SOURCE OF SALTS IN THE WAIANAE PART OF THE PEARL HARBOR AQUIFER NEAR BARBERS POINT WATER TUNNEL, OAHU, HAWAII

By Paul R. Eyre

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CONVERSION FACTORS AND ABBREVIATIONS

The following table may be used to convert measurements in the inch-pound system to metric units.

Multiply inch-pound units	By	To obtain metric units
foot (ft)	0.3048	meter (m)
mile, statute (mi)	1.609	kilometer (km)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
million gallons per day (10^6 gal/d or Mgal/d	0.04381	cubic meter per second (m^3/s)

CROSS REFERENCES OF WELL IDENTIFICATION

Name	State of Hawaii Well Number	Old Well Number
Ewa pumps 10-13	2006-01 to -11	276
Southern Fort Barrette well	2004-01	
Barbers Point shaft	2103-03	Shaft 14
T-19	2103-01	
T-20	2103-02	
Makakilo tunnel	2205-01	
Waipahu pump 5	2203-01, -06	274
Honouliuli exploratory wells	2303-01, -02	
Country Club well	2603-01	
Kunia well	2703-01	
Ewa pumps 15-16	2202-21	Shaft 3
Honouliuli observation well	2101-03	266
Waipahu pump 1	2301-01 to -10	247
Waipahu pump 2	2301-21 to -26	249
Waipahu pump 4	2301-11 to -20	248
Waipahu pump 7	2300-07	246
Waipahu deep monitor well	2300-18	
Waipahu pump 6	2459-01 to -14	239 A to N
Waiawa shaft	2558-10	Shaft 16
Pearl City I	2458-03, -04	202 1A, 1B
Pearl City II	2457-01 to -03	202 2A-2C
Punanani monitor well	2457-04	196-2
Schofield shaft	2901-01,02	

(Note: "Mean sea level" is used as the sea level datum for Hawaii and the other Pacific islands. NGVD of 1929 was never extended to the islands. Accordingly, "sea level" as used in the text refers to "mean sea level" as shown on illustrations)

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ABSTRACT

The salinity of the water supply of Barbers Point Naval Air Station has increased markedly since 1983. The Naval Air Station obtains its water, about 3 million gallons per day, from Barbers Point shaft, a water shaft that taps the Waianae part of the Pearl Harbor aquifer underlying the dry, southeastern flank of the Waianae mountains on the island of Oahu, Hawaii. From 1983 to 1985 the chloride concentration of the water, indicative of the overall salt content, increased from 220 to 250 mg/L (milligrams per liter) and has remained near that level through 1986. The U.S. Environmental Protection Agency has established 250 mg/L as the maximum recommended chloride concentration in drinking water because above that level many people can taste the salt.

Barbers Point shaft draws water from a large lens-shaped body of freshwater, which floats on the saltwater that has intruded into the island from the ocean. The lens is several hundred feet thick and is separated from the underlying saltwater by a thick transition zone in which the chloride concentration increases with depth. The shaft is designed to skim water from the surface of the freshwater lens to minimize the possibility of drawing water from the transition zone. Prior to 1983, the top 100 to 200 feet of the lens near Barbers Point shaft contained water with a chloride concentration of about 200 mg/L. The high chloride concentration in shallow ground water at all wells in the area indicates that most of the salts in the freshwater lens are contributed by rainfall, sea spray, and irrigation return water. At Barbers Point shaft, pumping may draw a small amount of saltwater from the transition zone and increase the chloride concentration in the pumped water by about 20 mg/L. Salinity of the lens decreases progressively inland in response to recharge from relatively fresher water and in response to an increasing lens thickness with increasing distance from the shoreline.

The increase, in 1983, in the chloride concentration of water at the shaft was most probably the result of saltier recharge water reaching the water table, and not the result of increased mixing of underlying saltwater with the freshwater. The chloride concentration of the recharge water has probably increased because, in 1980, the drip method of irrigation began to replace the furrow method on sugarcane fields near the shaft. Drip irrigation applies water directly to the base of the plant at a low but continuous rate through small tubes. With the furrow method, the plants receive water about twice a month when the rows of furrows that cross the fields are flooded.

The amount of water and dissolved salts applied to the fields by the two methods of irrigation differs by only about 15 percent, but when the drip method is used, much less water percolates past the root zone of the plants and recharge to the aquifer is reduced. While the plants use a large fraction of the irrigation water, most of the salts remain in the unused fraction of irrigation water that recharges the aquifer. Relative to the recharge resulting from furrow irrigation, the recharge water resulting from drip irrigation has a higher chloride concentration because the salts are dissolved in less water.

The recharge from irrigation return flow provides a large fraction of the ground water that flows through the aquifer, and as a result an increase in the salinity of the irrigation return water has resulted in a measurable increase in the salinity of ground water.

A mixing-cell model was used to estimate the effect of drip irrigation on the chloride concentration of the ground water in the vicinity of Barbers Point shaft. The model predicted an increase in chloride concentration of about 50 mg/L. The observed increase was about 30 mg/L and the chloride concentration is presently stable at 245 to 250 mg/L; hence, the chloride concentration is not expected to increase significantly more. The processes that control the chloride concentration at Barbers Point shaft are not fully understood, and it is possible that the abrupt increase in chloride concentration from 1983 to 1985 is a passing phenomenon, in which case, the concentration would decline in the next few years. However, the concentration will not decline below the ambient concentration level in the aquifer (200-220 mg/L). The chloride concentration of water from Barbers Point shaft can be lowered significantly only if the aquifer is recharged by fresher water or if a source of fresher water is blended with the Barbers Point shaft water.

INTRODUCTION

Background

Barbers Point Naval Air Station is located on the arid Ewa coastal plain at the southern tip of the Waianae mountains, Oahu, Hawaii (fig. 1). Water for the Naval air station comes from the Waianae part of the Pearl Harbor aquifer. Barbers Point shaft is a water tunnel that taps the upper part of this aquifer and supplies the Naval air station with about 2.5 Mgal/d (million gallons per day) of freshwater. Since 1983 the chloride concentration of water pumped from the shaft has increased from 220 to 250 mg/L. Because of the deterioration of the ground-water quality at Barbers Point shaft, the U.S. Geological Survey, in cooperation with the U.S. Department of the Navy, Naval Facilities Engineering Command, undertook a study to determine the cause of the increasing chloride concentration.

The abundant supply of water yielded by the Pearl Harbor aquifer, 167 Mgal/d in 1985 from wells and tunnels that produce from 1 to 20 Mgal/d, makes this aquifer the most important and most studied aquifer on Oahu. Stearns and Vaksvik (1935, 1938), Stearns (1940), and Wentworth (1945) provide clear and complete descriptions of the geology and hydrology of the area around Pearl Harbor, as well as a history of ground-water development that includes details of well construction and performance. Visher and Mink (1964) describe the processes that affect the water quality in the aquifer, particularly the interaction between the freshwater lens and the underlying saltwater on which the freshwater floats. They also note that elevated concentrations of nitrate, sulfate, and bicarbonate can be attributed to the large fraction of irrigation water that percolates through the soil, recharging the ground water and increasing its concentration of dissolved solids. Soroos and Ewart (1979) document the long-term decline in the water-table elevation (head) at many wells in the Pearl Harbor aquifer, and infer that the observed increase in chloride concentration in some deep wells has been caused by the shrinking of the freshwater lens and consequent rise in the underlying saltwater.

Since 1970, there have been major changes in both natural and man-made factors that affect the amount and quality of water flowing through the region. Average rainfall has been dramatically lower than normal, especially in the drier lowland areas. In 1983 only 7 inches of rain was recorded at Waipahu rain gage no. 750, the lowest rainfall since the gage was established in 1897, when only 4 months of rainfall were recorded (fig. 2). The lowest water levels and highest chloride concentrations on record occurred between 1973 and 1978 at several wells in the Pearl Harbor aquifer.

Since 1970, Oahu Sugar Company has removed from production several thousand acres of sugarcane fields that overlie the Pearl Harbor aquifer and converted 12,000 of their remaining 14,000 acres from furrow to drip irrigation. The reduction in acreage has allowed pumpage from Oahu Sugar Company wells to be much reduced. Both the reduction in irrigated acreage and the conversion to drip irrigation have diminished the amount of irrigation return water that recharges the aquifer. In addition, recharge water from fields irrigated by the drip method may be saltier than recharge water from fields irrigated by the furrow method (Ekern, 1977 and Lau, 1975).

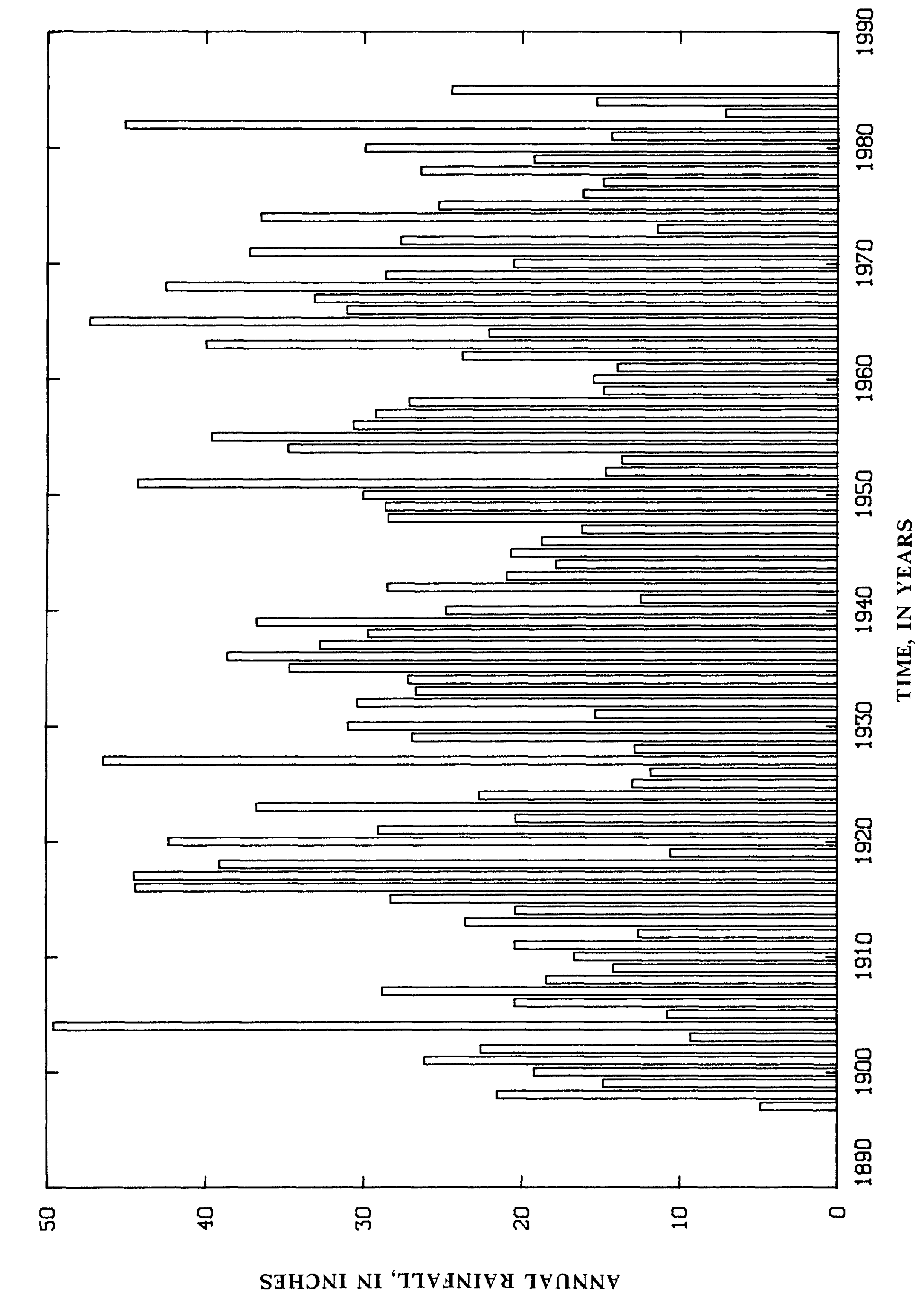

Figure 2. Annual rainfall at Waipahu rain gage 750, 1897-1985.

In 1979, concern over the continued availability of potable water from the aquifer, prompted mainly by the low rainfall and water levels, and also by the need to manage better the aquifer as water and land uses changed, prompted the State of Hawaii, Department of Land and Natural Resources, Division of Water and Land Development (DOWALD), to designate the Pearl Harbor aquifer as a "ground-water control area". The principal purpose of the designation was to control the amount and location of pumpage from the Pearl Harbor aquifer. Pumpage from the aquifer was limited to 225 Mgal/d, the recommended sustainable yield as estimated by the Hydrologic Advisory Committee appointed by the State in 1980. In past years, pumpage had exceeded 240 Mgal/d. Also, data from the ongoing monitoring of pumpage, water levels, and chloride concentrations at many wells are being studied by DOWALD, the U.S. Geological Survey, and the Honolulu Board of Water Supply to gain an understanding of the response of the aquifer to these new conditions.

Purpose and Scope

This report presents a description of ground-water flow in the Waianae part of the Pearl Harbor aquifer near Barbers Point shaft (shaft 14). This description will explain the causes of the increasing chloride concentration of water at the shaft. The quantity, quality, and flow paths of water from various sources that contribute to the aquifer will be described. Of particular concern is whether the increasing chloride concentration in water from the shaft results from upconing of the underlying saltwater, which could continue with increased development of the aquifer, or from irrigation return water that has become saltier as a result of changes in rainfall, land use, and irrigation practices. An attempt to answer this question will be made by analyzing the historic records of wells in the Pearl Harbor aquifer and the areal distribution of ground-water recharge.

Acknowledgments

Mr. Bobby Meyer, manager of the U.S. Navy's water system, was very helpful and supplied background information and water samples from Barbers Point shaft. The cooperation of Mr. Hugh Morita, irrigation engineer for Oahu Sugar Company, was essential for obtaining the history of land and water use of sugarcane fields in the study area. The efforts of Tom Nance of Belt Collins, Consulting Engineers, Chester Lao and Glenn Bauer of the Honolulu Board of Water Supply, and Ed Sakoda and Mitchell Ohye of DOWALD were invaluable in providing data from recently drilled exploratory wells that yielded new information on the geology and water quality of the Waianae part of the Pearl Harbor aquifer.

REGIONAL HYDROLOGY

Geologic Boundaries

The Pearl Harbor aquifer is separated from adjacent aquifer systems by (1) the valley fills between South Halawa and Kalihi streams to the east, (2) the northwest rift zone of the Koolau volcano to the northeast, (3) the southern boundary (of uncertain origin) of the Schofield aquifer system to the north, and (4) the south rift of the Waianae volcano to the west (fig. 3). The hydrologic effect of boundaries is seen from the abrupt change in the water table elevation (head) that occurs across them (fig. 4). In the Pearl Harbor aquifer, ground water flows through the permeable basalt lava flows of the Koolau and Waianae volcanoes.

The northern boundary of the Pearl Harbor aquifer leaks and allows some of the water in the Schofield aquifer to flow south into the Pearl Harbor aquifer. Dikes of the Koolau and Waianae volcanoes prevent the Schofield ground water from flowing east or west.

The southern boundary of the Pearl Harbor aquifer overlies the basalt aquifer and consists of a poorly permeable weathered skin of basalt (saprolite) overlain by marine and terrigenous sedimentary deposits of the Ewa coastal plain. This unit is called caprock. Farrington Highway, shown on figure 1, roughly follows the inland margin of the caprock. Inland of the highway are the basalt lava flows of the Koolau and Waianae mountains. The weathered skin of the basalt and the fine-grained parts of the sedimentary deposits form a leaky confining layer above the basalt aquifer (fig. 5) that inhibits the flow of ground water to the sea and causes heads to be several feet higher than they would be in the absence of the leaky confining layers.

Barbers Point shaft is located in the Waianae part of the Pearl Harbor aquifer, which is separated from the Koolau part by a leaky barrier that was created when the Koolau lavas flowed onto the weathered slopes of the Waianae volcano. The eastern flank of the older Waianae volcano had weathered to a clay-rich saprolite of low permeability when the younger Koolau lava flows banked against it. The structure of this barrier may be complicated by an interfingering of Koolau lava flows with ash and lava flows from the late stage of the Waianae volcanic activity.

