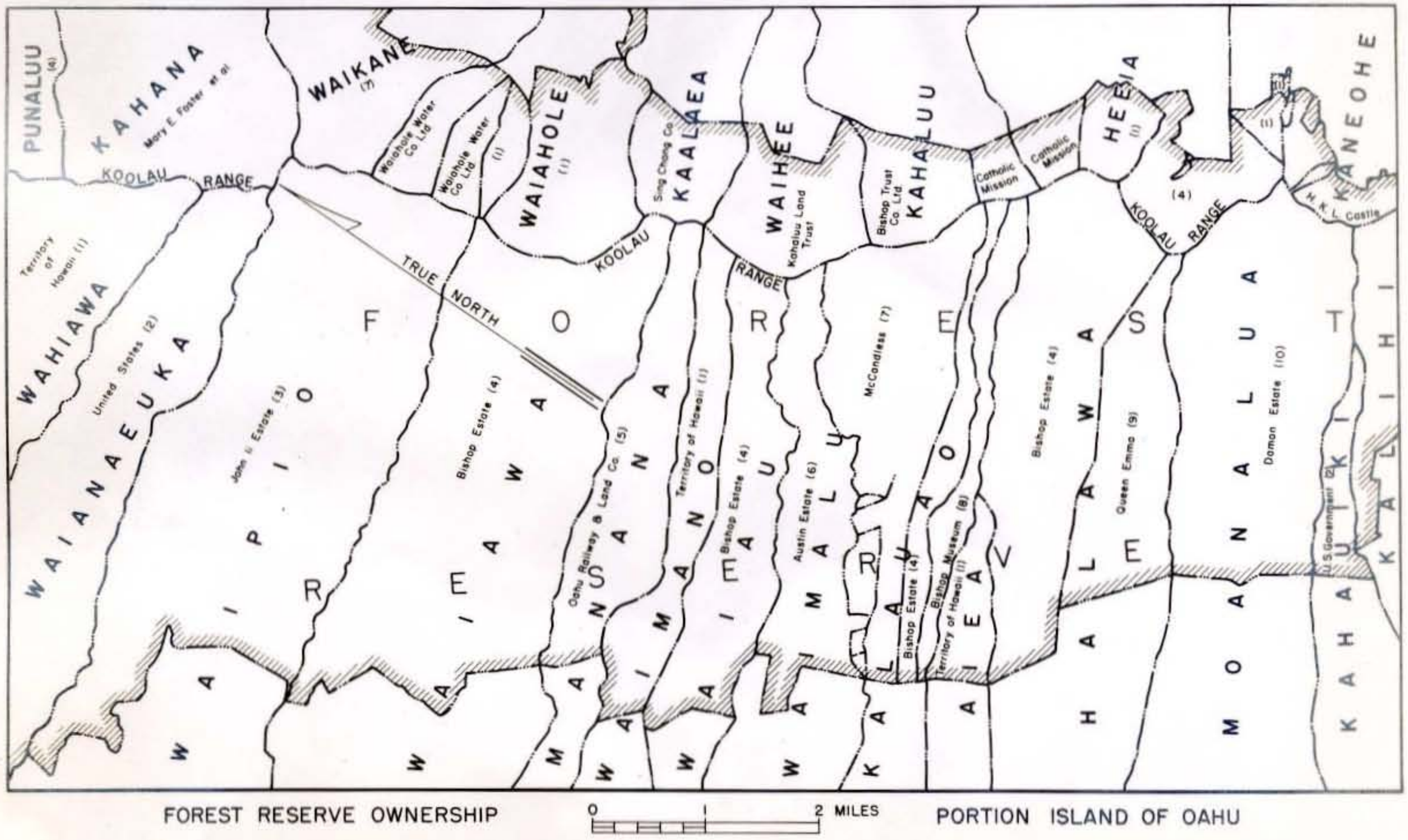

Figure 16 - Sketch map showing Forest Reserve ownership on the Koolau Range from Kalihi to Wahiawa. Most of this land is under the jurisdiction of the Division of Forestry under Regulation 1, but in some areas where owners elect to pay taxes, only a part of the provisions of Regulation 1 are in force. In Kalihi, and in parts of the Waiahole-Waikane area are Water Reserves, boundaries not shown.

GEOLOGY

General geology of the Koolau Range

The general geology of the Koolau Range has been set forth by Stearns (0), in previous reports of this series (1), and has also been outlined in a report which will eventually be published in the Bulletin of the Geological Society of America. (2) The leeward slope and underlying structure of the Honolulu part of the range are known in very much more detail than any other part. The geology of the Pearl Harbor portion has been studied much less intensively than the Honolulu portion but nevertheless more than any of the northern or windward part. Despite the differences in detail of study in various areas, we have a reasonably complete view of the more important features and are justified in making certain generalizations. If any of these are superseded it will only be by virtue of intensive studies of some area, or of some particular

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(0) Stearns, H. T., T. of H., Div. of Hydrography, Bull. 1, 1935.

(1) Geology and Ground-Water Resources, Palolo-Waialae District (1938), Manoa-Makiki (1940), Kalihi District (1941), Nuuanu-Pauoa District (1941), and Moanalua-Halawa District (1942).

(2) Wentworth, C. K. and Winchell, H., The Koolau Basalt Series, Oahu, Manuscript, 1941. (This paper somewhat delayed owing to failure of analyst to complete analyses of transmitted samples of rocks prior to going into war work. This work provided under Geol. Soc. Am. grant No. 297-39)

feature, which does not seem likely to be made in the near future.

Down to the elevation of approximately 1200 feet above present sea level the Koolau dome is elongate and quite regularly elliptical on its leeward side and the northern half of its windward side. The southern half of the windward side is much cut away, probably in part by aid of faulting. In this portion also the Kailua series of rocks is somewhat altered and injected by dikes to suggest that they not only represent a vent section of the formation of which they are a part, but also that they lie close to the vent from which a part of the later Koolau dome was built. No other exposure of rocks so altered has been found in any others of less eroded parts of the Koolau mass, and it is not known how distinctive this series is. The writer has not studied it in detail and has nothing to add to the description offered by Stearns. (Figure 17)

On the southwestern or leeward side, the slopes of the dome continue to the coast with the same slope directions at the northwestern and southeastern ends but in the middle section are greatly expanded and deflected toward the Waialua and Pearl Harbor coasts from the saddle terrane which has been built against the Waianae Range. The southeastern end of the range differs in two other respects from the remainder. First, the major valleys on the leeward side were eroded to a base of about 1000 feet below present sea

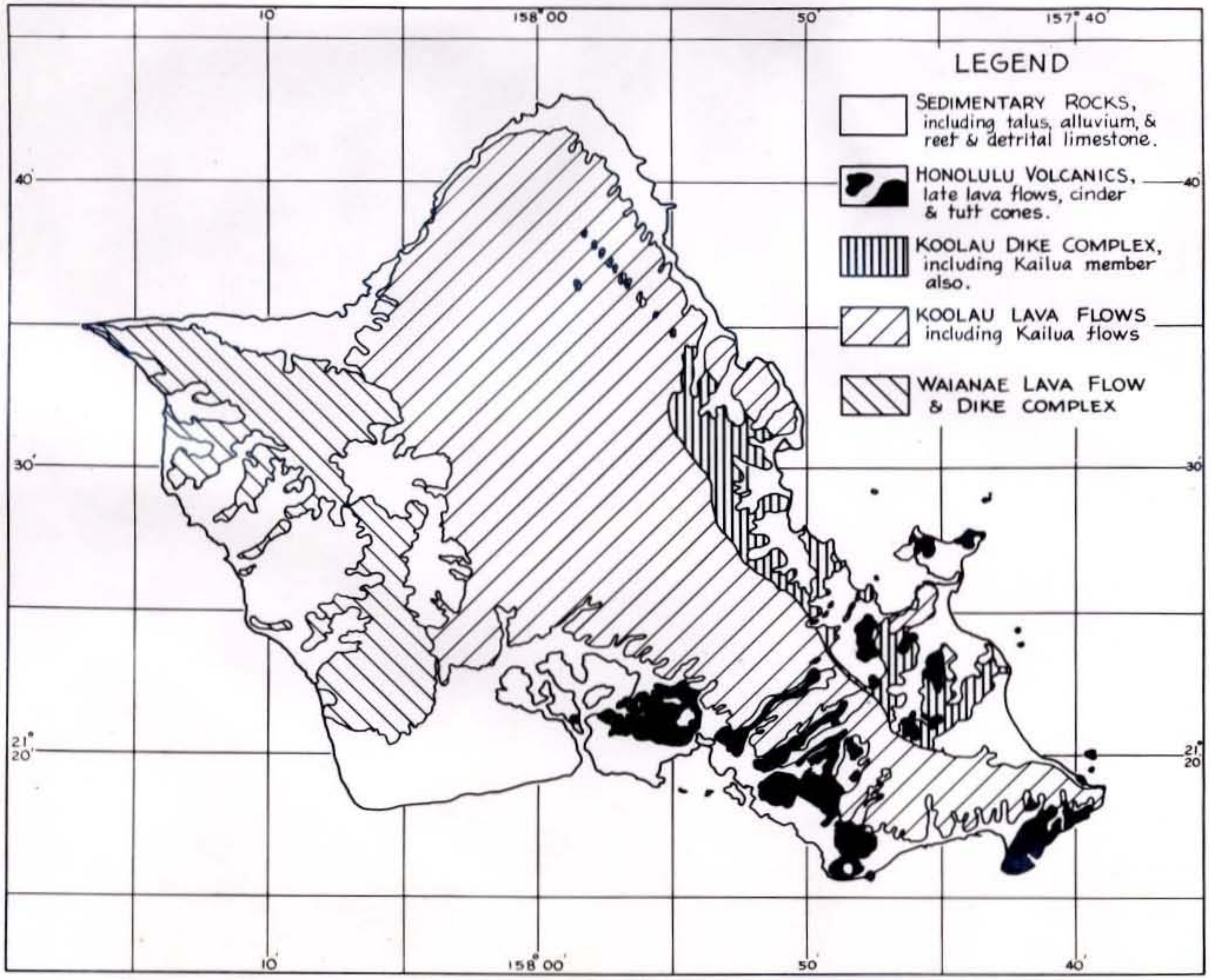

Figure 17 - Generalized geologic map of Oahu, showing chief groups of rock formations. Based on Geologic Map of Oahu, Bulletin 2, Division of Hydrography, T. H., by U. S. G. S.

level, and second, the entire series of secondary vents which yielded ultrabasic extrusive lavas and tuffs is confined to this southeastern part.

Set against these differences in the peripheral parts of the Koolau dome, which might suggest differences in age and in history of different parts, is the remarkably uniform character of the inner, axial part of the range. This portion, all the way from the dike complex, which lies chiefly a little to windward of the present crest, owing to erosional shift, to the margin at or near sea level, is composed of thin, basaltic lava flows in which no sign either of differentiation or of unconformity or division into distinct series, has ever been found. It is easy to postulate, having in mind, (1) the more altered Kailua Series, (2) the more completely eroded windward slope of Koolaupoko, and (3) the deeper cut major valleys southeast of Moanalua, and (4) the distribution of vents of the ultrabasic series, that the southeastern end of the range is older and has a more complex history. This remains entirely possible, but the concept remains a hypothesis so far as evidence from the major Koolau structure and the interior and upper part of the dome is concerned. No evidence of break or discontinuity or trend or difference between the ends of the range has been found. The southeastern end is slightly more eroded and dike complex is found out to the extreme point of the island; the northwestern end is rounded by normal dome slopes and no dike complex is known near the coast. The recognizable dike complex passes below the present surface and its outcrop fades in a line of small inlier exposures in the heads of windward valleys in the Malaekahana area.

It appears that the northwestern end of the range is either more deeply and fully covered by slope mantling lava flows not cut by subparallel dikes than the southeastern end ever was, or the southeastern end was once so covered and built up to 500 or 1000 feet higher than at present, and has since been eroded. These are the alternatives suggested by the relationship of dike complex and surface flows at these two ends. On the other hand, the configuration of lateral ridge crests and the slope of the restored dome contours at the Honolulu end does not suggest that there has been an erosion of more than 300 or 400 feet at the crest of the range and does not appear to justify explaining the whole difference as the result of erosion.

The principal secondary features that appear in an overall view of the Koolau dome are the erosion of many valleys and development of a mature topography over much of the interior, and the building and diversification of the coastal plain. The most important part of this coastal evolution is that around the Southeastern end of the range from Mokapu Peninsula to Pearl Harbor, including the Honolulu coastal plain. Prime factor in this evolution was the series of secondary cones built around the ultra-basic vents of the Honolulu series, as will be described in more detail below.

The Koolau formation

BASALT FLOWS

The entire inland portion of this district is underlain by thin basaltic lava flows of the Koolau series, (See Figure 18) with no other cover than soil or its own residuum. All other formations, such as the terrace alluvium, tuff, or coral reefs and sand, lie ultimately on the same base, the Koolau bedrock being covered near the present coastline by a maximum thickness of perhaps 900 feet of coral and alluvial accumulation which forms the coastal plain. We have no knowledge of the thickness of submarine sediment cover off the shoreline of the islands but this probably thins to a few feet within four or five miles.

The Koolau formation generally outcrops in the walls of the lower parts of valleys within a mile or two of the range margin, where thicknesses of 200 or 300 feet are often continuously exposed and where composite sections of somewhat less than 1000 feet can be compiled. On the flow-slope facets and over much of the area of the apron south of the Schofield Saddle, the bedrock lava flows are generally covered by 10 to 30 feet of Koolau residuum. Within these areas stream dissection locally exposes the lava flows or the

Figure 18 - Thin lava flows of the Koolau series on west side of Waiawa Gulch, loc. 13835. Negative No. 21603.

spheroidally weathered kernels one to several feet in diameter whose arrangement serves as an indicator of nearby bedrock. Thus without extensive exposure, it is still possible to identify the terrane and if necessary, to collect sound hand specimens.

In the lower bottoms of the larger valleys extensive fans of talus cover the rock outcrops and in some the rock profile is cut somewhat below sea level. In the middle sections of the larger valleys and generally inland, the more active streams cut into bedrock at water level on the outside of bends, often baring the base of a moderately well exposed cliff one or two hundred feet high. The main valley walls in the middle mountainous section are commonly somewhat fluted with chute-like channels down the depressions. Both the chute channels and the intervening ridges alternately reveal bedrock and a detrital cover. The valley walls, despite a general steepness, tend to alternate between strong lava flows and weaker flows or scoria beds which take a lower angle, and are mantled by talus and are more fully overgrown by vegetation. The farther inland we go, the more completely are the lateral ridges covered with soil and vegetation, so that the few outcrops of weathered rock in place are usually in the chute channels.

Under the conditions described, the dominant impression of the character of Koolau lava flows is gained from walls of the major valleys within a mile or two of the margin of the range. There are limited outcrops locally near the crest of the range, such as those near the drier Makapuu section, at which we can verify the general similarity between the inland and peripheral parts of the dome, except for the numbers of dikes and sills. While these give us some information, the scarcity and small extent of outcrops in the crest area, in the zones of higher rainfall, defeat any really valid local comparison between inland and marginal sections with regard to thickness of flows, whether aa or pahoehoe, amounts of clinker and the like. (See Figure 18, Moanalua-Halawa Report)

The Koolau basalt consists of two types of flows, known as pahoehoe and aa. The pahoehoe lava flows are the vesicular, banded masses formed when gas-laden magma pours from a volcanic vent and is cooled without undergoing certain chemical changes that would modify it to an aa flow. Pahoehoe flows usually show glassy, heavily wrinkled, "elephant-hide", or ropey surfaces and are built up by successive outpourings of small units. Commonly the surface of a pahoehoe flow is made up of somewhat displaced wrinkled blocks of crust, separated by cracks due to loss of molten lava from underneath, cooling, and other causes. (See Figure 19, Moanalua-Halawa Report)

Aa flows in motion move with a liquid interior on which is carried complete cover of solidified blocks of extremely irregular, rugged scoria. Because this scoria cover moves forward and rolls down the frontal slope, quantities of the scoria are deposited on the surface ahead of the flow. Hollows are likely filled more deeply than high spots, so that the liquid lava probably comes to rest on a slope that is somewhat smoother than the pre-flow terrane. The entire aa unit therefore consists of the dense interior, solidified from the residual liquid, plus the detrital clinker which forms layers both below and below and above the dense portion. The topographic surface of aa flows is irregular and hummocky, and because of the expanded, pustulate, delicately rugged or spongey form of the surface the terrane is almost unbelievable rough and unstable. Travel across such a surface, even where it is level, is slower and more arduous than over any other known, solid terrane that is bare of vegetation.

When seen in section, pahoehoe flows are distinguished by rather regular, banded arrangement of vesicles, the banding usually indicating thin-layered flow structure with overlapping, infolding, and various contorted forms indicating the order of emplacement. Often successive units are quite thin, a few inches thick, and the surfaces show a thin band which was chilled as a glass and is commonly altered to a rusty condition. Because pahoehoe flows have little or no scoria they fit closely together and contacts between distinct units may be shown only by the obscure rusty zones or slight differences of texture.

As flows consist of a dense interior portion which is usually relatively free from vesicles or has only a few large and somewhat irregular shaped bubble holes that are not arranged to show detailed banding. Most dense interiors of aa flows are sufficiently free from vesicles so that hand specimens often will show none and "one man stone" will show but few. Dense interior layers are somewhat irregular and thicken and thin according to the details of their formative conditions. Layers 1 to 3 or 4 feet thick are commonly separated by cooling joints into masses that are no more that 3 to 6 feet long and wide. In dense masses of the thicker flows, 10 to 30 feet thick, the cooling joints are arranged in somewhat less regular fashion, often are broadly curved, so as to outline large kernel blocks, the surfaces of which show patterns of secondary cooling joints which are apparently developed in accordance with the cooling history of the large primary blocks. In the Halawa section of the Pearl Harbor area at the level of the lower valley sides there are several unusually thick aa flows which have attracted extensive quarry operations. Without extensive measurements and controlled comparison it is not possible to state whether the flows of the Pearl Harbor area as a whole are thicker than those of the Honolulu area, but it is possibly the case, because of the greater length of slope.

The clinker layers of aa flows vary from somewhat less the thickness of the dense portion to mounds and lenses that are much thicker. In some places the aa clinker in masses perhaps 30 feet or more in thickness are subject to extensive caving and overbreaking when met in excavations. This is not always the case, since some of the aa carries large, interlocked pieces and is comparatively stable. Small, irregular lenses of lava or trickle flows are often found interbedded in the clinker masses. It is often not clear in the field whether a particular clinker mass belongs to the underlying or overlying aa flow and in some cases even a petrographic examination might not be decisive.

The genetic relationship between pahoehoe and aa lava flows is well understood from observations on historic lava flows on Hawaii. Newly expelled basaltic magma is always in the pahoehoe condition, since it is charged with gas and has not undergone the crystallization that accompanies the change to aa lava. Such issuing lava near the vent always produces pahoehoe flows. Lava may remain pahoehoe and flow for long distances, all the way down the side of the dome to the sea. On the other hand, due to causes not whooly understood or predictable, pahoehoe flows often change to aa flows. It appears clear that escape of gas and crystallization in connection with cooling are the most tangible modifications in the change from pahoehoe to aa lava. Apparently the thickness, the viscosity and the degree of stirring and mixing are important factors in effecting this change. (1)

(1) Formation of the crustal blocks and detrital clinker which accumulates on the flow and down its slopes, so as to largely cover the fluid lava of the interior of the aa flow, is responsible in large measure for the great contrast in the final form of the aa flow. Since all flows are originally pahoehoe and many flows later become aa, it is logical to suppose that a greater fraction of the total section in the crest area would be pahoehoe and that there would be a preponderance of aa flows in the peripheral parts of the dome. It has been stated that this is the case in the Koolau dome. (1) Though the writer has no reason for doubting that this is probably true, he does not feel that a valid observational conclusion can be drawn because of the marked differences in exposure in the drier, peripheral area as compared to those in the crest area.

In an examination of about 2000 feet of flows penetrated by diamond drill holes in the Red Hill, Kahauiki, Punchbowl and Kapahulu spurs in positions fairly near to the margin of the range it was found that about 75% of the section con-

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(1) Emerson, O. H., Formation of aa and pahoehoe, American Journal of Science, Vol. XII, 1926, pp. 109-114, 1926.

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(1) Stearns, H. T., The Geology and Ground Water Resources of the Island of Oahu, Hawaii, Territory of Hawaii, Division of Hydrography, Bulletin 1, p. 93, 1935.

sisted of aa flows. In one section of about 200 feet, there was a slight preponderance of pahoehoe flows. It is a matter of observation, however, that occasional sections of 50 or more feet thick, consisting wholly of pahoehoe flows, are found in the peripheral area, and probably no section as much as 100 or more feet thick is wholly free from pahoehoe flows.

Unfortunately we lack as clear a picture of the section in the axial part of the dome. Wherever any extensive exposures are found there are some aa flows as well as some pahoehoe flows. In general where exposures are limited, it is the aa flows that form conspicuous outcrops, so that it is quite likely that these are more than represented in the existing outcrops. Anything like a numerical statement or confident estimate of proportions in the crest area is not available.

We may now describe the gross structure of the Koolau mass which is the underlying bedrock of the entire area covered by this report. The structure taken in a broad way is not known to be other than homogeneous. Throughout it is made up of relatively thin basaltic lava flows of both aa and pahoehoe types, superposed at angles of 4 to 8 degrees in most of the mountainous area and with slopes as low as 2 to 3 degrees in the apron area south of the Schofield Saddle. The flows are elongated in the direction of the slope and range from 5 to 20 miles in length, excluding the submarine parts outside the present coast. Tracing of specific flows laterally is impracticable and we can only surmise that the wider flows may be two or three miles wide near their lower ends, by comparison with the historic flows from Kilauea and Mauna Loa.

Necessarily we mean primarily flow units when we speak of the thickness of flows; it is not practicable to segregate the units into groups which may represent formation during one continuous eruption as would be the case with historic flows that can be observed. In some instances where exposure and accessibility are exceptionally favorable, as on the bare steep slopes of Makapuu Head, it can readily be seen that several thin aa flows separated by clinker layers join and separate again, thus being units of a single flow. The same is locally true of pahoehoe flows. About the best that may be said is that flow units are preponderantly less than 15, possibly less than 10 feet thick, and that it is doubtful if units 40 feet thick occur so frequently as one per one thousand feet of thickness. Possibly a third of the total section may be made up of units over 15 feet thick.

Known behavior of lava flows in historic time on Hawaii suggests that units 5 or 10 feet thick may be superposed on the slopes of the mountain locally to form an aggregate flow addition of 30 to 40 feet. It is very doubtful if any flow averages so thick over its whole area. It is thought that average flow thickness as opposed to unit thickness might reach 25 feet, but certainly no more. It is probable that flows near the source are thicker and less wide than the same flow near the margin; it seems likely also that flows of somewhat similar types tend to be represented in a portion of the section owing to similar lines of flow from the vent governing accumulation over a limited period from successive eruptions.

The Koolau lava flows consist of normal basalts, olivine basalts and hypersthene-bearing basalts with or without olivine. Brief petrographic descriptions have been included in earlier reports of this series, and a more extended discussion of the Koolau petrography will be found in a paper by Wentworth and Winchell now in preparation. No new data have come to hand in relation to the Koolau series in the Pearl Harbor area, and it is only essential here to emphasize again the remarkably uniform character of the Koolau flows, from top to bottom and from end to end of the range.

KOOLAU ASH AND TUFF BEDS

In the Honolulu section of the leeward slope of the Koolau dome a considerable number of scattered beds and lenses of palagonitic tuff are found interbedded with the lava flows and these have been described in the several reports on parts of that area. Despite the earlier expressed belief of the writer that these were the results of sporadic phreatic explosions and might be expected in all sections, detailed examination of the leeward slope west of Kalihi has shown that interbedded tuff layers are much less numerous there than in the area from Waialae to Nuuanu. Such beds as have been located are shown on the geologic map but they appear to be of negligible importance.

KOOLAU DIKES AND SILLS

Following the study of the Honolulu area east of Kalihi, the distribution and general characteristics of the dikes and sills of the leeward slope of the Koolau Range were set forth in a paper by the writer and A. E. Jones. (1)

At that time, though the possibility was recognized, it was not known with certainty that scattered leeward dikes were much less abundant in the area west of Kalihi. However, since that has later appeared to be the case, little further information has come to hand and hence there is little to add in this report.

In the form of surface outcrops the dike complex, which marks the axial vent zone of the dome, lies within the present district only in a small area at the head of Waimano Valley. South of this place the southwestern margin of the

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(1) Wentworth, C. K., and Jones, A. E., Intrusive Rocks of the Leeward Slope of the Koolau Range, Oahu, Journal of Geology, Vol. 48, pp. 975-1006, 1940

dike complex, as mapped by Stearns, lies to the windward of the range crest by $\frac{1}{4}$ to $\frac{1}{2}$ mile; north of it the southwest boundary closely follows the range crest. The character of the dike complex is not intimately known from the occurrence in this area because of limited exposures but its average structure and dike concentration can best be estimated from the sections encountered in the various tunnels of the Waiahole system. In the main bore of the Waiahole tunnel, dikes were encountered first at about 2500 feet leeward of the crest of the range (1) and at this point also water was first met in significant amounts. This point is about 2500 feet leeward from and about 1300 feet lower than the leeward margin of the surface trace of the dike complex. It is also about 800 feet below the surface. It is not known whether this dike extends to the surface or not. Since dikes generally become more numerous downward it is quite possible that there are dikes farther leeward and that the margin of the dike complex on any basis would slope at a steep angle to the leeward.

It is thus quite possible that at sea level the dike complex (1) may extend a mile or more leeward of the general

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(1) Stearns, H. T., Op. cit., Figure 32, p. 400, 1935

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(1) The writer has elsewhere suggested that a concentration of 10 dikes to the mile would probably not be called

> a dike complex, but that 100 dikes to the mile, or a dike every 50 feet on the average very likely would be so considered. It is not known that anyone has had opportunity in the field to map formations on such a basis.
>
> Nuuanu Report, p. 31

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line of the crest. At any rate it appears that very little of the dike complex outcrops on the leeward slope and that any extension of area to leeward by downward flaring takes place at depths of some hundreds of feet so as not to be readily accessible to tunnels driven from the leeward side. In the Waiahole system the dikes are encountered by a long tunnel whose cost was largely justified by its function in transmitting both surface and ground water developed on the windward side of the range. Even in the small area where the dike complex outcrops on the leeward slope, the water it is known to impound is at such elevation that only a very extensive project could afford possibly to undertake its development because of the relatively gentle slopes on that side.

