NUMERICAL SIMULATION OF REGIONAL CHANGES IN GROUND-WATER LEVELS AND IN THE FRESHWATER-SALTWATER INTERFACE INDUCED BY INCREASED PUMPAGE AT BARBERS POINT SHAFT, OAHU, HAWAII

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 95-4206

Prepared in cooperation with the
U.S. DEPARTMENT OF THE NAVY,
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Numerical Simulation of Regional Changes in Ground-Water Levels and in the Freshwater-Saltwater Interface Induced by Increased Pumpage at Barbers Point Shaft, Oahu, Hawaii

By William R. Souza and William Meyer

ABSTRACT

The effect on the regional ground-water system of southern Oahu from increased pumpage at Barbers Point shaft was estimated by a numerical ground-water model developed for the Oahu Regional Aquifer Systems Analysis (RASA) study. The RASA model was updated by revising pumping and ground-water recharge data. Pumpage data used in the new simulations were based on the allocated pumping rates for 1995 as set by the State Commission on Water Resource Management. On the basis of numerical simulation, Barbers Point shaft can sustain a withdrawal rate of 4.34 million gallons per day without adversely affecting wells in the Waianae aquifer.

From results of numerical simulations, it is estimated that, as a result of increasing pumpage in Barbers Point shaft by 2 million gallons per day above the 1995-allocated rate of 2.337 million gallons per day, regional declines in ground-water levels will be about 0.4 to 0.7 feet throughout the Waianae aquifer and about 0.8 ft at the shaft. The corresponding rise of the freshwater-saltwater interface, as a result of declines in ground-water levels, is estimated to be about 20 to 30 feet. Numerical simulation also indicates that changes in ground-water levels greater than about 0.1 feet do not extend across either the Waianae-Koolau unconformity or the south Schofield barrier.

The model-estimated position of the freshwater-saltwater interface, as a result of additional pumpage, ranges from 500 to 860 feet below sea level in the southern and northern parts of the aquifer, respectively, and about 540 feet below sea level at the shaft. On the basis of an estimate of the thickness of the transition-zone, the freshwater lens would remain about 240 feet thick below the shaft. In addition, the estimated declines in ground-water levels throughout the aquifer are small compared with the thickness of the freshwater lens and these declines would not be expected to affect the yields of other wells in terms of quantity.

Chloride concentrations in the water pumped at Barbers Point shaft were about 240 milligrams per liter in 1992. The estimated background chloride concentration is 200 to 220 milligrams per liter because of low rainfall and the contamination of recharge water from natural salt accumulation in the soil. A reduction in irrigation through 1995 is expected to reduce recharge to the aquifer from irrigation-return water and chloride concentrations associated with the irrigation water throughout the Waianae aquifer. As a result of these combined effects, chloride concentrations of water pumped from the Barbers Point shaft will likely decrease, although the length of time required for this lowering is unknown.

INTRODUCTION

The aquifers in southern Oahu that lie south of the Wahiawa-Waialua district boundary and between the crests of the Waianae and Koolau Ranges (fig. 1), are the primary water supply for the island of Oahu, Hawaii. From the late 1800's through the early 1940's, the primary use of ground-water from this area was for irrigating sugarcane. As the population of Oahu increased

