THE EFFECTS OF PUMPAGE, IRRIGATION RETURN, AND REGIONAL GROUND-WATER FLOW ON THE WATER QUALITY AT WAIAWA WATER TUNNEL, OAHU, HAWAII

By Paul R. Eyre

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CONVERSION TABLE

The following table may be used to convert measurements in the inch-pound system to the International System of Units (SI).

Multiply inch-pound units	By	To obtain SI units
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
million gallons per day (10^6gal/d or Mgal/d)	0.04381	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)

CROSS REFERENCES OF WELL IDENTIFICATION

Name	State of Hawaii Well Number	Old Well Number
Waiawa shaft	2558-10	
Waipahu pump 6	2459-01 to -14	239 A to N
Waipahu pump 17	2658-01, -02	250 3A, 3B
Pearl City I	2458-03, -04	202 1A, 1B
Pearl City II	2457-01 to -03	202 2A-2C
T-39	2558-08	
T-40	2558-09	

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EXECUTIVE SUMMARY

The water sources used to supply water to the Pearl Harbor Naval Base complex and Hickam Air Force Base consist of three water tunnels (shafts) located at Waiawa, Red Hill, and Halawa, which are owned and operated by the United States Navy. Average water use within the Pearl Harbor-Hickam complex is about 20 Mgal/d (million gallons per day). The Waiawa shaft supplies about 70 to 90 percent (14 to 18 Mgal/d) of this demand. The shaft at Red Hill serves as a secondary source. The Halawa tunnel is used largely as a standby source. The Navy must rely on Waiawa shaft for most of its water supply, because the Red Hill and Halawa sources do not have the sustained capacity needed to supply the Pearl Harbor-Hickam complex without serious degradation of these sources.

Since 1970 the salinity of Waiawa shaft water has increased from about 125 mg/L Cl (milligrams per liter of chloride) to a high of 290 mg/L in April of 1979. The National Secondary Drinking Water Regulations (U.S. Environmental Protection Agency, 1977) recommend that the maximum chloride concentration in potable water not exceed 250 mg/L for aesthetic reasons; that is, many people can detect a salty taste if the chloride concentration exceeds that value.

Studies of the salinity problem at Waiawa shaft by the Public Works Center, Fourteenth Naval District, Pearl Harbor, have indicated that the increasing salinity is due to contamination from irrigation-return water or seawater intrusion. Because of the concern over the continuing deterioration of their principal source of water, the Pacific Division, Naval Facilities Engineering Command requested the U.S. Geological Survey to undertake this study.

Waiawa shaft is designed to skim large quantities of water from the surface of the freshwater lens that composes the Pearl Harbor basal-water body. The Ghyben-Herzberg principle states that a freshwater lens, floating on seawater, will have a thickness equal to 41 times the head (water-table elevation) of freshwater above sea level. Freshwater and seawater are actually separated by a transition zone where chloride concentrations increase sigmoidally with depth. At Waiawa shaft the lens thickness is about 800 feet.

By skimming water from a large area near the surface of the lens, the possibility of drawing underlying seawater into the shaft is reduced. Soroos and Ewart (1979) showed that pumping from the aquifer is causing the lens to shrink, probably causing seawater to move closer to the shaft.

Another source of salt in the water produced from Waiawa shaft is irrigation-return water. This water results from irrigation water (chloride concentration about 1,000 mg/L), which is drawn, in part, from the saline transition zone by deep wells and applied to sugarcane fields that overlie the shaft. A significant fraction of this water infiltrates through the ground and degrades the upper portion of the ground-water lens. This study was designed to determine the extent that the irrigation-return water and seawater affect the water at Waiawa shaft.

Historic and recent chloride and pumpage data, water-chemistry data, and pumping tests support the conclusion that nearly all the salts in Waiawa shaft water result from irrigation-return water. Water from many wells in the Pearl Harbor ground-water basin contains some fraction of irrigation-return water (Tenorio and others, 1969; Hufen and others, 1980). A continued shrinking of the freshwater lens will increase the potential for seawater contamination of water from Waiawa shaft in the future.

The quality of water produced from the shaft results from complex relationships among the ambient ground-water flow system, the pumping rate at Waiawa shaft, irrigation water quality and quantity, and the climactic fluctuations which affect ground-water recharge. When Waiawa shaft is pumped, the degraded water, which occurs near the top of the lens, is removed and diluted with freshwater that comes from deeper in the lens. At lower pumping rates there is less dilution. Although the water quality at the shaft can be controlled to some extent by changing the pumping rate, in general, the quality also will be subject to fluctuations or trends in irrigation, climate, and the regional ground-water flow system.

If high-salinity water continues to be used for irrigation, the chloride concentration of Waiawa shaft water will probably be about 200 to 220 mg/L in years of normal rainfall. In dry years, when more irrigation water of lower quality is applied, the chloride concentration of the shaft water will probably increase. The chloride concentration of the irrigation water used in the vicinity of Waiawa shaft has historically increased in steps, principally in response to local and regional increases in pumping. Presently, the chloride concentration appears to have stabilized. However, if it increases further, so will the chloride concentration of Waiawa shaft water.

If the application of high-chloride irrigation water is discontinued, the chloride concentration of the shaft water is likely to decline to about 100 mg/L within five years. This conclusion is based on ground-water flow rates and analogy with other wells in the Pearl Harbor basin.

A deep monitor well located near Waiawa shaft would provide the clearest understanding of the source of salts in the shaft water. Such a well would become even more useful if the lens continues to shrink and seawater encroaches farther into the lens.

INTRODUCTION

Acknowledgments

The author wishes to thank Maurice Kaya, Gordon Matsushita, and Tony Dilullo of the U.S. Navy Public Works Center at Pearl Harbor for their assistance in obtaining and compiling data on Waiawa shaft. Mr. Dilullo's management and knowledge of Waiawa shaft contributed greatly to the success of the pumping tests. David Morrell and Charles Farr of the Engineering Division of Oahu Sugar Co. were most helpful in providing data on Waipahu pump 6, the irrigation system, field locations, and in arranging access to Oahu Sugar land for field investigations.

Background Information

The U.S. Navy water tunnel and pumping station in Waiawa Valley on the Island of Oahu, withdraws water from the Pearl Harbor basal-water body (figure 1). Basal water refers to a lens shaped body of fresh ground water floating on underlying seawater. This basal-water body is the most heavily pumped water body in the State. It provides about 65 percent of the total ground water used on Oahu. In 1977, ground-water levels dropped to an all-time low in the Pearl Harbor area. This, coupled with prolonged periods of dry weather on Oahu, caused widespread concern over the adequacy of water supplies.

Acting in response to this concern, the Governor appointed a State Water Commission composed of scientists, state officials, and citizens, and charged them to assess the water situation throughout the State and to recommend appropriate administrative and legislative actions. One of the priority recommendations of the Commission report (1979) concerned the ground-water situation in the Pearl Harbor ground-water basin, expressed as follows:

"Control further development of ground water from the Pearl Harbor basin and tributary sources by the application of the Ground Water Use Act (Chapter 177 HRS). As an immediate interim measure, impose a moratorium on increased export of water from the Pearl Harbor area."

In September 1979, the State of Hawaii, Board of Land and Natural Resources designated the Pearl Harbor area as a ground-water control area.

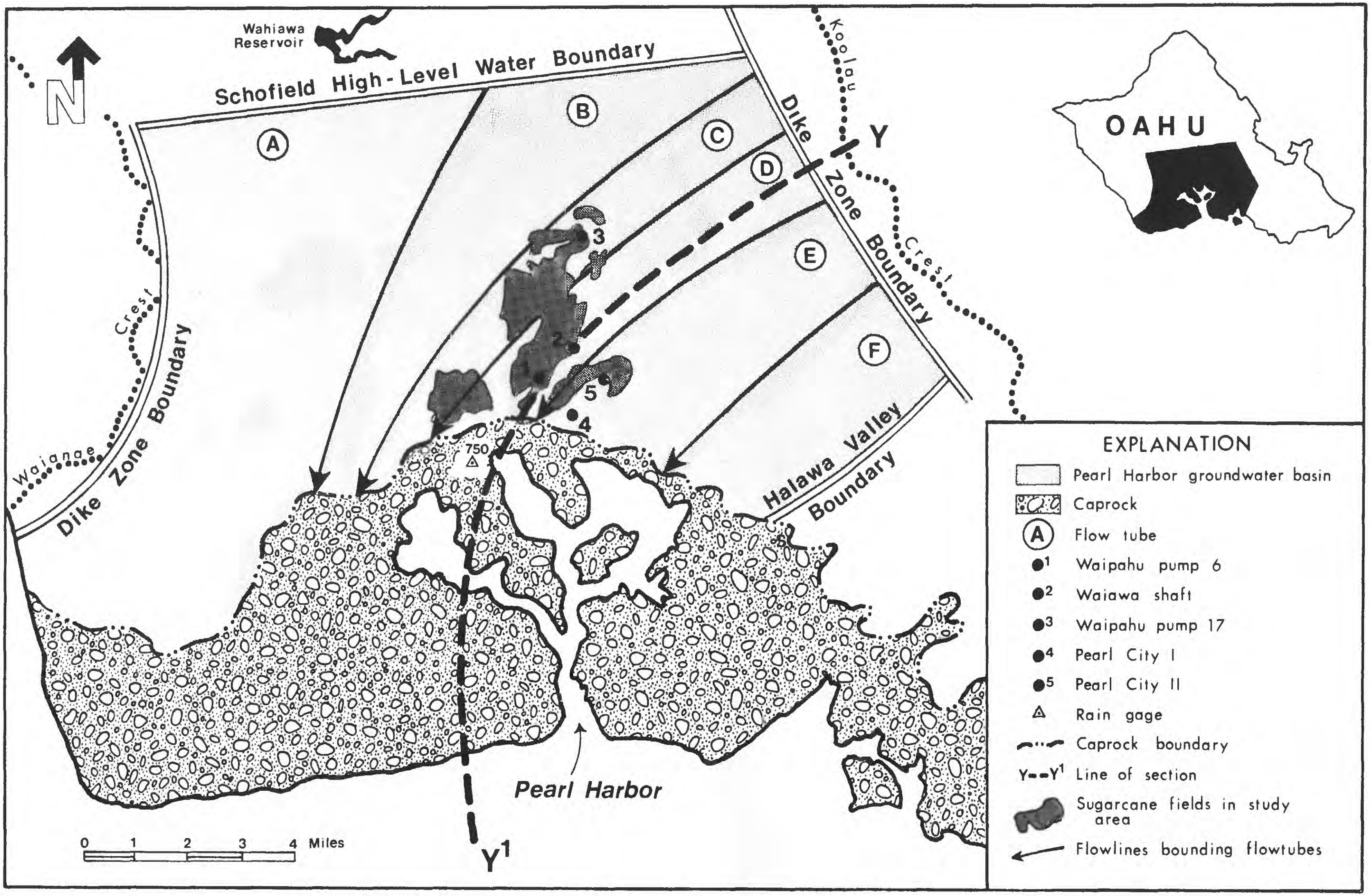

Figure 1. Map of region and plan view of flow paths of ground water in Pearl Harbor basal-water body (modified from Hufen and others, 1980).

A U.S. Geological Survey report (Soroos and Ewart, 1979) on the status of the ground-water situation in Pearl Harbor provided much of the information upon which the Board of Land and Natural Resources based their decision. The report documented historical trends in water-level decline, increased salinity, and pumpage over the 68-year period, 1910-77, and estimated the annual release of water from storage over this same period. Freshwater heads of the Pearl Harbor basal-water body have declined at a rate of about 0.1 foot per year (ft/yr) since 1910. This decline is equivalent to a reduction in storage of about 25 Mgal/d. Total annual basal-water discharge from the basin (springflow and pumpage) has been remarkably steady since 1910, averaging 275 Mgal/d according to Soroos and Ewart (1979). However, annual pumping from drilled wells and shafts has increased from about 104 Mgal/d in 1910 to about 240 Mgal/d in 1977. The greatest increase in pumping has occurred since 1960 and a large part of that increase has occurred in the vicinity of Waiawa shaft. Correspondingly, the discharge from the Pearl Harbor springs has declined from about 140 Mgal/d in 1910 to about 50 Mgal/d in 1977. Many sources of water have shown large increases in chloride concentration over the same period (1910-77) including the Navy's Waiawa shaft and Oahu Sugar Co.'s Waipahu pump 6 wells which supply irrigation water for sugarcane fields upgradient from and overlying the infiltration tunnel of the Navy's Waiawa shaft. Waipahu pump 6 wells are deep and draw water from the saline transition zone. The locations of Waiawa shaft, Waipahu pump 6 and the irrigated fields are shown in figures 1 and 2.

After the designation of the Pearl Harbor area as a Ground Water Control Area, the Board of Land and Natural Resources appointed a Hydrologic Advisory Committee to recommend criteria for ground-water management. Among the major issues considered by this Committee was the determination of the sustainable yield of basal ground water from the Pearl Harbor ground-water basin. The sustainable yield recommended by the Committee and subsequently adopted by the Board of Land and Natural Resources was 225 Mgal/d. The process by which this value was obtained, along with the other recommendations of the Committee, can be found in a report by the Hydrologic Advisory Committee (1980).