Older sedimentary series

OLDER ALLUVIUM

This formation consists of the main body of land-derived gravel and silt in valley bottoms, valley-side fans and in the coastal caprock mass which was deposited following the main period of valley cutting. The principal characteristic of all accessible parts of this formation is the high degree of weathering with the resultant compacting so as to close all voids of any size but the smallest. This closing of voids has resulted from the volume increase which accompanies chemical weathering of basaltic rocks. (Figure 19)

In many places this formation is overlain by later sediments and cannot be positively distinguished from these. The principal exposures are those in lower valley bottoms where the margins of fans and terrace remnants are cut to steep banks by the recent work of streams or in the course of road or other construction. In such exposures the formation shows its structure and origin by a vari-colored mottling but is usually so completely weathered that individual boulders are as soft and easily cut by tools as the finer grained matrix. The dominant colors are dark red, or red brown, and the formation retains moisture so effectively that it ravels only very slowly. Tool marks in outcrops exposed to the open air often remain 5 to 10 years and those in moist tunnels appear quite fresh after periods of 25 years or more.

Inland from the lower valley bottoms small masses of the older alluvium are commonly exposed in contact with bedrock in the bends of the stream channel. These are more commonly exposed in the channels of streams such as those of the Pearl Harbor area, which were never cut very far

Figure 19 - Outcrop of weathered gravel in north bank of Halawa Stream below Halawa Underground Shaft. This is part of the older alluvium; in the upper left part of the exposure is finer, harder gravel of intermediate age. Negative No. 21142.

below present sea level, than in the channels of the streams of the Honolulu area which mostly flow on deep fill.

Still farther inland, beyond the fairly low gradient of the main channel, and up the head and side branches, the older alluvium is scarcely ever exposed and probably never was deposited in typical form. This is probably because in these steeper parts of the drainage basin, even during the period of aggradation following that of deep cutting, the erosional phase and downslope mobility of detritus continued. The older alluvium apparently requires for its development as a formation a condition of stability and moderately deep burial. Hence, though sediments were being produced by erosion in the inland area and moved downslope across the whole terrane during the period of formation of the older alluvium, it was only in the middle and lower valleys and on the growing coastal plain that these sediments were deposited in sufficient amount and stability to produce typical and enduring masses. (Figure 20) The older alluvium forms the basal component of the Fort Shafter terrace which is found in various localities around the whole margin of Pearl Harbor.

OLDER MARINE FORMATIONS

Knowledge of marine formations contemporaneous with the older alluvium is very scanty and is derived chiefly from records of artesian well drilling. Stearns has com-

Figure 20 - Cemented, older gravel above railroad track in west wall of mouth of Waikakalaua Gulch. Negative No. 21570.

piled available information on the logs of artesian wells (1) (See Figure 24, Manoa-Makiki Report). Unfortunately detailed records of the formations encountered have been left only for very few wells and even under the best conditions the interpretation of the geology from churn drill cuttings is not very satisfactory. A group of wells numbered 162 to 170, in a zone extending from west of Rodgers airport to the shore of Pearl Harbor opposite Ford Island shows similar sections in which the lower part from - 800 feet to - 500 feet is chiefly indicated as clay. This may in part be submarine clay but may also be in large measure the weathered residue of coarser, land-derived marine sediments. In a few of the holes a layer of coral is indicated at about 550 feet below sea level. From about 500 feet below to 230 feet below sea level the section shows equal amounts of clay and coral, and above -230 feet, to sea level or above, the section is almost solid coral according to the well records. In the next series of wells, a group centered around Makalapa Crater about 2 miles nearer the margin of the Koolau Range than the others, there is very little coral. These wells are only 300 to 500 feet deep and show chiefly clay in the lower parts. Indications of tuffs of the Salt Lake series are confined to a few feet

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(1) Stearns, H. T. and Vaksvik, K. N., Op. cit., Plate 29

just below and above sea level. It is possible that tuff which lies below this level has been included as clay. Hence we do not have a clear answer to the question of the depth of the basement on which the Salt Lake craters were built, nor as to how much of the present form of the Pearl Harbor drainage had been outlined before these vents were first active.

The zone of nearly solid coral from -230 feet up to sea level corresponds rather closely to the similar zone shown in the well records of the Honolulu coastal plain from Manoa Valley to Nuuanu Valley. From this fact we can conclude that in the later stages of accumulation of the coastal plain wedge, fairly stable reef growth had been established in a position inland from Honolulu Harbor and in a zone across the inner entrance to Pearl Harbor. This more favorable and stable reef growth evidently came a long time after the beginning of the period of deposition, after the sea had risen to a level not over 100 or 200 feet below its present level.

Possibly the active growth of coral commenced following the Kahipa stand of the sea at - 300. At this time the streams were somewhat fixed in valleys already cut and muddy waters were more constricted than they may have been during the most active period of earlier deposition. At any rate the growth of coral seems to have been rather active through a long period of rise of sea level until the Kaena stage was reached. During the Kaena stage extensive terrace deposits were laid down which will be described below. Details of the pre-Kaena history of the Pearl Harbor area are missing. Only the fact of earlier, largely non-calcareous deposition followed by more notable growth of coral, to a total thickness of nearly a thousand feet can be offered. During the earlier part of this period of aggradation the several streams may have had separate and changing points of discharge into the ocean. The renewed erosion attendant on the lowering of the sea to the Kahipa stage was probably responsible for the permanent fixation of the combined discharge at the present Pearl Harbor entrance, and this event so favored the growth of coral reef that the reef that the reef itself served to fix this entrance and enclose the harbor. Stearns has suggested that widening of the various lochs of the harbor during recent periods of erosion has been facilitated by the lesser resistance to erosion of the non-calcareous sediments of the Kaena terrace in the section closer to the land. (1) This a point well taken and can be supplemented by the fact that calcareous deposits themselves form a strong resistant reef only on the side facing the ocean and the coral deposited in some-

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(1) Stearns, H. T. and Vaksvik, K. N., Op. cit., p. 52, 1935.

what enclosed bays is usually weak and easily eroded, as shown particularly well in Waianae and Lualualei valleys of Oahu.

Despite the lack of specific stratigraphic knowledge of the older marine deposits, we must emphasize that there is no doubt of their importance, combined with the older alluvium, in forming a comparatively effective caprock which restrains the outward movement of the basal water and gives rise to the artesian and basal water heads. These important properties and conditions will be alluded to elsewhere in this report.

Honolulu volcanic series

THE SALT LAKE TUFF

There is little need for detailed treatment of these rocks in this report since they have already been described in the Moanalua-Halawa Report and practically all their occurrence in substantial amounts in the Pearl Harbor area is in the eastern part already covered in that report. Though the lava flow from the Kahuauli vent near the crest of the range on the Kalihi-Manaiki divide is involved in the timing of various components of the Fort Shafter terrace (1), this lava flow is of no hydrologic significance even in Manaiki Valley. Except for a buried flow of the Honolulu

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(1) Moanalua-Halawa Report, p. 57-60, 1942

Series revealed in well 160, practically on the boundary line between Honolulu and Ewa districts, there is no other lava of the Honolulu Series in the entire area covered in this report.

Similarly, west of Aiea and the Makalapa area, the tuff from vents of the Salt Lake Series is confined to occasional layers that are interbedded as parts of the terrace formation. There are no crater masses or other deposits of sufficient continuity to be of independent hydrologic significance.

Intermediate sedimentary formations

INTERMEDIATE ALLUVIUM

This formation has been repeatedly defined in the preceding reports as the mass of detrital mantle rock that overlies bedrock through much of the mountainous area and which is neither so old nor so stable as the older alluvium, nor so recent and so homogeneous as the stratigraphically identifiable recent alluvium of valley bottoms and flat coastal areas, at present grade level. This formation has been described in detail in other reports and shows no new features in this area.

FORT SHAFTER TERRACE FORMATION

The most conspicuous remnant of the terrace known by this name is that on which the Fort Shafter post headquarters and parade ground is located. Various other remnants are found adjacent to the range margin or to the high ground of crater masses around the shore of Pearl Harbor as far west as Waipahu and the terrace is represented in the existing topographic surface of large areas of the slope inland from the Pearl Harbor shore from Waiawa Stream to the southern tip of the Waianae Range.

The basal portion of the Fort Shafter terrace formation often consists of older alluvium, which is only another way of saying that the older alluvium, and with cobbles that are harder and less weathered. This layer, in a general way, seems to correspond to the basal layer of what in the lower and middle valley bottoms is called the intermediate alluvium and which often lies on the eroded surface of older alluvium. This gravel in places is firmly comented but in others is much more loose and permeable than the older alluvium. Above this gravel layer in the terrace section is a top layer of soil or in some sections a thin layer of primary tuff from one of the later of the Salt Lake eruptions.

It is quite obvious that any alluvial accumulations that might have been formed in the early period of aggradation would have been left as remnants after a subsequent period of erosion in just the same places at the ends of spurs and between streams, as are the present day remnants of the later terrace deposits. Hence it is quite to be expected that existing sections of the Fort Shafter terrace of Kaena age, where they are exposed deeply enough, show exposures of the much older alluvium at the base. The dating of the several components of the terrace sections can be only approximate. The most significant time mark in the series is the finishing of the terrace grade in adjustment to the level of the Kaena sea. Because the deposition of the upper gravel was probably fairly rapid and indeed took place because of the retardation of streams as they approached grade, this whole upper gravel layer can be assigned to the Kaena stand. (See Figure 35, Moanalua-Halawa Report)

The underlying layer, which is often marine or partly marine, and in some places carries oyster beds, appears to represent a time when the sea had reached an elevation equal to or greater than the Kaena stand. If the overlying gravel in the terrace sections was deposited sub-aerially as its character suggests, this deposition must have taken place after a slight recession of level from that during the deposition of the preceding marine beds. However, both the marine beds and the overlying gravels, graded to approximately the same sea level, can be assigned to Kaena time. Older alluvium or gravel underlying the marine beds may clearly be very much older and the thin mantle of late tuff or of either residual soil or transported silt belongs in post-Kaena time, but has not been accurately dated.

EWA CORAL REEF FORMATION

The Ewa Coral Reef formation includes primarily those reef limestone masses which are exposed at the surface of the Ewa coral plain on the west side of the Pearl Harbor entrance, as well as smaller areas near and east of Puuloa on the east side of the entrance. No satisfactory age separation of the reef formations has been worked out. In an earlier section of this report reference has been made to a thick series of limestone reef formations extending from about 230 feet below sea level to sea level. The greater part of this mass, as revealed in artesian well borings, is apparently older than the Fort Shafter terrace and hence pre-Kaena in age, dating from a time when the sea was returning from the deep, -300 foot, Kahipa stand. This older limestone is overlain in places by the tuff of the Salt Lake craters, including the earliest of the Salt Lake tuffs.

On the other hand, it is not possible to assign all the exposed limestone reef masses to so early a date. The Ewa Coral Reef mass here under discussion has clearly been formed chiefly during the 25 foot, or Waimanalo stand of the sea. Reef masses at this level are found at nearly all the reef-bordered shores, such as Waimanalo to Kaneohe, Waialua, Kahuku, Honolulu to Barber's Point and the Waianae coast. In some individual instances it is not clear that masses which may have been formed at the Waimanalo stand could not also have been formed at a later stand at about 12 feet. Stearns, on the basis of shore deposits, has been reluctant to concede the existence of a 12 foot stand (1), though the present writer, while recognizing the confusion in existing evidence, believes that a stand at approximately 12 feet did take place and can eventually be demonstrated. (2)

None of these disputed points militate against the general fact of extensive reef masses with upper surfaces that generally rise from 10 to 15 feet at the coast to 20 and 25 feet inland which were probably formed during the Waimanalo stand. The Ewa coral flat is one of the conspicuous examples of this reef formation and is found over large areas in the seaward part of the Pearl Harbor area. It is readily seen in the Puuloa area, east of Pearl Harbor, that the latest of the Salt Lake eruptions must have come after the chief building of the Ewa Coral Plain. The same late eruptions came after the completion of the Fort Shafter

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(1) Stearns, H. T., Shore Benches on the Island of Oahu, Hawaii, Bull: Geol. Soc. Amer., Vol. 46, pp. 1478-1480, 1934.

(2) Wentworth, Chester K., and Hoffmeister, J. Edward, Geology of Ulupau Head, Oahu, Bull. Geol. Soc. Amer., Vol. 50, pp. 1570-1571, 1939.

terrace, and by the relation to the Waimanalo reef, must have been very much later.

These relationships indicate that both the formation of limestone reef and the formation of tuff members of the Salt Lake series have gone on over a long period. Only in its local situs can any one of the members be discriminated to some extent by its topographic position. Much of the outcrop of limestone or of tuff is assignable only by local relationship to any given, supposed period.

The coral reef consists of masses of coral, including molluscs and other shells, together with detrital accumulations of calcareous material, calcareous sand and silt. In places there are layers of marine clay or silt formed of wash from the land, often with included shells or thin calcareous layers. These grade in all proportions into the more completely calcareous members.

In some places the coral members of this formation have been made open textured by solution and may locally facilitate the formation of springs or serve as permeable lenses in the caprock formation. However, in general the coral is too readily weathered, too friable and easily compacted by crushing to form a permanent, large scale aquifer and most of the old coral masses form a component part of the general impermeable caprock. Moreover, because of the capacity of the coral to form a resistant shore platform, on which alluvium is deposited, the coral growth has been a dominant element in the expansion of the coastal plain and the building of a wide and thick caprock.

Recent sedimentary formations

RESIDUAL FORMATIONS

In the aggregate it is difficult to over-emphasize the importance of the residual cover that mantles much of the bedrock surface. A great share of the waste which is carried off the land by streams has been first prepared by weathering. Much of the weathering has taken place prior to the beginning of transportation, when the material in question was residual, in place, as the upper part of the bedrock lava flows. Much of the residuum escapes ordinary notice as a distinct formation because of its close identification with bedrock, or because a great share of it in lowland areas lies under and adjacent to and grades into the intermediate alluvium of the mountainous area. (Figure 21)

On the other hand, the surface of the little-dissected flow-slope facets, and especially the extension of these facets in the broad apron of Koolau terrane which extends from the Schofield divide to the margin of the terrace surrounding Pearl Harbor, is underlain by a residual layer which ranges from 10 to 40 feet or more in thickness and which shows a highly distinctive character and identity

Figure 21 - Basaltic residuum of the Koolau series showing spheroidal weathering. This is within the first eight feet below the surface on which sugar cane is growing and shows the rapid transition from soil to sub-soil and the lack of a well-marked soil profile. Negative No. 21618.

as a formation. The general process of weathering and the nature of the resulting formation has been described in an earlier report and need not be repeated here. (1)

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(1) Moanalua-Halawa Report, pp. 75-82, 1942.

It is important here to emphasize that in the Pearl Harbor area, this formation covers a large nearly continuous area south of the Schofield divide, as previously mentioned, and that in many places this formation, or very similar, weathered gravel of the terrace formation covers the bedrock of the Koolau aquifer down to sea level or below. This is due to the lesser degree of erosion of the Koolau margin in the spurs at and slightly above sea level in the Pearl Harbor area than in the Honolulu area.

Hence we find that in the Pearl Harbor area, especially in the vicinity of the Pearl Harbor Springs the Koolau residuum comes to be of very marked hydrologic significance in protecting the immediate vicinity of the springs from ground water contamination and also in impeding and localiging the outflow of basal water. Similar conditions have been encountered in the vicinity of the Houghtailing Spring in Kapalama and elsewhere in Honolulu, but not nearly on so large a scale as in the Pearl Harbor Springs. This condition will be the subject of more extended discussion elsewhere in this report.

EOLIAN, TALUVIAL AND COLLUVIAL FORMATIONS

Small patches of eolian silt and eolian lag grit are commonly found to leeward of erosion scars at the edges of exposed bluffs but these are of negligible importance and are usually deposited on formations that are themselves relatively impermeable.

Large amounts of taluvial and colluvial materials are included in the formation already described as the Intermediate Alluvium. In a country of such rugged topography and steep slopes, the discrimination of alluvium of the river-bottom type from the talus and colluvial materials occurring on slightly steeper slopes is impracticable, since they mingle and intergrade, both horizontally and vertically. Every combination of these phases is found and aside from the low valley and coastal flats where clear types of fine grained recent alluvium occur, or the bouldery lower channels of active streams where the channel detritus can be called recent alluvium, it is most useful to include all other detrital, transported accumulations of later date with the Intermediate Alluvium.

RECENT ALLUVIUM

Two types of recent alluvium have been identified in mapping this area. One of these is the channel gravel and nearby bar gravel in the lower gradient parts of the chief channels. (See Figure 39, Moanalua-Halawa Report)

In some places a fraction of the deposit consists of hard, unweathered basalt, especially larger boulders of dike columns and selected resistant flow basalt, and also much of the rest is material from which a reasonable sound hand specimen can be taken. But in most places the larger boulders are somewhat weathered on the outside, and much of the finer material is sufficiently soft that it tends to pulverize rather than shatter under the hammer. Well-graded gravel which would give a good rattler test to highway specifications is practically non-existent in Oahu stream channels or deposits and is rare on Oahu beaches. It is probable that some areas or lenses of recent gravel have been missed, but in general such materials so buried as to be obscure are also sufficiently weathered as not to qualify under this heading.

The other type of recent alluvium is the most recent cover on low coastal or stream-bottom areas which is identified largely by its topographic situation and non-indurated character. This layer is often somewhat sharply distinguished from older rocks underneath and may lie on an eroded surface, or on the solution-etched surface of a coral reef. This material is of relatively slight importance from the standpoint of developable water supply because of its shallow character and the fact that large underground water bodies do not occur in this valley bottom relationship in Hawaii.

RECENT MARINE FORMATIONS

Formation of sediments in offshore water goes on at present as in the recent past. However, except for the shore deposits of beach sand and gravel which are seen along parts of the coast, and the very few places where a thin veneer of growing reef organisms is found, little is known of them. Studies by Edmondson and others indicate in fact that the growth of coral is relatively feeble off Hawaiian coasts today, and most reef areas show more evidence of abrasion or of mantling and burial by calcareous or land-derived detritus than of effective growth.

A far more important process at present is the modification of the coast lines and extension of artificial fill in a seaward direction in connection with various civil and military projects. It would be incorrect to imply that this process is quantitatively large by comparison to the area or volume of the island, but it involves sufficiently large areas to be significant with reference to water utilization. The combination of extensive filling of coastal flats with material, making a relatively permeable mass, together with concurrent draining of such low areas, tends to produce an artificial desert terrain. Following the veneering of parts of such areas with top soil and planting of trees and grass, water for irrigation is used in considerable amounts. It is pertinent also that much of the area not planted to grass is covered by buildings and pavement and hence allows little natural groundwater recharge locally. The result is a wholly artificial hydrologic condition, the long-term result of which is not entirely clear, but is not likely to be beneficial. This pattern is true of much of the seaward margin of Honolulu and will hold in areas modified by an increasing number of civil and military projects. Detailed areal discussion of these projects is neither practicable nor desirable at this time.

TEST WELLS, HOLES AND PITS

Artesian wells

A total of 281 artesian wells have been drilled in this area of which 262 are in Koolau rock and have access to water from the Koolau aquifer. These wells reveal certain facts of geologic structure but unfortunately the records are not even approximately complete for most of the wells. (Figure 22)

The first artesian well to be drilled in the Hawaiian Islands was what is now known as Well No. 267, at Honouliuli village. This well was drilled by James Ashley and was commenced in July 1879. It encountered fresh water at about 250 feet below sea level at a head which permitted it to flow out of the well casing at an attitude of about 15 feet above sea level. The well was drilled for James Campbell, who was owner of the Honouliuli Ranch. Campbell had become acquainted with Ashley in the Santa Clara Valley in California where much drilling was being done at that time and because of the scarcity of fresh water in the Ewa District he was led to undertake water development by drilling at Honouliuli. There is nothing to indicate that the ground water conditions were understood or that any special technical considerations led to the selection of the site for this well. (1)

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(1) McCandless, J. S., Development of Artesian Water in the Hawaiian Islands, pp. 1-78, 1936, p. 17.

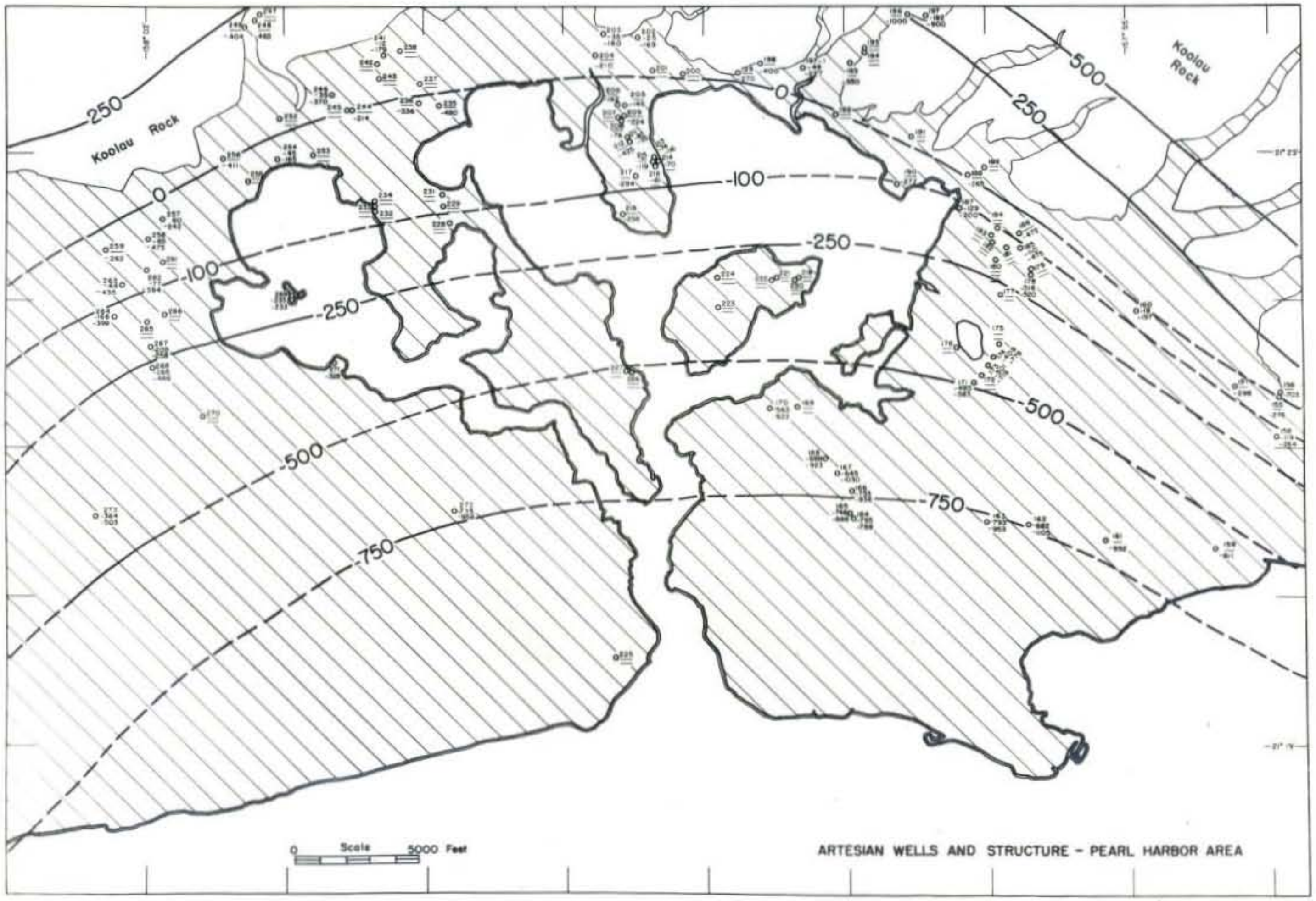

Figure 22 - Map showing locations and depths of artesian wells in the Pearl Harbor area. For each well the upper figure is the number in the new system, the middle figure is the depth measured from sea level to the top of the Koolau rock and the lower figure is the total depth below sea level. The data are summarized by the contours showing position of the surface of Koolau rock both below and above sea level. The limited data suggest a nearly uniform slope which nowhere departs greatly from 250 feet per mile except on the eastern side where the over-all slope is near 500 feet to the mile. Data are insufficient to define a cliff or bench in any particular position.

By April 28, 1880 the second well on Oahu and the first in Honolulu, the so-called Marques well, No. 38, had been drilled by another driller, A. D. Pierce. A great many other wells were drilled in various other parts of Oahu and Hawaii and gradually the areas in which flowing water could be expected were outlined. This early drilling was wholly experimental, guided only by what had been found to be useful working principles on the mainland and which were often wholly misleading in Hawaii. The reudimentary principle of the coastal cap rock was recognized by a few individuals (1) at the time of this drilling, but it was not until 1910 or later that any close regard was paid to the underlying conditions of geologic structure in drilling wells, and not until 1930 or later that practical use began to be made of the fact that nearby free basal water usually has the same head as the artesian water, that the two are in fact the same water and that the latter is commonly to be developed under much more advantageous conditions.

Such lag in understanding is strikingly shown by such installations as the artesian wells at Pump Stations 2 and 4 in Waimalu Valley, operated by the Honolulu Plantation Company. At these stations under the numbers 196A to T and 197A to I there is a total of 29 wells, with an aggregate of over 20,000 feet of drilling in the middle of a valley floor not over 1000 feet wides. The valley floor stands at an elevation of about 50 feet above sea level. These wells as nearly as the logs can be interpreted (1) go through 100 to 200 feet of detrital caprock and then enter Koolau aquifer rock which is apparently not very permeable and is rather generally weathered. The pump station floors are in deep excavations so that the pumps are below the basal artesian level. The alternative which would now be used in such a situation would be to drive a shaft and tunnel in the Koolau rock of the valley wall at about sea level so that basal water could be skimmed from the free water table. The superiority of this plan is indicated by the fact that many if not all the wells, of which a number approximated 900 feet deep, have been sealed below about 500 feet, because salinity runs high in many of them. It is obvious to us now that this would be so, since with a basal head that averages not much over 20 feet and at times is well under 20 feet, we could not possibly expect fresh water in wells reaching more than 600 or 700 feet below sea level. These wells were drilled from 1899 to 1904, at a time when drilling in a valley bottom seemed the natural thing to do and no one had been eccentric enough to even try drilling or tunneling in the aquifer rock of the valley walls. Data on these wells are tabulated in the section, ARTESIAN BASAL WATER, Table 10.