Beneath this sloping saprolite barrier is an aquifer composed of less weathered and more permeable Waianae basalts. Above the saprolite layer, is an aquifer composed of permeable basalts of the Koolau volcano. Flow may occur from the Koolau to the Waianae aquifer, but this flow is restricted, as evidenced by attenuated water-level fluctuations in wells that tap the Waianae relative to the Koolau aquifer (Palmer, 1956). Palmer's analysis is summarized in figure 6, which presents the water-level record at the Honouliuli observation well (well 266) in the Koolau basalts, and at Ewa Pump 10 and T-19 in the Waianae basalts.

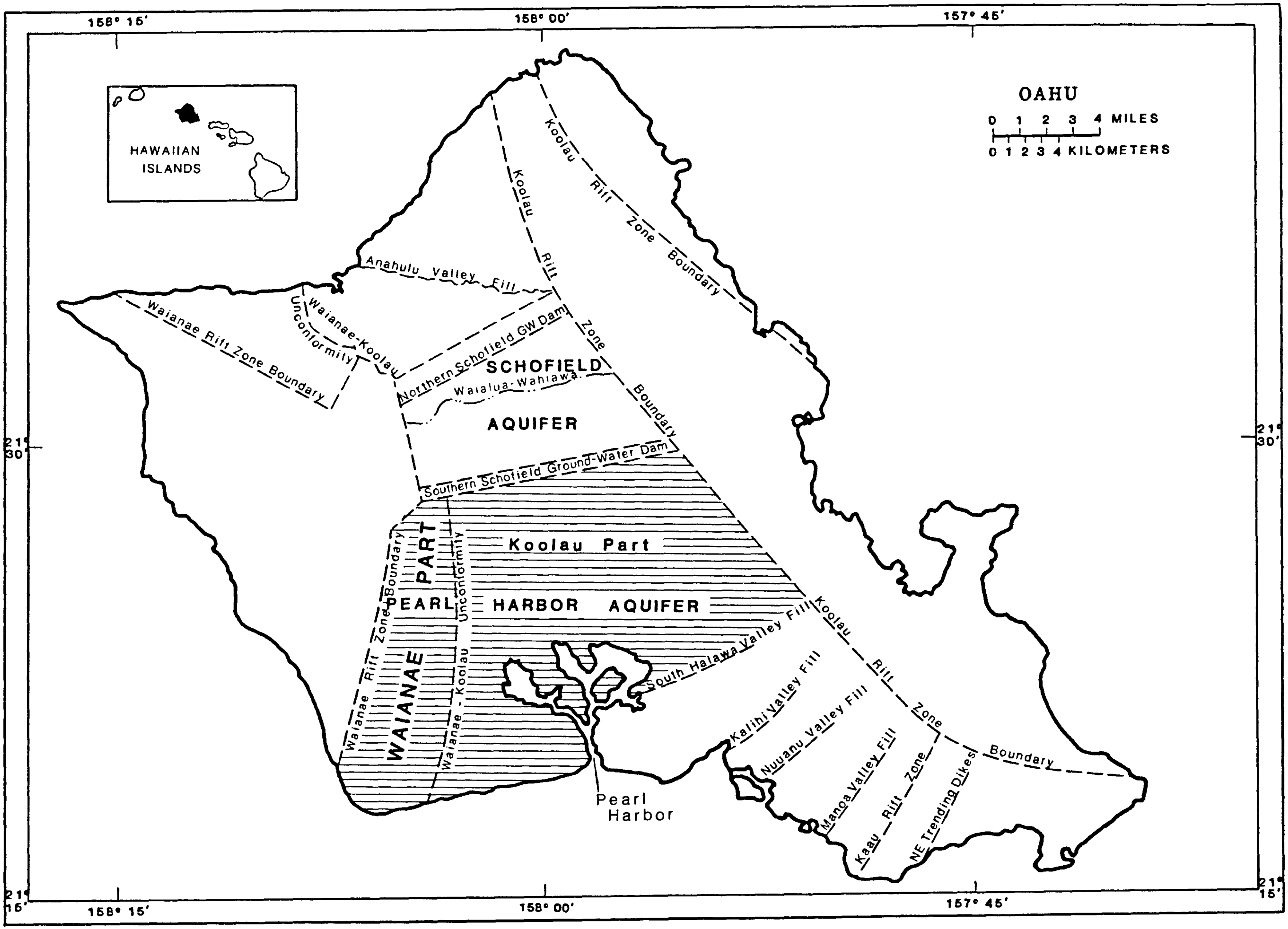

Figure 3. The boundaries of Oahu's ground-water bodies.

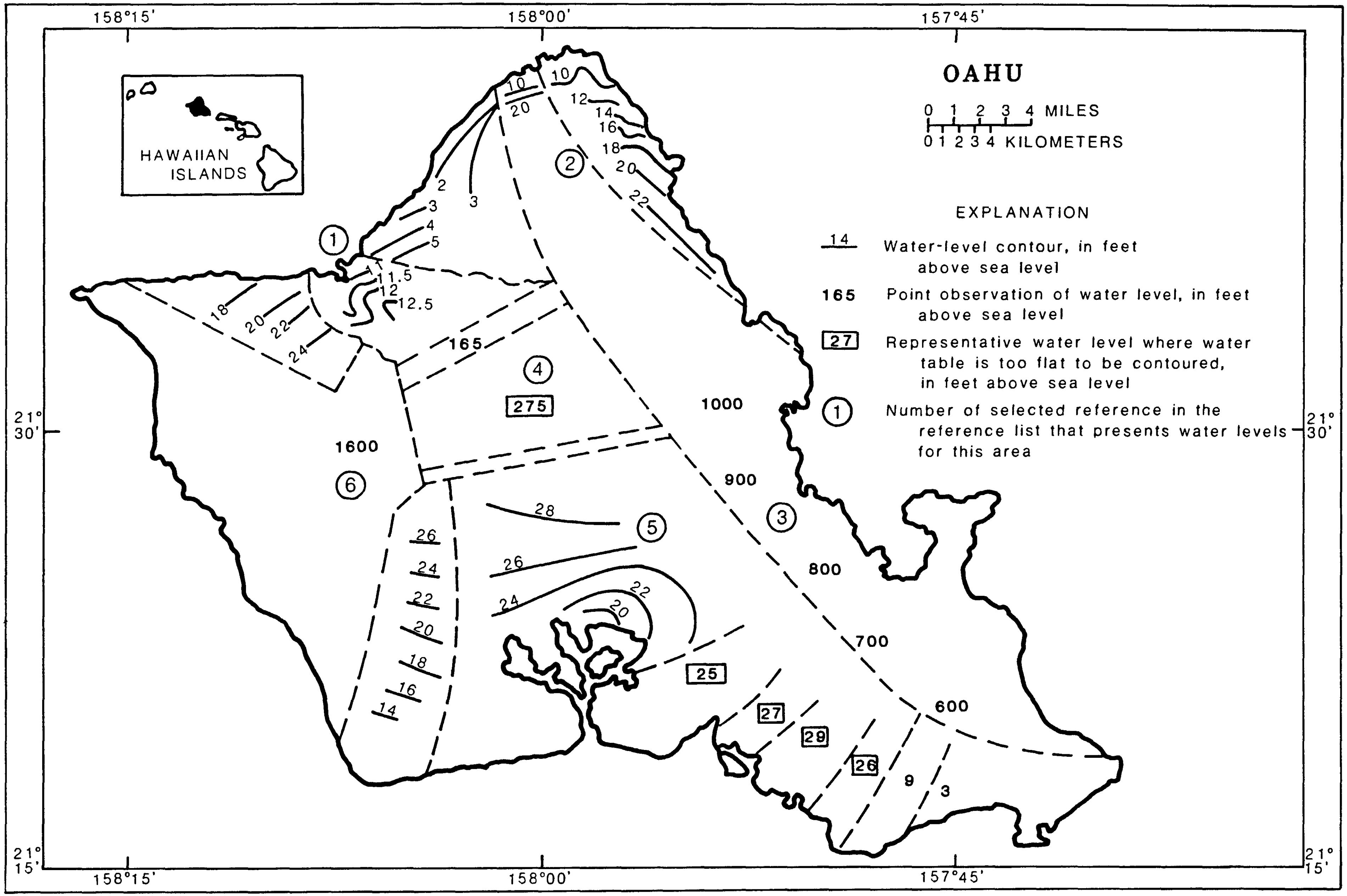

Figure 4. Water-level contours compiled from various U.S. Geological Survey studies of the island of Oahu.

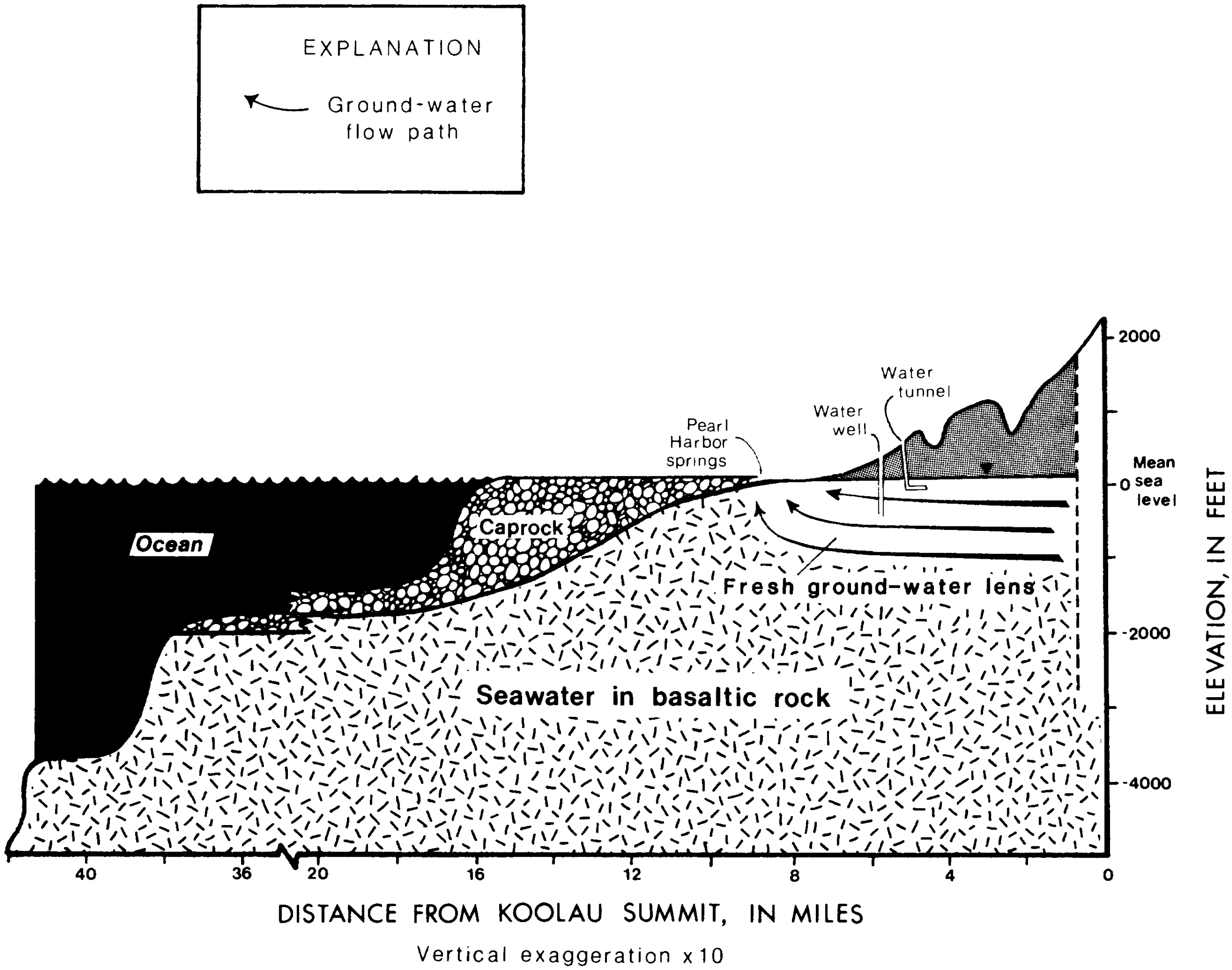

Figure 5. Longitudinal section showing impoundment of the freshwater lens by the caprock (modified from Eyre, 1983).

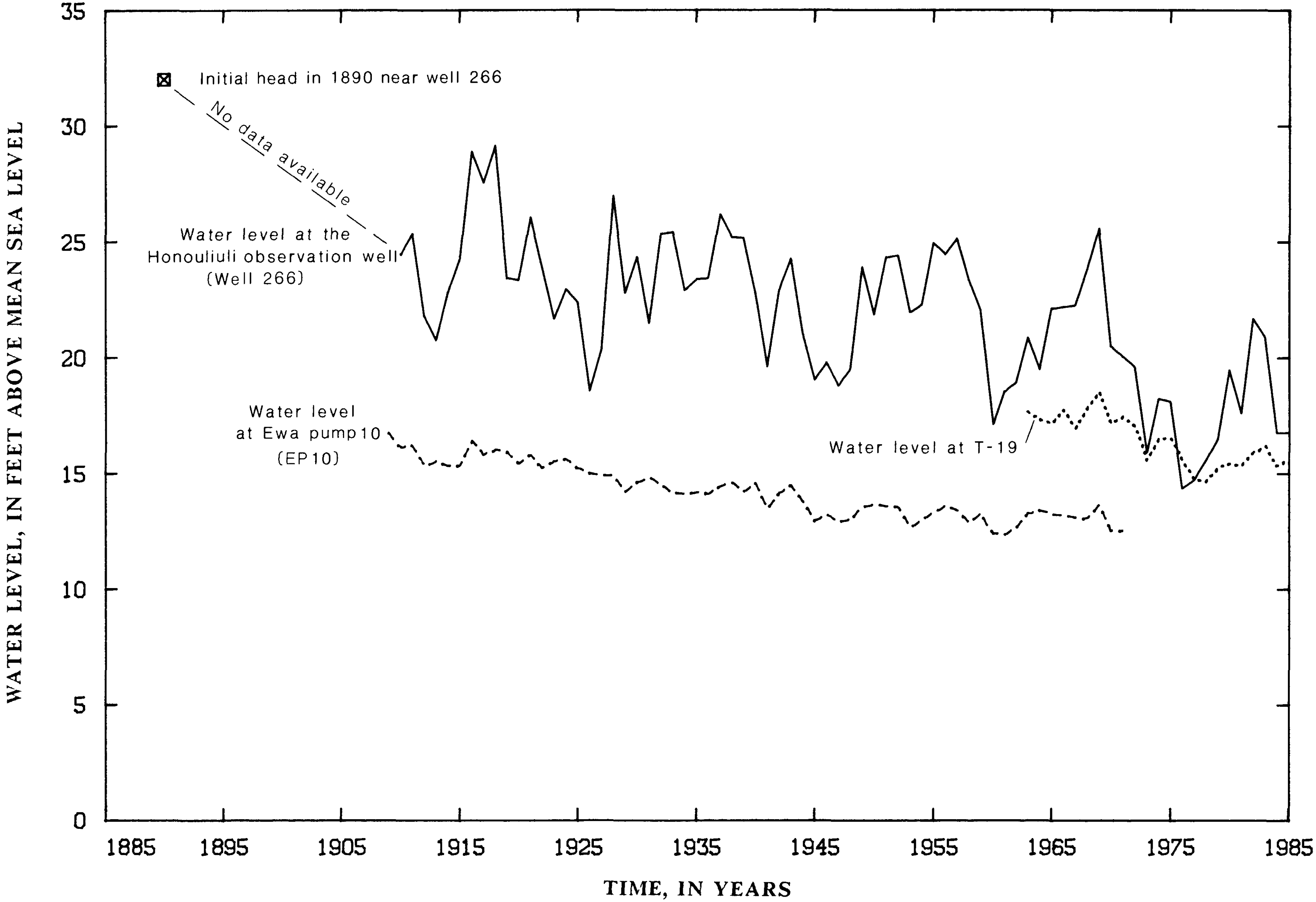

Figure 6. Annual maximum water levels at Ewa pump 10, T-19, and the Honouliuli observation well.

Recharge and Discharge

The spatial distribution of ground-water recharge for the Pearl Harbor aquifer was the outcome of a water budget calculated by Giambelluca (1986). The water budget was calculated for each of four different time periods characterized by different patterns of land and water use. The time periods for which the water budgets were calculated include: (1) the predevelopment period prior to 1879 when the first artesian well was drilled on Oahu, (2) the period from 1950 to 1960 when the water table had equilibrated to the pumpage and land-use patterns established during the "plantation era", (3) the present (1985) period of land and water use when urban areas are expanding and drip is the predominant method of irrigation, and (4) a future period that extrapolates urban expansion and decline in agriculture to the year 2000.