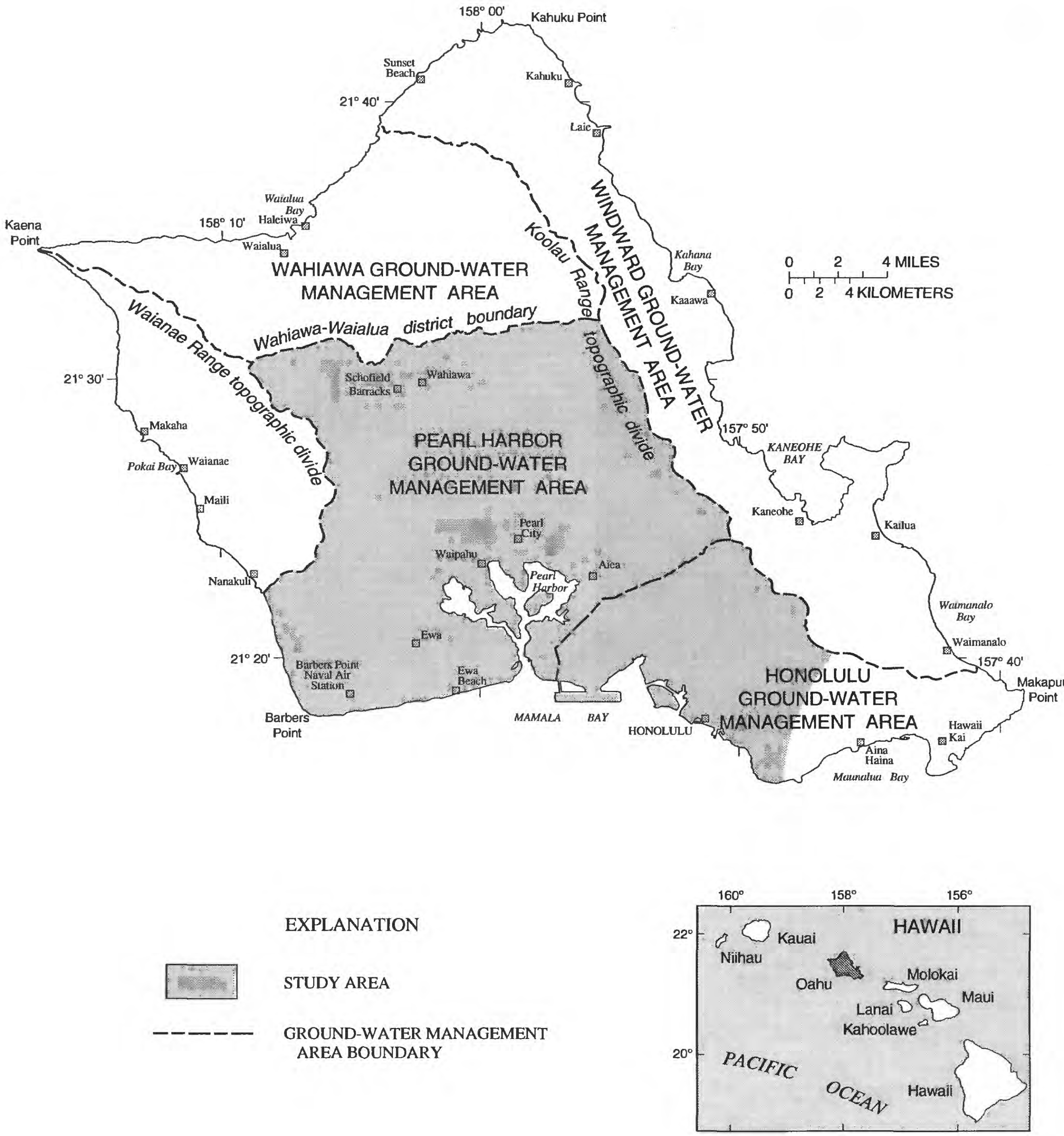


Figure 1. Island of Oahu and ground-water management areas designated by the State of Hawaii as of 1992.

after 1945, the rate of ground-water withdrawal also increased. In the late 1970's, because of concern for the long-term reliability of the ground-water supply, the State of Hawaii, Department of Land and Natural Resources designated areas where ground-water withdrawal is controlled. As of 1992, these areas on Oahu are the Pearl Harbor, Honolulu, Windward, and Wahiawa Ground-Water Management Areas (fig. 1). Any ground-water withdrawal in these areas more than that allocated requires approval by the State of Hawaii Commission on Water Resource Management.

Geohydrologically, Barbers Point shaft is located in the Waianae aquifer in the southern part of the central Oahu ground-water flow system (figs. 3*C* and 4). Using State nomenclature, the shaft is also located in the Ewa sector of the Pearl Harbor Ground-Water Management Area (fig. 1). The shaft is a single, horizontal water tunnel with a capacity of about 7 Mgal/d. Barbers Point shaft had an allocation of 2.337 Mgal/d in 1992 and supplied water to Barbers Point Naval Air Station.

The U.S. Department of the Navy, Naval Facilities Engineering Command, is proposing to increase pumpage from the Barbers Point shaft by 2 Mgal/d to meet a projected increase in water demand. Because of concern for the possible effects of increased pumpage at Barbers Point shaft, and in order to gain a better understanding of the geohydrology of southern Oahu, the U.S. Geological Survey (USGS), in cooperation with the U.S. Navy, conducted a study to estimate the effects of increased pumpage on regional ground-water levels, on the position of the freshwater-saltwater interface, and on potential changes in water quality at the shaft.