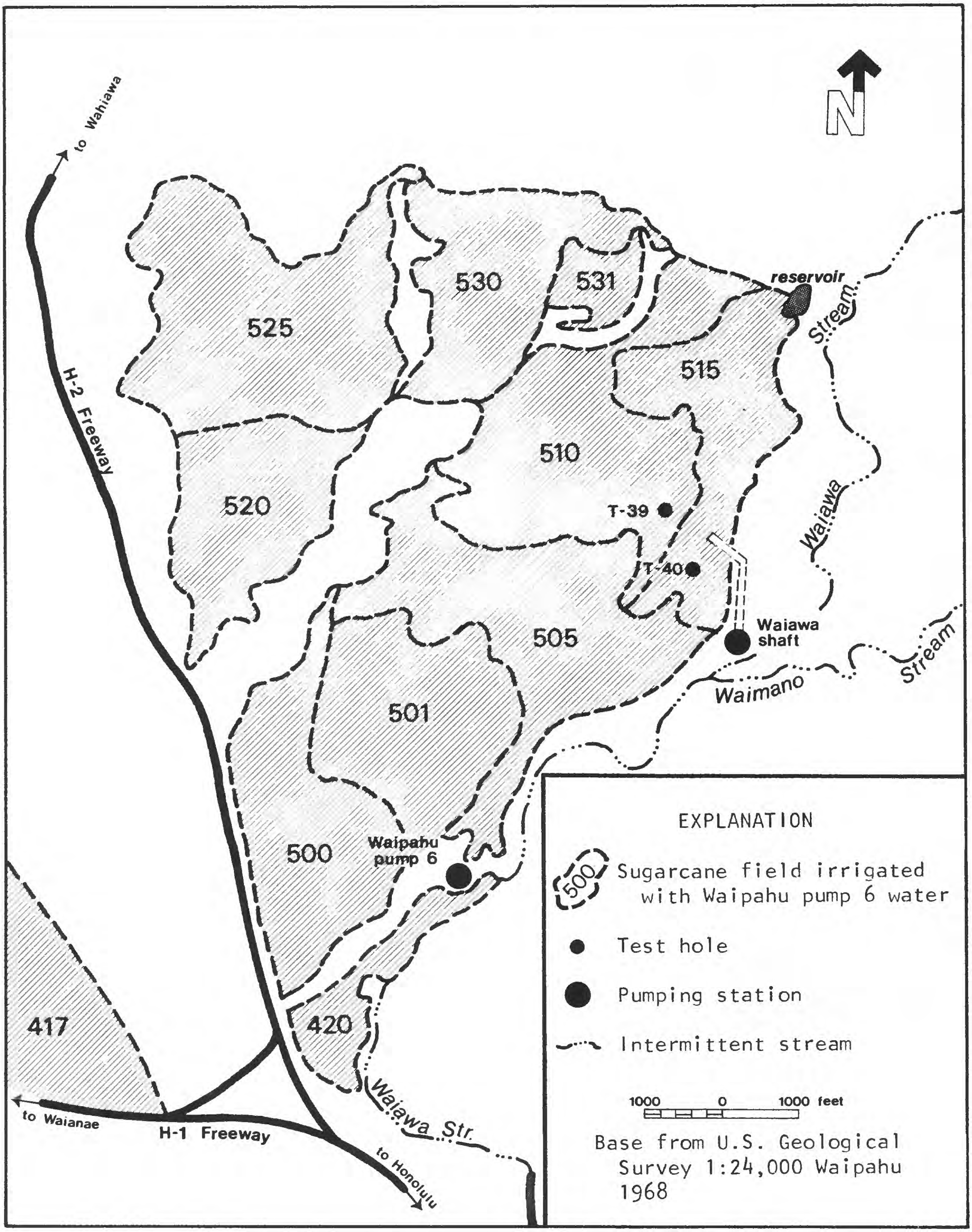

Figure 2. Map of study area.

REGIONAL HYDROLOGY

The Pearl Harbor ground-water basin is bounded on the southeast by a relatively abrupt head drop across Halawa Valley, on the northeast by the dike zone of the Koolau mountains, on the north by a barrier of unknown origin which impounds ground water to an elevation of about 200 feet beneath the Schofield Plateau, on the west by the dike zone of the Waianae mountains, and on the south by the sediments of the Ewa coastal plain (the caprock). The principal source of ground water is rainfall in the highlands of the Koolau Range.

Contours of ground-water head, figure 3, as well as flow paths determined by a water-budget/flow-net analysis (Hufen and others, 1980), indicate that ground water generally flows through the basin according to the flow paths shown in figure 1. The flux through each flow tube is about 30-40 Mgal/d. These flow paths present only a generalized picture of ground-water flow owing to uncertainties and variabilities in the distribution of recharge, discharge, and aquifer characteristics throughout the basin. Along section Y-Y' of figure 1, flow through the lens can be visualized as in figure 4.

Chloride data from deep observation wells are in approximate agreement with the Ghyben-Herzberg prediction that the thickness of the lens is about 41 times the freshwater head. The velocity of flow through the lens is about 1 to 5 ft/d (feet per day), calculated from a form of Darcy's Law:

$$\bar{v} = \frac{K\, dh/dl}{\theta}$$

where: $\bar{v}$ = average flow velocity;

K = aquifer hydraulic conductivity = 1,000 to 2,000 ft/d; (Soroos, 1973);

dh/dl = gradient of the water table = 0.5 to 2 ft/mi (feet per mile);

θ = effective porosity = 0.10. (Mink, 1980).

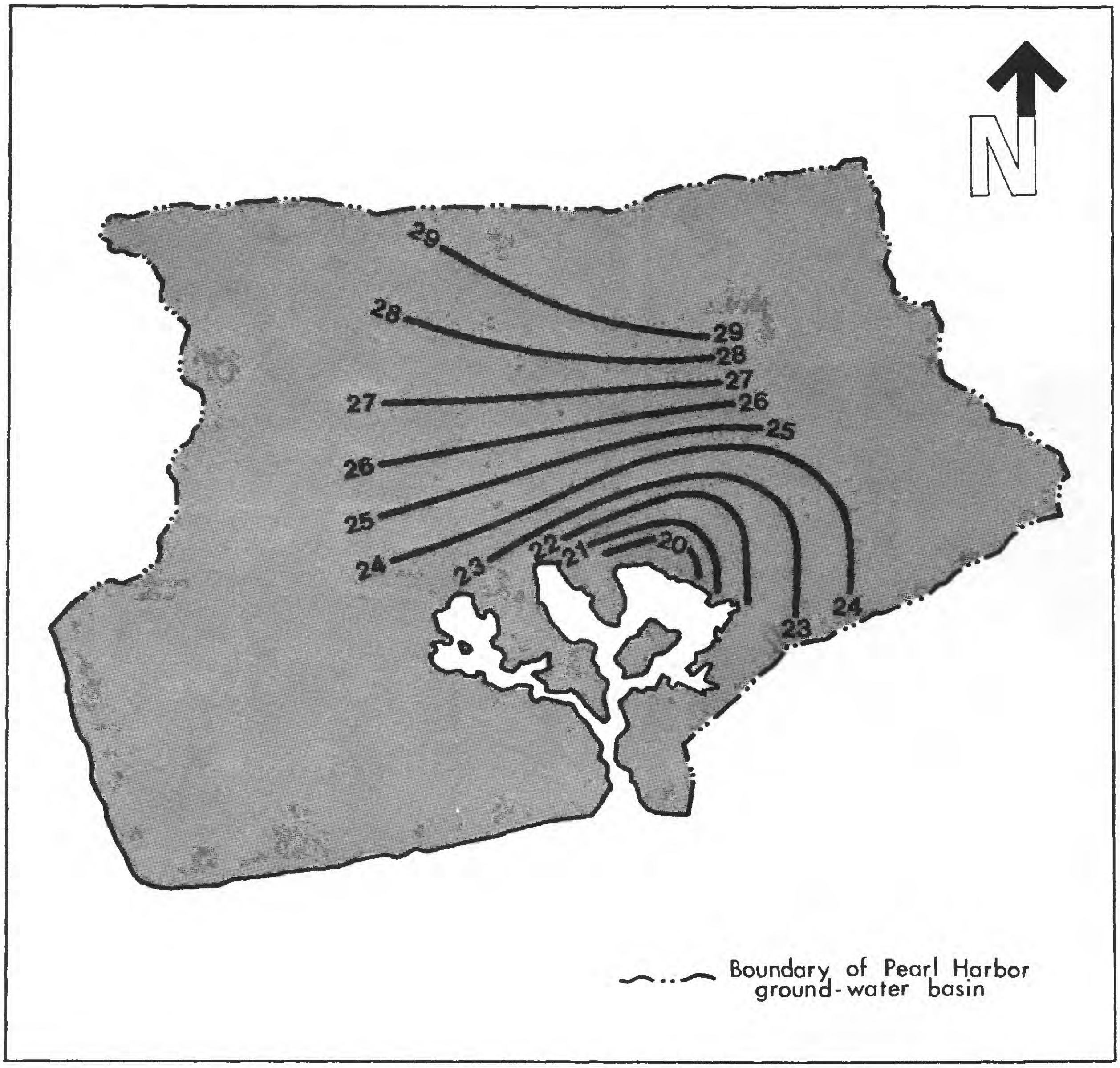

Figure 3. Head contours in the Pearl Harbor ground-water basin, in feet, based on measurements on May 31, 1958 (from Visher and Mink, 1964).

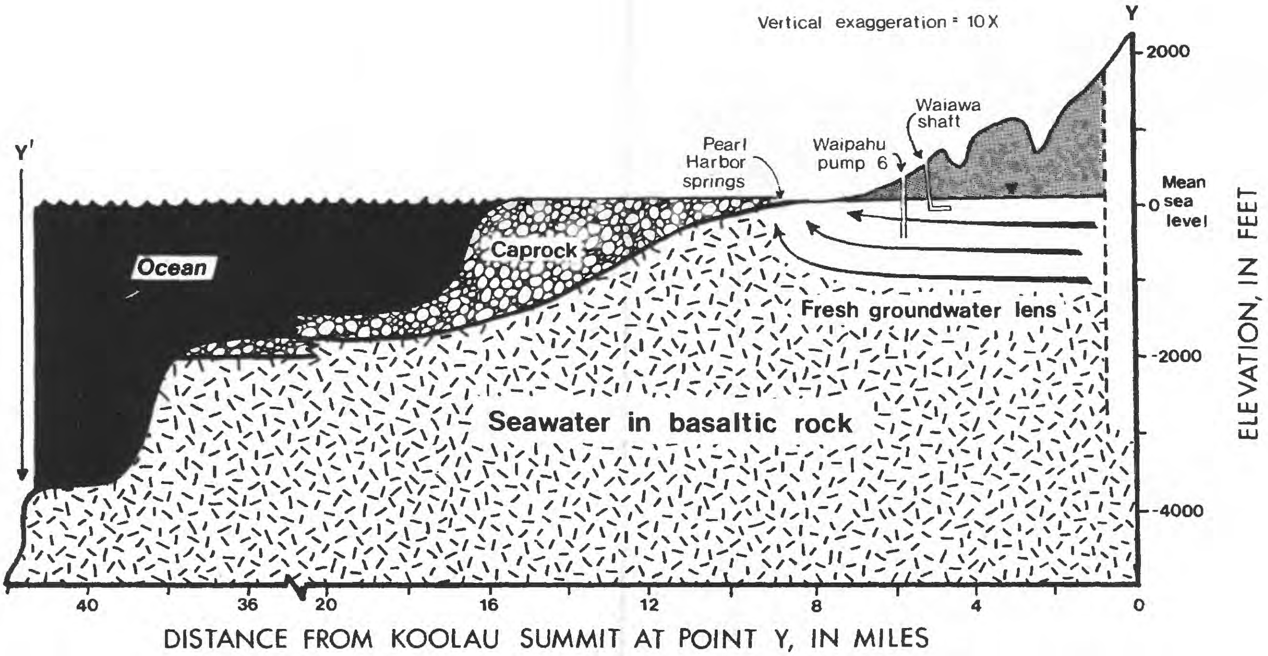

Figure 4. Longitudinal section showing flow lines of ground water in the Pearl Harbor ground-water basin (modified from Hufen and others, 1980).

Recharge to the lens also occurs from rainfall and irrigation-return water in the mid-to-low elevations of the region. Irrigation-return water generally contains a relatively high concentration of dissolved chemicals as does the rainfall-percolate when it leaches residual chemicals from irrigated fields. This recharge infiltrates through unsaturated soil, weathered basalt, and unweathered basalt. Data from infiltration tests on Wahiawa soils (Green and others, 1982) indicate a vertical infiltration rate of about 5 ft/d, although variations in rate are large owing to the nonhomogeneous nature of the vertical section. Upon reaching the water table, the recharge enters the ambient flow stream of the ground water. Ground-water flow is essentially horizontal through the basin, with hydraulic gradients from 0.5 to 2 ft/mi.

