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A Reevaluation of the Occurrence of Ground Water in the Nahiku Area, East Maui, Hawaii

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By William Meyer

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Conversion Factors

Multiply	By	To obtain
acre	4,047	square meter
foot (ft)	0.3048	meter
foot per foot (ft/ft)	1	meter per meter
foot per day (ft/d)	0.3048	meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
inch (in.)	2.54	centimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
gallons per minute (gal/min)	3.785	liters per minute
million gallons per day (Mgal/d)	0.04381	cubic meters per second

A Reevaluation of the Occurrence of Ground Water in the Nahiku Area, East Maui, Hawaii

By William Meyer

ABSTRACT

The Nahiku area is underlain by lavas of the Honomanu Basalt, Kula Volcanics, and Hana Volcanics. Stearns and Macdonald (H.T. Stearns and G.A. Macdonald, 1942, Geology and ground-water resources of the island of Maui, Hawaii: Hawaii Division of Hydrography Bulletin 7, 344 p., 2 pls.) concluded that the ground-water system in the Nahiku area consists of a succession of perched water bodies in the Kula Volcanics, a perched artesian water body in the upper part of the Honomanu Basalt and a basal water body with water levels 5 to 10 feet above sea level in the Honomanu Basalt. These authors further concluded that streams in the area are perennial in areas where they intersect perched water bodies in the Kula Volcanics, but otherwise either lose water or are intermittent. The artesian water body was believed to be the source of water to Big Spring, the biggest spring on Maui.

Analysis of hydrologic data collected since the work of Stearns and Macdonald and a reevaluation of the data available to them indicates an alternative conclusion for the occurrence of ground water in the area; namely, that the ground-water system in the Nahiku area consists of a vertically extensive ground-water body extending from below sea level into the Hana Volcanics. Given a fully saturated ground-water body, the source of the head in the artesian water body is the water table in the Hana Volcanics. The source of water to Big Spring is a zone of relatively high permeability located, on average, about 220 feet above the artesian water body.

Corroboration for a vertically extensive ground-water body is provided by water-level data collected from 88 test holes drilled as part of a test-drilling program in the Nahiku area during the 1930's and 1940's. These data indicate the presence of a significant amount of freshwater in the Hana Volcanics throughout the area. Stream gaging indicates the presence of perennial streamflow in streams underlain by these rocks. Also, discharge of ground water from springs in the Nahiku area is widespread, relatively large, and perennial in the Hana Volcanics.

The existence of a vertically extensive ground-water body is also confirmed by water levels measured in test holes completed at depths near sea level. Water levels in these test holes range from about 47 feet altitude near the shoreline to about 1,120 feet about 2 miles inland.

Evidence for the zone of high permeability located above the artesian water body is provided by water-level data and directional current-meter data collected in 10 of the test holes.

None of the test holes were dry as would be expected if the Hana Volcanics and the Honomanu Basalt outside of the artesian area and above the assumed basal aquifer were unsaturated. Instead water levels in many of the boreholes remained above the top of the Kula Volcanics as the holes were deepened into the Honomanu Basalt. The presence of water above the top of the Kula Volcanics is inconsistent with the mode of ground-water occurrence discussed by Stearns and Macdonald, but substantiates the concept of a vertically extensive water body extending from below sea level into the Hana Volcanics.

INTRODUCTION

The Nahiku area (fig. 1) is underlain by gently sloping lava beds of the Honomanu Basalt, Kula Volcanics, and Hana Volcanics that emanated from the rift zones of Haleakala, a broad shield-shaped volcanic dome. The ground-water system in these lavas was originally described by Stearns and Macdonald (1942) who concluded that the area is underlain by a succession of perched water bodies in the Kula Volcanics and a perched artesian water body in the upper Honomanu Basalt. Stearns and Macdonald (1942) also concluded that a basal water body in the Honomanu Basalt underlies the entire area. This description is still the most commonly accepted interpretation of the occurrence of ground water in the area. A considerable amount of hydrologic data has been collected in the Nahiku area since the completion of the Stearns and Macdonald report, however, and methods and techniques of evaluating hydrologic data have improved substantially since the early 1940's. The new data and improved methods of analysis, combined with previously available data, lead to an alternative explanation for the occurrence of ground water in the area. Collectively, the information indicates that ground water in the Nahiku area occurs as a single, vertically extensive water body, extending from below sea level to altitudes as high as about 2,100 ft. The water body extends through all three rock units. The existence of this type of ground-water body (outside of a rift zone) has recently been identified in the Lihue area of Kauai (Izuka and Gingerich, 1998), but otherwise has not previously been reported in the State.

Description of the Study Area

The study area is in east Maui, Hawaii, near the town of Nahiku on the coast of the windward (northeastern) side of Haleakala (fig. 1). Maximum altitude of Haleakala is 10,023 ft. Median annual rainfall in the area ranges from a high of about 350 in. at altitudes between 2,000 and 4,000 ft (Giambelluca, 1986) to about 160 in. at the town of Nahiku.

The Nahiku area, as described in this report, encompasses an area centered near Hanawi Stream and extends just beyond Paakea Stream to the west and Kuhiwa Stream to the east (fig. 2). This area is mainly undeveloped forest land that covers a gently sloping land surface (10° to 14°) from Haleakala to the ocean. As stated by Takasaki and Yamanaga (1970), "the gentleness is mainly the result of lava flows which filled deeply eroded canyons and which later veneered most of the mountain." Despite the overall gentleness of slope in the area, the major streams west of Makapipi Stream have deeply eroded canyons and waterfalls, making much of the area relatively inaccessible. Precipitation occurs throughout the year, although extended dry periods of a month or more are common. Ground-water discharge from the area is high. Stearns and Macdonald (1942, p. 256–57, 266–69, and plate 1) describe eight high-altitude springs with an aggregate average daily discharge of 14.26 Mgal/d (see table 1) and 17 high-altitude water-development tunnels constructed for agricultural purposes with an average aggregate discharge of 5.84 Mgal/d. As will be discussed in this report, a considerable amount of ground water also discharges at relatively high altitudes into streams in the area.

An irrigation ditch (Koolau Ditch) begins at East Branch Makapipi Stream and flows westward at an altitude of about 1,250 to 1,300 ft toward central Maui (fig. 1). The principal streams crossed by the Koolau Ditch are perennial, and the ditch intercepts all of the dry weather flow of the streams from Makapipi Stream westward (Takasaki and Yamanaga, 1970, p. 14). Koolau Ditch itself also intercepts ground water.

Background

The general modes of occurrence of ground water in Hawaii have historically been divided into basal and high-level ground-water bodies. Basal ground water is characterized as a lens-shaped water body floating on and displacing saltwater. The altitude of the basal water table has previously been assumed to range from near sea level to a maximum altitude of about 30 ft.

High-level ground-water bodies are found at altitudes greater than that associated with basal ground water. High-level ground-water bodies have been assumed to result from either the impedance of the horizontal movement of ground water by dikes intruded into the lava flows, or from the impedance of the vertical movement of water by stratigraphic layers of low permeability. These low-permeability layers are usually described as ash beds, soil interbedded in lava flows, and as the dense interior of lava flows. Water above these layers is considered perched and the rock immediately below them is considered unsaturated. As commonly accepted, neither type of high-level ground-

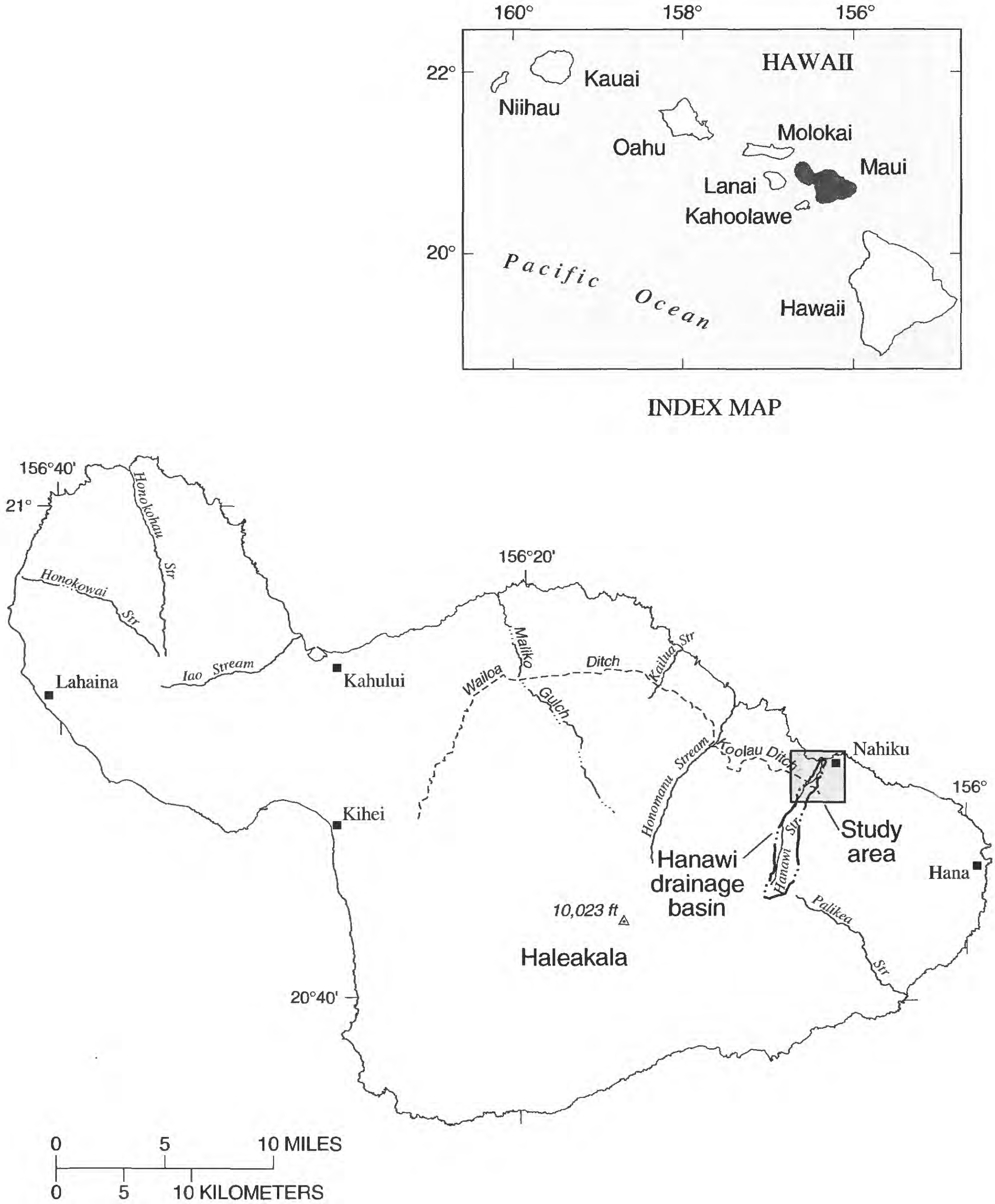


Figure 1. Hawaiian islands, island of Maui, and the study area.

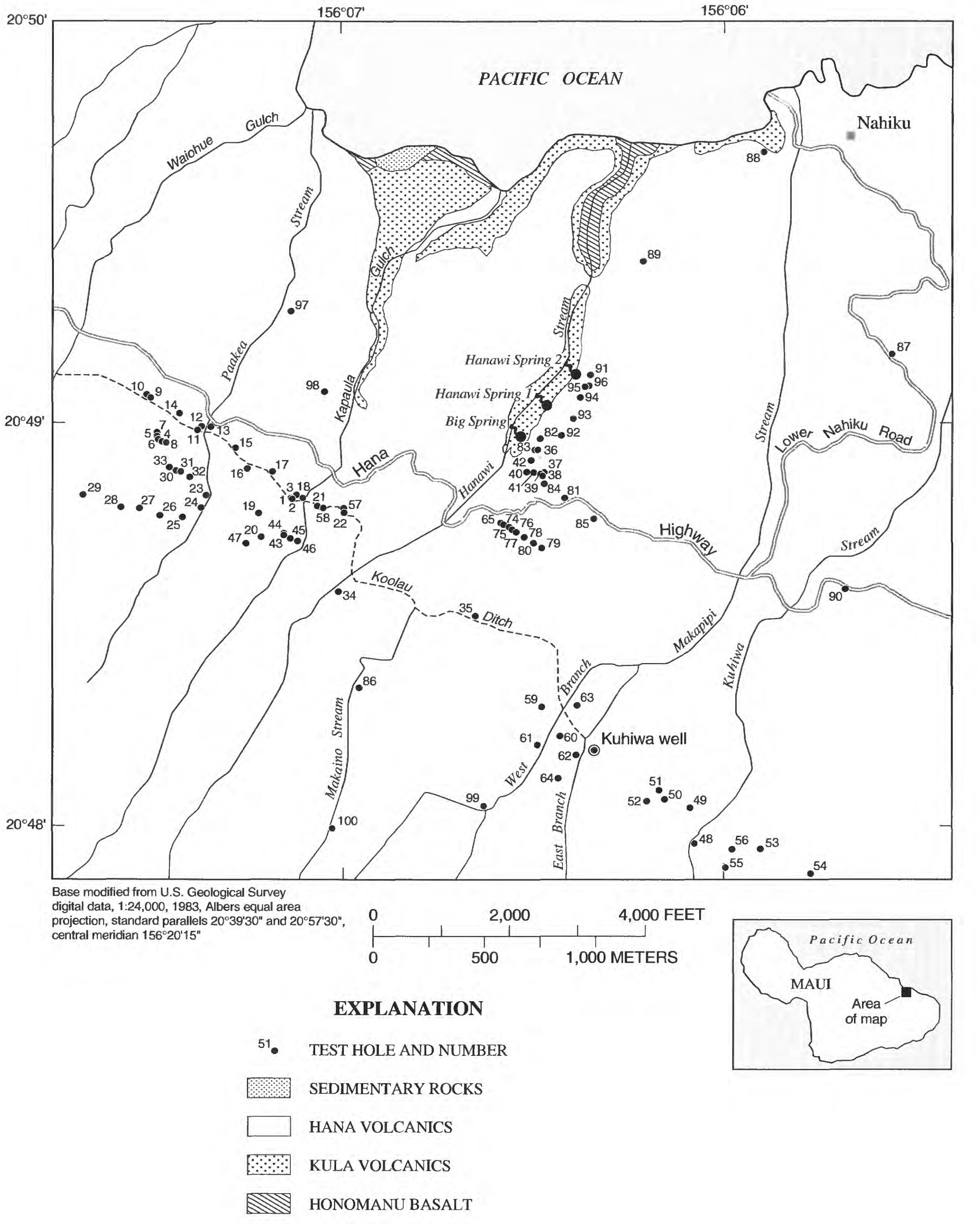


Figure 2. Test holes, Kuhiwa well, and springs, Nahiku area, Maui, Hawaii (geology from Stearns and Macdonald, 1942).

Table 1. Principal springs in the Nahiku area, Maui, Hawaii
[Modified from Stearns and Macdonald, 1942, p. 256; Mgal/d, million gallons per day; --, none]

Spring[1]	Name	Altitude (feet)	Location	Average discharge (Mgal/d)	Geologic unit
22	Ogino	1,237	Paakea Stream, between highway and Koolau Ditch	0.20	Hana Volcanics
23	Pali	950	West Kapaula Stream, near junction with East Kapaula Stream	[2]0.5	Hana Volcanics
24	Silveno	1,171	West Kapaula Stream, 150 ft north of highway	0.18	Hana Volcanics
25	Kapaula	1,113	Kapaula Stream, just below highway	0.44	Hana Volcanics
--	Big Spring	546	Hanawi Gulch, at 546 ft altitude	10.4	Kula Volcanics
--	Hanawi 1	767	East wall of Hanawi Gulch, 2,500 ft northeast of highway bridge	1.17	Hana Volcanics
--	Hanawi 2	660	East wall of Hanawi Gulch, 2,900 ft northeast of highway bridge	0.88	Hana Volcanics
29	West Makapipi	1,185	West Makapipi Stream, 450 ft north of Koolau Ditch	0.49	Hana Volcanics
			Total	14.26	

[1] Stearns and Macdonald, 1942, plate 1

[2] Estimated November 1, 1939

water body is considered to be in contact with saltwater. Water levels in high-level water bodies may be several thousands of feet above sea level. A basal water body is generally considered to exist beneath perched water bodies.

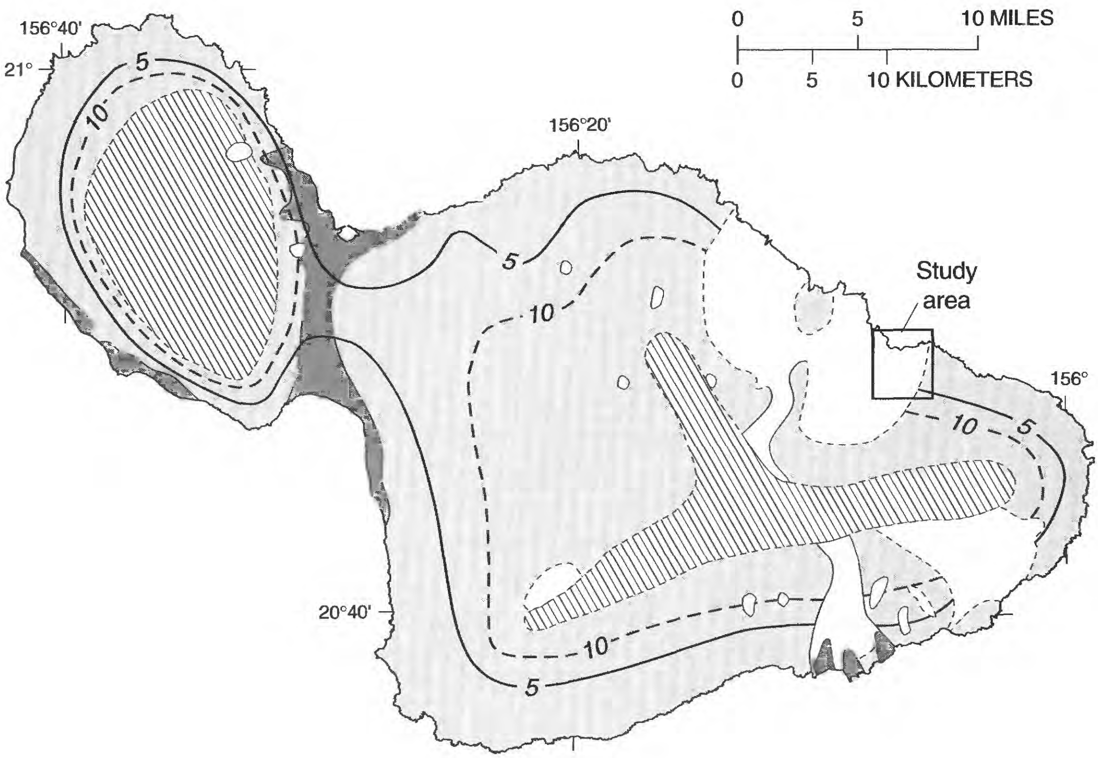
A different mode of occurrence of high-level water on Hawaiian islands has been identified by Izuka and Gingerich (1998). Their work indicates that vertically extensive ground-water bodies can also form in lavas with relatively low values of hydraulic conductivity. The high-level water body described by Izuka and Gingerich (1998) is in direct contact with saltwater.

Stearns and Macdonald (1942, p. 19) described Haleakala as consisting "chiefly of thin-bedded lava flows dipping away from their respective summit vents and rift zones." And because of high rainfall in the Nahiku area, "all of the lavas are to some extent water-bearing, although some carry much more water than others" (Stearns and Macdonald, 1942, p. 255). These authors indicated that a basal water body with water levels 5 to 10 ft above sea level exists in areas of east Maui outside of the rift zones associated with Haleakala, including the Nahiku area (fig. 3). They also indicated that water bodies above the basal water body were perched and that perching structures were "intrusive rocks, ash beds, soil, and alluvium" (Stearns and Macdonald, 1942, p. 132). They described one of the perched water bodies as artesian and recognized that a similar system had not previously been described for any other location in the Hawaiian islands.

Interpretation of the occurrence of ground water by Stearns and Macdonald was, at least in part, based on geologic and water-level data collected during an extensive test-drilling program done in the 1930's and 1940's in the Nahiku area by the East Maui Irrigation Company (EMI) (fig. 2). The purpose of the drilling was to discover the source of the largest spring on Maui, Big Spring (fig. 2), which discharges into Hanawi Stream (Stearns and Macdonald, 1942, p. 225) and to determine the geologic control on the occurrence and movement of ground water in the Nahiku area (Takasaki and Yamanaga, 1970). Big Spring, at an altitude of 546 ft, was reported to have an average daily discharge of about 10.4 Mgal/d (Stearns and Macdonald, 1942, p. 212). The spring discharges from the base of a cliff at an altitude of only a few feet above the base-flow stage of Hanawi Stream. Stearns and Macdonald (1942) concluded that the source of water for Big Spring was the "perched" artesian water body.

A total of 100 test holes were drilled during the EMI test-drilling program, and in 1948 the Kuhiwa well was drilled ending the program (Takasaki and Yamanaga, 1970). Data from the first 86 test holes were available to Stearns and Macdonald. The final 14 holes were completed from 1942 to 1945 after publication of their report. Drilling extended from near Paakea Stream in the west to just past Kuhiwa Stream in the east, a distance of about 2 mi (fig. 2). From north to south, the area of test drilling extended inland from the ocean also for a distance of about 2 mi.

Stearns (in Stearns and Macdonald, 1942, p. 225–226) indicates that between December 1934 and February 1942, the test drilling results provided "excellent records of interbedded soils and perched water tables." Stearns also indicates that artesian water was first encountered in 1941 while drilling test hole 85 and that its discovery came as a surprise to the scientific workers in the area. On the basis of the artesian water



EXPLANATION

BASAL WATER IN LAVAS

BASAL WATER IN SEDIMENTS

WATER CONFINED BY DIKES

WATER PERCHED ABOVE BASAL WATER

— 5 — LINE OF EQUAL BASAL-WATER ALTITUDE
Interval 5 feet. Datum is mean sea level. Dashed where inferred

Figure 3. Ground-water areas on Maui, Hawaii, as defined by Stearns and Macdonald (1942, plate 12).

level in the test hole, and the proximity of the test hole to Big Spring (fig. 2), Stearns concluded (Stearns and Macdonald, 1942, p. 225–226) that the artesian water body was the source of water to Big Spring. As stated by Stearns "In January 1941, while drilling a deep hole (no. 85) to locate supporting members that might perch Big Spring, Mr. Heizer encountered artesian water 395 feet above sea level. The water was directly below the spring [altitude 546] in a permeable basalt between two dense lavas with sufficient head to rise through cracks to supply the spring." As further stated by Stearns (Stearns and Macdonald, 1942, p. 226), "The important lesson gained from the discovery of the source of Big Spring is the addition of the artesian hypothesis to studies of high-level springs issuing from stratified lavas in the Hawaiian islands."

As discussed herein, the artesian water body is not perched, rather it is part of a vertically extensive ground-water body with a water table in the Hana Volcanics. As also discussed, the source of water to Big Spring is not the artesian water body. Instead the source of water to Big Spring is a zone of high permeability located, on average, 220 ft above the artesian water body. Water converges toward the zone of high permeability from a large vertical distance both above and below the zone.

Purpose and Scope

The purpose of this report is to describe the reexamination of the occurrence of ground water in the Nahiku area. The report describes the conceptual framework and evidence for the occurrence of ground water as a series of perched water bodies underlain by a basal water body and it describes the occurrence of ground water as a vertically extensive ground-water body. The general movement of water within the vertically extensive water body and the source of water to Big Spring is also described.

The test holes drilled by EMI still are the only source of data on water levels as functions of depth for the area. Unpublished well logs from all the holes in the test-drilling program are on file at the USGS office in Honolulu. Test holes 87 through 100 penetrated to generally lower altitudes than the first 86 test holes. Even so, information on water levels near or below sea level is available from only five of the test holes and from Kuhiwa well.

Streamflow data is available for Waiaaka, Hanawi, and Makapipi Streams; Paakea and Kapaula Gulches; and for several locations on the Koolau Ditch (see fig. 11). Data for these streams were examined in terms of base-flow and flow-duration characteristics. These data were supplemented with seepage measurements made on Hanawi Stream at selected time periods before and during this study. Ground-water recharge to the Hanawi Stream basin was calculated and evaluated against mean daily base flow estimated from streamflow data at two locations along the stream. The data permit an understanding of the rate of ground-water recharge and general direction of ground-water movement within the basin.

A water budget (Shade, 1999) was calculated for the Hanawi Stream basin as part of this study. This information was used in conjunction with the water levels measured during the test drilling program to calculate a value for the effective vertical hydraulic conductivity of the rocks in the Nahiku area. As part of this study also, Gingerich (1998) utilized the above information and the results of an aquifer test done at Kuhiwa well to construct a numerical ground-water model of the Hanawi Stream basin to investigate the relationship between ground-water levels and the hydraulic properties of the rocks in the basin.

GEOLOGIC SETTING

The lava flows of east Maui have been divided into the Honomanu Basalt, the Kula Volcanics, and the Hana Volcanics (Stearns and Macdonald, 1942; Langenheim and Clague, 1987). The Honomanu Basalt consists of pahoehoe and aa lava flows that range in thickness from 15 to 75 ft, although only a few exceed 40 ft.

The lavas of the Kula Volcanics cover the Honomanu Basalt to a thickness of "2,000 feet thick on the summit and 50 to 200 feet thick at the periphery," (Stearns and Macdonald, 1942, p. 7). Macdonald describes lava flows of the Kula Volcanics as "typically thick, dense, medium to light gray aa, sparingly vesicular to almost nonvesicular, with clinkery base and top and local streaks of clinker within the flow. The basal and upper clinkers are very persistent" (Stearns and Macdonald, 1942, p. 234). Macdonald gives values ranging from 50 to 80 ft for the thickness of individual lava flows within the Kula Volcanics.

Erosion during the final stages of emplacement of the Kula Volcanics formed deep canyons, and changes in sea level left thick alluvial deposits that extend high into the canyons. These deposits were later covered by the Hana Volcanics. The lavas of the Hana Volcanics "followed valleys and swales, chiefly, leaving many of the interstream divides bare" (Stearns and Macdonald, 1942, p. 62). Lavas of the Hana Volcanics range in thickness from about 1 to perhaps 150 ft.

The general features of the geologic setting of the Nahiku area were described by Macdonald (Stearns and Macdonald, 1942, p. 229–233) as follows (the updated geologic names of Langenheim and Clague, 1987, are in brackets):

> The rocks of the Nahiku area are all volcanic, and by far the greater proportion are lava flows. Both aa and pahoehoe lavas are present, and range in composition from picritic basalts through basalts to basaltic andesites. Individual aa flows are generally thicker and in their central parts denser than the pahoehoe flows. Clinker forms moderately persistent layers at the tops and bases of aa flows, and in places forms irregular masses within the flows. Pyroclastic rocks are of little volumetric importance, but many of the intercalated soil layers, which perch ground water at high levels, are tuffaceous, containing fine ash drifted by the wind from fire fountains along the east rift zone. The quantity of ash would be greater were it not that the prevailing northeast winds blew such ash away from the Nahiku area. A single bed of lithic-vitric tuff is exposed in the sea cliff in the upper part of the Honomanu [Basalt].
>
> The geologic history is one of a long succession of lava flows, covering surface drainage systems in various stages of evolution * * *. Many of the buried valleys support subterranean streams which move seaward through fractures and other apertures in the overlying lava. Stearns has divided the lava flows of East Maui into three groups—the Honomanu [Basalt], Kula [Volcanics], and Hana [Volcanics] (Part 1). In the Nahiku area the Honomanu [Basalt] lavas grade in petrographic character into the Kula [Volcanics] lavas, and the line of demarcation has been arbitrarily placed at the top of the transition zone at a surface marked by minor erosion. All the rocks in the Honomanu [Basalt] at Nahiku belong in the transition zone. The stratigraphic succession in the Nahiku area is shown in the table on page 230 [figure 4, this report].
>
> Intrusive rocks.—The only dike found in the area is exposed in the sea cliff 300 feet west of Kapaula Stream. The rock is a basaltic andesite, similar in petrographic character to several flows in the Hana and Kula [Volcanics]. It is dense and nonporphyritic, with prominent platy jointing parallel to the walls. It averages 4 feet thick and is essentially vertical, although in detail its course is somewhat sinuous. It cuts Honomanu Basalts in the lower part of the cliff, and passes upward into Kula lavas, where it is lost under a cover of soil and vegetation. Other dikes may be present, but have not been detected. They are certainly so few in number that they can have no important effect on the movement of ground water.
>
> Geologic structure.—The structure of the area consists essentially of a series of irregular sheet and prisms of lava sloping toward the sea. Folding and important faulting are absent. Minor slickensides are present in several of the cores from the drill holes, but probably do not indicate any great amount of movement. They probably were caused by the slipping of blocks of lava during adjustments accompanying the compaction of the intercalated layers of loosely integrated clinker, caused by the weight of overlying rocks. No other evidence of faulting have been observed.

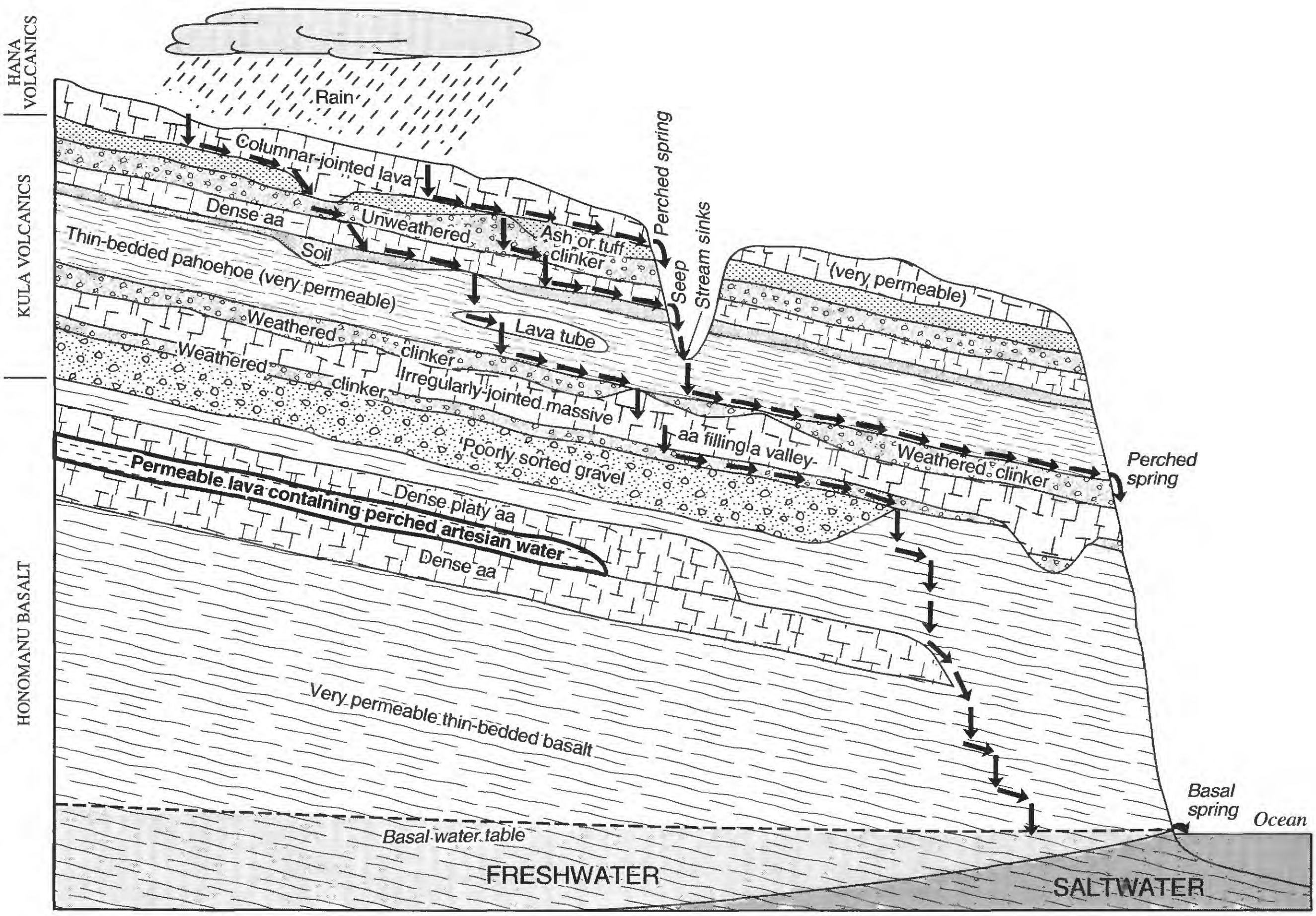
The stratigraphic succession in the Nahiku area is shown in figure 4 (modified from Stearns and Macdonald, 1942, p. 230–31), which also shows the descriptions by Stearns and Macdonald of the water-bearing properties of the various rocks within the stratigraphic columns.

STEARNS AND MACDONALD (1942) CONCEPTUAL FRAMEWORK OF GROUND-WATER OCCURRENCE

The conceptual framework of ground-water occurrence in the Nahiku area presented by Stearns and Macdonald (1942, fig. 13) is shown in figure 5. As shown, relatively small bodies of perched water are present in the Kula Volcanics, but for the most part this rock unit and the underlying Honomanu Basalt are unsaturated. The Hana Volcanics, which overlie the Kula Volcanics, are also assumed to be dry. The general movement of water is down the slope of the perching member and vertical where the perching member terminates. The "perched artesian water body" in the Honomanu Basalt identified by Stearns and Macdonald (1942) is shown in figure 5. The artesian water body is terminated some distance from the ocean by two joined aa lava flows. It is also of limited areal extent. Overlying streams would gain water from perched springs and seeps in and immediately above the Kula Volcanics, but otherwise the streams would lose water.

Major stratigraphic unit (formation)	Minor stratigraphic unit	Water-bearing properties
	Talus, landslide deposits, and beaches	Highly permeable, but of too local extent to have any importance as water bearers. One spring issues from talus, but the water is probably derived from the base of the Kula lavas beneath the covering of talus.
LOCAL EROSIONAL UNCONFORMITY		
Hana Volcanics	Hanawi flow	Its small area makes it unimportant as a water bearer. A few small springs and seeps issue from the base of the flow.
	Paakea flow	Yields water from its basal part in several tunnels; several springs issue from it along Paakea Stream.
	Kuhiwa flow	Yields water copiously in a water tunnel; also yields small amounts of water in two water tunnels and in several small springs along Makapipi Stream.
	LOCAL EROSIONAL UNCONFORMITY	
	Mossman flow	Unimportant as a water bearer, although a number of seeps and small springs emerge from it at various localities, and small amounts of water issue from it in a water tunnel and in the main transportation tunnel of the Koolau Ditch.
	LOCAL EROSIONAL UNCONFORMITY	
	Makaino flow	Yields water copiously in a water tunnel; Hanawi Springs 1 and 2, and other smaller springs also issue from this lava.
	Kapaula flow	Yields water in three water tunnels and a number of small springs issue from it.
	LOCAL EROSIONAL UNCONFORMITY	
	Waiaaka flow	Nearly everywhere carries water, but the amount yielded at any single place is not large.
	LOCAL EROSIONAL UNCONFORMITY	
	Makapipi flows	Unimportant as water bearers, although several small springs and seeps emerge from them.
	LOCAL EROSIONAL UNCONFORMITY	
	Big Falls flows	Several small springs emerge from these lavas in the sea cliff, at Big Falls on Hanawi Stream, and in the plunge pool at the mouth of Makaino Stream.
MAJOR EROSIONAL UNCONFORMITY		
Kula Volcanics		The largest spring in the region, Big Spring on Hanawi Gulch, issues from the clinker phase of a Kula lava, and small springs emerge from Kula lavas at other localities.
Honomanu Basalt		Basal ground water is abundant; artesian water occurs in the upper, transitional lavas.

Figure 4. Stratigraphic units and their water-bearing properties, Nahiku area, Maui, Hawaii (modified from Stearns and Macdonald, 1942, p. 230–231).



EXPLANATION

PERCOLATING WATER

PERCHED WATER

PERCHING STRUCTURES
- Ash or tuff
- Weathered clinker
- Dense aa
- Soil
- Poorly sorted gravel

Figure 5. Diagram illustrating the paths of percolating and perched water in a lava terraine containing various types of interbedded perching structures typical of the Kula Volcanics (rocks are unsaturated in the absence of perched water) (modified from Stearns and Macdonald, 1942, fig. 13).