Purpose and Scope

This report describes estimates of regional changes in ground-water levels and in the freshwater-saltwater interface that could occur in the ground-water system of southern Oahu as a result of increasing ground-water withdrawal at the U.S. Navy's Barbers Point shaft from its 1995-allocated rate of 2.334 Mgal/d to 4.334 Mgal/d. Currently (1992) the Pearl Harbor Ground-Water Management Area is undergoing changes in water allocations, primarily as a result of changes in the amount of agricultural cultivation. Allocations stabilize in 1995 and thus the 1995 distribution and rates of pumpage were selected as representative of long-term conditions in southern Oahu. Changes in ground-water levels and in the freshwater-saltwater interface ultimately need to be evaluated at all locations of ground-water withdrawal affected by increased pumping at the shaft. For reference, the location of other points of ground-water withdrawal in the vicinity of Barbers Point shaft were identified, and information on these wells was collected, tabulated, and is discussed in this report.

An existing ground-water model, developed by the USGS for the Oahu Regional Aquifer Systems Analysis (RASA) study (Eyre and Nichols, in press) was modified and used to estimate regional changes in ground-water levels and in the freshwater-saltwater interface associated with increased pumpage at the shaft. Increased pumpage at the shaft could potentially result in chloride concentrations unacceptable for drinking. This model, although considered accurate for regional estimates, cannot precisely estimate changes on a small scale such as that at a single well. Thus, the estimates of changes in ground-water levels made by the model do not necessarily reflect the actual conditions in the immediate vicinity of the shaft.

The ground-water model used in this study treats the boundary between freshwater and saltwater as a sharp interface, although in reality a transition zone exists where salinity gradually increases with depth. The interface in the model represents the location in the transition zone represented by 50-percent freshwater and 50-percent saltwater. The entire transition zone moves upward in response to long-term declines in ground-water levels. Some data on the shape and movement of the transition zone in response to ground-water pumpage are available at several locations in southern Oahu. These data are discussed in this report to provide field information available on the movement of the transition zone in response to ground-water withdrawals. Most of the data are not from the immediate area of Barbers Point shaft; however, because of the similar hydrologic and geologic setting throughout southern Oahu, transition-zone characteristics also are probably similar.

This report also includes a discussion of the geohydrologic framework of southern Oahu, including the distribution and rates of existing and allocated ground-water withdrawals, ground-water levels, and trends in chloride concentrations: this information is included, if available, to provide a more complete description of the study area, and a better context in which to evaluate the modeling results. Because of its greater importance to this study, more detailed discussions are provided for the Waianae aquifer than for the Koolau aquifer. In order to follow previously published nomenclature, the

Koolau aquifer is divided into the Pearl Harbor area and Honolulu area for discussion of data in this report (fig. 4). These two areas have been discussed in greater detail by Wentworth (1951); Visher and Mink (1964); Mink (1980); Mink and others (1988); and Soroos and Ewart (1979).

Description of the Study Area

The study area of this report includes most of southern Oahu (fig. 4), from the crest of the Waianae Range on the west to the crest of the Koolau Range on the east, and north from the Wahiawa-Waialua district boundary, an approximate topographic divide, to the southern coastline. To the southeast, the study area ends at the Kaau rift zone. This area is the same as that used by Eyre and Nichols (in press) for developing the ground-water model of southern Oahu used in this report. The study area encompasses the entire Pearl Harbor Ground-Water Management Area and part of the Honolulu Ground-Water Management Area.

Well-Numbering System and Local Names

Well numbers in this report follow the State well-numbering convention for Hawaii. The well numbers contain seven digits based on a latitude-longitude one-minute grid system. The well numbers, for example that of Barbers Point shaft, 3-2103-03, consist of three parts separated by dashes. The first number is the island code: "3" identifies Oahu. The island code, common to all wells discussed, is not used in this report. The second four-digit number identifies the location of the one-minute grid block that contains the well. The first two digits are minutes of latitude and the second two digits are minutes of longitude of the southeast corner of the grid. The third two-digit number was assigned sequentially within the one minute grid from the oldest well to the newest.