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(1) Stearns, H. T., Bull. 4, pp. 135-136, 1938.

Basal shafts and tunnels

Shafts and tunnels driven just below the basal water table differ in principle from artesian wells which reach the aquifer only after passing through caprock. However, shafts and tunnels, or combinations of these, even including some auxiliary drilling, are in principle all the same; only the form and size of the excavation differ from project to project.

The first basal tunnel on Oahu was driven in 1906 at Waikele Springs near Waipahu at 3 feet above sea level. This is No. 4B of the Oahu Sugar Company, and it has a length of 1140 feet in Koolau lava flows. (1) In 1906 and 1907 a similar tunnel, at 7 feet above sea level, was driven at Oahu Sugar Company Pump 8. It is 290 feet long. Comparative data for these tunnels are given in the section, BASAL WATER SUPPLY STATIONS, Table 7.

A number of basal tunnels, driven from the bottoms of vertical or inclined shafts, have been excavated on the Island of Maui and have proved very successful. Stearns has given to such installations the name Maui-type wells and has been active in recommending their more extensive use in developing basal water in place of artesian wells. (1) The effective development excavation in the Maui-type

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(1) Stearns, Bull. 1, p. 365, 1935.

(1) Stearns, Bull. 1, pp. 324-325, 1935.

well is a basal tunnel, and the advantage of the Maui-type well in skimming water from the basal water table with as little drawdown as possible, is equally true of any basal tunnel regardless of the form of access. It is immaterial from the standpoint of quality and quantity of water whether the basal tunnel is driven from the bottom of a shaft or from the base of a cliff; the sort of excavation required is purely a matter of topography and construction procedure and the terms basal tunnel, or basal shaft and tunnel, are more descriptive and seem preferable to the rather artificial and not immediately explanatory term Maui-type well.

Together with his perfectly acceptable recommendation of the basal tunnel as a great improvement over artesian wells, Stearns goes farther and contemplates a marked lowering of water level in basal tunnel installations "to or a little below sea level", with the stated effect of decreasing the natural discharge (leakage) and great extension of the cone of influence. He implies that such procedure would result in great increase of flow into the area in question from adjacent areas and hence result in a great increase in the water supply available to a given station. (1)

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(1) Stearns, Bull. 1, pp. 324-325, 1935.

Despite the elementary correctness of the reasoning behind this view, there are reasons for doubting if such a practice would be wholly advantageous and also if its application is indeed physically possible to the degree envisaged by Stearns. This problem is discussed in the section, Estimates of water quantities.

The next basal tunnel in the Koolau rock in the Pearl Harbor area was dug, 1936 to 1938, by Ewa Plantation Company, commencing by shaft from the elevation of about 150 feet on the south bank of Honouliuli Valley, about 2½ miles north of Ewa Mill. The total length of tunnel driven was 1138 feet and the final discharge was 38 M.G.D. Data on this project are contained in Table 7, in the section, BASAL WATER SUPPLY STATIONS.

Early in 1936 the Schofield shaft was commenced. This was dug from the surface elevation of 850 feet, under the direction of Lt. Col. J. D. Kilpatrick, U.S.A., who had conferred with many engineers and geologists of the Territory. The inclined shaft was driven to the level of the pump-room floor at 287 feet above sea level. Static water level varied from 276 to 284 feet during the period 1936 to 1938. The water taken from this station is developed in several 16 and 12 inch wells drilled from the level of 287 feet. The consensus of estimate among geologists in Hawaii at the time this project was proposed was that water in valuable amounts would be found. However no one expected it to stand higher than 30 feet, certainly not above 50 feet, since the gradient of basal water was understood to be low.

Geophysical tests

Since the shaft was dug and water encountered, geophysical measurements made by J. H. Swartz and his assistants of the Geological Survey have shown that water standing at above 50 feet lies under the Schofield Plateau from a short distance south of the shaft to a point near Kaukonahua Camp making a width of less than 3 miles. (1) So far as could be determined under the difficult conditions encountered, the high level of the water falls off at about these positions to reach the normal basal water level of the Pearl Harbor and Waialua coastal areas. The cause of the high ground water level and the reason for the indicated northern and southern limits is not known. No surface indication of a dike or dike complex is found, but the presence of dikes is perhaps the most plausible specific cause that can be suggested.

The greatest depth at which geophysical measurements proved the existence of fresh water was about 2200 feet. Since the water at Schofield shaft would require about 11,000 feet of fresh water to show Ghyben-Herzberg balance,

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(1) Swartz, J. H., Geophysical Investigations in the Hawaiian Islands, Amer. Geophysical Union Transactions 1939, pp. 292-298, 1939. Swartz, J
Swartz, J. H., Resistivity Survey of the Schofield Plateau, T. of H., Div. Hydrography, Bull. 5, pp. 56-59, 1940.

this condition was not demonstrated. The water table in this area is therefore not clearly basal water, and not true high level water, though it is probably fed from the rainy intake area leeward of the mapped Koolau dike complex, and some of it may come from water bodies restrained behind dikes. The station was completed and operations started October 5, 1938.

In 1936 and 1937 the basal shaft now known as the Navy Halawa station was constructed on the line between the land divisions Aiea and Halawa, inland from Aiea School, and at the elevation of about 95 feet. (1)

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(1) Stearns, H. T., Bull. 5, pp. 29-30, 1940.

In September 1940 a basal water shaft was completed by the City and County of Honolulu at a point about a half mile north of Pearl City junction. This is a vertical shaft 8 feet in diameter, extending to about 4.5 feet above sea level. There is a tunnel 8 feet long with its invert at 15 feet, and a total of 28 holes of 2-inch diameter and about 6 feet deep drilled in the bottom and sides to increase the yield.

In connection with the Underground Fuel Storage Project of the U. S. Navy at Red Hill, a basal water development tunnel has been driven from a sump that is connected underground with the transmission tunnel to Pearl Harbor. The work was done chiefly during 1942 and the excavation of the tunnel was finished late in December 1942. The first tunnel was driven from an invert of 15 feet above sea level and reached a length of 525 feet. At this stage, despite a known basal water level in the region of about 24 feet, the yield from the sump and tunnel was only 0.6 M.G.D. and practically none of this came from the tunnel. A new tunnel was started at invert level of 5 feet and stopped out to join with the upper tunnel with a total height of section of 19 feet. At 525 feet, the total yield was 2.0 M.G.D. The tunnel at the low level was turned 45° to the right and driven 596 feet more at a grade of 0.5%. Final discharge at the total length of 1121 feet was about 30 M.G.D. Especially in the early stages, the unit discharge in this tunnel per foot of exposed area, per foot of drawdown was very low.

Plans were made by the Board of Water Supply in 1941 to construct a basal water station in the north wall of Halawa Valley, a location determined largely by the encroachment of the Navy on the Moanalua area in Red Hill. Construction was commenced in May 1942, the inclined shaft was started in July, and the first basal water was reached on September 21, 1942. After completing the pump room chamber, an upper tunnel was driven to a total length of 321 feet. The sump was deepened to 18 feet below sea level and at this point the total of 2.0 M.G.D. was developed. The lower development tunnel, at an invert of - 2.0 feet, was commenced on June 17, 1943. It was driven to a total length of 919 feet with a discharge of slightly over 30 M.G.D. Track and tools were removed and pumping stopped on January 15, 1944. Details of various tests and geologic structure are presented on pages 64-73 of the 10th Biennial Report, Board of Water Supply.

The Honolulu Plantation Company, in January 1942, commenced the excavation of a vertical shaft, at the elevation of 195 feet, in the east side of the small valley that crosses the old road west of the Aiea Post Office. This shaft reached the level of basal water about May 1, 1942. The bottom of the shaft was finished by driving tunnel in the four directions at water level and deepening each of these tunnels as much as possible by working under water. In March 1945 this station was still under construction, in that extension of tunnel and sump area was in progress.

Test holes

In addition to the artesian wells and the various water development shafts and tunnels described, a number of test holes have been drilled in the Pearl Harbor area, and records of some of these are on file. These include several diamond drill holes along the axis of Red Hill ridge, on or near the line between the Honolulu and Ewa Districts, which were drilled in connection with the extensive excavations later carried out in the Underground Fuel Storage Project. The writer has had the use of records of some of these holes, has examined some of the cores, and on several occasions saw parts of the underground structure of the Red Hill ridge. Impressions gained from these sources form part of his understanding of the general rock character. Except for the water development tunnel in Red Hill, the excavations or holes did not go down to sea level, and they did not give any direct or readily recognizable sign of the relatively lower permeability shown by the actual yields in the first part of the Red Hill water project.

A 6-inch hole was drilled for Chester Clarke at the base of the rock slope on the south side of the Inter-Halawa spur, inland from the Board of Water Supply transmission tunnel. This hole, from an elevation of 255 feet, reached basal water and was used by this office for water table measurements from 1941 to 1944. It was covered by quarry waste in March 1944, and was accidentally filled in course of attempts to clear it. Water levels in this hole have been tabulated (Table 6) and will be discussed in the section, FREE BASAL WATER. No record of the section penetrated has been seen.

Before 1940 a diamond drill hole was put down under the direction of H. A. R. Austin, at elevation 216 feet, about ½ mile inland from Aiea mill in the east wall of Aiea Valley. This hole reached basal water and is still in use as a water-measuring point for this area. Normal Koolau rock was penetrated and no detailed presentation of records or cores is attempted here.

Hole 42 and 43 were drilled in 1942 on the east and west sides, respectively, of Moanalua Valley. Though these holes are both in the Honolulu District, they are mentioned here because they were drilled and are now in use for water table measurements in connection with the conjoint water problem of the Moanalua and Pearl Harbor areas.

The transmission tunnels through the Red Hill and Inter-Halawa ridges will be described in connection with the Halawa Project. They penetrated Koolau rock in the main, with tuff and other surficial formations as expected, on the east ends of each.

In addition to the various test holes and other excavations mentioned there are several quarries in the Pearl Harbor area which facilitate local examination of the character of the rock. The rock is known as well here as in any other district on Oahu but our information still suffers from certain limitations, such as lack of systematic drilling or other excavation in the inland, mountainous area, and lack of access to formations at and below sea level except through the occasional churn drill logs.

PHYSICAL PROPERTIES OF THE ROCK FORMATIONS

The Koolau formation

The only rock formation in this area that is of importance as an aquifer is the Koolau lava formation. The Koolau rock here retains in a broad way the same characteristics it has elsewhere. In the seaward section, revealed in various exposures, but particularly in the drill cores taken from test holes along the Red Hill axis, it can be seen that the larger part, perhaps 2/3 to 3/4 of the total section is made of aa flows and the remainder consists of pahoehoe flows. The features of these two types of flows have been described elsewhere but certain points need repetition.

The pahoehoe flows are formed of highly fluid and gas filled lava that has remained in the primitive condition in which it always emerges from the vent. Pahoehoe flows are usually formed in successive layers or tongues and usually have a glassy, fairly smooth surface that often shows wrinkles, ropey structures, large bubbles and often a broken, spongy surface. The edges of the different layers of a pahoehoe flow usually are quite vesicular, with rather small, regularly spaced, uniform-sized bubble holes, arranged in a banded configuration. The banding of the rock is often overlapping, infolded, and otherwise contorted in the course of flow. Successive unit layers or even successive lava flows may lie directly on the underlying ones, with no clinker layer, and they often show a slight rusty or weathered zone, a fraction of an inch thick, at the contact.

Pahoehoe lava flows are therefore chiefly solid lava rock of the "pukapuka" type, but not of the dense, blue rock type. On the other hand aa lava flows include, as seen in section, two sorts of material, the aa clinker layers and the aa dense layers. The liquid lava, which always issues as pahoehoe, may after a time become somewhat cooled and reduced in gas content and commence to undergo crystallization. Lava which commences this crystallization and forms a constantly broken and constantly renewed crust is known as aa. When an aa flow is in process of movement downslope, it is almost completely covered by a thick accumulation of very rough, irregular masses of solidified crust, from a few inches to several feet in diameter, which is borne along as a load on top of the fluid tongue inside. These masses move forward and continually cascade down the frontal slope; in a thick aa flow, this frontal slope may be 25 to 50 feet high and with an angle of 35 or 40 degrees. At the front, this loose material falls down to cover the ground over which the liquid interior mass will flow, so that the just recently solidified loose clinker, part of the flow itself, becomes lodged both in a lower layer and an upper layer. The dense layer is formed from the moving liquid lying between.

At the surface, on the slopes of Mauna Loa and Kilauea, the pahoehoe flows are relatively smoother areas over which travel is not too difficult for pedestrians and hores. On the contrary the surface of an aa flow, covered wholly by irregular, ragged clinker masses of all sizes, piled loosely in the most instable fashion, is about the roughest and most difficult surface over which to travel for either man or animal. On such a surface there is practically no view of the interior dense portion of the aa flow, and apparently most laymen in Hawaii take the loose aa clinker as being the entirety of an aa flow.

Actually it would be quite impossible for a lava flow to consist wholly of the clinker; the only way the clinker can move into an area is by transport on the body of a moving liquid interior. This liquid interior solidifies to form the dense part. Locally, for a few feet, the dense part may be thin, perhaps less than 20% of the whole thickness but in general the dense part is probably much over half the total. In small spots locally, due to the accidents of topography and behavior at the time of emplacement, either the top clinker or the bottom clinker may be thin or missing, but over the greater part of the area some clinker will be placed both above and below the dense part of any flow.

The dense parts of aa flows are the thick masses of blue lava rock which are essentially the only parts of the Hawaiian lava flows suitable for crushed rock or concrete aggregate. The body of pahoehoe lava flows, being "pukapuka" rock, is not suitable for use as concrete aggregate and is not used except in very limited or local operations. Quarry operators in seeking quarry sites choose valley walls and spurs where fairly thick dense members of aa flows can be seen. They then have to put up with handling such overburden and interbedded aa clinker as is found there. This reduces the percentage of usable rock taken out of the quarry, but only a few lava formations of quarry thickness and without clinker have been found. (Moiliili Quarry is in a thick mass of Honolulu basalt which came from Sugarloaf and piled up on the floor of Manoa Valley).

From the foregoing discussion it is seen that an aa flow consists both of the clinker layers, above and below, and the dense, "blue-rock", mass which lies in the middle. This dense rock, which has a few large vesicles, but is not finely vesicular, is the main part of the aa flow. Though the aa rock preponderates, as seen in the transmission tunnels and access shaft of the Halawa job, in the extensive excavations of the Red Hill project, and elsewhere, there is still a minor fraction of pahoehoe rock, which may be continuous for 25 or 50 feet of vertical section, and may be continuous for several hundred feet of any tunnel excavation. Such rock lined most of the sump and more than 500 feet of the development tunnel in the Halawa job.

In the eastern part of the Pearl Harbor area, especially from Moanalua to Aiea, various quarries and excavations show that the aa flows are thicker than is common in the Honolulu area, perhaps showing 15 to 20-foot flows rather than those less than 10 feet thick. Surface outcrops suggest that this condition may continue around the Pearl Harbor margin, being perhaps due to the lower angles of slope and the tendency of lava flows to thicken here. In various quarries and in the transmission tunnels aa clinker mounds 15 or 20 feet or more thick are not uncommon and the irregularities of the dense masses are correspondingly greater. Many small lava tubes and several large ones were encountered in the Inter-Halawa transmission tunnel. At one point a large tube, 15 to 30 feet wide and up to 8 or 10 feet high above the debris which partly filled it, crossed over the tunnel and was explored for two or three hundred feet inland. This tube and the opening of the vaulted roof over and along the tunnel where the wto were nearly parallel created a sufficient hazard to tunnel driving operations that it was deemed prudent to deflect the tunnel so as to get under solid cover. The center line was turned at 22½ degrees, till an offset of 45 feet was reached; the line was then carried parallel for 200 feet and thence returned to the original center line 400 feet from the first point of deflection.

The impression might be gained from the several rather large lava tubes encountered in the Inter-Halawa tunnel that lava tubes are very large contributors to the water-yielding capacities of rocks and that much of the water to be developed in a water development tunnel would come in through lava tubes. However, without denying that such tubes could indeed transmit large volumes of water, it is probable that the agency of lava tubes has been exaggerated. In the Halawa development tunnel about 1500 feet of tunnel was driven without encountering any but rather small tubes. All the tubes encountered in pahoehoe lava, which in general was a poor yielder of water. Several of the tubes brought in a steady flow of water, up to a quarter or half M.G.D. which lasted throughout the period of access to the tunnel. The flow of water from the sides and the roof of the tunnel, including the tubes, in the pahoehoe section was quite impressive and picturesque but measurements show us that such water, all told, from over 500 feet of tunnel, was less than the amount yielded into some sections of 100 feet in the aa clinker from the tunnel floor with hardly a ripple.

It would not be justified, from previous experience, or from the Halawa project, to make a general statement as to whether aa or pahoehoe lava flows are most productive of water. So many differences are found in each, and the thickness and jointing of flows, tubes, bubbles, and the like are all so variable that any summary statement would probably be misleading. Both aa flows and pahoehoe flows of the Koolau series can be highly productive of water in tunnel or well excavations, running up to yields of 1000 or more gallons per day per foot of exposed surface per foot of drawdown. It has commonly been supposed that any excavation in Koolau rock, below water table, a hundred feet or more below the weathered surface, and a few hundred square feet in area, would yield not less than 250 to 500 gallons per day per foot of drawdown per square foot of surface area. Experience in both the Red Hill and Halawa jobs taught us that combined shaft and tunnel excavations with total length of tunnel reaching several hundred feet and with exposed surface under the water table reaching 10 to 20 thousand square feet can show yields as low as 10 gallons per day per foot per square foot. This is a rate which may not justify investment and in both cases the rate was raised to almost ten times this amount by continuing to an excavation of more than double the earlier length and reaching more permeable rock.

Sedimentary formations

No sedimentary formation is found in the Pearl Harbor area which can be considered as a water-yielding rock. In a few places shallow pits and wells derive some supply of caprock water, usually brackish, from coral reef formations but in all cases these probably get the water by transfer from the Koolau rock ultimately.

GROUND-WATER RESOURCES

Rainfall

The total rainfall of the area trihtary to the Pearl Harbor shoreline is much less accurately known than for the adjacent Honolulu area, owing to lack of gages and long term records in much of the mountainous area. Locations of gages are shown in Figure 9 as well as the isohyets drawn from the data. Following the methods set forth in earlier reports the area has been divided into the hydrologic provinces shown in Figure 10. The areas of each of these components have been determined by planimeter and the mean rainfall estimated by inspection of the isohyets on that component. In Table 1 are given the areas, the estimated mean rainfall values, and the rainfall quantities that are derived from these. While these quantities cannot be regarded as being closer than perhaps 20% to the true value, they are the best we now have and despite the fact that the totals appear small in relation to known discharge, we have no direct basis for raising the estimates.

It is shown in the table that total rainfall amounts in the eastern, central and western sectors roughly are 118, 149 and 166 M.G.D., the grand total being 433 M.G.D. But of these amounts only 83, 117, and 93 M.G.D., respectively or a total of 292 M.G.D. are from the mountain intake area. If we combine the mountain intake, and facet and apron areas,

TABLE 1

RAINFALL QUANTITIES AND AREAS BY HYDROLOGIC PROVINCES IN PEARL HARBOR AREA

Number	Name of Province	Average Rainfall	Mountain Intake above 100"		Mountain Intake below 100"		Facet and Apron Area		Valley Bottom Area		Coastal Plain Area		Mountain Total		Mountain plus Facet-Apron Area		Grand Total		Component Sectors
		Inches	Sq.Mi.	M.G.D.	Sq.Mi.	M.G.D.	Sq.Mi.	M.G.D.	Sq.Mi.	M.G.D.	Sq.Mi.	M.G.D.	Sq.Mi.	M.G.D.	Sq.Mi.	M.G.D.	Sq.Mi.	M.G.D.	
100	South Halawa Mountain	130	1.24	7.66															Red Hill to West Limit Waimalu Drainage
101	South Halawa Mountain	75			0.86	3.14													
102	Halawa-Pualoa Coastal Pl.	25									5.58	6.64							
103	South & North Halawa Valley Bottom	72							1.54	5.28									
104	Inter-Halawa Facet	80					0.63	2.40											
105	North Halawa Mountain	145	3.01	20.79															
106	North Halawa Mountain	75			0.24	0.86													
107	Aiea Facet	70					2.16	7.20											
108	Kalauao-Waimalu Mountain	165	5.96	46.76															
109	Kalauao-Waimalu Mountain	75			0.71	2.53													
110	Kalauao-Waimalu Coastal Plain & Ford Is.	28									0.99	1.32							
111	Kalauao-Waimalu Valley Bottom	38							1.01	1.83									
112	Kalauao-Waimalu Facet	46					0.84	1.84											
113	West Waimalu Facet	73					2.42	8.41											
114	West Waimalu Facet Channels	60			0.38	1.09													
	Sub-Total												12.40	82.83	18.45	102.68	27.57	117.75	
115	Waimano-Waiawa Mountain	175	11.70	97.40															Waimano and Waiawa
116	Waimano-Waiawa Mountain	80			4.78	18.20													
117	Pearl Peninsula Plain	28									1.57	2.10							
118	Waimano-Waiawa-Panakauahi Val. Bot.	60							2.32	6.62									
119	Facet Channels	55			0.40	1.05													
120	Waimano Facet-Apron	58					3.21	6.86											
121	" " "	55					0.87	2.28											
122	" " "	34					1.17	1.89											
123	" " "	45					3.11	6.66											
124	" " "	80					0.13	0.49											

114	West Waimalu Facet Channels	60			0.38	1.09													
	Sub-Total												12.40	82.83	18.45	102.68	27.57	117.75	
115	Waimano-Waiawa Mountain	175	11.70	97.40															
116	Waimano-Waiawa Mountain	80			4.78	18.20													
117	Pearl Peninsula Plain	28									1.57	2.10							
118	Waimano-Waiawa-Panakauahi Val. Bot.	60							2.32	6.62									
119	Facet Channels	55			0.40	1.05													Waimano and Waiawa
120	Waimano Facet-Apron	58					3.21	8.86											
121	" " "	55					0.87	2.28											
122	" " "	34					1.17	1.89											
123	" " "	45					3.11	6.66											
124	" " "	80					0.13	0.49											
125	Panakauahi Apron	37					2.06	3.63											
	Sub-Total												1[illegible].38	116.65	27.43	140.46	31.32	149.18	
126	Kipapa-Waikakalaua Mt.	200	7.34	69.85															
127	Kipapa-Waikakalaua-Waieli Mountain	60			7.99	22.80													
128	Waipahu Coastal Plain	24									3.58	4.09							
129	Waipahu Valley Bottom	35							1.85	3.08									Waiawa to West Koolau margin
130	Kipapa Apron	35					3.05	5.08											
131	Kipapa Apron	65					0.30	0.93											
132	Kipapa-Waikakalaua Apron	44					6.67	13.97											
133	Waikakalaua-Waieli Apron	40					2.83	5.39											
134	Waieli Apron	34					2.33	3.77											
135	Waikakalaua-Waipahu Apron	27					2.60	3.34											
136	Honouliuli Apron	26					4.52	5.59											
137	Honouliuli Apron	26					0.66	0.81											
138	Honouliuli Valley Bottom	26							0.66	0.48									
139	Ewa Coastal Plain	20									28.00	26.66							
	Sub-Total												1[illegible].33	92.65	38.29	131.53	72.11	165.86	
	Grand Total		29.25	242.46	15.36	49.67	39.56	82.54	7.11	17.29	39.72	40.83	44.61	297.13	84.17	374.67	131.00	432.79	Pearl Harbor Topographic Drainage
	Grand Total										34.26(1)	33.91(1)			83.30(2)	368.89(2)	124.67 (3)	420.09(3)	Basal Area No. 6

(1) Reduced from corresponding area above by subtracting caprock area of Pearl Harbor drainage belonging to Isopiestic Area No. 4, to wit Areas 82, 84, 85, and ½ of Areas 83 and 86, or 5.46 square miles and 6.92 M.G.D. (See Halawa-Moanalua Report)

(2) Reduced from corresponding area above by subtracting mountain area of Pearl Harbor drainage belonging to Isopiestic Area No. 4, to wit Area 91 and ½ of Area 92, or 0.87 square miles and 5.78 M.G.D. (See Halawa-Moanalua Report)

(3) Corrected as in (1) and (2).

to make the largest possible source estimates, we derive the amounts 103, 140, and 132 M.G.D. respectively, or a total of 375 M.G.D. When we deduct the portion east of the axis of South Halawa Valley, the total corresponding the basal area 6 is 369 M.G.D. The latter figure is the total from which the actual draft must be derived, as we interpret the geologic structure.

Runoff

Records of natural runoff in this area are very meagre. According to compilations by the Territorial Planning Board of data collected by the Geological Survey and others, as well as conversations with Max Carson, District Engineer, U.S.G.S., the only record of natural runoff from a complete mountain basin is that for North Halawa. This covers a 4-year period and shows a mean discharge of 1.84 M.G.D. per square mile of drainage area. Just beyond the north margin of the area are two records of 23 years duration, for head basins of the Kaukonahua system above elevation 1200 feet, which show discharge rates of 6 to 7 M.G.D. per square mile.

In the Honolulu area the runoff from mountain sections ranges from 0.83 to 3.02, with an average of 1.80 M.G.D. per square mile (Kalihi Report, p. 68). These scattered records constitute the only basis for guessing the quantities of runoff for the whole Pearl Harbor area. Despite the high rate for Kaukonahua, it does not seem likely that the overall rate for the more inland part of the intake area (total area above 100" rainfall, 29.25 square miles) would exceed 3.00 M.G.D. per square mile, nor be under 2.50 M.G.D. per square mile. The high and low water quantities here would then be 87.75 and 73.12 M.G.D.

For the mountain intake area below 100" rainfall (15.36 sq. mi.) we can only assume say 1.5 to 1.0 M.G.D. per square mile, giving quantities of 23.04 and 15.36 M.G.D., respectively for high and low. For the facet and apron area of 39.56 square miles there is scarcely any basis for estimate, but since the total rain on this area is only 82.54 M.G.D. an estimate of 0.5 to 0.25 M.G.D. per square mile, giving 19.78 and 9.89 M.G.D. high and low totals, seems reasonable. These breakdowns give a high total for runoff from the mountain and apron area of 130 (130.57) and a low total of 100 (98.37) M.G.D. of runoff for the Pearl Harbor district. It should be pointed out that these figures are for immediate runoff to channels, there may be much loss from channels and the total runoff to the coast actually may be less than the totals shown above. How much less is the amount at the margin of the caprock we have no means of determining, nor do we know how much of the difference returns to basal water.