The conceptual framework of Stearns and Macdonald (1942) is based largely on assumed permeability characteristics for the major rock units. The rocks of the Honomanu Basalt were considered highly permeable as a result of the presence of thin layers of clinker at the top and base of aa flows and the existence of "filled and abundant partly filled lava tubes in the pahoehoe. These openings, together with numerous vesicles and columnar and cross joints, make the rock exceedingly permeable" (Stearns and Macdonald, 1942, p. 234). Stearns and Macdonald (1942, p. 72) report that, with the exception of a few small springs, only basal water had been found in the Honomanu Basalt. However, the existence of only basal water in the Honomanu Basalt is not supported by the data available from the Nahiku area. Presumably, Stearns and Macdonald were referring to other areas in central Maui where such data were available.

The artesian water body that Stearns and Macdonald (1942) identified and assumed to be perched in the Nahiku area is in the Honomanu Basalt, in rocks described as transitional between the Honomanu Basalt and the Kula Volcanics (Stearns and Macdonald, 1942). Takasaki and Yamanaga (1970, p. 30–33), quoting from unpublished reports of D.C. Cox (1946 and 1948), state that the water body was 50 to 200 ft thick and found in two separate areas. These areas, referred to as the 1,100 ft artesian area and the 800 ft artesian area together encompass about 300 acres (fig. 6). The 1,100 ft area is defined by Kuhiwa well, test holes 99 and 100. The 800 ft area is defined by test holes 85, 86, and 96.

Stearns and Macdonald (1942) considered the Kula Volcanics poorly permeable compared with the overlying Hana Volcanics and the underlying Honomanu Basalt although they state that the lavas of the Kula Volcanics are still "very permeable compared with most other rocks in the earth" (Stearns and Macdonald, 1942, p. 85). Big Spring issues from the basal clinker of a lava flow of the Kula Volcanics. Stearns and Macdonald (1942, p. 86), indicated that perched water in the Nahiku area occurs in the Kula Volcanics and results from the presence of "interstratified soils, vitric tuff beds, weathered clinker zones, and wide bands of dense rock" all within the Kula Volcanics. They also concluded that, for the most part, "individual lava beds of the Kula Volcanics are permeable and unable to perch water." Although the lavas of the Kula Volcanics were considered too permeable to perch water, Stearns and Macdonald observed that when viewed as a unit, the Kula "contains enough more or less impermeable layers, even though discontinuous, to retard greatly the downward percolation of water in areas where 100 to 400 inches of rain falls annually [such as in the Nahiku area]. Thus, perennial streams, unusual features outside the dike complexes of the Hawaiian Islands, are found in the Kula rocks" (Stearns and Macdonald, 1942, p. 86). Finally, the assumed high permeability of the rocks of the Honomanu Basalt precluded perched water in these rocks and, with the exception of the perched artesian water body, only basal water is present.

The lavas of the Hana Volcanics were considered highly permeable by Stearns and Macdonald (1942, p. 7) who indicated that the high permeability of the Hana Volcanics and the general lack of interstratified perching beds within them allowed most of the rain to percolate to the Kula Volcanics. They further indicated that high infiltration rates in the Hana Volcanics precluded the presence of perennial streams where streams are underlain by these rocks (Stearns and Macdonald, 1942, p. 102).

Water-level data that would support the conceptual framework in figure 5 would be test holes that were dry in the Hana Volcanics and the Kula Volcanics until a perched water body was penetrated (fig. 7*A*). Once the hole penetrated the perching layer, the only source of water, if any, in the hole would be from cascading water. Otherwise the hole would be dry until another perched water body was penetrated. Cascading water could cause water to be present in a hole but the amount of water would decrease as drilling progressed in the unsaturated rock. The water level would rise one time after the hole penetrated the perched artesian water body, but subsequently the depth of water in the hole would continue to decline and potentially the hole would become dry as the hole was deepened below the artesian zone. Depth to water in the borehole from cascading water would vary, but in general, less water would remain in the hole as a greater distance of permeable unsaturated rock was penetrated. Test holes in the Honomanu Basalt outside of the artesian water body would be expected to be dry or at least contain very little water at altitudes above the basal aquifer. Once the basal water body was penetrated, the water level in the hole would range from 5 to 10 ft above sea level. Presumably, the assumption by Stearns and Macdonald (1942) that basal water exists was based on the presence of springs near sea level, but this is not specifically discussed for the Nahiku area.

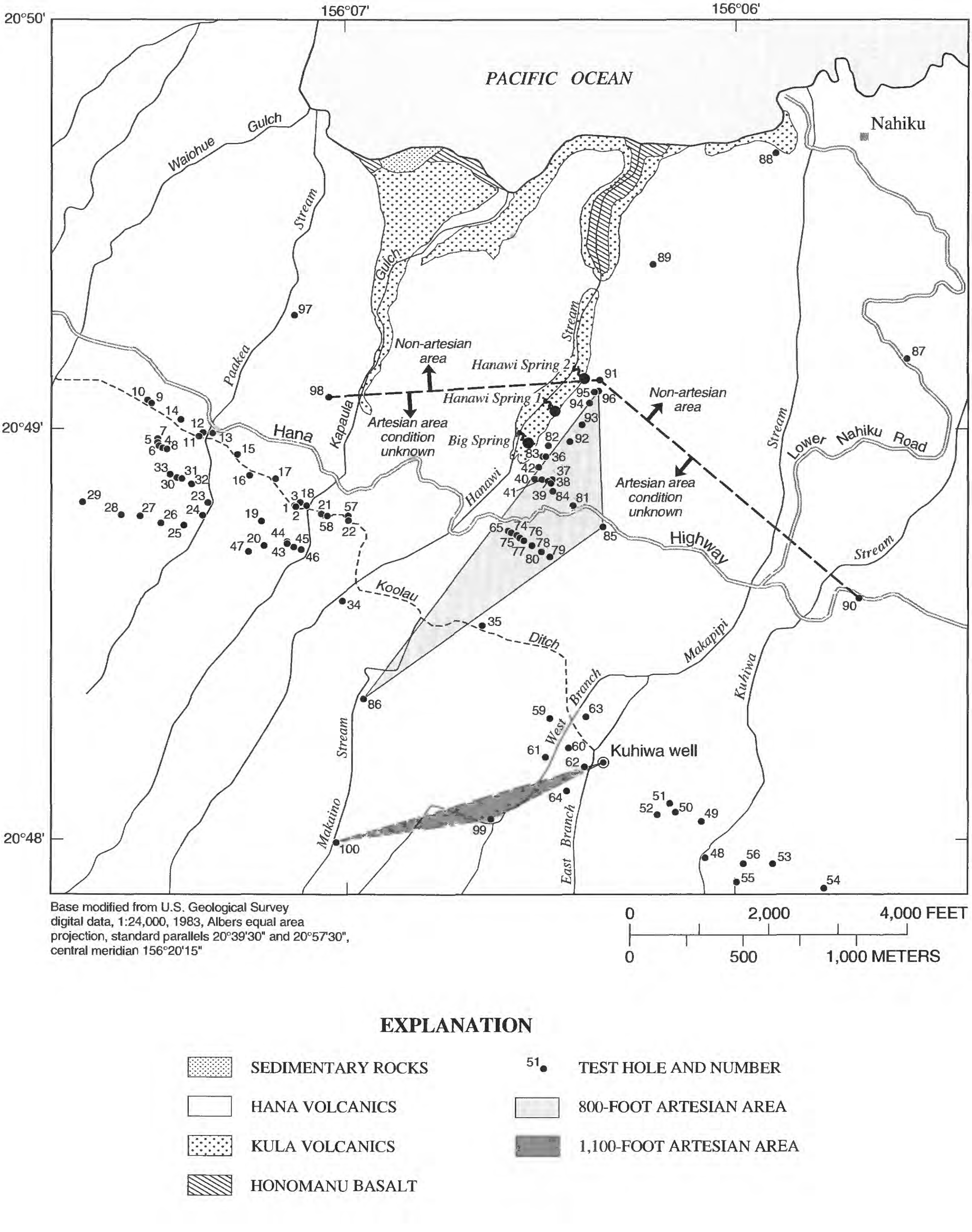


Figure 6. Geology; 1,100-foot and 800-foot artesian areas; and non-artesian areas according to D.C. Cox (*in* Takasaki and Yamanaga, 1970 fig. 9), Nahiku area, Maui, Hawaii.

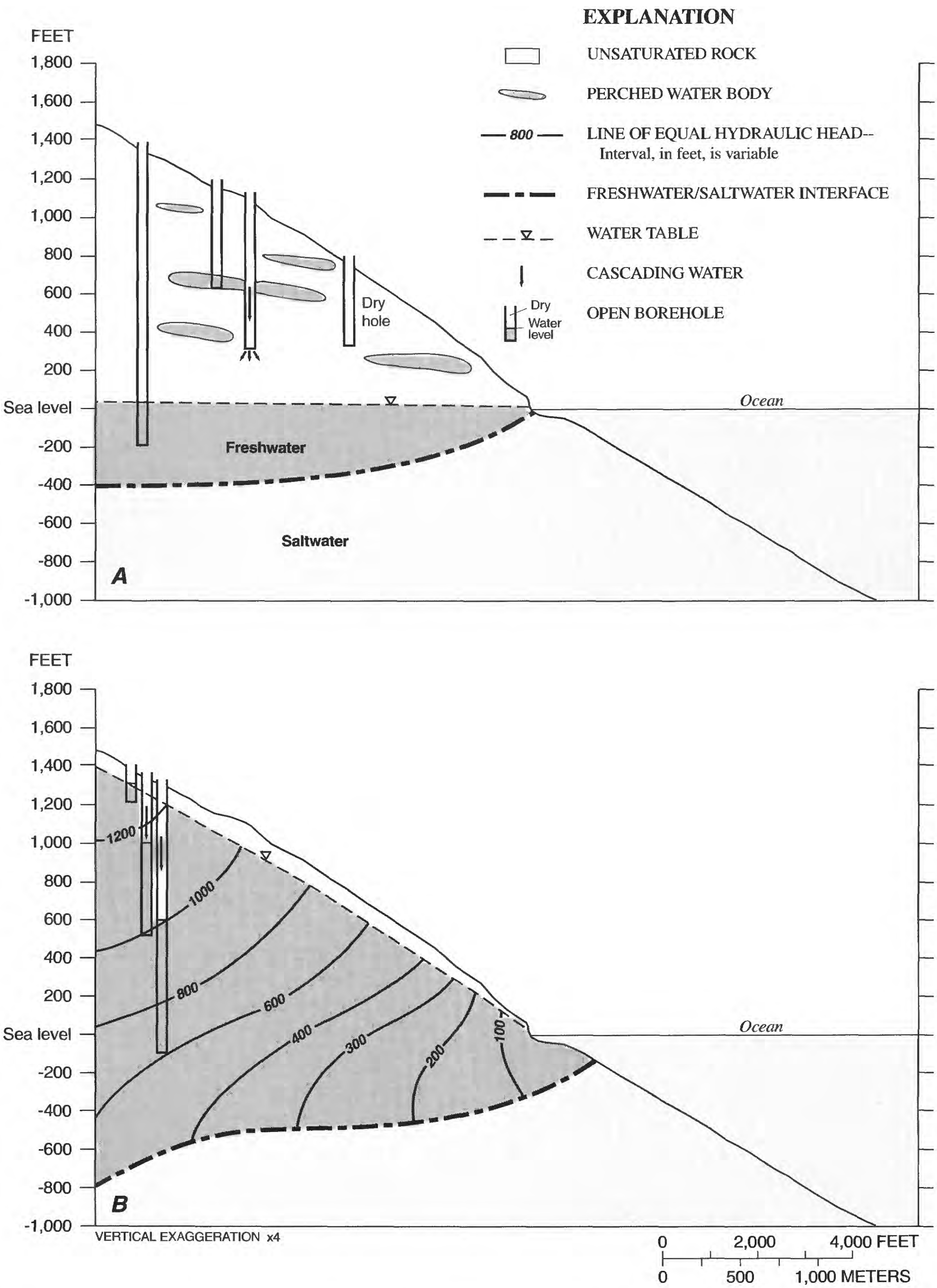


Figure 7. Conceptual section showing water levels in open boreholes (*A*) in an area underlain by perched water bodies and a basal water body, and (*B*) in an area underlain by a vertically extensive water body where hydraulic head declines vertically.

Given the conceptual framework of Stearns and Macdonald (1942), the first water encountered during test drilling, wherein water levels were relatively stable over some depth of the hole, has been interpreted as the first body of perched water underlying the area. Additional deeper bodies of perched water were identified at lower altitudes in test holes where water levels once again stabilized for some unspecified hole length (fig. 8) (Takasaki and Yamanaga, 1970). The water levels illustrated in figure 8 also support the concept of a vertically extensive ground-water body.

CONCEPTUAL FRAMEWORK FOR A VERTICALLY EXTENSIVE GROUND-WATER BODY

Water-level data that would support a vertically extensive water body wherein the general movement of water is toward the ocean and vertically downward is depicted in figure *7B* and discussed below. Once the water table was penetrated in a borehole, water would be continually present as the hole was deepened. In a fully saturated ground-water flow system in which the vertical movement of water is generally downward, the altitude of the water level in the borehole would be expected to decrease as the borehole was deepened, but overall, the amount of water in the hole (defined herein as the height of the water above the bottom of the hole, tables 5 and 6) should increase as the hole is deepened. Given the geologic setting of the Nahiku area, the distribution of hydraulic conductivity would be expected to be inhomogenous and anisotropic. As a result it would be possible for relatively large declines in the altitude of the water level to occur in a given borehole at those horizons where relatively low values of vertical hydraulic conductivity were encountered or at horizons where the horizontal hydraulic conductivity is relatively high. Such declines could be misinterpreted as evidence of perched water.

The conceptual framework of ground-water occurrence in the Nahiku area assuming a vertically extensive ground-water body is shown in figure 9 which depicts ground-water movement along section A-A′ (see fig. 16). As shown, the rocks are saturated from below sea level to an altitude of at least 1,400 ft about 2 mi inland from the ocean. Depth of the water table averages about 50 ft below land surface. On the basis of the water-level data to be discussed herein, the water table is found in the Hana Volcanics where this rock is present. Altitude of the water table ranges from about 47 ft near the ocean to about 1,400 ft 2 mi inland from the shoreline. Streamflow would be perennial where streams intersect the water table and would continue to gain water with decreasing altitude. Springs would occur wherever the land surface intersected permeable sections below the water table.

A principal feature within the section shown in figure 9 is the zone of convergence in which water is moving both downward and upward into the high permeability zone (see fig. 27) that is the source of water to Big Spring (not located in fig. 9). The zone is vertically extensive, averaging about 462 ft. The artesian water body is not depicted in the section in figure 9 but lies immediately below the bottom of the convergence zone. The artesian water body would be indicated by an increase in the altitude of the water level in the test hole once the artesian water body was penetrated (test holes 93 and 99 in fig. 8).

The general movement of water is toward the ocean, streams, and major springs. The vertical movement of water would generally be downward, except in the area underlain by the artesian water body where upward flow from the latter body would occur. Upward flow would also begin at some point near the ocean.

Finally, as stated in the preceding section, Stearns and Macdonald (1942) assumed that the lava flows of the Hana and Kula Volcanics and the Honomanu Basalt were highly permeable in the Nahiku area. This assumption is significant and forms the conceptual basis for the relationship assumed by these authors among geology, ground-water occurrence, and streamflow. Although Stearns and Macdonald (1942) indicated that the volcanic rocks underlying the area are highly permeable, these authors had no quantitative data for the area for this conclusion. As will be discussed, a vertically extensive ground-water body requires that the horizontal hydraulic conductivity of the three rock units be significantly lower in the study area than the values normally assumed for volcanic rocks in the Hawaiian islands.

EVIDENCE FOR THE EXISTENCE OF THE STEARNS AND MACDONALD (1942) CONCEPT OF GROUND-WATER OCCURRENCE

Stearns and Macdonald (1942) did not specifically describe the evidence supporting their conceptual framework of ground-water occurrence in the Nahiku

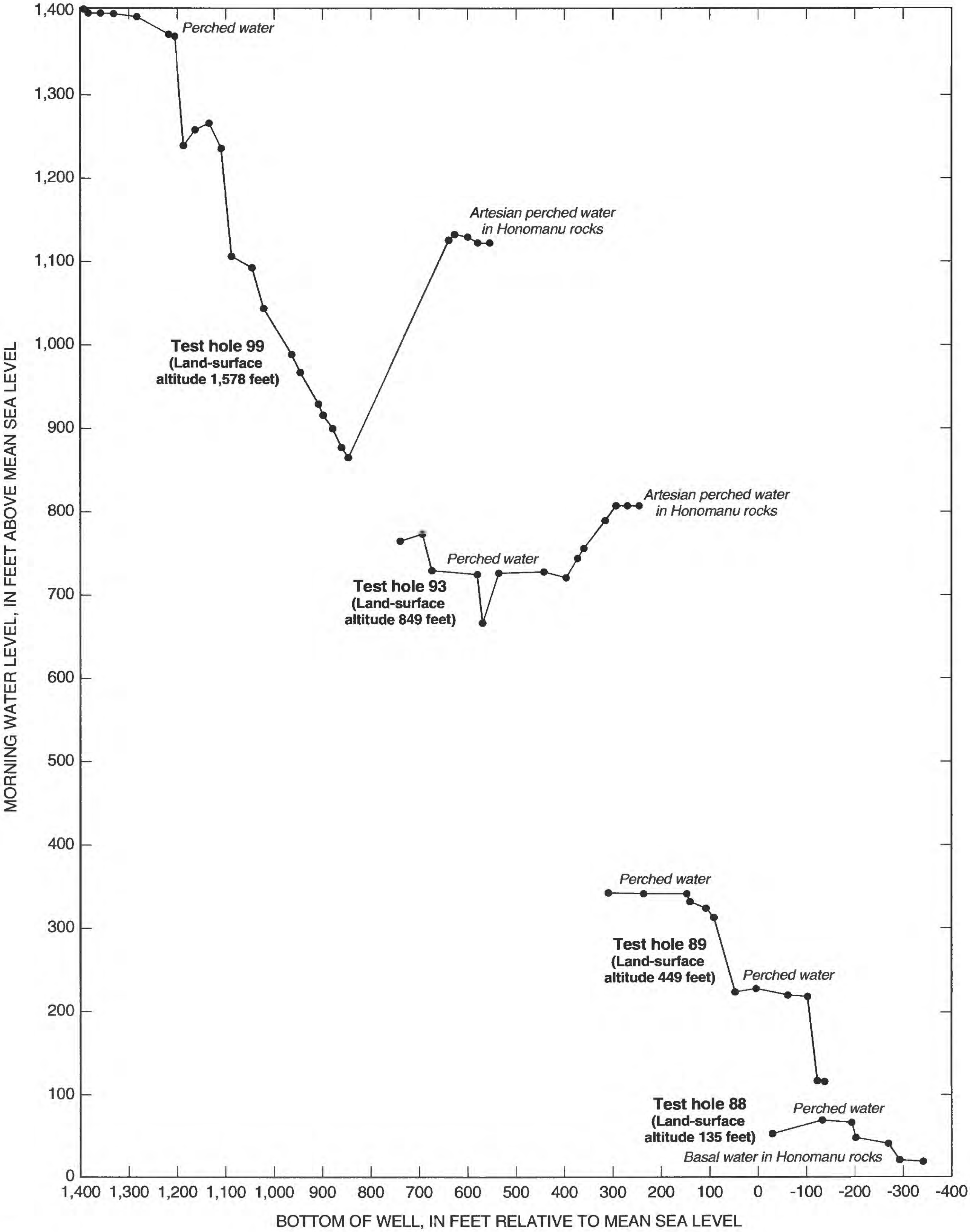
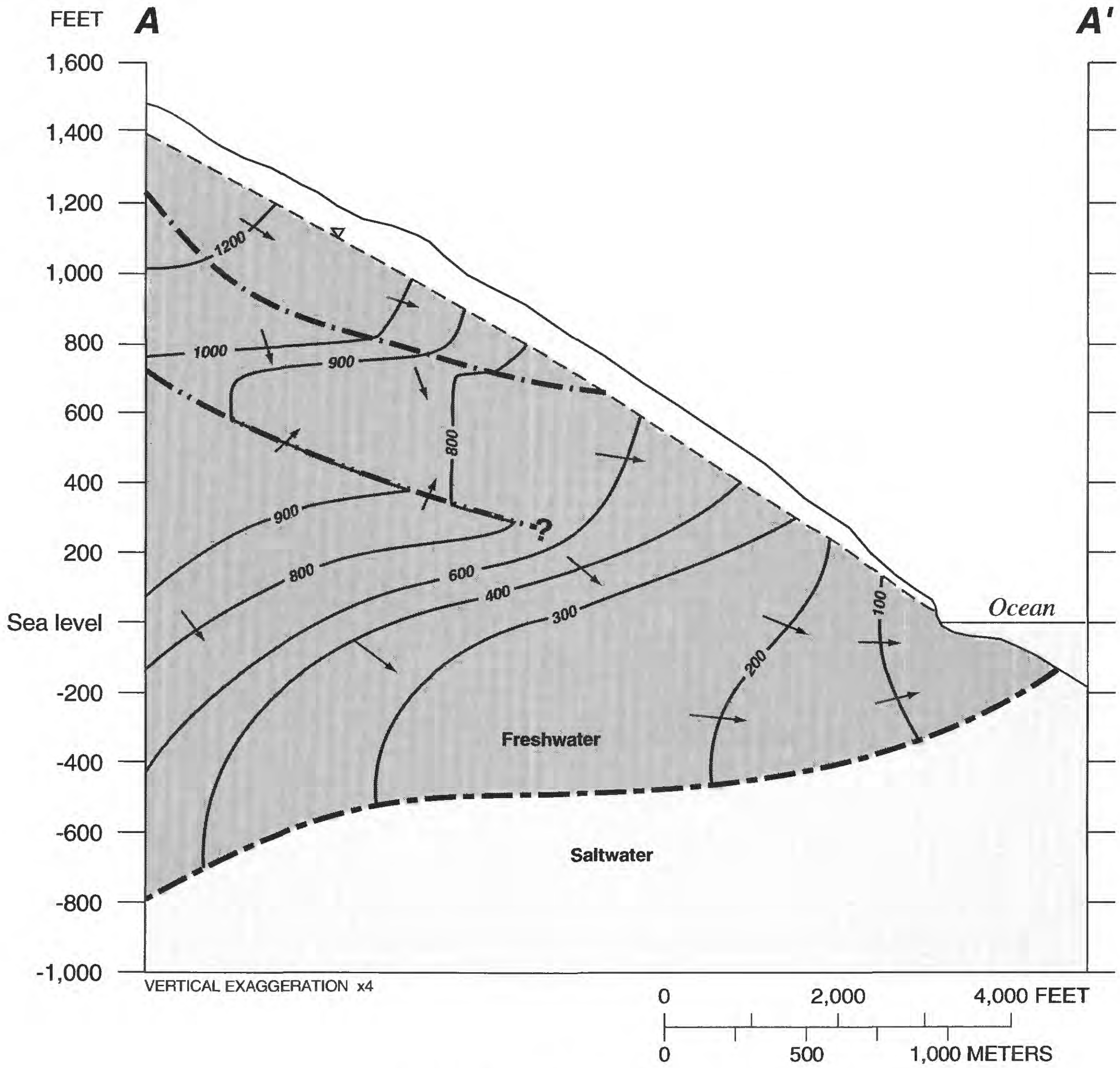


Figure 8. Hydrograph showing water levels of various water bodies during drilling, Nahiku area, Maui, Hawaii (from Takasaki and Yamanaga, 1970).



EXPLANATION

TOP OF CONVERGENCE ZONE

BOTTOM OF CONVERGENCE ZONE

APPROXIMATE POSITION OF FRESHWATER/SALTWATER INTERFACE

WATER TABLE

800 LINE OF EQUAL HYDRAULIC HEAD--
Interval, in feet, is variable.

DIRECTION OF GROUND-WATER MOVEMENT

Figure 9. Generalized section along line *A-A'* (fig. 16) showing ground-water movement within a vertically extensive ground-water body. Vertical head loss based on water-level data at sea level (fig. 20).

area. Peterson (1981), however, states that the major features used to identify perched water bodies in the Hawaiian islands have been high-level springs. Presumably the high-level springs in the Nahiku area (table 1) would have formed some of the basis for Stearns and Macdonald's (1942) conceptual framework. In addition, Stearns and Macdonald had access to the water-level data from the first 86 test holes, and this data indicated that water levels in some of the test holes fell abruptly as they were deepened over a vertical distance of several feet or less, thus suggesting that a "perching layer" had been penetrated. These data, however, are not incompatible with the concept that ground-water occurs as a vertically extensive water body.

EVIDENCE FOR THE EXISTENCE OF A VERTICALLY EXTENSIVE GROUND-WATER BODY

Evidence indicating the existence of a vertically extensive ground-water body is summarized briefly here and is described in detail in the following sections.

An aquifer test in the upper 300 ft of the Honomanu Basalt (131 to 471 ft above sea level) at Kuhiwa well yielded a value for the horizontal hydraulic conductivity of the rock equal to 0.8 ft/d. This value is about three orders of magnitude lower than that normally assumed for the volcanic rocks of the Hawaiian islands. In contrast, Stearns and Macdonald (1942) had assumed highly permeable rocks in the Nahiku area.

In addition, although Stearns and Macdonald (1942) stated that streams overlying the Hana Volcanics are not perennial, the opposite is true. Streams underlain by Hana Volcanics become perennial at altitudes as high as 2,100 ft and continue to gain water from ground-water inflow with decreasing altitude. The existence of water in the Hana Volcanics is consistent with the presence of perennial streams where underlain by Hana Volcanics.

Water-level data obtained during the test-drilling program indicate the presence of a water table in the Hana Volcanics and a significant amount of freshwater in the Hana Volcanics throughout the study area. These results differ significantly with the conclusion of Stearns and Macdonald (1942) that the Hana Volcanics are unsaturated because of the high permeability of the rocks.

Water persisted in the test holes once encountered, and the amount of water tended to increase as each hole was deepened. Twenty-three test holes penetrated into the Honomanu Basalt and five were sufficiently deep to have bottom hole altitudes near to or below sea level. On average, the amount of water at the completed depth of a given hole was 50 percent of the total length of the hole. The depth of the test holes ranged from 441 to 1,132 ft and averaged 718 ft. Water in Kuhiwa well, completed to 9 ft below sea level, stood 1,135 ft above the bottom of the well for a final hole depth of 1,405 ft. Once again, the conceptual model of Stearns and Macdonald (1942) would require that the test holes be dry or nearly so over a significant part of the rock each hole penetrated, and the water in Kuhiwa well would be expected to stand within 5 to 10 ft of sea level.

The water level in many of the test holes remained above the top of the Kula Volcanics as the test holes were deepened through the Kula and remained above the Kula for significant distances into the Honomanu Basalt. However, if the Hana Volcanics were dry, and the Honomanu Basalt were dry outside of the artesian water body and above the assumed basal water body, as assumed by Stearns and Macdonald (1942), water would not be found above the top of the Kula Volcanics. For water levels to be in the Hana Volcanics, either (1) numerous perched water bodies would have to exist throughout the stratigraphic column from the Hana Volcanics to the bottom of the test holes in the Honomanu Basalt, and cascading water into the borehole would maintain a water level above the top of the Kula; or (2) the rocks would have to be saturated from the Hana Volcanics on down. Both of these conclusions present a different conceptual picture of ground-water occurrence than that of Stearns and Macdonald (1942). Given the general lack of interstratified perching beds in the Hana Volcanics and the Honomanu Basalt, the first interpretation is the least likely.

The general vertical movement of ground water in the study area is downward and the average vertical hydraulic gradient associated with this movement is 0.47 ft/ft. Given this rate of head loss, it is not necessary for the water level in the test holes to remain above the top of Kula Volcanics as the test holes were deepened to conclude that the rocks are saturated below the first water encountered in the Hana Volcanics. The Kula Volcanics is relatively thick and an average vertical head loss of 0.47 ft/ft could easily result in the water levels falling below the top of the Kula with depth in many of the test holes even though the rocks are saturated. On the other hand, water level remained above the Kula Volcanics in many of the holes as they were deepened into the Honomanu Basalt. This reinforces a conclusion that the rocks are saturated below a water table in the Hana Volcanics.

Water levels in the five test holes that penetrated to altitudes near to or below sea level did not indicate the existence of a basal water body with water levels between 5 to 10 ft as indicated by Stearns and Macdonald (1942). Rather, water levels ranged from about 47 ft near the shoreline to 1,400 ft 2 mi inland.

Water levels in four of the five test holes described above were higher than the top of the Honomanu Basalt at their bottom hole altitudes near sea level. The water level in one of these test holes was still above the top of the Kula Volcanics. The water level in Kuhiwa well at its final bottom hole altitude of 9 ft below sea level was only 12 ft below the top of the Kula Volcanics. These data are inconsistent with the Stearns and Macdonald (1942) concept that the Honomanu Basalt is unsaturated and support the concept of a vertically extensive ground-water body.

Nine of the 23 test holes that were completed in the Honomanu Basalt were drilled at locations outside of the area of the "perched artesian aquifer" assumed by Stearns and Macdonald to exist in the Honomanu. The water levels in five of these test holes were above the top of the Kula Volcanics at their final bottom hole altitudes that ranged from 190 ft above sea level to 259 ft below sea level. Water levels in 7 of the 9 holes were above the top of the Honomanu Basalt for bottom hole altitudes ranging from 260 to -340 ft. The water level in yet another remained above the top of the Honomanu Basalt to a bottom hole altitude of 99 ft below sea level. These data further reinforce the concept that the rocks of the Kula Volcanics and the Honomanu Basalt are saturated.

Geologic and hydrologic information were reported for 88 of the 100 test holes and water was reported in the each of those 88 holes. The Stearns and Macdonald (1942) concept would require holes completed in each of the three geologic units in the area to be dry.

Hydraulic Conductivity and Ground-Water Levels

In general, volcanic rocks in Hawaii are considered uniformly highly permeable (Peterson, 1981, p. 7). This concept is part of the underlying foundation for the current division of ground water in Hawaii into basal and high-level water bodies. Values for hydraulic conductivity of the unweathered basaltic lava flows that make up the major basal aquifers in the State range from about 1,000 to 5,000 ft/d and average about 2,000 ft/d (Mink and Lau, 1980, p. 7) and this approximate range of values is commonly assumed for all lava flows in the State. As a result, high-level water bodies are believed to form only from the impedance to horizontal ground-water movement by dikes or from the impedance to the vertical movement of ground water by stratigraphic zones of low permeability. In general, the high permeability assumed for the volcanic rocks probably results from the young age of the lava flows and, more importantly, from the thin vertical extent of individual lava flows (Peterson, 1981, p. 7). Average thickness of the permeable flows is less than 10 ft (Mink and Lau, 1980, p. 1).

In contrast, Izuka and Gingerich (1998) indicate that the regional hydraulic conductivity of the Koloa Volcanics in the southern Lihue Basin on the island of Kauai is probably less than 1 ft/d, about 3 orders of magnitude less permeable than the Mink and Lau (1980) average. The combination of low regional hydraulic conductivity and relatively high ground-water recharge results in a vertically extensive ground-water body with the water table reaching altitudes of several hundreds of feet above sea level.

Values of hydraulic conductivity for the underlying volcanic rocks are not known for many areas of the State, either because no tests have been done on existing wells or because no wells exist. Also, in some areas such as east Maui, individual lava flows are much thicker than those associated with the high-permeability flows. The thickness of lava flows in the Honomanu Basalt ranges from 15 to 75 ft, in the Kula Volcanics thickness ranges from 50 to 80 ft, and individual lava flows of the Hana Volcanics range from about 1 to 150 ft.

The only data on the hydraulic conductivity of the rocks in the Nahiku area are from an aquifer test at the Kuhiwa well, which indicated that the horizontal hydraulic conductivity (K_h) of the rocks penetrated by the well is 0.8 ft/d (unpub. aquifer-test archives, U.S. Geological Survey, Honolulu). This value is about three orders of magnitude lower than those values normally associated with Hawaiian basalts and of the same order of magnitude as reported by Izuka and Gingerich (1998) for the Koloa Volcanics in the southern Lihue Basin. As discussed in a later section of this report, the

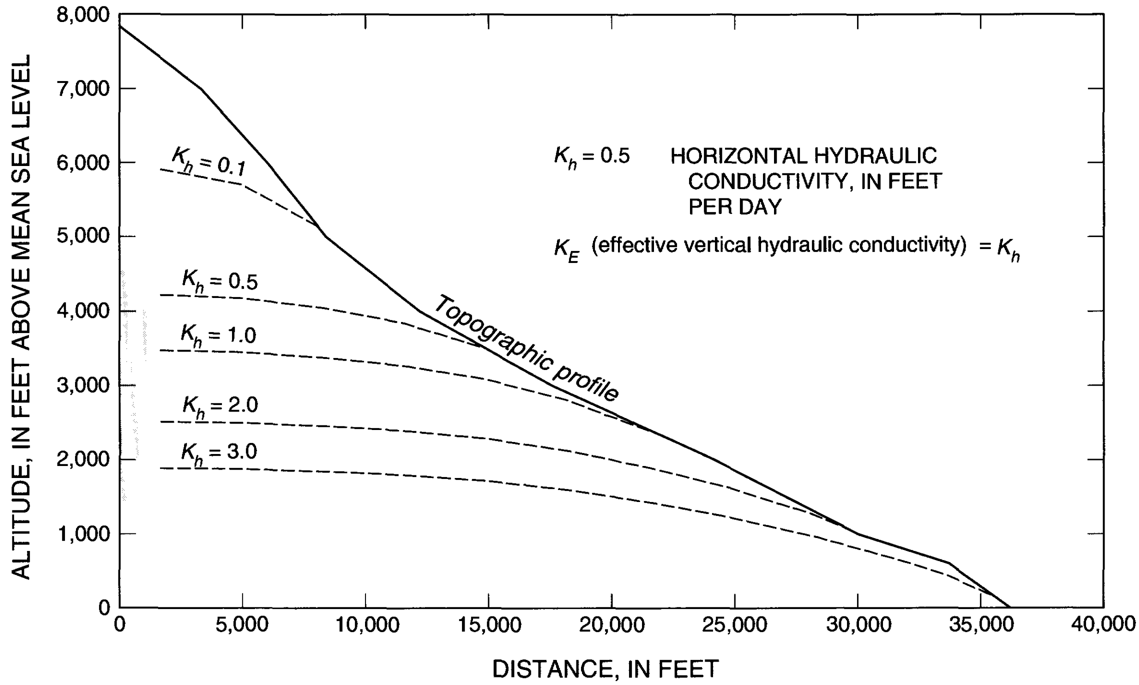


Figure 10. Model-calculated water-table positions for simulations using various values of horizontal hydraulic conductivity in an isotropic aquifer, Nahiku area, Maui, Hawaii. The shaded area represents the range in elevation where water is observed to discharge to the stream (modified from Gingerich, 1998).

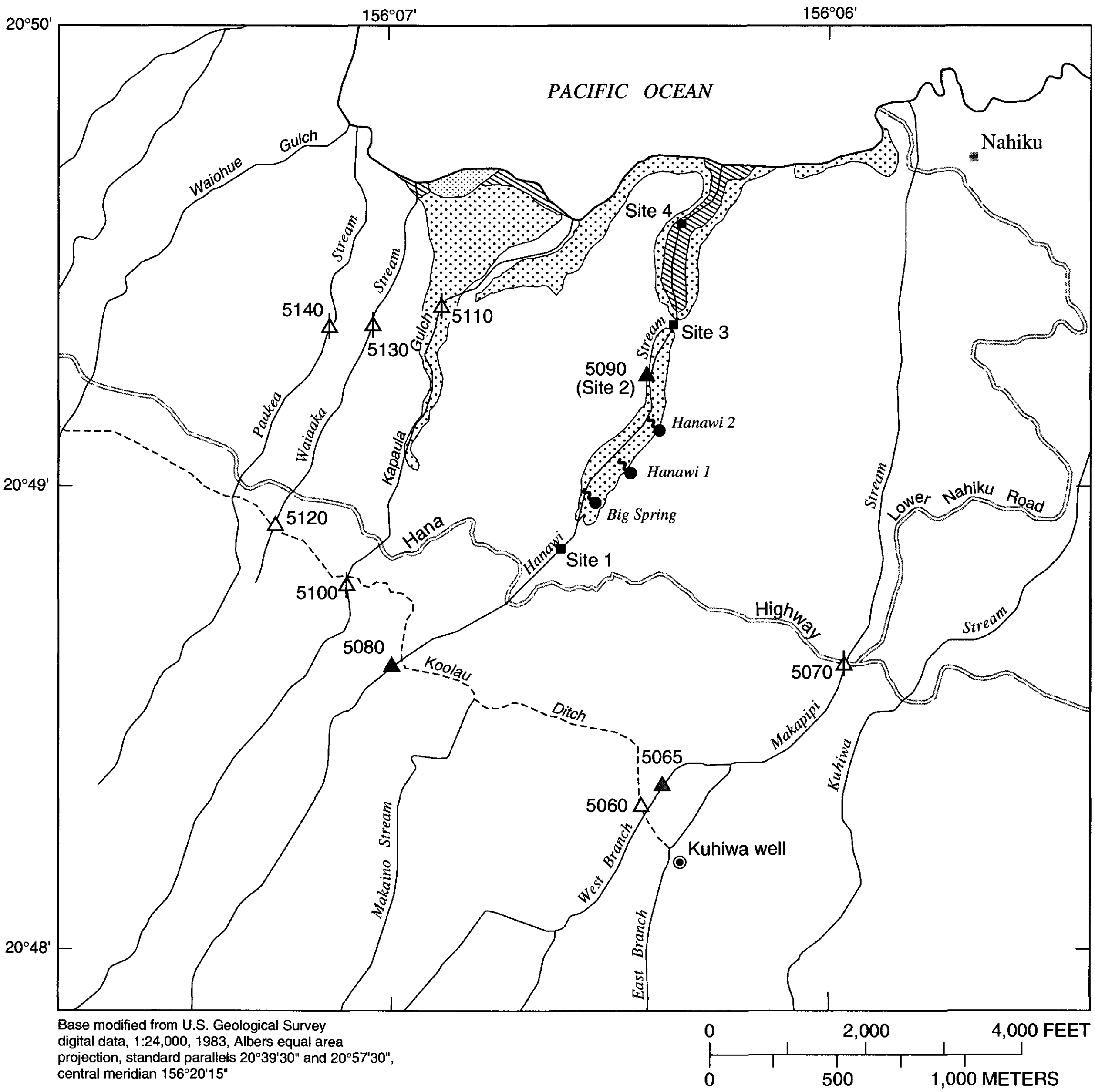
upper bound for the effective vertical hydraulic conductivity (K_E) of the rocks in the Nahiku area is 0.1 ft/d.