Table 1 shows that since the cultivation of sugarcane began, the distribution of ground-water recharge has been altered. During the plantation era, furrow irrigation increased ground-water recharge in the Waianae part of the Pearl Harbor aquifer to 27 Mgal/d, from a natural rate of only 8 Mgal/d. In recent years, the change to drip irrigation has decreased the recharge to about 17 Mgal/d.

Because it is not known how much of the ground water in the Schofield aquifer flows to the north and south, the system is divided into a northern and southern part by the Wahiawa-Waialua district boundary (fig. 3). Recharge to the southern part is assumed eventually to flow south into the Pearl Harbor aquifer. If the southern Schofield water flows equally across the length of its boundary to the Pearl Harbor aquifer, then about 25 Mgal/d flows into the Waianae part and about 75 Mgal/d flows into the Koolau part; however, there are no definite data to substantiate the total amount or its distribution along the boundary. Until more data are available, the estimated total flow through the Waianae area includes about 25 Mgal/d contributed from the Schofield area, 8 Mgal/d from the recharge of rainfall, and 17 Mgal/d from irrigation return. Several million gallons per day of freshwater may flow from the Koolau part to the Waianae part of the Pearl Harbor aquifer; that flow will be considered negligible, however, for this report. Continued observation of changes in water level, chloride concentration, and pumpage will provide more accurate determinations of the flow through the aquifer.

In the Waianae part of the Pearl Harbor aquifer flow is contained between the Waianae rift and the Waianae-Koolau unconformity, thus flow is from the north to the south. The velocity of ground-water flow is roughly 5 to 15 ft/d (feet per day), calculated from a form of Darcy's Law;

$$v = \frac{K\, dh/dl}{\theta}, \qquad (1)$$

where:

v = average flow velocity,

K = aquifer hydraulic conductivity = 1,000 to 2,000 ft/d, (Soroos, 1973; Mink, 1980; Eyre and others, 1986)

dh/dl = the gradient of the water table = 2 feet per mile (fig. 4), and

θ = effective porosity = 0.05 to 0.1 (Mink, 1980, Eyre and others, 1986).

These velocities are close to values calculated for aquifers of similar geologic structure in the Koolau part of the Pearl Harbor aquifer (Eyre, 1983) and in leeward southeast Oahu (Eyre and others, 1986). The slight slope of the water table throughout the aquifer indicates that ground-water flow is virtually horizontal within the area monitored by wells, with a significant component of vertical flow only where the water begins to discharge into the caprock.

Flow not removed from the aquifer by pumpage discharges into the caprock, probably into the permeable limestone layer that occupies much of the top 200 feet of the caprock. About 30 Mgal/d of freshwater discharged into the caprock south of the Waianae part of the Pearl Harbor aquifer during the plantation era, when total recharge was about 52 Mgal/d and pumpage was 23 Mgal/d. In 1985 flow into the caprock was still about 30 Mgal/d, as recharge was about 42 Mgal/d, due to the conversion to drip irrigation, and pumpage was only 14 Mgal/d.

Table 1. Recharge, and pumpage in the Pearl Harbor aquifer and in the southern part of the Schofield aquifer

[Mgal/d, million gallons per day]
(based on Giambelluca, 1986)

	Waianae area (Mgal/d)	Koolau area (Mgal/d)	Southern part of Schofield area (Mgal/d)
Pre-1879 Predevelopment			
Recharge from rainfall	8	142	88
Pumpage	0	0	0
1950-1960 End of plantation era			
Recharge from furrow irrigation and rainfall	27	216	99
Pumpage	23	142	5
1985 Present			
Recharge from drip irrigation and rainfall	17	165	99
Pumpage	14	153	7

Freshwater Lens

Ground water in the Pearl Harbor aquifer (fig. 3) floats on the saltwater that has permeated most of the island below sea level. The freshwater flows from the interior of the island, where recharge is great and ground-water levels are high, toward the shore, where the water discharges and water levels are lower (fig. 4).

Assuming a simplified static model of this system, Badon Ghyben (1888) and Herzberg (1901) independently developed the principle that predicts the thickness of the freshwater body. The Ghyben-Herzberg relation states that a static (motionless) body of freshwater (with density = 1.0 grams/cm^3 (grams per cubic centimeter)) floating on saltwater (with density = 1.025 grams/cm^3), will extend to a depth below sea level equal to 40 times the head of freshwater above sea level. The higher density of seawater results from its higher concentration of dissolved solids. The chloride concentration of seawater around Oahu is about 19,500 mg/L (Wentworth, 1939). The full thickness of freshwater implied by the 40 to 1 ratio does not occur because freshwater and saltwater mix and form a transition zone in which the chloride concentration of the water increases with depth. Where ground water flows in a horizontal direction, Lau (1962) has shown that the midpoint of the transition zone, the depth at which the chloride concentration is half that of the underlying saltwater, occurs at the depth predicted by the Ghyben-Herzberg principle.

Hubbert (1969) considered a dynamic, flowing freshwater lens and derived a solution for the thickness of the lens that is more correct than the Ghyben-Herzberg solution. However the lens thickness, calculated by the two methods using head data in the vicinity of Barbers Point shaft, differs by less than 0.1 feet for a lens that is 600 feet thick. The difference is small because Hubbert's solution differs from the Ghyben-Herzberg solution only where there is a large component of vertical flow and the head gradient is steep.

The use of 1.025 grams/cm^3 for the density of seawater around Hawaii is by convention and not the result of actual density determinations. Wentworth (1939) presents the density determinations of many Hawaiian seawater samples and concludes that a density of 1.026 grams/cm^3 is more precise; thus 38 to 1 may be a more accurate estimate of the ratio between depth of freshwater below sea level and head above sea level.

The ratio of 40 to 1 has been adhered to because of uncertainties in the hydrogeology of the area, including uncertainty regarding the actual composition and density of the saltwater on which the freshwater floats. Data from several monitor wells in Hawaii indicate that the maximum chloride concentration beneath the lens is only 17,000 to 18,000 mg/L. A ratio of 46 to 1 corresponds to the density of 1.0218 grams/cm^3 associated with a chloride concentration of 17,000 mg/L. In addition, the freshwater heads change over time, and it is not obvious which value for head to use in calculating the depth of the midpoint of the transition zone. Because of these uncertainties, the midpoint of the transition zone and the associated chloride distribution can be predicted, using head data, only within 10 to 20 percent of their actual depths; that is, within about 100 to 200 feet of their actual depths in the Pearl Harbor aquifer. Because of these uncertainties, the ratio of 40 to 1 has become established as a general rule of thumb.

SOURCES OF SALT IN THE GROUND WATER

The Transition Zone Between Freshwater and Saltwater

Figure 7 shows the variation of specific conductance with depth at the Waipahu deep monitor well. Depths are relative to the top of the casing, 28 feet above sea level. Specific conductance is a measure of the concentration of dissolved ions, including chloride, in the water. The specific conductance of the water starts to rise rapidly at a depth of 550 feet below the top of the casing, or about 520 feet below sea level. The midpoint of the transition zone is at a depth of about 720 feet and corresponds, in this case to a specific conductance of about 22,200 μS/cm (microsiemens per centimeter). The specific conductance continues to rise to a maximum of about 44,400 μS/cm at a depth of 983 feet. A sample obtained from a depth of 1,020 feet had a chloride concentration of 17,000 mg/L and a specific conductance of 44,400 μS/cm.

The head of freshwater above sea level at the Waipahu well averaged about 15.5 feet from 1984 through 1986 from which, using a ratio of 40 to 1, a depth below sea level of 620 feet would be predicted for the location of the midpoint of the transition zone. Using a ratio of 46 to 1 that corresponds to a density of 1.0218 grams/cm^3 and a chloride concentration of 17,000 mg/L for the water on which the freshwater floats, yields a depth to the midpoint of 710 feet below sea level, much closer to the observed depth of 720 feet. The deep water may be lighter than expected because it contains less salt than seawater, about 17,000 mg/L chloride. Warming of deep water by the geothermal gradient may also affect the location of the midpoint of the transition zone as well as the thickness of the transition zone.

Vertical flow of ground water beneath this well could also affect the location and thickness of the transition zone, especially if the hydraulic conductivity of the aquifer is anisotropic (Essaid, 1986). Some wells near the shore of the Koolau part of the Pearl Harbor aquifer do show significant increases in head with depth (Stearns and Vaksvik, 1935, and U.S. Geological Survey well files, Honolulu, Hawaii). The steps in the specific conductance log presented in figure 7 may be the result of anisotropy in the aquifer because the depths of the steps correspond to permeable zones in the aquifer as shown by a caliper log of the hole. Differences in head across dense lava flows may cause water to flow vertically in the well; flowing into and out of more permeable zones.

Because there are no deep observation wells in the Waianae aquifer, the profile of the transition zone shown in figure 7 for the Waipahu deep monitor well gives an approximation of the chloride-with-depth profile beneath Barbers Point shaft (see locations on fig. 1). The ground-water head at Barbers Point shaft is about a foot less than at the Waipahu observation well; hence, the lens is probably thinner and the chloride profile should be shifted upward, closer to the water table.

The salinity of water from many wells in Hawaii has increased over time because shrinkage of the freshwater lens has brought the transition zone within the influence of the wells. An example of this process is seen at Waipahu pump 6 where the freshwater lens is about 800 feet thick and the wells

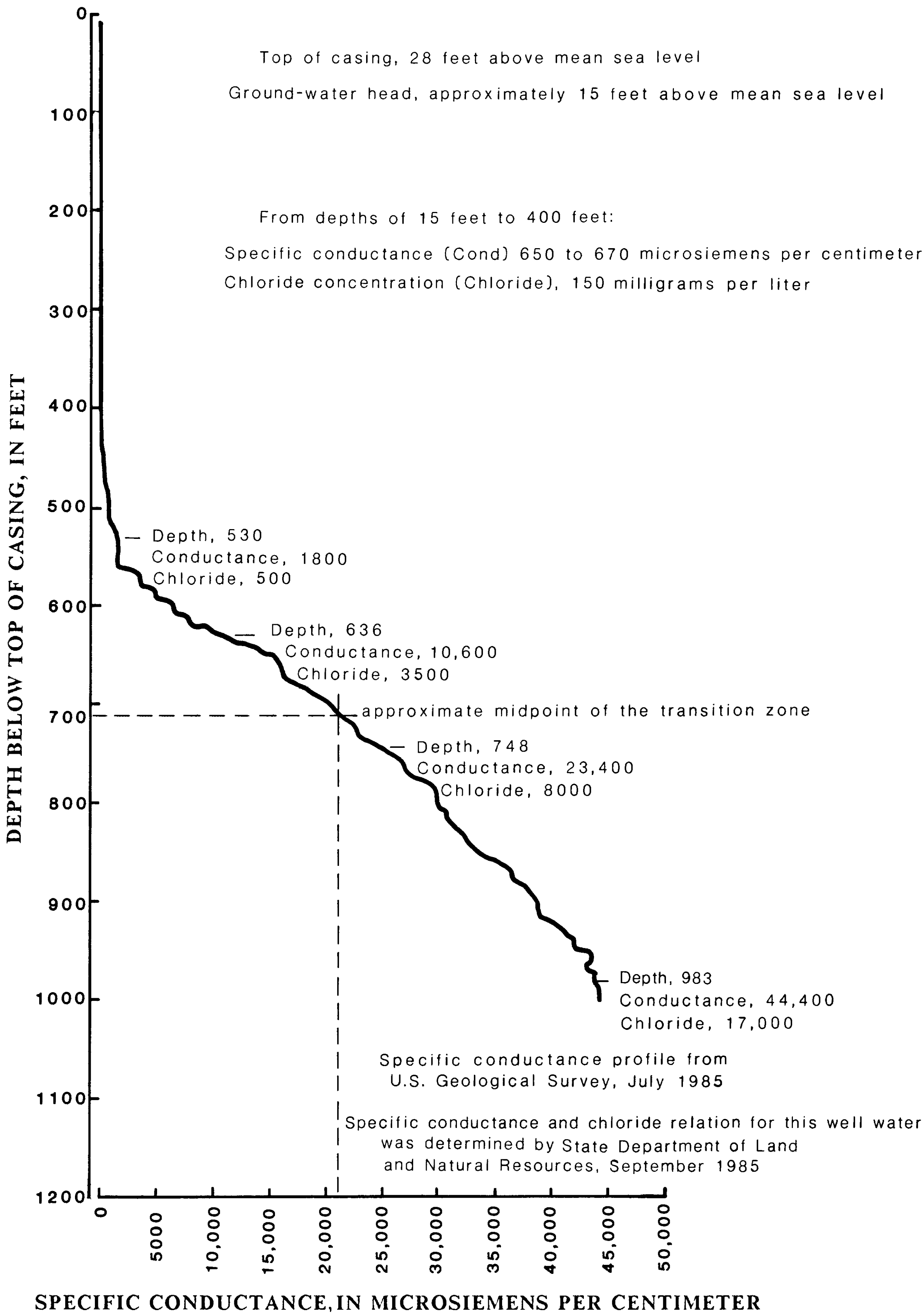

Figure 7. Specific conductance related to depth at the Waipahu deep monitor well.

penetrate to about 700 feet below sea level. Upconing, when pumping draws water from the transition zone, is shown by the correlation between fluctuations in chloride concentration and seasonal fluctuations in pumping rate at Waipahu pump 6, shown in figure 8. A similar situation is documented by Souza (1981) for the Lahaina district on the island of Maui, Hawaii, where seasonal fluctuations in pumpage for the irrigation of sugarcane cause large fluctuations in chloride concentration.

Data from the Pearl Harbor aquifer indicate that wells should remain more than 200 feet above the freshwater-saltwater interface, as calculated by a Ghyben-Herzberg ratio of 40 to 1, to minimize the risk of upconing. However, a closer inspection of the data shows that the relation between well depth and chloride concentration is exceedingly complex. At Waipahu pump 6 a deeper well may produce water with a significantly lower chloride concentration than an adjacent and more shallow well. Wentworth (1951) explains this phenomenon eloquently when he states,

> It has been observed in a great many wells that water somewhat more saline than infiltrated rain water is often yielded by wells whose uncased bottom portion is within 1 or 2 hundred feet of the theoretical boundary between fresh water and salt, and it has been stated that the 'depth of the zone of diffusion may be considerable--as much as 100 to 300 feet'. It is more and more apparent that there can be no single figure for the thickness of this zone, and from the variability of depths at which saline encroachment takes place we are forced to conclude that the boundary must take the form of extremely irregular interpenetration of fresh into salt and salt into fresh water by streamers of water of one quality drawn by hydraulic conditions into the realm of the other. The average effect of such irregular interpenetration must be a transition thickness of several hundred feet in most places but with great variation in the way in which individual wells cut the irregular transition zone, as well as increasing deviations due to more drastic withdrawal from wells and general lowering of the basal head....

The chloride concentration in pumped water is more stable and shows less response to pumping rate in shallow wells than in deep wells. Still, high chloride concentrations do occur at some shallow wells. The chloride concentration of water from both Waiawa and Barbers Point shafts has exceeded 250 mg/L on occasion, yet these water tunnels penetrate less than 20 feet below sea level. Pumpage at the two sites is very different, 15 Mgal/d at Waiawa shaft and 3 Mgal/d at Barbers Point shaft. Prior to 1981, when sugarcane was grown in the fields overlying Waiawa shaft, there was a negative correlation between pumpage and chloride concentration at the shaft; that is, the chloride concentration increased when the pumpage decreased (Eyre, 1983). These observations suggest that there is a source of salts in the shallow ground water other than the transition zone.