Because of the horizontal flow, mid-to-low elevation recharge tends to remain at the top of the lens, as shown in figure 5 and degrade the water there. Water-quality, fluid conductivity, and temperature profiles obtained by Tenorio and others (1969) and by Lao and others (1969) show that this more saline zone can be as much as 300 feet thick. Hufen and others (1980) showed that this zone becomes thinner and/or more dilute with distance inland (upgradient) from the basin's southern boundary. A schematic representation of the chloride ion distribution in the Pearl Harbor ground-water lens is presented in figure 6.

METHODS OF STUDY

The study undertaken by the Geological Survey was designed to evaluate the impact of four factors on the resultant chloride concentration of the water pumped from Waiawa shaft: (1) the ambient flow and water quality of the ground water of the Pearl Harbor ground-water basin; (2) the quantity and quality of the irrigation water applied to fields in the vicinity of Waiawa shaft; (3) the depth to the transition zone which underlies the fresh basal water; and (4) the rate of pumping at Waiawa shaft which determines the extent of mixing and removal of these waters of different chemical compositions. The following activities were performed to obtain the information required for this study.

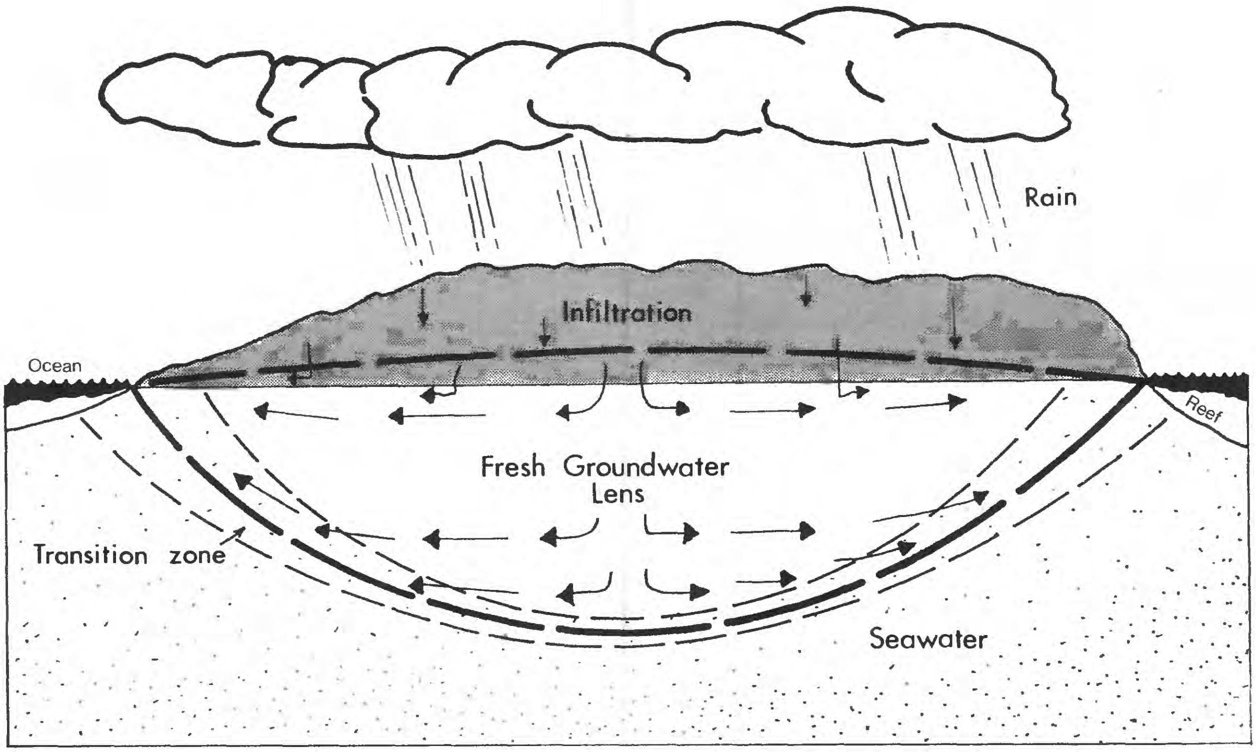

Figure 5. A schematic drawing showing the distribution of recharge in a Ghyben-Herzberg lens (modified from Mink, 1976).

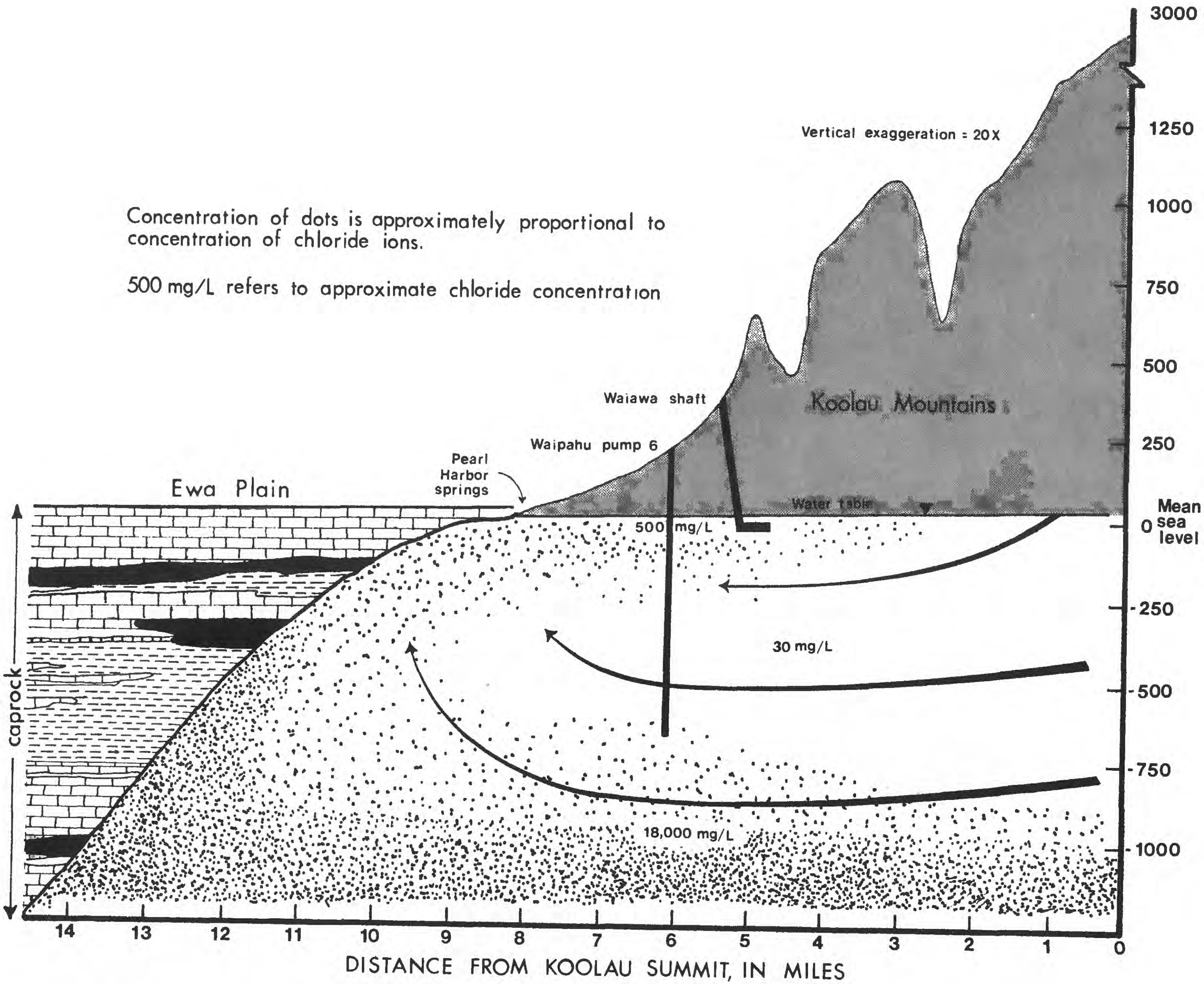

Figure 6. Schematic distribution of chloride ions underlying Waiawa shaft.

Review of Existing Records and Reports

Several reports provide regional descriptions of the hydrology of the Pearl Harbor ground-water basin. These reports include:

(1) Geology and Ground-Water Resources of the Honolulu-Pearl Harbor Area, Oahu, Hawaii (Wentworth, 1951);

(2) Ground-Water Resources of Southern Oahu (Visher and Mink, 1964);

(3) Ground-Water Status Report, Pearl Harbor Area, Hawaii, 1978 (Soroos and Ewart, 1979); and

(4) State of the Groundwater Resources of Southern Oahu (Mink, 1980).

Several other reports address the changes in water quality resulting from irrigation and increased development of water from the Pearl Harbor ground-water basin. These reports include:

(1) Land Use and Its Effect on the Basal-Water Supply, Pearl Harbor Area, Oahu, Hawaii, 1931-65 (Dale, 1967);

(2) Identification of Return Irrigation Water in the Subsurface: Water Quality (Tenorio and others, 1969);

(3) A Model Describing the Effects of Irrigation on Groundwater Quality: Pearl Harbor Region, Oahu, Hawaii (Mink and Kumagai, 1971); and

(4) Underground Residence Times and Chemical Quality of Basal Groundwater in Pearl Harbor and Honolulu Aquifers, Oahu, Hawaii, (Hufen and others, 1980).

Existing data used for this report included monthly records of pumpage and chloride concentration at Oahu Sugar Co.'s Waipahu pump 6 from 1898 until 1978, monthly records of the pumpage and chloride concentration and occasional measurements of water levels at Waiawa shaft from 1950 until the present, monthly records of pumpage and chloride concentration at the Board of Water Supply's wells, Pearl City I and II, from 1965 to 1973, and rainfall data from Waipahu rain gage 750 from 1950 to 1980. The locations of these sites are shown in figure 1.

Pumping Tests

Constant-rate pumping tests were designed and monitored for Waiawa shaft. These tests were designed to identify the cause of the change in chloride concentration at Waiawa shaft. For these tests the water level at Waiawa shaft was monitored continuously, samples to be analyzed for chloride concentration were obtained once or twice daily, and a sample for nitrate analysis was obtained weekly. Most of the samples were obtained and analyzed by Navy personnel. Replicate samples analyzed by the Geological Survey and the Navy laboratories were in agreement.

Three pumping tests were performed. For the first test, an average daily pumping rate of 14 Mgal/d was maintained from July 1, 1980 until March 15, 1981. This was considered a medium-rate pumping test. The second test, a recovery and low-rate test, was performed in two parts.

For the first part, from March 17 until March 31, 1981, Waiawa shaft pumps were completely shut down. Samples for chloride analyses were obtained daily from the shaft's sump. The second part, from March 31 through April 13, 1981, entailed pumping at a daily average rate of 5 Mgal/d from Waiawa shaft.

From April 14 through June 13, a high-rate pump test was performed. A rate of approximately 19 Mgal/d was maintained almost constantly during this period.

Additional Activities

Additional activities included:

(1) Discussions with Oahu Sugar Co. personnel detailing the irrigation pattern of Waipahu pump 6 water.

(2) Sampling of Waipahu pump 6 water for chloride and nitrate concentrations on approximately a monthly basis from January through June 1981. Water levels were also recorded.

(3) Sampling of Oahu Sugar Co. reservoir water to verify the chloride and nitrate concentrations of the irrigation water.

(4) Performing statistical and spectral time-series analyses on monthly data for Waipahu pump 6 and Waiawa shaft for the period from 1947 through 1979. This analysis included auto-correlations, and cross-correlations at different lag times between the variables.

(5) Sampling the water quality at the surface of the water table at test wells near Waiawa shaft.

EVALUATION OF DATA

Review of Existing Records and Reports

With an understanding of the hydrology of the Pearl Harbor aquifer as described in the Introduction and Regional Hydrology section, a history of the hydrology of the area in which Waiawa shaft is located can be formulated from existing records and reports. Prior to the late 1800's, ground water in the area of Waiawa shaft had a head of about 34 feet above mean sea level (Visher and Mink, 1964) and probably had a chloride concentration of about 10-20 mg/L as indicated by recent analyses of water from an uncontaminated source, Waipahu pump 17 (fig. 1).

In 1898, drilling began for the 14 wells at the Waipahu pump 6 station. Excavations were made from the ground elevation, 40 feet above sea level, to about 7 feet above sea level where drilling commenced. The wells were drilled to depths of 500 to 700 feet below sea level. Because the tops of the wells were below the water table (the elevation of the water table was approximately 34 feet in 1898 and was 17.5 feet in 1980), water flowed freely from the wells. A header system connected all the wells and transmitted the water to pumps 6A and 6B. The pumps then raised the water to the fields which were at elevations of more than 400 feet.