Some of the wells discussed in this report are best known by their local names or old well numbers used before 1971 and will be referred to as such in this report when appropriate. These wells are Barbers Point shaft (well 2103-03); Ewa pumps 10, 11, and 12 (wells 2006-01 through -11); Waipahu pump 5 (well 2203-01 through -06); T-19 (well 2103-01); T-4 (well 2006-12); and T-20 (well 2103-02). All wells discussed in this report are listed in table 1 by State well number, old well number, and by local name.

Table 1. Well numbers and designations, southern Oahu, Hawaii

Well no.	Old well no.	Other well designation or local name
1748-11	T-86	Kaimuki monitor well
1749-22	25-1A	Kaimuki High School well
1851-02	83	none
1851-34	88-F	none
1851-57	T-85	Beretania monitor well
1905-01	T-79	none
1905-02	T-84	none
1905-03	275-4	none
1905-04	none	State de-salt well
1905-05	none	
2004-01	275	S. Fort Barrette well
2004-02	274-1	none
2004-03	274-2	none
2004-04	none	Makakilo well
2005-01	275-5	none
2006-01	276-A	Ewa pump 11
2006-02	276-C	Ewa pump 11
2006-03	276-D	Ewa pump 11
2006-04	276-E	Ewa pump 10
2006-05	276-F	Ewa pump 10
2006-06	276-G	Ewa pump 10
2006-07	276-H	Ewa pump 10
2006-08	276-J	Ewa pump 12
2006-09	276-K	Ewa pump 12
2006-10	276-B	Ewa pump 11
2006-11	276-I	Ewa pump 12
2006-12	T-4	none
2006-13	none	West Beach Golf Course
2006-14	none	Makakilo nonpotable
2006-15	none	Makakilo nonpotable
2101-03	266	none
2103-01	T-19	Honouliuli observation well
2103-02	T-20	none
2103-03	SH-14	Barbers Pt shaft
2103-04	none	Barbers Pt shaft monitor well
2104-01	none	none
2153-05	156	Moanalua monitor well
2203-01 to -06	274-A to -F	Waipahu pump 5
2256-10	187-B	none
2256-12	187-C	none
2300-10	244	none
2300-12	246-D	Waipahu deep monitor well
2300-18	241	none
2303-01, -02	none	Honouliuli 1 and 2
2303-03	none	Honouliuli 3
2303-04	none	Honouliuli 4
2303-05	none	Honouliuli 5
2303-06	none	Honouliuli 6
2303-07	none	Honouliuli monitor well
2358-02	201	Waipahu monitor well
2457-04	196-2	Punanani monitor well
2603-01	330-8	Hawaii Country Club
2659-01	none	Waipio monitor well
2703-01	330-5	Del Monte Kunia well

GEOHYDROLOGIC DESCRIPTION OF SOUTHERN OAHU

The island of Oahu is made up of two large shield volcanoes, the older Waianae Volcano to the west and the Koolau Volcano to the east (fig. 2). In central Oahu the volcanoes have merged and are separated by an erosional unconformity where the weathered slopes of the older Waianae Volcano are covered by the lava flows of the Koolau Volcano. These two volcanoes form two major aquifer systems, the Waianae and Koolau. Ground-water is found throughout most of the volcanic structure of the island. However, hydraulic continuity within each aquifer system, as well as between aquifers, is limited by numerous geologic features that form barriers to flow. These barriers impede the flow of water to various degrees and form areas with common hydrologic properties that are separated from the surrounding areas. Common types of barriers include the Waianae-Koolau unconformity, rift zones, and deeply eroded valleys filled with sediment. The principal geohydrologic barriers that govern the occurrence and movement of water on Oahu are shown in figure 3*A* and the resulting generalized patterns of ground-water movement are shown in figure 3*B*.