Transpiration and evaporation

Possibilities of estimating transpiration and evaporation are no better than in the case of runoff. If we follow the procedure of Kunesh and use 20% of rainfall for evaporation, the amount for the mountain and facet area would be 75 M.G.D. If we use his method also for transpiration, we must take 30 inches of rain on an area of approximately 70 square miles that receives 30 inches. This makes a total of 2100 x 0.0476, or 100 M.G.D. (99.96). This, assuming that all transpiration for areas getting under 30" was supplied by irrigation, would make a total of 175 M.G.D. for transpiration and evaporation.

If, on the other hand, we assume that all evaporation and transpiration in the irrigated areas is supplied by irrigation, this will lead to a smaller estimate of loss by these avenues. The irrigated area above the caprock is nearly 20 square miles. If we omit this part there is somewhat under 70 square miles of natural vegetation. If on this area we assume an evaporation as low as 20 inches and transpiration as low as the 10-inch minimum of recent measurements, the total of 30 inches on 70 square miles is equal to about 100 M.G.D. We have no data or facts that seem to justify a direct estimate of average evaporation and transpiration on the mountain and facet area of less than about 100 M.G.D.

Infiltration remainder

TABLE 2

Breakdown A (Kunesh Method)

NOTE - This breakdown, so far as data permit is identical with that used in the Honolulu area.

Total Rainfall on Mountain Area and Facet Area (Excluding Caprock) (M.G.D.)			369
Runoff (M.G.D.)			
Inland area above 100", 28.5 sq. miles @ 2.75 M.G.D. per,	78		
Inland area below 100", 15.36 sq. miles @ 1.25 M.G.D. per,	19		
Facet and apron area, 39.56 sq. miles @ 0.375 M.G.D. per,	15		
Total		112	
Evaporation (M.G.D.) 20% of 369 M.G.D.		74	
Transpiration (M.G.D.) 30" on 70 square miles		100	
Total (M.G.D.)			286
Remainder for infiltration (M.G.D.)			83
Deduct for Pearl Harbor Springs (assumed) (1) (M.G.D.)			30
Remainder for artificial draft (M.G.D.)			53

(1) A table in this report shows net measured loss to ocean of unused water from large springs of 33.7 M.G.D.

TABLE 3

Breakdown B (Modification of Runoff Quantities)

Total Rainfall on Mountain Area and Facet area (Excluding Caprock)			369
Runoff			
Inland area above 100", 28.5 sq. miles @ 2.00 M.G.D. per, (Honolulu mean to gage stations)	57		
Inland area below 100" 15.36 sq. miles @ 1.00 M.G.D. per,	15		
Facet and apron area, 39.56 sq. miles @ 0.25 M.G.D. per,	10		
Total		82	
Evaporation 20% of 369 M.G.D.		74	
Transpiration 30" on 70 Square miles		100	
Total (M.G.D.)			256
Remainder for infiltration			113
Deduct for Pearl Harbor Springs (assumed)			30
Remainder for artificial draft			83

TABLE 4

Breakdown C (Runoff and Evaporation and Transpiration greatly modified)

Total Rainfall on Mountain Area and Facet area (Excluding Caprock)			369
Runoff			
Inland area above 100", 28.5 sq. miles @ 2.00 M.G.D. per, (Honolulu mean to gage stations)	57		
Inland area below 100" 15.36 sq. miles @ 1.00 M.G.D. per,	15		
Facet and apron area, 39.56 sq. miles @ 0.25 M.G.D. per,	10		
Total		82	
Evaporation and Transpiration			
Omit all losses from agricultural area, assume losses from remaining 70 square miles of natural vegetation as low as 20" for evaporation and 10" for transpiration, approximately the same as lowest measurements made on Oahu		100	
Total (M.G.D.)			182
Remainder for infiltration			187
Deduct for Pearl Harbor Springs (assumed)			30
Remainder for artificial draft			157
Present total used draft, 1944, artificially from wells, tunnels and springs			220

In the preceding tables there are three attempts to balance the hydrologic equation. In Breakdown A it appears that the use of Kunesh's procedure based on the meagre runoff data and with the same application of percentages on evaporation and transpiration as used for Honolulu by him and by Wentworth, in earlier reports, results in a water supply estimate that is less than a fourth of the known draft, and deficient by at least 150 M.G.D.

In Breakdown B, rather arbitrarily, the runoff estimate is cut down to the average rate for Honolulu, despite the much higher rainfall in the Pearl Harbor mountainous district. With this change the possible water supply remainder is raised to 83 M.G.D., still far short of known draft.

Finally in Breakdown C, the evaporation and transpiration figures are cut down to the minimum known measurements and the loss restricted to the forest area, with no allowance for loss from cultivated area. By this drastic reduction, supportable purely as an adjustment to known draft, we get a possible water supply figure of 157 M.G.D., which is still much under the known draft.

From the adjustments that are shown to be required in order to even approach the known draft, it appears that such tabulations cannot by any means be considered as estimates of actual available water supply, but are merely breakdowns which can by extreme juggling be brought into line with the known draft. Certainly on the basis of present data we cannot use the hydrologic equation to make even a guess as to potential water supply. The chief value lies in the figure for total rainfall which suggests an outside total on which the area draws.

The plain fact is that we have as yet no basis for estimating the total annual rainfall on the watershed area tributary to the basal water at over 369 M.G.D., nor the net infiltration at even as much as 200 M.G.D. Yet we know that total artificial draft plus loss from the Pearl Harbor Springs in 1944 was over 250 M.G.D. (See Table 9). It would be very attractive to offer an explanation for the recovery of at least 50 M.G.D. and possible 100 M.G.D. more water than appears to enter the system.

It is commonly said that return irrigation water must account in large measure for such discrepancies. It is worth while to examine this suggestion. A rough analysis has been made for the Pearl Harbor area. From this it appears that not over 12,000 acres of irrigated sugar land lies inland of what we believe to be caprock. All this area is on facet and apron land where residual soil and sub-soil are thick and from which infiltration is believed to be relatively ineffective. The average rainfall on this area is about 35 inches or about 2700 gallons per day per acre. The total amount of irrigation water applied to this area is probably not over 80 M.G.D. In view of the character of the soil and the fact that even uncontrolled rainfall would not likely supply so much as 40%

to infiltration, it seems to the writer doubtful if the effective deep infiltration from irrigation amounts to more than 15% of the irrigation applied. (This is of course a different figure from that for loss from irrigation in transmission; much of the later is still retained in the soil.) On this basis, it seems unlikely that more than 12 or 15 M.G.D. is returned to basal water from irrigation water in the Pearl Harbor area from Halawa Valley to the Koolau margin west of Honouliuli. This belief is strengthened by knowledge of the practice of plantations in measuring water quantities and the fact that nearly all this water is pumped water. It seems unlikely that large or continuous losses of water over and above a calculated application to soil would be undetected and persist. Recently, in course of discussing this problem, Dr. Harry Clements, plant phisiologist of Castle and Cooke and the University of Hawaii, stated that in a few instances in the past, owing to excessively concentrated applications of irrigation water, as much as 1/3 of the total has probably been lost into the sub-soil structure. But even in these cases, only a fraction of the operations of a given plantation would be involved, and then only for a short time. He felt that continuous loss over a large area for a period of months would be well under 1/4 of the whole, a view which accords with the present writer's opinion. (1)

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(1) Clements, Harry, Personal communication, Mat 17, 1945

The suggested possible amount of 15 M.G.D. from return irrigation water is too little to materially assist us in reconciling the figures for rainfall and infiltration with those for discharge from basal water. Similar studies in the Honolulu area have led to the belief that part of the excess of discharge over plausible infiltration figures may be explained as draft from so-called bottom storage. In the Honolulu area it is known that there has been a permanent lowering of the basal water table by 10 to 15 feet and according to the Ghyben-Herzberg theory such lowering of the water table would result eventually in a rise of the diffusion zone by 400 to 600 feet, a shrinkage in bottom storage which would yield all told a very large amount of water. In the Honolulu area, the fact of shrinkage in the amount of stored water is proved by the encroachment of salt water at the bottoms of well which formerly drew only fresh water.

In the Pearl Harbor area the evidence of progressive salting and rise of the salt water boundary is less clear and the amount of possible sprinkage of the fresh water is relatively less. Moreover, we have as yet less data on the storage per foot in the Pearl Harbor area, so that reliable data are lacking to support a suggestion that an excess of discharge over inflow of the required 50 or more million gallons daily could have come during the past 20 years or more from storage. Such a draft, totalling 365,000,000,000 gallons, would represent water stored at 1 gallon per cubic foot (13.3% porosity, roughly comparable to what is indicated in the Honolulu area) in 13,000 square-mile-feet, or an area of 52 square miles to a thickness of 250 feet. Beyond the observation that such figures for area of basal water table and possible thickness of rock depleted of salt water are plausible limits in the Pearl Harbor area, no assertion seems justified.

Much less than in the Honolulu area are we able to say that the observed excess of discharge over any plausible infiltration can be readily explained by recourse to draft from bottom storage or that the depletion of bottom storage to some considerable degree is demonstrated. There remains for the Pearl Harbor area the challenging fact that we are measuring much more water than we know the source of.

Occurrence and behavior of ground water

SURFICIAL GROUND WATER

Surficial ground water, or what is called soil water by some, is water held in the soil and ground immediately below the surface. It is mostly water still susceptible of return to the surface by evaporation and of use by plants. (1) It is of chief significance to us in that vegetation is depend-

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(1) Meinzer, O. E., Outline of Ground Water Hydrology, U.S.G.S., Water Supply Paper 494, p. 23, 1923.

ent on it and it is the source of evaporation and transpiration. In turn, the vegetation cover and the weathering responses of the rock in different zones control the existing intake character of the mountainous terrane. Direct artificial draft of water from the surficial ground water is quantitatively impracticable. The chief occurrence of surficial ground water is in soil-covered areas where the infiltration of water to deeper ground water is perhaps not active. It is not known accurately how much of the infiltration of rainfall to deeper layers takes place through what might be called surficial water and how much takes place more directly as percolating water in permeable rock channels, rock walls, and the like, but there is reason to think the latter process preponderant.

VAGRANT PERCOLATING WATER

The water included under this term is equivalent to the water designated by Meinzer as "intermediate vadose water". It is water that is moving or percolating downward or laterally in accordance with the structure of permeable rock between the overlying zone of surficial water and the underlying water table, which is the upper surface of the zone of saturation. In some places where the downward or lateral movement of the vagrant percolating water is impeded, bodies of perched or confined water are formed, as described in the section, PERCHED AND RESTRAINED HIGH-LEVEL WATER. These are not strictly a part of the vagrant percolating water but they may feed, or be fed by, the latter. If the passage of water downward is by trickling through openings in such a way as to fall freely and not to develop a definite water column with indicated head, this would be called vagrant percolation. Where a column of saturation with a head is set up it would locally be considered confined water, if known.

The movement of water downward from the surface of the ground to the main or basal water table evidently must take place either by vagrant percolation or through confined water channels or columns. It is impossible to say which of these is of most quantitative importance. One of the most impressive features of the intermediate, aerated rock zone through which movement by either method must take place is the exceeding small amount of water to be met in any random traverse through it. We know by prolonged experience that random tunneling will not pick up even detectable amounts of water in most parts of the Koolau rock above the water table and outside the dike complex. This condition can be explained by a little calculation.

For example, if we assume the annual transit downward of infiltrated water to be equal to 50 inches, this will mean a daily amount equal to a layer about 1/7-inch thick. If we assume a tunnel section 10 feet wide and 100 feet long, or 1000 square feet, this 1/7-inch layer would amount to about 12 cubic feet or 90 gallons. Ninety gallons of water a day is approximately 1 quart every four minutes, or 1 cup per minute. Such an amount would not show up at all in 100 feet of tunnel unless it were all concentrated in one dripping point. Or, on the other hand, if we consider some such flow as 50,000 gallons a day, worth putting in a pipe line for municipal use, it is seen that this amount would correspond to some 60,000 feet of tunnel. Since the passage of all the water involved could take place with very little observable flow, we cannot assert that the water we find in the water table must flow by certain concentrated channels that we do not often find. There is no valid reason for saying that this is true, though some such channels do exist.

We may ask whether vagrant percolating water moves to any marked extent laterally, in course of its downward movement. It is well known that in many parts of the world there are certain nearly horizontal beds of water saturated rocks which serve as channels to transmit ground water for scores or hundreds of miles from the point of infiltration. Since the Hawaiian lava flows are thin formations, laid one on another, it is reasonable to ask if water commonly follows individual flows so as to move perhaps thousands of feet horizontally while moving downward by a few hundred feet only. Field evidence shows that movement of this kind is exceptional. A few volcanic ash beds, occasional sills, rarely a weathered zone or a soil layer may perch water above it, but only for very limited distances does water follow individual lava flows. It appears, in the main, because of cooling joints and the breaking of lava flows into blocks that are no longer or wider than they are thick, that the total mass of lava flows is to all practical purposes just as permeable vertically as it is horizontally. It is true that some lava flows are more permeable than others and that water may be yielded into a tunnel from one flow at a rate 10 to 50 times greater than that from another. However, the general permeability is so great that such differences do not appear to result in horizontal diversion for great distances. Apparently the distances of horizontal diversion are less than the vertical distances through which the vagrant water moves. After the vagrant percolating water reaches the basal water table, differences in permeability and in ease of escape may, in some places, result in horizontal movement for several miles.

PERCHED AND RESTRAINED HIGH-LEVEL WATER

In places where percolating water accumulates in porous rocks above some impervious layer so as to saturate the rock and to establish a local water table it is known as perched water. The impervious layers of this kind found in Hawaii are; (1) ash or tuff beds, (2) basaltic sills, or (3) soil and other weathered layers. Only in a few places in Hawaii are such layers so placed as to cause the accumulation of significant amounts of perched water, though it is not at all uncommon for small amounts of seepage to pass out of the face of a rock exposure along the weathered contacts between flows or from above sills and ash beds. Such zones often are marked by growth of grass or ferns but usually they involve very superficial and small supplies of water. In the eastern part of the Pearl Harbor mountain section it appears that both sills and ash beds are much less abundant than they are in the Nuuanu to Waialae part of the Honolulu watershed. As stated elsewhere, the western part of the mountainous watershed has not been examined in detail but according to all indication there is no increase in the abundance of either exposed sills or ash beds in the leeward slope of the range.

Restrained high-level water consists of local ground water bodies accumulated behind nearly vertical barriers such as dikes. In many cases it is not known if these do or do not also have impervious layers such as sills under them. The most extensive and best known body of high-level, restrained ground water in Hawaii has been developed in the Waiahole project. The greater part of the accessible water of this body is probably derived from rainfall on the windward side of the range, outside the Pearl Harbor area and is chiefly reached by development from the windward slope. It does not appear that any significant part of this water can economically be reached from the leeward slope by tunnels driven expressly for that purpose.

THE WAIAHOLE TUNNEL PROJECT (1)

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(1) Only a brief discussion on this project is offered here, since it is mainly outside the Pearl Harbor drainage area.

The Waiahole Tunnel was commenced in 1913, with the aim of transmitting water, derived largely from surface sources on the windward slope, through the Koolau Range for use on the leeward slope. The tunnel was completed late in 1915, and delivers water into the head of Waiawa Valley at an elevation of 724 feet. From this point the water is carried in a ditch which contours the south slope of the Schofield Saddle and extends several miles westward to reach the slope of the Waianae Range at an elevation of about 650 feet. In much of this area the level of the Waiaho'e Ditch marks the boundary of sugar-cane agriculture; above it are pineapple fields, active or abandoned.

The Waiahole Tunnel at present is a combined project deriving ground water from tunnels driven into the dike complex on the windward side of the range and also surface water from windward channels that pass across its collection ditch system. (Figure 23) Additional water enters the tunnel within the 14,000 odd feet of the main bore. The water entering the main tunnel leeward of the crest is computed on the basis of weir readings in the tunnel at the line of the crest and at the leeward portal; the difference being the water entering this part of the tunnel. This quantity has approximated 6 M.G.D. in recent years.

At the time the Waiahole Tunnel was planned, it was recognized by the designer, J. B. Lippincott, that large amounts of water would probably be developed in driving the first

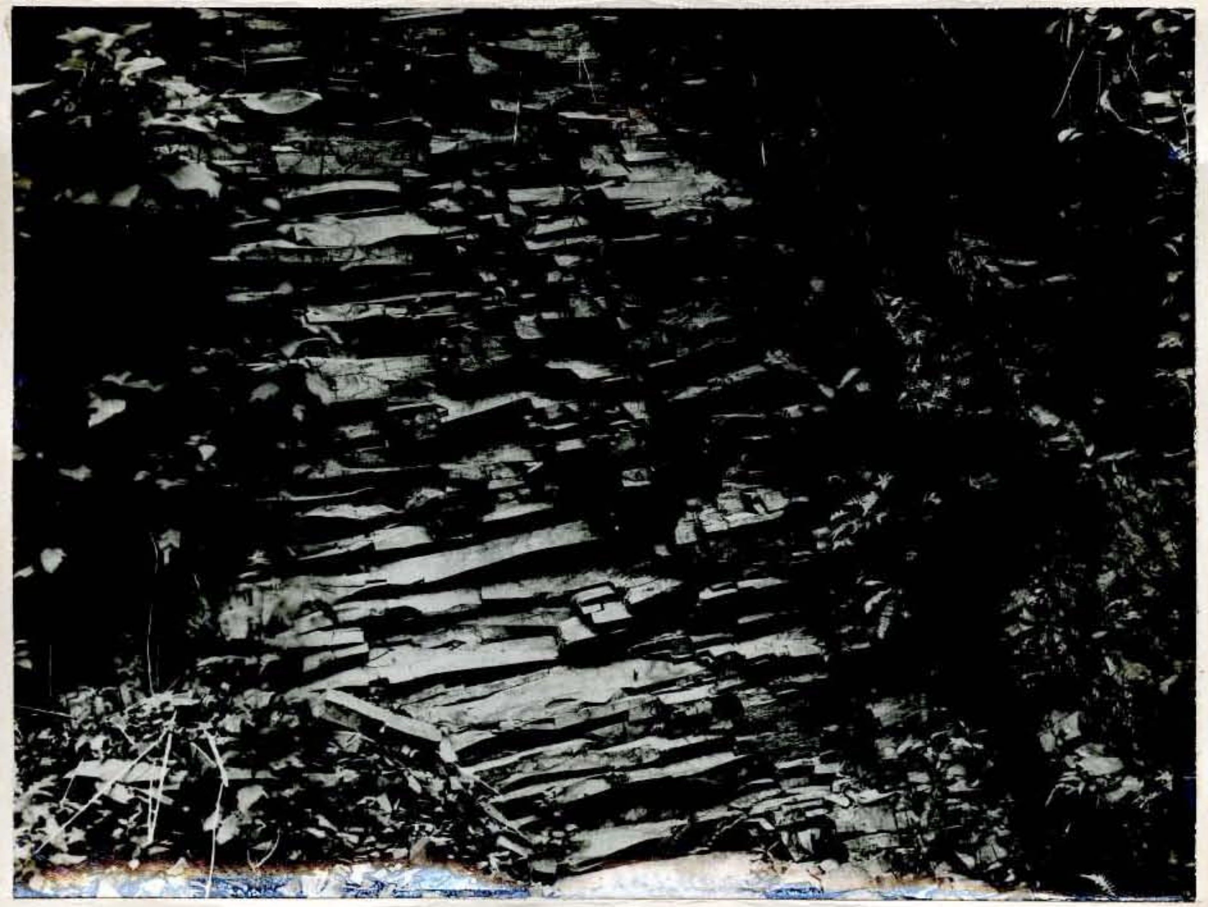

Figure 23 - Detail of compound dike in the dike complex on the road to Waikane, windward slope. The close jointing of these dikes undoubtedly has its origin in the stresses set up at the time of cooling but at depth underground apparently does not take the form of openings capable of transmitting significant amounts of water. The release in the form of visible cracks seems to come only after the reduction of pressure near the surface. Negative No. 13721.

2000 feet of tunnel on the windward side of the range and also that a considerable amount of percolating water tributary to the leeward side might be encountered in the tunnel on that side. (1) But on the other hand, there is no indication, in the report cited, of any knowledge of the possible confining of water behind dikes, of the existence of a dike complex, or of its hydrologic significance. The suggestion that water might be expected in the tunnel on the windward side would easily follow from observation of flowing, high-level springs. However, Mr. Jorgen Jorgenson has stated that he and perhaps others connected with the work were aware of the possibility of confined water being encountered behind dikes on the leeward side. (2) In any event it is clear that the distinction between vagrant percolating water and water confined between dikes was not then generally understood, and it appears that the geologic structure and hydrologic significance of the dike complex was not even suggested at that time. Experience in the Waiahole Tunnel and especially the large amounts of water

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(1) Lippincott, J. B., Report to Board of Directors of Oahu Sugar Co., August 19, 1911, Copy in Report Honolulu Water Commission of 1917, Vol. 4, pp. 4-32, 1917.

(2) Personal communication.

encountered under pressure behind dikes was a most vivid object lesson and suggested to many persons the possibility of development of high level water by tunneling in other places. Not all the projects undertaken were based on sufficient study of geologic and rainfall conditions and we know today that each area has its own specific features which must be taken into account.

Perhaps the most important consideration in the development of confined high-level water is the distinction between the copious, initial flow under high pressures, based on rapid depletion of underground storage, and the steady, permanent flow which can reasonably be expected after a new equilibrium has been reached. With a short tunnel and a small drainage area, fairly steady conditions may be reached in one or two years, but in some of the larger projects decline of the rate of discharge may continue for a decade or more. In such projects very careful attention should be given to the question of how it is desired to use the accessible water. Only the most stringent emergency conditions can justify the discharge and use of the water as rapidly as it will run out. To allow the water to run out unused after construction is completed is contrary to either private or public policy. In constructing such a tunnel project the excavation should be completed as rapidly as possible, using as much of the water as possible, and bulkheads should then be placed so that the flow can be controlled. How the flow should be controlled involves consideration of present and future value in a manner similar to that involved in financial problems. If emergency conditions give the full flow of water an exceptional present value, it can be used to full capacity, but with realization that the amount will surely decline and may reach values 1/3 or 1/10 of initial amounts. On the other hand preservation of the stored supply for as long as possible may be important and at the same time it should be recognized that natural losses are greater at higher bulkhead pressures. Here there is need for close weighing of all the conditions to set up a program that will gradually take and utilize the stored water and reduce the rate of outflow to approach that expected on a permanent basis. Only continued operation over a long period will determine the steady rate that will permit balancing of annual or longer periods of high and low rainfall.

The total discharge of ground water from the Waiahole system has been increased by progressive extension of several development tunnels on the windward side of the range. In recent years the total from the windward tunnels has been above 20 M.G.D., and that from the leeward tunnel section about 6 M.G.D., in addition to surface water that ranges from 5 to 12 M.G.D. The total area from which it is reasonable to suppose that rain water could reach the Waiahole system either as ground water or surface water hardly exceeds 6 square miles. The rainfall is above 200 inches per year, but probably does not average 250 inches. The product of 6 square miles and

200 inches is about 57 M.G.D.; the total yield from the Waiahole system has for some years been in excess of half that amount but it will probably not maintain that fraction. At the southern end of the same dike system, at Haiku, is a development tunnel now taking somewhat under 4 M.G.D., and a project about to be commenced at Kahaluu contemplates developing about 3 M.G.D., of which a large fraction is said to be in sight in the existing springs.

At increasing expense for tunneling and pipelines, it is probable that moderate amounts of additional ground water can be developed in the five-mile stretch from Haiku to Waiahole and that some surface water can also be added, but the fact that the dike complex lies progressively farther to windward of the Koolau crest and that its exposed leeward boundary is lower than in the Waiahole section does not justify a very optimistic estimate. In the Waiahole portion, with its high rainfall and favorable position of the dike complex the water currently yielded from the ground approximates 5 M.G.D. per square mile of supposed area of intake or something like 7.5 M.G.D. per linear mile of Koolau crest. The present writer thinks it doubtful if more than half of either of these rates can be reached in the five miles from Waiahole to Haiku, and it is believed that the area from which water can be taken at high levels is much less, probably not over 3 square miles.

General plans for combination development and transmission tunnels to connect the Waiahole system with the city of

Honolulu have been proposed by Jorgensen, Palmer, Kunesh, and Stearns. For various details reference is made to the discussion by Stearns. (1) Stearns stated that the total water recoverable from the proposed Kalihi-Waiahole tunnel system might be as great as the then-shown recovery of the Waiahole system (ca. 33 M.G.D.) but that a conservative estimate would offer a substantially lower figure. (2) Kunesh in his report suggested considerably larger total figures for total tunnel yield from Kalihi to Waiahole. In these very preliminary remarks, the present writer's belief is that the total ground water to be developed by tunnel systems from Haiku to Waiahole, including the present Haiku tunnel and the proposed Kahaluu project will not exceed a permanent flow of 15 to 18 M.G.D.

As stated above, the full discussion of the Waiahole and Waiahole to Honolulu tunnel systems, existing and proposed, is outside the scope of this report. The preceding comments have been offered as a part of the text on confined high-level

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(1) Jorgensen, J., Honolulu Water Commission Report, pp. 92-97, 1918.
Palmer, H. S., Manuscript Report, 1921.
Kunesh, J. F., Honolulu Sewer and Water Commission Report, p. 132, 1929.
Stearns, H. T., T. of H., Division of Hydrography, Bull. 1, pp. 444-451, 1935.

(2) Op. cit., p. 448, 1935.

water, since small parts of the dike complex system border on the Pearl Harbor drainage area and a small fraction of the water is involved in the inventory attempted in this report.

Intermediate between known perched or confined high-level water and true basal water is the elevated water body found in the Schofield shaft. It seems most likely that this is confined on the north and south sides by some structure in the Koolau lavas, possibly dikes or dike systems, and by the weathered and soil-covered surface of the Waianae dome on the west. On the east it probably merges with the dike-confined water of the Koolau axis and is fed in large measure by leaks from the latter. We have no basis for estimating the position of a ground water divide here and no means of stating that this water body or the Pearl Harbor basal water is fed from an area larger than the topographic watershed in the Wahiawa region. This body was discussed in the section on shafts and tunnels.