The earliest recorded chloride concentration of Waipahu pump 6A water was 46 mg/L on October 24, 1898 (Stearns and Vaksvik, 1938). From 1902 (when records were available again) until about 1951, the chloride concentration over a year's cycle generally ranged from 200 to 400 mg/L. Fluctuations in chloride concentration show a positive correlation with fluctuations in pumpage during this and subsequent periods. The maximum recorded chloride concentration, prior to 1953, was 716 mg/L in October 1912 when pumpage from Waipahu pump 6 was exceptionally high, 510 Mgal (million gallons) for the month. In October 1953 when the chloride concentration again reached more than 700 mg/L, the pumpage for the month was only 190 Mgal. A monthly pumpage in March 1978 of 299 Mgal, had a corresponding chloride concentration of 1700 mg/L. Because the wells at Waipahu pump 6 penetrate from 500 to 700 feet below sea level, they draw water from near the bottom of the basal lens where the chloride concentration is high. Because chloride concentration of Waipahu pump 6 water was many times greater in 1981 than it was in 1900 without a corresponding increase in pumpage, it is evident that the decline in freshwater heads experienced at Waipahu pump 6 has been accompanied by a rise in the bottom of the lens which has brought saltier water within the radius of influence of the wells.

The ground water in the vicinity of Waiawa shaft had become degraded to a point when, in 1950, the first water pumped from the shaft had a chloride concentration of more than 300 mg/L. However, pumpage from the shaft removed some of the more saline water and caused mixing with subjacent fresher water, such that the average chloride concentration of Waiawa shaft water was 80 mg/L until 1961, with only small annual variations.

From 1898 until 1950, the chloride concentration of Waipahu pump 6 water ranged from about 200 to 400 mg/L and fluctuated annually owing to variation in pumping and rainfall but with no long-term trend of increasing chloride concentration. However, from 1950, when construction required Waiawa shaft to be dewatered at a rate of about 30 Mgal/d, until 1968, the chloride concentration of the water from Waipahu pump 6 ranged from about 300 to 500 mg/L. This rise in the chloride concentration of Waipahu pump 6 water occurred because of regional and local shrinking of the freshwater lens in part caused by pumping from Waiawa shaft. The low rainfall of the early 1950's was not the major cause of the rise in the chloride concentration of Waipahu pump 6 water because the chloride concentration did not decline to its previous levels when the rainfall increased in the mid-50's. Accompanying this rise in the chloride concentration of Waipahu pump 6 water was a slight rise in the chloride concentration of the water from Waiawa shaft, which reached 110 mg/L in 1968.

The preceding chain of events set the stage for the significant changes in the chloride concentrations of water from both Waipahu pump 6 and Waiawa shaft that were to follow. Rainfall in the area decreased from 1968 to 1977, with an exceptional low in 1973 (fig. 7). The increased pumping from Waipahu pump 6 required to supply increased irrigation needs, in combination with the rising transition zone, caused the yearly average of the chloride concentration of Waipahu pump 6 water to rise from 510 mg/L in 1968 to 1300 mg/L in 1977. Consequently, the yearly average of the chloride concentration of the water from Waiawa shaft rose from 110 mg/L in 1968 to 188 mg/L in 1977.

In 1978 the chloride concentration of Waiawa shaft water rose to 290 mg/L as a result of low pumpage from Waiawa shaft drawing water mostly from the upper degraded portion of the lens and as a result of increased rainfall leaching residual salts from the soil. Presently (1978-1981) Waiawa shaft water ranges from 220 to 290 mg/L Cl^-, depending on the time of year and the pumpage.

Much of the previous description of the hydrology of the Waiawa shaft area was taken from existing records. However, some of the description was based on hypotheses which must be verified and quantified by the evaluation of data obtained specifically for this investigation.

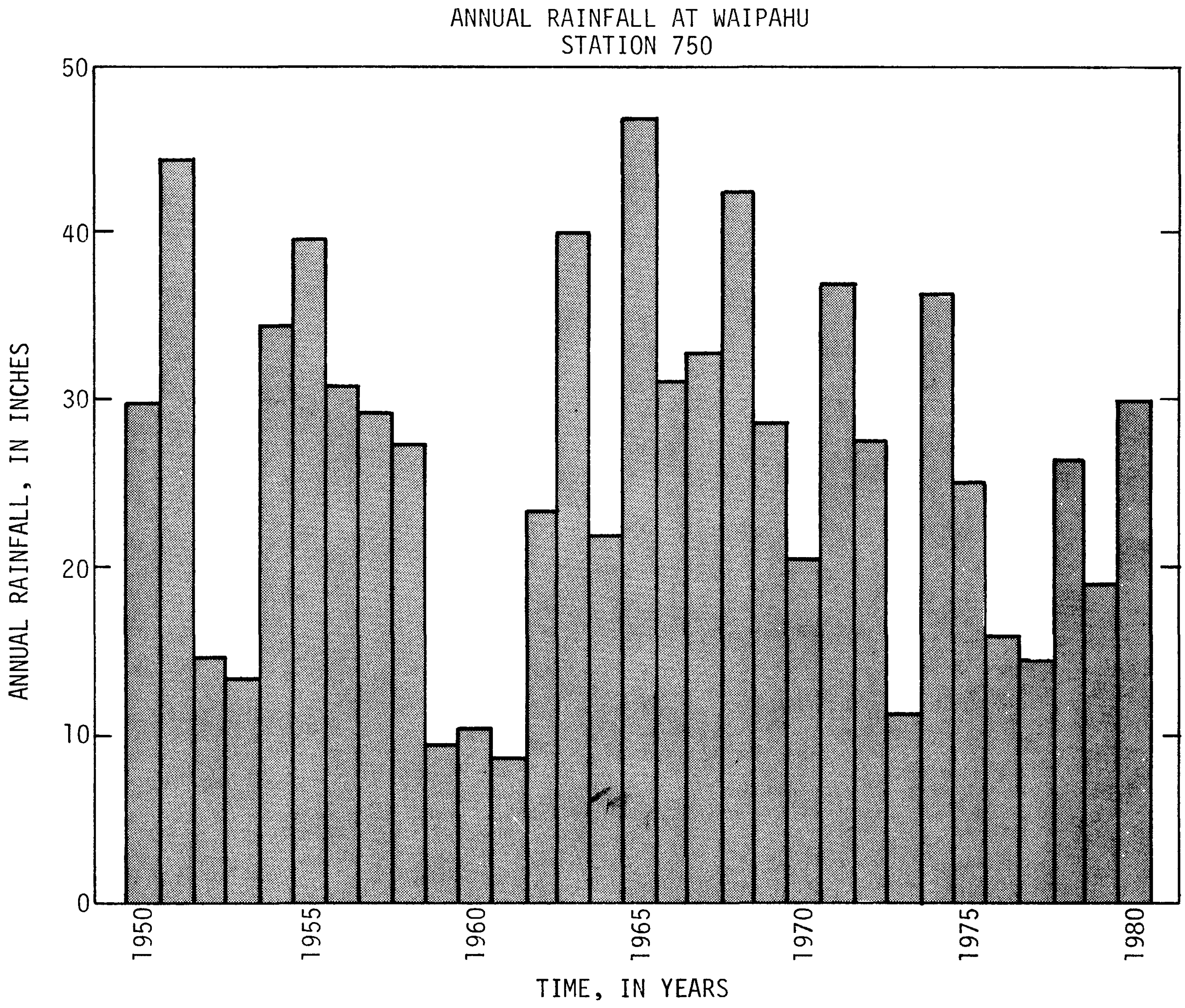

Figure 7. Annual rainfall at Waipahu rain gage 750, 1950-80.

Data from Oahu Sugar Company

Discussions were held with Oahu Sugar Company personnel to determine the quantity and quality of irrigation water applied to fields in the vicinity of Waiawa shaft and the temporal and spatial distribution of irrigation. This information was intended to provide data for the determination of the mass balance of water and chloride in the area. However, it became clear that the situation is too complex and data are insufficient to perform a meaningful mass balance. The following generalized description of the irrigation distribution in the vicinity of Waiawa shaft did result from the discussions.

From the early 1900's until the mid-1960's, the following sugarcane fields were irrigated by water from Waipahu pumps 6A and 6B, and from Waiahole and Ahrens ditches: Nos. 500, 501, 505, 510, 515, 520, 525, 530, and possibly 417, and 420. These sources and sugarcane fields are shown in figure 2.

In the mid-1960's the routing of Waiahole and Ahrens ditch water (10 mg/L Cl^-) to sugarcane fields 515 and below was discontinued. In December 1978, the use of Waipahu pump 6B was virtually discontinued. Sugarcane is grown on a 23-month cycle, and irrigation is withheld for 2 to 3 months prior to harvest. About half the sugarcane fields in the 500-series fields are harvested in odd years (for example, 1979) from February through October and about half are harvested in even years.

Irrigation during periods of high evapotranspiration (the summer months) is insufficient to meet the sugarcane's water needs; thus, soil moisture is lower and the proportion of irrigation which infiltrates past the root zone is less than during periods when irrigation is in excess of plant requirements (the winter months). Therefore, during the summer, salts from the irrigation water accumulate in the soil. During the winter, irrigation and rainfall in excess of plant requirements dissolve the accumulated salts from the soil and produce ground-water recharge containing a fairly high concentration of salts. Neither Oahu Sugar Co. nor Hawaiian Sugar Planter's Association could provide soil water data for fields irrigated by Waipahu pump 6 water, but their experience in other fields indicates that there is no long-term trend of rising soil chloride.

Work by Green and others (1982) indicates that the flow rate of water through the unsaturated section may average about 5 feet per day. The vertical distance that irrigation-return water must travel to arrive at the water table is about 400 feet in the vicinity of Waiawa shaft, which indicates a travel time of about 3 months. Therefore, within a year of the time that irrigation with high-chloride water is discontinued Waiawa shaft water quality will start to improve.

Eight field trips to Waipahu pump 6 and the reservoir which it supplies were made from June to October 1980 to determine the quality of water applied to the sugarcane fields. The irrigation water comes directly from the pipeline fed by Waipahu pump 6 or the reservoir fed by Waipahu pump 6. Water samples from the two sources were analyzed for specific conductance, chloride, and nitrogen. Partial results of these analyses are shown in table 1.

Table 1. Chloride and nitrogen concentrations of Waipahu pump 6 water

(Concentrations, in milligrams per liter)

Date of collection 1980	Waipahu pump 6		Reservoir	
	Chloride	Total nitrogen	Chloride	Dissolved nitrogen
June 12	900	2.2	920	
June 19	840		840	
June 29	1000		860	
July 9	1100	1.8	880	
July 24	1200		1000	
July 30	1200		1100	
Aug. 14	1200		1300	2.1
Oct. 9	1300		1300	

These data show that the quality of irrigation water is almost the same as that of water being pumped from Waipahu pump 6.

Also, a number of field trips were made to test holes T-39 and T-40, which are located in fields 510 and 515, respectively (fig. 2). These wells were drilled to approximately 20 feet below sea level to provide hydrologic and geologic data for the construction of Waiawa shaft. The initial chloride concentration from T-39 was 176 mg/L in 1949 and ranged from about 100 to 200 mg/L from 1949 to 1953. A water sample obtained for this study on July 25, 1980, had a chloride concentration of 470 mg/L and 2.8 mg/L total nitrogen. Samples from T-40, which initially had a chloride concentration of 203 mg/L in 1949, are presented in table 2.

Table 2. Chloride concentration at well T-40 in milligrams per liter

Date of collection	Chloride	Date of collection	Chloride
Mar. 19, 1981	350	Aug. 25, 1981	550
Mar. 23, 1981	430	Sept. 30, 1981	460
Mar. 25, 1981	460	Oct. 30, 1981	340
Mar. 26, 1981	500	Nov. 25, 1981	670
Apr. 2, 1981	680	Dec. 29, 1981	980
June 23, 1981	760	Feb. 26, 1982	500

The data indicate that, in the vicinity of Waiawa shaft, the upper part of the basal lens has chloride concentrations ranging from about 300 to 1,000 mg/L. The thickness of this degraded layer was not determined from field work for this study. However, as stated earlier, work by Mink and Kumagai (1971) and Tenorio and others (1969) indicates that this layer was from 200 to 300 feet thick in 1969. The layer may presently be thicker, owing to continued irrigation with water of higher chloride concentration.

Time-Series Analysis

The Stanford Biomedical statistical computer package, BMD-02T, was used to make statistical and spectral time-series analyses on the chloride concentration of Waiawa shaft water versus the pumping rate of Waiawa shaft, the chloride concentration of Waiawa shaft water versus the chloride concentration of Waipahu pump 6 water, and the chloride concentration of Waipahu pump 6 water versus the pumping rate of Waipahu pump 6, in order to investigate the statistical and phase relationships among these variables. Specifically, the time-series analysis was made to determine whether or not the data support the hypotheses that (1) the chloride concentration of Waipahu pump 6 water is derived from the underlying transition zone; (2) the chloride concentration of Waiawa shaft water is derived from high-chloride irrigation water from Waipahu pump 6; and (3) the chloride concentration in water at Waiawa shaft can be reduced if pumping at Waiawa shaft is increased to its pre-1978 levels.

If the data support these hypotheses, then the time-series analysis would show that the pumping rate of Waipahu pump 6 and the chloride concentration of Waipahu pump 6 water are positively correlated (when the pumping rate of Waipahu pump 6 increases, the chloride concentration of the water from Waipahu pump 6 generally increases); that the chloride concentrations of the water from Waiawa shaft and Waipahu pump 6 are positively correlated, and that the chloride concentration of the water from Waiawa shaft and the pumping rate of Waiawa shaft are negatively correlated (when the pumping rate of Waiawa shaft increases, the chloride concentration of the water from Waiawa shaft generally decreases).