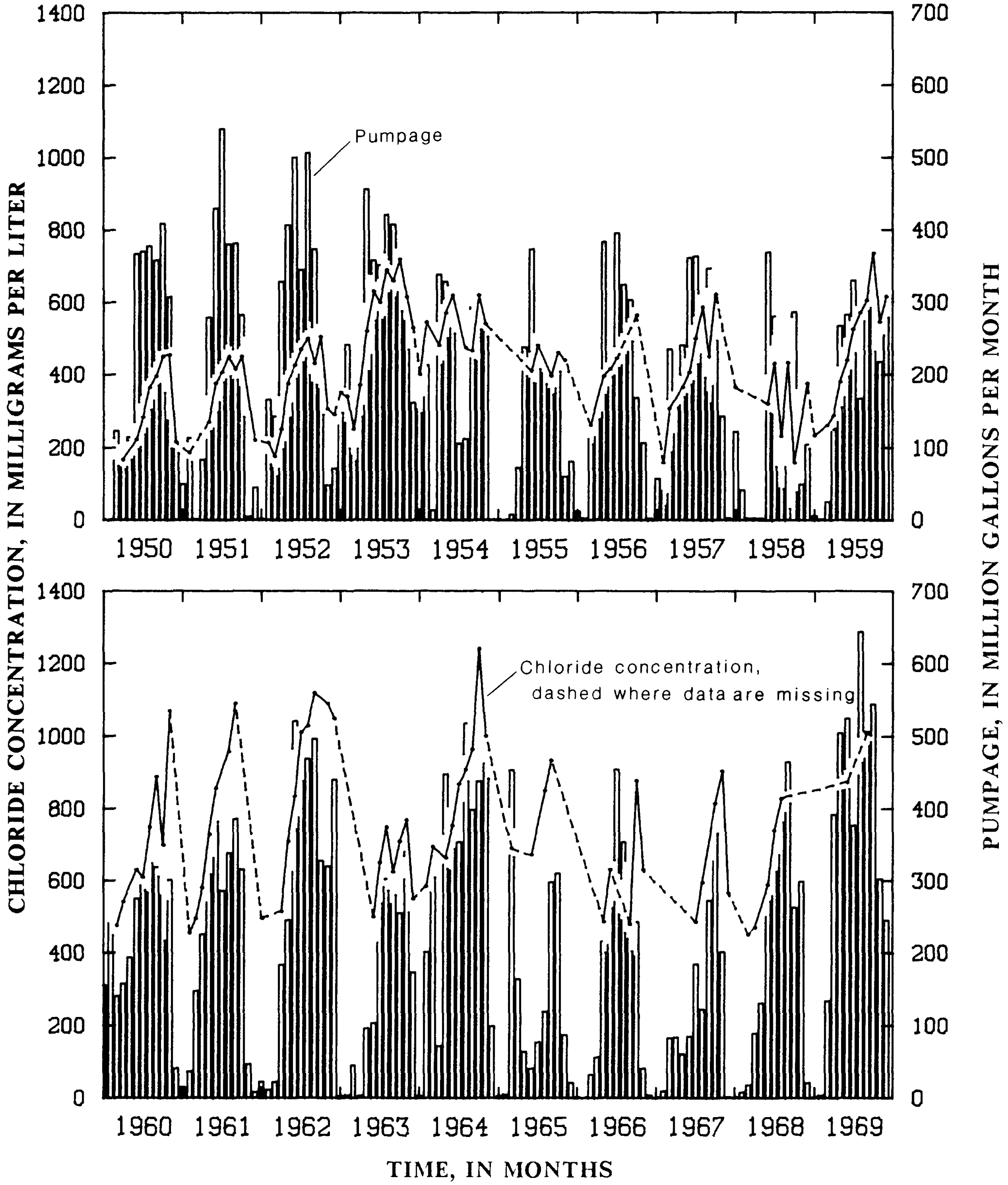

Figure 8. Monthly pumpage and chloride concentration for Waipahu pump 6, 1950-1969.

Irrigation Return Water

Water-budget calculations and chemical data indicate that irrigation return water is a large source of recharge to the aquifer and can have a measurable effect on the ambient water quality.

Water budget.--Most of the area of sugarcane cultivation that overlies the Pearl Harbor aquifer receives between 20 and 40 inches of rain per year, 15 to 20 percent of which reaches the aquifer as ground-water recharge. During the time the area was in furrow irrigation the fields were irrigated with about 112 to 130 inches of water per year (Dale, 1967 and Giambelluca, 1986). With the furrow method, the plants receive water about twice a month when the rows of furrows that cross the fields are flooded. By this method much of the irrigation water infiltrates quickly past the root zone of the plant. Various calculations show that from 40 to 65 percent of the irrigation water recharged the aquifer (Dale, 1967, Giambelluca, 1983, and Lau, 1975). Recharge from furrow irrigation and rainfall ranges from 84 to 97 inches per year for most of the area cultivated in sugarcane that overlies the Pearl Harbor aquifer (Giambelluca, 1986).

From 1980 to 1984 drip irrigation replaced the furrow method for sugarcane fields in the vicinity of Barbers Point shaft. Drip irrigation applies water at a low but continuous rate through small tubes directly to the base of the plant; thus the plants are able to use most of the applied water. In 1985 about 14,000 acres of sugarcane in the Pearl Harbor area was irrigated, mostly by the drip method, with 75 Mgal/d of pumped water and about 25 Mgal/d of Waiahole ditch water imported from the windward side of the island. This amount of irrigation water applied to 14,000 acres yields an irrigation rate of 96 inches per year, a reduction of about 15 to 25 percent from the furrow irrigation rate of 112 to 130 inches per year.

If plant requirements are the same as the evaporation from evaporating pans in the area, the plants could use from 80 to 90 inches of water per year (Ekern and Chang, 1985), leaving only about 10 to 20 inches of water per year to recharge the aquifer. Giambelluca (1986) calculates that about 30 inches of water per year recharges the aquifer under drip irrigated fields in the Waianae part of the Pearl Harbor aquifer, as opposed to his calculation of about 90 inches per year when furrow irrigation was used.

From this analysis it appears that the method of irrigation will have a large effect on the ground water, especially in dry areas where natural recharge is low. Table 1 shows that irrigation return water has increased the flow of ground water through the Koolau and Waianae parts of the Pearl Harbor aquifer by 34 and 58 percent, respectively, when furrow irrigation is used, and by 11 and 27 percent when drip irrigation is used. These percentages were arrived at by dividing the increase in recharge between predevelopment and pumping periods by the total predevelopment flow through the aquifer. The total predevelopment flow was obtained by adding 75 Mgal/d and 25 Mgal/d from the Schofield high-level water body to the predevelopment recharge of the Koolau and Waianae aquifers, respectively. These calculations do not address the net decrease in flow through the aquifer caused by pumpage.

Chemical data.--The presence of irrigation return water in the aquifer can be identified by its higher concentration of dissolved chemicals than the ambient water. Sources of dissolved salts in irrigation return water are fertilizers used in the sugarcane fields and transition-zone water pumped from deep irrigation wells. In irrigated areas, the nitrate concentration at wells declines with distance inland, from about 15 mg/L (as nitrate) at Ewa pumps 10-13 to less than 5 mg/L (as nitrate) at the Kunia well, inland from all sugarcane fields (Hufen and others, 1980). Rainfall and seawater are not sources of nitrate as rainfall in Hawaii contains about 0.5 mg/L nitrate (Swain, 1973) and seawater contains about 3 mg/L nitrate (Hem, 1985). The lowest chloride concentration (10-20 mg/L) also occurs at wells inland from all sugarcane fields. These data support a hypothesis in which the irrigation return water progressively accumulates in the aquifer as successive fields contribute recharge to the seaward flow through the aquifer.

Hufen and others (1980) also show that there is a decline in nitrate and bicarbonate concentration with distance east of the Waianae crest, which may indicate that the irrigation return water contributes a progressively smaller fraction to the ground-water flow at more eastern wells, a conclusion in general agreement with the water budget information. East of Waiawa shaft, where there has been no irrigation since the late 1960's, concentrations of chloride, bicarbonate, and nitrate have declined and cease to show a correlation with distance from the Waianae crest. These data indicate that, east of Waiawa shaft, the amount of irrigation return water in the aquifer has decreased and no longer has a measurable effect on the water quality.

The chloride concentration at the Pearl City wells, east of Waiawa shaft, has declined from 140 to 40 mg/L since the cessation of irrigation in the area (Eyre, 1983). Since 1982, when irrigation of the fields above Waiawa shaft was discontinued, the chloride concentration at the shaft has declined steadily from over 250 mg/L to about 60 mg/L in 1986 (fig. 9). The concentration has remained near 60 mg/L in 1987. Because natural recharge in the immediate area of Waiawa shaft and the Pearl City wells is low, the decline in chloride concentration can be attributed to the washing away of the degraded water by the ambient ground-water flow.

Because the irrigation return recharges the horizontally flowing ground water from the top, a layer of degraded water has formed there. This layer has been measured directly at the Punanani monitor well, a mile east of the Pearl City wells. At the Punanani well the specific conductance was 900 μS/cm in the top 160 feet of the aquifer and declined to 400 μS/cm by a depth of 250 feet (fig. 10). The chloride concentration of the water was roughly one-fourth of the specific conductance. The negative correlation between chloride and pumpage at Waiawa shaft mentioned earlier can be explained if higher pumping rates breached the degraded layer and drew fresher, deeper water to the pumps. Figure 11 illustrates this concept. A similar 3-layered system would be expected in the Waianae aquifer.

Chemical data also allow ground-water flow velocity to be estimated. Noting that the irrigated fields extended 5,000 feet upgradient from Waiawa shaft and that it took about 4 years for the degraded water to wash away (fig. 9), a velocity of about 3.5 ft/d can be calculated for the rate of ground-water flow. A rate of about 5 ft/d was calculated when this approach was used for the Pearl City well chloride data (Eyre, 1983). Values of 3.5 to 5 ft/d are minimum estimates of the rate of ground-water flow (average pore

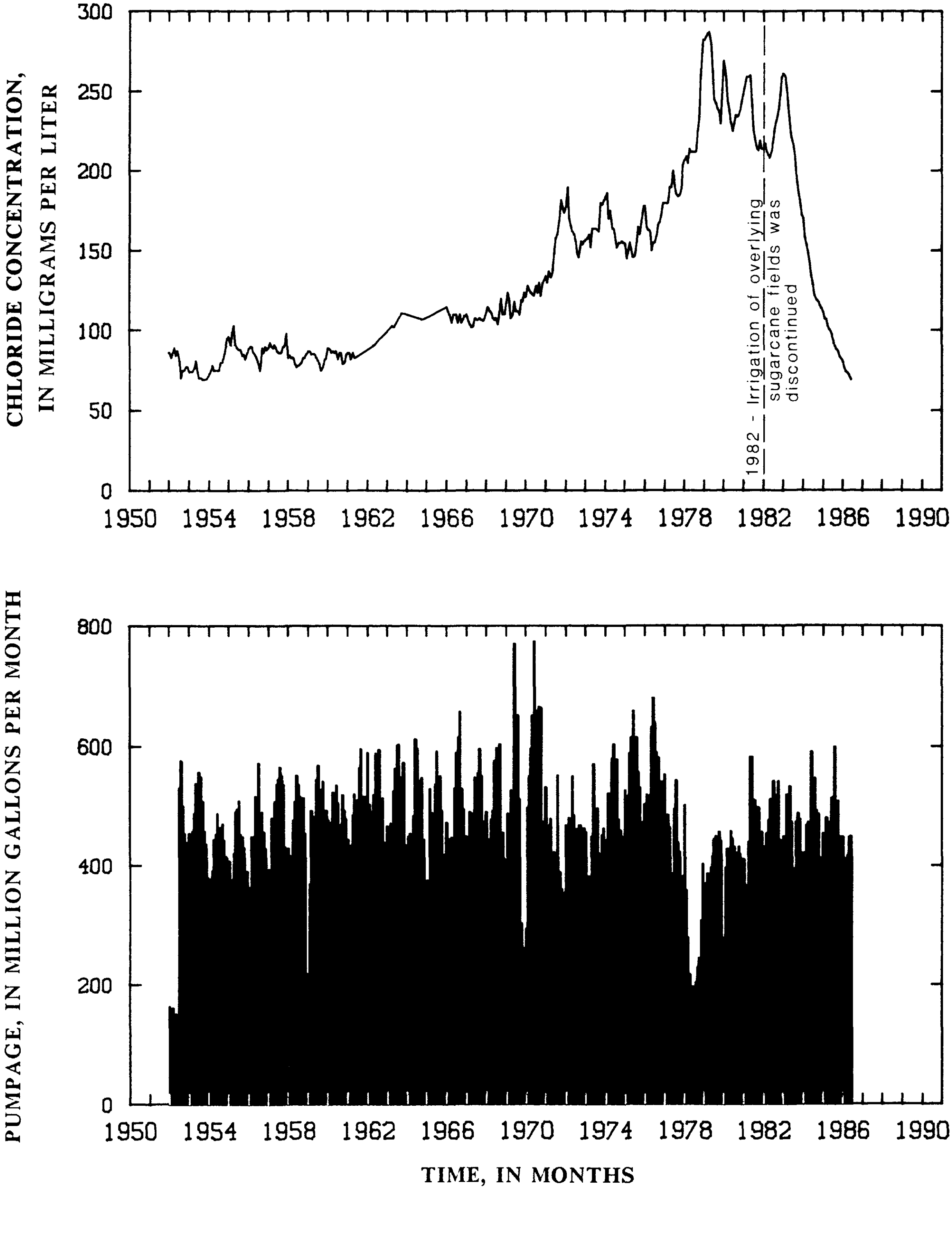

Figure 9. Monthly pumpage and chloride concentration for Waiawa shaft, 1952-1986.

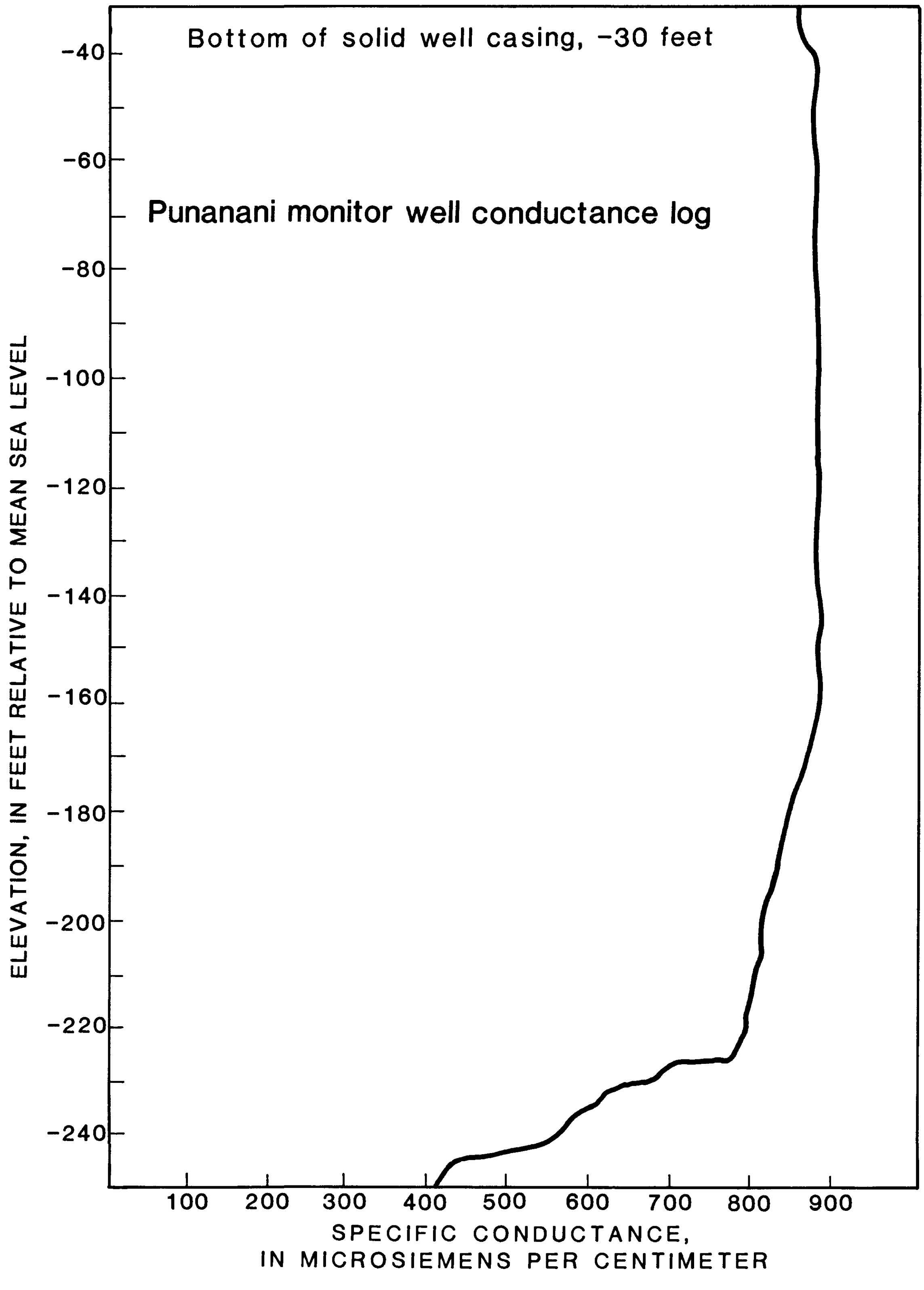

Figure 10. Specific conductance related to depth at the Punanani monitor well (modified from Bowles, 1968).