Gingerich (1998) constructed a numerical ground-water model of the Hanawi Stream basin to evaluate the relation between the position of the water table in the basin and the values of horizontal and vertical hydraulic conductivity of the aquifer.The model used ground-water recharge rates calculated for the basin as part of this study (Shade, 1999), a range of values for horizontal hydraulic conductivity consistent with the Kuhiwa well aquifer-test results ($0.1 < K_h < 3$ ft/d), and a range of vertical hydraulic conductivity consistent with the calculation of this value discussed herein ($0.005 < K_E < 3.0$ ft/d). The model predicted a range in the altitude of the water table from about 1,000 to 6,000 ft (fig. 10). This result is significant in that it demonstrates that, incorporating data from two independent sources (a water-budget study, and an aquifer test) into a ground-water model that simulates saturated flow, results in model-predicted water levels in the range of those observed in the Nahiku area.

Streamflow Characteristics

Seven stream-gaging stations and two ditch- and one spring-gaging stations have been maintained by the USGS on the major streams between Paakea Gulch and Kuhiwa Stream (fig. 11) for various periods of time since 1923. Data on the altitude, period of record, and type of flow recorded at each of the gaging stations (perennial or intermittent) are given in table 2. As of 1997, only two of these stations (5080 and 5090) were still operated by the USGS, both on Hanawi Stream (fig. 11).

Besides Hanawi Stream, stream gages were located on Kapaula and Paakea Gulches and on Makapipi and Waiaaka Streams. Five of the stations, including one of the two stations presently operating at Hanawi Stream (5090) were below the Koolau Ditch (fig. 11). Altitudes of these five stations ranged from 500 to 920 ft (table 2), although the altitudes of four of the stations were within 500 to 650 ft. The other two stations, including the second stream gage still operating on Hanawi Stream (5080) are above the ditch.



EXPLANATION

SEDIMENTARY ROCKS	5090 ACTIVE STREAM-GAGING STATION AND ABBREVIATED NUMBER	5060 INACTIVE DITCH-GAGING STATION AND ABBREVIATED NUMBER
HANA VOLCANICS	5100 INACTIVE STREAM-GAGING STATION AND ABBREVIATED NUMBER	5065 INACTIVE SPRING-GAGING STATION AND ABBREVIATED NUMBER
KULA VOLCANICS	Site 1 STREAMFLOW MEASUREMENT SITE	
HONOMANU BASALT		

Figure 11. Stream-gaging stations, Nahiku area, Maui, Hawaii.

Table 2. Selected flow characteristics at surface-water gaging stations in the Nahiku area, Maui, Hawaii
[ft, feet; ft^3/s, cubic feet per second; Q50 and Q90, discharge equaled or exceeded 50 or 90 percent of the time]

Gaging station	Name	Altitude (ft)	Q50 (ft^3/s)	Q90 (ft^3/s)	Mean base flow (ft^3/s)	Type of flow	Years operated	Geologic unit
Stream-gaging station								
5070	Makapipi Stream	920	2.40	0.00	3.4	Intermittent	1933–44	Hana Volcanics
5080	Upper Hanawi Stream	1,318	6.97	2.70	6.1	Perennial	1923 to present	Hana Volcanics
5090	Lower Hanawi Stream	500	21.0	16.6	20.1	Perennial	1933–46; 1993 to present	Kula Volcanics
5100	Upper Kapaula Gulch	1,346	5.20	1.50	4.0	Perennial	1923–62	Hana Volcanics
5110	Lower Kapaula Gulch	540	2.40	2.00	2.8	Perennial	1933–46	Kula Volcanics
5130	Waiaaka Stream	650	0.82	0.57	0.8	Perennial	1933–46	Hana Volcanics
5140	Paakea Gulch	650	3.8	3.0	3.9	Perennial	1933–46	Hana Volcanics
Ditch- and spring-gaging station								
5060	Koolau Ditch	1,300	3.80	1.70	3.6	Perennial	1949–65	Hana Volcanics
5065	West Makapipi Spring	1,150	0.79	0.00	1.0	Intermittent	1933–35; 1937–43	Hana Volcanics
5120	Koolau Ditch	1,289	28.5	10.6	23.3	Perennial	1919–85	Hana Volcanics

Altitude of the gage currently operating on Hanawi Stream above Koolau Ditch is 1,318 ft. The second gaging station (5100) above the ditch was on Kapaula Gulch. Altitude of this gage was 1,346 ft. Five of the stations were on Hana Volcanics and the other two stations were on Kula Volcanics (fig. 11 and table 2).

Discharge measurements in the Koolau Ditch were made at gaging station 5120 from 1919 through 1985 and at station 5060 from 1949 through 1965 (fig. 11 and table 2). The ditch is in Hana Volcanics within the study area. Discharge also was measured at West Makapipi Spring (5065) from 1933 through 1935 and from 1937 through 1943. Flow from this spring is diverted into Koolau Ditch.

Flow-duration curves indicate that discharge at all of the stream-gaging stations was perennial with the exception of station 5070 on Makapipi Stream (fig. 12). Streamflow at this station was intermittent, although during some years, flow was continuous. Discharge in the Koolau Ditch at station 5120 underwent several periods of zero flow, which probably resulted from the diversion of water from the ditch for construction or repair purposes (Garrett Hew, East Maui Irrigation Company, oral commun., 1996); otherwise, discharge was continuous. Streamflow was perennial at the gaging stations on Hanawi Stream and Kapaula Gulch. Streamflow also was perennial at the gaging stations below Koolau Ditch on Waiaaka Stream and Paakea Gulch. Discharge at West Makapipi Spring was intermittent, although during some years discharge was continuous.

Because Koolau Ditch diverts all of the base flow of the streams above it, perennial streamflow at gages below the ditch indicates that ground water discharges continuously at one or more locations between the ditch and the gage at each stream. Perennial streamflow at the gages above the ditch also indicates that ground water is discharging continuously at altitudes above these gages and at the ditch as well. Although rainfall is substantial above the ditch and the gages, drought can cause extended periods during which the streams and ditch would not flow without ground-water discharge.

The base-flow hydrograph for each gaging station was estimated using procedures proposed by the Institute of Hydrology (1980a, b), and although these procedures may not yield the true base flow, the subjectivity in manual methods is overcome and the results are indicative of the base flow (Wahl and Wahl, 1988). These hydrographs were used to calculate the mean base flow at each gage over their respective periods of record (table 2).

The cumulative mean annual discharge of ground water (base flow) at all the gaging stations is 54.3 ft^3/s (35.1 Mgal/d). This value includes an estimated value for mean annual ground-water discharge of 8.6 ft^3/s into the Koolau Ditch above gage 5120, which is obtained by subtracting mean annual

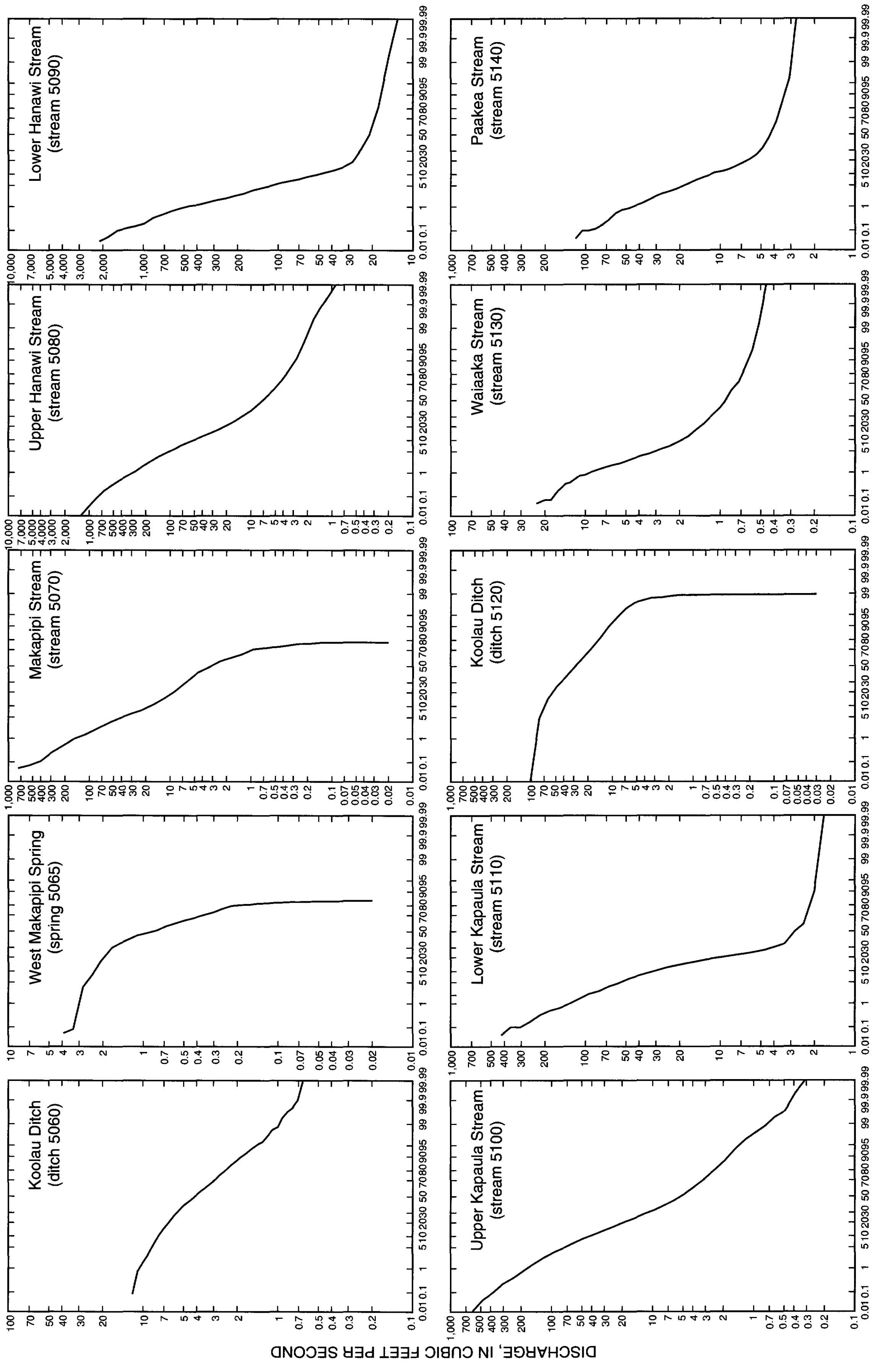


Figure 12. Flow-duration curves of daily flows for selected streams, Koolau Ditch, and West Makapipi Spring, Nahiku area, Maui, Hawaii.

ground-water discharge at upstream gages 5060, 5065, 5080, and 5100 from the mean annual ground-water discharge reported for 5120 in table 2. The cumulative mean annual discharge of ground-water from the Hana Volcanics is 31.4 ft^3/s. Given that the mean annual discharge for these gages was estimated for different periods, some error is possible in the estimates of mean annual ground-water discharge at any location.

Ground-water discharge into Hanawi Stream below the ditch has been investigated by measuring instantaneous stream discharge simultaneously at selected sites. Simultaneous measurements were made at three locations below the Hana Highway at Hanawi Stream (sites 2, 3, and 4) on October 9, 1974 (fig. 11 and table 3). Measurements were repeated at these sites and one other site (site 1, fig. 11) during May 21–22, 1975 (U.S. Geological Survey, 1976). These measurements were made at a time when discharge at site 2 (station 5090) was below the discharge value equalled or exceeded 90 percent of the time (16.6 ft^3/s, table 2), and below the value calculated for mean ground-water discharge.

The data in table 3 show that below Hana highway streamflow increased with decreasing altitude as a result of ground-water discharge into Hanawi Stream. About 15.4 ft^3/s entered the stream between sites 1 and 2. Big Spring and Hanawi 1 and 2 springs would have accounted for much, but not all of this discharge. The stream continues to gain from ground-water discharge below site 2. Flow of 3 to 4 ft^3/s was gained between sites 2 and 3, and 1 to 3 ft^3/s was gained between sites 3 and 4. Total gain in streamflow from site 1 to site 4 for May 21–22, 1975 was 21.44 ft^3/s. Because, as indicated by streamflow data at site 2, the seepage measurements were made at streamflow conditions during below-average ground-water discharge, the mean gain in streamflow from ground-water discharge between sites 1 and 4 would be somewhat greater than the rates estimated from the May 21–22, 1975 seepage run.

Hanawi Stream flows over Kula Volcanics for most of the reach between sites 1 and 3 (fig. 11). The stream flows over Hana and Kula Volcanics and Honomanu Basalt between sites 3 and 4, with the Honomanu Basalt being the predominant rock type. Big Spring issues from a basal clinker zone in the Kula Volcanics and Hanawi 1 and 2 springs issue from a lava flow in the Hana Volcanics (Stearns and Macdonald, 1942).

Seepage measurements on Hanawi Stream during July 26–28, 1994 indicated that ground-water discharge into the stream began at an altitude of about

Table 3. Discharge at selected sites on Hanawi Stream, Maui, Hawaii

[ft, feet; ft^3/s, cubic feet per second; mi, mile; --, not measured. Datum from U.S. Geological Survey (1976)]

Site (fig. 5)	Measured previously (water years)	Measurements: Date	Measurements: Discharge (ft^3/s)	Geologic unit
1	--	5/21/75	0.56	Hana Volcanics
2	1927–32	10/9/74	14	Kula Volcanics
	1932–47	5/22/75	16	
3	--	10/9/74	18	Hana Volcanics
		5/22/75	19	
4	--	10/9/74	19	Honomanu Basalt
		5/21/75	22	

2,120 ft (R.A. Fontaine, U.S. Geological Survey, unpub. data, 1994). Flow below this altitude was continuous. At altitudes higher than this, several locations were found where ground water was discharging into the stream, but the discharge was small and the stream remained dry below these locations. These measurements were made following a period of dry weather when the source of water in the Hanawi Stream was ground water. The altitude at which ground-water discharge into the stream begins would be expected to vary seasonally.

In summary, because the lower gage on Hanawi Stream (5090) and the lower gage on Kapaula Gulch (5110) are on Kula Volcanics (fig. 11), perennial streamflow at these gages would be expected from either a perched or vertically extensive ground-water body. All of the other gages, however, are on Hana Volcanics (fig. 11). Perennial streamflow at these stations (excluding 5070) is not consistent with the conceptual model of the ground-water flow system of Stearns and Macdonald (1942) but is consistent with the vertically extensive ground-water flow system concept.

The relatively high and perennial spring discharge at Hanawi 1 and 2 and the discharge of ground water into Koolau Ditch (all of which are on Hana Volcanics) are also inconsistent with a conceptual model that the Hana Volcanics is dry. Also inconsistent with the Stearns and Macdonald concept is the fact that Hanawi Stream becomes perennial at an altitude of 2,120 ft. This area also is immediately underlain by Hana Volcanics.

Water Levels in the Hana Volcanics

The study area is, for the most part, immediately underlain by Hana Volcanics (fig. 2). Sixty-six of the first 86 test holes were completed in the Hana Volcanics, although two of these holes (test holes 12 and 85) were later deepened into the Honomanu Basalt.

Water-level data were collected in 88 of the 100 test holes drilled in the Nahiku area although the procedures for obtaining water-level measurements were not consistent. In nearly all of the deeper holes, water-level measurements were recorded each day as drilling progressed, while in some of the shallower holes water levels were reported only once for a single hole depth.

For the most part, water-level measurements were made through the center of the drill rod after the drill string was lowered to the bottom of the hole. The core bit usually was at the bottom of the hole or within a foot or so of the bottom when the water level was measured. Water levels so obtained should not be considered representative of the composite water level in the borehole assuming an open hole. Rather, as discussed in appendix A, the water level is probably an approximate measure of the composite head in the borehole for the interval below the drill rod, which in most cases would be the head at the bottom of the hole on the morning the measurement was made. Available data indicate that the composite water level for the entire borehole was actually higher than that recorded with the drill rod with the bit at the bottom of the hole. General considerations in the use of the water-level data are discussed in appendix B.

Altitude and depth of the test holes, the geologic unit in which each hole was completed, and the altitude at which water was first reported are shown in table 4. Most of the test holes were relatively shallow. Land-surface altitude of the test holes ranged from 1,845 to 135 ft. Altitude of the bottom of the holes ranged from 1,409 ft above sea level to 340 ft below sea level. The altitude of the first water level reported during drilling ranged from 1,468 to 47 ft.

The majority of the test holes completed in the Hana Volcanics were located above the Hana highway, in an area extending from west of Paakea Stream to east of Kuhiwa Stream (fig. 2). The average depth of these holes was about 70 ft, with the actual depths ranging from 10 to 204 ft. Ground-surface altitude of the test holes completed in the Hana Volcanics ranged from 965 to 1,553 ft. Water-level data were reported for 43 of these holes, although for some, water level was reported only once during drilling. Depth below land surface to the first water reported ranged from 3 to 193 ft and averaged 46 ft.

Data from test holes completed in the Hana Volcanics for which more than one water level was reported indicate that, once encountered, water remained in the holes and the amount of water in the hole generally increased as the hole was deepened (fig. 13). In general, 50 ft or more of water was in the test holes at hole depths of about 100 ft in the Hana Volcanics. This is consistent with the vertically extensive flow system concept and inconsistent with the perched ground-water flow concept.

Water-level data from test holes that penetrated the Kula Volcanics or the Honomanu Basalt indicate the presence of a significant amount of freshwater in the Hana Volcanics throughout the study area because water levels in the test holes remained above the top of the Kula Volcanics for initial hole depths into the Kula (fig. 14). In general the height of the water level in the holes above the top of the Kula Volcanics for initial depths in the Kula ranged from 50 to 150 ft (fig. 15).

The configuration of the first water encountered in the Hana Volcanics is shown in figure 16. These water levels are assumed to represent the water table in the study area. The general slope of the water table is about 16 degrees toward the ocean. Altitude of the water table ranges from about 1,400 ft at the inland extent of the test drilling to about 47 ft near the shoreline at test hole 88. Ground water also discharges into the major streams, but detailed ground-water levels are not available to show this.

The test holes in the Nahiku area were drilled over a number of years and, as a result, there is the potential for error in the contour map. However, given that seasonal changes in water levels are probably not more than ten or several tens of feet, and that the area, with the exception of the ditch, is essentially unaffected by human development, the general characteristics of the movement of ground water indicated by the water levels in figure 16 should be accurate.

Ground-Water Level as a Function of Test-Hole Depth

Profiles of water levels compared with depth for the 23 test holes that penetrated the Honomanu Basalt indicate that, overall, water levels fell as the holes were deepened (fig. 17 and table 5, at end of report). These test holes (12, 62, 65, 74, 81, 82, 83, 84, 85, 86, 87, 88,

Table 4. Altitude, depth, and first reported water levels in test holes and Kuhiwa well in the Nahiku area, Maui, Hawaii
[--, not measured or not applicable; datum is mean sea level. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Test hole or well	Altitude		First reported water level			Geologic unit in which completed
	Top (feet)	Bottom (feet)	Hole depth (feet)	Depth to water (feet)	Water-level altitude (feet)	
1	--	--	--	--	--	--
1	--	--	--	--	--	--
1	--	--	--	--	--	--
1	--	--	--	--	--	--
1	--	--	--	--	--	--
1	--	--	--	--	--	--
1	--	--	--	--	--	--
1	1,325	1,259	26	10	1,315	Hana Volcanics
1	--	--	37	15	--	--
1	1,286	1,230	--	53	1,233	Hana Volcanics
1	1,286	1,192	55	24	1,262	Hana Volcanics
1	1,282	345	38	35	1,247	Honomanu Basalt
1	1,285	1,166	51	37	1,248	Hana Volcanics
1	1,241	1,213	14	5	1,236	Hana Volcanics
1	1,285	1,192	10	9	1,276	Hana Volcanics
1	1,291	1,228	27	22	1,269	Hana Volcanics
1	1,290	1,213	32	15	1,275	Hana Volcanics
1	1,293	1,128	149	83	1,210	Hana Volcanics
1	1,384	1,257	102	81	1,303	Hana Volcanics
1	1,409	1,265	50	5	1,404	Hana Volcanics
1	1,293	1,176	37	20	1,273	Hana Volcanics
1	1,295	1,166	50	38	1,257	Hana Volcanics
1	1,382	1,259	80	39	1,343	Hana Volcanics
1	1,411	1,241	20	10	1,401	Hana Volcanics
1	1,456	1,345	--	--	--	Hana Volcanics
1	1,478	1,376	102	26	1,452	Hana Volcanics
1	1,477	1,394	50	13	1,464	Hana Volcanics
1	1,500	1,409	55	32	1,468	Hana Volcanics
1	--	--	74	19	--	--
1	1,375	1,248	14	13	1,362	Hana Volcanics
1	1,375	1,305	34	28	1,347	Hana Volcanics
1	1,368	1,295	54	18	1,350	Hana Volcanics
1	1,381	1,296	20	3	1,378	Hana Volcanics
1	1,332	1,222	52	23	1,309	Kula Volcanics
1	1,293	1,070	55	36	1,257	Kula Volcanics
1	943	574	--	--	--	Kula Volcanics
1	966	820	98	62	904	Hana Volcanics
1	967	838	62	51	916	Hana Volcanics
1	965	895	12	6	959	Hana Volcanics
1	970	552	49	44	926	Honomanu Basalt
1	969	791	89	68	901	Kula Volcanics
1	960	773	59	52	908	Kula Volcanics
1	--	--	27	13	--	--
1	1,404	1,297	--	--	--	Hana Volcanics
1	1,398?	1,385?	--	--	--	--
1	1,395?	1,258	21	4	--	Hana Volcanics
1	1,455	1,298	67	11	1,444	Hana Volcanics
1	1,500	1,309	166	108	1,392	Hana Volcanics
1	1,484	1,297	180	164	1,320	Hana Volcanics
1	1,468	1,331	104	100	1,368	Hana Volcanics
1	1,453	1,318	77	62	1,391	Hana Volcanics
1	1,521	1,347	156	154	1,367	Hana Volcanics

Table 4. Altitude, depth, and first reported water levels in test holes and Kuhiwa well in the Nahiku area, Maui, Hawaii--Continued
[--, not measured or not applicable; datum is mean sea level. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Test hole or well	Altitude: Top (feet)	Altitude: Bottom (feet)	First reported water level: Hole depth (feet)	First reported water level: Depth to water (feet)	First reported water level: Water-level altitude (feet)	Geologic unit in which completed
1	1,472	1,316	145	136	1,336	Hana Volcanics
1	1,483	1,253	204	193	1,290	Hana Volcanics
1	1,553	1,332	148	138	1,415	Hana Volcanics
1	1,470	1,338	126	123	1,347	Hana Volcanics
1	1,295	1,166	50	43	1,252	Hana Volcanics
1	1,294	1,179	51	45	1,249	Hana Volcanics
1	1,388	1,166	57	34	1,354	Hana Volcanics
1	1,403	1,180	46	35	1,368	Kula Volcanics
1	1,454	1,179	35	23	1,431	Hana Volcanics
1	1,395	380	60	37	1,358	Honomanu Basalt
1	1,329	1,144	42	39	1,290	Hana Volcanics
1	1,470	844	55	50	1,420	Kula Volcanics
1	1,066	425	18	15	1,051	Honomanu Basalt
1	above Waiaka tunnel		52	40	--	--
1	above Waiaka tunnel		46	36	--	--
1	above Waiaka tunnel		76	70	--	--
1	above Waiaka tunnel		41	31	--	--
1	above Waiaka tunnel		30	22	--	--
1	above Waiaka tunnel		32	29	--	--
1	above Waiaka tunnel		47	44	--	--
1	above Waiaka tunnel		--	--	--	--
1	1,072	440	131	83	989	Honomanu Basalt
1	1,073	823	54	38	1,035	Hana Volcanics
1	1,076	860	73	29	1,047	Hana Volcanics
1	1,089	809	83	35	1,054	Kula Volcanics
1	1,107	807	55	46	1,061	Kula Volcanics
1	1,124	824	122	65	1,059	Kula Volcanics
1	1,103	830	72	43	1,060	Kula Volcanics
1	984	463	177	10	974	Honomanu Basalt
1	924	446	71	61	863	Honomanu Basalt
1	945	155	170	106	839	Honomanu Basalt
1	977	536	65	36	941	Honomanu Basalt
1	1,003	12	45	44	959	Honomanu Basalt
1	1,494	677	496	323	1,171	Honomanu Basalt
1	465	-273	194	90	375	Honomanu Basalt
1	135	-340	166	88	47	Honomanu Basalt
1	449	-138	137	109	340	Honomanu Basalt
1	864	17	181	131	733	Honomanu Basalt
1	762	214	184	106	656	Honomanu Basalt
1	902	148	131	81	821	Honomanu Basalt
1	849	235	155	105	744	Honomanu Basalt
1	796	147	352	189	607	Honomanu Basalt
1	780	632	--	--	--	Honomanu Basalt
1	785	255	284	87	698	Honomanu Basalt
1	826	231	192	129	697	Honomanu Basalt
1	1,015	260	140	91	924	Honomanu Basalt
1	1,578	548	184	174	1,404	Honomanu Basalt
100	1,845	713	596	449	1,396	Honomanu Basalt
Kuhiwa well	1,396	-9	954	260	1,135	Honomanu Basalt

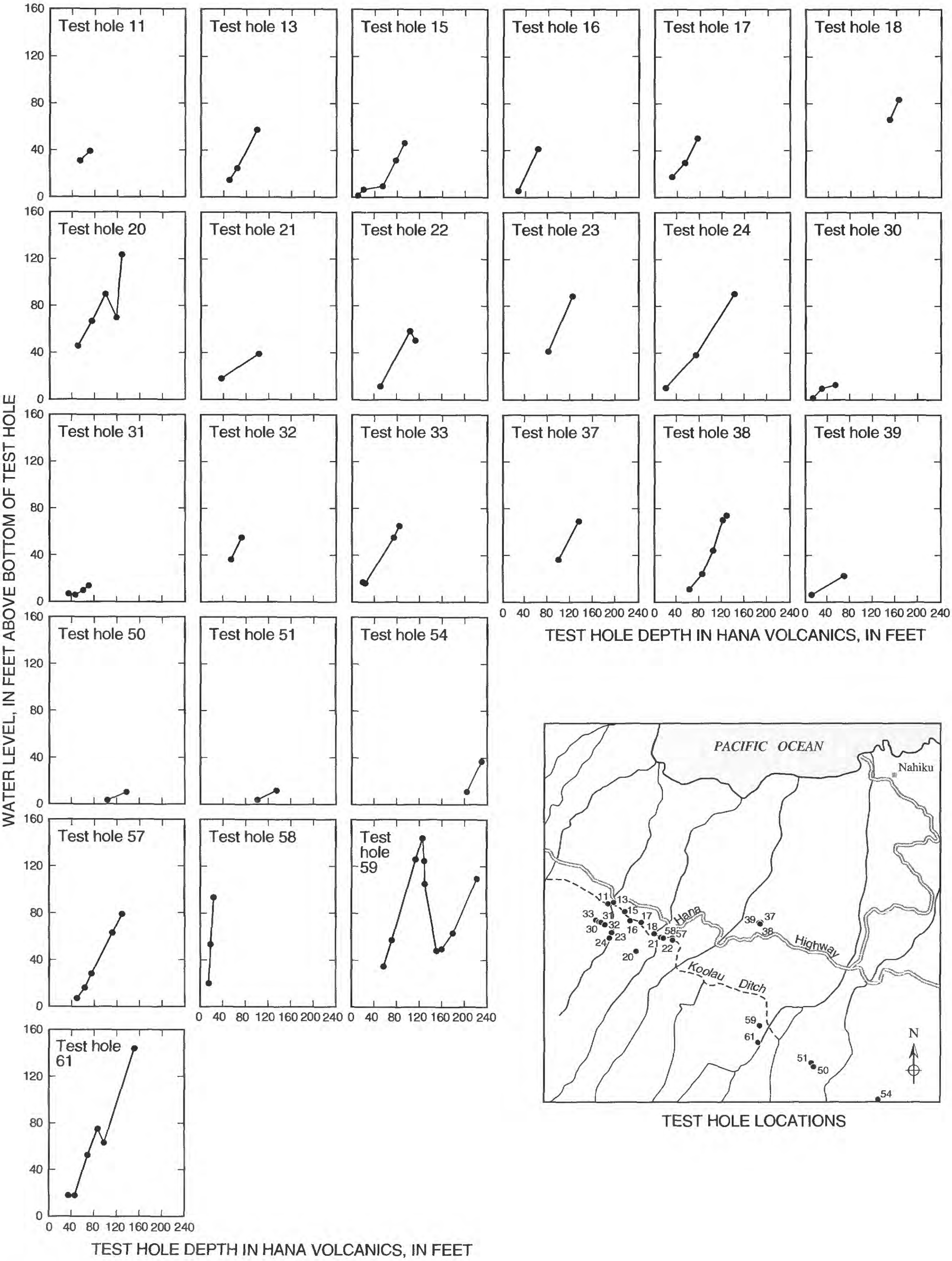


Figure 13. Water level above the bottom of the test hole as a function of hole depth in the Hana Volcanics, Nahiku area, Maui, Hawaii.

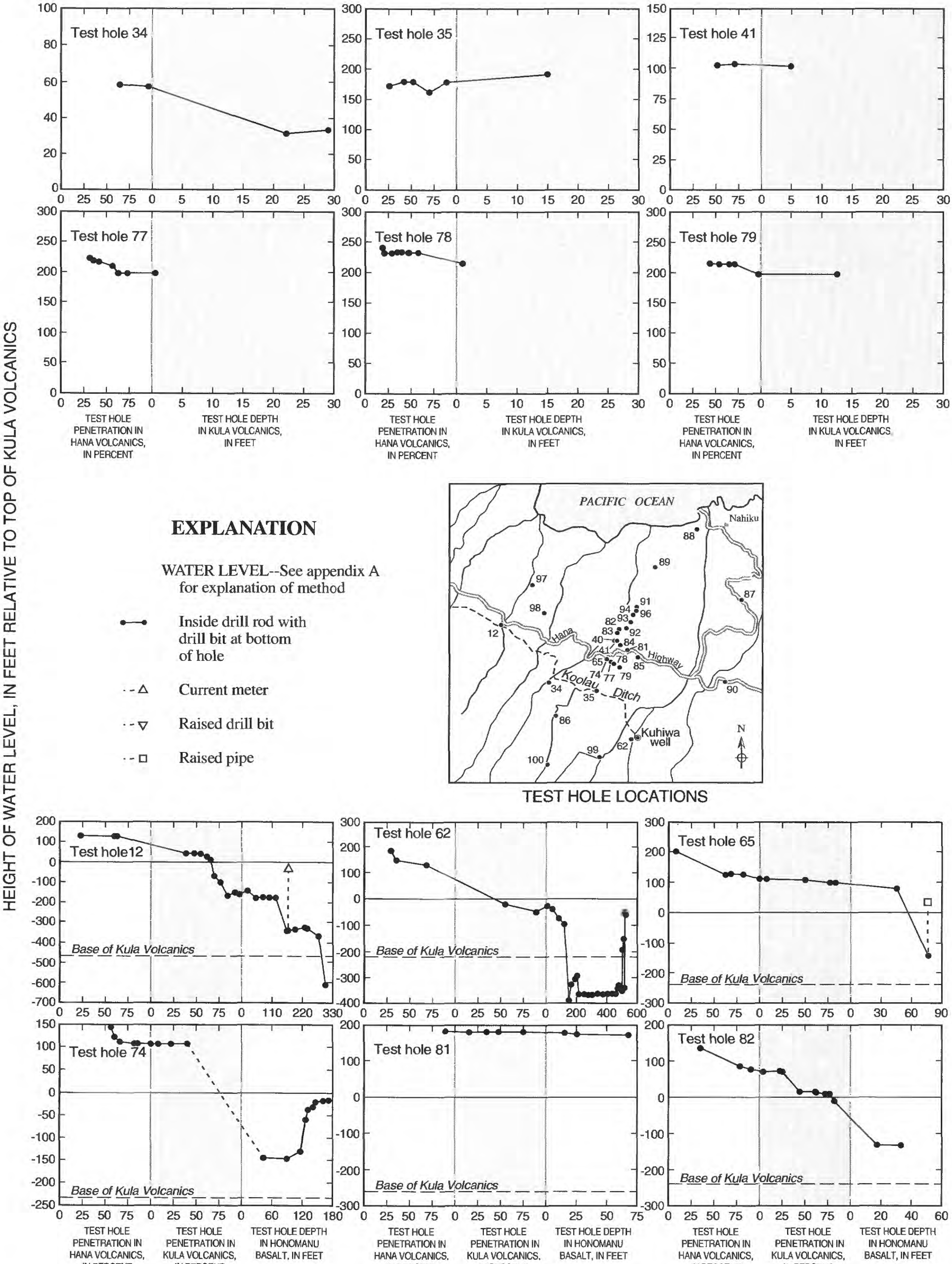


Figure 14. Water levels in test holes compared with depth in the Hana Volcanics, Kula Volcanics, and Honomanu Basalt, Nahiku area, Maui, Hawaii.