In addition, the time-series analysis should show that the time delay between a change in one variable and a corresponding change in a related variable is consistent with hydrologic data. The time lag which produced the highest correlation coefficient is the time lag between the two series.

Graphs of the pumping rate of Waipahu pump 6, the chloride concentration of Waipahu pump 6 water, the pumping rate of Waiawa shaft, and the chloride concentration of Waiawa shaft water are presented in figures 8 through 11.

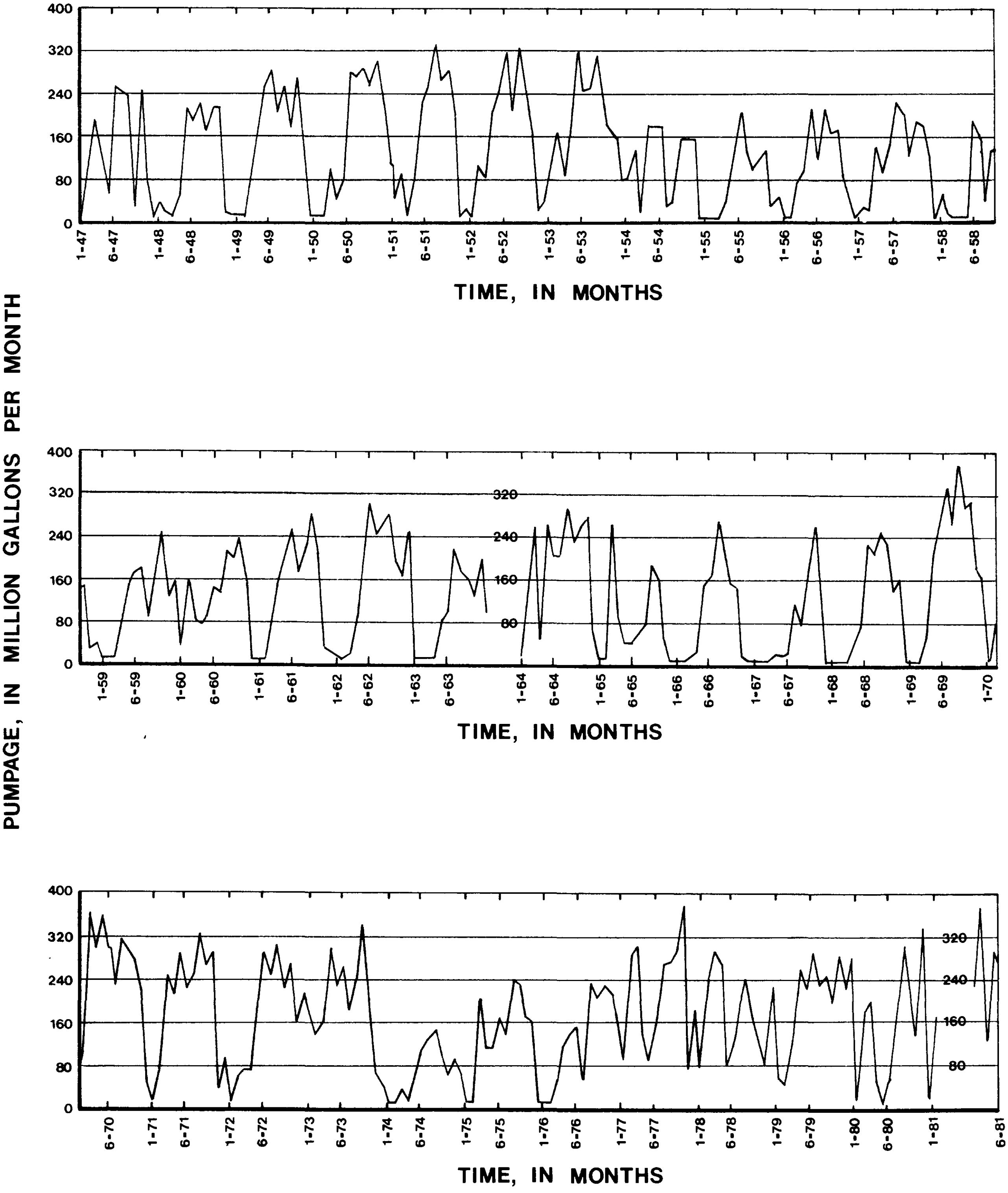

Figure 8. Waipahu pump 6 monthly pumpage, January 1947 - June 1981.

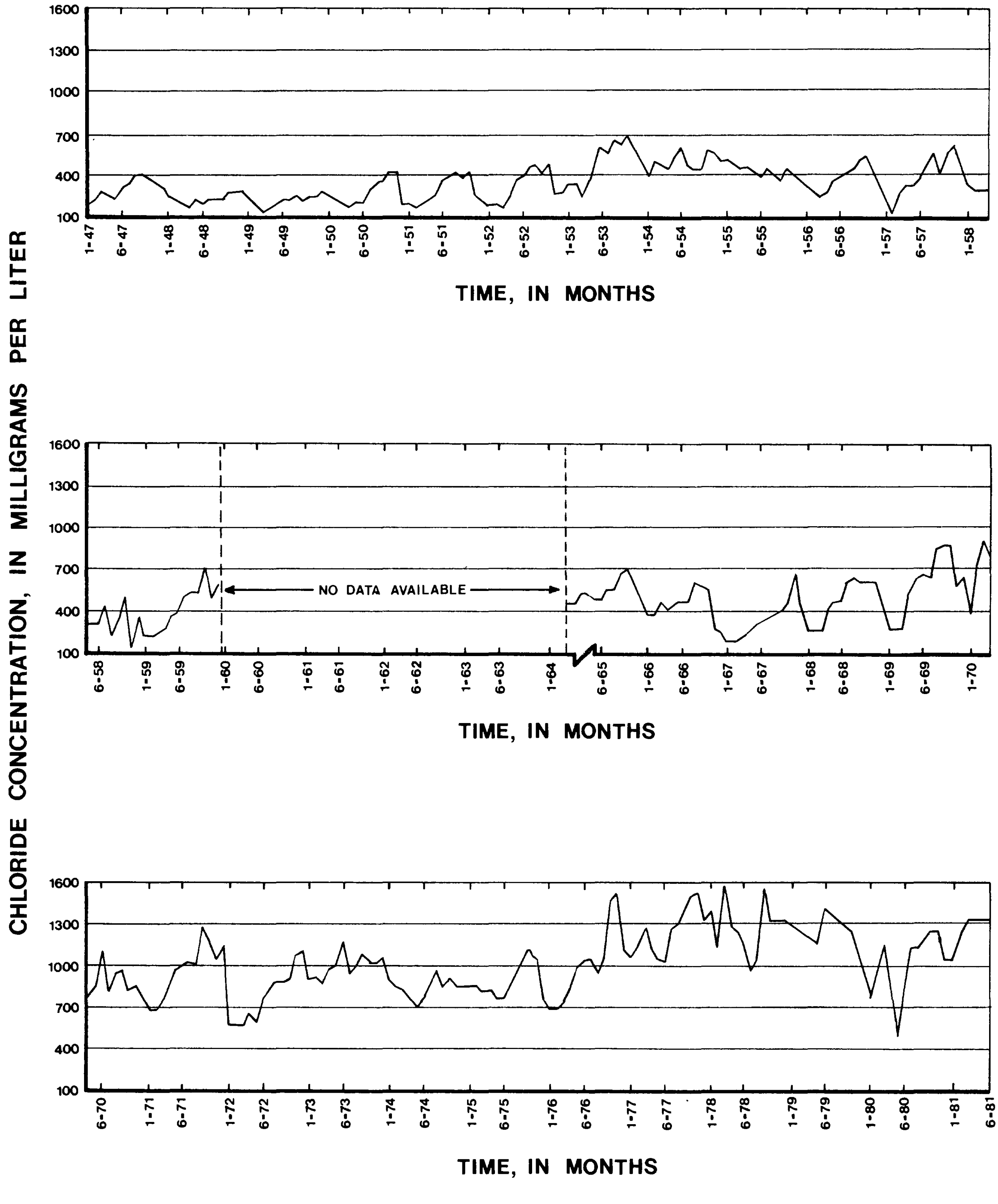

Figure 9. Waipahu pump 6 average monthly chloride concentration, January 1947 - June 1981.

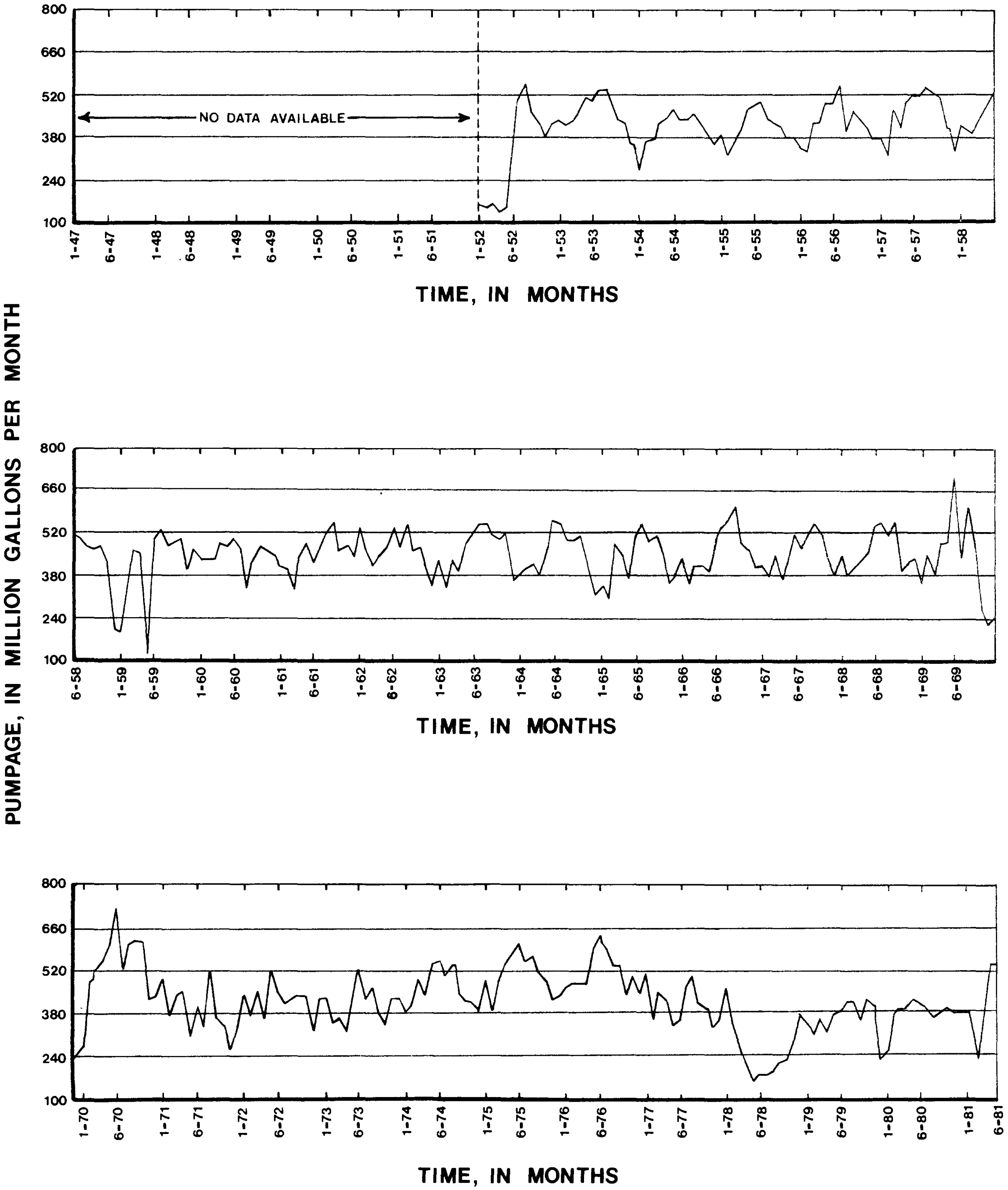

Figure 10. Waiawa shaft monthly pumpage, January 1947 - June 1981.