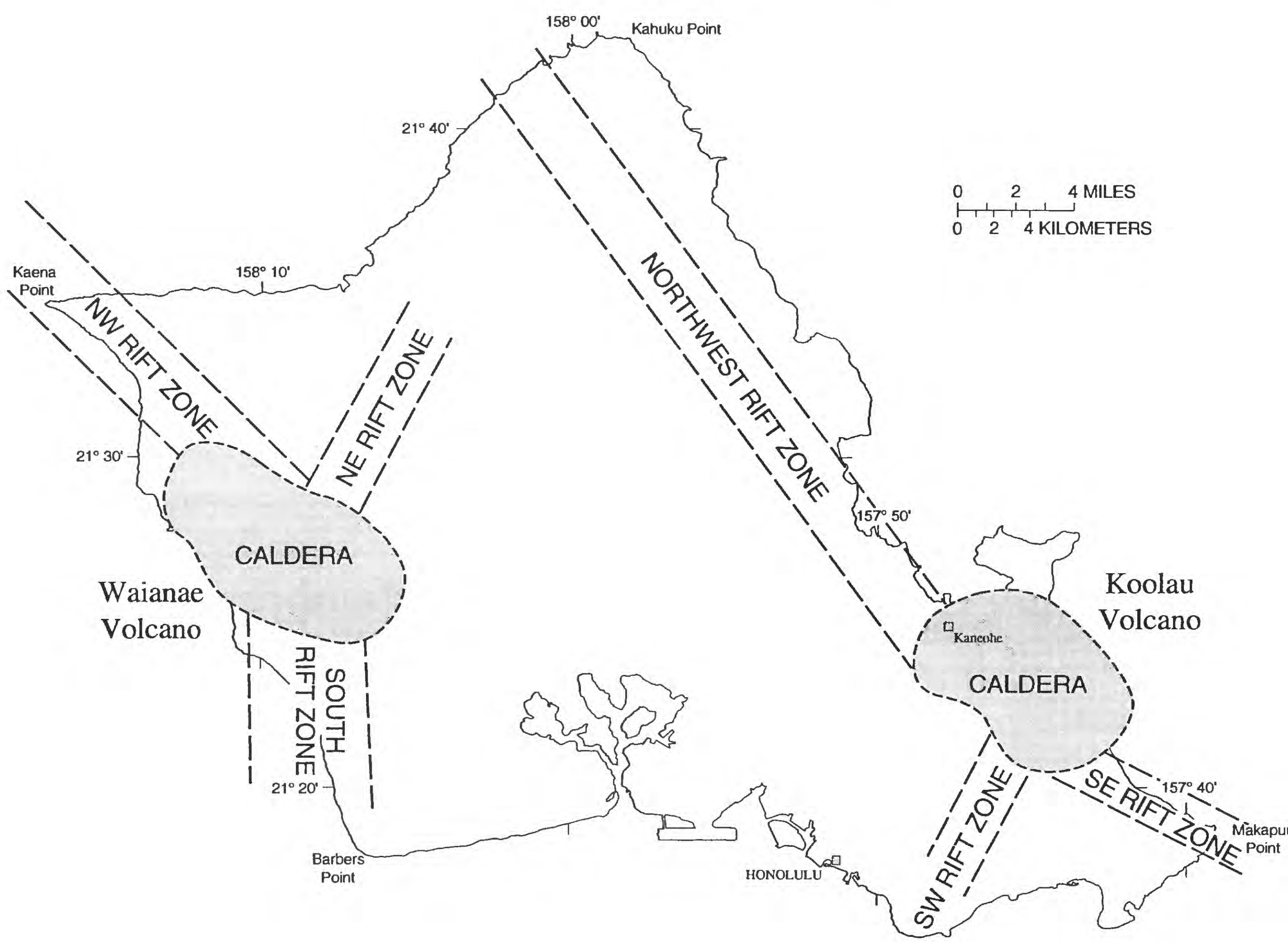


Figure 2. Major rift zones and caldera complexes of Oahu, Hawaii (modified from G. A. Macdonald, VOLCANOES © 1972, p. 377. Reprinted by permission of Prentice Hall, Englewood Cliffs, New Jersey).