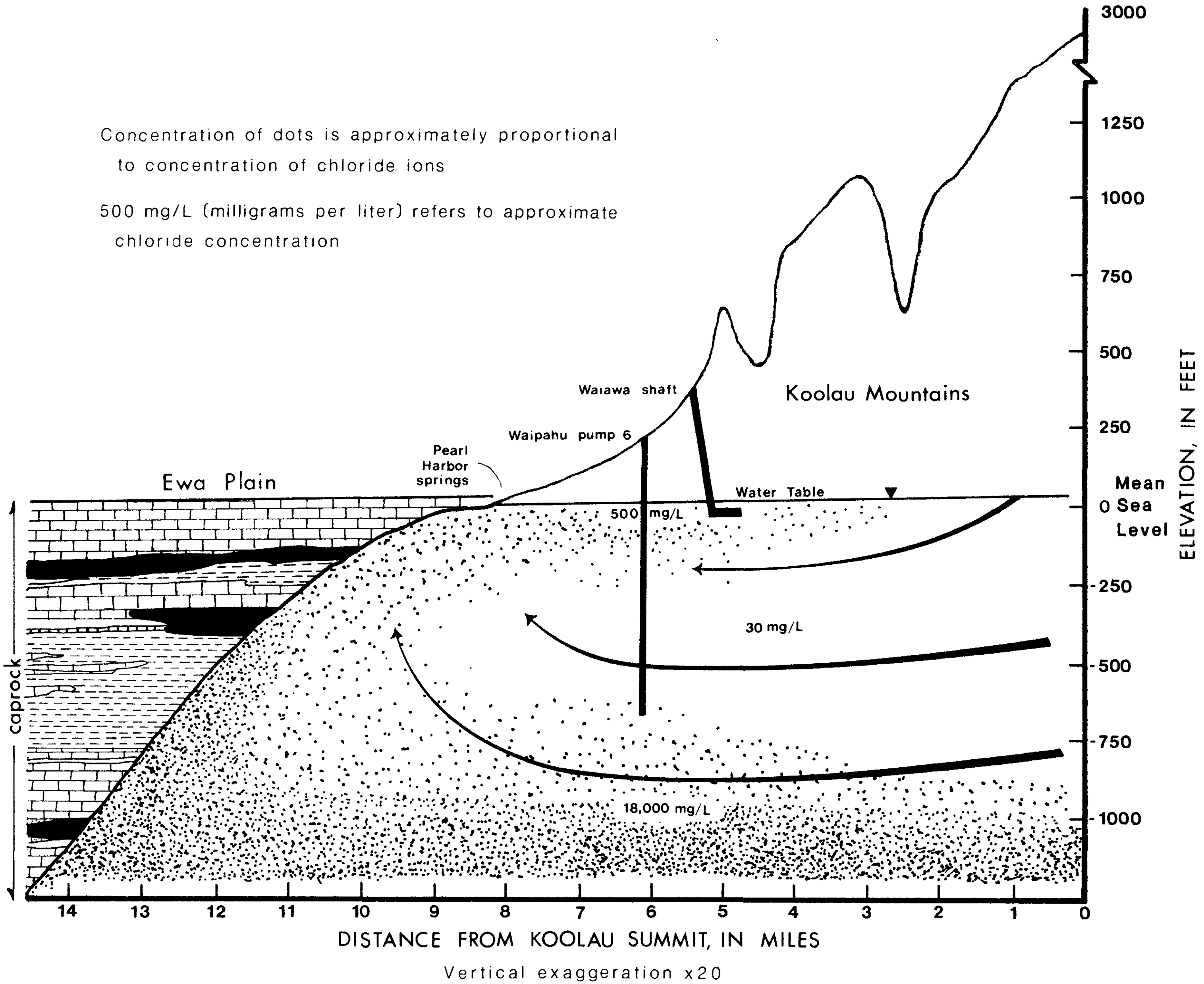

Figure 11. Schematic distribution of chloride ions underlying Waiawa shaft (modified from Eyre, 1983).

velocity of the water) because the effect of hydrodynamic dispersion of the chloride ions was not considered in the calculation. If dispersion is considered, and one-dimensional flow is assumed, the average pore velocity of the fluid is calculated using the time required for the concentration to reach a value half-way between the initial and final concentrations (Ogata, 1970). Thus the rate of ground-water flow in the vicinity of Waiawa shaft and the Pearl City wells may be closer to 7 to 10 ft/d. These values are close to the values of 5 to 15 ft/d presented earlier for the velocity of ground-water flow in the Waianae part of the Pearl Harbor aquifer.

Concentration of Sea Spray and Rainfall by Evaporation

Although a ready explanation is available for the sources of chloride ions in the Waiawa area, there are several places in Hawaii, the Waianae aquifer included, where the chloride concentration may be relatively high throughout the full thickness of the freshwater lens, or where there is a degraded layer at the top of the lens but there is no irrigation in the area to which it can be attributed. Wells where unexpectedly high chloride concentrations occur are almost always located in a dry area or a coastal area buffeted by strong winds blowing in from the ocean. When the surf is high a blanket of salt mist may cover the coastal area for days.

Takasaki (1971) documents several profiles of decreasing chloride concentration with depth in coastal wells in the Waianae district on the western coast of Oahu. Several wells in the Waianae district also have elevated nitrate concentrations (6-10 mg/L as nitrate). There is no irrigation in the area of these wells to explain these data. Apparently, salts accumulate in the soil from sea spray and the evaporation of rainfall. When infrequent large storms, from which most of the ground-water recharge is derived, occur, these salts are leached to the aquifer. The saltier recharge that occurs closer to the shore would overlie the fresher recharge moving seaward from farther inland; thus water at the top of the aquifer would be saltier than deeper water.

Another explanation for the chloride related to depth profile and the occurrence of elevated nitrate concentrations in some Waianae wells involves koa haole (Leucaena glauca) and kiawe (Prosopis chilensis) trees, both of which are phreatophytes, plants that have a deep tap root. At lower elevations, where their roots extend down to the water table, these trees may transpire as much as 70 inches of water per year (Zones, 1963). Transpiration at this rate may appreciably concentrate the dissolved solids at the water table, and create the observed chloride with depth profile.

These trees are also nitrogen fixers. Nitrogen-fixing bacteria live on the tree roots and convert nitrogen in the air to protein in nodules on the tree roots, thus increasing the nitrogen concentration there. This nitrogen may be converted to nitrate, causing the elevated concentrations of nitrate observed in some wells in the area. However, Jones (1973) investigated in great detail the high nitrate concentrations in the soil and ground water of Runnels County, Texas, and had to conclude that the cause of the high concentrations was much too complex to be explained in a quantifiable way. A similar conclusion may be appropriate for the Hawaiian situation where irrigation return, nitrogen-fixing plants, and other poorly understood processes may be sources of nitrate.

Four more examples of chloride concentrations that are difficult to explain are at:

1) The Aina Koa well in southeastern Oahu. This well tapped a thin layer of unusually salty water with a chloride concentration of 2,000 mg/L sitting atop the freshwater of the basal aquifer (Takasaki and Mink, 1982). Upon pumping, the chloride concentration declined and in 1982 was 150 mg/L. An explanation of these conditions might invoke the concentration of sea spray or rainfall by evaporation. Gypsum, generally formed by the evaporation of seawater, has been found in some valley floors below the level of the former shoreline of the 45-foot stand of the sea (Macdonald and Abbott, 1970). This suggests that halite (sodium chloride) may have been deposited during the regression of higher stands of the sea that occurred several tens of thousands of years ago. Although such a source of chloride is possible it seems unlikely, because even in areas of low rainfall, the soluble halite deposit would probably have been leached from the soil long ago.

2) The Waialee wells, at the northeastern end of Oahu. Here one well had a chloride concentration of about 350 mg/L, and an adjacent well had a concentration of 50 mg/L. An explanation for these observations may involve sea spray, from strong tradewinds and high surf, and vertical basalt dikes that compartmentalize the water.

3) The Waipahu deep monitor well. This well shows a constant chloride concentration of 160 mg/L in the top 400 feet of the ground-water lens. The chloride concentration increases below a depth of about 400 feet. An explanation for these data might involve sea spray or concentrated rainfall, irrigation return water, and the underlying transition zone. A thorough mixing of some or all of these components might produce a thick zone of constant and elevated chloride concentration, although it is difficult to explain a mechanism that would create this much mixing. The most likely explanation for the lack of a freshwater core in the lens is that the freshwater zone has been "pinched out" between salty recharge water and upward flow from the transition zone. Near the Waipahu deep monitor well much of the water in the lens discharges to wells, springs, and the caprock, which causes the lens to become thinner and the deep salty water to flow upward. The seaward part of the lens shown in figure 11 illustrates this possibility.

4) The Makakilo tunnel. The tunnel, located 840 feet above sea level, is about one-half mile northwest of Puu Makakilo (fig. 1), and taps perched ground water that had a chloride concentration of between 500 and 1,000 mg/L in the 1930's (Stearns and others, 1935, and Stearns, 1940). This perched water eventually recharges the basal water body. Although not all the water that recharges the basal aquifer in this area is of this quality, the water quality at Makakilo tunnel supports the hypothesis that sea spray or the concentration of rainfall, which contains a small amount of salts from the ocean, can supply substantial amounts of salts to the ground water. The possibility that the salts at Makakilo tunnel were leached from an ancient fumarole deposit, as the tunnel is near a large cinder cone, was considered unlikely by Stearns and others (1935). Bryson (1954) believed the water had the chemical character of diluted seawater whose salts were derived from sea spray.

HYDROLOGIC SETTING NEAR THE BARBERS POINT SHAFT

An analysis of the wells in the Waianae part of the Pearl Harbor aquifer utilized depth, location, history of pumpage, and variation in chloride concentration to determine the source of salt at Barbers Point shaft and in the aquifer as a whole. The wells used are shown on figure 1 and are included in the following discussions.

Kunia and Country Club wells.--The most inland well in the Waianae part of the Pearl Harbor aquifer is at Kunia. The well was completed in 1946 to a depth of 129 feet below sea level. The water then had a head of 25 feet, and a chloride concentration of about 25 mg/L. Nitrate analyses in the 1960's produced values of between 1 to 3 mg/L as nitrate. These values are representative of pristine ground water unaffected by the sources of salts previously mentioned. Farther seaward by 1.5 miles, the Hawaii Country Club well (shown as CC in fig. 1) was drilled in 1961 to a depth of 246 feet below sea level. Below sea level the well taps the Waianae aquifer, as indicated by the eastward projection of the slopes of the Waianae mountain, by the geologic log of the well, and by pumping test data. The head was about 22 feet in 1961, the chloride concentration was about 50 mg/L, and the nitrate concentration was about 10 mg/L as nitrate. Pineapple and sugarcane have been cultivated in the vicinity of this well for several decades. The higher chloride and nitrate concentrations at the Country Club well may result from irrigation return flow in the aquifer. However, the fields in the area are irrigated by Waiahole ditch water, which has only about 10 mg/L chloride. Irrigation of this quality is not expected to increase the chloride concentration in the ground water.

Farther seaward, chloride and nitrate concentrations of water in this aquifer become progressively higher, probably as a result of the accumulation of recharge water from irrigation.

Honouliuli exploratory wells.--At the Honouliuli exploratory wells, shown in figure 1 near the Waianae-Koolau contact, the head in December 1986 was 16 feet above sea level. Changes in head at these wells compared to changes in head at other wells in both the Waianae and Koolau aquifers, all measured several times between December 1986 and April 1987, confirm that these exploratory wells tap the Waianae aquifer. Chloride concentration of the well water was 150 mg/L to a depth of 300 feet below sea level where it increased abruptly to 300 mg/L. At the bottom of the well, 380 feet below sea level, the chloride concentration was 440 mg/L. This chloride distribution suggests that the freshwater lens in the Waianae aquifer is similar to but thinner than the lens penetrated by the Waipahu deep monitor well, where the chloride concentration started to rise at a depth of 430 feet below sea level (fig. 7). The absence of a fresh mid-portion of the lens is probably the result of the upward flow of the upper part of the transition zone as the lens discharges into the caprock, about 1 mile south of the Honouliuli exploratory wells and the large amount of irrigation return flow that recharges the aquifer.

Waipahu pump 5.--The wells at Waipahu pump 5 (WP5 on fig. 1), drilled in 1901 when the head was greater than 20 feet above sea level, penetrate between 160 and 260 feet below sea level and can deliver water at a rate of 20 Mgal/d. Apparently the ground water had an ambient chloride concentration of between

100 and 200 mg/L, as that concentration was observed in 1901 to 1902 before irrigation return was likely to have had an effect on the water quality (fig. 12).

The relatively shallow depth of the wells would minimize upconing of saline water. The chloride concentration at Waipahu pump 5 was relatively constant from 1902 to 1960 even though the head in the aquifer declined about 3 feet during that period. If the salts at Waipahu pump 5 were from the transition zone, the chloride concentration would be expected to increase as the lens became thinner with the declining head.

It is difficult to resolve the extent to which salts in Waipahu pump 5 water are derived from the transition zone. The increase from 180 mg/L to 250 mg/L chloride between 1950 and 1973 probably resulted from upconing of saline water caused by the increase in the annual average pumping rate from about 7 Mgal/d to 15 Mgal/d during that period (fig. 12). Some of the increase in chloride concentration also may have resulted from the concurrent increase in irrigation return flow to the aquifer. The relatively salty water pumped from Waipahu pump 5 in the 1970's and applied to the sugarcane fields near Barbers Point shaft may have contributed to the rise in chloride concentration at Barbers Point shaft in 1983. Further discussion of this possibility is presented in a later section of this report.

Upconing of saline water is also indicated by the correspondence between the seasonal fluctuations in pumping rate and chloride concentration shown in figure 13. The chloride concentration fluctuates seasonally about 20 mg/L while the pumping rate varies between 0 and 20 Mgal/d. The magnitude of the upconing at depth cannot be inferred from these data, but the effect within the radius of influence of the well is certainly small.

Another approach to estimate the potential for upconing is to apply ground-water flow equations to data from the area. Equation 2, modified from Schmorak and Mercado (1969), predicts the distance that the saltwater-freshwater interface may rise beneath a well of a certain depth pumping at a specified rate. Up to a certain level of upconing, their theoretical predictions agreed well with results from field tests of a coastal aquifer in Israel. Beyond that level, more upconing occurred than the equations predicted. The equation is:

$$z = (\rho_f \times Q) / (2 \times \pi (\rho_s - \rho_f) K \times L) \qquad (2)$$

where:

z = rise in the saltwater-freshwater interface (ft)

Q = well discharge (ft^3/d)

L = depth of freshwater-saltwater interface below the bottom of the well prior to pumping (ft)

K = the horizontal hydraulic conductivity of the aquifer (ft/d)

ρ_s = density of saltwater ($grams/cm^3$)

ρ_f = density of freshwater ($grams/cm^3$)

π = 3.14

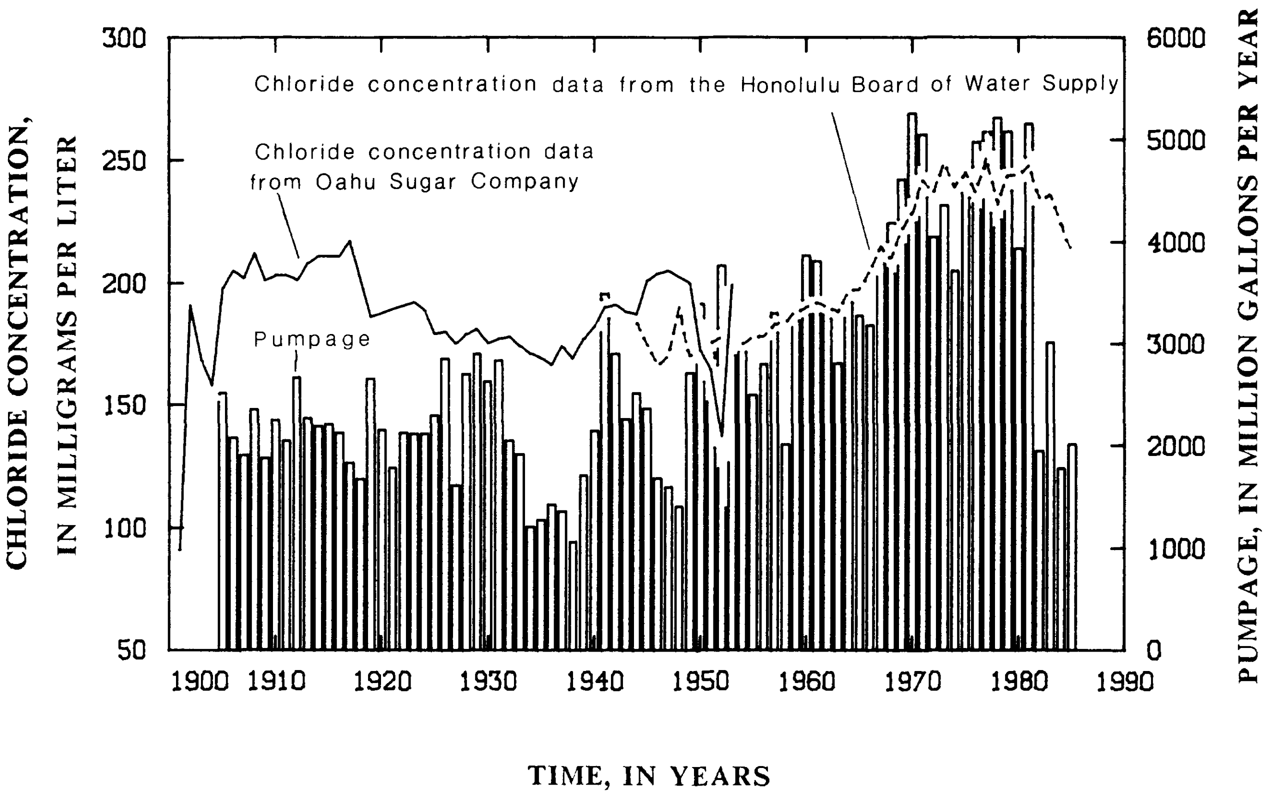

Figure 12. Annual pumpage and mean chloride concentration for Waipahu pump 5, 1901-1986.