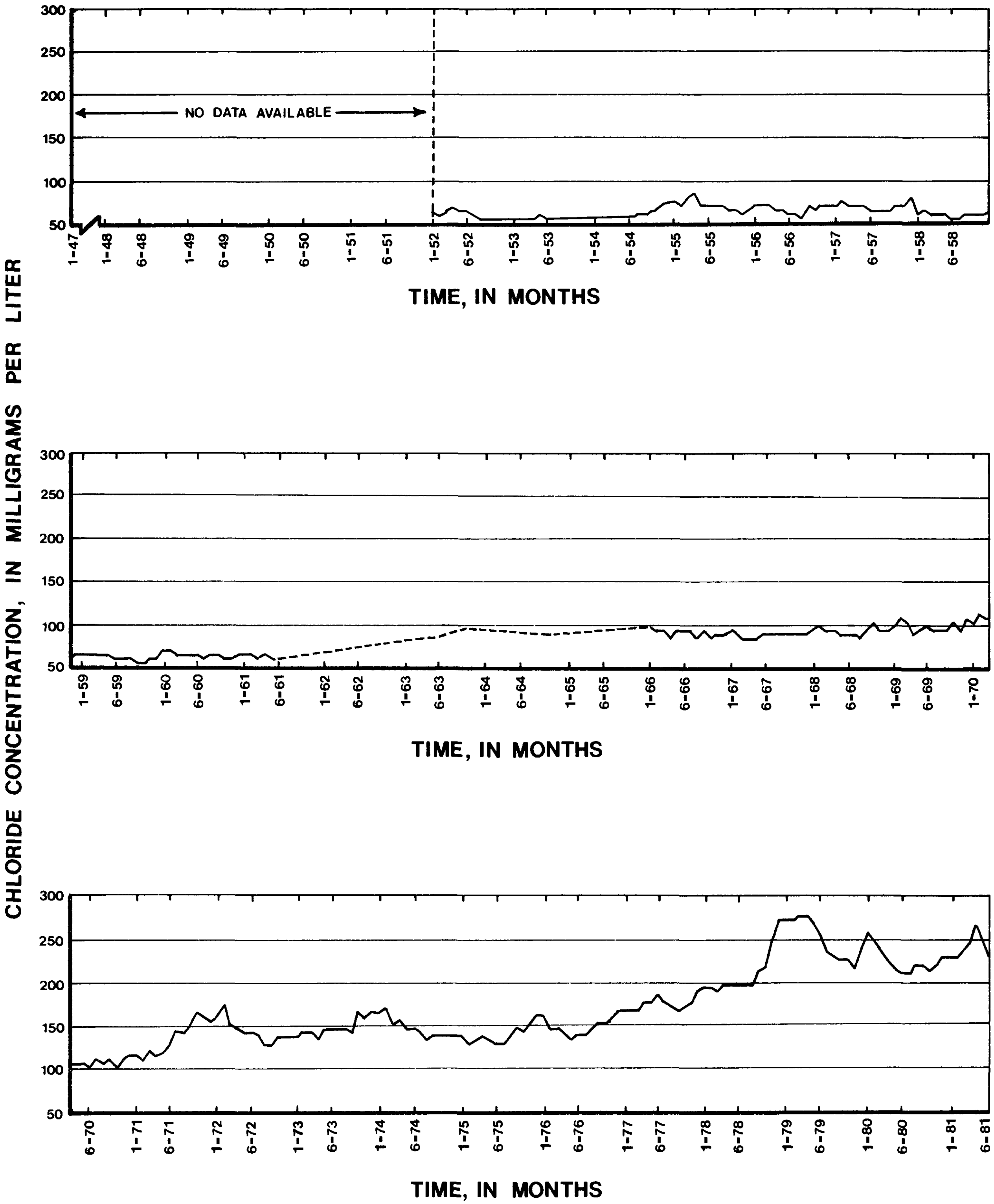

Figure 11. Waiawa shaft average monthly chloride concentration, January 1947 - June 1981.

Results

Analysis of chloride concentration and pumping rate at Waipahu pump 6.

Monthly data 1947-1959

1. Both series show a strong yearly cycle.

   Peaks in the annual cycle of chloride concentration occur about August and October; minima occur about March. Peaks in the pumping rate occur near the months of June and October; minima occur between December and February.

2. The pumping rate cycle precedes the chloride concentration cycle by 1.5 months, which is hydrologically reasonable.

   In a study of the Waialua ground-water basin, Dale (1978) determined that it took about 5 weeks for the saline transition zone to start moving toward the wells after the onset of the summer pumping season.

3. The correlation coefficient, r, between the two series at a 1.5-month lag is 0.46.

Analysis of chloride concentrations of Waiawa shaft water and Waipahu pump 6 water.

Monthly data 1952-1959

1. Both show yearly cycles, though the cycle of chloride concentration of Waiawa shaft water is weaker.

   Peaks in the chloride cycle at Waiawa shaft occur about January with some indication that a second maximum also occurs about April. Minima occur about August.

2. The Waipahu pump 6 chloride cycle precedes the Waiawa shaft chloride cycle by 5 months. Five months is a reasonable length of time for irrigation water to infiltrate to the water table. Calculations using Darcy's Law with data obtained by Green and others (1982) and observations that infiltrating winter rain arrives at the Schofield shaft in the summer indicate that 3-6 months is the approximate time of infiltration.

3. The correlation coefficient, r, between the two series is 0.13 at a 5-month lag. Although the r value is low, indicating only weak correlation between the two series, a t-test showed that the value was statistically significant within 95-percent confidence limits. From 1952-1959 the chloride concentrations at Waiawa shaft and Waipahu pump 6 were relatively low, thus other factors, such as variability in rainfall, could easily obscure the effect that irrigation water had on groundwater. Because the correlation coefficient between the two series was greatest at a 5 month lag, the physical process of irrigation-return water percolating through the over burden then mixing with the groundwater appears to be reflected in this data.

Analysis of chloride concentration and pumping rate at Waiawa shaft.
Monthly data 1952-1960

1. Both series show a yearly cycle:

   The pumping rate cycle is strong and the chloride concentration cycle is weaker.

   Peaks in the pumping rate cycle occur about July and minima occur about January.

2. Peaks in the pumping rate cycle precede minima in the concentration cycle by about a month. The actual lag time is probably less than a month; however, such a lag time would be difficult to resolve in an analysis of monthly data.

3. The correlation coefficient, r, between the two series lagged by 1 month is -0.27.

Analysis of chloride concentration and the pumping rate at Waiawa shaft.
Monthly data 1972-1976

1. The chloride concentration of the water from Waiawa shaft shows a strong 2-year cycle and a weaker 1-year cycle.

   The pumping rate at Waiawa shaft shows a strong 1-year cycle.

   The 2-year cycle in the chloride concentration may be due to the sugarcane harvesting schedule for field 515, which overlies the northern end of the shaft. This field was harvested in the summers of 1972, 1974, and 1976. Irrigation was withheld from this field 2-3 months prior to harvesting. The decreased amount of irrigation-return water may explain the lack of high-chloride water at Waiawa shaft in the winters of 1972 and 1974.
2. Maxima in the pumping rate of Waiawa shaft's 1-year cycle and minima in the chloride concentration of the water from Waiawa shaft's 1-year cycle are concurrent.
3. The correlation coefficient, r, between the two series is -0.29 at 0-month lag time.

Although the correlation coefficients (r) between these pairs of time series are numerically low, t-tests showed that they are statistically significant within 95-percent confidence limits. Such low r values indicate that the prediction of the chloride concentration of the water from Waiawa shaft by a multiple regression equation would have a large standard error and would not be very useful. However, the fact that the correlation between Waiawa shaft pumping rate and chloride concentration is negative whereas the correlation between the other pairs of variables is positive supports the hypotheses that (1) the chloride concentration in water from Waipahu pump 6 is derived from the underlying transition zone; (2) the chloride concentration in water at Waiawa shaft is derived from high-chloride irrigation water from Waipahu pump 6; and (3) the chloride concentration in water at Waiawa shaft can be reduced if pumping at Waiawa shaft is increased to its pre-1978 levels. The reasonable lag times determined for pairs of related variables lend additional support to the hypotheses.

Analysis of Pumping and Chloride Concentration, Waiawa Shaft 1978 through 1979

Although the previous analysis supports the hypotheses concerning the processes which affect the chloride concentration of the water from Waiawa shaft, the analysis does not indicate the relative extents to which the chloride concentration of the water from Waipahu pump 6 or the pumping rate of Waiawa shaft controls the chloride concentration of Waiawa shaft water. Fortunately, the manner in which Waiawa shaft was pumped in 1978 and 1979 produced some evidence indicating that an increase of the Waiawa shaft pumping rate to its pre-1978 level, will help maintain the chloride concentration below 250 mg/L. Specifically, from January through December 1978, pumpage from Waiawa shaft followed a pattern almost opposite to its ordinary pattern, as disclosed by the time-series analysis. Ordinarily, pumpage from the shaft was minimum around January, increased through July, then decreased through the following January. However, in January 1978 pumpage increased to a yearly maximum, then steadily decreased to a yearly minimum in May-June, then steadily increased through December 1978. These patterns are shown in figure 10.

In 1978 the low pumpage at Waiawa shaft resulted in an accumulation of degraded water in the upper layer of the lens. Irrigation water having the highest annual average chloride concentration on record (1400 mg/L) contributed significantly to the degradation of the upper part of the lens. By April 1979 the chloride concentration of Waiawa shaft water was 290 mg/L. Continued pumping at medium rates removed some of the accumulation of degraded water and brought deeper, fresher water to the shaft, resulting in a chloride concentration of 230 mg/L at Waiawa shaft in December 1979.

The amount of high chloride irrigation-return water that recharged the groundwater may have been enhanced by the increased rainfall in 1978, relative to the rainfall in 1977 (fig. 7). Salts probably accumulated in the soil in 1977 owing to the low rainfall and high-chloride irrigation water. These salts, leached by the 1978 rainfall, may have created a brackish slug of ground-water recharge. This brackish slug of recharge, in combination with the low pumpage at Waiawa shaft, could explain the sharp rise in chloride concentration in 1979.

Pumping Tests

The pumpage and chloride values at Waiawa shaft, which were obtained daily for some parts of the year-long test and twice daily for other parts of the test, were averaged and analyzed on a weekly basis. Graphs of the weekly values are presented in figure 12.

Medium-Rate Pumping Test, 14 Mgal/d,

July 11, 1980 - February 28, 1981

Two rates of pumping, 10,420 gal/min (gallons per minute) for 20 hours and 6,250 gal/min for 4 hours, were maintained each day so that the daily average rate was about 14 Mgal/d. The pumpage value of 14 Mgal/d was chosen because it was the lowest rate that could be practically maintained for an extended period of time. A low rate was desired to maximize the effects of irrigation-return water.

The average weekly chloride concentration at 6,250 gal/min exceeded the average weekly concentration at 10,420 gal/min for 27 of the 34 weeks of this test. For the remaining 7 weeks, the concentrations were the same. Although the difference in chloride concentrations ranged from only 1 to 5 mg/L, it seems clear that even if a daily time scale is used (the weekly values are averages of daily values), the pumping rate at Waiawa shaft has a negative correlation with the chloride concentration of the water from Waiawa shaft.

The pumpage at Waiawa shaft was relatively constant from July 1980 until March 1981 yet the chloride concentration rose from 225 to 255 mg/L. The data obtained from this pumping test are in agreement with the trend revealed by the time-series analysis. Chloride concentration is low in the summer and high in the winter.

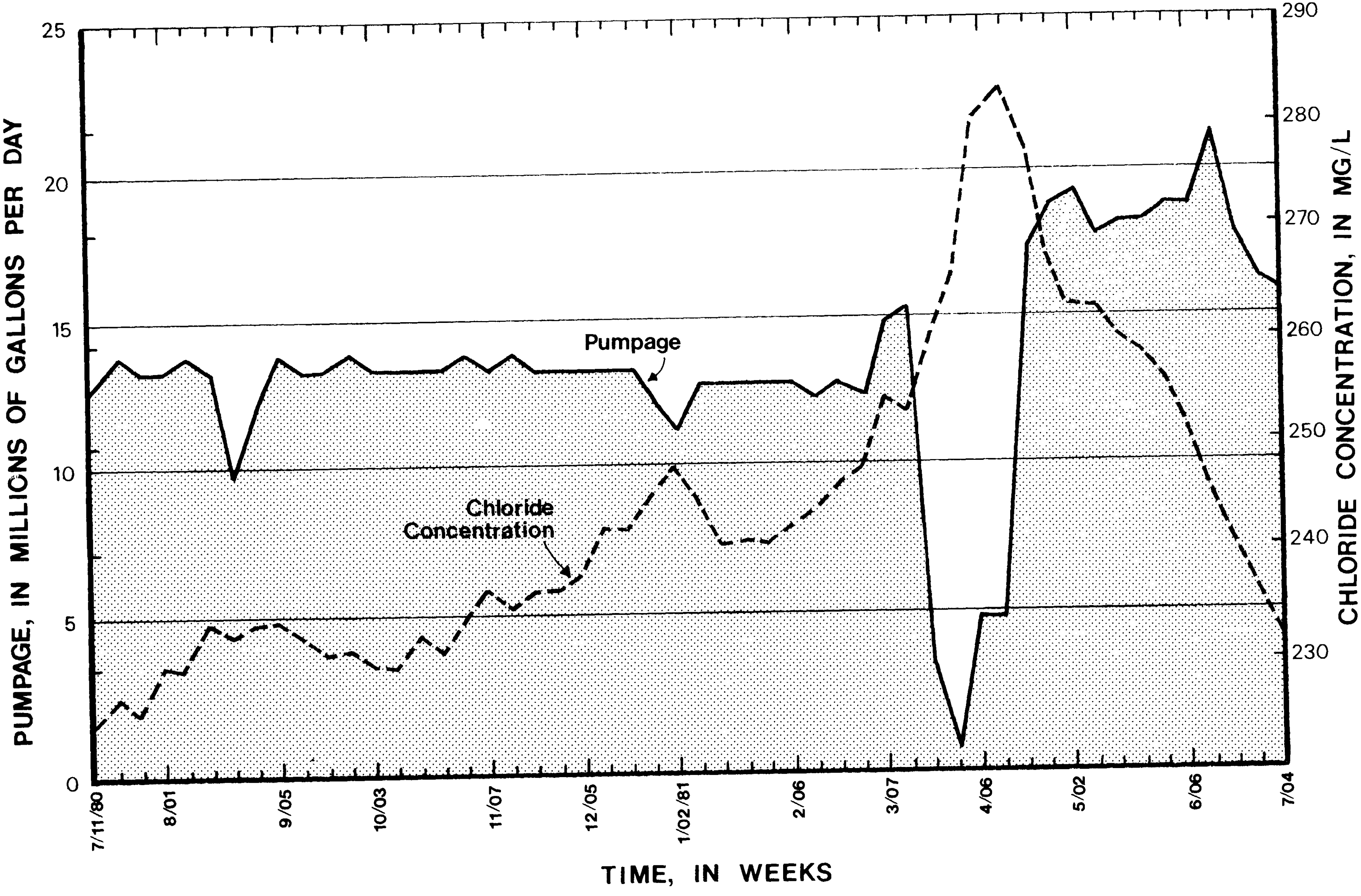

Figure 12. Weekly average of daily pumpage and chloride concentration at Waiawa shaft, July 11, 1980 - July 4, 1981.