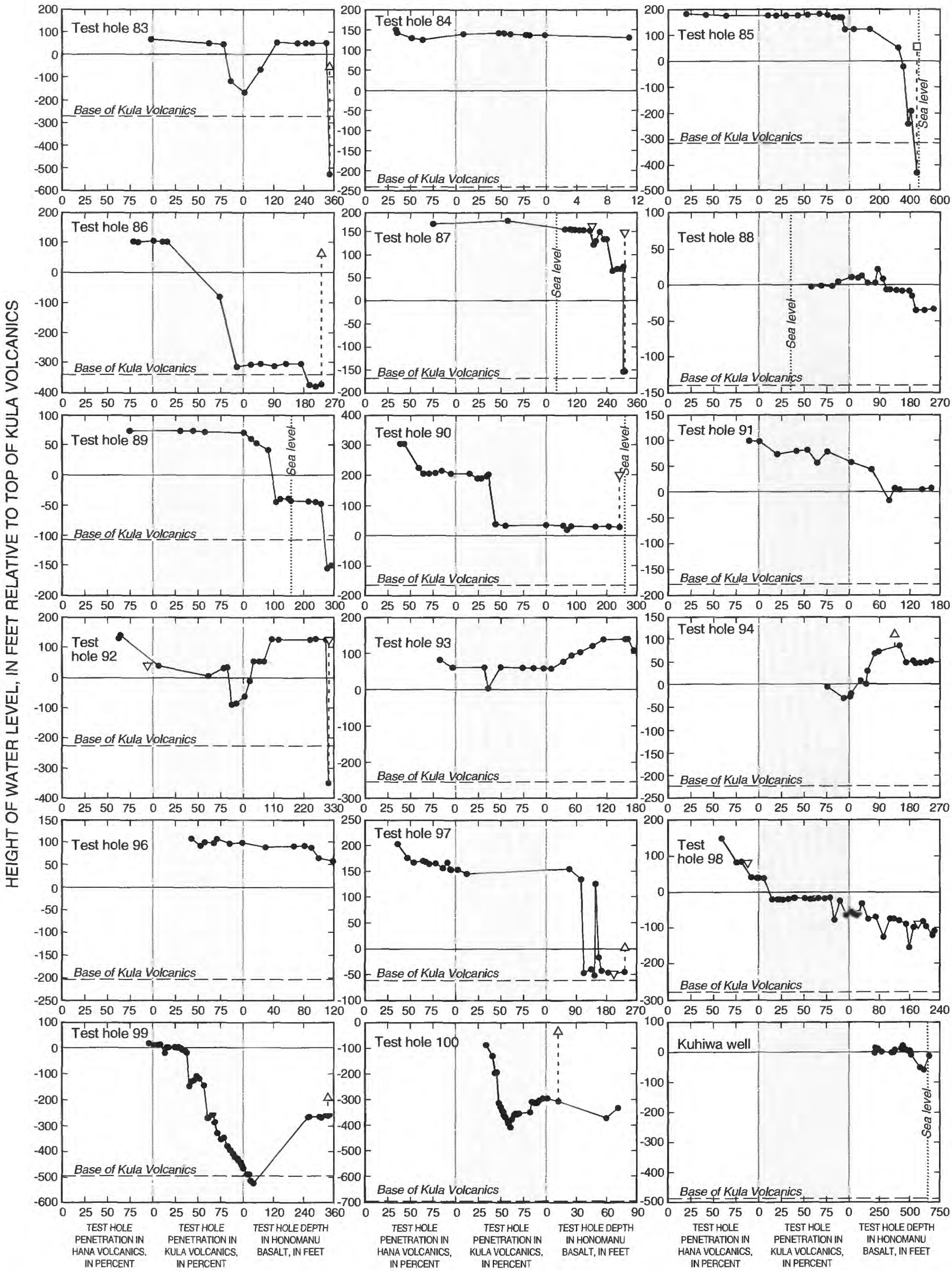
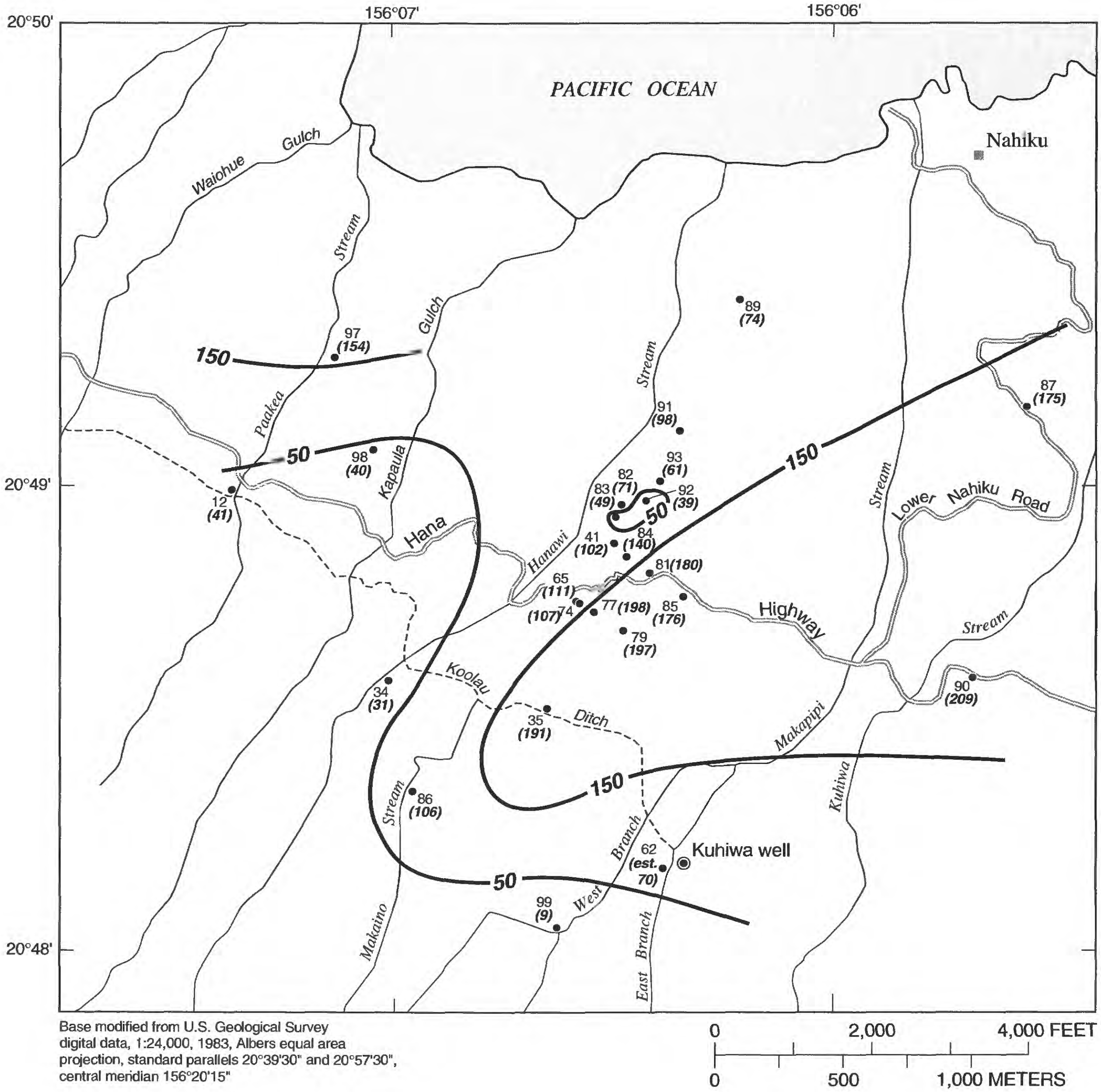


Figure 14. Water levels in test holes compared with depth in the Hana Volcanics, Kula Volcanics, and Honomanu Basalt, Nahiku area, Maui, Hawaii--*Continued.*

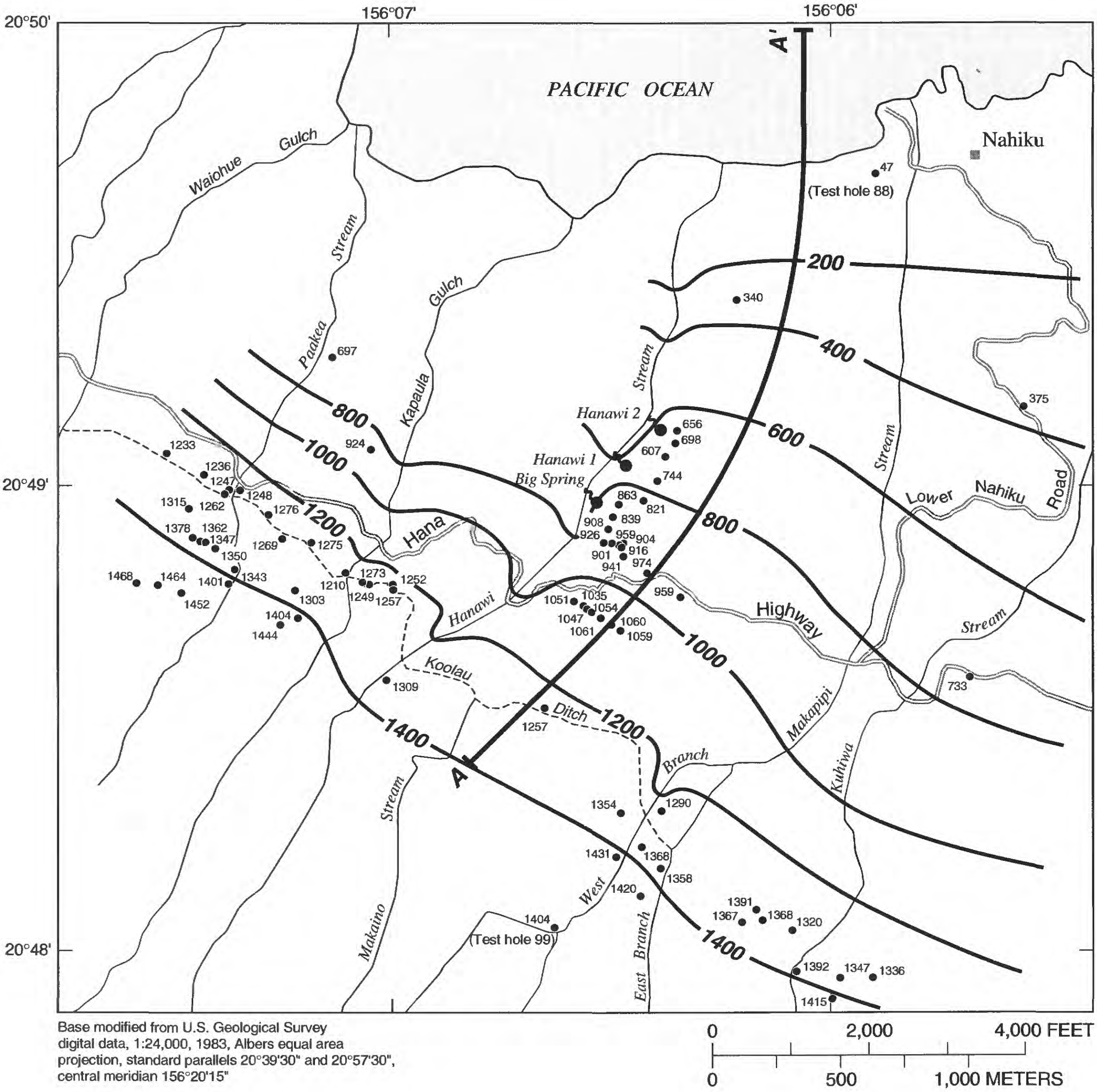


EXPLANATION

— 50 — LINE OF EQUAL WATER LEVEL--Interval 100 feet

12 (41) • TEST HOLE AND NUMBER--Number in parentheses is initial water level in the Kula Volcanics, in feet above top of Kula Volcanics

Figure 15. Water levels above the contact between the Hana and Kula Volcanics for test-hole depths in the upper Kula Volcanics, Nahiku area, Maui, Hawaii.



EXPLANATION

—600— LINE OF EQUAL WATER-LEVEL ALTITUDE--Interval 200 feet. Datum is mean sea level

A A' LINE OF HYDROGEOLOGIC SECTION

388 ● TEST HOLE AND ALTITUDE OF FIRST REPORTED WATER LEVEL, IN FEET ABOVE MEAN SEA LEVEL

Figure 16. First reported water levels in test holes, Kuhiwa well, and springs, Nahiku area, Maui, Hawaii.

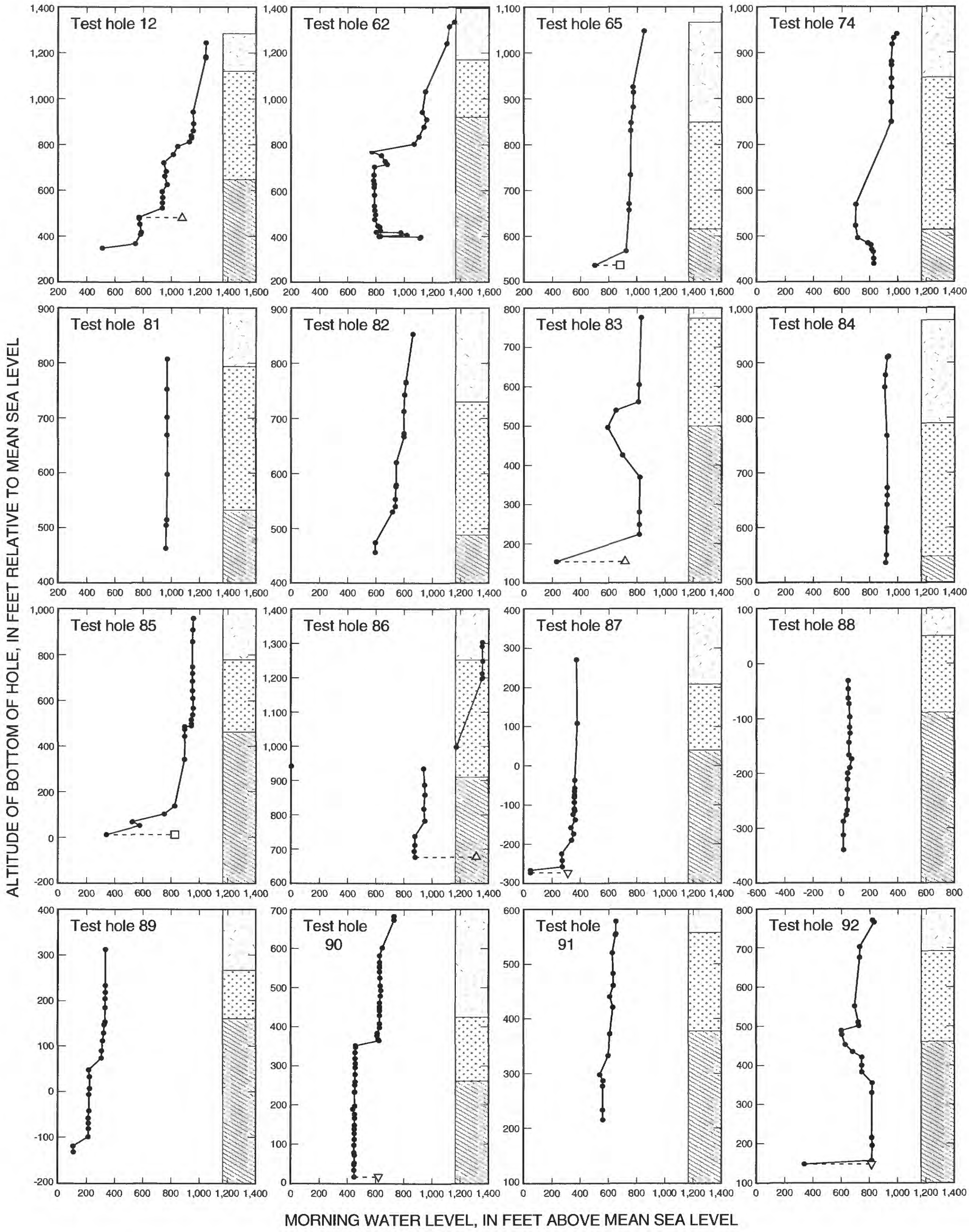
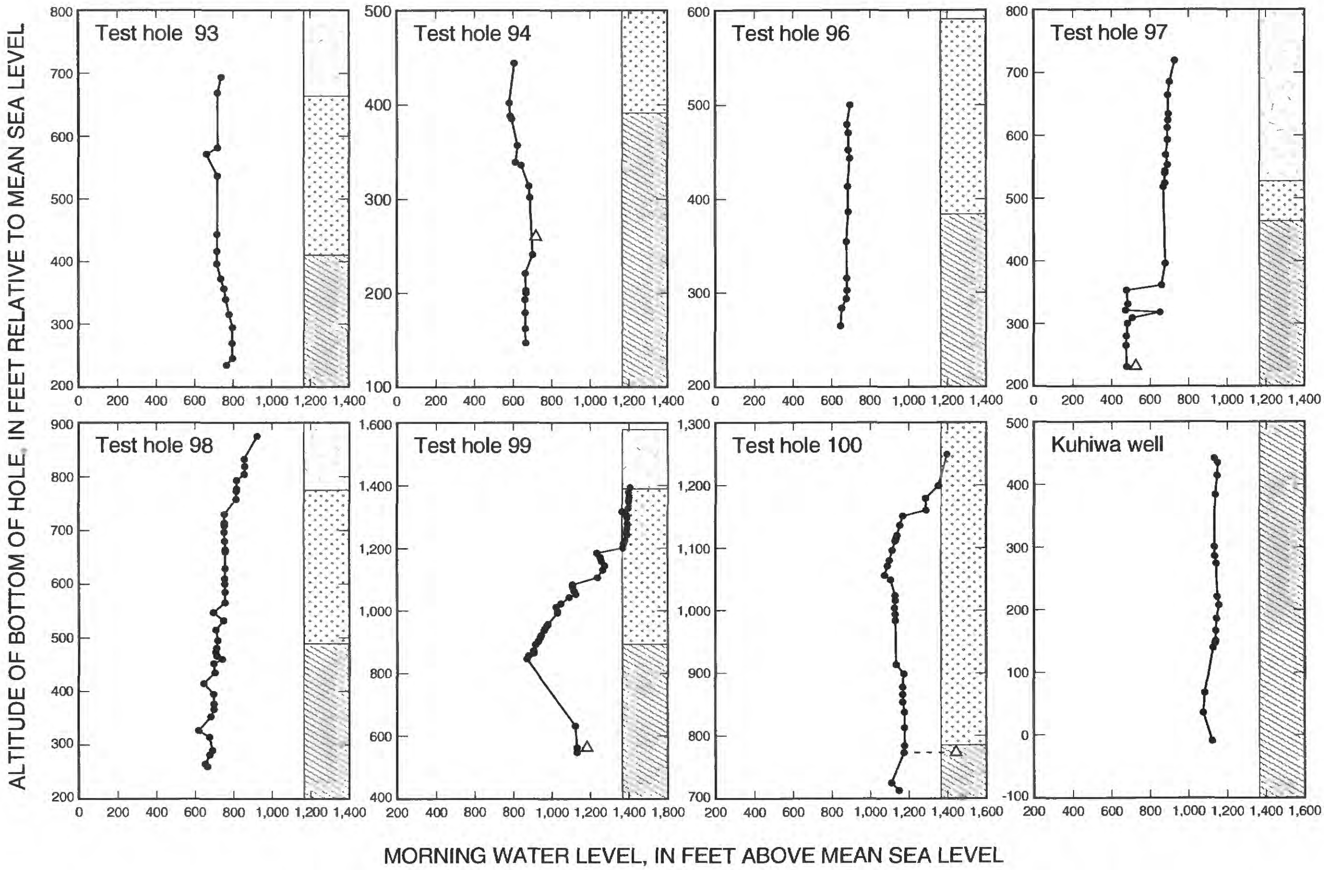


Figure 17. Morning water levels in selected test holes and Kuhiwa well, Nahiku area, Maui, Hawaii.



EXPLANATION

WATER LEVEL--See appendix A for explanation of method

Inside drill rod with drill bit at bottom of hole

Current meter

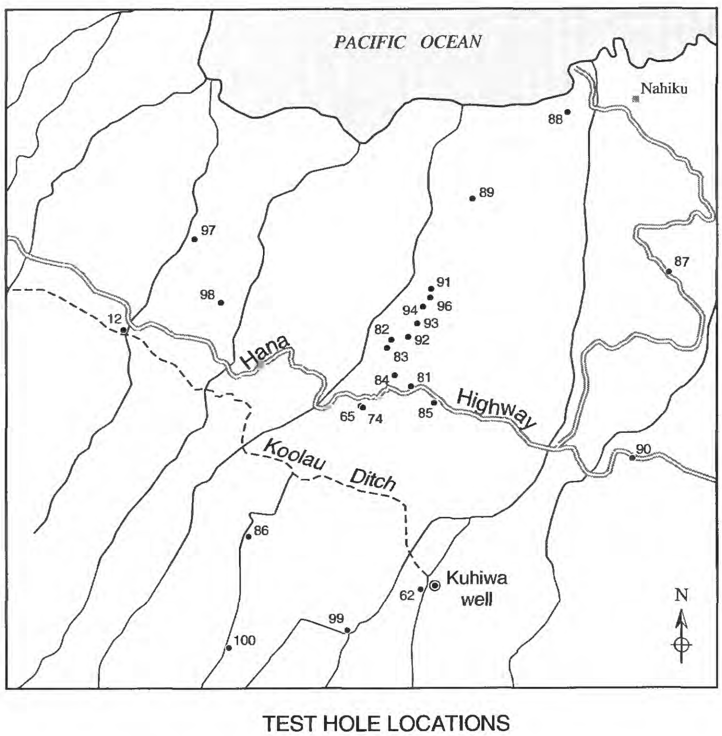
Raised drill bit

Raised pipe

HANA VOLCANICS

KULA VOLCANICS

HONOMANU BASALT



TEST HOLE LOCATIONS

Figure 17. Morning water levels in selected test holes and Kuhiwa well, Nahiku area, Maui, Hawaii--*Continued.*

89, 90, 91, 92, 93, 94, 96, 97, 98, 99, 100, and Kuhiwa well) encompass the entire geographic area explored by the test-drilling program and include all of the test holes drilled to depths near to or below sea level (85, 87, 88, 89, 90, and Kuhiwa well). Major rock units penetrated by a given test hole also are shown in table 5 and figure 17.

The height of the water level above the bottom of the hole generally increased as each hole was deepened (fig. 18). Depth of the test holes ranged from 441 to 1,132 ft and averaged 718 ft. The height of the water level above the bottom of the holes ranged from 81 to 722 ft and averaged 350 ft. The height of the water level above the bottom of the hole in 14 of the 23 test holes equalled or exceeded 350 ft. With the exception of test hole 86 (where no water was recorded at a hole depth of 552 ft) and test hole 62 (which had only 3 ft of water at a bottom hole altitude of 770 ft), there was always water in each test hole as they were deepened (table 5). Water levels in test holes 86 and 62 are discussed further in appendix C.

The overall vertical hydraulic gradient (defined as the difference in the initial and final water level measured in the test hole divided by the hole length over which the difference in water levels was measured) in each of the deeper test holes is downward in all but two of the test holes (93 and 94, table 5). Downward gradients ranged from 0.03 to 0.97 ft/ft and averaged 0.47 ft/ft. The vertical hydraulic gradient in Kuhiwa well was 0.02 ft/ft. Artesian water was encountered in eight of the test holes (62, 74, 83, 92, 93, 94, 99, and 100; see fig. 14), but the overall hydraulic gradient in only two of these holes (93 and 94) was upward with gradients equal to -0.06 and -0.20 ft/ft, respectively.

Water Levels in the Kula Volcanics

Water levels in the Kula Volcanics are available from 29 test holes (fig. 14 and table 5). Six of these test holes, 34, 35, 41, 77, 78, and 79 (table 6) were completed at relatively shallow depths in the Kula Volcanics and the remaining 23 (table 5) were completed in the Honomanu Basalt. Water levels in the six test holes remained above the top of the Kula Volcanics for hole depths in the Kula.

Water levels in 11 of the 23 test holes completed in the Honomanu Basalt were above the top of the Kula Volcanics for all hole depths in the Kula Volcanics while water levels in another test hole, T-88, were a few feet above or below the contact. Once in the Honomanu Basalt, the water level in this hole varied from 2 to 21 ft above the Kula Volcanics for the first 100 ft into the Honomanu Basalt. Water levels in yet another test hole, 74, were above the top of the Kula at depths where measurements were made, but these depths were all in the upper half of the Kula.

Water levels in the remaining 10 test holes ultimately fell below the top of the Kula Volcanics for hole depths in the Kula, although the water level in three of these holes rose back above the Kula Volcanics for hole depths in the Honomanu Basalt.

The 11 test holes wherein water levels remained above the top of the Kula as each hole was deepened through the Kula Volcanics were test holes 65, 81, 84, 85, 87, 89, 90, 91, 93, 96, and 97 (fig. 14). Water levels in these holes also remained above the contact between the Hana and Kula Volcanics as each hole was initially deepened into the Honomanu Basalt. The water levels at the initial hole depth in the Honomanu Basalt ranged from 33 to 178 ft above the contact. The water level in one of these holes, test hole 85, remained above the contact between the Hana and Kula Volcanics for depths as much as 322 ft into the Honomanu Basalt. This hole depth corresponds to an altitude of 138 ft.

The ten test holes in which water levels ultimately fell below the top of the Kula Volcanics as drilling proceeded through the Kula were test holes 12, 62, 82, 83, 86, 92, 94, 98, 99, and 100. Six of these holes (62, 83, 92, 94, 99, and 100) also encountered artesian water and two others (82 and 86) probably were completed at depths just above the artesian water body where water levels were still declining. Water levels in three (83, 92, and 94) of the six holes that encountered artesian water ultimately rose back above the top of the Kula for hole depths in the Honomanu Basalt, while the water level in test hole 62 rose to within about 50 ft of the top of the Kula.

The areal distribution of water levels in the 23 test holes completed in the Honomanu Basalt relative to the altitude of the contact between the Hana and Kula Volcanics is shown in figure 19. The water levels indicated represent the measurement in the hole at the altitude nearest to the contact. The test holes in which the water level ultimately fell below the top of the Kula Volcanics are those farthest inland from the ocean.

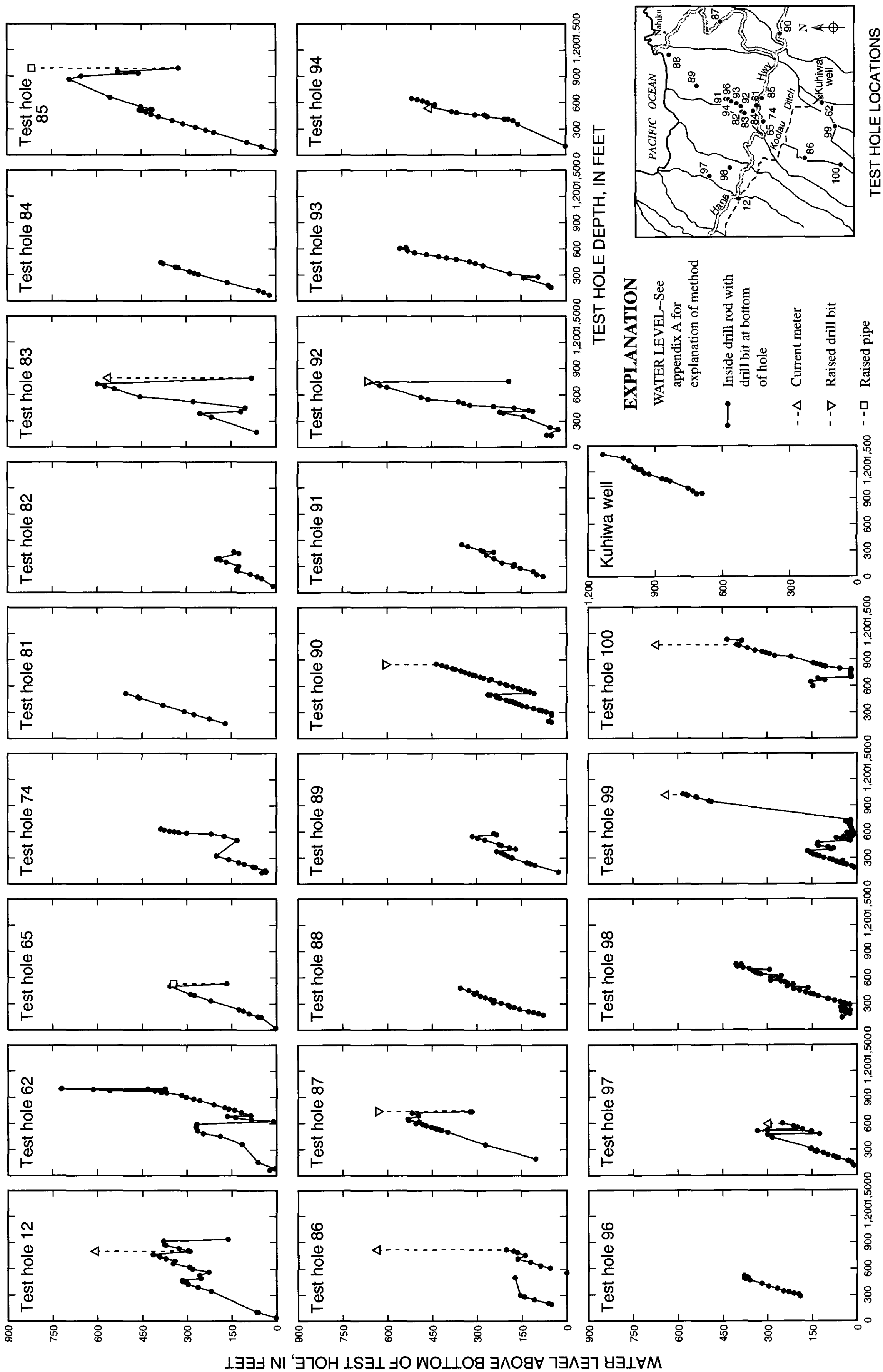
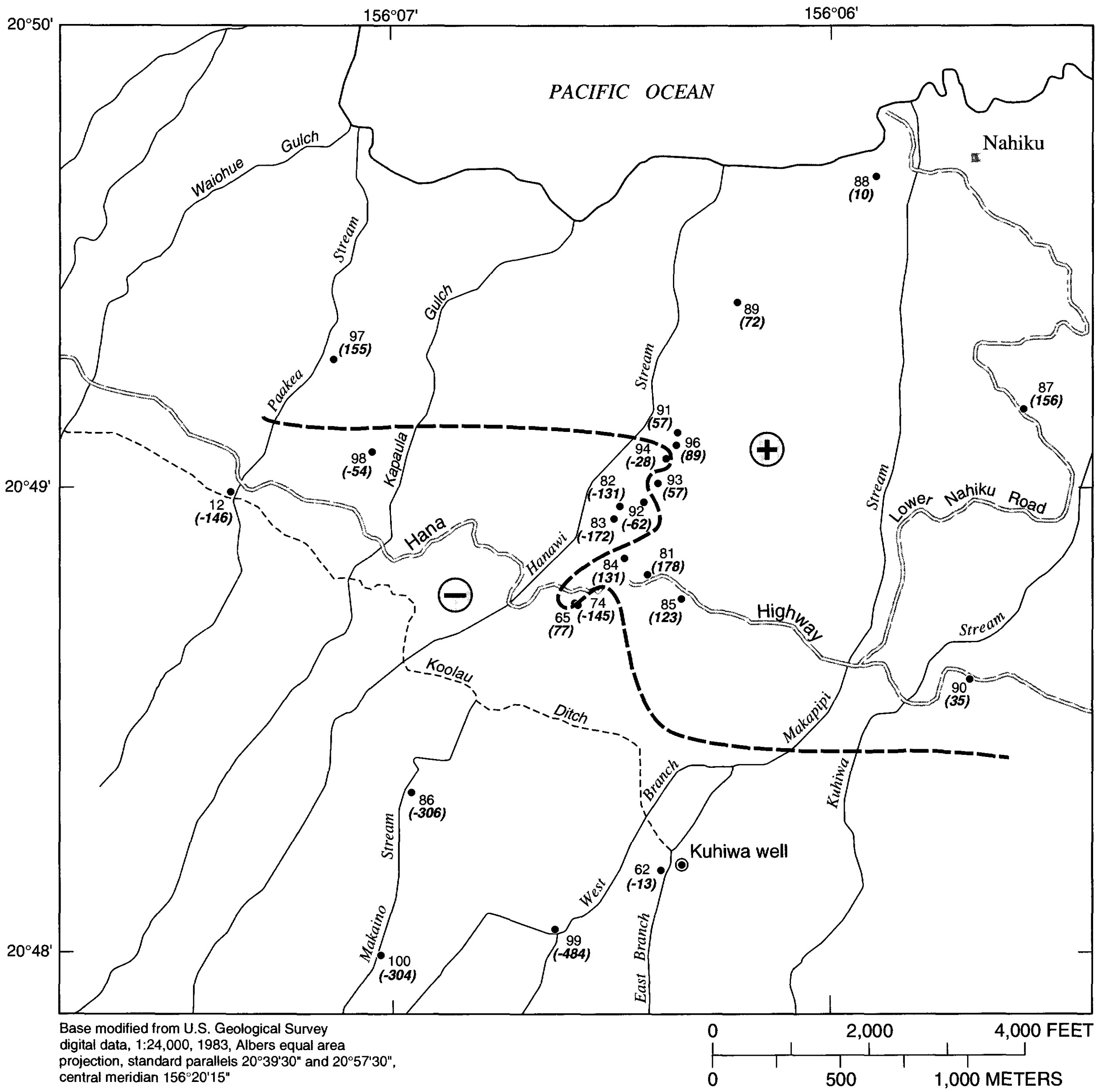


Figure 18. Water level above the bottom of selected test holes as a function of hole depth, Nahiku area, Maui, Hawaii.

Table 6. Water levels in selected test holes completed in Kula Volcanics, Nahiku area, Maui, Hawaii
[Values in feet; --, no data or not applicable; Kula, Kula Volcanics; Hana, Hana Volcanics. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Land surface altitude	Total depth	Depth to top of Kula Volcanics	Depth to base of Kula Volcanics	Vertical hydraulic gradient	Hole depth	Bottom hole altitude	Depth to water	Water level altitude	Water level above top of Kula Volcanics	Rock unit[1]	Percent penetration of rock unit	Depth of hole in Kula Volcanics	Water level above bottom of hole
						Test hole 34							
1,332	110	81	--	--	52	1,280	23	1,309	58	Hana	64	--	29
					77	1,255	24	1,308	57	Hana	95	--	53
					103	1,229	50	1,282	31	Kula	--	22	53
					110	1,222	48	1,284	33	Kula	--	29	62
						Test hole 35							
1,293	223	208	--	--	55	1,238	36	1,257	172	Hana	26	--	19
					88	1,205	29	1,264	179	Hana	42	--	59
					108	1,185	29	1,264	179	Hana	52	--	79
					145	1,148	46	1,247	162	Hana	70	--	99
					186	1,107	30	1,263	178	Hana	89	--	156
					223	1,070	17	1,276	191	Kula	--	15	206
						Test hole 41							
969	178	171	--	--	89	880	68	901	103	Hana	52	--	21
					122	847	67	902	104	Hana	71	--	55
					176	793	69	900	102	Kula	--	5	107
						Test hole 77							
1,089	280	258	--	--	83	1,006	35	1,054	223	Hana	32	--	48
					92	997	39	1,050	219	Hana	36	--	53
					108	981	41	1,048	217	Hana	42	--	67
					147	942	48	1,041	210	Hana	57	--	99
					163	926	60	1,029	198	Hana	63	--	103
					189	900	60	1,029	198	Hana	73	--	129
					259	830	60	1,029	198	Kula	--	1	199
						Test hole 78							
1,107	300	287	--	--	55	1,052	46	1,061	241	Hana	19	--	9
					59	1,048	55	1,052	232	Hana	21	--	4
					84	1,023	55	1,052	232	Hana	29	--	29
					101	1,006	53	1,054	234	Hana	35	--	48
					115	992	53	1,054	234	Hana	40	--	62
					135	972	54	1,053	233	Hana	47	--	81
					138	969	54	1,053	233	Hana	48	--	84
					167	940	54	1,053	233	Hana	58	--	113
					283	824	73	1,034	214	Hana	99	--	210
					288	819	73	1,034	214	Kula	--	1	215
						Test hole 79							
1,124	300	280	--	--	62	1,062	--	--	--	--	22	--	--
					122	1,002	65	1,059	215	Hana	44	--	57
					150	974	66	1,058	214	Hana	54	--	84
					182	942	66	1,058	214	Hana	65	--	116
					200	924	66	1,058	214	Hana	71	--	134
					271	853	83	1,041	197	Hana	97	--	188
					293	831	83	1,041	197	Kula	--	13	210



EXPLANATION

⊕ WATER LEVEL ABOVE TOP OF KULA VOLCANICS

⊖ WATER LEVEL BELOW TOP OF KULA VOLCANICS

– – – – BOUNDARY BETWEEN WATER LEVEL ABOVE AND BELOW TOP OF KULA VOLCANICS

12 (-146) • TEST HOLE AND NUMBER--Number in parentheses is initial water level in the Honomanu Basalt, in feet relative to the top of the Kula Volcanics

Figure 19. Water levels in test holes relative to the contact between the Hana and Kula Volcanics for initial hole depth in the Honomanu Basalt, Nahiku area, Maui, Hawaii.

Water Levels at Test-Hole Depths Near Sea Level

Five test holes (85, 87, 88, 89, 90) and Kuhiwa well were drilled to depths near to or below sea level and water levels in these holes were examined to address the existence of a basal water body with water levels 5 to 10 ft above sea level (table 5, fig. 20). Except for Kuhiwa well, water levels shown in figure 20 were obtained from inside the drill rod with the bit at the bottom of the hole. These water levels are much higher than would be expected in a basal water body as defined by Stearns and Macdonald (1942). Water levels increase steeply from 47 ft at test hole 88 (a distance of about 300 ft from the ocean) to 1,126 ft at Kuhiwa well (about 2 mi inland from the ocean). These data support the framework for a vertically extensive ground-water system.

Water Levels Outside the Artesian Water Body in the Honomanu Basalt

Test holes 12, 87, 88, 89, 90, 91, 96, 97, and 98 (see fig. 23) were drilled outside of the artesian water body and water levels in these holes were examined to understand ground-water occurrence in the Honomanu Basalt outside of the artesian body. In general, the presence of little or no water in these holes as they were deepened into the Honomanu Basalt would indicate that the rocks of the Honomanu Basalt are unsaturated in areas outside of the artesian water body and above the basal water body as defined by Stearns and Macdonald (1942). However, if water levels in the holes remained above the top of the Honomanu Basalt, the data would indicate that the rocks of the Honomanu Basalt are saturated, which is consistent with the concept of a vertically extensive water body.

Water levels in the test holes generally declined as each hole was deepened in the Honomanu Basalt, but even so, with the exception of test holes 12 and 89, the altitude of the water level in the holes remained above the top of the Honomanu Basalt (fig. 14 and table 5).