FREE BASAL WATER

The ultimate accumulation of infiltrated water, not withdrawn at higher levels and not trapped in the lower dike complex, is found in the basal water body. This water is bounded below by salt water and is mainly if not wholly in hydraulic balance with it. The seaward portion of basal water in places extends far under the coastal caprock and is hence under artesian pressure. This portion is artesian basal water. The portion which lies inland of the caprock, or that in areas where there is no caprock and which exhibits a free water table is free basal water. The height to which the water table rises at a given point is a measure of the pressure required to discharge from that area the amount of water reaching it, by all available avenues of escape, toward the nearest sea margin or to adjacent areas of lower head. The head is greater in areas where a coastal caprock is relatively tight and continuous and low where there is no caprock. It is higher in areas, or in periods, with high rainfall than with the reverse, and is subject to continuous fluctuation. It is one of the notable features of Hawaii, that within the body of many of the chief island domes, free of specific barriers such as dikes, the permeability of the lava flows is so great that the water table is remarkably uniform in level, showing differences of level of the order of 0.2 or 0.3 foot over one or more square miles, apart from the seaward slope which may reach a foot or more per mile.

The basal water in the Pearl Harbor area reaches a general level of from 16 to 25 feet above sea level, according to prevailing conditions of rainfall and draft. Next to the Honolulu area, the Pearl Harbor area has the broadest and probably thickest caprock of any area in Hawaii. Study of the Honolulu area has shown the existence of unit areas within which basal water levels and the equal artesian heads are commonly uniform within 0.1 or 0.2 foot. These areas are separated by tongues of caprock fill in the chief valleys where the rock bottoms are cut some hundreds of feet below sea level. That these valley fills act as hydraulic barriers is now well established but it does not appear that any of the valleys of the Pearl Harbor area are cut sufficiently low to form effective boundaries. Accordingly, the major part of the Pearl Harbor area has been considered to be one isopiestic area, despite the fact that head measurements show its water levels to be slightly more irregular than those of any single isopiestic area of the Honolulu section. In general, if we take the Halawa-Waimalu part, wells 180 to 197, as the datum, we find that wells in the Pearl City area, 200 to 220, have heads 1 to 2 feet lower, with occasional individuals still lower. Wells in the Waiawa-Waipahu section, 225 to 260, have heads up to a foot higher than the datum, and those in the western area of Honouliuli and Ewa, 261 to 266, may be of equal elevation or as much as 2 feet lower. The differences mentioned are so variable and subject to individual deviations that a separation into isopiestic areas, with postulated valley barriers has not seemed practicable.

Knowledge of basal water heads up to the present is almost wholly based on artesian wells; the better wells are often actively pumped and not available for systematic static measurements; those only little used are often in course of developing leaks and of doubtful or changing validity. Wells in the Pearl Harbor area show much more salinity and and much greater variety in salinity than in Honolulu and salinity in turn may be associated with low heads. Accordingly, plans have been laid for the installing of four continuous recording basal water level stations. These are to be 12-inch holes reaching the free surface of basal water in Koolau rock at the margin in the Koolau dome at elevations of not over 100 feet. They are to be surmounted by small concrete kiosks large enough to carry the clock-driven water level recorders and to permit changing of records. The location and present status of each is shown in the following table.

TABLE 5

BASAL WATER-LEVEL RECORDING STATIONS

Location	Latitude	Longitude	Elevation of Ground	Status May, 1945
Manaiki Valley, west wall, inland from Moanalua Garden	21-21-25	157-53-30	61.05 (casing)	(a)(b)
Waimalu Valley, east wall, near bend in old highway	21-23-30	157-56-57	28.51 (coupling)	(a)
Waiawa Valley, east side, rock bluff, Schofield Highway cut-off	21-24-?	157-59-15?		(c)
Honouliuli, on old Waianae Road, 1/4 mile west of Kunia Road	21-22-52	158-01-58	83.19 (BM.)	(a)

(a) Drilled and cased.
(b) Recorder started 2/6/45.
(c) New location probably nearer Pearl City.

Three of these stations are in the Pearl Harbor area and it is expected that they will give a more reliable and steady picture of basal water level changes than is obtained from the wells now used as index wells. A further discussion of artesian heads is given in the section, ARTESIAN BASAL WATER.

Since 1941, free basal water levels have been measured at several points in the eastern Pearl Harbor area as shown in Table 6.

Measurements made in 1942 and 1943 showed that the basal water table of Area 4, Kalihi to Moanalua, was then very uniform in level with only about 0.15 foot fall from east to west. From the latter part of 1944 to the present time the level at the Kalihi end has declined most and is now about 0.60 foot lower than at Hole 42, at the Moanalua end.

Throughout the period of measurement the basal head of Area 4 has ranged from 3 to 5 feet above the water level at the Aiea-Austin hole which has been taken as representative of the eastern part of Area 6. The transition from Area 4 to Area 6 is shown to consist of a small drop across Moanalua Valley and a small difference from Halawa Tunnel to the Aiea-Austin hole, with larger and nearly equal drops across both South and North Halawa valleys. Though these differences indicate some degree of separation, none of the subdivisions have sufficiently clearly defined intake areas

TABLE 6, BASAL WATER-LEVEL MEASURING POINTS

Name	Location	Area	Elevation of Bench	Basal Water Levels				
				1942-1945			Recent	Date
				Maximum	Minimum	Mean		
D. D. Hole No. 19	Kalihi, end of	4	187.84	24.06	20.42	21.99	20.55	5/30/45
Manaiki Recording Well	West wall, Manaiki Valley	4	61.05			(4)	20.56	"
Hole No. 42	East wall, Moanalua Valley	4	176.87	23.91	20.46	21.87	21.16	"
Hole No. 43	West wall, Moanalua Valley	4	235.00	22.91	19.31	20.57		
Clarke-Halawa Hole	North wall, S. Halawa Valley	6	255.62	20.25	(1)	(1)	(2)	
Aiea-Austin Hole	Aiea Valley 1/2 mi. from Mill	6	216.36	20.85	16.32	17.99	16.82	5/23/45
Waimalu Recording Well	East wall, Waimalu Valley	6	28.51			(4)	15.07	5/30/45
Waiawa Recording Well	East of Waiawa Valley	6	(3)			(4)		
Kunia Recording Well	West of Kunia Road	6	85.44			(4)	13.99	5/30/45

(1) This hole not operating during later part of period.
(2) Access lost.
(3) Hole not yet drilled.
(4) Period too short.

and sufficient independence of head to justify calling them even sub-areas from the standpoint of water supply or calculation of quantities. No basis is found for deviating from the original boundary between Areas 4 and 6 as set by Stearns in South Halawa Valley. (1)

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(1) Stearns, Op. cit. p. 258, 1935.

Heavy draft from the Red Hill station of the Navy in recent months has resulted in a slow but progressive increase in the difference of level across Moanalua Valley. On the other hand, as stated above, the level of water at Hole 19 has gone below that at Hole 42, thus leaving the east side of Moanalua Valley as the high point of the basal water table on Area 4.

BASAL WATER SUPPLY STATIONS

The history of construction of basal water supply stations has been sketched in another part of this report. Table 7 gives data on existing stations.

TABLE 7, BASAL SHAFTS AND TUNNELS

Name	Number	Owner	Date Completed	Elevation-feet		Dimensions		March 1945		
				Bottom Sump	Invert Tunnel	Tunnel length (feet)	Area (2) approx., sq. ft.	Head	Discharge (3) M.G.D.	Chlo-
MOANALUA AREA (NO. 4)										
Red Hill	11	U.S. Navy	Dec. 1942	Holes 30' below S.L.	5.00	1121	42,000	19.3	19.5	97
PEARL HARBOR AREA (NO. 6)										
Halawa	12	B.W.S.	Jan. 1944	-18	-2	919	36,000	17.2	6.68	31
Halawa	5	U.S. Navy	Mar. 1937	- 5	15.0	?	2,000	16.7	10	93
Aiea	13	Hon.P.Co.	?				7,000	16.7	1.43	178
Waiau	8	H.E.Co.	Jan. 1939		3.0	428	6,000		10.9	130
Pearl City	9	C&C Hon.		4.5	15	Several wells, holes, & tunnel.				
Ewa	3	Ewa P. Co.	Sept. 1939	-4	-4	1086	36,000	[illegible]	21.2	
Schofield (4)	4	U. S. Army	Aug. 1938	Wells below S.L.		Ca. 600' of wells	2,000	275	6.4	
Waikele	4B	O.S. Co.	1906		3	1140	23,000		3.99	
Waikele		O.S. Co.	1906		7	290	6,000			

(1) After H. T. Stearns.
(2) Estimated by C. K. Wentworth
(3) Mean 1944.
(4) Not strictly a basal tunnel.

Except Schofield, these stations are all based on the concept of drawing water from the upper few feet of the basal water table without penetrating deeply into the fresh water lens. The stations vary greatly in area of aquifer exposed below the water table, the variation being in part determied by construction limitations and in part by the accident of type of rock encountered. The choride content of water drawn from these stations under operating conditions also varies greatly but it is certain that it is much less than that of water drawn in similar amount from deep artesian wells in the same sector.

The water drawn from basal stations in the Pearl Harbor area has now, in 1945, become about 25% of the total used, with 60% from artesian wells and about 15% from springs. (Table 9) (In Honolulu, areas 1 to 5, the draft from basal stations at the end of 1944 was about 46% of the total public and private draft.) This is a trend which will continue, though some draft from artesian wells will doubtless continue for many years.

It is evident that the basal water supply problem is a problem of the whole and that building of new stations may provide more advantageous points and methods of draft but very likely will not provide additional water, except as the general change to basal stations will permit draft to lower heads. This matter will be discussed in the section, Estimates of water quantities.

PEARL HARBOR SPRINGS

It has been emphasized that the high basal water levels of the Honolulu and Pearl Harbor areas are due to overlapping of the water-bearing Koolau rock by the less permeable caprock to elevations above the basal head. In the Pearl Harbor area are a number of places where the Koolau rock with its overlying soil passes down nearly to sea level without a cover of detrital caprock. In most such places, the Koolau rock is sufficiently weathered and made so tight by this weathering that its surface parts serve as a caprock. This is well shown in the current excavations at the Hawaiian Electric Company plant at Waiau. In a number of other places however, adjacent to stream channels, or elsewhere where erosion has taken place, the Koolau rock with open cracks and other openings is exposed at elevations below 20 feet. At these points there are a number of very large springs which have long been known as the Pearl Harbor Springs. Issue of basal water at these points has from early times encouraged the development of terraced wet gardens where rice, taro, water cress and other such crops are grown. Until quite recently no large scale development of water has been carried out, though small spring pools have been build and much season-to-season repair and elaboration of the terraces and channels goes on.

The names, locations, and other characteristics of these springs are given in Table 8.

At Kalauao Spring is Pump No. 6 of the Honolulu Plantation Company, the channel, gathering spring effluent from the two sides of the spur on which the station stands. All excess water passes under the road to reach Pearl Harbor. This channel is gaged by U.S.G.S. The amount drawn by Pump 6 is reported by the Honolulu Plantation Company.

Waiau Springs, as here considered, commences with the inland portion, on property owned by H. Dowsett, and includes spring outflow on both sides of the main highway. Water from this part is carried in the channel gaged by U.S.G.S. at the so-called rice mill and chiefly led along the railroad to the spring pool at the Hawaiian Electric Plant. A large amount of water rises in this pool. Additional water comes from the west group of springs (called Kaluaoopu) and is added to the pool. Finally the discharge from the Hawaiian Electric tunnel and the wells connected to it is added to the pool. From this gathering pool the Hawaiian Electric Company pumps about 36.4 M.G.D. which is used for plant condensers. Of this, after use in the plant, 11 M.G.D. is pumped to Honolulu Plantation Company ditches inland. The remainder of 25.4 M.G.D., with about 1 M.G.D. not drawn from the pool, is discharged through the Kaluaoopu channel where it is gaged by U.S.G.S. The breakdown of these quantities for 1944 is shown in Table 8. Net result shown here is that about 97% of all tunnel and well, and spring water collected

TABLE 8, BASAL SPRINGS - PEARL HARBOR AREA (NO. 6)

Source	Operator	Measured Total	Local Irrigation (M.G.D.)	Pumped Irrigation (M.G.D.)	Plant Condensers (M.G.D.)	Discharge to Sea (M.G.D.)	Chloride (p.p.m.)
Kalauao Spring	Hon.P.Co.	15.3	?	1.4		13.9	69(a) 80(b) 154(c)
Waiau Springs		6.1(A)	?				138
Tunnel & Wells	H.E.Co.	10.9(B)					136
West Spring Group		8.7(C)	?				
Pool	H.E.Co.	11.7(D)					
Total ABCD	H.E.Co.	37.4		11.0 Hon.P.Co.	36.4	26.4 Kaluaoopu	134
Loko Kukona		1.7	?			1.7	1050
Puukapu		3.4	?			3.4	167
Waiawa	O.S.Co.	13.2	?	2.8		10.4	288
Waikele	O.S.Co.	8.0(d)	?	4.7		3.3	
Totals		79.0(e)	?	19.9		59.1	

(a) At spring wall. (b) At pump intake. (c) At ocean discharge weir. (d) Based on measurements reported by Kunesh, 1928-1931; conditions believed to be similar in 1944. (e) With exception of (d), these are measured means for fiscal year 1943-1944, records by U.S.G.S. and H.E. Co.

in the pool is used once, for cooling, and about 1/3 of the total is used a second time for irrigation.

Two groups of springs known as Loko Kukona and Puukapu (Waimano Group) lie to the west of Waiau in the west corner of East Loch and discharge about 5.1 M.G.D. to the sea, after local use in gardens.

The Waiawa channel gaged by U.S.G.S. is reported by Max Carson to carry small amounts of stream runoff at times, but includes the discharge from the Waiawa Springs. The Oahu Sugar Company currently uses only about 2.8 M.G.D. from this flow, with about 10.4 M.G.D. going to the sea.

At the Waikele Spring a tunnel has been driven and the Oahu Sugar Company pumps about 4.7 M.G.D. for irrigation. No recent measurements have been made on the discharge to the sea but it is believed to be a little over 3 M.G.D.

The data shown in the preceding table lead to the following conclusions. The total natural measured discharge of the Pearl Harbor Springs in 1944 continued at about 68 M.G.D. There is no question that small unmeasured flows plus water used by growing plants inland from the weirs would make the real total considerably higher. To the 68 M.G.D. is added 10.9 M.G.D. of tunnel and well water. From this total of 79 M.G.D. the Honolulu Plantation Company, directly and through Hawaiian Electric Company, uses about 12.4 M.G.D., Oahu Sugar Company uses about 7.5 M.G.D. and Hawaiian Electric Company uses not only 11 M.G.D. of the above but an additional 25.4

M.G.D. for cooling. The total use of water is about 45.3 M.G.D., of which 11 M.G.D. is used twice. A large amount of water is used in local agriculture but not from the above total. Finally 33.7 M.G.D. is wholly unused and passes to the sea in five channels, as gaged by U.S.G.S.

In the past, except for limited draft at certain points, the flow from the Pearl Harbor Springs has not been utilized in developing the very large use of ground water for agriculture in the Pearl Harbor area. Ease of developing water from artesian wells has caused the springs to be ignored owing to their location, problems of gathering, fluctuation of flow and the like. Each single agency, public and private, has at any given juncture, found it cheaper and more satisfactory to develop ground water directly by well or tunnel. At the same time, it has long been recognized that here was a large outflow of fresh water that should not be allowed to waste into Pearl Harbor.

Present use is chiefly by draft of spring water after it has emerged. In view of the increasingly heavy draft on the whole system and the lack of control of outflow from the springs it seems clear that long term public policy would be better served by a program of construction designed to largely reduce the uncontrolled leakage, together with a coordinated development of water so conserved. Such a plan, if successful, would confer a great ultimate benefit on all water users in the area, but would not necessarily or immediately accrue to the benefit of any individual. It is not clear that it will be undertaken by private enterprise nor by any existing public authority. Further details of such a plan are offered in Appendix II.

ARTESIAN BASAL WATER

Artesian basal water is that water which is obtained under artesian pressure from artesian wells drilled through the caprock of the coastal plain or of valley bottoms. It is well known that it is the same water in origin as the free basal water and that its exhibited head is due to the height of the free water table inland from it. Much of the artesian water of the Pearl Harbor area is more saline than that of the Honolulu area, owing in part to the excessive depth of certain wells, and in part to the probable greater erosion of parts of the caprock and opportunity for sea water to mix with fresh. The least saline basal water of the Pearl Harbor area is of substantially the same quality as that of the Honolulu area, but very little water of such quality comes from artesian wells.

The amount of water drawn in 1944 from the Koolau rock in artesian wells in this area was estimated at 131.3 M.G.D., as compared to 54.81 M.G.D. drawn from basal shafts and tunnels, and 68.1 M.G.D. measured discharge from the Pearl Harbor Springs. The sources and uses of this water are shown in Table 9.

TABLE 9

TOTAL KNOWN BASAL GROUND WATER DISCHARGE IN PEARL HARBOR AREA (NO. 6)(KOOLAU WATER)(M.G.D.)

Type of Opening	U.S. Navy	Suburban Water C. and C.	Board of Water Supply	Hono'ulu Plantation Company		Oahu Sugar Company	Ewa Plantation Company	Other (a)	Unused Water	Total
Artesian Wells	7.70 (b)			27.91		42.18	51.26	2.25	?	131.30
Basal Shafts, Tunnels, Wells	10.00	0.61	6.68 (e)	1.43	10.9 (c)	3.99	21.2			54.81
Large Springs				1.4	25.5	7.5			33.7	68.10
Totals	17.70 (d)	0.61	6.68	30.74 (f)	36.4 (f)	53.67 (g)	72.46 (g)	2.25	33.7 (h)	254.21

(a) No measurements available; this estimate is based on an assumed average of 0.05 M.G.D. for each of 45 wells.

(b) This amount will be much greater for 1945, owing to taking over of wells late in 1944.

(c) This amount is tunnel and well water, but is added to spring total at H.E. Co. pool.

(d) To this amount from Area 6, must be added about 19.3 M.G.D. from Red Hill and certain other smaller amounts to get Navy over-all total in Honolulu-Pearl Harbor region.

(e) This is rate for period September to December, 1944.

(f) Hawaiian Electric Co. pumped 11.0 M.G.D. of its total 36.4 M.G.D. to Honolulu Plantation Company for irrigation. Thus of total 37.4 M.G.D. collected by H.E. Co. 36.4 M.G.D. is used once for condensers and 11.0 of this is used again for irrigation.

(g) Both these plantations develop some water from Waianae Rock, area 11, not included here.

(h) This amount consists of excess discharge to the ocean from various of the Pearl Harbor spring groups. Prior to its discharge it has contributed to local wet garden irrigation in unmeasured amounts.

Data concerning the artesian wells of the Pearl Harbor area are shown in Table 10.

Of the total of 27 wells in the Koolau aquifer, shown in Table 10, 38 are at present owned or controlled by the U.S. Navy, 5 of these being unused. Four unused wells are owned by the U.S. Army. Twenty-two wells, mostly privately owned, are devoted to domestic uses and 4 of these are currently unused. Discharge from all of these is small. Within the group used for irrigation are 187 wells, including 147 wells in groups of 2 to 20 wells at each of 15 stations, operated by one or another of the three sugar plantations. The remaining 40 wells of this group are owned by independent land holders and are devoted chiefly to small scale agriculture. Thirteen of these are unused at present. Eight wells are indicated as used industrially and 12 wells are known to have been sealed.

Recent data for head, discharge and salinity are given in the table, so far as comparable measurements are available. It will be noted that for a great number of irrigation wells of low discharge the assumption of 0.05 M.G.D. each has been made. It is probable that a few of these wells discharge more, but that the average visible discharge is less. On the other hand leakage of unknown and greater amounts is probably taking place. The rate assumed is the best we can do at present.

The number of artesian wells that have been sealed in

TABLE 10, INVENTORY OF ARTESIAN WELLS - PEARL HARBOR AREA (NO. 6)

Well No.	Date Drilled	Status	Head	Mean Discharge (M.G.D.) (1944)	Chloride (p.p.m.)
169		Unused (U.S.N.)			
170		" "			
171		Sealed (1939)			
172	Before 1908	" "			
173	" "	" "			
174	" "	" "			
175	" "	" "			
176	" "	" "			
177	" 1902	" (1944)			
178	1900	Unused			
179	"	"			
180	Before 1902	Sealed (1939)			
181	" "	Unused			
182	" 1908	"	16.33 (d)		246 (d)
183	" 1902	"	16.67 (d)		
184	" 1908	"			
185 A-Q 17 wells	1900	H. P. Co. Pump 1 (U. S. Navy)		4.39 (a)	420 (f)
186 A-H 8 wells	1900	H. P. Co. Pump 3 (U. S. Navy)		8.47 (b)	128 (f)
187 A-D 4 wells	3 in 1923 1 in 1942	U. S. Navy		4.51	186
188	Before 1902	Unused			
189 A-E 5 wells	1908	Irrigation, H. P. Co. Pump 5		6.13	72 (f)
190	1889	Domestic	16.18 (e)	(c)	
190-1	1941	"		(c)	131 (d)
191		Unused (Lost) H. P. Co.			

TABLE 10 (CONT'D.)

Well No.	Date Drilled	Status	Head	Mean Discharge	Chloride
192	Before 1910	Irrigation	15.63 (d)	(c)	384 (d)
193	" 1902	Domestic	15.45 (e)	(c)	
194	" 1910	Unused	16.15 (d)		
195	" "	"	16.29 (d)		
196 A-T		Irrigation,			
20 wells	1899	H. P. Co. Pump 2		4.13	128 (f)
196-1	1941	Domestic (Basal)			
197 A-1		Irrigation,			
9 wells	1904	H. P. Co. Pump 4		7.92	435 (f)
197-1	1934	Irrigation	16.17 (d)	(c)	153
198	Before 1910	"		(c)	
198-1	1938	"		(c)	
199	Before 1910	Domestic	15.49 (d)	(c)	119 (d)
200	" "	Irrigation	13.73 (d)	(c)	131 (d)
201	" "	"	14.85 (e)	(c)	
202 A-C	1905	Domestic			
3 wells	1926			(c)	
203 A-D		(U. S. Navy)		0.04	
4 wells	1926	H. P. Co. Pump 7			
204	1906	Irrigation,	12.88 (d)		119 (d)
		H. P. Co.,			
204-1		Irrigation		(c)	
204-2	1943	"		(c)	
205	1897	"	15.32 (d)	(c)	188 (d)
205-1		U. S. Navy		(c)	
206		Irrigation	15.24 (d)	(c)	174 (d)
207	Before 1924	Unused			305 (d)
208	1922	" (With 207)			
209	Before 1912	Sealed (1912)			
210	1939	Swimming pool			
211	1922	Sealed (1941)			

TABLE 10 (CONT'D.)

Well No.	Date Drilled	Status	Head	Mean Discharge	Chloride
212	Before 1912	Industrial		(c)	
213	1928	Domestic	13.30 (d)	(c)	1450 (d)
214		"			
215	1921	With 214	14.67 (d)	(c)	1220 (d)
215-1		Unused			
216		Sealed (1940)			
216-1			14.77 (d)	(c)	1380 (d)
217	Before 1910	Sealed (1928)			
218	1906	Unused			
218-1	1934	Irrigation		(c)	
218-2	1939				
218-3	1940		11.90 (d)	(c)	2200 (d)
219		Unused			
220	Before 1915	"			
221	" 1900	"			
222	" "	"			
223	" "	"			
224	" 1905	"			
225	" 1930	Industrial		(c)	
226	" 1931	Domestic	16.50 (d)	(c)	1600 (d)
227		Unused			1570 (d)
228	" 1931	Fishpond		(c)	
230	" 1910	Irrigation		(c)	
231	" "	Domestic		(c)	
232	" 1930	Unused			
233	" "	"			
234		Fishpond		(c)	
235	1899	Unused			
236	Before 1910	"			
237	" 1930	Irrigation		(c)	1190 (d)
238	" 1910	"	17.65 (d)	(c)	172 (d)
239 A-N 14 wells	1898	Irrigation, O.S. Co., Pump 6 & 6B		10.69	
240		Domestic	17.49 (d)	(c)	134 (d)

TABLE 10 (CONT'D.)

Well No.	Date Drilled	Status	Head	Mean Discharge	Chloride
241	1926	"			143 (d)
242	Before 1910	Irrigation	17.54 (d)	(c)	
243	" "	"	17.53 (d)	(c)	138 (d)
244	1909	Domestic	15.97 (e)	(c)	
245	Before 1930	"		(c)	130 (d)
246 A-H 8 wells	3 in 1900 3 in 1917 2 in 1924	Irrigation & Industrial, O. S. Co. Pump 7		8.75	
247 A-J 10 wells	Before 1898	Irrigation, O. S. Co. Pump 1		7.38	
248 A-J 10 wells	Before 1901	Irrigation, O. S. Co. Pump 4		3.67	
249 A-L 12 wells	Before 1898	Irrigation, O. S. Co. Pumps 2 & 3		11.69	
251	Before 1926	Unused			
252	" 1910	Irrigation	16.95 (d)	(c)	85 (d)
253	1898	Domestic	16.65 (d)	(c)	267 (d)
254 A-B	1 before 1905 1 in 1923	Irrigation, E. P. Co., Apokaa		1.29	
255	Before 1930	Irrigation	16.47 (d)	(c)	111 (d)
256	" "	Domestic	15.85 (d)	(c)	50 (d)
257 A-C 3 wells	1890 1921	Irrigation, E. P. Co. Pump 2		3.07	
258	Before 1910	Irrigation	17.68 (d)	(c)	191 (d)
259 A-L 12 wells	7 in 1896 5 in 1897	Irrigation, E.P. Co., Pumps 5 & 6		13.74	
261	Before 1931	Irrigation	14.61 (d)	(c)	176 (d)
262	" 1930	"	14.51 (d)	(c)	193 (d)
263 A-F 6 wells	1 in 1899 5 in 1900	Irrigation, E.P. Co. Pump 7		7.08	
264 A-T 20 wells	1 in 1890 11 in 1891	Irrigation, E.P. Co. Pumps 3 & 4		17.52	

TABLE 10 (CONT'D.)