Recovery and Low-Rate Pumping Tests of Waiawa Shaft

0 Mgal/d from March 17-30, 1981
5 Mgal/d from March 31-April 14, 1981

To further refine the analysis of the hydrologic system at Waiawa shaft, the pumps were completely shut down for two weeks from March 17-30, 1981, and samples for chloride analyses were taken daily from the pump sump. Data are presented in figure 12.

In the first week of shutdown, the chloride concentration of the water from Waiawa shaft rose from 254 to 268 mg/L. During the second week of the test, the chloride concentration of the water from Waiawa shaft remained constant at 268 mg/L. These data can be explained by the following sequence of events.

1. Pumping at 14 Mgal/d mixes deep fresher water with shallow water that had a chloride concentration of about 380 mg/L (chloride concentration at well T-40, March 19, 1981) resulting in the chloride concentration of 254 mg/L.
2. At shutdown, the water in the sump remains there and is augmented by more saline water that fills the cone of depression in the water table created by the previous pumping. The inflow of the water results in an admixture with a chloride concentration of 268 mg/L.
3. The process described above was completed within the first week of shutdown, thus the chloride concentration of the admixture remained constant at 268 mg/L during the second week of shutdown.

On March 31, 1981, pumping commenced at Waiawa shaft at an average rate of 5 Mgal/d, which was maintained by operating one pump for approximately 13 hours and then shutting it down for the remainder of the day. A conductivity probe had been placed in the sump and a continuous-reading strip chart recorded the conductivity of the water as it started to flow through the sump.

The following description supports the hydrogeologic understanding of Waiawa shaft derived from flow-rate data obtained along the length of the tunnel in 1951. These data, presented in figure 13, show that nearly half the flow from the tunnel originates from a 400-foot zone at the northern end of the 1,700-foot tunnel.

At 8 a.m., March 31, 1981, the pump was turned on. For the next hour, while water in the tunnel was removed, the conductivity of water remained constant and a water sample had a chloride concentration of 270 mg/L. From 9 a.m. until 12 m. (noon), the conductivity increased as water from the northern end of the tunnel, which underlies the sugarcane fields, arrived at the sump. At 12 m., the conductivity leveled off and a water sample had a chloride concentration of 290 mg/L. For the next two weeks of pumping at a daily average rate of 5 Mgal/d, the chloride concentration of the water from Waiawa shaft remained constant at 285 mg/L.

Figure 13 also illustrates the effects of anisotropy and chemical weathering on the permeability of the aquifer. The tunnel was excavated approximately 20 feet below the water table and yet, relatively little water entered the tunnel in the 600-feet length near the sump. The geologic log shows the presence of weathered basalt, which has low permeability, and the absence of clinker zones of aa lava flows (aa clinker), which have high permeability. From 600 to 850 foot from the sump, the specific flow rate (flow rate per foot of tunnel) greatly increased and the geologic log shows the presence of aa clinker. From about 850 to 1,050 feet from the sump, the specific flow rate became relatively small and the geologic log indicates only massive lava, probably the central core of an aa lava flow. From about 1,050 feet to the northern end of the tunnel at 1,700 feet, the specific flow rate was again relatively high and the geologic log shows the continuous presence of an aa clinker layer.

Evidently the poor yield from 0 to 600 feet from the sump is due to chemical weathering of basalt. In the valley a weathered rind probably extends several hundred feet below the ground, (R. M. Towill Corp, 1978) and possibly 100 feet laterally from the valley walls. The poor yield from 850 to 1,050 feet from the sump is caused by the location of the tunnel within massive lava; probably the yield could be increased in this section by drilling vertically until aa clinker is encountered.

The specific flow rates of the tunnel in aa clinker and in massive rock are 0.05 and 0.005 Mgal/d respectively. The ratio of these rates is 10:1. Because vertical flow through the aquifer is limited by the hydraulic conductivity of the massive layers, the ratio of horizontal to vertical hydraulic conductivity of this aquifer is on the order of 10:1.

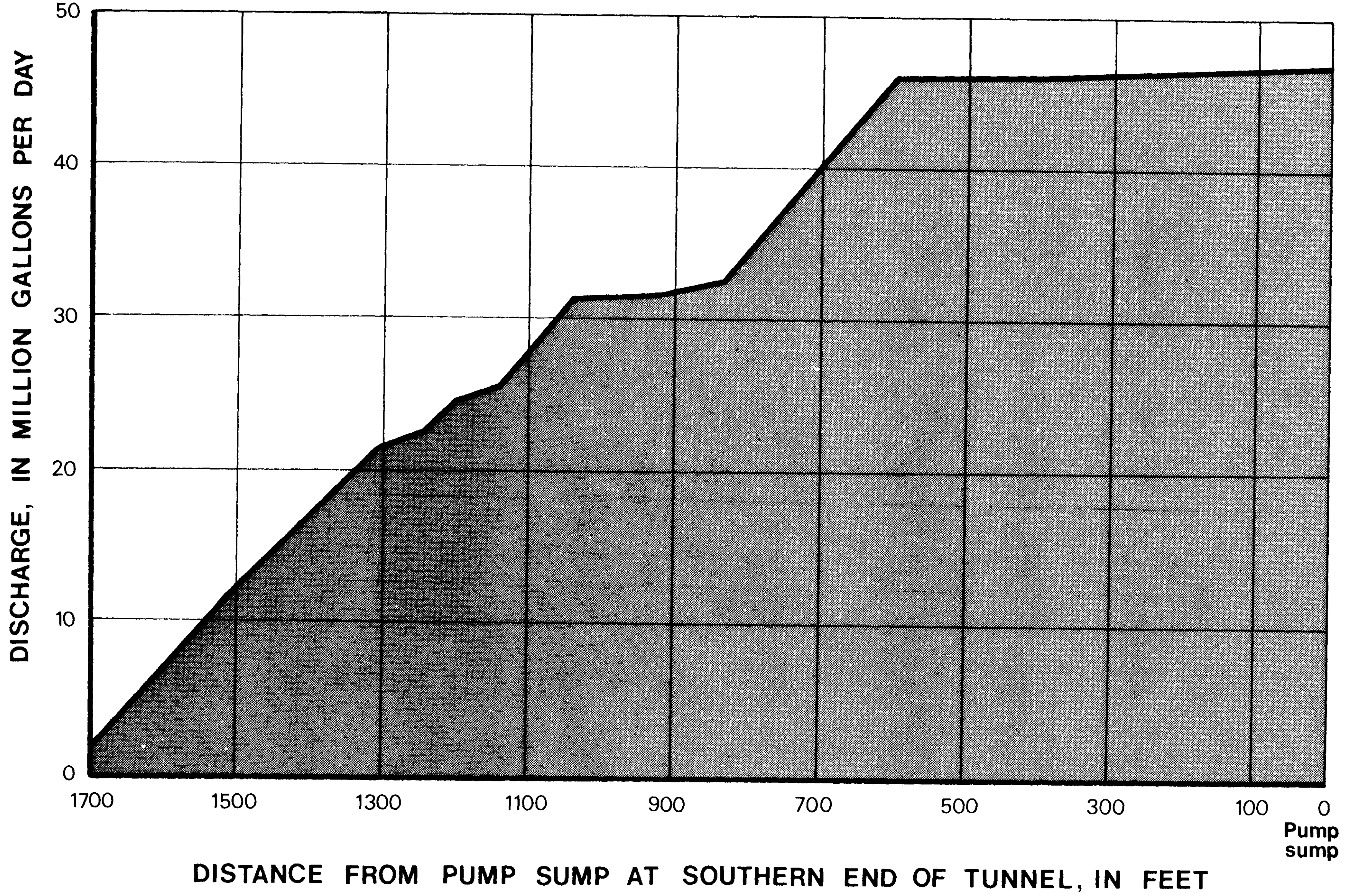

Figure 13. Discharge versus distance along the tunnel, Waiawa shaft (March 9-19, 1951).

High-Rate Pumping Test

Pumping rate of Waiawa shaft = Approximately 19 Mgal/d

From April 14 to June 20, 1981

From April 14 to June 20, 1981, the pumping rate of Waiawa shaft averaged 19 Mgal/d and the chloride concentration of the water from Waiawa shaft decreased steadily from 285 mg/L to 235 mg/L (fig. 12). The decrease in the chloride concentration of the water from Waiawa shaft resulted from the removal of accumulated irrigation-return water from the upper layer and from the contribution of fresher, deeper water drawn to the sump. Extrapolation of the chloride concentration versus time graph (fig. 12) suggests that the chloride concentration of the water from Waiawa shaft would reach 200 mg/L in a few more months if the 19 Mgal/d rate is maintained. However, pumping Waiawa shaft at this rate for extended periods of time could cause Waipahu pump 6 water to become more brackish, which in turn would have an adverse effect on the water quality at the shaft.

DECLINE IN CHLORIDE CONCENTRATION AT PEARL CITY I AND II WELLS AND AN ANALOGY TO WAIAWA SHAFT

Figures 14 and 15 show the changes in chloride concentration and pumpage at the Board of Water Supply's Pearl City I and II wells from 1965 through 1973. These wells and the fields that they once irrigated are shown in figure 1. These sugarcane fields were also irrigated with water from the Hawaiian Electric Co. springs which contained chloride at a concentration of several hundred mg/L. From 1967 to 1969 the Honolulu Board of Water Supply was preparing to go into full production and the sugar company was phasing out its activities in the area. The figures clearly show a decline in chloride concentration of the well water after irrigation with brackish water had ceased. The chloride concentration of Waiawa shaft water would decline in a similar manner if the fields in the vicinity of the shaft were no longer irrigated.

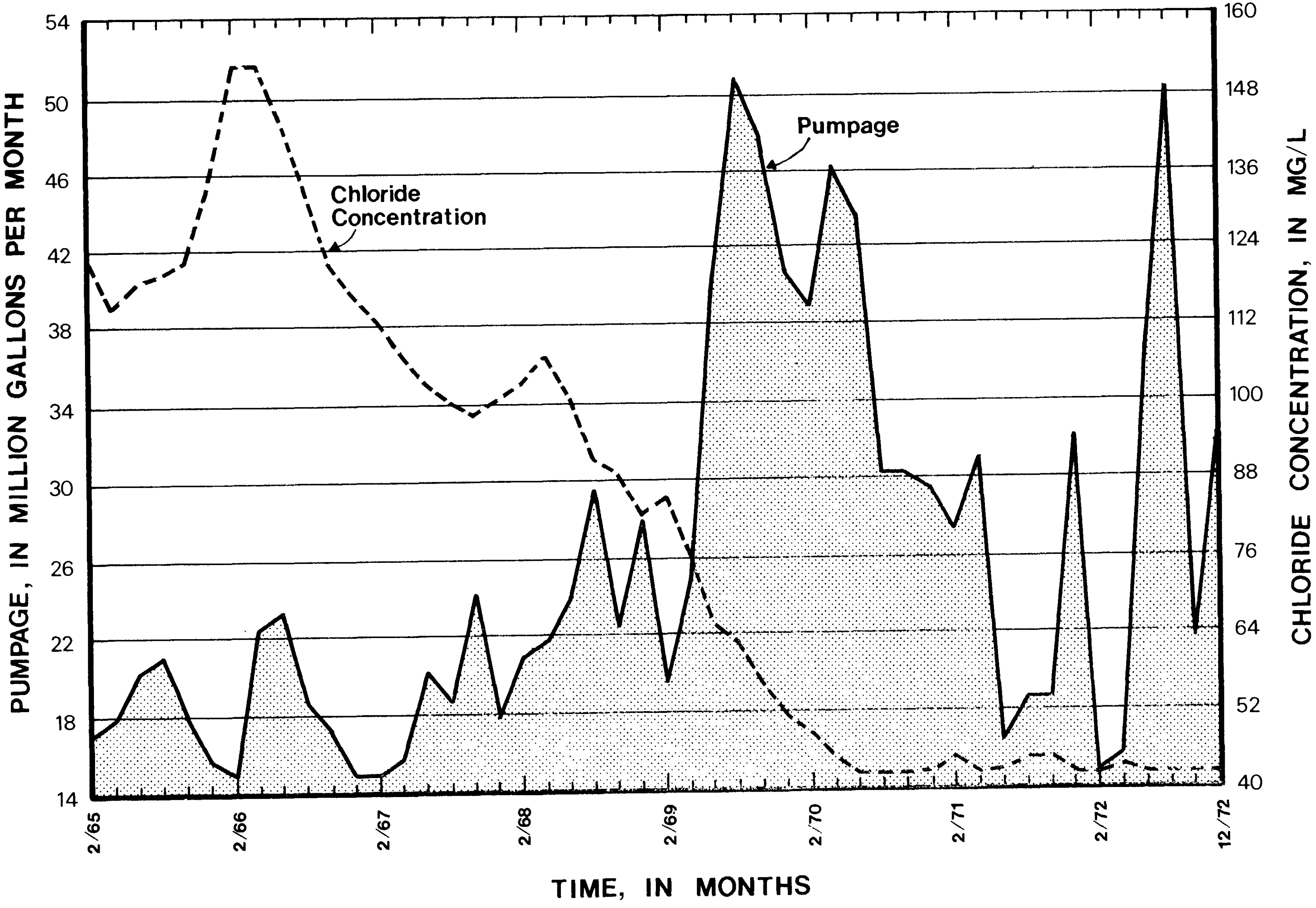

Figure 14. Pearl City I pumpage and chloride concentration, February 1965 - December 1972.