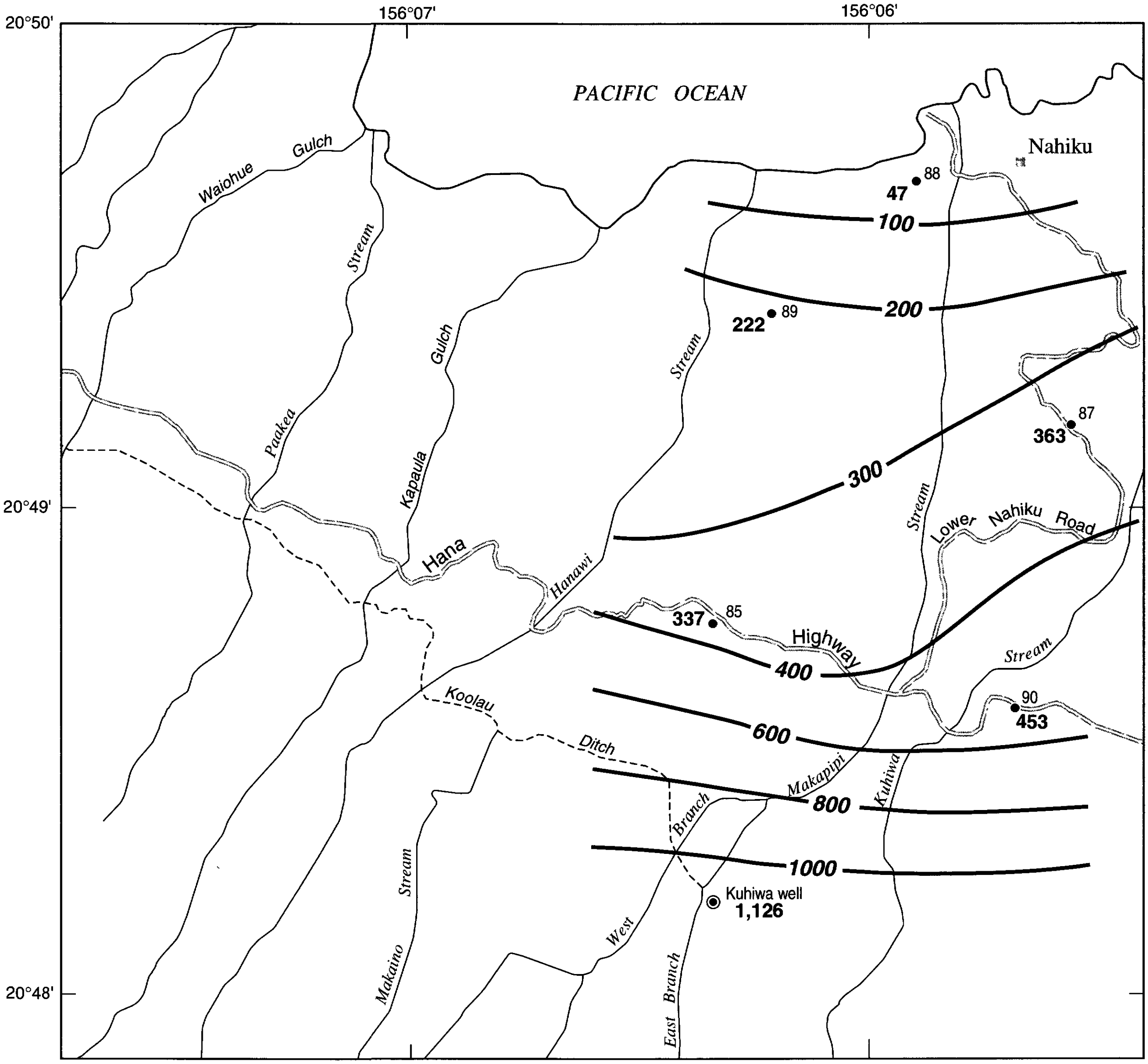
The water level in test hole 89 was 44 ft below the top of the Honomanu Basalt at the final depth of the hole. However, the water level in test hole 89 remained above the top of the Honomanu Basalt to a borehole depth of 99 ft below sea level, indicating that the Honomanu is saturated at this location. The water level in test hole 12 was 138 ft below the top of the Honomanu Basalt at the final bottom hole altitude of 345 ft.

The water level in three test holes (87, 88, and 90) also remained above the top of the Kula Volcanics for bottom hole altitudes near to or below sea level (-259, -190, and 17 ft, respectively) and the water levels in two other holes (91 and 96) were still above the top of the Kula at their final bottom hole altitudes in the Honomanu Basalt of 163 and 119 ft, respectively (table 5).

GROUND-WATER MOVEMENT ASSUMING A VERTICALLY EXTENSIVE GROUND-WATER BODY

The general movement of ground-water in the Nahiku area, assuming a vertically extensive ground-water body, is shown in figure 9. One of the major features shown is a water table that ranges from about 1,400 ft 2 mi inland from the ocean to 47 ft near the shoreline. On the basis of the results of the test drilling, the water table is in the Hana Volcanics. The areal configuration of this surface (fig. 16) indicates a general movement of water toward the ocean. Another major feature shown in figure 9 is the presence of a convergence zone, so named because both water level and directional current-meter data collected during the test drilling program indicates that water is moving into this zone from above and below. The artesian water body is immediately below the convergence zone. Not shown in figure 9, but located in figure 27, is a layer of high permeability contained within the broader zone into which water is converging. The existence of this layer is indicated by directional current-meter data (figure 24) and it represents a horizon wherein the movement of ground water is predominately lateral. The altitude of the high permeability layer relative to Big Spring and the results of dye test experiment done during the test drilling indicate that the water moving within the layer is the source of water to Big Spring. Finally, the general decline of water levels as the test holes were deepened in the areas outside of the artesian water body indicates that the vertical movement of water is generally downward. Water levels and directional current-meter data collected in test holes 12 and 87, which are outside the artesian water body, illustrate this movement (fig. 21).

Although the discussion in the preceding sections demonstrates that the Nahiku area is underlain by a vertically extensive water body, the following



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 20°39'30" and 20°57'30", central meridian 156°20'15"

0 2,000 4,000 FEET

0 500 1,000 METERS

EXPLANATION

—600—	LINE OF EQUAL WATER-LEVEL ALTITUDE--Interval, in feet, is variable. Datum is mean seal level
85 ●	TEST HOLE AND NUMBER
50	WATER LEVEL, IN FEET ABOVE MEAN SEA LEVEL

Figure 20. Water levels at hole depths near sea level, Nahiku area, Maui, Hawaii.

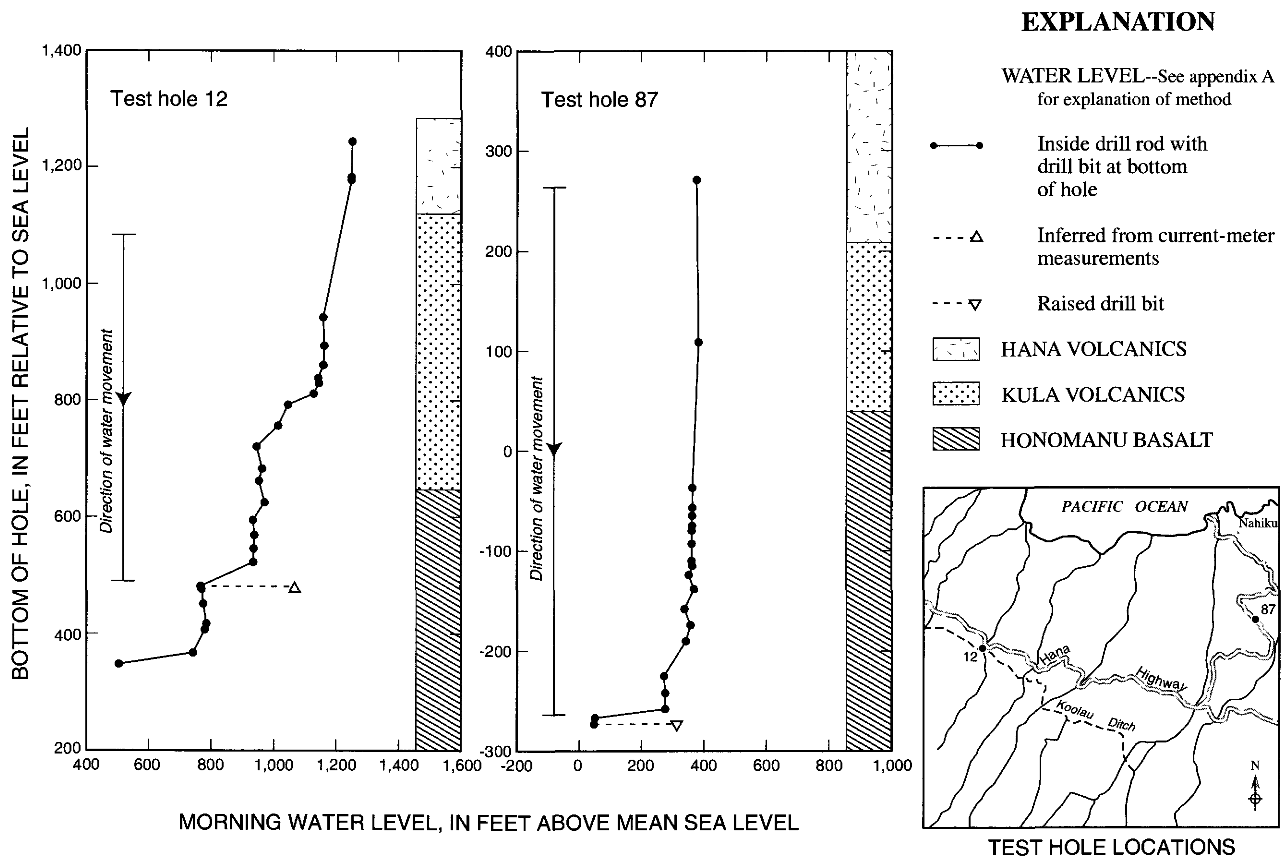


Figure 21. Morning water levels and current-meter data indicating downward ground-water movement in selected test holes, Nahiku area, Maui, Hawaii.

sections describe the main features of the water body so that a complete picture of ground-water occurrence in the area is presented.

The Artesian Water Body

As indicated by water levels, only test holes 62, 74, 83, 92, 93, 94, 99, and 100 intercepted artesian water at hole altitudes of 418, 485, 426, 453, 373, 357, 633, and 1,049 ft, respectively (table 5). These altitudes represent the altitude in the holes at which a rise in water levels began. The artesian water body was encountered in the Honomanu Basalt, except at test hole 100, where it is in the Kula Volcanics. Depth to the artesian water body in the Honomanu Basalt was 501, 127, 72, 7, 36, 34, and 258 ft for test holes 62 through 99, respectively (table 5). These data indicate that, toward the ocean, the position of the artesian water body in the Honomanu Basalt is generally higher in the stratigraphic column. A generalized geologic section showing selected test holes completed in the Honomanu Basalt; the altitude in test holes 62, 74, 83, 92, 93, 94, 99, and 100 at which artesian water was first encountered; and the depth in each borehole at which water levels were last measured is shown in figure 22.

Although, as discussed, Stearns and Macdonald (1942) as well as Cox (*in* Takasaki and Yamanaga, 1970) (fig. 6) indicate that artesian water was encountered in test hole 85, this conclusion is not actually confirmed by water levels in the test hole (table 5). As discussed by Stearns (Stearns and Macdonald, 1942, p. 226), it was the apparent presence of artesian water in this hole that led to his conclusion that the artesian water body is the source of water for Big Spring. Their conclusion that test hole 85 intercepted artesian water may have been based on the results from directional current-meter data that were collected in the test hole during the test-drilling program. Current-meter data from test hole 85 indicate upward moving water between hole altitudes of 343 and 501 ft (table 7). Altitude of the water level in the hole over this interval ranged from 899 to 946 ft, respectively. That water levels increased in the same direction as the movement of

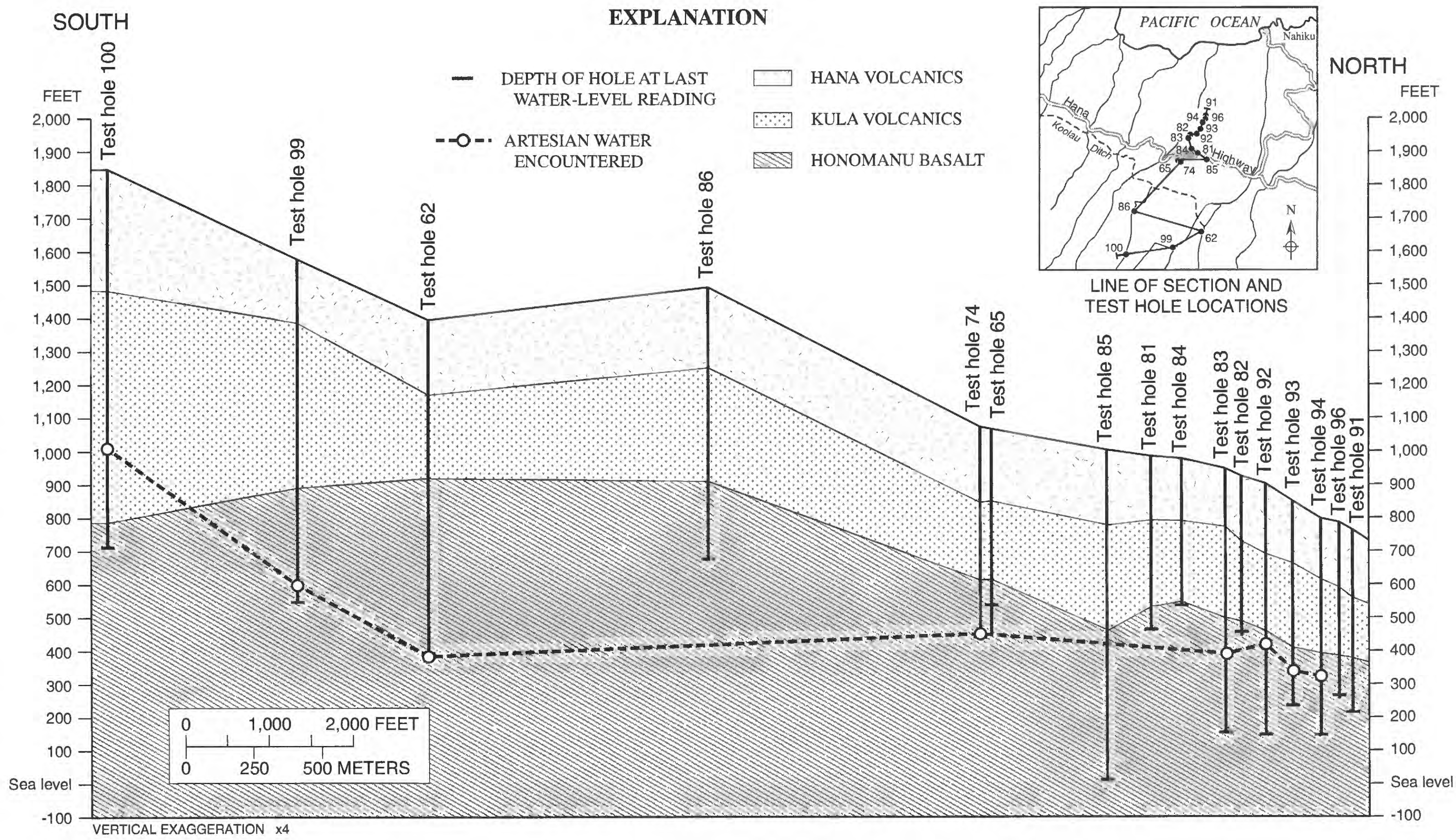


Figure 22. Test holes completed in the Honomanu Basalt and the altitude at which artesian water was encountered at test holes 62, 74, 83, 92, 93, 94, 99, and 100, Nahiku area, Maui, Hawaii.

Table 7. Altitude of the top and base of the zone of converging ground-water movement at selected test holes, Nahiku area, Maui, Hawaii

[≤, less than or equal to; --, not measured or not known; est, estimated]

Test hole	Altitude (feet) Top	Altitude (feet) Base	Thickness (feet)	Directional current-meter data (altitude, in feet)
62	911	380	531	downward, 895 to 715; upward, 405 to 652
65	568	--	--	none
74	≤750	440	310	upward at 453 and 460; no other data
82	667	--	--	none
83	715	370	345	downward, 715 to 625 and 385 to 165; upward, 387 to 606
85	[1]803	[1]343	460	downward, 803 to 511; upward, 343 to 501
86	1,314	--	--	downward, 1,314 to 748
92	[1]805	355	450	downward, 805(?) to 707; upward, 402 to 624
93	--	246	--	upward, 349 to 729
94	(est) 716	241	475	downward, 716 to 615; upward from 328 to 582; downward, 318 to 228
99	1,201	548	653	downward, 1,194 to 978; upward, 641 to 901
100	1,355	878	477	downward, 1,355 to 1,155; upward, 945 to 1,132

[1] From current-meter data

water in test hole 85 indicates the possibility of an error in the water-level measurements or the current-meter data.

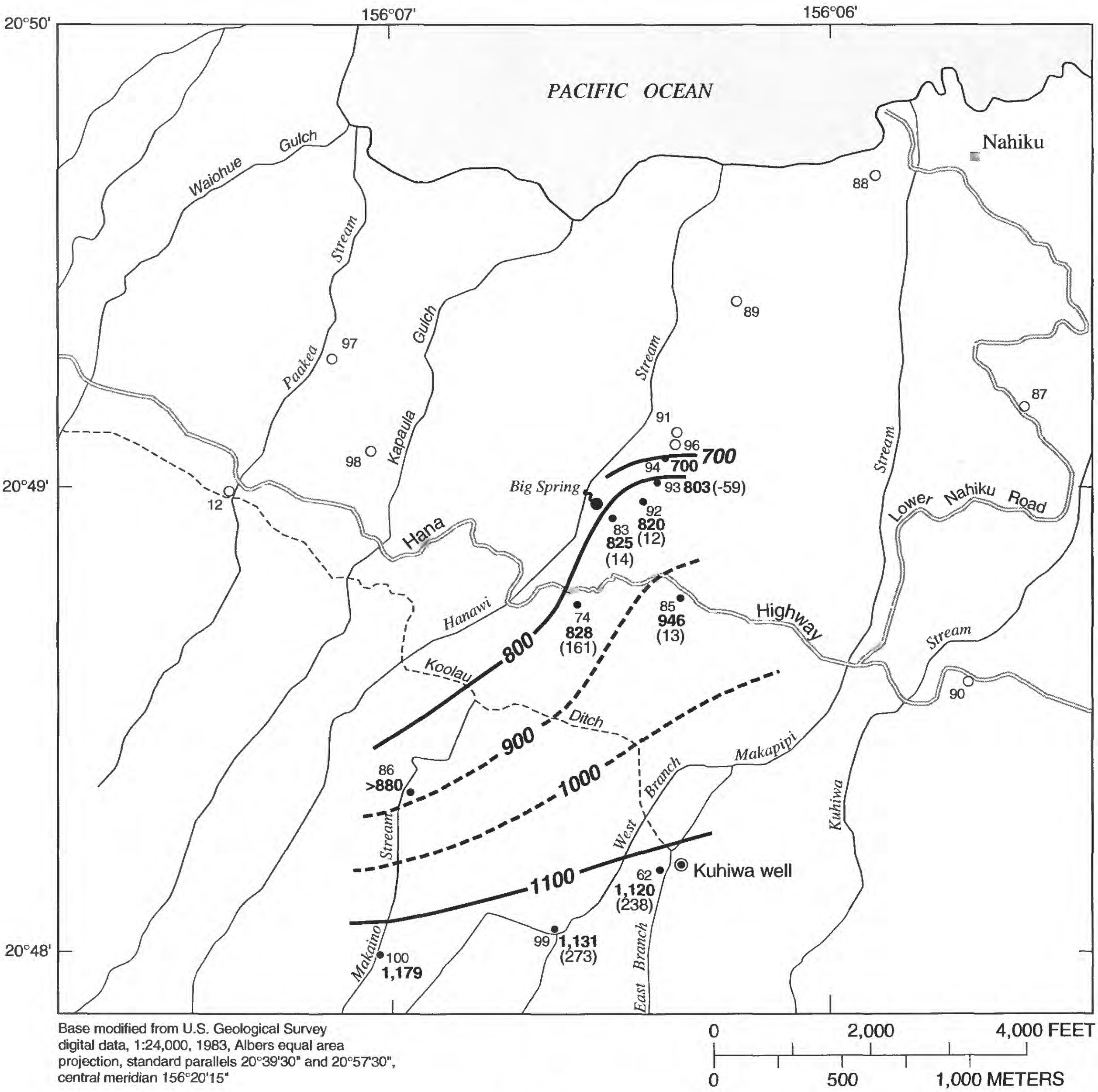
Cox (*in* Takasaki and Yamanaga, 1970) also included test hole 86 into those holes that penetrated the artesian water body (fig. 6) but water levels do not confirm this (table 5 and fig. 14), and directional current-meter data only indicate water moving downward (table 7). Cox may have included test hole 86 as one of the holes that penetrated artesian water because the water levels measured over the last 61 ft of the hole ranged from 873 to 880 ft in altitude (table 5) which is within the 800 ft artesian area defined by Cox (fig. 6). As will be discussed subsequently, the trend of water-level data in the hole may indicate that the test hole was completed just above the artesian water body.

Finally, a comparison of water levels in Kuhiwa well with those in nearby test hole 62 indicates that Kuhiwa well was completed in the artesian water body (table 5). Water-level measurements in Kuhiwa well, however, did not begin until the well had penetrated the artesian water body.

Test holes 65, 81, 82, 84, and 86 were all within the general area in which artesian water was encountered, but neither changes in water levels nor current-meter data in these holes indicate artesian water (fig. 14). On the basis of a projection between holes of the altitude at which artesian water was first encountered, these test holes probably were completed at depths too shallow to have intercepted the artesian water body, if present, or the last water-level measurements in the boreholes were made at depths too shallow to indicate artesian water (fig. 22). For example, a comparison of water levels compared with depth in nearby test holes 65 and 74, indicates that the water-level measurement in test hole 65 was made just above the altitude that water levels began to increase at test hole 74. Test hole 82, which was near test hole 83, was completed at an altitude just above that in test hole 83 where the water level began to increase.

The Potentiometric Surface in the Artesian Water Body.--Figure 23 shows the potentiometric surface in the artesian water body, assuming that the water body is continuous throughout the area underlain by test holes 62, 74, 83, 92, 93, 94, 99, 100, and Kuhiwa well. The value of head selected was the highest artesian head in each test hole. As discussed and as shown in figure 6, previous work also assumed artesian water at test holes 85 and 86 and concluded that two separate artesian water bodies exist. The surface is dashed in the area of these two test holes to indicate the possibility of the latter conclusion. If a continuous water body is assumed (which is not fully supported by the data), artesian water levels decrease from an altitude of over 1,100 ft at test holes 100, 99, 62, and Kuhiwa well to about 900 ft at test holes 85 and 86; to 800 ft at test holes 74, 83, 92, and 93; and to about 700 ft at test hole 94. The potentiometric surface slopes about 9 degrees toward Hanawi Stream.

Because an artesian water level was not encountered at test hole 85, the hydraulic head for this test hole (946 ft) represents the highest water level in the hole over the range in borehole altitude that upward moving water was indicated by the directional current-meter



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 20°39'30" and 20°57'30", central meridian 156°20'15"

EXPLANATION

—600- - LINE OF EQUAL POTENTIOMETRIC HEAD--Interval 100 feet. Datum is mean sea level. Dashed where uncertain

TEST HOLE AND NUMBER

99 ● In artesian area

12 ○ Outside artesian area

1131 HYDRAULIC HEAD, IN FEET ABOVE MEAN SEA LEVEL

(273) INITIAL WATER LEVEL IN HANA VOLCANICS, IN FEET RELATIVE TO POTENTIOMETRIC WATER LEVEL

Figure 23. Potentiometric surface in the artesian water body, Nahiku area, Maui, Hawaii.

data. The 880-ft head indicated for test hole 86 is the final measurement in the hole. If the artesian water body actually underlies this hole, the artesian head would be expected to be greater than this value given that water levels were not increasing substantially at the final hole depth.

Water levels measured within the artesian water body reached altitudes that were both above and below the top of the Kula Volcanics (fig. 14). The artesian water levels in test holes 62, 74, 99, and 100 were below the top of the Kula Volcanics with those in test hole 100 being the farthest below and those in test hole 74 being the least. Artesian water levels in test holes 83, 92, 93, 94, and Kuhiwa well were all above the top of the Kula Volcanics. Except at Kuhiwa well, this pattern of water levels represents a trend, in an oceanward direction, of increasing artesian head relative to the altitude of the top of the Kula Volcanics.

If the rocks are assumed to be saturated below a water table in the Hana Volcanics, the head in the Hana Volcanics would be higher than that in the artesian water body and the water table can be assumed to be the source of the head in the artesian water body. The difference between the uppermost or highest water level in the Hana Volcanics and the artesian head was calculated at most of the above test holes (fig. 23). Except at test hole 93, the water level in the Hana Volcanics exceeded the artesian head with the difference between the two generally decreasing in a downgradient direction. The uppermost water level in the Hana Volcanics was about 273 ft greater than the artesian head at test hole 99 and about 12 ft greater at test hole 92. The artesian head at test hole 93 exceeds the head in the Hana Volcanics at this hole by 59 ft. Except for test hole 92, these results indicate that the water table in the Hana Volcanics is the source of head for the artesian water body. Because the water level in the Hana Volcanics is greater than the head in the artesian water body it is clear that the artesian water body cannot be the source of water to Big Spring.

The Convergence Zone and Source of Water to Big Spring

Water levels above the artesian water body exhibited two distinct patterns with regard to characteristics of water level compared with depth (fig. 14). The first pattern is best exemplified by test hole 62 and the second is characterized by test hole 100. Water levels at test hole 62 declined abruptly at about 300 ft above the artesian water body after which water levels remained fairly constant with increasing hole depth until the artesian water body was encountered. Test holes 74, 83, and 92 exhibit this general pattern. Water levels at test hole 93 exhibit the pattern of relatively stable water levels immediately above the artesian water body. In contrast to this general pattern, water levels at test holes 99 and 100 declined abruptly before encountering the artesian water body after which water levels began to rise.

The pattern of water-level change compared with depth above the artesian water body exemplified by test hole 62 suggests a vertical zone above the artesian water body into which water is converging (see fig. 9). Water would be moving downward into the zone from the area above the point where water levels begin to decrease abruptly and it would be moving upward into the zone from the artesian water body. Current-meter data were collected over various intervals of the test holes that encountered artesian water and these data (table 7) combined with water levels plotted against depth in the boreholes illustrate this type of movement (fig. 24). The zone into which water is moving is relatively wide, ranging from 310 ft at test hole 74 to 653 ft at test hole 99 (table 7). The top of the zone was selected as the altitude at which an abrupt decrease in water levels occurred or as the altitude at which current-meter data indicated downward flow of water. The bottom of the zone was selected as the altitude where an abrupt increase in water levels ceased to occur or as the altitude at which current-meter data indicated upward flow of water.

Water-levels in test holes 65 and 82 declined abruptly, with the decline occurring at about the altitude which would be expected if the zone into which water is converging underlies these two test holes (fig. 22). Given this, values for the altitude of the top of the zone at these test holes are included in table 7. Test holes 65 and 82 were completed above the artesian water, assuming artesian water exists at these two locations.

Finally, water levels in test hole 85 fail to indicate the presence of artesian water whereas current-meter data indicate the upward movement of water between the altitudes of 343 to 501 ft (fig. 14 and table 7). Current-meter data also indicate downward movement between the altitudes of 803 to 511 ft (table 7). The altitudes of the top and bottom of the convergence zone indicated by the directional current-meter data at test hole 85 are roughly compatible with the top and

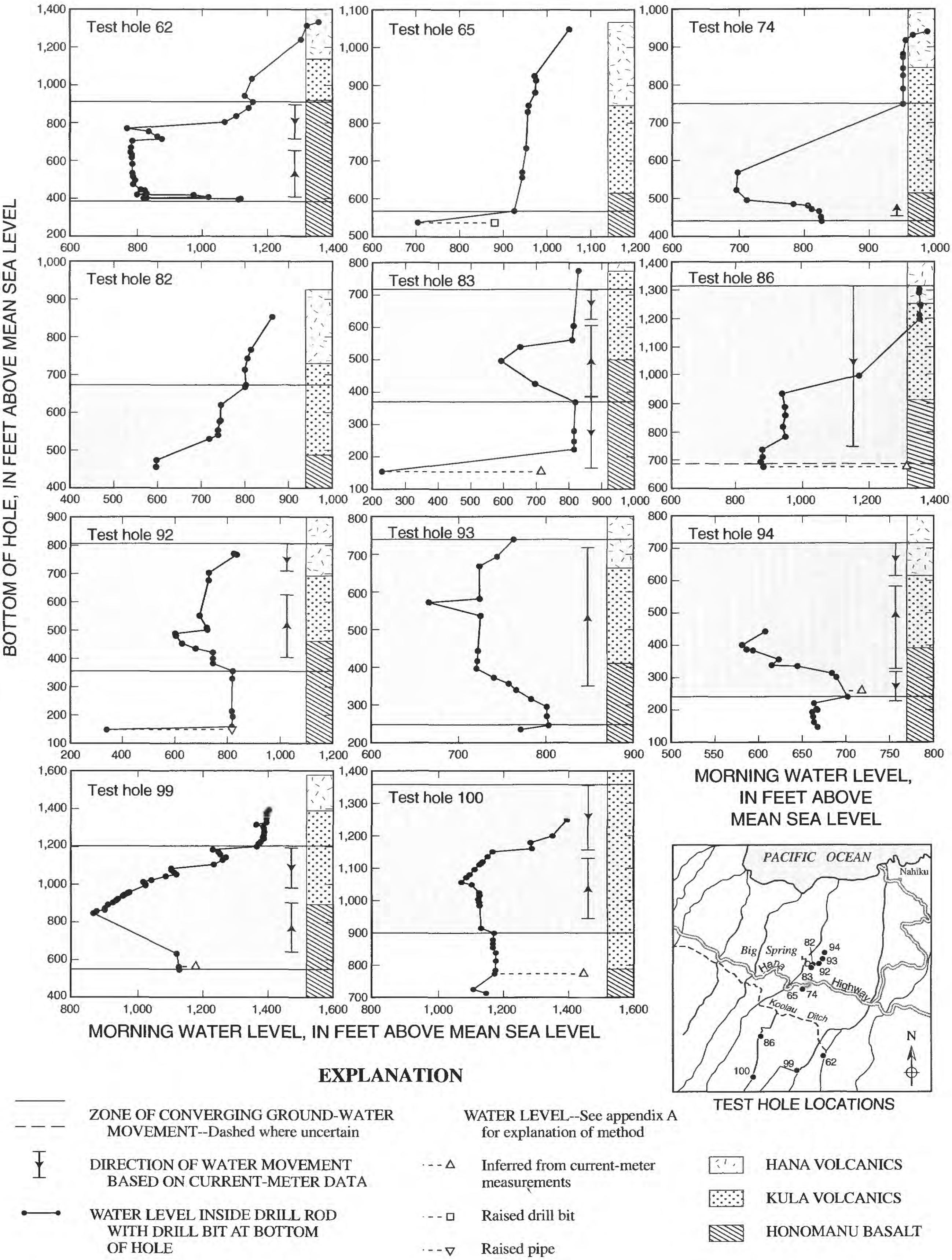


Figure 24. Zone of converging ground-water movement and morning water levels in selected test holes, Nahiku area, Maui, Hawaii.

bottom of the convergence zone indicated at test hole 83.

The estimated altitudes of the top and base of the zone into which water is converging above the artesian water body are shown in figures 25 and 26, respectively, and are also provided in table 7. Not all of the test holes completely penetrated the zone and, as a result, the bottom of the convergence zone could not be determined at these holes. The zone, if continuous, slopes downward toward the ocean at about 10 degrees. The altitude of the top of the zone ranges from 1,355 ft at test hole 100 to 568 ft at test hole 65.

A transect through test holes 100, 99, 62, 74, 85, 83, 92, 93, and 94 indicates that the convergence zone lies wholly within the Kula Volcanics at test hole 100, extends from the Kula Volcanics into the Honomanu Basalt at test hole 99, and is almost wholly within the Honomanu Basalt at test hole 62 (fig. 27). Further downslope it extends from the lower half of the Kula Volcanics to the upper part of the Honomanu Basalt at test hole 74. At test hole 83 the convergence zone extends from the upper two-thirds of the Kula Volcanics to the upper Honomanu Basalt. At test holes 92 and 94, the zone extends from the Hana Volcanics into the Honomanu Basalt. On the basis of current-meter data alone, the downward movement of water at test hole 85 begins several feet above the bottom of the Hana Volcanics while the upward movement begins in the Honomanu Basalt.

The current-meter data in seven of the holes also indicate the existence of a narrow zone (zone of high permeability, fig. 27) in which the upward and downward movement of water was not detected and the lateral movement of water presumably dominates. The convergence of water into this narrow zone suggests that the permeability of the zone is relatively high. The thickness of the high permeability zone ranges from 10 ft at test hole 85 to 103 ft at test hole 92. The zone of high permeability is contained within the Kula Volcanics at all of the test holes except test hole 62, where it is in the Honomanu Basalt.

Given that the general lateral movement of water in the area is toward the major discharge areas, such as streams, springs, and the ocean, the lateral movement of water in the convergence zone probably conforms to this movement. One of the consequences of this movement would be that areas of significant ground-water discharge into Hanawi Stream should occur within the area defined by the intersection of the stream and the convergence zone. The zone of high permeability in the test holes where the horizontal movement of water predominates would be expected to represent an area of relatively significant ground-water discharge even within the larger convergence zone.

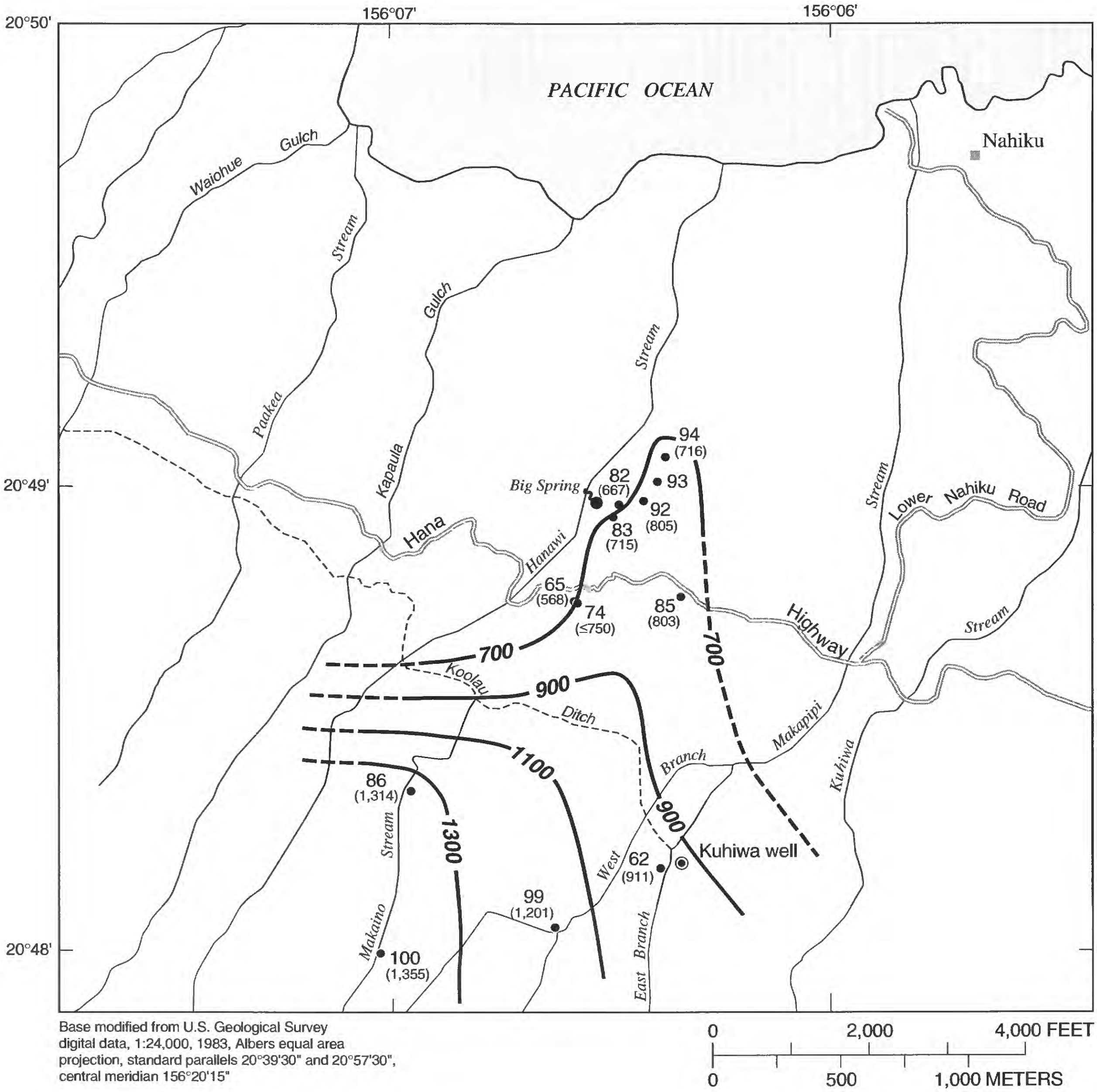
Ground-water discharge into Hanawi Stream increases with descending altitude, and seepage data indicate that most ground water discharges where the stream has eroded onto Kula Volcanics, beginning in the area of Big Spring and extending to the ocean. From Big Spring to site 3 (fig. 11), Hanawi Stream overlies Kula Volcanics, while from site 3 to site 4 (fig. 11) the stream mainly flows on Honomanu Basalt, although Hana and Kula Volcanics are present. This area of ground-water discharge is consistent with the analysis in the preceding paragraphs that indicates the convergence zone lies within the Kula Volcanics and the upper part of the Honomanu Basalt. Even more significantly, the altitude of the zone of high permeability at test hole 83 (625 to 606 ft) which is near Big Spring and the altitude of Big Spring (546 ft) (fig. 27) strongly suggest that water moving in the zone of high permeability is the source of water for Big Spring.