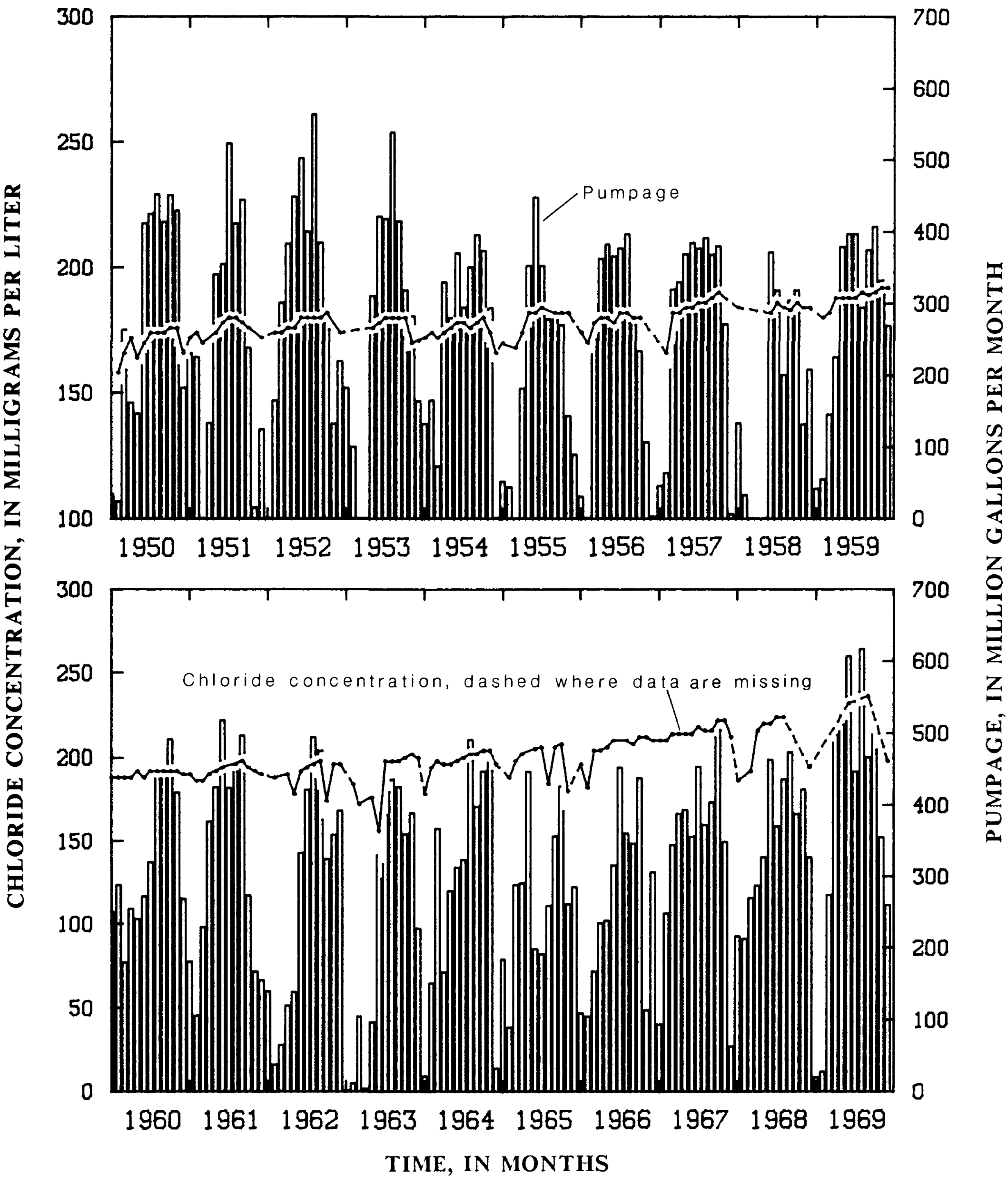

Figure 13. Monthly pumpage and mean chloride concentration for Waipahu pump 5, 1950-1969.

Data from Waipahu pump 5 were used in the equation to see if a significant amount of upconing would be expected at that site. For conditions representative of the high pumping period in the the 1970's;

Q = 14 Mgal/d

L = 538 feet, assuming a head of 18 feet, thickness of lens of 18 x 41 feet, and depth of well of 200 feet below sea level

K = 1,000 to 2,000 ft/d

$\rho_s = 1.025$

$\rho_f = 1.000$

then;

z, the rise in the saltwater-freshwater interface, is 10 to 20 feet.

The equation represents a simplification of the true flow situation because (1) it does not address the dispersion of salts about the interface, (2) it assumes a linear approximation to a nonlinear boundary condition, and (3) the data are only approximate. However, the small value of z indicates that it is not likely that the ambient chloride concentration of 200 mg/L results from upconing of the freshwater-saltwater interface. However, the seasonal fluctuations of 20 mg/L, and a large part of the increase from 180 to 250 mg/L that occurred between 1950 to 1973, may be the result of upconing. Barbers Point shaft, which pumps only 3 to 4 Mgal/d and penetrates less than 20 feet below sea level, is expected to cause much less upconing.

Barbers Point shaft and T-19.--In the vicinity of Barbers Point shaft, chloride concentration in the aquifer was about 200 mg/L prior to any pumping from the shaft, as indicated by the initial chloride concentration of 200 mg/L at test boring T-19. Well T-19 was drilled in 1942, prior to the shaft's construction, to determine the type of rock and the water-table elevation that the shaft would encounter. The earliest record of chloride concentration in water from Barbers Point shaft was 230 mg/L during its construction in 1943. After pumping 4.5 Mgal for a day, the chloride concentration was 250 mg/L. The draw down resulting from a pumping rate of 4.5 Mgal/d was 19 inches.

The chloride concentrations of 230 to 250 mg/L, observed in 1943, may have been the result of upconing caused by the dewatering of the water tunnels during their excavation. Although no records are available, dewatering at a rate of more than 20 Mgal/d may have been required to draw down the water table to the tunnel invert, 20 feet below sea level. With the tunnels completed, a drawdown of only 0.5 to 1 foot resulted from a pumping rate of 7 Mgal/d.

The shaft went on line in 1944, but records of chloride concentration from 1944 to 1952 and from 1962 to 1977 have been lost. This loss impairs our ability to understand the aquifer. Apparently, the chloride concentration remained between 215 and 220 mg/L until 1983 when the steady rise to about 250 mg/L commenced (fig. 14). The large fluctuations in chloride concentration observed from 1952 to 1962 are either in error or are a characteristic of the aquifer or pump station that no longer exists. Analysis of pumping, irrigation, and rainfall rates does not provide an explanation for these fluctuations.

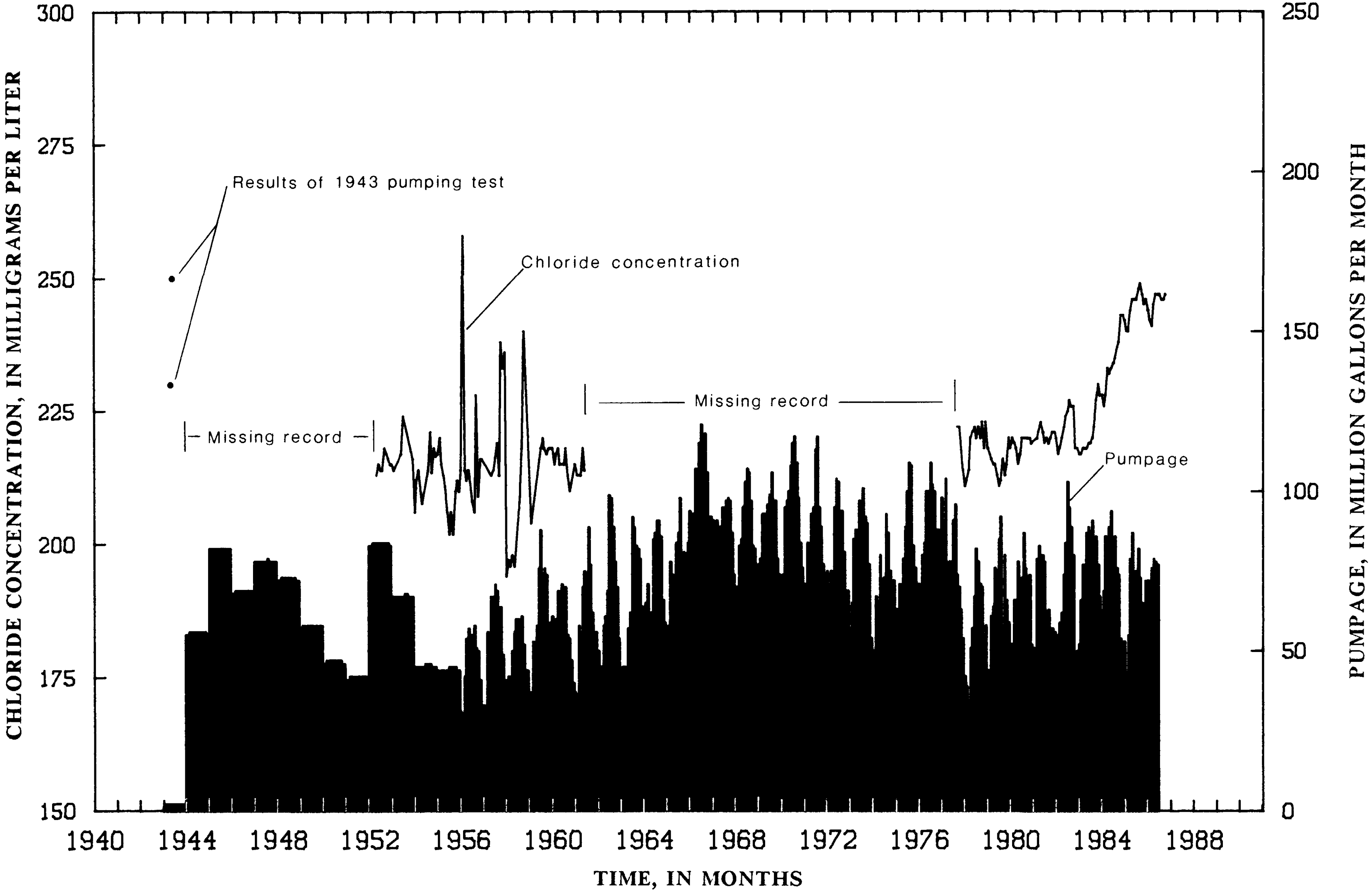

Figure 14. Monthly pumpage and chloride concentration for Barbers Point shaft, 1943-1986.

The occurrence of a small amount of upconing is supported by a comparison of water samples bailed from well T-19 and samples taken from Barbers Point shaft's discharge line. T-19 is less than 400 feet from the shaft and was drilled to 4 feet above sea level, about 10 feet below the water table. The Navy Public Works Center's environmental/industrial laboratory analyzed nine samples for chloride and nitrate concentration obtained from both sites between August and September 1986. In all but one pair of samples the chloride concentration at T-19 was 20 mg/L less than the concentration of water from the shaft. In addition, the nitrate concentration of T-19 water was generally greater than the nitrate concentration of the water from Barbers Point shaft, although a t-test shows that the two sets of nitrate concentrations are not statistically different at the 95 percent confidence level. Table 2 presents the analyses.

These data suggest that the undisturbed ground water in the vicinity of Barbers Point shaft has a chemical character similar to that of the water at well T-19. Apparently, pumpage from the shaft causes slight upconing, increasing its chloride concentration by 20 mg/L and slightly decreasing its nitrate concentration, relative to T-19.

Although upconing may occur at the shaft, it does not explain the steady rise in chloride concentration observed from 1983 to 1985. There have been no large pumping stresses to which upconing can be attributed and, in fact, pumpage from the aquifer as a whole has been dramatically reduced since 1980, as shown in figures 12 and 15.

Table 2. Chloride and nitrate analyses at T-19 and Barbers Point shaft, August-September 1986

[Mgal/d, million gallons per day; mg/L, milligrams per liter]
(Collected and analyzed by the Navy Public Works Center)

		Chloride concentration (mg/L)		Nitrate concentration (mg/L as NO_3)	
Date	Flow at the shaft (Mgal/d)	T-19	Barbers Point shaft	T-19	Barbers Point shaft
08/14/86	4.4	225	247	14.7	14.4
08/21/86	4.0	225	246	14.4	14.1
08/28/86	4.0	225	246	14.7	14.4
09/04/86	4.4	225	247	14.1	13.5
09/11/86	4.4	246	247	13.8	13.8
09/18/86	4.4	227	246	13.8	13.8
09/25/86	4.0	225	247	14.0	13.2
10/02/86	4.0	225	246	12.9	12.6
10/09/86	4.0	226	247	14.0	13.3
	Mean	228	247	14.0	13.7
	Standard Deviation	6.9	.5	.5	.6

In response to the decline in pumpage, heads have become higher and the freshwater lens is probably thicker than it was in the late 1970's (fig. 6). If the lens has become thicker, it is not likely that the transition zone is the source of the increased concentration in salts at Barbers Point shaft. Further discussion of the chloride concentration at Barbers Point shaft will follow the presentation of data from wells south of the shaft, at Ewa pumps 10-13 and the southern Fort Barrette well.

Ewa pumps 10-13 and the southern Fort Barrette well.--The most seaward wells that tap the aquifer are the wells at Ewa pumps 10-13 in the southwestern corner of the aquifer, and the southern Fort Barrette well (fig. 1). The southern Fort Barrette well, drilled in 1933, penetrates 60 feet below sea level. The chloride concentration in water sampled during drilling rose from 400 mg/L to 500 mg/L as the well was deepened. The wells at Ewa pumps 10-13, drilled between 1905 and 1923, penetrate to 120 feet below sea level and produced water containing about 400 mg/L chloride that increased to nearly 550 mg/L after a few years of pumping (fig. 15).

The wells' proximity to the caprock, where the ground-water lens discharges into the limestone, and the early rise in chloride concentration suggest that significant upconing has occurred at Ewa pumps 10-13. Yet the chloride concentration did not continue to increase even though the head continued to decline until 1945 (figs. 6 and 15). Also, seasonal fluctuations in pumpage have very little effect on the chloride concentration, as shown in figure 16.

If the chloride concentration of 500 mg/L were from the transition zone, a strong correlation between pumpage and chloride concentration would be expected, as at Waipahu pump 6, figure 8. In addition, the nitrate concentration of the water from Ewa pumps 10-13, 15 mg/L as nitrate, is the highest in the Pearl Harbor aquifer, suggesting the presence of a large fraction of irrigation return water in the ground water. Seawater, diluted to a chloride concentration of 500 mg/L, would contain less than 0.1 mg/L nitrate (Hem, 1980).

Because neither the irrigation return nor the upconing argument is completely satisfactory, it appears that a layer of salty recharge water, from both rainfall and irrigation, overlies a broadly diffuse transition zone, whose upper part is of the same concentration as that of the recharge water. The broadly diffuse transition zone may be the result of upward flow of saltwater from deep in the lens as the freshwater discharges into the caprock. The consequence is a thick zone of salty water that has some characteristics of both irrigation return water and the transition zone and which is only slightly affected by pumpage from relatively shallow wells.