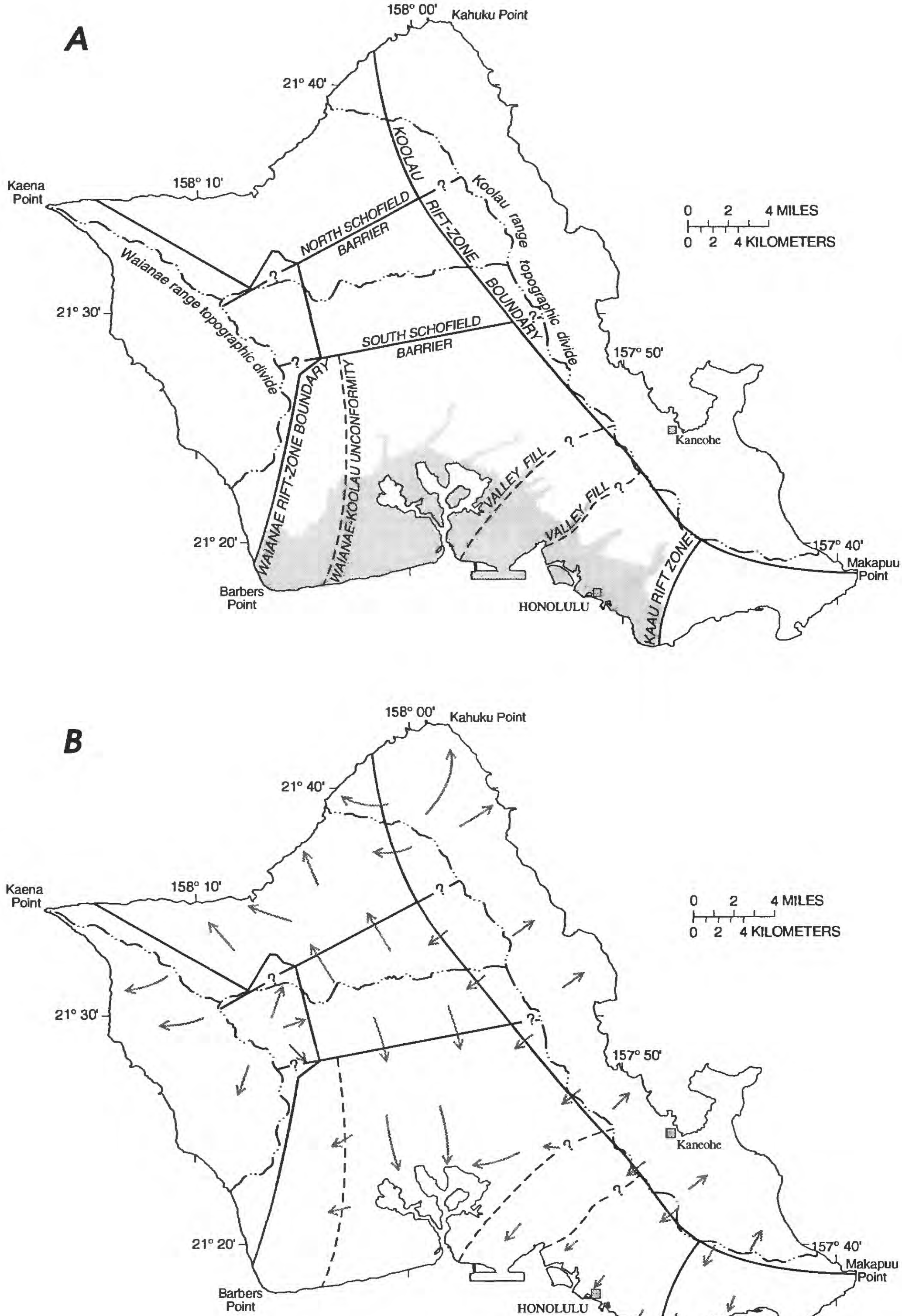
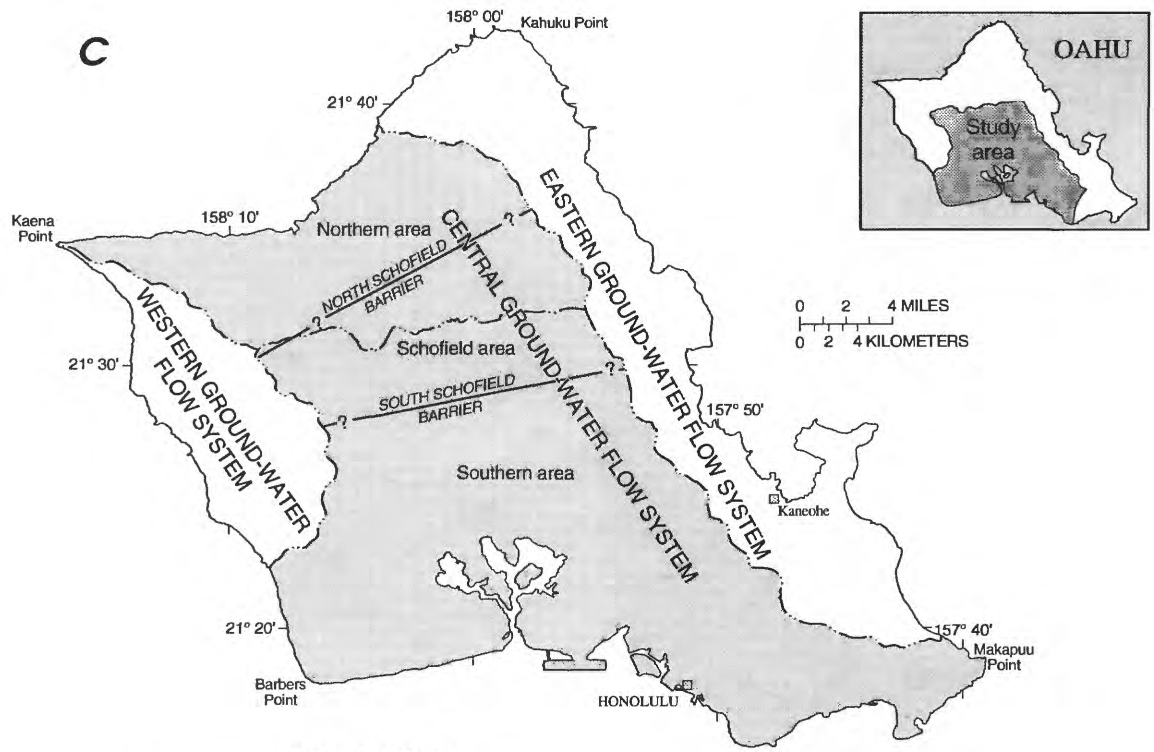