Further support for the relation between the convergence zone and ground-water discharge to Hanawi Stream is available from dye experiments done at test holes 82, 83, and 92 during the test-drilling program. Dye was injected into these holes at altitudes of 576, 554, and 489 ft, respectively, and appeared in Big Spring several hours later. The injection of the dye at test holes 83 and 92 was in the range of altitude where water is moving upward toward the zone of high permeability.

VERTICAL THICKNESS OF THE FRESH GROUND-WATER LENS

The water table increases from an altitude of about 47 ft in the vicinity of test hole 88 to about 1,400 ft in the vicinity of test hole 99 (fig. 16). On the basis of the results of the seepage measurements on Hanawi Stream, the height of the water table can be expected to increase inland from this point to at least 2,100 ft in altitude.

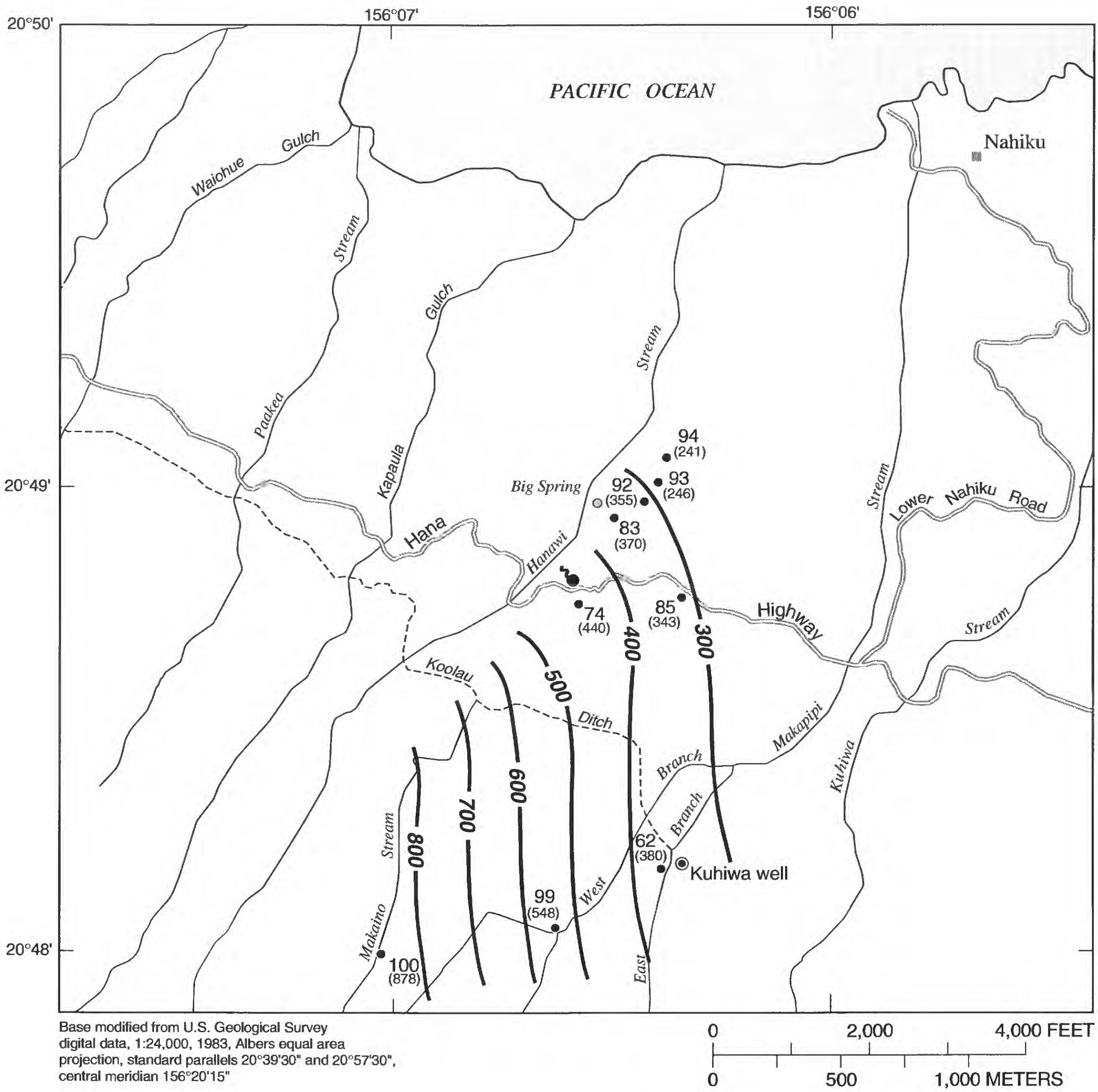
In general, water-table altitudes of the magnitude of those discussed above would be assumed to imply that the thickness of freshwater below sea level is relatively large, assuming that the depth to the freshwater-saltwater interface can reasonably be approximated by the Ghyben-Herzberg relation. Izuka and Gingerich (1998) have shown, however, that in areas where



EXPLANATION

—700— —	LINE OF EQUAL ALTITUDE OF TOP OF CONVERGENCE ZONE--Interval 200 feet. Datum is mean sea level. Dashed where approximate
99 ●	TEST HOLE AND NUMBER
(1,201)	TOP OF CONVERGENCE ZONE, IN FEET ABOVE MEAN SEA LEVEL

Figure 25. Estimated altitude of the top of the convergence zone, Nahiku area, Maui, Hawaii.



EXPLANATION

—400— LINE OF EQUAL ALTITUDE OF BOTTOM OF CONVERGENCE ZONE--Interval 100 feet. Datum is mean sea level

99 ● TEST HOLE AND NUMBER

(548) BOTTOM OF CONVERGENCE ZONE, IN FEET ABOVE MEAN SEA LEVEL

Figure 26. Estimated altitude of the bottom of the convergence zone, Nahiku area, Maui, Hawaii.

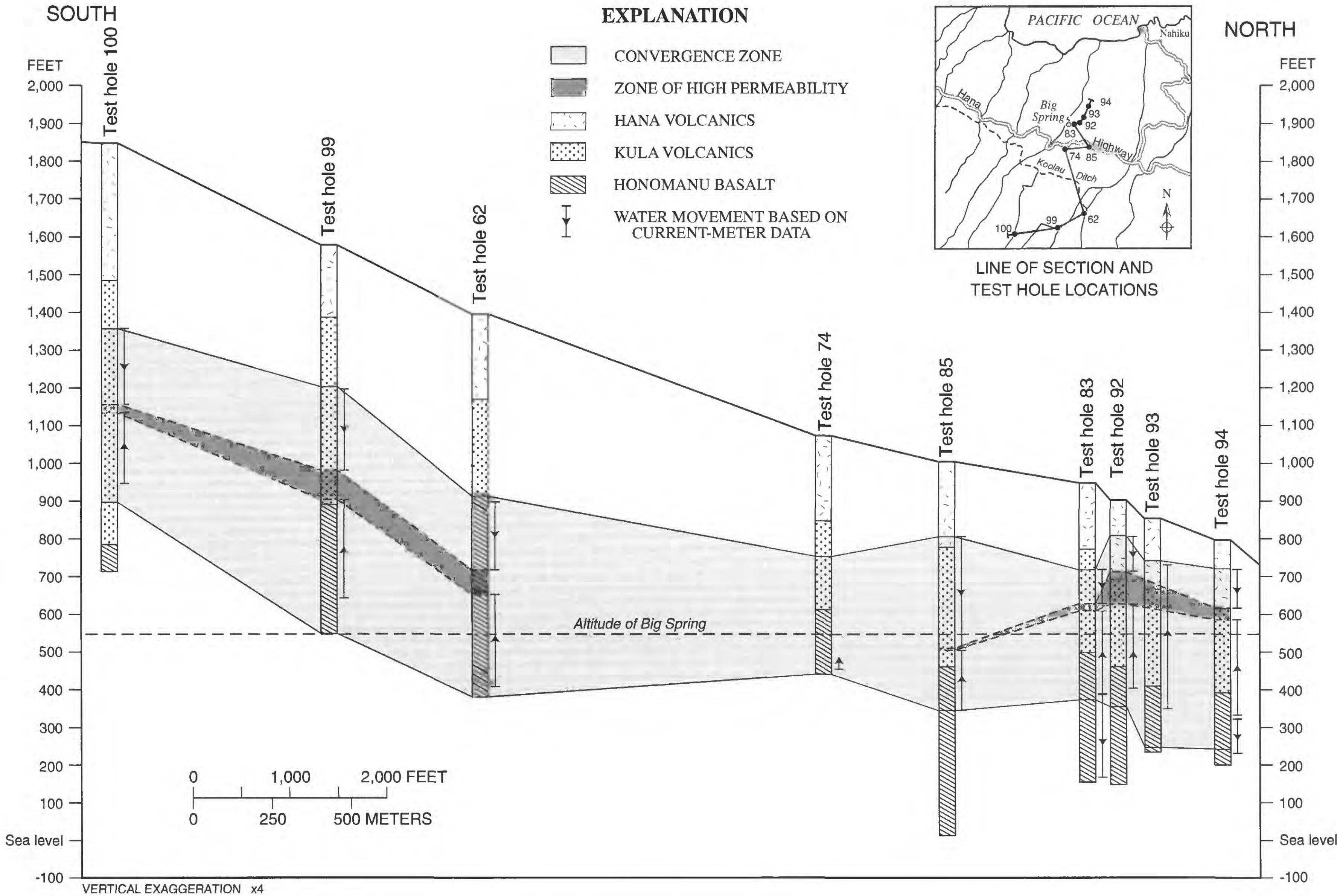


Figure 27. Convergence zone, zone of high permeability, and well logs in selected test holes in the Nahiku area, Maui, Hawaii.

Table 8. Calculated altitude (in feet below sea level) of the midpoint of the transition zone between freshwater and saltwater, Nahiku area, Maui, Hawaii

Test hole	Vertical hydraulic gradient (feet/feet)	Bottom hole altitude (feet)	h_o (feet)	Altitude of the midpoint of the transition zone (feet)
85	0.66	12	344	-502
87	0.60	below sea level	317	-507
88	0.10	below sea level	53	-424
89	0.51	below sea level	223	-417
90	0.42	17	446	-1,002

significant vertical movement of ground water exists (such as in the Nahiku area) the depth to the freshwater-saltwater interface can best be approximated from the relation:

$$z = -h_o / (0.025 + \Delta h/\Delta z), \qquad (1)$$

for:

z = altitude relative to sea level of the midpoint in the transition zone between freshwater and saltwater,

h_o = head in the well at sea level, and

$\Delta h/\Delta z$ = vertical hydraulic gradient measured over the total open interval of the well.

Equation 1 was used to estimate the altitude relative to sea level of the freshwater-saltwater interface at the deepest test holes in the study area and the results (table 8 and fig. 28) are consistent areally. Calculated depth to the interface ranges from 417 ft below sea level at test hole 89 to 1,002 ft below sea level at test hole 90.

HYDRAULIC CHARACTERISTICS OF THE ROCK UNITS

The only information available for the horizontal hydraulic conductivity of the rocks in the Nahiku area is from an aquifer test on Kuhiwa well done by Maui Pineapple, Inc., and the USGS in May 1992. This well is open to the aquifer between the altitudes of 131 to 471 ft above sea level. Results of a 7-day aquifer test, from May 12 through May 19, 1992, indicate an average value for the hydraulic conductivity of the rock between the altitudes tapped by the well of 0.8 ft/d (unpub. aquifer-test archives, U.S. Geological Survey, Honolulu). The horizontal hydraulic conductivity of individual clinker zones in the interval is probably higher.

An estimate of an upper bound for the effective or equivalent vertical hydraulic conductivity of the rock units, K_E (Domenico and Schwartz, 1990, p. 69), can be calculated from water-budget information and the average vertical hydraulic gradients shown in table 5. The average hydraulic gradient over a horizon consisting of many rock units with varying thickness and vertical hydraulic conductivity values would be a function of the rate of water moving vertically through the horizon and the vertical hydraulic conductivity, K_V, and thickness, m, of each rock unit according to the form of Darcy's Law:

$$v_z = K_E\left(\frac{\partial h}{\partial z}\right)_{ave}, \qquad (2)$$

where:

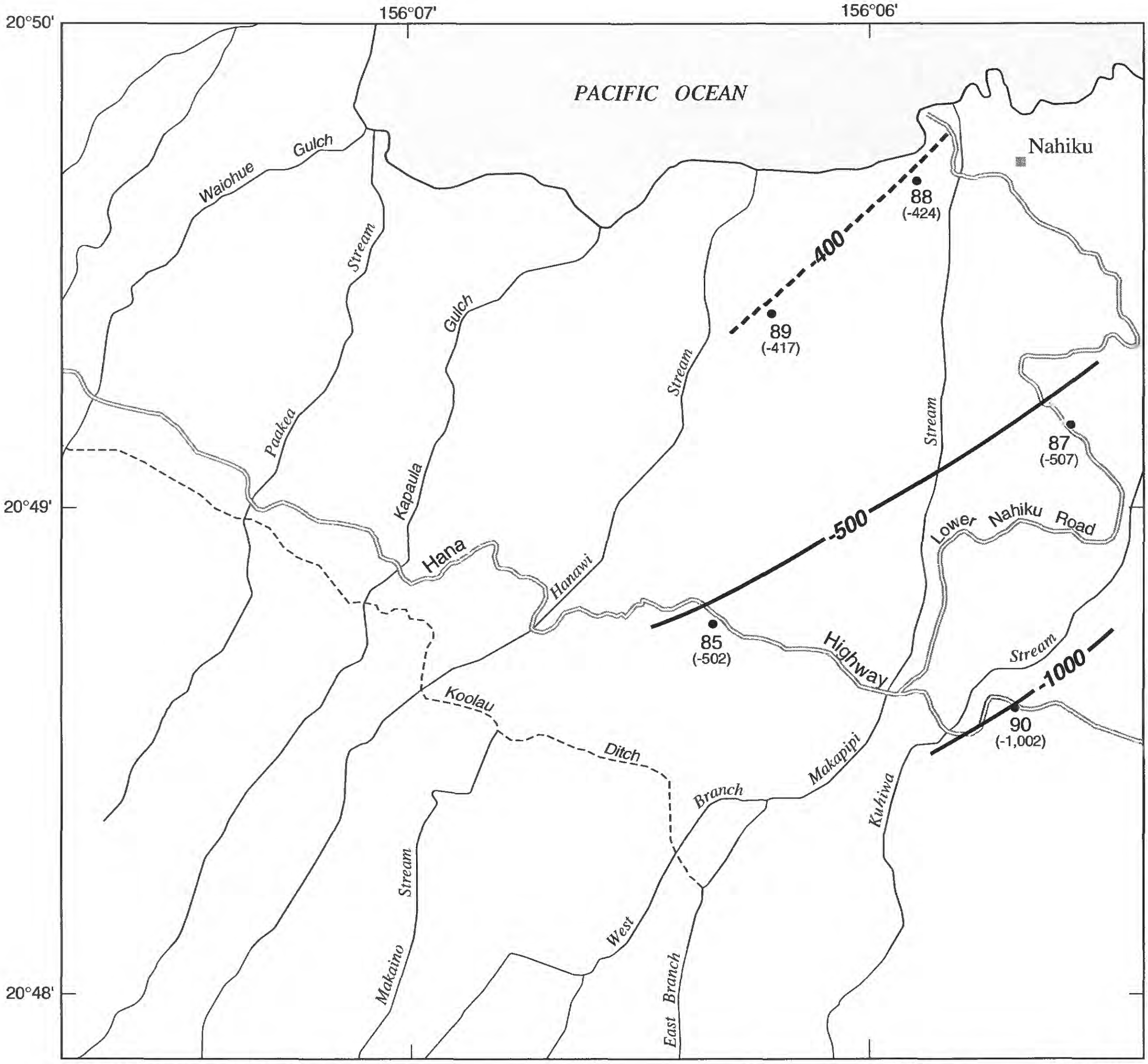
v_z is the vertical rate of ground-water movement per unit area,

$\left(\frac{\partial h}{\partial z}\right)_{ave}$ is average vertical hydraulic gradient, and

K_E is $\dfrac{\sum m_i}{\sum m_i/K_v}$.

For m_i equal to the thickness of an individual layer within the horizon and K_v equal to the vertical hydraulic conductivity of that layer. The summation would be for all layers in the horizon.

Test holes 65, 74, 82, 83, 86, and 93 are all in the Hanawi drainage basin (fig. 2) and above the lower gage (5090) (fig. 11). The average hydraulic gradient for both upward and downward movement calculated for those test holes from table 5 is 0.56. Mean annual recharge above the gage is 37.9 Mgal/d over an area of 13.94×10^7 ft^2 (Shade, 1999). This converts to an average rate of water movement per unit area of 3.7×10^{-2}



EXPLANATION

—-500-- LINE OF EQUAL ALTITUDE OF FRESHWATER-SALTWATER INTERFACE--Interval, in feet, is variable. Datum is mean sea level. Dashed where approximate

87● TEST HOLE AND NUMBER

(-507) ALTITUDE OF FRESHWATER-SALTWATER INTERFACE, IN FEET BELOW MEAN SEA LEVEL

Figure 28. Calculated altitude of the freshwater-saltwater interface, Nahiku area, Maui, Hawaii.

ft/d above the lower gage. The average hydraulic gradient of 0.56 and the average rate of water movement (3.7×10^{-2} ft/d) can be used in equation 2 to solve for K_E. This value of K_E, 0.07, should be considered to be an upper bound on the value of K_E in the area, because at any given location in the flow system, water generally would be moving both horizontally and vertically whereas this calculation assumes only vertical movement of water.

SUMMARY AND CONCLUSIONS

The Nahiku area is underlain by lavas of the Honomanu Basalt, the Kula Volcanics, and the Hana Volcanics. The Hana Volcanics forms the surface of most of the area. Stearns and Macdonald (1942) assumed that the ground-water system in the Nahiku area consists of a succession of perched water bodies in the Kula Volcanics, a perched artesian water body (of limited areal extent) in the upper part of the Honomanu Basalt and a basal water body with water levels 5 to 10 feet above sea level in the Honomanu Basalt. The Hana Volcanics, which overlies the Kula Volcanics, was assumed to be dry as was the Honomanu Basalt outside of the perched artesian aquifer and the basal aquifer. Streams were considered perennial in areas where they intersected perched water bodies in the Kula Volcanics, but otherwise lost water or were intermittent. Springs, which are widespread in the area, were believed to issue from perched water bodies in the Kula Volcanics except at the shoreline where they also issued from the basal aquifer.

The underlying premise of Stearns and Macdonald (1942) for the relationship among geology, streamflow, and ground-water occurrence was that the lava flows of all three rock units were considered highly permeable and unable to perch water. Despite this assumption, Stearns and Macdonald (1942) indicate that the Kula Volcanics, when viewed as a unit, "contains enough more or less impermeable layers, even though discontinuous, to retard greatly the downward percolation of water in areas where 100 to 400 inches of rain falls annually." Stearns and Macdonald state that because high-level water occurred only as perched water in the Kula Volcanics, streamflow was perennial only where streams intersected high-level water. However, they indicate that the source of water to Big Spring was a "perched" artesian water body in the Honomanu Basalt.

In general, the modes of occurrence of ground water in Hawaii have historically been divided into high-level and basal water bodies. Inherent in this description is the assumption that the permeability of the volcanic rocks that constitute the major bulk of the islands is uniformly high (averaging 2,000 feet per day). As a consequence, high-level water bodies are believed to result only from the impedance of the lateral movement of ground water by dikes in rift zones or from the impedance of the vertical movement of ground water by low-permeability features. Water levels in high-level ground-water bodies reach altitudes of several thousand feet above sea level. Basal water bodies with water levels of 30 feet or less form in the flank flows that extend beyond rift zones.

The relatively high value of hydraulic conductivity assumed for the volcanic rocks that form basal aquifers in Hawaii probably results from the young age of the flows and from their limited thickness (less than 10 feet on the average). In many areas of the State, such as east Maui and Kauai, however, the underlying lava flows are relatively thick. In these areas the hydraulic conductivity of the volcanic rocks is much lower (three orders of magnitude) than that normally associated with that of basal aquifers.

The assumption by Stearns and Macdonald (1942) that the lavas of the three rock units underlying the Nahiku area are highly permeable was not founded on field data from this area. In contrast to this assumption, an aquifer test conducted at Kuhiwa well in 1992 yielded a value for the horizontal hydraulic conductivity of the upper 340 feet of the Honomanu Basalt equal to 0.8 feet per day, or about three orders of magnitude lower than values normally assumed for the volcanic rocks in the State.

The alternative concept to that of Stearns and Macdonald (1942) for the occurrence of ground water in the Nahiku area, supported by this report, is that ground water occurs as a vertically extensive water body extending from below sea level into the Hana Volcanics. This concept is based on the assumption that the value for the horizontal hydraulic conductivity of the upper part of the Honomanu Basalt identified by the aquifer test at Kuhiwa well is more representative of the hydraulic properties of the rocks in the area than is the assumption by Stearns and Macdonald (1942) that the rocks are highly permeable, and a reinterpretation of existing data.

Considerable evidence beyond the results of the aquifer test at Kuhiwa well supports the alternative concept for ground-water occurrence. Much of this evidence contrasts sharply with some of the basic conclusions reached by Stearns and Macdonald (1942). Some 100 test holes were constructed during a test-drilling program during the 1930's and 1940's with geologic and hydrologic data reported for 88 of these holes. In general, Stearns and Macdonald's (1942) concept of ground-water occurrence would have been substantiated had holes in each of the three geologic units in the area been dry. However, water was reported in all 88 of the 100 test holes for which hydrologic data were recorded.

Although Stearns and Macdonald (1942) assumed that the rocks of the Hana Volcanics are unsaturated, the results of the test-drilling program indicate that an extensive body of freshwater exists in these rocks throughout the Nahiku area. In addition, despite the assumption by Stearns and Macdonald (1942) that streams overlying the Hana Volcanics are not perennial, streamflow is perennial in streams underlain by the Hana Volcanics owing to the ground-water discharge.

Not only was water found in the Hana Volcanics throughout the area, but the water level in many of the test holes remained above the top of the Kula Volcanics as the holes were deepened from the Hana and Kula Volcanics into the Honomanu Basalt in areas outside of the artesian water body. This result would not be possible if the occurrence of ground water in the area were consistent with the concept of Stearns and Macdonald (1942). Such a result requires that either (1) numerous perched water bodies exist throughout the stratigraphic column from the Hana Volcanics to the bottom of the test holes in the Honomanu Basalt, and cascading water into the holes maintains a water level above the top of the Kula; or (2) the rocks are saturated from the Hana Volcanics on down. Either of these conclusions would present a different conceptual framework of ground-water occurrence in the area than that of Stearns and Macdonald (1942), but given the lack of interstratified perching beds in the Hana Volcanics and the Honomanu Basalt, the first interpretation is the least likely.

Water remained in the test holes once encountered and the amount of water in the holes generally increased as each hole was deepened. These results are consistent with the concept that the area is underlain by a vertically extensive water body. The Stearns and Macdonald (1942) mode of ground-water occurrence would require the test holes to be dry in the Hana Volcanics and contain water when perched water bodies were encountered in the Kula Volcanics. Below these bodies the amount of water in the borehole would be expected to decrease. Ultimately as the hole was deepened to greater depths into unsaturated but presumably permeable rock, the Stearns and Macdonald mode of ground-water occurrence requires a dry hole or cascading water from perched water bodies above the bottom of the hole could cause the presence of a limited, but decreasing amount of water in the borehole.

Five test holes and Kuhiwa well were drilled to depths near to or below sea level and water levels in these holes failed to identify the existence of a basal water body with water levels 5 to 10 feet above sea level. Water levels ranged from 47 feet at a distance of about 300 feet from the ocean to 1,126 feet at Kuhiwa well located about 2 miles inland of the ocean, which further supports the existence of a vertically extensive ground-water system.

The results of a numerical model of the Hanawi Stream basin indicate that a vertically extensive ground-water body is possible with water levels consistent with those obtained from the test-drilling program (Gingerich, 1998). The numerical model used values of the hydraulic properties of the rocks obtained for the Honomanu Basalt from the Kuhiwa well aquifer test and the effective vertical hydraulic conductivity of the rocks discussed in this report. Precipitation in the area ranges from 160 to 350 inches per year and about 60 percent of this becomes ground-water recharge (Shade, 1999). The simulated vertically extensive ground-water body results directly from the combination of high ground-water recharge rates, the low hydraulic conductivity of the rocks, and the geometry of the ground-water flow system.

The general movement of ground water in the area, assuming a vertically extensive water body, is laterally toward the ocean and streams and vertically downward. The vertical movement of the water is generally downward outside of the artesian water body except in the artesian water body and near the ocean where movement is upward. The water body extends from below sea level up into the Hana Volcanics. The water table is in the Hana Volcanics and ranges in altitude from about 47 feet near the shoreline to about 1,400 feet 2 miles inland. The artesian water body is in the upper part of the Honomanu Basalt and has limited areal extent.

The area of greatest ground-water discharge into Hanawi Stream, including Big Spring, corresponds to a zone of high permeability located an average 220 feet above the artesian water body into which water is moving from above and below. The vertical zone in which water is converging toward the high permeability zone is large, 420 feet on average. The bottom of this zone is the artesian water body while the top is demarked by a horizon wherein water levels abruptly declined as test holes were deepened.

Despite the relatively high water table in the area, the depth to the freshwater-saltwater interface is probably much less than that which would be predicted from the Ghyben-Herzberg equation. This results from the loss of head in the vertical direction which averages about 0.47 feet per feet.

In conclusion, the preponderance of hydrologic data supports the existence of a vertically extensive aquifer in the Nahiku area, east Maui, and that the source of Big Spring is a large zone of high permeability adjacent to the spring. This research and the work of Izuka and Gingerich (1998) on the island of Kauai may indicate that vertically extensive aquifers are much more prevalent than previously thought; therefore, this concept could be further explored as a controlling mechanism for ground-water movement and occurrence on other volcanic islands.

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APPENDIX A: METHOD OF WATER-LEVEL DATA COLLECTION AND WATER LEVELS IN SELECTED TEST HOLES

Method of Water-Level Data Collection

The water-level data and descriptions of methods for collecting the data comes from unpublished well logs on file at the USGS, Honolulu. As discussed in the section "Water levels in the Hana Volcanics," water-level data were collected in 88 of the 100 test holes and although the procedure for collecting water-level data was not consistent, water levels were measured each day in the deeper test holes as drilling progressed. Water levels generally were measured in the test holes before the start of the day's drilling although some measurements also were made at the end of the day. For the most part, water-level measurements were made through the center of the drill rod after the drill string was lowered to the bottom of the hole. The core bit usually was at the bottom of the hole or within a foot or so of the bottom when the water level was measured.

Water levels measured inside the drill rod with the drill rod lowered to a given depth in a borehole probably provide a closer approximation of the composite head in the borehole below the drill bit than of the water level in the entire borehole. This is because the annular space between the drill rod and the borehole was only $^{3}/_{32}$ in. (the diameter of the borehole was 1-$^{1}/_{2}$ in. and the outside diameter of the drill rod was 1-$^{5}/_{16}$ in.). Given this small annular space between the borehole and the drill rod, and the length of borehole the drill rod occupied when the measurements were made, it is reasonable to expect a measurable resistance to vertical flow and some head loss as a result.

In a ground-water flow system wherein heads decline with depth, as in the Nahiku area outside the artesian water body, the water level in an open borehole completed to a given depth will be some composite of the heads encountered to that depth. As drilling progresses, water levels will decline in the borehole because the composite head will decline. Because heads are declining with depth, and because the water level in the borehole is some composite of the range in head over the length of the borehole, the water level in the borehole would be expected to always be below the actual water table. The head at the bottom of the hole would be the lowest head in the hole. Because the water level in the boreholes was measured inside the drill rod with the drill bit at or near the bottom of the hole, it is reasonable to assume that the resulting value of water level more closely approximates the head at the bottom of the hole than the composite water level that would exist in an open borehole of the same depth.

Water-level measurements made in five test holes (65, 85, 87, 90, 92) completed in the Honomanu Basalt support the concept that the water level measured inside the drill rod with the bit at the bottom of the hole was the lowest head in the hole. These measurements showed that water levels in the boreholes were actually higher than that indicated by the measurement inside the drill rod with the bit at the bottom of the hole. Following the measurement of the water level in these holes with the drill bit at the bottom of the hole, water levels also were measured in one of the following two ways: (1) For selected hole depths (generally the final hole depth), the water level was recorded inside the drill bit with the bit at the bottom of the hole after which the bit was raised from the bottom of the hole and the water level inside the drill rod was measured at successively higher altitudes in the borehole; or (2) water-level measurement was made as in (1) but a 1-in. pipe was initially inserted to the bottom of the hole. These two methods of measurement indicated that water levels were significantly higher in the boreholes than those measured inside the drill rod with the bit at the bottom of the hole. The highest water levels were associated with the highest altitudes of either the drill bit or the pipe. The difference between the water level measured with the drill bit at the bottom of the hole and that measured using the above techniques ranged from 171 to 493 ft and averaged 325 ft (table A1).

The annular space between the borehole and the 1-in. pipe (0.25 in.) was greater than that between the drill rod and the borehole (3/32 in.) so that less resistance to vertical flow would be expected for a pipe measurement as compared with the measurement obtained inside the drill rod. Of interest is that both techniques indicated that head measured at any point in the borehole was higher than that measured at the bottom of the hole. Neither measurement technique would have been expected to indicate the actual or composite water level in the entire open borehole. Presumably, it was higher than that indicated by either of these techniques. A detailed discussion of the water-level measurements made in test holes 65, 85, 87, 90, and 92 is provided in the next section (Water Levels in Selected Test Holes").

Data obtained from the use of a current meter lowered in selected holes completed in the Honomanu

Table A1. Water levels measured inside the drill rod with the bit at the bottom of the hole and using alternative methods at selected hole depths in 12 test holes completed in the Honomanu Basalt, Nahiku area, Maui, Hawaii

[Values in feet; datum is mean sea level; 1 and 2 indicate method of water-level measurement; 1, bit at bottom; 2, alternative method; datum is mean sea level. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Test hole	Location	Land surface altitude	Hole depth	Bottom of hole altitude	Depth in Honomanu Basal	Depth to water		Altitude of water level		Water level relative to top of Kula Volcanics		Water level above bottom of hole		Difference between methods 1 and 2 for measuring water level above bottom of hole [2 – 1]	Alternative method used
						1	2	1	2	1	2	1	2		
83	artesian	945	790	155	343	709	230	236	715	-536	-57	81	560	479	current meter
92	artesian	902	754	148	312	561	86	341	816	-350	125	193	668	475	raised bit to depth of 649 ft
94	artesian	796	596	200	191	130	98	666	698	52	84	466	498	32	current meter
99	artesian	1,578	1,024	554	337	451	385	1,127	1,193	-260	-194	573	639	66	current meter
100	artesian	1,845	1,072	773	12	669	400	1,176	1,445	-307	-38	403	672	269	current meter
65	above artesian	1,066	529	537	77	362	184	704	882	-144	34	167	345	178	raised pipe to depth of 190 ft
86	above artesian	1,494	817	677	233	614	180	880	1,314	-371	63	203	637	434	current meter
12	outside artesian	1,282	806	476	170	508	200	774	1,082	-344	-36	298	606	308	current meter
87	outside artesian near to or below sea level	465	738	-273	312	415	105	50	360	-157	153	323	633	310	raised bit to depth of 175 ft
90	outside artesian near to or below sea level	864	847	17	243	411	240	453	624	30	201	436	607	171	raised bit to depth of 300 ft
97	outside artesian	826	595	231	232	345	298	481	528	-45	2	250	297	47	current meter
85	near to or below sea level	1,003	991	12	448	666	173	337	830	-440	53	325	818	493	raised pipe to depth of 791 ft

Basalt also indicated that water levels in the borehole were higher than the value obtained from the water-level measurement inside the drill rod with the bit at the bottom of the hole. A directional current meter was lowered into the water column in some of the boreholes and used to determine the direction of water movement at selected altitudes within the column. Although the water level was not directly measured during this procedure, the presence of moving water at a given altitude was detected. It was possible to compare the water level measured inside the drill rod with the bit at the bottom of the hole to the highest altitude of water in the borehole where water movement was recorded in seven of the test holes (12, 83, 86, 94, 97, 99, and 100). The latter altitudes were always greater than the former. Differences ranged from 32 to 479 ft and averaged 234 ft (table A1). A detailed discussion of the data obtained from the use of the directional current meter is also contained in the next section ("Water Levels in Selected Test Holes").

Water Levels in Selected Test Holes

Water-level data collected at test hole 90 demonstrates that the altitude of the water level inside the drill rod increased as the drill rod was raised 547 ft from the bottom of this hole (table A2). The altitude of the water level in test hole 90 generally declined as the hole was being drilled. The altitude of the water level with the drill rod at the bottom of the hole was 453 ft. Following completion of the hole, the drill rod was raised from the bottom and the depth to water recorded at selected altitudes in the hole as the drill rod was raised. The altitude of the water level measured inside the drill rod increased from 453 to 624 ft as the drill rod was raised 544 ft. The total increase in the altitude of the water level in the borehole was 171 ft.

A somewhat similar set of data is available from test hole 65. As with test hole 90, the altitude of the water level in the test hole generally decreased as the test hole was deepened. A $^3/_4$-inch pipe was inserted into the hole after the hole was completed, and water levels were measured as the pipe was progressively raised to higher altitudes in the hole (table A3). The altitude of the water level measured inside the pipe increased from 704 to 882 ft as the pipe was raised 336.

The relation between the altitude of the water level and the depth of the pipe or drill rod is just the opposite of that which would be expected if the displacement of water by the drill rod (or pipe) played a major role in the depth of water inside the drill rod. The observed relation is consistent, however, with what would be expected if the rocks are saturated below the first water encountered during drilling and the general movement of water is downward.

These results indicate that, for those test holes in which water levels generally declined as the test holes were deepened, the actual water level in the test hole may have been higher, and perhaps much higher, than that obtained with the drill bit on the bottom of the hole. Other test holes for which there is data that pertain to this discussion are test holes 85, 87, 92, 12, 83, 86, 94, 97, 99, and 100.

The altitude of the water level measured inside the drill rod with the bit at the bottom of the hole at test hole 87 was 50.3 ft at the final hole depth of 737.8 (272.8 ft below sea level) (table A4). Another water-level measurement was made the following day with the drill bit at 562.8 ft above the bottom of the hole. The altitude of the water level was 360 ft, or 309.7 ft higher than the water level measured with the bit at the bottom of the hole.

The altitude of the water level measured inside the drill rod at test hole 92 ranged from 820 to 817 ft for bottom hole altitudes ranging from about 330 to 157 ft (table A5). At a final bottom hole altitude of 148 ft, the altitude of the water level decreased to 341 ft. The altitude of water level measured 2 days after completion of the test hole was 816 ft. This measurement was made with the drill bit at an altitude of 253 ft which is 105 ft above the bottom of the hole. The difference between the two water-level measurements (475 ft) could indicate a lower hydraulic head at the final hole depth or a transient filling of a "hole" reported by the driller between the altitudes of 151 and 148 ft.

The altitude of the water-level measurement at test hole 85 was 337 ft at the final bottom hole altitude of 12 ft. This water-level measurement was made inside a 1-in. pipe lowered to the bottom of the hole (table A6). Following this measurement, the pipe was removed from the hole and reinserted. The hole was bridged at an altitude of 205 ft, however, precluding the possibility of lowering the pipe to the bottom. Iron filings, salt, and humus were used to fill the hole between the altitudes of 12 to 212 ft after which the pipe was lowered to an altitude of 212 ft. The altitude of the water level measured inside the pipe at this depth was 830 ft.