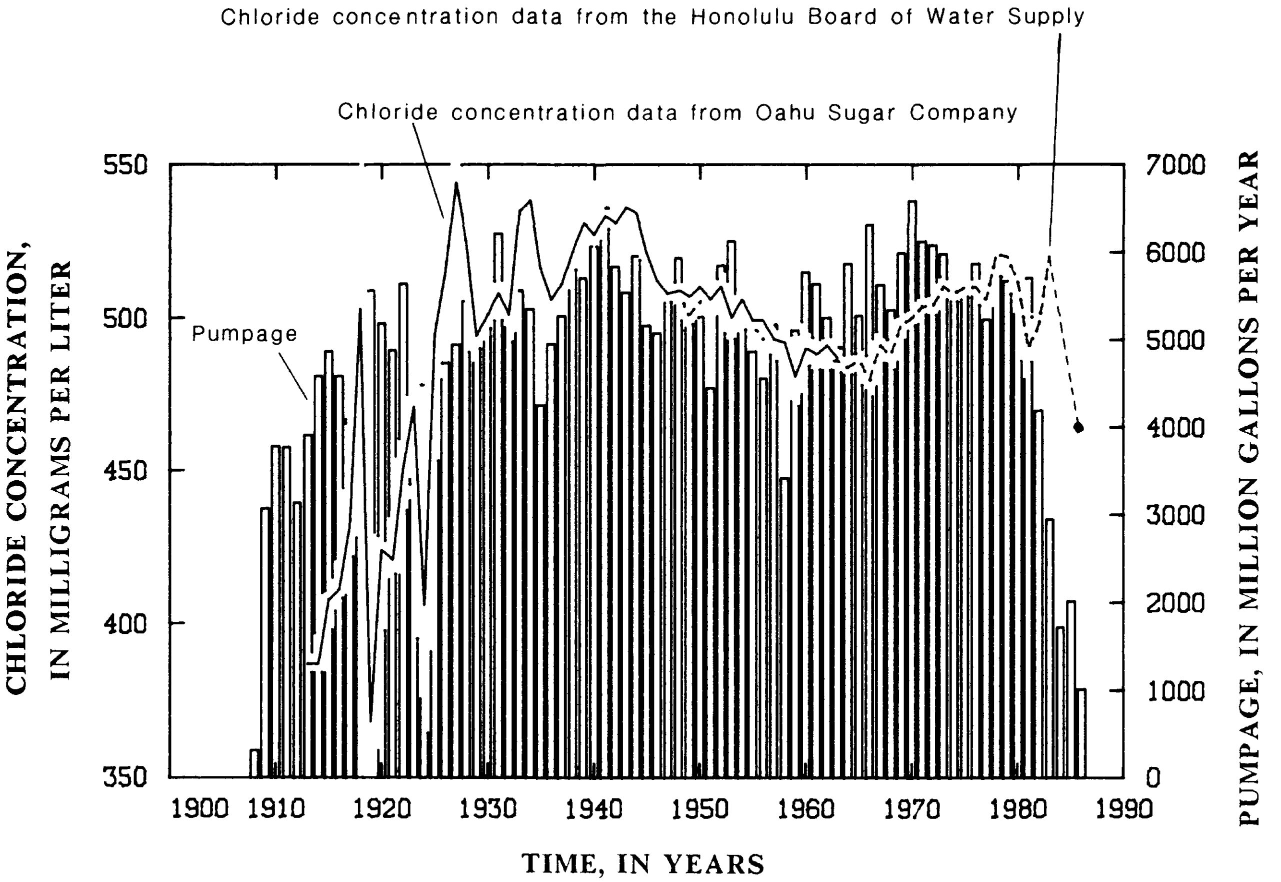

Figure 15. Annual pumpage from Ewa pumps 10-13 and mean chloride concentration for Ewa pump 12, 1908-1986.

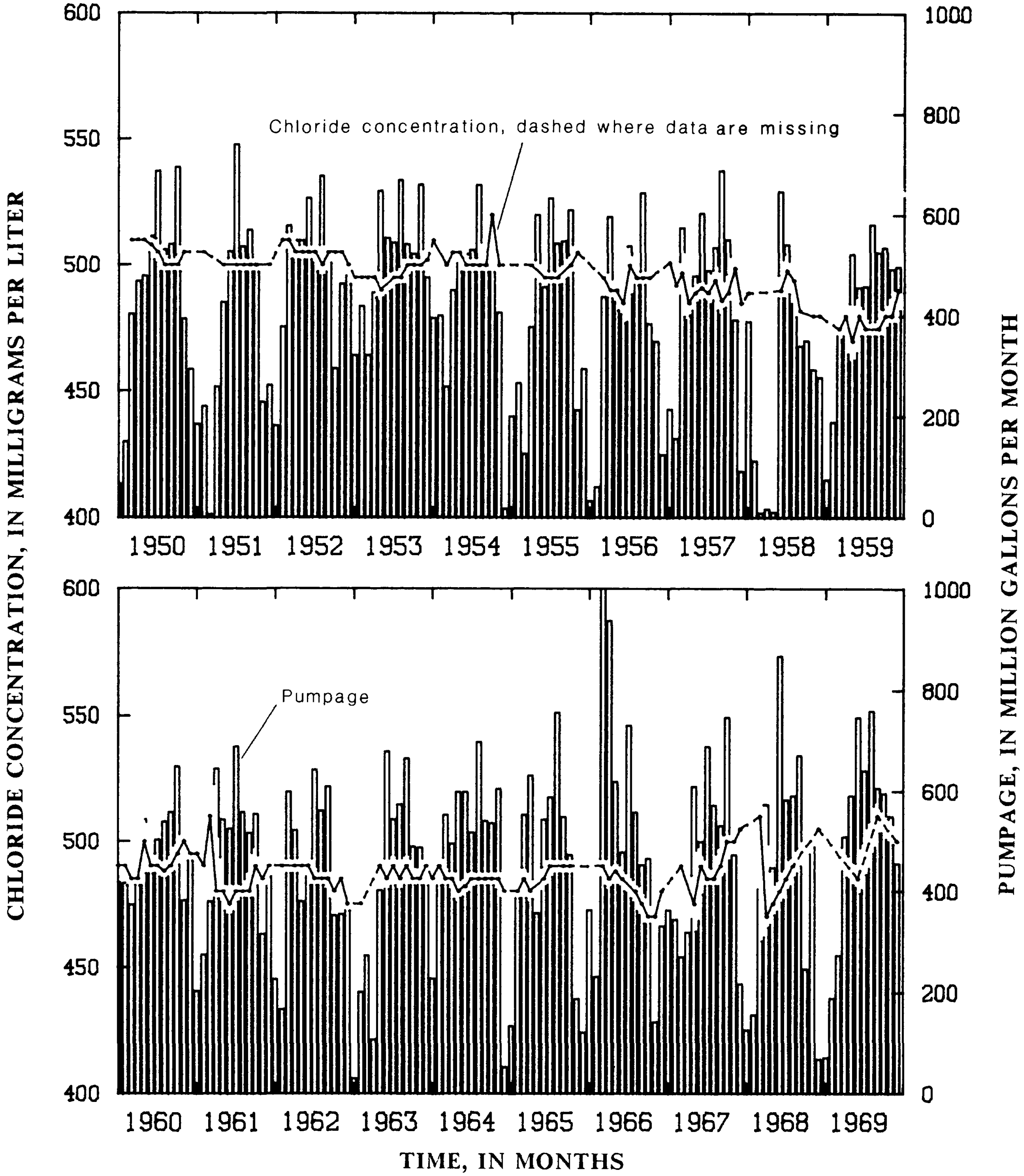

Figure 16. Monthly pumpage from Ewa pumps 10-13 and monthly chloride concentration for Ewa pump 12, 1950-1969.

CHANGES IN CHLORIDE CONCENTRATION AT BARBERS POINT SHAFT SINCE 1983

The steady rise in chloride concentration at Barbers Point shaft from 1983 to 1985 has caused concern because the present level is very near the U.S. Environmental Protection Agency's recommended maximum chloride concentration in drinking water of 250 mg/L. In the past 20 years there have been three major impacts on the hydrology of the aquifer that could be the cause of the chloride increase. These impacts are: (1) the unusually low rainfall from 1973 to 1983 (fig. 2), (2) the planting from 1961 to 1963, and subsequent abandonment in 1982, of approximately 1,300 acres of sugarcane fields on the eastern flanks of the Waianae range shown in figure 1, and (3) the conversion from 1980 to 1984, to drip irrigation of the sugarcane fields near Barbers Point shaft. These fields are irrigated by water from Ewa pumps 15 and 16 with a chloride concentration from 150 to 200 mg/L and by water from Waipahu pump 5 with a chloride concentration of about 200 to 250 mg/L.

Effects of Rainfall

Prolonged periods of dry weather will cause the freshwater lens to shrink and increase the potential for upconing of saltwater. Low rainfall in the 1970's and early 1980's (fig. 2) did contribute to the period of lower-than-normal heads at T-19 in the mid to late 1970's (fig. 6). However, that period does not correspond to the period of rising chloride concentration at Barbers Point shaft from 1983 to 1985. Although rainfall remained low in the early 1980's, the water level in the aquifer has actually risen since 1980 because of the large decrease in pumpage at Waipahu pump 5 and Ewa pumps 10-13 (figs. 12 and 15). The only apparent effect that variability in rainfall has had on the chloride concentration at Barbers Point shaft occurred as a result of a large storm in January 1982, when 12 inches of rain fell on the area. Chloride concentrations at the three water tunnels in the Pearl Harbor aquifer, Barbers Point shaft, Waiawa shaft, and the water tunnel at Ewa pumps 15-16, reached markedly high levels in the months following the storm, indicating that the storm had displaced a slug of salty recharge water from the overlying soil and saprolite. The chloride concentrations then declined as the impact of the slug dissipated. However, the chloride concentration at Barbers Point shaft rose again in 1983 and continued to increase until 1985 when it stabilized between 245 and 250 mg/L.

Effects of Recently Installed Sugarcane Fields

The planting from 1961 to 1963, and subsequent abandonment in 1982, of approximately 1,300 acres of sugarcane fields on the eastern flanks of the Waianae range (fig. 1) would be expected to noticeably affect the quality of water in the aquifer. The following analysis describes the predicted impact of the irrigation of these fields.

Prior to 1961 the land received little to no irrigation, as it was either vacant or used to grow pineapple, which is rarely irrigated (Giambelluca, 1983). Since 1961 heavy irrigation of the land from several different sources increased the ground-water recharge through the fields from about 0.5 Mgal/d to about 8 Mgal/d, calculated from information reported by Giambelluca (1986). Waiahole ditch supplied water with about 10 mg/L chloride, Waipahu pump 5 supplied water with about 200 to 250 mg/L chloride, and effluent from Waipahu sugar mill of unknown quality was pumped from Waipahu pump 7, to these fields. It is not possible to estimate the average chloride concentration of the irrigation water because the amount of irrigation from each of these sources is not known. Salts that had accumulated in the soil of this dry area from evaporation of rainfall and sea spray were probably flushed to the aquifer with the irrigation water. This "new" recharge water infiltrated down to the water table, entered the southerly flow of ground water in the aquifer, and eventually some fraction of it reached Barbers Point shaft.

The "new" recharge would be expected to appear first at Barbers Point shaft between 1974 and 1976, 11 to 13 years after the irrigation of the southern fields started in 1963. The values of 11 to 13 years were determined by adding the infiltration time through the unsaturated zone, vertical flow taking from 8 to 10 years, to the travel time through the aquifer, horizontal flow taking about 3 years. Dispersion of solutes was not considered in this analysis; thus the initial response would occur sooner and the final or steady state response would occur later than this analysis predicts.

Because estimates of infiltration time are subject to large errors owing to the extreme variability and complexity of the processes of recharge and solute transport, the following paragraphs explain three different methods that were used to calculate the time required for water applied to the ground surface to reach the water table several hundred feet below.

Infiltration Rate

Pesticide tracer.--One estimate of the natural infiltration rate (the average downward velocity of the recharge water) was made from soil borings collected in a pineapple field northeast of Mililani well II (MW II in fig. 1). Rainfall there averages about 100 inches per year, similar to the rate of irrigation of cane fields. In 1983, 2 years after the first application of the pesticide ethylene dibromide (EDB) to the pineapple field, cores of soil and weathered basalt were taken at approximately 1-foot intervals from the ground surface to a depth of 60 feet. Chemical analyses of the cores showed that the peak EDB concentration had moved to a depth of 30 feet, yielding an average infiltration rate, or pore velocity, of 15 feet per year (Ogata, written commun., 1985). The rate of 15 feet per year is a gross average. During dry periods infiltration may cease completely and during a storm, when 3 inches of rain may be absorbed into the soil in a few hours, the rate may be considerably more than the average rate of 15 feet per year (Shade, 1984).

The drilling log of the Country Club well shows that the unsaturated zone beneath the Waianae sugarcane fields installed in the early 1960's is about 500 feet thick, 100 feet of soil and saprolite and 400 feet of permeable basalt. At an infiltration rate of 15 feet per year, the return irrigation water from the fields planted in the early 1960's would pass through the 100 foot thick layer of soil and saprolite in about 7 years.

The infiltration rate through the unsaturated basalt that underlies the soil-saprolite layer is much faster. The saturated hydraulic conductivity of the basalt aquifer is generally greater than several hundred feet per day (Soroos, 1973), and its effective porosity or saturated volumetric water content is about 5 to 10 percent (Mink, 1980). In contrast, the saturated hydraulic conductivity of soils overlying much of the Pearl Harbor aquifer range from 0.5 to 13 ft/d. In irrigated areas or areas receiving high rainfall, the soil-saprolite layer remains near saturation at a volumetric water content of about 50 percent (Foote and others, 1972, Rotert, 1977, Green and others, 1982). Thus, water moves slowly through the soil-saprolite formation and relatively rapidly through the underlying and more permeable basalt. Because the soil-saprolite formation remains near saturation, large storms can force pulses of water from the bottom of the soil-saprolite formation which may arrive at the water table several months to a year later.

The good correlation (r = 0.94) between annual average water table elevations and smoothed annual rainfall of the previous year (Eyre and others, 1986, p. 51) suggests that the average infiltration time through the unsaturated basalt is probably less than 1 year. The correlation of rainfall and water levels yields an estimate of infiltration time by matching peaks in the two data sets. This method overestimates the average infiltration time because most of the recharge arrives at the water table prior to the water-level peak. That is, the rising limb of the hydrograph, not the peak, reflects the arrival of recharge water.

Additional support for an average infiltration time of less than a year comes from a statistical analysis of 22 years (1937 through 1958) of monthly rainfall and water level data from the Schofield area (fig. 17). The Schofield area was chosen because pumping stresses are slight and do not mask the relationship between rainfall and water level. Recharge in the area travels about 550 feet from the ground surface to the water table; about 150 to 200 feet through poorly permeable soil-saprolite, and about 350 to 400 feet through permeable basalt.

The correlation coefficient between rainfall at Wahiawa mauka gage no. 882 and water level at the Schofield shaft is highest when rainfall is lagged 14 months relative to the water level data. More specifically, a correlation coefficient (r) of 0.76 is obtained when water levels of successive months are correlated with the smoothed rainfall data from 14 months earlier. The smoothed rainfall time series was obtained by applying a 13-month center-weighted moving average to the monthly rainfall.

Hunt (oral commun., 1984) found that within about 3 months after a very large storm, the water level at the Schofield shaft starts to rise, leveling off about 5 to 8 months later. Water levels following the storms of November 1954 and January 1963 provided the most concrete evidence for this conclusion. The difference in infiltration time determined by the time series analysis approach and the rainfall event-water level response approach is relatively small. The difference is probably attributable to the difference in the methods of analysis, or possibly to changes in hydraulic conductivity as moisture content of the soil-saprolite changes, or to macroporosity and microporosity in the soil and rock material that may produce different infiltration rates depending on the moisture distribution in the material.