Well No.	Date Drilled	Status	Head	Mean Discharge	Chloride
	4 in 1899 4 in 1921				
264-1	1880	Sealed (1940)			
265	Before 1910	Irrigation	14.22 (d)	(c)	
266	" "	"	14.16 (d)	(c)	
267	1879	Sealed (1939)			
268 A-H 8 wells	6 in 1890 2 in 1899	Irrigation, E. P. Co. Pump 1		3.11	
269	1928	Fishpond		(c)	
270	Before 1905	Sealed (1938)			
271	1931	Unused			
272	1902	Sealed (1938)			
273 A-H 8 wells	2 each in 1891, 1899, 1900 & 1908	Irrigation, E. P. Co. Pump 9		5.45	

(a) Water from this station used by U. S. Navy, July to December, 1944, Plantation total for year was 1.24 M.G.D.
(b) Navy commenced taking water December 18, 1944.
(c) Discharges from these wells not known. They are mostly small and certainly average less than 0.05 M.G.D. each.
(d) Measurements taken August to October, 1944.
(e) Head measurement on index well, March 1945.
(f) Measurements in November 1944.

the Pearl Harbor area is much less, relatively, than in the Honolulu area, owing to several factors. First, the vesting of the problem of domestic water supply in the Board of Water Supply and the conduct of an active program of water conservation has led to sealing of many wells in the municipal area. The process has been greatly aided by changing land use and urbanization combined with the superior value of steady standby of high pressure water from a municipal system. To a far larger extent, the Pearl Harbor area has retained an agricultural pattern of water use. Some changes and considerable increase of use has come with the war but there is still no overall distribution system of the sort which threatens the convenience of an individual well. The dates of drilling show a marked falling off in the drilling of new wells and it is rather clear that neither small independent owners nor the larger plantations or other agencies will drill more than an occasional new well. This is because of a greatly reduced value of a single well, relatively, and also because the larger water users are now well convinced of the superiority of basal stations over wells. The inactivation, if not the sealing, of large numbers of wells may be expected within the next two or three decades, and perhaps by 1970 the percentage of draft from wells may fall from the present 60% to under 20% of the total.

CAPROCK WATER

Small amounts of water are taken locally from permeable caprock layers but no systematic attention has been given to such use. In general, the areas of caprock standing at suitable elevations are relatively smaller than in Honolulu and the relative value incentive has been lacking.

The hydrologic problem

GENERAL

The only ultimate source of water for human, agricultural, military or industrial use on Oahu is rainfall. If reliance were placed on direct rainfall it would quickly be found that the annual rainfall can range from less than 2/3 to more than 3/2 the mean and that the monthly rainfall can range from 1/5 to 5 times the mean. Storage of water supplies for periods of longer than a day has not proved effective or economical in most parts of Hawaii. Because variations of rainfall, high permeability of rocks, and relative steep and short stream courses, stream water is of only limited and local value. In the Honolulu and Pearl Harbor areas the large underground storage represented by the basal ground water is of extraordinary value. By valid inference from the Ghyben-Herzberg principle (1) the amount of fresh water

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(1) Wentworth, C. K., Storage Consequences of the Ghyben-Herzberg Theory, Amer. Geophysical Union Transactions, 1942.

in the Ghyben-Herzberg lens must be very large. Calculations in the Honolulu area give a basis for an estimate of 200 million gallons per vertical foot at the water table in the combined areas 1, 2, 3, and 4. There is much reason for taking a somewhat larger figure as the average storage per foot from sea level downward to the bottom of the fresh water and on this basis a conservative guess as to the total storage in the Honolulu area down to 1000 feet would be 200,000 million gallons.

It follows that any changes in the position of the zone of transition would involve gain or loss of very large amounts of water and since the dominant trend has been toward shrinkage it is thought that there must be marked lag in the shrinkage of the lower part of the fresh water lens and that this process has made available large amounts of water above those provided by current and recently past rainfall. Similarly it is thought that yield of water from shrinkage of the bottom of the lens has limited, beyond the initial three or four feet, the marked loss of head that would be expected from sustained overdraft. This doctrine is discussed in Appendix II entitled THE CONCEPT OF BOTTOM STORAGE.

Whatever view is held as to the mechanism of the basal water body, it is clear that it is of the greatest importance to develop from measurements, mathematical analysis, and all possible inference from geologic and other facts a comprehensive and sound understanding of the behavior of this ground-water body and its past and probable future responses to short and long term variations in rainfall and draft. To accomplish this will require concerted attention in gathering adequate data on head, rainfall, and draft, as well as on salinity and other elements of quality.

RELATIONS AND CONTRASTS BETWEEN THE HONOLULU AND PEARL HARBOR AREAS

In certain ways the Honolulu areas, 1, 2, 3, and 4, combined, are better known than the Pearl Harbor area. It is not necessarily true that relationships established in the Honolulu area will hold in the Pearl Harbor area, but it is desirable to tabulate certain common measures of the two for comparison. This is done in Table 11.

In addition to the features listed in the table, certain other differences are known. For example, during the past 20 years, the most rapid changes of head in the Honolulu system reach, but do not greatly exceed, 1 foot in one month. In terms of storage at the water table, using the value of 200 million gallons per foot, this would indicate excesses or deficiencies of rainfall in relation to draft of the order of 6 to 7 M.G.D. through a month, which is at least roughly consistent with the known variations of draft or of rainfall intake.

On the other hand, the Pearl Harbor mean head has been known to rise at least 4 and possible 5 feet in a month. A

TABLE 11

COMPARISON OF PEARL HARBOR AND HONOLULU AREAS

	Honolulu	Pearl Harbor
Total Apparent Drainage Area, Sq. Mi.	67.47	124.67
Basal Intake Drainage Area, Sq. Mi.	25.59	83.30
Total Average Rainfall, M.G.D.	226.6	420.1
Basal Intake Area Rainfall, M.G.D.	129.0	368.9
Average Intake Area Rainfall, Inches	106	93
Length of Outflow Shoreline, Miles	12	10
Intake Area Rainfall per Shoreline Mile, M.G.D.	10.75	36.9
Storage per Foot at Water Table, Estimate from Head Change Residuals, M.G.	200	1450
Measured Discharge 1944, M.G.D.	65	254
Maximum Monthly Mean Head, Feet	(Mar. 1938) 31.10	(Dec. 1927) 26.10
Minimum Monthly Mean Head, pre-1944, Feet	(Oct. 1926) 23.07	(Oct. 1926) 16.80
Minimum Monthly Overall Mean Head, Feet	(Sep. 1944) 21.99	(Sep. 1944) 16.05

fall of so much as 3 to 4 feet is apparently less frequent. These changes must represent very much larger differences in daily draft and are consistent with the fact that the daily draft in the Pearl Harbor area may in one month drop to a third of the previous month and that the ratio of high to low month in a year may be over 9:1. Using the estimate of 1450 million gallons per foot for storage in the Pearl Harbor area, the changes of 4 feet could perhaps mean 6,000 million gallons per month, hence perhap 200 M.G.D. This is in line with difference in mean draft of 80 to 100 M.G.D. ~~This is in line with difference in mean draft of 80 to 100 M.G.D. This is in line with difference in mean draft of 80 to 100 M.G.D.~~ These data have not as yet been so fully analysed as those of the Honolulu area, but are consistent as far as we can go.

MULTIPLE CORRELATION OF RAINFALL, DRAFT, AND HEAD

Because of less complete data the mathematical analysis of rainfall, draft, and head in the Pearl Harbor area has been carried less far than that for the Honolulu area, but some conclusions can be reached. A rainfall factor for the period 1925-1940 has been derived on the same basis as that earlier used for the Honolulu areas, as will now be described. The ratio of actual rainfall to normal rainfall for each month is determined for the ten rainfall stations used. The square root of each such ratio is determined. Both the ratio and the square root, in use, are multiplied by 100 so that 100 is equal to normal rainfall. The monthly figures now consist of numbers above and below 100 by the square root of the actual variation of rainfall above and below normal. These monthly numbers are now cumulated by adding the excess above 100 and subtracting the deficiency below 100 for each month, and each month deducting from the new total 3% of its absolute value. The process is shown in Table 12.

TABLE 12

METHOD OF COMPUTING RAINFALL FUNCTION

Actual Rainfall	Ratio, Actual to Normal, (x 100)	Square Root of Ratio, (x 100)	Cumulation	
			Added	3% off
6.96	79	89	-11	-11
4.08	46	68	-43	-42
13.27	150	122	-20	-19
9.35	106	103	-16	-16
5.89	67	82	-34	-33
8.41	95	92	-41	-40
6.46	73	85	-55	-53
6.33	71	84	-69	-67
4.98	56	75	-92	-89
6.96	79	89	-100	-97
10.17	115	107	-90	-87
4.16	47	69	-118	-114

The final 3% debited cumulations have been found to correlate with draft and head to give smaller standard deviations than any other rainfall function yet devised.

Using annual averages for rainfall functions, for draft, and for head, the following equation was derived by least squares:

$$D = 431.4 + 13.9\ RR - 12.01\ H$$

where D is draft, RR is the rainfall function, and H is the mean head. As this is written the values for RR have been again divided by 100 so that normal rainfall for one month is 1.00.

This equation suggests that within the range of head fluctuation represented in the period 1925-1940, the increase of natural leakage for each foot of rise in head is about 12 M.G.D. and that at a head of 17 feet (May, 1945) with normal rainfall cumulation we might expect a yield of about 431 - 204, or 227 M.G.D. During 1944, exclusive of spring leakage which is related to head, the total yield approximated 220 M.G.D. Since the rainfall has been less than normal there is reason to suspect that some benefit came from storage, but we do not have full data to deal with this factor as yet.

Using the equation above calculations have been made for each month from 1926 to 1939, showing the difference between actual draft and the draft called for by the equation. These show that during periods of falling head the pumps draw more water and with rising head less water than the equation calls for. These differences, taken by the month, have been divided by the amount of corresponding head change of proper sign to show the apparent amounts of excess or deficient water per 0.01 foot of head change. Annual averages for these, representing a total of 168 months, are tabulated in Table 13.

TABLE 13

STORAGE RATES

Year	Quantities of water per 0.01 foot head change. Combined excesses and deficiencies. Based on monthly averages. (Millions of gallons per 0.01 foot.)	Mean Head
1926	11.78	18.8
1927	12.79	20.2
1928	11.86	22.3
1929	12.70	20.5
1930	14.06	22.0
1931	14.11	20.4
1932	14.83	22.4
1933	15.62	21.4
1934	15.55	20.1
1935	15.75	20.5
1936	15.45	20.0
1937	15.75	23.4
1938	16.12	23.0
1939	16.70	21.7
Average	14.49	

These values represent the running ratio between plus and minus draft differences and minus and plus head changes. That there are other conditions causing gain or loss of water is clear and the values shown in the above table from 1926 to 1930 suggest some systematic departure. However, the general agreement is surprisingly close and it is believed that the average of 14.49 M.G. per 0.01 foot or 1449 M.G. per foot is at least a rough measure during monthly periods of water available from rock storage near the water table in the Pearl Harbor area.

Other applications of this and improved formulas are planned, which will be facilitated as more complete data are made available.

SUMMARY AND RECOMMENDATIONS (1)

Estimates of water quantities

We have seen that present data indicate a total rainfall on the Pearl Harbor topographic drainage area of 432 M.G.D. When corrected to correspond to artesian area No. 6 this amounts to 420 M.G.D. We see no basis for including much of the coastal plain area, and the net amount of rainfall on ground where it might reach the

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(1) While the factual material in this report pertains chiefly to the Pearl Harbor area, it is unavoidable that the summary and recommendations in large degree apply to both the Honolulu and Pearl Harbor areas, as considered by the writer at this time.

Area 6 basal water is calculated at 369 M.G.D.

Several attempts have been made to derive a figure for net infiltration by subtraction of evaporation, transpiration and runoff. The results, in relation to known draft, are such as to show that no valid estimate can be made on the basis of existing data. For the period 1926-1940 an analysis of head, draft and rainfall was made, using a rainfall index based on the square root of the monthly ratio debited 3% per month. The derived equation indicates the amount of water to be expected under specified rainfall and head conditions, if head is to be held constant. It should be understood that such indicated amounts are not absolute, that they are postulated on the existing stations and methods of draft. With the building of new stations in favorable localities, it is probable that larger amounts of water can be drawn for considerable periods, and that the amounts might seem to be new water, or water in excess of the amounts indicated by an earlier equation. However, it is the writer's view that these apparent excess amounts are like the apparent excesses of draft that are found at times of very low head. Even after allowance has been made for reduced leakage and for draft from water table storage, these excesses are probably only sustained inroads on storage at points more remote than the water table and are probably not truly permanent.

Building of new stations will undoubtedly increase flexibility of operation, give a measure of control to new agencies, and probably for a considerable period appear to yield a greater total from the whole area. There is still much room for doubt if the water is new water in the sense of ultimate supply

TABLE 14

CONSTANT-HEAD DRAFT QUANTITIES (AREA 6)
(M.G.D. exclusive of any benefit from springs)

Rainfall Condition	Mean Head (Feet)		
	25	20	15
Under 60% of normal for preceding year (End of 1926)	114	174	234
Normal Rainfall	131	191	251
About 20% in excess of normal for year (End of 1937)	142	202	262

(1) Based on the equation: $D = 431 + 13.9 RR - 12.01 H$

For comparison we note that total Pearl Harbor draft in the past 20 years has, for single months, been as low as 30 M.G.D. and as high as 275 M.G.D., and for yearly averages the extremes, prior to 1942, were 145 and about 210 M.G.D. respectively. These figures of use have included water taken from the Pearl Harbor Springs; those in the table do not.

Table 15 indicates the amount of water considered to be available from Area 6 under certain specified conditions. These estimates are based in part on the equation given above, and in part on existing approximate data. They represent the writer's present studied opinion.

The immediate question which arises is whether draft aimed at holding the head down to 15 feet or some lower value is safe. This is difficult to answer categorically. To lower the head to 15 feet and hold it there would probably, at present, bring salinity changes at several of the chief producing stations which would discourage draft unless the need were extraordinarily severe. Despite the fact that the head in 1944 went below 17 feet for four months, it is not expected that the head will be taken below 15 feet and held there for any period of 6 months or more until at least some time after 1950. To accomplish this, in the writer's estimate, would take a more favorable layout of basal stations, and more concerted action and need, and disposition to ignore salinity, than is possible at present. This is equivalent to saying that in respect to water quality it would be unsafe to hold the head below 15 feet with existing equipment.

However, it is believed that when wells producing half

TABLE 15

WATER QUANTITIES IN AREA 6 (M.G.D.)

Component	Head to be Maintained (Feet)			
	21	18	15	
Water directly available from current Normal Rainfall indefinitely (Steady Flow, 1975)	179	215	251	A
Additional water derived from Head lowering at two feet per year, estimated	---	---	8	B
Additional water possibly derived as Lagging Yield following Head lowering of four feet in year or less	---	---	50	C
Water taken currently from Pearl Harbor Springs	(20)	(20)	(20)	D
Water apparently available from present springs at indicated Head,	62	50	38	E
Total under most favorable but temporary conditions	241	265	347	ABCE
Total permanent	241	265	289	AE
Total permanent, without increase at springs	199	235	271	AD

of the water now produced from artesian wells have been replaced by properly designed basal stations, assuming that those now in most precarious position in relation to salt are included among those replaced, lowering of the head permanently below 15 feet will be practicable. This would probably result in an average steady draft of 270 M.G.D. without increase in spring use, or over 300 M.G.D. with increased spring use. Whether the pressure of need and the growth of enterprise to bring about the expensive conversions mentioned will reach the suggested stage by 1960 or not until after 1980 is not known at present.

Much emphasis has been given by H. T. Stearns to the doctrine that operating the artesian system at lower heads will greatly increase the amount of water available by reducing natural leakage and also by promoting the inflow of water from other areas. (1) It is believed that the advantage of lowering heads, as a policy and as a basis for optimistic estimate of future water supplies, has been overstated and that insufficient consideration has been given by Dr. Stearns to the problem of retirement of artesian wells that would be injured by such head lowering, and also to the value of storage represented by a high head. At one point it has

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(1) Stearns, H. T.; T. of H., Div. of Hydrography, Bull. 1, p. 455, 1935.

been stated that "A low water table leaves more space available for ground water storage during wet years and reduces leakage from the basin through springs _________". (1)

This is true, but calls to mind the conflicting policies and needs of the flood-control group and of the power-development group in the management of dual-purpose dams and reservoirs in various projects in the United States. Without doubt the greatest total amount of water can be accounted for by keeping heads and storage low and utilizing accumulated water somewhat promptly. On the other hand, the maximum condition of safety by virtue of stored water is achieved by keeping heads and storage as high as possible. Complete freedom to choose between these alternatives does not exist in the Honolulu-Pearl Harbor area because of the continued use of wells which will not function successfully with too drastic a lowering of heads. The question of how far it will eventually prove feasible to lower the heads, when artesian wells have been completely replaced by basal stations, is one for which the complete answer will require more exact knowledge of drought probability, and amounts and rates of gain to or loss from storage, than we yet have. Data for statistical analysis of this probelm can be had only im-

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(1) Stearns, H. T.; T. of H., Div. of Hydrography, Bull. 5, p. 9, 1940.

perfectly from past and present performance since ultimate behavior will depend on complete conversion of stations to the basal type. Data taken during a rapid change of head will be vitiated by the additional effect of loss from storage, and apparent increases in available water supply during such changes will only in part be permanent.

We do not deny that heads in both Pearl Harbor and Honolulu areas may ultimately be safely lowered to perhaps 12 feet above sea level. However, there is abundant indication that rapid lowering of heads to such a figure, say within a shorter period than 30 years, will involve such drastic modification of production facilities, such hostility between operation programs, and such confusion as to the amounts and qualities of sustained supplies made available by any procedure, that it is regarded as unsafe public policy. The size and inertia of the system is such that it is considered both unlikely and undesirable for rapid or drastic changes to be made. The size and inertia are both hydrologic and economic. In the opinion of the writer the position of a public agency at this time should be that of promoting an orderly and deliberate change consistent with growing knowledge of the long term consequences. This will involve the construction of stations of the basal type to eventually replace all the present, publicly used, artesian wells as well as continuing and centralizing the collection and analysis of data. Paramount in the whole procedure is the recognition of the unity of the problem as a whole and the need for centralized guidance. Legislation aiming at a ground-water control commission, which was offered in the 1945 legislature, and on which action was deferred, is deemed an important and necessary step.

Recommended Investigations

The size, geologic structure, and climatic situation of the Honolulu-Pearl Harbor basal water system, and especially the degree of development and close approach to full ultimate yield, make continued study of every detail of its behavior a necessity both for safety and for the most economic operation. All existing programs of recording of draft, rainfall, head, and salinity should be continued and no opportunity lost to supply missing data and to impress on private owners and the smaller operators the necessity for pooling information. In writing the following section, the writer has referred to the memorandum, Units of a Program of Research on Hydrologic Problems of the Honolulu and Pearl Harbor Water Supply Areas, dated August 7, 1944, and prepared by Wentworth and Samson after a series of conferences with other water department engineers.

(1) Head

Installation of water-level recorders at the Manaiki, Waimalu, Waiawa, and Kunia holes should be completed. Measurements made at these holes should be compared over a period of years with those currently made at artesian wells 187B, 190, 193, 201, 244, and 266, as well as with measurements made at test holes 19, 42, 43, and the Aiea-Austin hole. It is expected that the readings in the new holes will prove steadier and more reliable as a measure of the position of the water table and of the condition of storage above sea level than the readings on the artesian wells. It will probably later be in the public interest to publish the readings on the new holes in place of the others. It will continue to be useful to measure the elevation of the water table at various points for special purposes, as heretofore. It is particularly urged that, as each basal station is built, a pilot hole be drilled prior to construction, so as to determine the local peculiarity of water table position, and also to permit static measurements to be continued after completion at a distance preferably of about 100 feet away from the sump or tunnel. Data from such a hole will be of the same value in relation to the station as that of the index well at many of the artesian stations.

(2) Draft

Measurements of draft are made as a matter of routine at Board of Water Supply stations and at most of the other larger pumping stations. It is of continued importance that data on draft be compiled and that effort be made to secure production figures for every active well, spring, or other point of outflow from the ground water supply. War time shortages of labor have made securing of full data difficult; every effort should be made as war time difficulties are reduced to resume the fullest recording of data on draft and salinity, so that a quantitative inventory can be compiled and maintained.

(3) Rainfall

It has been recognized that rainfall data are not adequate to make a close estimate of rainfall quantities on the Pearl Harbor watershed. Not even an approximate spread of inland high rainfall records exist for years before 1908 and the number is insufficient up to now. The Water Resources Division plans to install additional gages and employ necessary help to read them as soon as personnel can be obtained. The gages are already in hand. Need for a carefully located pattern of 12 to 15 gages is by no means lessened by the apparent impossibility of deducing ground water supply by the subtraction method. The rain gage readings not only give data for the overall total rainfall, but also for the deviations from the mean, which are most essential in developing the rainfall function and setting up the various multiple correlation problems that give increasingly useful results on the relations between head, draft, and rainfall. It is not to be expected that rainfall in the Pearl Harbor area will always closely parallel that in the Honolulu area and continuing local data are needed.

(4) Salinity

The salinity of water drawn from wells and basal stations under closely defined conditions is an extremly valuable indication of the sub-sea-level conditions and it is desirable that careful attention be given to the choosing and defining of conditions so that they can be duplicated at some later date.

(5) Performance of wells

Recent studies have reiterated the fact that the behavior of any given well in relation to draft and salinity is highly individual, and depends on the form and size of openings extending outward in all directions from the intake part of the well. In most cases we have no specific knowledge of these openings and can only speculate on their character from the changes in salinity that are induced by draft under different conditions and at different times. In marking the successive changes of fresh water storage it is highly important to take samples of water yielded under undisturbed conditions from various depths in a well. Samples taken from a flowing well are typical only of that well at he exibsting rate of flow at the existing reginal head.

If the slight increases of salinity that we believe accompany early stages of salt encroachment are to be detected when they start the initial and later samples must be collected under very carefully controlled conditions that can be reproduced, so that the only change is the supposed change in actual ground water available to the well. Careful tests of a given well must be made so that necessary conditions can be defined. Tests of two such wells have been made in the Honolulu area and others should be made so that we have at least one critical observation well in each area, including several in the larger area 6.

(6) Transition zone

Next to draft, basal head, and rainfall, the most important measure of the state and prospects of water supply is the position of the transition surface or zone between fresh and salt water. It has been emphasized in various statements on the doctrine of bottom storage that the total amount of fresh water in any portion of the basal water lens cannot be indicated along by the position of the water table, but must also depend on the position of the transition surface. The tacit assumption made in some earlier work that the head could be tkken as a measure of position of both the water table and the transition surface and hence as an index of total storage is believed to be unsound.

If this is the case, and especially since the transition surface according to the Ghyben-Herzberg theory is subject to such great change, probably with marked lag, it is of the greatest importance to secure information on the position of the transition zone, as the basis for estimates of changes in total storage. It is quite evident, if the 40:1 ratio holds, and if the doctrine of lag holds, that without taking account of the actual position of the transition zone, very large errors in estimates of storage change are unavoidable.

Measurement of the effective position of the transition zone has not yet been accomplished; because of the width of the zone, or the irregularities of interpenetration of salt and fresh water, any valid determination will probably be very difficult. It has been suggested elsewhere (Kalihi Report, pp. 103-104) that a diffusion zone test hole be drilled and fitted for continuing measurements of the quality of water at different levels all the way from fresh to salt and with sealing of each test point from each of the others. This is considered to be the most desirable ultimate method. Meantime, certain well tests are being made which yield information of value and which should guide any subsequent fitting of a test well.

(7) Mathematical correlation

Most important of the recommendations contained in the Wentworth-Samson memorandum of August 7, 1945, referred to above, was that calling for continued analysis and correlation of data on rainfall, draft, heads, and head differences. This is again endorsed as a necessary continuous duty, as much as possible independently of trends, whether momentarily favorable or unfavorable. Progress has been made on this work, but with the continuing change in draft conditions, not to mention the expected rainfall fluctuations, questions arise faster than answers can be found, and such work will be needed more rather than less.

Recommended projects

The projects suggested are those which, in the writer's judgment, have an important relation to the water supply problem. No comment is made with reference to projects that are related to operations or distribution procedure.

As stated above, both the Honolulu and Pearl Harbor area are considered. Omission of a specific problem does not mean disapproval but merely that no particular emphasis is offered at this time.

(a) Basal recharge

Completing of one or more of the proposed basal recharge projects is considered of very great importance, both because of the increase of water supply to be expected and because the testing of this method on a full scale is extremely desirable. The long-term value of such a project can only be fully assayed after several years of operation and it is desirable, as a matter of policy, to determine what may be expected. Projects of this kind have been laid out for Palolo, Manoa, Nuuanu and Kalihi valleys. Existence of extensive data on water levels for the past 10 years make the Palolo project most likely to yield valuable data on water quantities, though the other projects involve larger amounts of water.

(9) Basal stations

Building of basal stations in the Waahila, Papakolea, and Kapalama areas to replace the present Kaimuki, Beretania, and Kalihi artesian well stations in areas 1, 2, and 3 (Moiliili, Beretania, and Kalihi) is regarded as imperative within the next 10 years. These stations are needed in order to provide adequate water supply without the existing hazard from salting due to lowered head, and to enable this public agency to lead, rather than to follow, in the orderly transition from artesian well development to basal water development, with attendant slow lowering of head to a mean level of 15 feet by 1970. It is not financially desirable to retire the investment in the existing stations for another 10 to 15 years but it is believed that orderly transition in solving the hydrologic problem will justify accelerating the process somewhat over the simple financial procedure, as in any other case of technological obsolescence.

(10) Waialae tunnel extension

The extension of the development tunnel of Waialae basal station, as planned and interrupted by war conditions, is a project which should be completed as soon as sufficient distribution relief for the Waialae area has been provided so that the station can be shut down.

(11) Diffusion zone test well

In view of the recommendation made above (No. 6) that test wells be fitted so as to yield data on the position of the transition zone, and the earlier recommendation that a full, multiple-pipe installation be placed in a deep well, it is strongly urged that at the time of sealing any well released for this purpose, the most careful consideration be given to installing one or more small pipes from which water samples can be taken at various levels. The installation of one or two half-inch pipes leading from chosen zones near the bottom and surrounded by the cement seal need not be regarded as a continuation of the hazard of uncontrolled leakage, and such minor legal discrepancies as may appear can presumably be resolved by modification of the form of agreement.

Moreover, difficulties in the sealing operation, due to the presence of the test pipe, can presumably be overcome more economically than by drilling a new well. Since continued consideration of drilling a new well for the purpose is urged, it appears that the very much less expensive possiblity of using an occasional old well is well worth considering. Such test wells will eventually be fitted in each of the basal areas, Honolulu and Pearl Harbor. It is believed that a start in the continuous recording of salinity changes from such an installation is one of the most important moves we can make in the near future.

(12) Pearl Harbor program

The construction of water supply projects in the Pearl Harbor area is mostly outside the province of the Board of Water Supply. As a result of the study here reported, it is evident that the most important problem facing the Pearl Harbor area is that of transforming the development facilities for maximum, controlled use of the total supply. With the present machinery and with the premise of holding heads above 20 feet and salinities at present value, the area is at present being overdrawn. The present writer believes that the head would fall at a considerably greater rate if large benefits were not coming from deep storage. These benefits will decline in course of time.