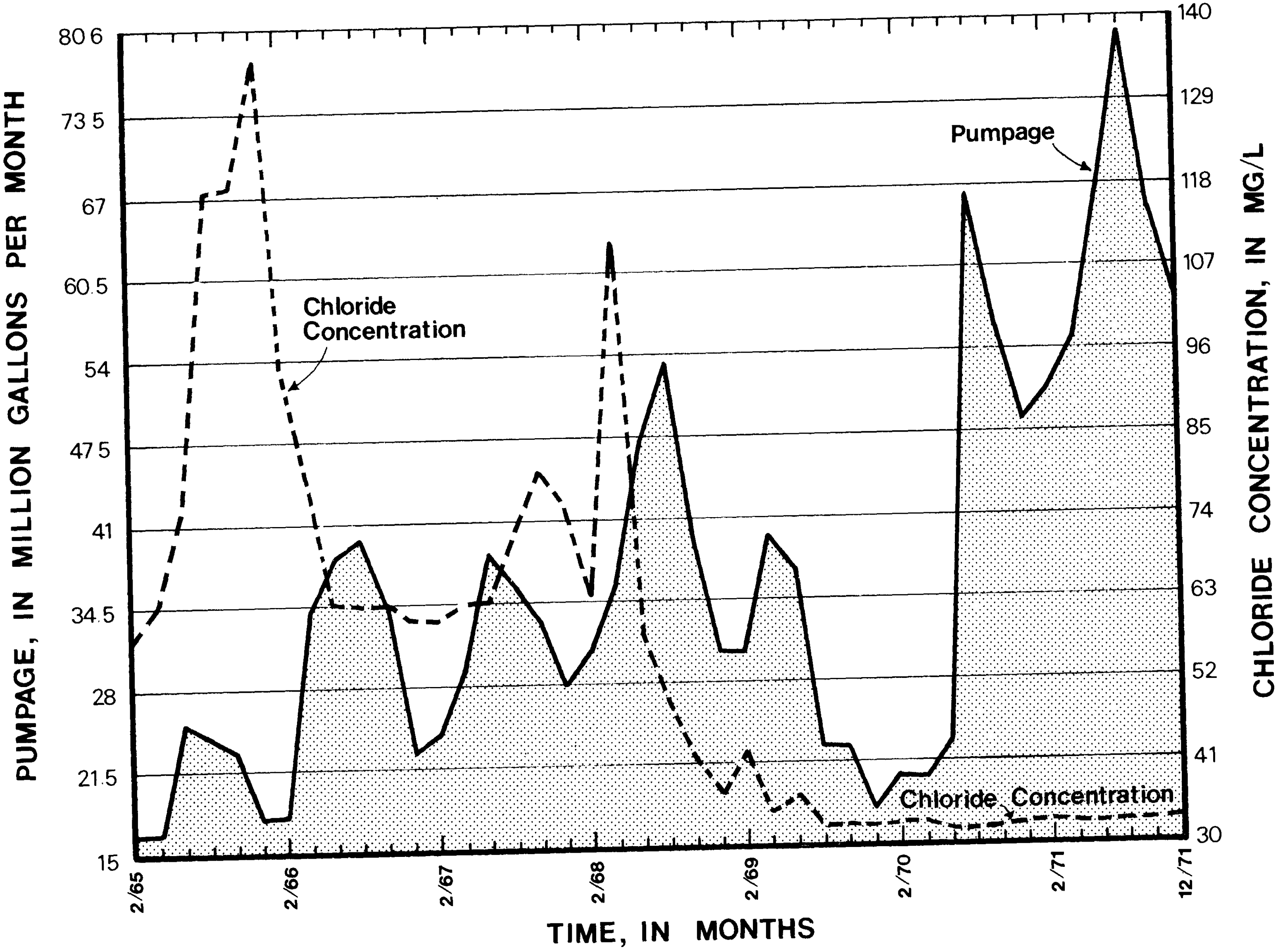

Figure 15. Pearl II pumpage and chloride concentration, February 1965 - December 1971.

The following calculations, based on the removal rate of degraded water from the vicinity of the Pearl City wells, produce ground-water flow rates of about 5 ft/d. About 3 years were required for the degraded zone to disappear from the Pearl City I wells and 2 years to disappear from the Pearl City II wells. Pearl City I and II are 6,500 feet and 4,000 feet, respectively, from the upgradient extent of the irrigated fields. Flow rates for these times and distances are;

6,500 ft/3 yrs = 5.9 ft/d for Pearl City I, and

4,000 ft/2 yrs = 5.4 ft/d for Pearl City II.

Waiawa shaft is about 5,000 feet from the upgradient extent of fields irrigated with brackish water. Assuming a flow rate of 5 ft/d, the degraded zone should be washed away in about 3 years from the time the fields are no longer irrigated with brackish water. The leaching of residual salts from the soil might extend that time somewhat.

CONCLUSIONS

Virtually all chloride ions in water pumped from Waiawa shaft can be attributed to irrigation-return water. From 1978 through 1980 the chloride concentration of Waiawa shaft water rose at an alarming rate. This rise resulted from the combined effects of brackish irrigation-return water and from the very low pumpage from Waiawa shaft during this time. If the higher average pumping rates that were maintained prior to 1978 (15 Mgal/d) are maintained in the future, it is estimated that the average chloride concentration of Waiawa shaft water will be about 220 mg/L, if irrigation with brackish water continues. This prediction may apply to the next 5 to 10 years only. Natural and man-made changes make it impossible to predict over a longer term. Fluctuations in precipitation and irrigation may cause the chloride concentration at Waiawa shaft to exceed 250 mg/L occasionally.

If irrigation with brackish water in the vicinity of Waiawa shaft is discontinued, the salinity of the ground water in the area should begin to decrease within a year and should reach an average chloride concentration of about 100 mg/L within 5 years.

A deep monitor well located near Waiawa shaft would provide the clearest understanding of the source of salts in the shaft's water. Such a well would become even more useful if the lens continues to shrink and seawater encroaches farther into the lens.

RECOMMENDATIONS

In order to maintain the chloride concentration of the water from Waiawa shaft below 250 mg/L, it is recommended that the average pumping rate of Waiawa shaft be 15 Mgal/d. Secondarily, if the annual variation in pumpage could be reduced so that pumpage ranged from 13 to 17 Mgal/d rather than the present range of approximately 10 to 20 Mgal/d, a more efficient removal of the more saline water could be accomplished. A rate of about 13 rather than 10 Mgal/d, maintained from approximately November through February, would reduce the accumulation of irrigation-return water in the degraded layer that generally occurs during those months.

If the static ground-water level were to decline to such a level that a pumping rate of 15 Mgal/d could not be maintained (because of cavitation in the pump sump), a degradation of Waiawa shaft's water quality similar to that which occurred in 1978-1979 would result; 6 feet is a rough approximation of that critical static level. Presently, the static level ranges from about 17 feet in the summer to 20 feet in the winter.

The recommended pumping schedule will reduce the average annual chloride concentration of Waiawa shaft water to about 220 mg/L. This solution to the chloride problem at Waiawa shaft should suffice for several years. Available data do not allow long-term predictions to be made. However, if the Pearl Harbor basal lens continues to shrink, the chloride concentration of Waipahu pump 6 water and possibly seawater intrusion or upconing could become perpetual problems to Waiawa shaft. It is recommended that pumpage and chloride data continue to be collected at Waiawa shaft. After about 5 years the data can be analyzed to determine whether the problem is under control or whether other actions need to be implemented.

If the recommended pumping rates are not able, in the long run, to maintain the chloride concentration of Waiawa shaft water below 250 mg/L, then vertical wells could be drilled in the tunnel. Wells drilled through the floor of the infiltration tunnel, through the upper degraded layer of ground water, and into the underlying fresh basal water should produce water of acceptable quality. These wells should be drilled to a depth of approximately 400 feet below sea level. A review of existing data and additional testing would be required for a more complete appraisal of this alternative.

REFERENCES

Dale, R. H., 1967, Land use and its effect on the basal-water supply, Pearl Harbor area, Oahu, Hawaii, 1931-1965: U.S. Geological Survey Hydrologic Investigations Atlas HA-267.

----- 1978, A ground-water inventory of the Waialua basal-water body, island of Oahu, Hawaii: U.S. Geological Survey Open-File Report 78-24, 71 p.

Green, R. E., Ahuja, L. R., Chong, S. K., and Lau, L. S., 1982, Characterization of water conducting and water storage properties of Hawaii's watershed soils for watershed modeling: Water Resources Research Center, University of Hawaii, Technical Report No. 143 /‾in press_7.

Hufen, T. H., Eyre, Paul, and McConachie, William, 1980, Underground residence times and chemical quality of basal groundwater in Pearl Harbor and Honolulu aquifers, O'ahu, Hawai'i: Water Resources Research Center, University of Hawaii, Technical Report No. 129, 75 p.

Hydrologic Advisory Committee, 1980, Recommendations for ground water use regulation; A report to the Department of Land and Natural Resources, State of Hawaii: Hawaii Division of Water and Land Development Circular C80, 33p.

Lao, Chester, Peterson, F. L., and Cox, D. C., 1969, Application of electric well logging and other well logging methods in Hawaii: Water Resources Research Center, University of Hawaii, Technical Report No. 21, 108 p.

Mink, J. F., 1976, Groundwater Resources of Guam: Occurrence and Development: Water Resource Research Center, University of Guam, Technical Report No. 1, 276 p.

----- 1980, State of the groundwater resources of southern Oahu: Board of Water Supply, City and County of Honolulu, Honolulu, Hawaii, 83 p.

Mink, J. F., and Kumagai, J. S., 1971, A model describing the effects of irrigation on groundwater quality: Pearl Harbor region, Oahu, Hawaii: Unpublished processed report, U.S. Geological Survey, Honolulu, Hawaii, 29 p.

Soroos, R. L., 1973, Determination of hydraulic conductivity of some Oahu aquifers with step-drawdown data: Master of Science Thesis in Geology and Geophysics. University of Hawaii, Honolulu, Hawaii, 47 p.

Soroos, R. L., and Ewart, C. J., 1979, Ground-water status report, Pearl Harbor area, Hawaii, 1978: U.S. Geological Survey Water-Resources Investigations 79-1542, 3 sheets.

State Water Commission, 1979, Hawaii's water resources; Directions for the future: A report to the Governor of the State of Hawaii, Honolulu, Hawaii, 40 p.

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

----- 1938, Records of the drilled wells on Oahu, Hawaii: Hawaii Division of Hydrography Bulletin 4, 213 p.

Tenorio, P. A., Young, R. H. F., and Whitehead, H. C., 1969, Identification of return irrigation water in the subsurface: Water Quality: Water Resources Research Center, University of Hawaii, Technical Report No. 33, 90 p.

R. M. Towill Corporation, 1978, Feasibility study, Surface Water Impoundment/ Recharge Pearl Harbor Basin: conducted under U.S. Army Corps of Engineers contract no. DACW-84-78-C-0016.

U.S. Environmental Protection Agency, 1977, National secondary drinking water regulations: Federal Register, v. 42, no. 62, p. 17143-17147.

Visher, F. N., and Mink, J. F., 1964, Ground-water resources in southern Oahu, Hawaii, U.S. Geological Survey Water-Supply Paper 1778, 133 p.

Wentworth, C. K., 1951, Geology and ground-water resources of the Honolulu-Pearl Harbor area, Oahu, Hawaii: Board of Water Supply, City and County of Honolulu, Honolulu, Hawaii, 111 p.