Table A2. Selected water-level measurements at test hole 90, Nahiku area, Maui, Hawaii
[--, not measured. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Date	Hole depth (feet)	Bottom hole altitude (feet)	Method of measurement	Depth to drill bit (feet)	Depth to water (feet)	Water-level altitude (feet)
Aug. 20, 1942	180.5	683.5	chop bit	179	130.6	733.4
Aug. 21, 1942	191.4	672.6	chop bit	190	131	733.0
Aug. 22, 1942	211.5	652.5	chop bit	211.5	--	--
Aug. 29, 1942	261.8	602.2	chop bit	259	212.6	651.4
Sept. 3, 1942	281.9	582.1	chop bit	279	231.5	632.5
Sept. 4, 1942	281.9	582.1	chop bit	279	231.5	632.5
Sept. 5, 1942	299.3	564.7	chop bit	299	231.5	632.5
Sept. 7, 1942	307.8	556.2	chop bit	304.5	231.5	632.5
Sept. 8, 1942	312.1	551.9	chop bit	312.1	231.5	632.5
Sept. 9, 1942	322.7	541.3	chop bit	319	231.5	632.5
Sept. 10, 1942	338.5	525.5	chop bit	338.5	230.1	633.9
Sept. 12, 1942	359.2	504.8	chop bit	359.2	227.1	636.9
Sept. 14, 1942	371.1	492.9	chop bit	369	223.4	640.6
Sept. 15, 1942	385.4	478.6	chop bit	385.4	226.4	637.6
Sept. 16, 1942	402.8	461.2	chop bit	399	231.8	632.2
Oct. 26, 1942	516.3	347.7	diamond bit	514	402.8	461.2
Oct. 27, 1942	529.7	334.3	diamond bit	529	407.1	456.9
Dec. 7, 1942	830.3	33.7	diamond bit	829	412.5	451.5
Dec. 9, 1942	847.3	16.7	diamond bit	844	411	453.0
Dec. 9, 1942	847.3	16.7	diamond bit	700	413.4	450.6
Dec. 9, 1942	847.3	16.7	diamond bit	600	413.4	450.6
Dec. 9, 1942	847.3	16.7	diamond bit	500	412	452.0
Dec. 9, 1942	847.3	16.7	diamond bit	400	262.4	601.6
Dec. 9, 1942	847.3	16.7	diamond bit	300	240	624.0

Table A3. Selected water-level measurements at test hole 65, Nahiku area, Maui, Hawaii
[--, not known. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Date	Hole depth (feet)	Bottom hole altitude (feet)	Method of measurement	Depth to bottom of pipe (feet)	Depth to water (feet)	Water-level altitude (feet)
Aug. 19 (1937?)	18	1,048	--	--	15	1,051
Sept. 6 (1937?)	140	926	--	--	93	973
Sept. 20 (1937?)	152	914	--	--	90	976
Sept. 29 (1937?)	171	895	--	--	99	967
Nov. 11 (1937?)	395	671	--	--	121	945
Nov. 12 (1937?)	409	657	--	--	121	945
--	529	537	$^{3}/_{4}$-inch pipe	526	362	704
--	529	537	$^{3}/_{4}$-inch pipe	426	349	717
--	529	537	$^{3}/_{4}$-inch pipe	306	280	786
--	529	537	$^{3}/_{4}$-inch pipe	232	221	845
--	529	537	$^{3}/_{4}$-inch pipe	190	184	882
--	529	537	$^{3}/_{4}$-inch pipe	148	no water	--

Table A4. Selected water-level measurements at test hole 87, Nahiku area, Maui, Hawaii
[--, no data. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Date	Hole depth (feet)	Bottom hole altitude (feet)	Method of measurement	Depth of drill bit (feet)	Depth to water (feet)	Water-level altitude (feet)
Mar. 6, 1942	84.4	380.6	blow	--	78.6	386.4
Mar. 6, 1942	194.2	270.8	chop bit	194.2	89.5	375.5
Mar. 19, 1942	356.3	108.7	diamond bit	356.3	82.9	382.1
Mar. 19, 1942	375.9	89.1	blow	--	77.6	387.4
Mar. 21, 1942	415.4	49.6	blow	--	78.6	386.4
Mar. 23, 1942	445	20	blow	--	71	394.0
Mar. 25, 1942	502	-37	blow	--	76	389.0
Mar. 26, 1942	502	-37	chop bit	502	102	363.0
Mar. 27, 1942	521.7	-56.7	diamond bit	521.7	101.9	363.1
Mar. 28, 1942	529.7	-64.7	diamond bit	529.2	102.7	362.3
Mar. 28, 1942	540.3	-75.3	diamond bit	540.3	102.5	362.5
Mar. 30, 1942	545.1	-80.1	chop bit	545.1	104	361.0
Mar. 31, 1942	558	-93	diamond bit	558	104.3	360.7
Mar. 31, 1942	574.6	-109.6	chop bit	574.6	104.1	360.9
Mar. 31, 1942	574.6	-109.6	chop bit	528	103.6	361.4
Mar. 31, 1942	574.6	-109.6	chop bit	348	100.1	364.9
Apr. 1, 1942	579.6	-114.6	chop bit	579.6	102.2	362.8
Apr. 2, 1942	588.6	-123.6	diamond bit	588.6	106.3	358.7
Apr. 2, 1942	600.1	-135.1	diamond bit	600.1	105	360.0
Apr. 3, 1942	603.4	-138.4	diamond bit	603.4	97.1	367.9
Apr. 3, 1942	608.6	-143.6	diamond bit	348	94.6	370.4
Apr. 4, 1942	615.3	-150.3	diamond bit	615	135.9	329.1
Apr. 6, 1942	623.3	-158.3	chop bit	623	127.5	337.5
Apr. 6, 1942	639	-174	diamond bit	638.7	107.5	357.5
Apr. 7, 1942	639	-174	diamond bit	638.7	107.5	357.5
Apr. 7, 1942	645.2	-180.2	diamond bit	645	113.4	351.6
Apr. 7, 1942	655.1	-190.1	diamond bit	655	123.5	341.5
Apr. 8, 1942	655.1	-190.1	diamond bit	655	122.5	342.5
Apr. 8, 1942	666.3	-201.3	diamond bit	665	123.9	341.1
Apr. 9, 1942	692	-227	diamond bit	690	193.3	271.7
Apr. 10, 1942	690	-225	diamond bit	690	193.3	271.7
Apr. 11, 1942	707	-242	diamond bit	705	188.7	276.3
Apr. 11, 1942	724	-259	diamond bit	723.7	191.2	273.8
Apr. 14, 1942	724	-259	diamond bit	724	188.6	276.4
Apr. 16, 1942	732	-267	chop bit	--	183.6	281.4
Apr. 17, 1942	732	-267	chop bit	732	415	50.0
Apr. 17, 1942	737.8	-272.8	diamond bit	737	414.7	50.3
Apr. 18, 1942	737.8	-272.8	blow	--	84	381.0
Apr. 18, 1942	737.8	-272.8	chop bit	175	105	360.0

Table A5. Selected water-level measurements at test hole 92, Nahiku area, Maui, Hawaii
[Datum is mean sea level; data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Date	Hole depth (feet)	Bottom hole altitude (feet)	Method of measurement	Depth of drill bit (feet)	Depth to water (feet)	Water-level altitude (feet)
Mar. 17, 1943	467	435	chop bit	464	222	680
Mar. 18, 1943	481	421	chop bit	479	157	745
Mar. 23, 1943	502	400	diamond bit	499	157	745
Mar. 24, 1943	519	383	diamond bit	518	157	745
Mar. 31, 1943	572	330	diamond bit	569	85	817
Apr. 9, 1943	681	221	diamond bit	684	85	817
Apr. 10, 1943	707	195	diamond bit	704	82	820
Apr. 16, 1943	745	157	diamond bit	744	85	817
Apr. 17, 1943	754	148	diamond bit	752	561	341
Apr. 19, 1943	754	148	chop bit	649	86	816

Table A6. Selected water-level measurements at test hole 85, Nahiku area, Maui, Hawaii
[Datum is mean sea level; --, no data. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Date	Hole depth (feet)	Bottom hole altitude (feet)	Method of measurement	Depth to drill bit or pipe bottom (feet)	Depth to water (feet)	Water-level altitude (feet)
Jan. 10, 1941	517	486	drill bit	517	103	900
--	804	199	drill bit	--	103/104	899
--	804	199	1-inch pipe	804	174	829
Apr. 3, 1941	865	138	diamond bit	865	176	827
Apr. 8, 1941	900	103	diamond bit	900	250	753
Apr. 12, 1941	951	52	diamond bit	951	424	579
--	991	12	1-inch pipe	991	666	337
--	991	12	1-inch pipe	[1]791	173	830

[1] Iron filings were used to fill hole from 991 to 791 feet prior to water-level measurement. Driller notes that a little humus and salt were added from time to time as the filings were placed in hole

Table A7. Depth-to-water measurements made inside the drill rod and inferred from current-meter measurements at selected test holes, Nahiku area, Maui, Hawaii
[Values in feet; datum is mean sea level; data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Test hole	Hole depth	Bottom hole altitude	Depth to water inside drill bit	(A) Water-level altitude inside drill bit	Depth to water inferred from current-meter measurement	(B) Water-level altitude inferred from current-meter measurement	Difference between columns (A) and (B) [(B) – (A)]
12	806	476	508	774	200	1,082	308
83	790	155	768	177	230	715	479
86	817	677	614	880	180	1,314	434
94	596	200	130	666	98	698	32
97	595	231	345	481	298	528	47
99	1,024	554	451	1,127	385	1,193	66
100	1,072	773	669	1,176	400	1,445	269

The data from test holes 12, 83, 86, 94, 97, 99, and 100 that pertain to this discussion are current-meter measurements that were made when these holes were completed, or, for selected hole depths, while drilling was in progress. To measure the direction of water movement, a directional current meter was placed at the bottom of the drill string and lowered into the hole. Current-meter measurements were then made at selected depths in each hole. Although as previously noted, the water level was not directly measured during this procedure, the presence of moving water was detected at specific altitudes. A comparison of the water level measured inside the drill rod with the bit at the bottom of the hole to the highest altitude of water in the borehole where water movement was recorded during the current-meter measurements indicated that the latter measurement was always greater than the former (table A7). The difference between the altitude of the water level measured at or near the bottom of test holes 12, 83, 86, 94, 97, 99, and 100 as indicated by measurements inside the drill rod and highest altitude of the water level in the borehole as indicated by current-meter measurements was 308, 538, 434, 32, 47, 66, and 269 ft, respectively.

As shown in table A7, the altitude of the water level measured inside the drill rod at test hole 12 at a bottom hole altitude of 476 ft was 774 ft. Current-meter measurements made in the hole at this depth, however, indicated water moving downward between the altitudes of 1,082 to 492 ft thereby indicating the presence of water some 308 ft above that indicated by the measurement inside the drill rod.

The altitude of the water level measured inside the drill rod in test hole 83 (table A7) at the final bottom hole altitude of 155 ft was 236 ft. Current-meter measurements made in this hole 1 day after its completion indicated upward flow in the hole between the altitudes of 387 to 715 ft. This would indicate that the water level in the test hole was at least 479 ft higher than that indicated by the measurement inside the drill rod.

The altitude of the water level measured inside the drill rod at test hole 86 (table A7), at its final bottom hole altitude of 677 ft was 880 ft. Current-meter measurements made following completion of the hole, however, indicated that water was moving downward between the altitudes of 1,314 to 748 ft. Assuming a water level of at least 1,314 ft in the test hole, the difference between this value and that obtained from inside the drill rod at the bottom of the hole is 434 ft.

The altitude of the water level measured inside the drill rod at test hole 94 (table A7), at a bottom hole altitude of 200 ft was 666 ft. Current-meter measurements made at this hole depth indicated that water was moving downward between the altitudes of 698 to 618 ft indicating that the water level in the hole was at least 698 ft, or 32 ft higher than that indicated by the measurement inside the drill rod.

The altitude of the water level measured inside the drill rod at test hole 97 (table A7) was 481 ft at a bottom hole altitude of 231 ft. Current-meter measurements indicated that water began moving downward at an altitude of 528 ft, however, which would suggest that the altitude of the water level was at least 47 ft higher than that indicated by the drill rod measurement.

The altitude of the water level measured inside the drill rod in test hole 99 (table A7) at a bottom hole altitude of 554 ft was 1,127 ft. Current-meter measurements obtained at this depth, however, indicated water movement in the hole at 1,193 ft altitude, or 66 ft higher than the water level obtained inside the drill rod.

The altitude of the water level in test hole 100 (table A7) measured inside the drill rod at a bottom hole altitude of 773 ft was 1,176 ft. Current-meter measurements, however, indicated that water began to move downward at an altitude of 1,445 ft.

The data shown in table A7 indicate that the actual water level in the hole was probably higher and potentially hundreds of feet higher than the measurement made inside the drill rod with the drill bit at the bottom of the hole.

All of the water levels in the test holes described above support the existence of the vertically extensive ground-water system.

APPENDIX B: GENERAL CONSIDERATIONS IN THE USE OF THE WATER-LEVEL DATA

The main points in the previous discussion on the method for collecting water-level data are, for a ground-water flow system in which the movement of water is downward and heads decline with depth, (1) the water table and the composite head in the test hole (assuming an open hole) would be expected to be at higher altitudes than that indicated by the water level measured inside the drill rod with the bit at the bottom of the hole, and (2) the water level measured inside the drill rod with the bit at the bottom of the hole can only be assumed to approximate the head at the bottom of the hole. Despite these restrictions on the accuracy of the water-level data it can still be used as described below to examine the occurrence of ground water.

The first reported water levels in the test holes can be considered to closely approximate the water table in the area. Also, if water remained in the test holes as they were bored through the Hana Volcanics, clearly the presence of water in the Hana Volcanics is indicated.

In general, the remaining use of water levels measured inside the test holes with the bit at the bottom of the hole addresses the relations between water levels measured in the test holes and the geologic framework. In particular, it addresses the relation between the altitude of the water level measured inside the drill rod with the bit at the bottom of the hole at a given hole depth and the altitude of the top of the Kula Volcanics or the Honomanu Basalt. Absolute values are stated in this regard, but the significance of the discussion is not with regard to the absolute value.

The water level that would be used to assess this situation discussed immediately above would be the composite water level in the open borehole and not the hydraulic head at the bottom of the hole. The previous discussion on the accuracy of the water-level measurements indicated that the water level measured with the drill bit at the bottom of the hole represents a minimum value for the water level in the hole at a given depth. Thus, if the water level measured inside the test hole with the bit at the bottom of the hole indicates that the water level is above the top of the Kula Volcanics in a given test hole, then the composite water level in the hole should be above the top of the Kula also.

APPENDIX C: EFFECT OF DRILLING ON WATER-LEVEL MEASUREMENTS

Drilling imposes a stress on the ground-water system with the result that a difference may exist between water levels in the ground-water body before drilling and those measured during drilling. Factors that can influence this potential difference include, (1) the introduction of drilling fluid under pressure, (2) cascading water, (3) displacement of water by the drill string prior to measurement, and (4) movement of water in the open hole (both upward and downward at altitudes below the water level in the hole).

Introduction of Drilling Fluid Under Pressure

Ground water was encountered at shallow depths throughout the area and once present it remained in the test holes. The introduction of drilling fluid under pressure causes an upward movement of the drilling fluid and ground water in the annulus of the hole. As a result, ground water is effectively being pumped. Circulation of water and drilling fluid may continue to the surface, or may be lost in some permeable zone in the borehole, thereby introducing water into this area. It was not uncommon for the driller to report the presence of "leaks" as some holes were drilled in the EMI test-drilling program. This is particularly true for test holes in the area between Makapipi and Kuhiwa Streams. Such leaks were places where significant drilling pressure and thus fluid was lost. Water levels in the test holes often declined when these zones were encountered, although in some instances the decline was temporary. Even so, virtually all significant water-level declines in the test holes occurred under such circumstances.

Some indication of the possible effect that the introduction of drilling fluid under pressure may have had on water levels measured in the test hole can be discerned by comparing water levels measured at the end of the day's drilling to those measured before drilling the next morning. Wells, dates, and water levels for which this comparison can be made are shown in table C1. For example, the water level in test hole 89 was measured on the afternoon of July 3, 1942 at 3:00 pm. Test hole depth was 320 ft. Depth to water in the hole was 120.5 ft. An identical water level was measured the next morning before drilling. Also shown in table C1 are water levels measured over a period of 2 or 3 days after drilling temporarily ceased. For example, the water level in test hole 90 was measured the morning of October 3, 1942 at a hole depth of 486.3 ft. The water level was 248.7 ft. The water level measured on October 5, 1942 before additional drilling was the same as that measured on October 3.

If the introduction of drilling fluid under pressure caused a substantial change in the water level in a borehole from that prior to drilling, then water levels should have begun to measurably change after drilling stopped. This change could possibly continue for several months or more, but even so, water levels measured the next morning or several mornings after drilling ceased should indicate the presence of the

Table C1. Depth to water in selected test holes for selected hole depths and times, Nahiku area, Maui, Hawaii
[Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Test hole	Date	Time	Hole depth (feet)	Depth to water (feet)
87	Apr. 6, 1942	2:00 pm	639	107.5
	Apr. 7, 1942	morning	639	107.5
	Apr. 7, 1942	2:30 pm	655.1	123.5
	Apr. 8, 1942	morning	655.1	122.5
	Apr. 11, 1942	2:00 pm	724	191.2
	Apr. 14, 1942	10:24 am	723	188.6
89	July 3, 1942	3:00 pm	320	120.5
	July 4, 1942	morning	320	120.5
	July 15, 1942	3:00 pm	507.1	227.0
	July 16, 1942	morning	507.1	231.0
	July 20, 1942	3:12 pm	530.4	228.3
	July 21, 1942	morning	530.4	229.5
	July 21, 1942	3:00 pm	548.2	228.3
	July 22, 1942	morning	548.2	230.7
	July 22, 1942	3:00 pm	568.1	338.6
	July 23, 1942	morning	568.1	336.6
90	Sept. 3, 1942	morning	281.9	231.5
	Sept. 4, 1942	morning	281.9	231.5
	Sept. 18, 1942	morning	416.2	233.2
	Sept. 19, 1942	morning	416.2	232.3
	Sept. 23, 1942	morning	456.2	232.3
	Sept. 24, 1942	morning	456.2	232.3
	Sept. 25, 1942	morning	465.7	232.3
	Sept. 26, 1942	morning	465.7	232.3
	Sept. 28, 1942	morning	465.7	232.3
	Sept. 29, 1942	morning	465.3	232.3
	Oct. 3, 1942	morning	486.3	248.7
	Oct. 5, 1942	morning	486.3	248.7
	Nov. 8, 1942	morning	631.2	408.2
	Nov. 9, 1942	morning	631.2	408.2
	Nov. 10, 1942	morning	631.2	411.3
	Dec. 2, 1942	afternoon	811.6	411
	Dec. 3, 1942	morning	811.6	411
	Dec. 3, 1942	afternoon	816.2	412.5
	Dec. 4, 1942	morning	816.2	412.5
	Dec. 5, 1942	morning	830.3	412.5
	Dec. 7, 1942	morning	830.3	412.5
93	June 14, 1943	morning	533.1	66.3
	June 16, 1943	morning	533.1	66.3
98	July 13, 1944	morning	449.5	257.6
	July 14, 1944	morning	449.5	257.6
	Aug. 9, 1944	morning	700	339.2
	Aug. 10, 1944	morning	700	339.2
99	Sept. 21, 1944	1:30 pm	184.4	174.4
	Sept. 22, 1944	morning	184.4	174.4
	Sept. 23, 1944	morning	200	181.6
	Sept. 25, 1944	morning	200	181.6
	Nov. 4, 1944	morning	566.4	558.2
	Nov. 6, 1944	morning	566.4	558.2
	Feb. 24, 1945	12:30 pm	950.3	453.7
	Feb. 28, 1945	11:00 am	950.3	453
	Mar. 7, 1945	3:30 pm	1,015.4	448
	Mar. 8, 1945	9:30 am	1,015.4	448

change and provide some idea of its magnitude. The maximum difference between water levels at the end of a day's drilling and those measured 1 to 3 days later and before the resumption of drilling was 4 ft (at test hole 89), although it was more common for the measurements to be identical or nearly so, indicating little effect on water levels.

Other data are available from test holes 74, 83, and 85 that indicate that the effects of drilling did not substantially alter water levels measured in the test holes from pre-drilling values. One-inch pipes perforated at the bottom, were placed in test holes 74, 83, and 85 following their completion and water levels were measured at selected times in the pipes as shown in table C2. These data indicate that little change in water levels occurred over a period of 1 to 2 months following completion of the holes. The maximum change was 6.6 ft at test hole 85. The maximum change after more than 2 years was 20.5 ft at test hole 74 and much of this change was probably seasonal. Given the altitude of the water levels recorded in the test holes, the data shown in tables C1 and C2 indicate that, although drilling may have induced changes in the ground-water system, these changes were relatively small in terms of the absolute value of the pre-drilling water level.

Displacement of Water by the Drill Rod

Another stress imposed in the test holes during drilling and measurement of water levels was the displacement of water caused by the drill string itself. For the most part, water levels were measured inside the drill rod after lowering the drill string into the hole each morning. The core bit usually was at the bottom of the hole or within a foot or so of the bottom when the water level inside the drill rod was measured. The diameter of the test holes was $1\text{-}^{1}/_{2}$ in. whereas the outside and inside diameters of the drill rod were $1\text{-}^{5}/_{16}$ and $^{7}/_{8}$ in. respectively. As a result, the drill string occupied about 42 percent of the volume of the hole and would have displaced a significant amount of water in the hole, at least initially.

The displacement by the drill string would create a potential difference between pre-drilling water levels in the vicinity of the test hole and those measured during drilling by an amount dependent on the height of the initial displacement, the hydraulic properties of the aquifer, the diameter of the test hole, and the length of time the drill string had been in the hole at the time the water level was measured. Ultimately, given sufficient time, the water level inside the hole would decline to its value before the drill rod was inserted.

The time, t, required for water levels to return to approximate pre-insertion values after insertion of the drill string was estimated using the methodology described by Cooper and others (1967) (table C3). This technique assumes that (1) the displacement of water by the drill string is equivalent to an instantaneous "slug" of water of the same volume as the drill string; and (2) the hydraulic conductivity of the aquifer is about 1 ft/d and the transmissivity equals the hydraulic conductivity of the aquifer times the depth of water in the hole. The methodology described by Cooper and others (1967) is strictly applicable only to fully penetrating wells in confined aquifers of low transmissivity. It can be used in other conditions, such as those described for the Nahiku area, only to make approximate estimates. As shown in table C3, estimated values for t are made for depths of water in the hole of 200, 100, and 10 ft. The times required for water levels to return to pre-insertion values are 0.28, 0.56, and 5.6 minutes respectively.

Although the times shown in table C3 represent approximate times necessary for water levels to return to their pre-insertion levels, they are sufficiently low to indicate that the effect of the displacement of water by the drill string on water levels in the test hole was essentially dissipated within a few minutes or less, given the general depth of water in the hole as depicted in figure 17. Because the drill string was not instantly lowered to the bottom of the hole it would appear that the difference between the water level in the well before insertion of the drill rod and following its insertion probably was negligible at the time of the water-level measurements.

This conclusion is further supported by a test done by the driller on test hole 85 to estimate the static water level at a depth of 712 ft in the hole. The water level inside a 1-in. pipe, perforated on the bottom 60 ft, was measured before directing a stream of water "amounting to about 7 gpm' [gal/min], into the pipe for a few minutes, after which a measurement was again made which established the water level at the same elevation" (J.M. Heizer, 1941, unpub. driller's notes, in files of U.S. Geological Survey, Honolulu).

Perhaps the most significant data with regard to assessing the potential effect of the displacement of water in the test holes by the drill rod are the water levels measured in the 12 test holes completed in the

Table C2. Altitude of water level in selected test holes for selected times, Nahiku area, Maui, Hawaii
[--, no data; datum is mean sea level. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Date	Altitude of the water level (feet) test hole 74	test hole 83	test hole 85
Mar. 21, 1941	--	[1]806.8	--
Apr. 12, 1941	--	--	[1]830
Apr. 17, 1941	--	805.9	830.9
Apr. 28, 1941	--	803.7	830.1
May 29, 1941	[1]827.4	802.0	823.4
May 31, 1941	827.7	--	--
Mar. 5, 1943	848.2	815.9	831.1
June 21, 1943	--	816.4	--
June 23, 1943	835.2	813.7	831.4

[1] Water level at end of drilling

Table C3. Estimated time, *t*, for water levels to decline to pre-drill-rod insertion values, following drill-rod insertion, Nahiku area, Maui, Hawaii

Depth of water in the test hole (feet)	*t* (minutes)
200	0.28
100	0.56
10	5.6

Honomanu Basalt by methods other than from inside the drill rod. Water levels in these holes were always higher than those measured from inside the drill rod with the bit at the bottom of the hole. In those holes where the drill rod (or pipe) was raised, the depth to water decreased. This is exactly the opposite of what would occur if displacement of water by the drill rod was a major factor with regard to the water level in the boreholes.

Movement of Water in the Open Test Hole

For most, if not all of their depths, the test holes were uncased while drilling was in progress and afterwards. Water is free to move in an open hole in saturated rock from areas of high head to areas of low head, where perched water exists, from the perched water body down the hole. The effect of movement on the water level in a hole is potentially significant in that the altitude of the water level in the hole would be expected to change over some unknown time period.

In a perched ground-water system, water moving down a hole could cause water to be detected in the hole when, in fact, the hole was being drilled in unsaturated rock. Even so, the altitude of the water level in the hole would generally decline with increasing hole depth. In a saturated ground-water system where the general movement of water is downward, the movement of water down the hole would be expected to increase the altitude of the water level in the hole compared to the pre-drilling hydraulic head at any given depth. If the movement of water is upward, the altitude of the water level in the borehole would also be greater than the pre-drilling hydraulic head at a given depth of the hole. The magnitude of the head change above the pre-drilling head at any given depth would depend on the rate of water movement in the hole, the time over which the movement of water existed, and the hydraulic properties of the rock within which water is moving. It is clear from the directional current-meter data collected in some of the boreholes that water was moving vertically in at least some of the test holes. It is also clear from the driller's log that water was cascading downward in some of the holes.

The potential effect of cascading water on the altitude of water levels in the test holes is somewhat difficult to completely address. Cascading water was reported in about 30 percent of the holes completed in the Hana or the Kula Volcanics. On the one hand, cascading water could cause water levels in a given hole to be greater than they would be otherwise. On the other hand, the data indicate that cascading water was generally associated with large declines in the water level in the test holes. These declines generally occurred during drilling at zones where drilling pressure was lost over small vertical distances (generally several inches or so). These large losses in water level in the test holes, in turn, resulted in cascading water from zones above the new water level in the hole and below the previous water level. The latter phenomena could occur in either a succession of perched water bodies or in a fully saturated anisotropic ground-water system where heads decline with depth.

Previous work in the area concluded that the Hana Volcanics was unsaturated and the lavas of the Kula Volcanics and the rocks of Honomanu Basalt were considered to be too permeable to perch water outside of the artesian water body (Stearns and Macdonald, 1942). Ground water in the area was considered to occur as perched water bodies in the Kula Volcanics, as two artesian water bodies of limited areal extent in the upper part of the Honomanu Basalt, and as a basal water body with water levels of 10 ft or less in the Honomanu Basalt. Although the Kula Volcanics was considered too permeable to perch water, Stearns and Macdonald (1942, p. 86) state that "when viewed as a unit, the Kula contains enough more or less impermeable layers, even though discontinuous, to retard greatly the downward percolation of water in areas where 100 to 400 inches of rain falls annually [such as in the Nahiku area]." The Stearns and Macdonald (1942) description of ground-water occurrence indicates that cascading water should occur only after the Kula Volcanics had been penetrated.

The presence of water in the Hana Volcanics in all of the test holes and water levels significantly above the Kula Volcanics in most of the holes clearly cannot be the result of cascading water from the underlying Kula Volcanics. Even if the water levels in the boreholes are to some extent the result of cascading water within the Hana Volcanics, it is still clear from the data that there is a considerable amount of water in the Hana Volcanics. Because water was initially encountered at shallow depths in the test holes, it is doubtful that cascading water, if present, had any significant effect on the altitude of the first water encountered in the borehole.

The continual presence of water above the top of the Kula Volcanics for hole depths into the Honomanu Basalt (including depths far below sea level) for the majority of the boreholes also makes it difficult to explain the presence of water in the holes solely as a product of cascading water from the Kula Volcanics. Instead, the continual presence of water above the Kula Volcanics in many of the test holes as they were deepened from the Hana Volcanics into the Honomanu Basalt indicates that either: (1) the rocks are saturated from the Hana Volcanics on down, or (2) that numerous perched water bodies occur throughout the stratigraphic column from the Hana Volcanics to the Honomanu Basalt and that cascading water from these perched water bodies maintains the water level in the borehole above the Kula Volcanics. On the basis of stratigraphic knowledge alone, the presence of numerous water bodies in the Hana Volcanics and the Honomanu Basalt is difficult to justify.

Several other factors indicate that cascading water may have not played a significant role in the water levels in some of the test holes. Surface casing was installed in some of the test holes including test holes 34, 35, 41, and 81. The water level in these holes remained above the bottom of the casing and above the top of the Kula Volcanics as the holes were deepened from the Hana Volcanics into the Kula Volcanics and, at test hole 81, into the Honomanu Basalt. It is safe to assume that cascading water played no role in the water levels in these holes. These data indicate that the rocks of the Hana and Kula Volcanics are saturated below the first water encountered during drilling. Water-level data from other nearby test holes are similar to water-level data in test holes 34, 35, 41, and 81 even though water levels in these holes either fell below the casing or no casing was reported.

If cascading water was responsible for maintaining water in the test hole at the end of the day's drilling, then the rate of cascading water would have to have been sufficient to establish and maintain hundreds of feet of water in the holes (fig. 9). This would, in turn, cause the altitude of the water level in the well to continue to increase overnight or for a period of several days or more in the continued absence of drilling and in the continued presence of cascading water until equilibrium was reached. The available data (tables C1 and C2) do not support this. The maximum difference between water levels measured at the end of a day's drilling and those measured 1 to 3 days before the resumption of drilling was 4 ft, although identical measurements were more common. The maximum change after 1 to 2 months was 6.6 ft. The maximum change in water levels following completion of drilling that was observed after more than 2 years was 20.5 ft. The latter measurements were only made during March and June over the 2-year span and are, therefore, not necessarily indicative of the greatest change over the 2-year time period. Because they were made during the same months of each year, however, the measurements are still comparable.

The directional current-meter data also indicate that the effect of cascading water on the overall profile of water levels in at least some of the boreholes was not significant. This is indicated by the fact that the direction of water movement in those holes where these data were obtained is in accord with the water levels measured in the holes as drilling progressed.

Several test holes bear special mention with regard to what was apparently a major movement of water down the hole. As shown in table 5, no water was in T-86 at a hole depth of 552 ft. Before this, the water level measured inside the drill rod at a hole depth of 496 ft stood 173 ft above the bottom of the hole. Between the hole depths of 496 and 552 ft, the driller reported "heavy leaks" at depths of 500, 510, and 552 ft. Water was reported in the hole at hole depths below 552 ft, but the depth to water in the hole ranged from 546 to 621 ft. As noted in appendix A, at the final hole depth of 817 ft, depth to water measured inside the drill rod was 614 ft and directional current-meter measurements made following the completion of the hole indicated water at a depth of only 180 ft.

The complete loss of water in test hole 86 at a depth of 552 ft did not happen in any other test hole once water was encountered although it nearly occurred at test hole 62. Given that once water was encountered in the other test holes it remained in the holes, the complete loss of water in test hole 86 was probably in response to some localized condition such as a partially saturated lava tube.

The altitude of the water level in test hole 62 fell from 1,071 ft, at a bottom hole altitude of 804 ft, to 773 ft, at a bottom hole altitude of 770 ft (table 5). The height of water fell from 267 to 3 ft above the bottom of the hole. The test hole was deepened 16 ft and the water level rose 82 ft. At this point the height of water was 85 ft above the bottom of the hole. The altitude of the water level and the height of water above the bottom of the hole generally tended to increase from this point on. Ultimately, the altitude of the water level in the well was 1,212 ft for a bottom hole altitude of 380 ft. This corresponds to a water level of 832 ft above the bottom of the hole.

The situation at test hole 62 was sufficiently rare as to receive a comment from the driller. As reported in the driller's log: "With reference to the low water levels found at 425 and 625 [bottom hole altitude of 770 ft] it is occasionally observed that a freak low level is found in the course of drilling which may be accounted for by the assumption that an area may have been cut into, which, until it has been filled with water, may temporarily lower the water in the hole, and which, after being filled, permitting the water to again rise in the hole, may give the impression of an artesian movement."