On the other hand, with retirement of more wells and their replacement by basal stations, and with conditions thus set to permit lowering the Pearl Harbor head permanently to as low as 12 feet in the course of the next 30 years, it is believed that the total draft can be continuously held as high as 270 M.G.D., particularly with greater use of spring flow. It must be emphatically stated that this does not mean that any single user should take comfort in drawing apparent new water because he has built a basal station. Only by the meeting of all the conditions of this paragraph by all users does it appear that the present or slightly greater draft be made permanent; under existing conditions the present amount is believed to be overdraft.

(13) Pearl Harbor spring repair

Appendix II carries a suggestion in regard to repair of leakage of the Pearl Harbor Springs. This can only be considered as a conservation measure on a regional basis under federal or other overall authority. From its nature, it is probable that no single user of water can undertake it on the basis of short-term water supply economics.

APPENDIX I

The concept of bottom storage

The doctrine of bottom storage is thought to be a natural consequence of the Ghyben-Herzberg principle of hydrostatic balance between fresh and salt warer in the permeable rocks of an oceanic island. (1) According to this theory, the fresh water of the main ground water body floats on sea water with one part above sea level and 40 parts below. Thus for each foot of fresh water above sea level, there are 40 feet of fresh water below sea level. (2) If this be true, then if the water table changes by one foot, up or down, a new equilibrium will be reached only when the lower limit of fresh water has changed by 40 feet in a reverse direction, down or up, correspondingly. The two parts of the fresh water body, above and below sea level, which are

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(1) Brown, J. S., A Study of Coastal Ground Water, U.S.G.S., Water Supply Paper 537, pp. 16-17, 1925. Carries references to papers by W. Baden Ghyben and Herzberg.

(2) The ratio 1:40 is based on sea water with a specific gravity of 1.025, about 1/40 heavier than fresh water. According to extensive measurements, the true figure is probably nearer to 1.026 and the ratio nearer to 1:38.

thus in balance at a 1 to 40 ratio, have been called top and bottom storage. (3)

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(3) Wentworth, C. K., Storage Consequences of the Ghyben-Herzberg Theory, American Geophysical Union, Transactions, 1942, pp. 683-693, 1942.

It follows from the Ghyben-Herzberg principle that when the ratio of top to bottom storage is not that required for equilibrium, water will tend to move toward the deficient part. Direct and rapid gains or losses of water take place primarily in top storage by rise or fall of the water table. Slower, secondary changes in bottom storage take place in response to the more rapid fluctuations of top storage.

There is probably a fairly steady loss from bottom storage direct to the ocean at and near the seaward edge of the caprock. This is part of the equilibrium condition and does not bring about changes in volume of bottom storage. Marked changes in volume of bottom storage, plus or minus, come about only in response to changes in equilibrium due to change in top storage by rise or fall of the water table. Bottom storage can gain fresh water only by transfer from top storage; losses from bottom storage induced by lowering of the water table must take place by transfer to top storage and removal from top storage by draft or other augmented discharge.

Dynamically, top storage is free to gain or lose rapidly as a net result of excesses or deficiencies of rainfall, draft, and various kinds of leakage. But top storage variations are damped by the demands of transfer to or from bottom storage as equilibrium is disturbed.

The large volume ratio of 40 to 1, or possibly greater, between bottom storage and top storage gives the bottom storage great stability against rapid change and by the transfer effect limits the amplitude of variations in top storage.

In their 40 to 1 ratio between equivalent storage quantities, the bottom and top storage seem to behave like paired reservoirs, one large and one small, connected by a pipe offering resistance to flow. Except for certain nearly steady leaks from the large reservoir all changes are made through the small reservoir. Analogy with such reservoirs is imperfect since the movable boundary of bottom storage in the rocks is not a water-air boundary but a fresh water-salt water boundary. Movement can be achieved only by moving salt water out to the free ocean. The free surface in this direction is the surface of the ocean. The great area of the ocean, the resistance to flow in rock from the transition surface out to the sea bottom, and the 40 to 1 volume ratio of bottom storage give great stability to the transition surface.

As a result, sudden or abrupt changes in input or outgo, even when applied to bottom storage water, as in a well below sea level, will be shown first by changes in the water table. In turn, the top storage is at any time a cumulation of plus or minus effects and a leading element with which bottom storage tends to seek equilibrium. When bottom storage is nearly in balance, the water table may vary from positions above to those below equilibrium with the transition surface. Bottom storage and the position of the transition surface fluctuate with movement of water from or to top storage but in an amplitude far less than required for new equilibrium.

If bottom storage, in lagging response to large past changes of the water table, is out of balance in one direction, the fluctuations of the water table will not lead to reversal of movement of the transition surface but only to changes in its rate of movement.

It is evident that if the unit transfer rate of water between top and bottom storage is great, balance will be achieved quickly. This will come about as the result of movement of large amounts of water in short periods. If we postulate a too rapid rate of movement the indicated amounts of water will exceed those we can account for in relation to rainfall or draft fluctuations. Similarly such rates would tend to restrict the amplitude of water table movement below the values we observe. On the other hand, if the unit transfer rate is very small the Ghyben-Herzberg principle would be inoperative, which we know is not correct. Thus the possible unit rate must lie between the large values which would damp out nearly all water table fluctuation and the small values which would nullify the principle of balance.

In order to explore the possibilities of the bottom storage doctrine it is desirable to consider actual amounts of water. This will be useful despite lack of exact or direct knowledge in some respects. Data used apply to the Honolulu system, areas 1 to 4. Total average rainfall in the mountain intake area is 129 M.G.D. The amount known taken (1930-1939) by artificial draft at sustained heads approximates 35 M.G.D. The amount which reaches the basal water body must lie between these values and will be assumed to average 80 M.G.D. This figure, assuming no change in storage, must equal the sum of draft plus all leakage.

Artificial draft may vary between 20 and 60 M.G.D. and infiltration for short periods may be as little as 50 or as much as 120 M.G.D. By combining somewhat less than opposite extremes we conclude that against the mean steady condition, where infiltration equals draft plus leakage, the net daily residues may vary from about 30 M.G.D. excess to 30 M.G.D. deficiency. Any hypothesis requiring daily quantities, plus or minus, materially more than these must attempt to indicate their source.

There are several estimates of the unit volume of top storage per foot of water table change in the range from 20 to 30 foot head. They vary from 200 to 500 million gallons per foot in areas 1 to 4, combined. For discussion we will take the value 300 million gallons.

Rates of change of head for short periods of a few days approach but do not exceed 0.10 foot per day, either rise or fall. Such a change corresponds on the above storage rate to 30 M.G.D. per day excess or deficiency. The coincidence is accidental; but the essential fact is that variations of supply are sufficient to achieve the indicated change in top storage.

But the probable unit amount of bottom storage corresponding to 1 foot of head is in the order of 40 times 300 M.G. or 12,000 M.G. and for 0.10 foot it is 1200 M.G. Whether this figure is valid or is double or half the true figure is immaterial. The variation of + 30 M.G.D. to -30 M.G.D. is wholly inadequate to make such changes in bottom storage. The lag, even without reference to friction, would have to be many days or months.

If there were no friction so that 40/41 of all variations were at once transmitted to bottom storage the daily rise or fall of the water table would be restricted to one or two thousandths of a foot.

The conclusion is indicated that fluctuations in the water table, and hence in the amount of top storage, of the magnitude observed are only possible because the interchange of water between top and bottom storage is impeded. This is due to all the rock lying between the two boundary surfaces and also out to the ocean bottom. This occurs to a degree that permits the temporary application of the amounts of daily fluctuation mainly to the top storage and delays dissipation of these amounts to the enormously larger storage change demanded by ultimate equilibrium. To summarize this brief exposition of the doctrine of bottom storage, the following corollaries are set forth:

(1) The ratio of depth below sea level to height above sea level in the Ghyben-Herzberg system approximates 40 to 1. The ratio of corresponding storage amounts of water at the bottom and at the top in a balanced system is probably 40 to 1, or greater.

(2) The amounts of water involved in daily fluctuations of draft and infiltration are of closely similar order of magnitude to the amounts of storage at the water table, corresponding to observed extreme daily rates of change of basal head. Assuming the ratio indicated above, these amounts are wholly inadequate to effect the corresponding changes of storage at the zone of transition on any assumption of immediate or prompt transfer of water between top and bottom storage.

(3) Each fluctuation of the water table and of top storage, away from equilibrium under the Ghyben-Herzberg theory, tends to be cancelled, either by reversal at the water table through movement from or to bottom storage, or by corresponding change in bottom storage through similar movement. If the new position of the water table is maintained by persistent application of excesses or deficiencies, the balancing will eventually be accomplished by complete change at the bottom storage; if the change at the top is not maintained, the equilibrium will be much more quickly restored by almost immediate reversal at the top, since the latter restoration only requires approximately 1/40 the amount of water and time that the former would require.

(4) In the sense of movement, the top storage is the independent element, and the bottom storage follows with lag; in the sense of static inertia, the bottom storage is independent and the top storage tends to swing back to equilibrium with it except as it is held above or below by persistent excesses or deficiencies.

(5) The rate of interchange of water between top and bottom storage is presumably proportional to the degree of unbalance which exists between them; its absolute

rate is not yet known. To assume that it is very rapid is to postulate the movement of greater amounts of water than we can account for in any plausible way; to assume the rate too low is to nullify the Ghyben-Herzberg principle below the validity indicated by common observations.

(6) If the lagging response of bottom storage be correct, whatever the rate of response is, there is here a definite challenge to the supposition earlier made that when the head returns to a former value, the total storage in the system has returned to the same value. In view of the 40 to 1 ratio, it is evident that even if a considerable part of the response of bottom storage is achieved, the non-completed part may still be several times as great as the whole amount of change in top storage. Hence, it would vitiate any such postulate as that earlier made in regard to the basal head as a direct index of total storage.

(7) Consideration of the amounts of water involved make it difficult to see how the shift of the transition zone by the forty feet corresponding to a one foot change in basal head can be achieved short of many months if not years. Moreover, the rise of the transition zone and shrinkage of bottom storage by the 600 feet corresponding to 15 feet loss of head since 1880, on the data we have, is presumed to have yielded something of the order 600 x 300 million gallons (180,000 M.G.) of water to draft and artificial leakage over and above the normal net amount from rainfall. If this entire shrinkage has been completed in the past 60 years (about 20,000 days) it has approximated 9 M.G.D. of draft from bottom storage over that period. If it has not been completed, the average amount will have been less, but there may still be a fraction of present draft from that source. These are conservative figures, twice these amounts are more plausible than any lesser amount. Whether the balancing of bottom storage is rather rapid, with only a few months lag and large amounts of water yielded into the daily inventory from storage, or whether the lag is much greater and over many years, the accounting for the water involved in the shifting of the transition zone and its effect on estimates of safe yield, or justifiable draft, remains a problem of the greatest importance in the future operation of the Honolulu water supply.

APPENDIX II

Conservation of Pearl Harbor Springs

INTRODUCTION

The Pearl Harbor Springs include the large, basal springs of Kalauao, Waiau, Waimano, Waiawa, and Waikele with other named components of these. There is little doubt that various other, probably smaller springs exist around the shores of Pearl Harbor. Submarine springs have also often been reported but the major problem of repair and conservation centers around the springs and localities named. Springs of this size have been well known to the Hawaiians from the date of their first settlements on Oahu, and it is equally clear that they must have been the sites of some of the first wet gardens for growth of taro and similar crops. Measurements of discharge at various of the Pearl Harbor Springs were first made in 1911 by the U. S. Geological Survey (1), which has made many measurements since that time.

Other measurements were made under the direction of J. F. Kunesh in the course of a study of water resources for Honolulu, and some general statements were made concerning their

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(1) Martin, W. F., and Pierce, C. H., Water Resources of Hawaii, U. S. Geol. Survey, Water-Supply Paper 318, p. 190, 1913.

character (1). Further descriptions were presented by H. T. Stearns (2). Palmer, in 1926 (3) recognized that these springs represented points of escape or leakage of basal ground water, which is a better way of stating the condition than to call the springs "artesian", as some have done. The locations of the chief springs are shown in Figure 1. The local pattern of each is shown in Figure 2.

HYDROLOGIC CHARACTER

The geologic structure causing these springs is very simple. The inner margin of the Pearl Harbor lochs is the landward edge of the very wide coastal plain in which all of Pearl Harbor lies. The edge of the coastal plain, except for a few slightly higher remnants of the Fort Shafter-Halawa

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(1) Kunesh, J. F., Surface Water Supply of the Island of Oahu, Supplement, Report of Honolulu Sewer and Water Commission, pp. 277-282, 1929.
------------ Surface, Spring, and Tunnel Water Investigations, Rept. Honolulu Sewer and Water Commission, Part IV, pp. 116-124, 1929.

(2) Stearns, H. T., T. of H., Div. of Hydrography, Bull. 1, pp. 365-370, 1935.

(3) Palmer, H. S., Geology of the Honolulu Artesian System, p. 43, 1926.

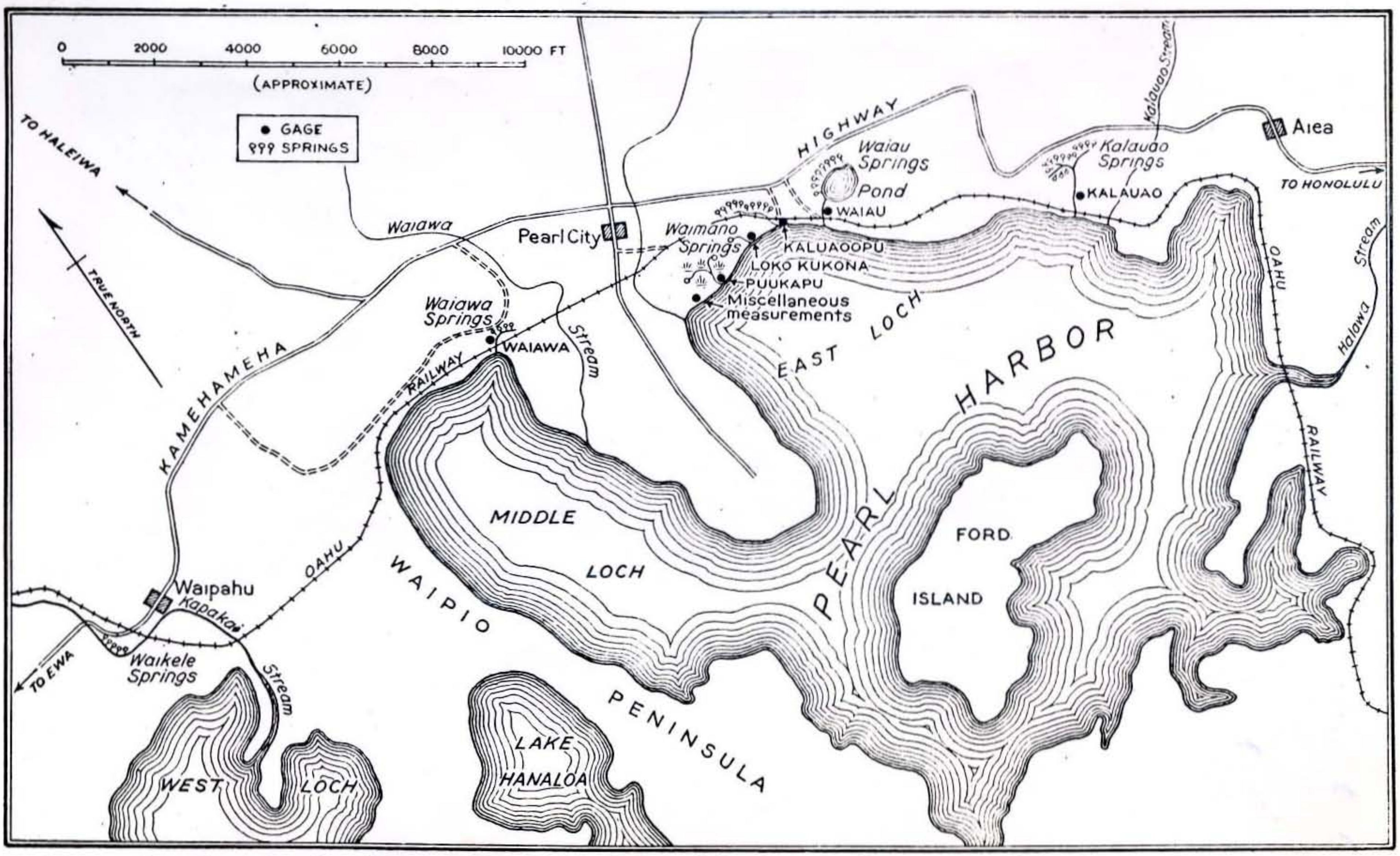

Figure 1 - Map showing locations of chief Pearl Harbor Springs. By photostat, without change, from Bulletin 1, Figure 29, T. H., Div. of Hydrography, 1935.

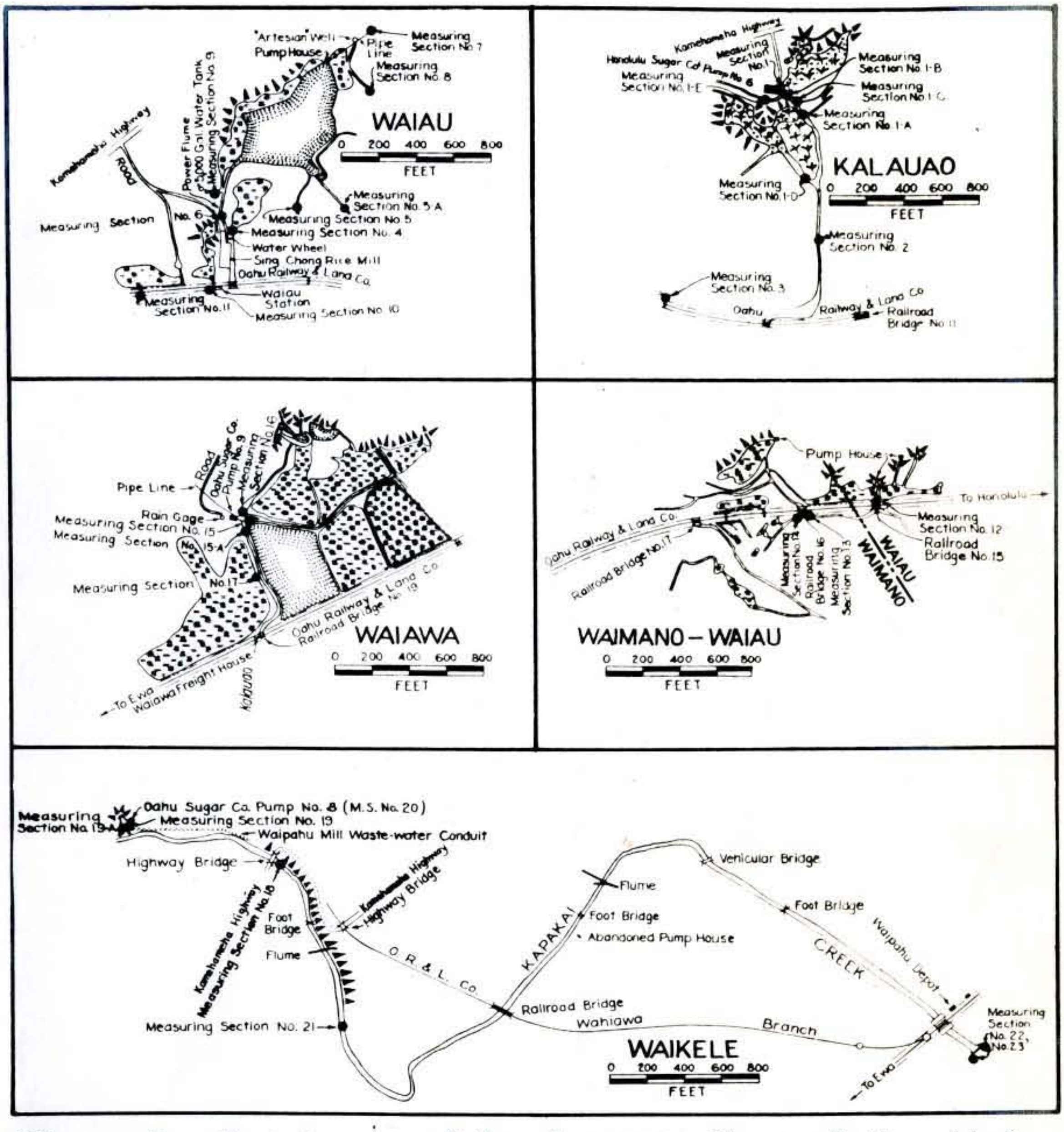

Figure 2 - Sketch maps of local surroundings of the chief Pearl Harbor Springs. (From Plate L, 1929 Report, Honolulu Sewer and Water Commission, rearranged and photostated.)

terrace, lies within a few feet of sea level, and coincides very closely with the sea level margin of the Koolau basalt formation of the Koolau Range. This is not a universal condition; in eastern Honolulu, back of Diamond Head, the coastal plain is surmounted by 200 feet of late lava formations and the margin of the Koolau rocks passes beneath this thicker mass as a wave cut sea cliff.

In general in the Pearl Harbor area the Koolau rock, covered by its residuum, passes down fairly near to sea level at the ends of the spurs, and in the valleys the rock bottom is below sea level but not nearly so deep as in the larger valleys of the Honolulu area. The relatively narrower valley bottoms of the Pearl Harbor area have a tongue of caprock fill which extends from a few rods to a mile or more inland. At most points on the spurs between the valleys, at the places where unweathered Koolau rock lies under the least cover, the rock stands above the highest artesian head of 25 feet. At most places in the centers of the valleys where sound rock lies between sea level and the level of artesian head, the rock is covered by thick caprock layers.

However, along the sides of valleys, at points where there is now or has been some lateral scour in the zone between sea level and the level of artesian head, Koolau rock that is not too deeply weathered is locally exposed. At such points there is leakage of basal ground water and if the openings in the rock are favorable there may be very large springs. (Figures

3 & 4) The question of whether the escape of water is over the edge of a low place in the caprock, or through a perforation in it, and whether the springs can be called artesian springs, depends partly on facts and partly on definitions.

At any place where water rises through well defined holes in a caprock formation and is capable of rising to a level higher than any of the surrounding surface, the spring should certainly be called artesian. On the other hand if the water emerges at an intermediate level on a sloping surface, in both larger and smaller openings and seeps, even though the head on larger openings would cause a rise of several feet if confined, it does not seem justified to call this condition an artesian spring. In many of the spring areas the Koolau rock is sufficiently weathered so that its surface is less permeable than the mass of the interior of the rock. Such a surface portion operates as a sort of a cap, though it extends inland to high elevations and is not to be counted as true caprock formation. In view of the fact that the various Pearl Harbor Springs are not, in the main, fed through demonstrable holes in an effective caprock and since the free surface of basal ground water appears everywhere to occur in the Koolau rock within a few feet or yeards, they are not here considered to be artesian springs. More properly they are side-hill springs where the exposure of permeable rock has been accomplished both by esternal erosion and their own flow. The water comes from a nearby ground water body of extraordinary freedom of flow

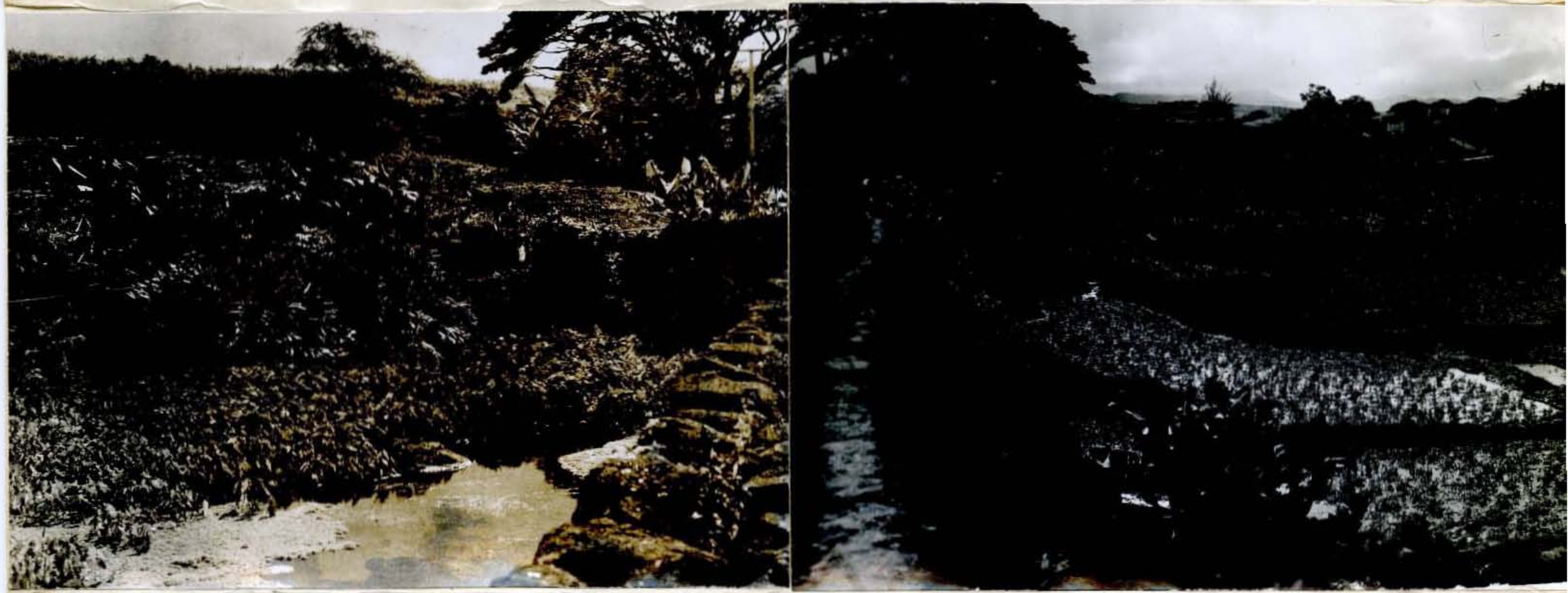

Figure 3 - View northeastward along wall to chief outflow point, Kalauao Spring. At left is the spring pool with water standing at about 13 or 14 feet above sea level. The outflow of water through a pipe is concealed in the near foreground on the right. Near and middle ground at the right consists of irrigated terraced gardens for taro and cress. Figure 4, following, is a view looking toward the camera position for this picture from a point near the apex of the wet gardens. Negatives No. 21620-21.