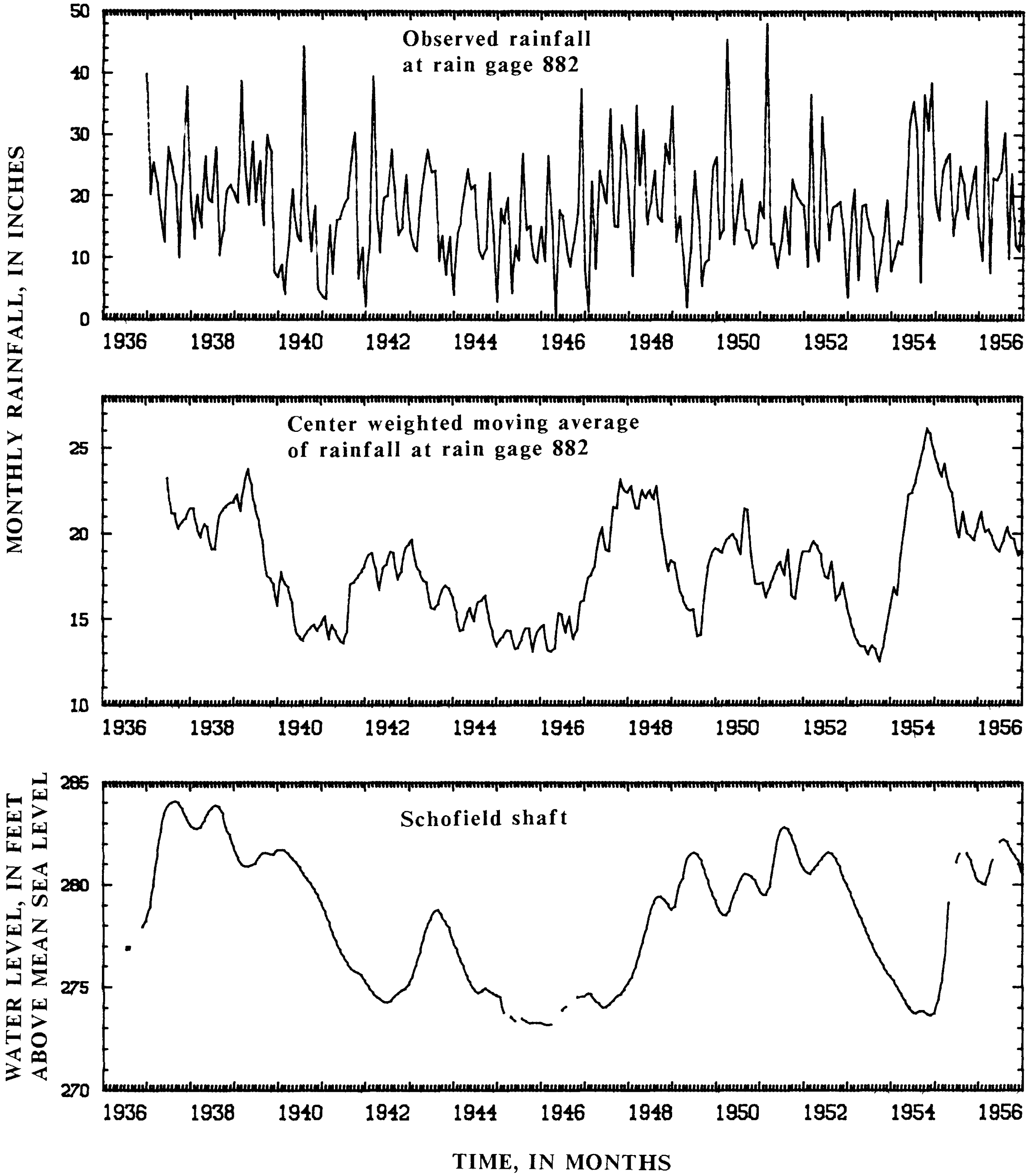

Figure 17. Rainfall, moving average of rainfall, and water levels in the Schofield area, 1937-1956.

To summarize, 8 years is the approximate average time for recharge to reach the water table beneath the sugarcane fields planted in the early 1960's, 7 years to penetrate 100 feet of soil-saprolite and 1 year to penetrate about 400 feet of permeable basalt.

Once the recharge enters the ground-water flow system it will travel at approximately 5 to 15 ft/d, as discussed earlier. The velocity of ground-water flow in the Waianae and Koolau aquifers is about the same, as indicated by the similar hydraulic conductivity and head gradient in the two aquifers. The distance to Barbers Point shaft from the southern portion of the fields planted in the early 1960's is 6,000 feet. Assuming velocity of 5 ft/d, the travel time in the aquifer is about 3 years. These southern fields were installed in 1963 so recharge from these fields would first appear at Barbers Point shaft about 1974, 11 years later, or sooner if a faster velocity is assumed.

The amount of irrigation return in the ground water reaching Barbers Point shaft would continue to increase until recharge from the northern fields, planted in 1961 and 23,500 feet away, reached the shaft. Recharge from the northern fields would reach the shaft after 8 years of infiltration and 13 years ground-water travel time, in 1982. After this time the amount of "new" irrigation return water, and associated salts, would remain constant in the ground-water as long as pumpage and irrigation practices did not change.

Displacement model.--A displacement model, which calculates the time required to displace existing water from the soil with new recharge water, also yields an infiltration time of about 8 years. The time for displacement is estimated for a soil-saprolite thickness of 100 feet, an average volumetric water content of the soil-saprolite of 50 percent, and a rate of recharge, from rainfall and irrigation, through the sugarcane fields of 90 inches per year (Giambelluca, 1986). Thus, 100 feet of soil-saprolite holds 50 feet of water, which could be displaced in about 7 years if recharged by 90 inches of water per year. An additional year is needed for the infiltration through the unsaturated basalt. The travel time in the aquifer is the same as previously calculated.

These observations suggest that the relatively high chloride concentration at Waipahu pump 5 in the 1970's could contribute to the rise in chloride concentration at Barbers Point shaft between 1983 and 1985. A detailed model of ground-water flow and solute transport in the aquifer would help determine whether the increase in chloride concentration of 50 to 70 mg/L at Waipahu pump 5 could cause the increase of 20 to 30 mg/L observed at Barbers Point shaft. An increase of 200 to 300 mg/L chloride at Waipahu pump 6 may have caused the increase of 25 to 50 mg/L at Waiawa shaft. Such a modeling effort is beyond the scope of this project.

Chloride tracer.--A travel time through the unsaturated zone of about 10 years is suggested by the record of chloride concentration at Waiawa shaft and Waipahu pump 6. A direct relation between the chloride concentrations at Waiawa shaft and Waipahu pump 6 was shown to exist in a study of Waiawa shaft (Eyre, 1983). Waipahu pump 6 supplies irrigation water for the fields that overlie Waiawa shaft. The distance infiltrated water travels from the ground surface to the water table is about 400 feet, through 100 feet of soil and saprolite of low permeability, and 300 feet of permeable basalt lava flows.

The increase in chloride concentration at Waiawa shaft that occurred around 1963 may have been caused by the increase in chloride concentration of irrigation water from Waipahu pump 6 that occurred in 1953 (see figs. 8 and 9). Prior to 1950 the chloride concentration at Waipahu pump 6 ranged annually from about 200 to 400 mg/L. Another abrupt increase in chloride concentration at Waipahu pump 6, in 1960, may have produced a similar response in water from Waiawa shaft in the early 1970's. The infiltration time of about 10 years indicated by the chloride data is in good agreement with the value of 8 years calculated previously.

In summary, three independent methods indicate that irrigation return flow from fields planted in the early 1960's would first reach Barbers Point shaft between 1974 and 1976. The full effect of the new irrigation return flow would be felt by about 1982. The chloride concentration at Barbers Point shaft did increase (fig. 14), but did not follow the pattern that would be expected if the new recharge were the major cause of the change in chloride concentration. Possibly the new irrigation return water did not affect the ground-water quality because the freshwater of Waiahole ditch composed a large fraction of the irrigation water. The abrupt rise in ground-water salinity at Barbers Point shaft in 1983 may be related to the advent of new irrigation practices.

Effects of Drip Irrigation

The other large-scale event that would affect the volume and quality of water recharging the aquifer is the transition from furrow to drip irrigation of fields in the vicinity of Barbers Point shaft that occurred from 1980 through 1984. The soil-saprolite is only 50 feet thick near the shaft, and some of the recharge through the fields irrigated by Waipahu pump 5 and by Ewa pumps 15 and 16 is likely to reach Barbers Point shaft in a relatively short time. Recharge through these fields has decreased about 70 percent because of the shift to drip irrigation. Although the recharge from irrigation return water clearly has been reduced, it is not clear what the net effect would be on the chloride concentration of the water in the aquifer.

Mixing-cell model.--A simple algebraic equation can be derived to calculate the chloride concentration in ground water if the water is assumed to be a mixture of irrigation return water and the ambient ground water. Applying the equation to periods of furrow and drip irrigation, the chloride concentration in the ground water during the two periods can be compared. For steady state conditions the equation is:

$$CONCm = (CONCg \times FLOWg + CONCi \times FLOWi)/(FLOWg + FLOWi) \qquad (3)$$

where:

CONCm = the chloride concentration in ground water after mixing

CONCg = chloride concentration of the ambient ground water

FLOWg = the flow rate of the ambient ground water

CONCi = the chloride concentration of the irrigation return water

FLOWi = the flow rate of the irrigation return water

The equation simply divides the mass rate of chloride flowing through the aquifer by the volume rate of water flowing through the aquifer.

To illustrate the possible change in chloride concentration that may result from changing irrigation practices, the equation is solved assuming that the mass of chloride in the irrigation return water is the same for furrow and drip conditions, but that the amount of irrigation return water reaching the aquifer is less for the drip conditions. That is, because the sugarcane takes up more of the irrigation water when irrigated by the drip method, the concentration of salts remaining in that irrigation return water increases.

Using approximate data for the period of furrow irrigation:

CONCm = 200 mg/L, based on the initial chloride concentration at T-19

CONCg = 25 mg/L, based on the chloride concentration at the Kunia well

FLOWg = 33 Mgal/d, based on 25 Mgal/d coming from Schofield plus 8 Mgal/d naturally recharging the Waianae aquifer (table 1)

FLOWi = 19 Mgal/d, the recharge to the Waianae area during the period of furrow irrigation minus the natural recharge of 8 Mgal/d (table 1)

CONCi = to be solved for.

Solving equation 3 for CONCi, the chloride concentration in the irrigation return water during the period of furrow irrigation was 500 mg/L.

The increase in chloride concentration from the applied concentration of about 200 mg/L, to the concentration of 500 mg/L in the irrigation return water, was caused by the evapotranspiration of the irrigation water.

For the period of drip irrigation, and assuming that the mass rate of chloride carried to the aquifer for drip and furrow conditions is the same:

CONCi x FLOWi = 9,500 (mg/L)(Mgal/d) as during furrow conditions

CONCm = to be solved for

CONCg = 25 mg/L, based on the chloride concentration at the Kunia well

FLOWg = 33 Mgal/d, based on 25 Mgal/d coming from Schofield and 8 Mgal/d naturally recharging the Waianae aquifer (table 1)

FLOWi = 9 Mgal/d, the total recharge during the period of drip irrigation minus the natural recharge of 8 Mgal/d (table 1)

Then CONCm, the chloride concentration after mixing in the aquifer during the period of drip irrigation is 250 mg/L.

Depending on the actual values of the terms in equation 3, the chloride concentration in the aquifer may either rise or decline as a result of the change to drip irrigation. The approximate values used in this example indicate that the change to drip irrigation may cause the chloride concentration to rise about 50 mg/L, a value in good agreement with the observed rise of 30 mg/L.

The simplicity of the mixing model does not allow some important details to be incorporated into the solution. If the spatial distribution of recharge, or the removal of water and salts from the mixing cell by pumpage from Waipahu pump 5 were to be addressed, a more complex approach, such as a computer model of ground-water flow and solute transport through the aquifer, would be required. Also, samples of the actual recharge water beneath the fields would provide a more accurate value for the chloride concentration of the irrigation return water.

The effects of drip irrigation would be expected to be seen at Barbers Point shaft within a few years of its implementation in 1980. The shaft is bordered on 3 sides by sugarcane fields irrigated with water from Ewa pumps 15 and 16, which have a chloride concentration ranging from 150 to 200 mg/L. The water tunnels at Barbers Point shaft are only 150 feet below the land surface and the soil-saprolite layer is only 50 feet thick there. Using the infiltration and flow rates calculated earlier, recharge from drip irrigation applied in 1980 could reach Barbers Point shaft around 1983. The full impact of the change to drip irrigation may take several more years to occur. However, most of the expected change in chloride concentration has already occurred as a result of the proximity of the irrigated fields to Barbers Point shaft.

Additional examples of the effect of drip irrigation are seen at some wells that tap the caprock aquifer, where irrigation return is a much larger fraction of the total flow through the aquifer. The rise in chloride concentration from about 500 to 1,000 mg/L (data files of Oahu Sugar Company, Waipahu) at some of the caprock wells can be attributed, in part, to the increase in chloride concentration of the drip irrigation return water.

In summary, the conversion to drip irrigation of sugarcane fields in the early 1980's appears to be the most likely cause of the rise in chloride concentration at Barbers Point shaft since 1983. Both the magnitude and timing of the observed change at Barbers Point shaft correspond to calculations based on a mass balance of the mixture of recharge from drip irrigation and the ambient flow of ground water through the aquifer.

CONCLUSIONS

In the Waianae part of the Pearl Harbor aquifer, tapped by Barbers Point shaft, a freshwater lens floats on seawater. In the past, the natural chloride concentration of the ground water near Barbers Point shaft was about 200 mg/L in the top 100 to 200 feet of the freshwater lens, then increased with depth. Pumpage at the shaft may cause slight saltwater upconing, increasing the chloride concentration to about 220 mg/L.

Salts in the top 100 to 200 feet of the lens are derived primarily from recharge water, which is mostly irrigation return water with a chloride concentration of approximately 500 mg/L. This recharge water merges with the southerly flow of the relatively pristine water from the Schofield aquifer. Ground water becomes progressively saltier in the southerly, seaward direction as the irrigation return water accumulates in the aquifer. In the southern part of the Waianae aquifer there is no ground water of low chloride concentration because the water of relatively pristine quality has thoroughly mixed with the recharge water and the underlying saltwater.

Analysis of chloride, pumpage, and rainfall data in the area indicates that the abrupt rise from 220 to 250 mg/L, from 1983 to 1985, probably is the result of saltier recharge water arriving at the water table near Barbers Point shaft during that time. The chloride concentration of the recharge water increased because between 1980 and 1984, drip irrigation was initiated on the fields near the shaft. With the drip method, the sugarcane uses more of the applied irrigation water, causing an increase in the chloride concentration of the remaining irrigation return water.

The chloride concentration of the irrigation return water was calculated from existing data. The accuracy of this report's predictions would be improved by a site-specific study of drip-irrigated fields bordering Barbers Point shaft. Such a study would measure the infiltration rate and water quality beneath a sugarcane field over the 2-year growing cycle of the sugarcane plant and would determine the average recharge rate and chloride concentration of the irrigation return water.

The relatively high chloride concentration of irrigation water from Waipahu pump 5, during the 1970's, has contributed to the rise in chloride concentration in the ground water, but probably not to the extent that the conversion to drip irrigation has. A more accurate determination of the relative effect on ground-water quality caused by the high chloride concentration at Waipahu pump 5 or the conversion to drip irrigation cannot be attained without further effort. This effort would involve extensive field work to determine the quality and amount of the irrigation return water, coordinated with a detailed computer model of the flow of water and solutes through the aquifer.

The transition zone is not a likely source of the rising chloride concentration at Barbers Point shaft because the ground-water head has been higher in the 1980's than it was in the 1970's. Also, withdrawals from the shaft are insufficient, and its depth is too shallow, to cause substantial upconing of the underlying saltwater. The amount of upconing that does occur could be better evaluated by doing high rate and low rate pumping tests at the shaft. Such tests would disturb the normal operation of Barbers Point shaft for about a month.

One analysis presented in this report predicted that the irrigation of 1,300 acres of sugarcane between about 1960 and 1980 would increase the chloride concentration at Barbers Point shaft. This prediction was not verified by the data, possibly because the freshwater from Waiahole ditch composed a large fraction of the irrigation water for these fields.

The flow rates and chloride concentrations of the various sources of ground-water recharge mentioned in this report are estimates. Our understanding of this aquifer is far from complete, as indicated by the inability to fully explain the lack of correlation between pumpage and chloride concentration at Ewa pumps 10-13. It is possible that the abrupt increase in chloride concentration from 1983 to 1985 is a passing phenomenon. If that is the case, the chloride concentration may decline in the next few years. However, the chloride concentration will not decline below the ambient concentration level of 200 to 220 mg/L, which is the consequence of the typically low rainfall in the area and the addition of salts from sea spray and irrigation return water.

In conclusion, the chloride concentration of water in the Pearl Harbor aquifer near Barbers Point shaft can be lowered substantially only if the aquifer is recharged by fresher water or if a source of fresher water is blended with water pumped from Barbers Point shaft. According to this interpretation, the chloride concentration of water pumped from the aquifer near Barbers Point shaft probably will remain near 250 mg/L, or increase slightly, as long as irrigation practices and pumping rates in the aquifer remain the same.

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*Note: 1, 2, 3, etc. at the end of a reference, refers to the areas in figure 4 and identifies the reference from which the water levels were obtained.