Table 5. Water levels in selected test holes completed in Honomanu Basalt, Nahiku area, Maui, Hawaii

[Values in feet; --, no data or not applicable; Kula, Kula Volcanics; Hana, Hana Volcanics; Honomanu, Honomanu Basalt. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Land surface altitude	Total depth	Depth to top of Kula Volcanics	Depth to base of Kula Volcanics	Vertical hydraulic gradient	Hole depth	Bottom hole altitude	Depth to water	Water-level altitude	Water level above top of Kula Volcanics	Rock unit[1]	Percent penetration of rock unit	Depth of hole in Honomanu Basalt	Water level above bottom of hole
						Test hole 12							
1,282	937	164	636	0.82	38	1,244	35	1,247	129	Hana	23	--	3
					99	1,183	37	1,245	127	Hana	60	--	62
					104	1,178	37	1,245	127	Hana	63	--	67
					342	940	123	1,159	41	Kula	38	--	219
					386	896	123	1,159	41	Kula	47	--	263
					421	861	125	1,157	39	Kula	54	--	296
					443	839	141	1,141	23	Kula	59	--	302
					452	830	139	1,143	25	Kula	61	--	313
					470	812	155	1,127	9	Kula	65	--	315
					489	793	236	1,046	-72	Kula	69	--	253
					525	757	268	1,014	-104	Kula	76	--	257
					561	721	335	947	-171	Kula	84	--	226
					599	683	318	964	-154	Kula	92	--	281
					620	662	328	954	-164	Kula	97	--	292
					657	625	310	972	-146	Honomanu	--	21	347
					687	595	346	936	-182	Honomanu	--	51	341
					713	569	342	940	-178	Honomanu	--	77	371
					736	546	344	938	-180	Honomanu	--	100	392
					759	523	345	937	-181	Honomanu	--	123	414
					800	482	510	772	-346	Honomanu	--	164	290
					806	476	508	774	-344	Honomanu	--	170	298
					806	476	[2]200	1,082	-36	Honomanu	--	170	606
					830	452	503	779	-339	Honomanu	--	194	327
					865	417	493	789	-329	Honomanu	--	229	372
					874	408	498	784	-334	Honomanu	--	238	376
					915	367	535	747	-371	Honomanu	--	279	380
					937	345	774	508	-610	Honomanu	--	301	163
						Test hole 62							
					60	1,335	37	1,358	188	Hana	27	--	23
					79	1,316	73	1,322	152	Hana	35	--	6
					153	1,242	91	1,304	134	Hana	68	--	62
					362	1,033	243	1,152	-18	Kula	55	--	119
					452	943	263	1,132	-38	Kula	90	--	189
					482	913	238	1,157	-13	Honomanu	--	6	244
					489	906	238	1,157	-13	Honomanu	--	13	251
					516	879	251	1,144	-26	Honomanu	--	40	265
					559	836	289	1,106	-64	Honomanu	--	83	270
					592	803	324	1,071	-99	Honomanu	--	116	268
					625	770	622	773	-397	Honomanu	--	149	3
					641	754	556	839	-331	Honomanu	--	165	85
					667	728	529	866	-304	Honomanu	--	191	138
					680	715	515	880	-290	Honomanu	--	204	165

Table 5. Water levels in selected test holes completed in Honomanu Basalt, Nahiku area, Maui, Hawaii--Continued

[Values in feet; --, no data or not applicable; Kula, Kula Volcanics; Hana, Hana Volcanics; Honomanu, Honomanu Basalt. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Land surface altitude	Total depth	Depth to top of Kula Volcanics	Depth to base of Kula Volcanics	Vertical hydraulic gradient	Hole depth	Bottom hole altitude	Depth to water	Water-level altitude	Water level above top of Kula Volcanics	Rock unit[1]	Percent penetration of rock unit	Depth of hole in Honomanu Basalt	Water level above bottom of hole
Test hole 62--Continued													
					691	704	605	790	-380	Honomanu	--	215	86
					727	668	609	786	-384	Honomanu	--	251	118
					751	644	611	784	-386	Honomanu	--	275	140
					766	629	606	789	-381	Honomanu	--	290	160
					780	615	607	788	-382	Honomanu	--	304	173
					814	581	605	790	-380	Honomanu	--	338	209
					829	566	602	793	-377	Honomanu	--	353	227
					862	533	605	790	-380	Honomanu	--	386	257
					881	514	603	792	-378	Honomanu	--	405	278
					900	495	597	798	-372	Honomanu	--	424	303
					921	474	603	792	-378	Honomanu	--	445	318
					948	447	580	815	-355	Honomanu	--	472	368
					954	441	567	828	-342	Honomanu	--	478	387
					976	419	591	804	-366	Honomanu	--	500	385
					977	418	418	977	-193	Honomanu	--	501	559
					988	407	373	1,022	-148	Honomanu	--	512	615
					994	401	562	833	-337	Honomanu	--	518	432
					997	398	275	1,120	-50	Honomanu	--	521	722
					1,001	394	293/[3]281	1,102/1,114	-68/-56	Honomanu	--	525	708/720
Test hole 65													
1,066	642	218	452	0.68	18	1,048	15	1,051	203	Hana	8	--	3
					140	926	93	973	125	Hana	64	--	47
					152	914	90	976	128	Hana	70	--	62
					184	882	92	974	126	Hana	84	--	92
					218	848	107	959	111	Hana/Kula	100	--	111
					236	830	109	957	109	Kula	8	--	127
					332	734	112	954	106	Kula	49	--	220
					395	671	121	945	97	Kula	76	--	274
					409	657	121	945	97	Kula	82	--	288
					498	568	141	925	77	Honomanu	--	46	357
					529	537	362	704	-144	Honomanu	--	77	167
					529	537	[4]184	882	34	Honomanu	--	77	345
Test hole 74													
1,072	632	227	460	0.32	131	941	83	989	144	Hana	58	--	48
					140	932	105	967	122	Hana	62	--	35
					154	918	116	956	111	Hana	68	--	38
					191	881	120	952	107	Hana	84	--	71
					199	873	120	952	107	Hana	88	--	79
					228	844	120	952	107	Kula/Hana	100	--	108
					247	825	120	952	107	Kula	9	--	127

Table 5. Water levels in selected test holes completed in Honomanu Basalt, Nahiku area, Maui, Hawaii--Continued

[Values in feet; --, no data or not applicable; Kula, Kula Volcanics; Hana, Hana Volcanics; Honomanu, Honomanu Basalt. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Land surface altitude	Total depth	Depth to top of Kula Volcanics	Depth to base of Kula Volcanics	Vertical hydraulic gradient	Hole depth	Bottom hole altitude	Depth to water	Water-level altitude	Water level above top of Kula Volcanics	Rock unit[1]	Percent penetration of rock unit	Depth of hole in Honomanu Basalt	Water level above bottom of hole
Test hole 74--Continued													
					280	792	120	952	107	Kula	23	--	160
					322	750	120	952	107	Kula	41	--	202
					503	569	372	700	-145	Honomanu	--	43	131
					549	523	374	698	-147	Honomanu	--	89	175
					576	496	358	714	-131	Honomanu	--	116	218
					587	485	287	785	-60	Honomanu	--	127	300
					591	481	265	807	-38	Honomanu	--	131	326
					601	471	259	813	-32	Honomanu	--	141	342
					606	466	248	824	-21	Honomanu	--	146	358
					621	451	245	827	-18	Honomanu	--	161	376
					632	440	244	828	-17	Honomanu	--	172	388
Test hole 81													
984	521	192	453	0.03	176	808	10	974	182	Hana	92	--	166
					231	753	12	972	180	Kula	15	--	219
					282	702	11	973	181	Kula	34	--	271
					314	670	11	973	181	Kula	47	--	303
					386	598	11	973	181	Kula	74	--	375
					469	515	14	970	178	Honomanu	--	16	455
					479	505	18	966	174	Honomanu	--	26	461
					521	463	20	964	172	Honomanu	--	68	501
Test hole 82													
924	478	195	434	0.67	60	864	--	--	--	Hana	31	--	--
					71	853	61	863	134	Hana	36	--	10
					158	766	110	814	85	Hana	81	--	48
					181	743	118	806	77	Hana	93	--	63
					211	713	124	800	71	Kula	7	--	87
					251	673	122	802	73	Kula	23	--	129
					257	667	124	800	71	Kula	26	--	133
					304	620	179	745	16	Kula	45	--	125
					345	579	179	745	16	Kula	62	--	166
					348	576	181	743	14	Kula	63	--	167
					371	553	185	739	10	Kula	73	--	186
					384	540	185	739	10	Kula	78	--	199
					394	530	205	719	-10	Kula	83	--	189
					450	474	326	598	-131	Honomanu	--	16	124
					468	456	327	597	-132	Honomanu	--	34	141
					478	446	--	--	--	Honomanu	--	48	--
Test hole 83													
945	790	173	447	0.97	170	775	106	839	67	Hana	98	--	64
					340	605	124	821	49	Kula	61	--	216

Table 5. Water levels in selected test holes completed in Honomanu Basalt, Nahiku area, Maui, Hawaii--Continued

[Values in feet; --, no data or not applicable; Kula, Kula Volcanics; Hana, Hana Volcanics; Honomanu, Honomanu Basalt. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Land surface altitude	Total depth	Depth to top of Kula Volcanics	Depth to base of Kula Volcanics	Vertical hydraulic gradient	Hole depth	Bottom hole altitude	Depth to water	Water-level altitude	Water level above top of Kula Volcanics	Rock unit[1]	Percent penetration of rock unit	Depth of hole in Honomanu Basalt	Water level above bottom of hole
Test hole 83--Continued													
					384	561	129	816	44	Kula	77	--	255
					405	540	287	658	-114	Kula	85	--	118
					448	497	345	600	-172	Honomanu	--	1	103
					519	426	242	703	-69	Honomanu	--	72	277
					575	370	120	825	53	Honomanu	--	128	455
					664	281	123	822	50	Honomanu	--	217	541
					696	249	123	822	50	Honomanu	--	249	573
					721	224	123	822	50	Honomanu	--	274	598
					777	168	122	823	51	Honomanu	--	330	655
					790	155	709	236	-536	Honomanu	--	343	81
					790	155	[2]230	[2]715	[2]-57	Honomanu	--	343	[2]560
Test hole 84													
977	441	187	430	0.05	65	912	36	941	151	Hana	35	--	29
					67	910	45	932	142	Hana	36	--	22
					99	878	58	919	129	Hana	53	--	41
					121	856	63	914	124	Hana	65	--	58
					209	768	47	930	140	Kula	9	--	162
					304	673	45	932	142	Kula	48	--	259
					318	659	45	932	142	Kula	54	--	273
					335	642	47	930	140	Kula	61	--	288
					377	600	49	928	138	Kula	78	--	328
					386	591	50	927	137	Kula	82	--	336
					427	550	50	927	137	Kula	99	--	377
					441	536	56	921	131	Honomanu	--	11	385
Test hole 85													
1,003	991	226	543	0.66	45	958	44	959	182	Hana	20	--	1
					95	908	48	955	178	Hana	42	--	47
					146	857	50	953	176	Hana	65	--	96
					256	747	50	953	176	Kula	9	--	206
					284	719	50	953	176	Kula	18	--	234
					318	685	50	953	176	Kula	29	--	268
					360	643	50	953	176	Kula	42	--	310
					393	610	47	956	179	Kula	53	--	346
					436	567	44	959	182	Kula	66	--	392
					465	538	48	955	178	Kula	75	--	417
					489	514	57	946	169	Kula	83	--	432
					505	498	57	946	169	Kula	88	--	448
					514	489	58	945	168	Kula	91	--	456
					517	486	104	899	122	Kula	92	--	413
					521	482	103	900	123	Kula	93	--	418

Table 5. Water levels in selected test holes completed in Honomanu Basalt, Nahiku area, Maui, Hawaii--Continued

[Values in feet; --, no data or not applicable; Kula, Kula Volcanics; Hana, Hana Volcanics; Honomanu, Honomanu Basalt. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Land surface altitude	Total depth	Depth to top of Kula Volcanics	Depth to base of Kula Volcanics	Vertical hydraulic gradient	Hole depth	Bottom hole altitude	Depth to water	Water-level altitude	Water level above top of Kula Volcanics	Rock unit[1]	Percent penetration of rock unit	Depth of hole in Honomanu Basalt	Water level above bottom of hole
Test hole 85--Continued													
					554	449	103	900	123	Honomanu	--	11	451
					658	345	104	899	122	Honomanu	--	115	554
					865	138	176	827	50	Honomanu	--	322	689
					900	103	250	753	-24	Honomanu	--	357	650
					934	69	475	528	-249	Honomanu	--	391	459
					951	52	424	579	-198	Honomanu	--	408	527
					991	12	666	337	-440	Honomanu	--	448	325
					991	12	[5]173	830	53	Honomanu	--	448	818
Test hole 86													
1,494	817	243	584	0.76	191	1,303	[6]139	1,355	104	Hana	79	--	52
					203	1,291	[6]141	1,353	102	Hana	84	--	62
					246	1,248	[6]137	1,357	106	Kula	1	--	109
					282	1,212	[6]140	1,354	103	Kula	11	--	142
					296	1,198	[6]140	1,354	103	Kula	16	--	156
					496	998	323	1,171	-80	Kula	74	--	173
					552	942	no water	--	--	Kula	91	--	--
					559	935	556	938	-313	Kula	93	--	3
					606	888	549	945	-306	Honomanu	--	22	57
					635	859	546	948	-303	Honomanu	--	51	89
					676	818	554	940	-311	Honomanu	--	92	122
					711	783	546	948	-303	Honomanu	--	127	165
					756	738	616	878	-373	Honomanu	--	172	140
					782	712	616	878	-373	Honomanu	--	198	166
					800	694	621	873	-378	Honomanu	--	216	179
					817	677	614	880	-371	Honomanu	--	233	203
					817	677	[2]180	1,314	63	Honomanu	--	233	637
Test hole 87													
465	738	258	426	0.60	194	271	90	375	168	Hana	75	--	104
					356	109	83	382	175	Kula	58	--	273
					502	-37	102	363	156	Honomanu	--	76	400
					522	-57	102	363	156	Honomanu	--	96	420
					530	-65	103	362	155	Honomanu	--	104	427
					540	-75	103	362	155	Honomanu	--	114	437
					558	-93	104	361	154	Honomanu	--	132	454
					575	-110	104	361	154	Honomanu	--	149	471
					600	-135	105	360	153	Honomanu	--	174	495
					609	-144	[7]95	370	163	Honomanu	--	183	514
					615	-150	136	329	122	Honomanu	--	189	479
					623	-158	128	337	130	Honomanu	--	197	495
					639	-174	108	357	150	Honomanu	--	213	531

Table 5. Water levels in selected test holes completed in Honomanu Basalt, Nahiku area, Maui, Hawaii--Continued

[Values in feet; --, no data or not applicable; Kula, Kula Volcanics; Hana, Hana Volcanics; Honomanu, Honomanu Basalt. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Land surface altitude	Total depth	Depth to top of Kula Volcanics	Depth to base of Kula Volcanics	Vertical hydraulic gradient	Hole depth	Bottom hole altitude	Depth to water	Water-level altitude	Water level above top of Kula Volcanics	Rock unit[1]	Percent penetration of rock unit	Depth of hole in Honomanu Basalt	Water level above bottom of hole
Test hole 87--Continued													
					655	-190	124	341	134	Honomanu	--	229	531
					666	-201	124	341	134	Honomanu	--	240	542
					690	-225	193	272	65	Honomanu	--	264	497
					707	-242	189	276	69	Honomanu	--	281	518
					724	-259	189	276	69	Honomanu	--	298	535
					732	-267	415	50	-157	Honomanu	--	306	317
					738	-273	415	50	-157	Honomanu	--	312	323
					738	-273	[8]105	360	153	Honomanu	--	312	633
Test hole 88													
135	475	85	225	0.10	166	-31	88	47	-3	Kula	58	--	78
					181	-46	87	48	-2	Kula	69	--	94
					198	-63	87	48	-2	Kula	81	--	111
					208	-73	81	54	4	Kula	88	--	127
					232	-97	75	60	10	Honomanu	--	7	157
					251	-116	76	59	9	Honomanu	--	26	175
					262	-127	73	62	12	Honomanu	--	37	189
					279	-144	83	52	2	Honomanu	--	54	196
					302	-167	83	52	2	Honomanu	--	77	219
					309	-174	64	71	21	Honomanu	--	84	245
					325	-190	77	58	8	Honomanu	--	100	248
					335	-200	92	43	-7	Honomanu	--	110	243
					346	-211	92	43	-7	Honomanu	--	121	254
					365	-230	93	42	-8	Honomanu	--	140	272
					382	-247	94	41	-9	Honomanu	--	157	288
					403	-268	94	41	-9	Honomanu	--	178	309
					411	-276	101	34	-16	Honomanu	--	186	310
					423	-288	121	14	-36	Honomanu	--	198	302
					448	-313	121	14	-36	Honomanu	--	223	327
					475	-340	119	16	-34	Honomanu	--	250	356
Test hole 89													
449	587	183	290	0.51	137	312	109	340	74	Hana	75	--	28
					216	233	109	340	74	Kula	31	--	107
					231	218	109	340	74	Kula	45	--	122
					245	204	111	338	72	Kula	58	--	134
					296	153	111	338	72	Honomanu	--	6	185
					320	129	121	328	62	Honomanu	--	30	199
					337	112	128	321	55	Honomanu	--	47	209
					375	74	139	310	44	Honomanu	--	85	236
					401	48	228	221	-45	Honomanu	--	111	173

Table 5. Water levels in selected test holes completed in Honomanu Basalt, Nahiku area, Maui, Hawaii--Continued

[Values in feet; --, no data or not applicable; Kula, Kula Volcanics; Hana, Hana Volcanics; Honomanu, Honomanu Basalt. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Land surface altitude	Total depth	Depth to top of Kula Volcanics	Depth to base of Kula Volcanics	Vertical hydraulic gradient	Hole depth	Bottom hole altitude	Depth to water	Water-level altitude	Water level above top of Kula Volcanics	Rock unit[1]	Percent penetration of rock unit	Depth of hole in Honomanu Basalt	Water level above bottom of hole
Test hole 89--Continued													
					415	34	223	226	-40	Honomanu	--	125	192
					442	7	222	227	-39	Honomanu	--	152	220
					455	-6	227	222	-44	Honomanu	--	165	228
					507	-58	227	222	-44	Honomanu	--	217	280
					530	-81	228	221	-45	Honomanu	--	240	302
					548	-99	231	218	-48	Honomanu	--	258	317
					568	-119	339	110	-156	Honomanu	--	278	229
					581	-132	334	115	-151	Honomanu	--	291	247
Test hole 90													
864	847	441	604	0.42	181	683	131	733	310	Hana	41	--	50
					191	673	131	733	310	Hana	43	--	60
					262	602	213	651	228	Hana	59	--	49
					282	582	232	632	209	Hana	64	--	50
					308	556	232	632	209	Hana	70	--	76
					339	525	230	634	211	Hana	77	--	109
					371	493	223	641	218	Hana	84	--	148
					413	451	232	632	209	Hana	94	--	181
					465	399	232	632	209	Kula	15	--	233
					480	384	248	616	193	Kula	24	--	232
					486	378	248	616	193	Kula	28	--	238
					496	368	241	623	200	Kula	34	--	255
					499	365	235	629	206	Kula	36	--	264
					512	352	403	461	38	Kula	44	--	109
					530	334	407	457	34	Kula	55	--	123
					605	259	406	458	35	Honomanu	--	1	199
					661	203	408	456	33	Honomanu	--	57	253
					674	190	422	442	19	Honomanu	--	70	252
					687	177	410	454	31	Honomanu	--	83	277
					767	97	412	452	29	Honomanu	--	163	355
					811	53	411	453	30	Honomanu	--	207	400
					847	17	411	453	30	Honomanu	--	243	436
					847	17	[9]240	624	201	Honomanu	--	243	607
Test hole 91													
762	548	205	385	0.25	184	578	106	656	99	Hana	90	--	78
					207	555	107	655	98	Kula	1	--	100
					209	553	110	652	95	Kula	2	--	99
					242	520	132	630	73	Kula	21	--	110
					280	482	126	636	79	Kula	42	--	154
					302	460	124	638	81	Kula	54	--	178
					322	440	149	613	56	Kula	65	--	173

Table 5. Water levels in selected test holes completed in Honomanu Basalt, Nahiku area, Maui, Hawaii--Continued

[Values in feet; --, no data or not applicable; Kula, Kula Volcanics; Hana, Hana Volcanics; Honomanu, Honomanu Basalt. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Land surface altitude	Total depth	Depth to top of Kula Volcanics	Depth to base of Kula Volcanics	Vertical hydraulic gradient	Hole depth	Bottom hole altitude	Depth to water	Water-level altitude	Water level above top of Kula Volcanics	Rock unit[1]	Percent penetration of rock unit	Depth of hole in Honomanu Basalt	Water level above bottom of hole
Test hole 91--Continued													
					342	420	127	635	78	Kula	76	--	215
					390	372	148	614	57	Honomanu	--	5	242
					430	332	162	600	43	Honomanu	--	45	268
					465	297	222	540	-17	Honomanu	--	80	243
					476	286	198	564	7	Honomanu	--	91	278
					486	276	201	561	4	Honomanu	--	101	285
					530	232	201	561	4	Honomanu	--	145	329
					548	214	198	564	7	Honomanu	--	163	350
Test hole 92													
902	754	211	442	0.77	131	771	81	821	130	Hana	62	--	50
					136	766	70	832	141	Hana	64	--	66
					199	703	[10]171	731	40	Hana	94	--	28
					226	676	172	730	39	Kula	6	--	54
					351	551	206	696	5	Kula	61	--	145
					392	510	180	722	31	Kula	78	--	212
					401	501	177	725	34	Kula	82	--	224
					413	489	300	602	-89	Kula	87	--	113
					423	479	296	606	-85	Kula	92	--	127
					449	453	273	629	-62	Honomanu	--	7	176
					467	435	222	680	-11	Honomanu	--	25	245
					481	421	157	745	54	Honomanu	--	39	324
					502	400	157	745	54	Honomanu	--	60	345
					519	383	157	745	54	Honomanu	--	77	362
					547	355	83	819	128	Honomanu	--	105	464
					572	330	85	817	126	Honomanu	--	130	487
					687	215	85	817	126	Honomanu	--	245	602
					707	195	82	820	129	Honomanu	--	265	625
					745	157	85	817	126	Honomanu	--	303	660
					754	148	561	341	-350	Honomanu	--	312	193
					754	148	[11]86	816	125	Honomanu	--	312	668
Test hole 93													
849	614	186	440	-0.06	155	694	105	744	81	Hana	83	--	50
					180	669	125	724	61	Hana	97	--	55
					267	582	125	724	61	Kula	32	--	142
					271	578	127	722	59	Kula	33	--	144
					277	572	183	666	3	Kula	36	--	94
					312	537	124	725	62	Kula	50	--	188
					374	475	126	723	60	Kula	74	--	248
					405	444	127	722	59	Kula	86	--	278
					432	417	128	721	58	Kula	97	--	304

Table 5. Water levels in selected test holes completed in Honomanu Basalt, Nahiku area, Maui, Hawaii--Continued

[Values in feet; --, no data or not applicable; Kula, Kula Volcanics; Hana, Hana Volcanics; Honomanu, Honomanu Basalt. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Land surface altitude	Total depth	Depth to top of Kula Volcanics	Depth to base of Kula Volcanics	Vertical hydraulic gradient	Hole depth	Bottom hole altitude	Depth to water	Water-level altitude	Water level above top of Kula Volcanics	Rock unit[1]	Percent penetration of rock unit	Depth of hole in Honomanu Basalt	Water level above bottom of hole
Test hole 93--Continued													
					452	397	129	720	57	Honomanu	--	12	323
					476	373	109	740	77	Honomanu	--	36	367
					492	357	92	757	94	Honomanu	--	52	400
					509	340	83	766	103	Honomanu	--	69	426
					533	316	66	783	120	Honomanu	--	93	467
					554	295	48	801	138	Honomanu	--	114	506
					597	252	47	802	139	Honomanu	--	157	550
					602	247	46	803	140	Honomanu	--	162	556
					614	235	78	771	108	Honomanu	--	174	536
Test hole 94													
796	649	182	405	-0.20	352	444	189	607	-7	Kula	76	--	163
					394	402	215	581	-33	Kula	95	--	179
					408	388	210	586	-28	Honomanu	--	3	198
					411	385	203	593	-21	Honomanu	--	6	208
					439	357	174	622	8	Honomanu	--	34	265
					456	340	182	614	0	Honomanu	--	51	274
					460	336	153	643	29	Honomanu	--	55	307
					482	314	114	682	68	Honomanu	--	77	368
					494	302	109	687	73	Honomanu	--	89	385
					536	260	[2]77	719	105	Honomanu	--	131	459
					555	241	96	700	86	Honomanu	--	150	459
					575	221	134	662	48	Honomanu	--	170	441
					596	200	[1]98	698	84	Hana	--	191	498
					596	200	130	666	52	Honomanu	--	191	466
					596	200	132	664	50	Honomanu	--	191	464
					603	193	136	660	46	Honomanu	--	198	467
					617	179	135	661	47	Honomanu	--	212	482
					634	162	134	662	48	Honomanu	--	229	500
					649	147	130	666	52	Honomanu	--	244	519
Test hole 96													
785	530	195	401	0.21	284	501	87	698	108	Kula	43	--	197
					305	480	103	682	92	Kula	53	--	202
					314	471	95	690	100	Kula	58	--	219
					332	453	97	688	98	Kula	67	--	235
					341	444	88	697	107	Kula	71	--	253
					371	414	98	687	97	Kula	85	--	273
					398	387	96	689	99	Kula	99	--	302
					430	355	106	679	89	Honomanu	--	29	324
					469	316	104	681	91	Honomanu	--	68	365
					482	303	103	682	92	Honomanu	--	81	379

Table 5. Water levels in selected test holes completed in Honomanu Basalt, Nahiku area, Maui, Hawaii--Continued

[Values in feet; --, no data or not applicable; Kula, Kula Volcanics; Hana, Hana Volcanics; Honomanu, Honomanu Basalt. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Land surface altitude	Total depth	Depth to top of Kula Volcanics	Depth to base of Kula Volcanics	Vertical hydraulic gradient	Hole depth	Bottom hole altitude	Depth to water	Water-level altitude	Water level above top of Kula Volcanics	Rock unit[1]	Percent penetration of rock unit	Depth of hole in Honomanu Basalt	Water level above bottom of hole
Test hole 96--Continued													
					491	294	107	678	88	Honomanu	--	90	384
					501	284	130	655	65	Honomanu	--	100	371
					520	265	137	648	58	Honomanu	--	119	383
Test hole 97													
826	595	300	363	0.51	107	719	[12]96	730	204	Hana	36	--	11
					141	685	[12]123	703	177	Hana	47	--	18
					162	664	[12]132	694	168	Hana	54	--	30
					192	634	129	697	171	Hana	64	--	63
					202	624	131	695	169	Hana	67	--	71
					214	612	135	691	165	Hana	71	--	79
					233	593	134	692	166	Hana	78	--	99
					257	569	143	683	157	Hana	86	--	114
					273	553	132	694	168	Hana	91	--	141
					283	543	145	681	155	Hana	94	--	138
					286	540	146	680	154	Hana	95	--	140
					302	524	146	680	154	Kula	3	--	156
					308	518	154	672	146	Kula	13	--	154
					430	396	145	681	155	Honomanu	--	67	285
					465	361	165	661	135	Honomanu	--	102	300
					473	353	347	479	-47	Honomanu	--	110	126
					495	331	340	486	-40	Honomanu	--	132	155
					505	321	352	474	-52	Honomanu	--	142	153
					508	318	[12]174	652	126	Honomanu	--	145	334
					517	309	317	509	-17	Honomanu	--	154	200
					526	300	343	483	-43	Honomanu	--	163	183
					546	280	346	480	-46	Honomanu	--	183	200
					561	265	[13]348	478	-48	Honomanu	--	198	213
					595	231	345	481	-45	Honomanu	--	232	250
					595	231	[2]298	528	2	Honomanu	--	232	297
Test hole 98													
1,015	755	241	528	0.42	141	874	91	924	150	Hana	59	--	50
					182	833	158	857	83	Hana	76	--	24
					196	819	156	859	85	Hana	81	--	40
					211	804	[14]159	856	82	Hana	88	--	52
					222	793	199	816	42	Hana	92	--	23
					238	777	199	816	42	Hana	99	--	39
					242	773	201	814	40	Kula	<1	--	41
					257	758	202	813	39	Kula	6	--	55
					285	730	261	754	-20	Kula	15	--	24
					301	714	261	754	-20	Kula	21	--	40

Table 5. Water levels in selected test holes completed in Honomanu Basalt, Nahiku area, Maui, Hawaii--Continued

[Values in feet; --, no data or not applicable; Kula, Kula Volcanics; Hana, Hana Volcanics; Honomanu, Honomanu Basalt. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Land surface altitude	Total depth	Depth to top of Kula Volcanics	Depth to base of Kula Volcanics	Vertical hydraulic gradient	Hole depth	Bottom hole altitude	Depth to water	Water-level altitude	Water level above top of Kula Volcanics	Rock unit[1]	Percent penetration of rock unit	Depth of hole in Honomanu Basalt	Water level above bottom of hole
Test hole 98--Continued													
					306	709	261	754	-20	Kula	23	--	45
					318	697	262	753	-21	Kula	27	--	56
					335	680	260	755	-19	Kula	33	--	75
					352	663	257	758	-16	Kula	39	--	95
					355	660	257	758	-16	Kula	40	--	98
					388	627	258	757	-17	Kula	51	--	130
					405	610	260	755	-19	Kula	57	--	145
					415	600	259	756	-18	Kula	61	--	156
					430	585	258	757	-17	Kula	66	--	172
					450	565	258	757	-17	Kula	73	--	192
					468	547	256	759	-15	Kula	79	--	212
					483	532	318	697	-77	Kula	84	--	165
					500	515	265	750	-24	Kula	90	--	235
					520	495	305	710	-64	Kula	97	--	215
					534	481	295	720	-54	Honomanu	--	6	239
					542	473	302	713	-61	Honomanu	--	14	240
					549	466	306	709	-65	Honomanu	--	21	243
					555	460	300	715	-59	Honomanu	--	27	255
					563	452	273	742	-32	Honomanu	--	35	290
					580	435	316	699	-75	Honomanu	--	52	264
					600	415	310	705	-69	Honomanu	--	72	290
					620	395	366	649	-125	Honomanu	--	92	254
					638	377	315	700	-74	Honomanu	--	110	323
					648	367	315	700	-74	Honomanu	--	120	333
					662	353	320	695	-79	Honomanu	--	134	342
					680	335	330	685	-89	Honomanu	--	152	350
					688	327	395	620	-154	Honomanu	--	160	293
					700	315	339	676	-98	Honomanu	--	172	361
					712	303	[15]330	685	-89	Honomanu	--	184	382
					725	290	323	692	-82	Honomanu	--	197	402
					733	282	337	678	-96	Honomanu	--	205	396
					750	265	361	654	-120	Honomanu	--	222	389
					755	260	349	666	-108	Honomanu	--	227	406
Test hole 99													
1,578	1,030	191	687	0.32	184	1,394	174	1,404	17	Hana	96	--	10
					200	1,378	182	1,396	9	Kula	2	--	18
					216	1,362	181	1,397	10	Kula	5	--	35
					224	1,354	182	1,396	9	Kula	7	--	42
					229	1,349	182	1,396	9	Kula	8	--	47
					239	1,339	182	1,396	9	Kula	10	--	57

Table 5. Water levels in selected test holes completed in Honomanu Basalt, Nahiku area, Maui, Hawaii--Continued

[Values in feet; --, no data or not applicable; Kula, Kula Volcanics; Hana, Hana Volcanics; Honomanu, Honomanu Basalt. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Land surface altitude	Total depth	Depth to top of Kula Volcanics	Depth to base of Kula Volcanics	Vertical hydraulic gradient	Hole depth	Bottom hole altitude	Depth to water	Water-level altitude	Water level above top of Kula Volcanics	Rock unit[1]	Percent penetration of rock unit	Depth of hole in Honomanu Basalt	Water level above bottom of hole
						Test hole 99--Continued							
					250	1,328	182	1,396	9	Kula	12	--	68
					261	1,317	213	1,365	-22	Kula	14	--	48
					272	1,306	191	1,387	0	Kula	16	--	81
					280	1,298	189	1,389	2	Kula	18	--	91
					300	1,278	188	1,390	3	Kula	22	--	112
					315	1,263	189	1,389	2	Kula	25	--	126
					328	1,250	192	1,386	-1	Kula	28	--	136
					335	1,243	189	1,389	2	Kula	29	--	146
					353	1,225	199	1,379	-8	Kula	33	--	154
					363	1,215	206	1,372	-15	Kula	35	--	157
					377	1,201	211	1,367	-20	Kula	38	--	166
					393	1,185	345/[16]305	1,233/1,273	-154/-114	Kula	41	--	48/88
					406	1,172	327	1,251	-136	Kula	43	--	79
					419	1,159	322	1,256	-131	Kula	46	--	97
					434	1,144	305	1,273	-114	Kula	49	--	129
					448	1,130	315	1,263	-124	Kula	52	--	133
					472	1,106	342	1,236	-151	Kula	57	--	130
					494	1,084	472	1,106	-281	Kula	61	--	22
					501	1,077	472	1,106	-281	Kula	63	--	29
					515	1,063	463	1,115	-272	Kula	65	--	52
					525	1,053	456	1,122	-265	Kula	67	--	69
					535	1,043	489	1,089	-298	Kula	69	--	46
					547	1,031	533	1,045	-342	Kula	72	--	14
					555	1,023	533	1,045	-342	Kula	73	--	22
					566	1,012	558	1,020	-367	Kula	76	--	8
					578	1,000	551	1,027	-360	Kula	78	--	27
					584	994	551	1,027	-360	Kula	79	--	33
					602	976	585	993	-394	Kula	83	--	17
					611	967	595	983	-404	Kula	85	--	16
					616	962	594	984	-403	Kula	86	--	22
					620	958	600	978	-409	Kula	86	--	20
					624	954	605	973	-414	Kula	87	--	19
					633	945	615	963	-424	Kula	89	--	18
					639	939	620	958	-429	Kula	90	--	19
					655	923	635	943	-444	Kula	94	--	20
					662	916	640	938	-449	Kula	95	--	22
					674	904	650	928	-459	Kula	97	--	24
					685	893	665	913	-474	Kula	100	--	20
					705	873	675	903	-484	Honomanu	--	18	30
					713	865	676	902	-485	Honomanu	--	26	37

Table 5. Water levels in selected test holes completed in Honomanu Basalt, Nahiku area, Maui, Hawaii--Continued

[Values in feet; --, no data or not applicable; Kula, Kula Volcanics; Hana, Hana Volcanics; Honomanu, Honomanu Basalt. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Land surface altitude	Total depth	Depth to top of Kula Volcanics	Depth to base of Kula Volcanics	Vertical hydraulic gradient	Hole depth	Bottom hole altitude	Depth to water	Water-level altitude	Water level above top of Kula Volcanics	Rock unit[1]	Percent penetration of rock unit	Depth of hole in Honomanu Basalt	Water level above bottom of hole
Test hole 99--Continued													
					720	858	700	878	-509	Honomanu	--	33	20
					731	847	710	868	-519	Honomanu	--	44	21
					945	633	456	1,122	-265	Honomanu	--	258	489
					950	628	454	1,124	-263	Honomanu	--	263	496
					990	588	454	1,124	-263	Honomanu	--	303	536
					998	580	458	1,120	-267	Honomanu	--	311	540
					1,015	563	448	1,120	-257	Honomanu	--	328	567
					1,024	554	451	1,127	-260	Honomanu	--	337	573
					1,024	554	[2]385	1,193	-194	Honomanu	--	337	639
					1,030	548	447	1,131	-256	Honomanu	--	343	583
Test hole 100													
1,845	1,132	362	1,060	0.46	596	1,249	449	1,396	-87	Kula	34	--	147
					646	1,199	492	1,353	-130	Kula	41	--	154
					666	1,179	559	1,286	-197	Kula	44	--	107
					685	1,160	555	1,290	-193	Kula	46	--	130
					694	1,151	675	1,170	-313	Kula	48	--	19
					709	1,136	690	1,155	-328	Kula	50	--	19
					725	1,120	705	1,140	-343	Kula	52	--	20
					730	1,115	710	1,135	-348	Kula	53	--	20
					734	1,111	715	1,130	-353	Kula	53	--	19
					749	1,096	730	1,115	-368	Kula	55	--	19
					765	1,080	745	1,100	-383	Kula	58	--	20
					774	1,071	755	1,090	-393	Kula	59	--	19
					789	1,056	770	1,075	-408	Kula	61	--	19
					796	1,049	739	1,106	-377	Kula	62	--	57
					821	1,024	716	1,129	-354	Kula	66	--	105
					829	1,016	715	1,130	-353	Kula	67	--	114
					841	1,004	719	1,126	-357	Kula	69	--	122
					851	994	716	1,129	-354	Kula	70	--	135
					861	984	715	1,130	-353	Kula	71	--	146
					931	914	711	1,134	-349	Kula	82	--	220
					946	899	671	1,174	-309	Kula	84	--	275
					967	878	675	1,170	-313	Kula	87	--	292
					979	866	675	1,170	-313	Kula	88	--	304
					991	854	675	1,170	-313	Kula	90	--	316
					1,007	838	666	1,179	-304	Kula	92	--	341
					1,032	813	666	1,179	-304	Kula	96	--	366
					1,061	784	666	1,179	-304	Honomanu	--	1	395
					1,072	773	669	1,176	-307	Honomanu	--	12	403
					1,072	773	[2]400	1,445	-38	Honomanu	--	12	672

Table 5. Water levels in selected test holes completed in Honomanu Basalt, Nahiku area, Maui, Hawaii--Continued

[Values in feet; --, no data or not applicable; Kula, Kula Volcanics; Hana, Hana Volcanics; Honomanu, Honomanu Basalt. Data from unpub. well logs in files at U.S. Geological Survey, Honolulu]

Land surface altitude	Total depth	Depth to top of Kula Volcanics	Depth to base of Kula Volcanics	Vertical hydraulic gradient	Hole depth	Bottom hole altitude	Depth to water	Water-level altitude	Water level above top of Kula Volcanics	Rock unit[1]	Percent penetration of rock unit	Depth of hole in Honomanu Basalt	Water level above bottom of hole
Test hole 100--Continued													
					1,120	725	734	1,111	-372	Honomanu	--	60	386
					1,132	713	695	1,150	-333	Honomanu	--	72	437
Kuhiwa well													
1,396	1,405	258	744	0.02	954	442	260	1,136	-2	Honomanu	--	210	694
					961	435	243	1,153	15	Honomanu	--	217	718
					982	414	246	1,150	12	Honomanu	--	238	736
					1,012	384	256	1,140	2	Honomanu	--	268	756
					1,095	301	259	1,137	-1	Honomanu	--	351	836
					1,110	286	259	1,138	0	Honomanu	--	366	852
					1,122	274	250	1,146	8	Honomanu	--	378	872
					1,175	221	245	1,151	13	Honomanu	--	431	930
					1,188	208	236	1,160	22	Honomanu	--	444	952
					1,210	186	249	1,147	9	Honomanu	--	466	961
					1,229	167	253	1,143	5	Honomanu	--	485	976
					1,245	151	253	1,143	5	Honomanu	--	501	992
					1,248	148	256	1,140	2	Honomanu	--	504	992
					1,256	140	267	1,129	-9	Honomanu	--	512	989
					1,328	68	309	1,087	-51	Honomanu	--	584	1,019
					1,360	36	317	1,079	-59	Honomanu	--	616	1,043
					1,405	-9	270	1,126	-12	Honomanu	--	661	1,135

[1] Based on unpublished geologic logs in files at USGS, Honolulu District office
[2] Current-meter reading
[3] Depth to water after 17 hours, no water pumped in hole
[4] Raised pipe in hole; pipe at hole depth of 190 feet
[5] Raised pipe to a depth of 791 feet
[6] Measurement made by air pressure in drilling rods
[7] Measurement made with drill bit at a depth of 348 feet
[8] Measurement made with drill bit at a depth of 175 feet
[9] Drill bit raised to a hole depth of 300 feet
[10] Measurement made at a drill bit depth of 194 feet
[11] Measurement made at a drill bit depth of 649 feet
[12] Measurement made with air in drill column
[13] Raised pipe in hole to a depth of 519 feet
[14] Raised pipe in hole to a depth of 199 feet
[15] Raised pipe in hole to a depth of 700 feet
[16] Water level dropped to 345 feet, gradually rose to 305 feet

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