Figure 4 - Detail of terraces and walls with face of spring wall and pump station in left distance at Kalauao Spring. The large basalt boulders seen near all the springs are residual kernels from the spheroidally weathered Koolau formation. Basal ground water emerges all along the slope just above the level of the terraces but at present, June, 1945, is at the lowest rate ever observed. Negative No. 21543.

and continuity of free water table.

It may be found that certain of the springs or outlets are fed by tubes or openings that come from considerable depth but, in advance of proof, it is believed that the contrary should be assumed, and that the flow is chiefly lateral. In tunnels and other excavations below the water table, the more conspicuous flows of water often come from one or more larger openings that appear near the surface of emergence to have a relatively greater importance than is really the case. Experience with the behaviour of ground water entering drilled wells or dug tunnels or pits in the Koolau aquifer indicates that the formation as a whole, despite the irregularity of its openings and voids, does not have markedly greater permeability in one direction than in another, and that lacking specific data it should be taken as isotropic. Hence we are justified only in assuming that emergence of water to the seeps and pools that constitute the Pearl Harbor Springs involves no more, in general, of vertical movement than is indicated by an ideal flow net portraying the hydrologic conditions.

METHODS OF CONSERVATION

There are three elementary methods of repairing the leakage of a side-hill spring. These are as follows: (1) Place cutoff structures uphill so as to stop the major channels entering the spring or other places of escape, (2) Place cutoff structures below and around the spring so as to permit its head to rise to the full level of the ground water source, thus using water as a seal, and (3) Place fill and patching material in and around the excavated spring so as to wholly stop leakage at that point. In the case of a spring situated adjacent to a standing water body, such as the ocean, where the hidden leakage effects of patching and of a change in water level might not be determinable, the work should proceed with caution and with installation of measuring devices to keep account of the results. Moreover it might be essential to construct a parallel development tunnel so arranged that basal heads could be held as low as formerly to be sure that hidden leakage was no greater than before.

If in a given place we knew exactly where the larger fissures run we could choose the best method of repair with some accuracy, but in most places we know practically nothing of the directions of fissures which feed the spring. Much can be learned by direct excavation, but it is believed that before this is done a preliminary exploration is desirable. Let it be assumed that the total job of spring repair and development excavation at a single spring, without including pumping machinery, is likely to cost $50,000 with a permanent supply of 10 M.G.D. in sight. There will probably be a total of two or three thousand yards of excavation. To guide this work expenditure of at least $2,000 for preliminary drilling will certainly save more than that sum in improved design.

The drilling should be inland from the spring or springs so as to reveal the existing water table, and indicate the directions of water flow and the water table slopes under contemporary conditions.

In Figure 5 is shown a schematic cross section of a basal spring fed from the basal water table in Koolau rock. The level of water in this spring as now managed is 12 feet, as compared to the basal head of 20 feet. The spring basin is assumed to be bordered by Koolau rock on one side and by caprock and constructed embankment on the seaward side.

The object of the repair construction, togeyher with the development tunneling, is to; (1) Seal or reduce pressure on openings that are responsible for leakage, (2) Seal or at least not reduce pressure on openings that probably bring up salt water, and (3) Excavate a tunnel or system of tunnels that will permit large draft with only small drawdown at the deepest point.

SUGGESTED CONSTRUCTION PROCEDURE

A great variety of construction procedures can be outlined, but chief emphasis will be given to one in which the excavation for a cutoff wall is combined with that for a development tunnel. The essential features in diagrammatic form are shown in Figure 6. It is assumed that the work is to be done on a stretch of leaking Koolau aquifer in which a spring

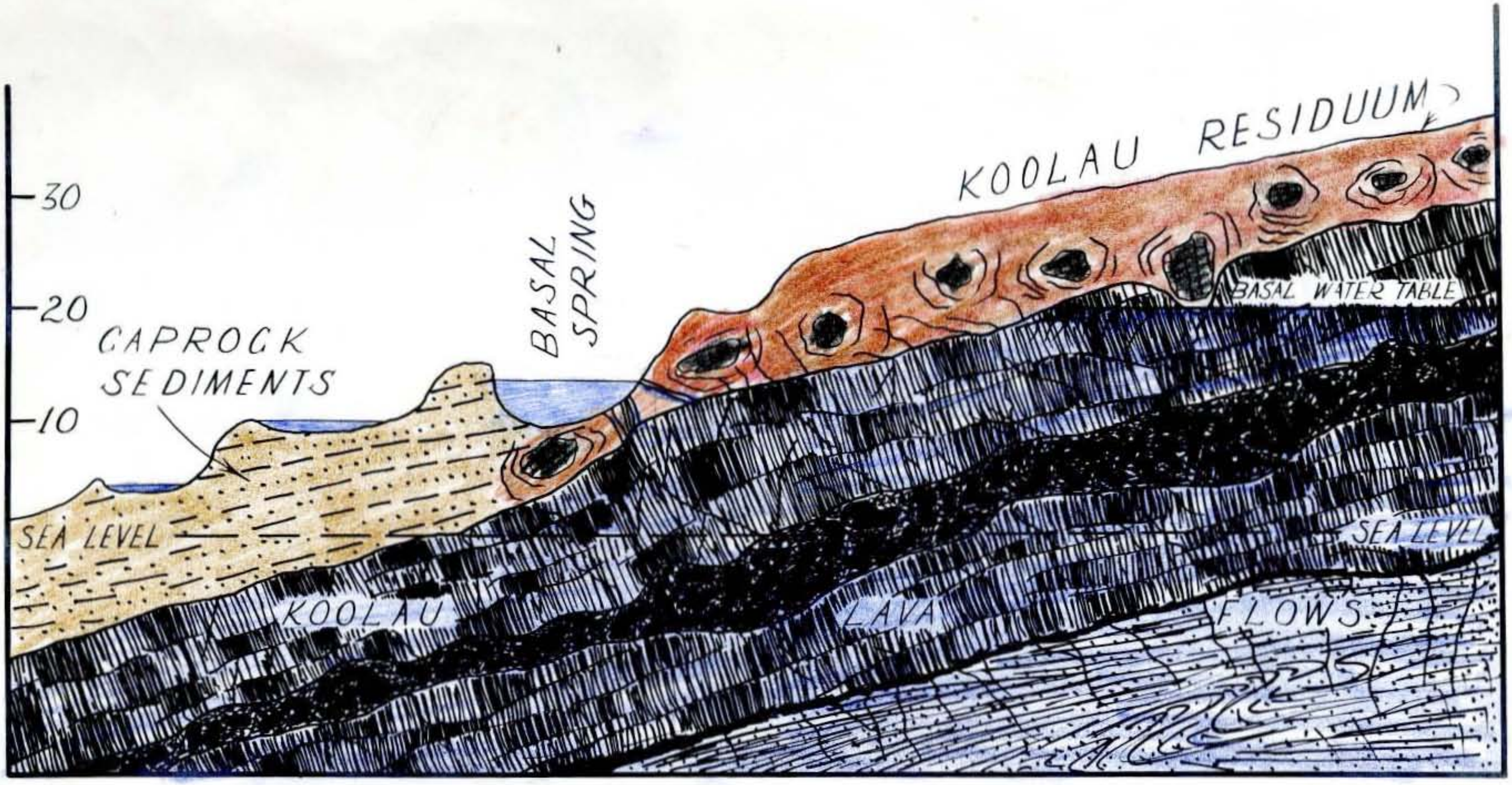

Figure 5 - Ideal section of basal spring of the Pearl Harbor type. The water emerges at the point where the residuum is thin and the caprock edge is low. At some of these points saturated Koolau aquifer is nearest to low ground below the elevation of the water table. The actual transition from residuum to aquifer is much more gradual and irregular than is practical to show here.

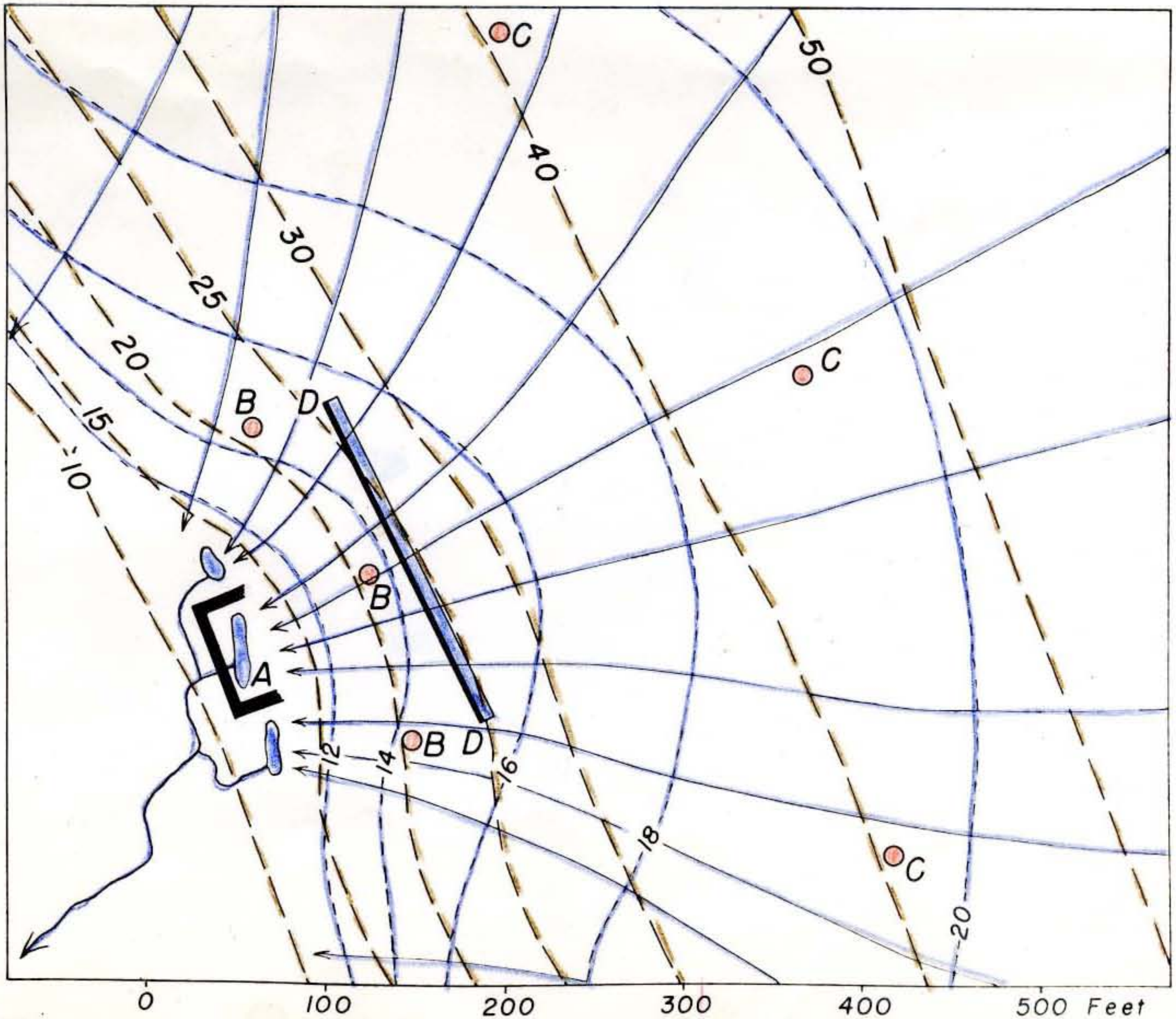

Figure 6 - Schematic diagram of ground water conditions around a unit basal spring. Surface contours are in brown; water table contours and lines of flow are blue. Other features are spring wall, A; drill holes, BBB, and CCC, and a section of cut-off wall and development trench, DD.

outflow of 8 to 10 M.G.D. is visible. Discussion is centered around repair of leaks and reducing flow for a group of springs not over 100 to 200 feet long. The same procedure can be extended for more extensive spring groups.

Figure 6 shows a group of springs which constitutes a concentrated leakage from basal water. It has been shown in the discussion that leakage from basal water cannot, on the average, exceed more than 5 to 10 M.G.D. per shoreline mile, or about 100,000 to 200,000 gallons a day per 100 feet. Discharge of 1 or more M.G.D. from a single spring represents a very concentrated flow and must obviously be fed by water following converging flow lines in the basal water table as shown. The suggested procedure is as follows:

(1) The existing spring, without disturbing its bottom or margins, should be surrounded by a masonry wall so that it can be allowed to fill up to the static head of the inflowing water. The wall should be fitted with a valve or gate for outflow control and the outflow stream with a weir. If necessary, to gather the outflow from a frontage of one or several hundred feet, ditches should be arranged to lead all streams through a master weir.

(2) Water table test holes should be drilled so as to place one hole directly back of the largest outflow and at a point where bedrock is presumed to rise 20 to 25 feet above sea level. This may be 20 to 60 feet back of the spring it-

self. At least two other near holes should be drilled, one on each side and in a slight arc centered somewhat seaward of the spring. Another row of holes at a distance of 200 or 300 feet back and spaced at 200 or 300 feet apart will also be needed. These holes should be drilled to about sea level and should be tested to see that they provide a responsive indication of the prevailing water level. Since the outflow at the main spring represents a convergence of flow we should expect an indented form of water table contours centered on the main outflow, somewhat as sketched in Figure 6. It is believed that such a configuration will be easily outlined by not over 6 holes, but if the form is not clear it may be necessary to drill additional holes at critical points. The holes can be any diameter from 2 inches up and should be cased at the top so as to preserve access to the water. They should be drilled as long in advance of construction as possible.

(3) The survey of existing conditions should include a topographic map with a contour interval of say 2 feet over an area as wide as the spring group under attention. This should extend back to surface elevation of 60 to 100 feet, at any rate some 500 feet or more from the springs. The level of water in the test holes should be measured systematically over a period of several months, and a continuous-recorder record made on one hole, if drilling a large hole proves practicable. The water table contour map should be made with care, with an interval sufficiently small to show its distinc-

tive form in relation to the spring outflow. Finally, the spring flow and the group flow at the master weir should be measured by continuous-recording gages. Tests should be made in the spring pool to show relation between its discharge rate and its maintained pool height during some period of fairly steady basal level. These measurements are needed to serve as background for the experimental construction procedure.

(4) The suggested sealing plan is that of placing a concrete cutoff wall on the seaward side of a transverse trench cut in rock to approximately sea level. This trench can be dug in sections made sufficiently short so that dewatering will be practicable and so that wastage of water will be small. The line of this trench, as suggested in Figure 6, should be far enough inland from the chief spring so that its seaward face will be in rock up to 20 or more feet above sea level, but should be close enough to the spring so that its line will cut as many as possible of the lines of flow in the bundle which converges at the spring. It is suggested that a section of about 50 feet in length be dug first, with a width determined by construction considerations but probably about 10 feet. This can be excavated from the surface, after cutting a berm by bull-dozer to about 25 feet above sea level. When such a pit has been excavated to sea level much information can be derived by studying water flow through it, probably at night using submerged lights, current meters, jets to release pigment clouds, and the like. It is unlikely that movement will

be other than across it in a seaward direction, but the general plan can be modified in relation to any local conditions discovered.

On completing excavation and tests, a single face form can be built at about 2 feet from the seaward side and a facing of water-tight concrete poured. Whether it is also desirable to line the bottom, and perhaps even a few feet up on the inland side, must be estimated from the form of flow lines shown by tests. At any rate it is assumed that a large fraction of the outflow channels can be plugged and a large fraction of the inflow channels left open.

(5) On completing one such section, another can be excavated next to it, separated by perhaps 10 feet of natural rock. If it seems necessary a concrete facing can be placed against the natural rock at the end of the first pit to reduce the cross flow. Successive sections can thus be dug so long as the rate of leakage through natural rock seems to indicate their utility. If there is indication that leakage through the 10 foot gap in the seaward barrier is great, that section can be excavated and concrete poured after the main sections have been completed, using such concrete, or other types of bulkheading as appears most economical while doing the work.

(6) The ultimate aim is a tight concrete facing along the seaward side and possibly sections of the bottom, with an unlined exposure of aquifer along the inland face through a continuous section parallel to the line of springs. It may be

found quite practicable to leave the 10 foot cross walls in place and merely break through them near the bottom, or it may be desirable to place a pipe section with valve in a cast, concrete bulkhead, separating the successive sections. There is good reason, from observations on the Hawaiian Electric Waiau plant excavation made in 1945, to suppose that in many places the trenches may be excavated as continuous trenches, with need for separation by bulkheads only as especially strong water yields are encountered. It may be desirable later to tunnel along these lines of inflow.

(7) The resulting trench, with a comparatively tight seal on the seaward side, will be well fitted for draft of water quantities equal to or in excess of those in the former springs, and at the same time it is believed that spring leakage can be reduced to less than 20% of its former value. (Figure 7) If this is the case the station and barrier wall can assume a real control of water supply. Hourly rates of draft greatly exceeding any formerly in force will be possible and at other times, when there is no draft, the natural seaward flow will to to build up storage.

(8) The trench, when completed, should be roofed over at 25 to 30 feet above sea level and probably backfilled above with 5 to 10 feet of earth so arranged that natural sterile conditions can be restored. If yield rates are still low after the sections necessary to reduce leakage have been dug, sections of tunnel can be taken inland until the yield has reached

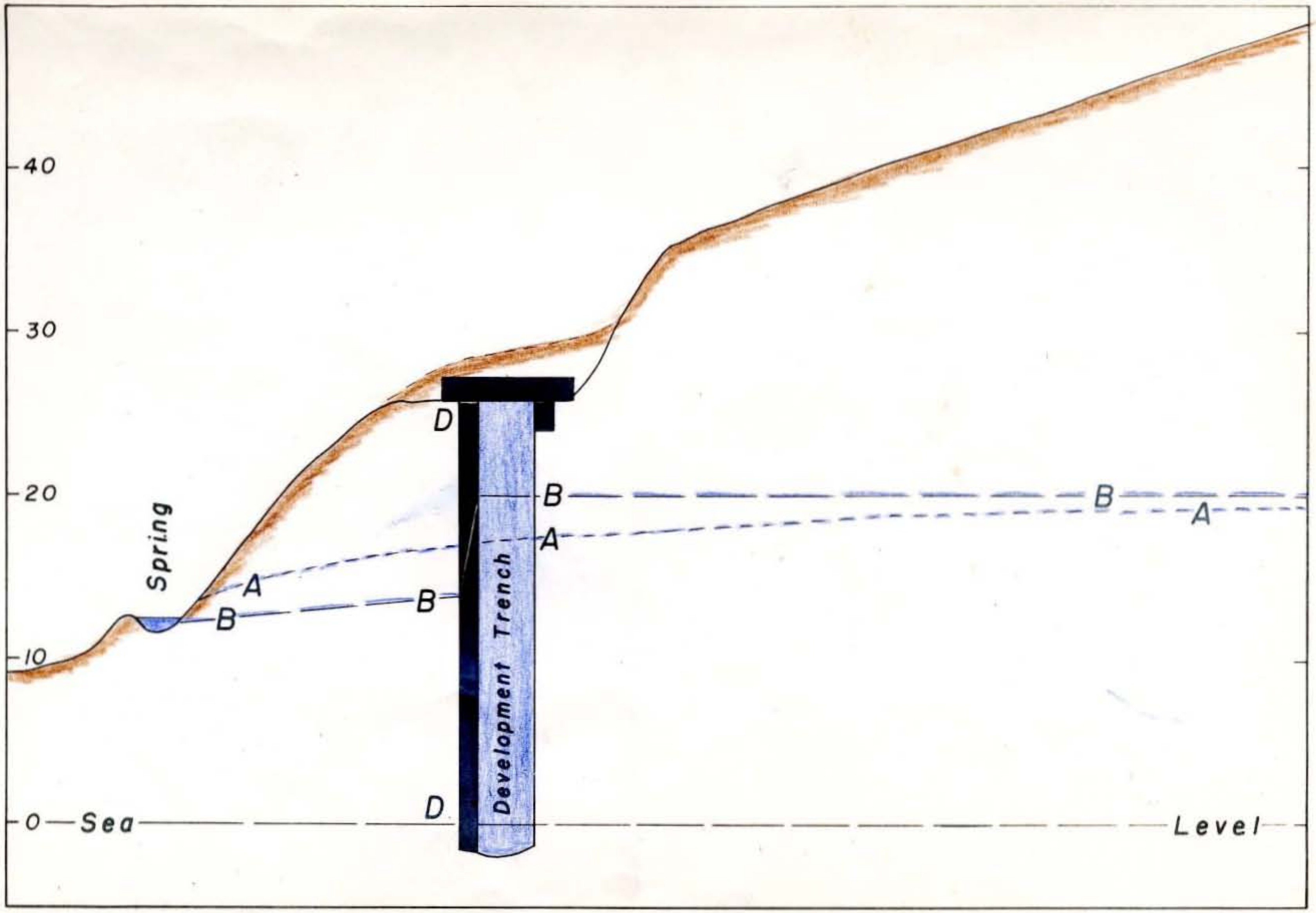

Figure 7 - Ideal section showing ground water conditions before and after construction of cut-off wall and development trench. Water table before construction, AAA: after construction, BBBB.

the desired value, consistent with over-all regional capacity.

(9) The present writer has no adequate basis for making a close estimate of costs on such work but needs certain assumptions in course of discussion. It will therefore be assumed that this open-cut excavation, even with some water to be handled, will not run to higher costs per yard than the general cost of rock excavation in the transmission tunnels on the Halawa job. The latter cost was about $10 per yard. If we take as a unit a section 50 feet long, 25 feet deep and 10 feet wide, the total yards of excavation will be about 470, estimated at $5,000 excavation cost. If we assume placement of 1/4 as much concrete in a tight facing and at a unit cost of $20 a yead, the total for this will be $2,500. This will be $7,500 for a 50-foot section without roof, pumping machinery, such sections can be built for $20,000 each.

(10) Only a test will show quantitatively just how successful such projects can be, but the writer is convinced that they will ultimately be much more than worth the cost in the total economy. By way of example, the Kalauao Spring group can be discussed. At this station in 1944 the mean total flow was 15.3 M.G.D., of which 1.4 M.G.D. was used by the Honolulu Plantation Company. It is believed that by the procedure set forth and the building of not more than 5 such 50 foot sections in places indicated by drill tests, the leakage can be reduced by at least 12 M.G.D. and at the same time a composite intake station of 30 M.G.D. peak capacity provided.

To reach the suggested intake capacity 100 to 500 feet of intake tunnel might have to be driven inland, at a cost of possibly $10,000 more. Possibly the whole project, without pumping station, would total $125,000

The writer does not pretend to possess knowledge of the marginal values of the continuous saving of 12 M.G.D., the continuous use value of 12 M.G.D., nor the standby value of 30 M.G.D. Data analysed by Cox (1) suggest that, even at a low price for sugar and a medium land value, sugar irrigation water is worth at least $10 a million gallons and under special conditions may be worth much more. It appears very conservative to estimate the ultimate community value of continuous saving of 12 M.G.D. at $50 a day, or $18,000 a year. It is immaterial how the worth is figured, whether for saving or by use; by any method it appears greater than the investment cost of around $5,000 a year for such an installation.

However, such a station cannot be justified economically until the competition of escaping water, which can be had for the cost of pumping, is eliminated, either by legal enactment making such escape the responsibility of the land owner, by need of water that is safe for domestic use, or by sufficient water shortage to force public action toward adequate conser-

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(1) Cox, Joel B., Water and Hawaiian Agriculture, Paradise of the Pacific, April, 1942.

vancy measures. It is hoped that the foregoing suggestion will arouse discussion of feasibility of a combined project at such time as one or another of the above conditions develops.

BENEFITS TO BE DERIVED

The present condition of the Pearl Harbor Springs, speaking collectively is as follows. Owing to the exposure of permeable Koolau rock at ground surface below the level of basal head, large amounts of water emerge freely into the pools and are variously diverted through the existing wet garden systems at successively lower levels and eventually are discharged into the ocean. There is considerable use of such gravity flow water in some of the wet gardens but the over-all conditions and management are such that effective agricultural application accounts for a very low percentage.

In addition to such use in wet gardens, there are some stations at which water coming from large springs is pumped to higher levels for use in sugar cane irrigation or industrially. To such extent as such water is intercepted from entering the ocean, it is used and saved; to such extent as this draft lowers the head in spring pools it may locally reduce hidden leakage. On the other hand, whether it be free flow from the springs or augmented flow by pumpage which still further lowers head, it is removal of basal water under drawdown conditions which favor incursion of salt. Such draft is not in the better interests of long term use of the basin and gives practically no opportunity for effective conservation during times of the day or seasons of the year when water is not needed or the condition of the head is threatening. Such use is comparable to taking a shower bath in a jet from a leaking water main; it may save the water that would so be used at one's home, but it is not a planned procedure and its conservation effects are not evident if the main is the same one that serves the home.

Measurements have indicated that in 1944 about 59 M.G.D. of water escaped from the basal springs with very little use. The proposed construction, undertaken at the sites of the chief springs, is believed susceptible of design such that perhaps as much as 40 M.G.D. net can be brought under control. The successive effects to be achieved are conceived as follows. First, the present night and day uncontrolled leakage would be materially reduced and to considerable extent any remainder could be applied as a part of the amount needed for operation of wet gardens, though this wet garden agriculture is considered not likely to survive as a sound land use in this vicinity. (1) Second, the water saved from leakage, let us say

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(1) Frazier, W. B., Hawaii Agricultural Experiment station, Personal communication.

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40 M.G.D. would be the same as 40 M.G.D. less draft or 40

M.G.D. more infiltration from rainfall. This would tend to raise the general head of the Pearl Harbor area by a certain amount. According to studies of head, draft, and rainfall, made by the writer, the increase in head so caused, under average head and rainfall would be of the order of 3 feet. Such a rise in head would be of material general benefit in improving both quantities and qualities of water at other fixed points in the Pearl Harbor area. However since we suspect that losses to the ocean at unknown points must increase markedly with increased head in this area the most efficient operation as well as increased demand will probably result in draft and utilization of the extra water in the areas near the repaired springs.

This would be accomplished by the construction and operation of development trenches constructed as suggested, or other types of local basal tunnels. It is believed that through the repair measures described, reducing the amount of leakage at points that can be indentified, and by using the development tunnels to take the extra water, the average heads can be kept as low as at present. By the gradual retirement of wells and transfer of draft to a complete installation of basal tunnels including those at the spring sites, the use of all rainwater which is accessible as basal ground water will be brought to a maximum of control and conservation and greater freedom from unpredicted and disastrous shortage.