Figure 3. Ground-water flow on Oahu, Hawaii; ***A***, barriers to ground-water flow; ***B***, directions of ground-water flow; ***C***, the western, central, and eastern ground-water flow systems and the major areas within the central system.



EXPLANATION

SEDIMENTARY DEPOSITS (CAPROCK)

MAJOR GEOHYDROLOGIC BOUNDARY
Queried where questionable or by convention

SUBORDINATE GEOHYDROLOGIC BOUNDARY
Queried where questionable or by convention

DISTRICT BOUNDARY AND TOPOGRAPHIC DIVIDE

GENERALIZED DIRECTION OF GROUND-WATER FLOW

Two of the most effective hydrologic barriers on Oahu are the major rift zones of each volcano. The rift zones are elongate, deep-rooted structural features of the volcanoes and hydraulic stresses are not transmitted across them from one area to another (Hunt and others, 1988). Topographic highs along the mountain crests associated with the rift zones of these volcanoes separate the island into three major ground-water systems: the eastern, the western, and the central Oahu systems (C.D. Hunt, U.S. Geological Survey, written commun., 1992) (fig. 3*C*). The eastern system is in that part of the island east of the topographic divide along the Koolau rift zone. Ground water in this area is contained mainly in the Koolau aquifer. The western ground-water system is in that part of the island west of the topographic high along the Waianae rift zone. Ground water in this area is in the Waianae aquifer. The central Oahu ground-water system is that area of the island west of the topographic divide of the Koolau Range and east of the topographic divide of the Waianae rift zone. The Waianae and Koolau aquifers are located in this area.

The mountainous areas along the rift zones receive the highest precipitation on the island and correspondingly are the locations for most of the island's ground-water recharge by direct infiltration. Ground-water divides on Oahu generally coincide with topographic divides, so that ground water moves from the topographic divide of the mountainous areas of the two rift zones into central Oahu, to eventually flow either northward or southward to discharge into the ocean. The Wahiawa-Waialua district boundary, an approximate topographic divide for the central Oahu system, probably represents the approximate ground-water divide for water moving either to the north or to the south.

The most important of the three major ground-water systems is the central Oahu system. Within this system three major geohydrologic areas can be identified; the northern, southern, and Schofield areas (fig. 3*C*). The Schofield area is separated from the northern and southern areas by geologic features that create barriers and impede the northward and southward movement of ground water. These barriers, generally referred to as the north and south Schofield barriers, are of unknown origin. Ground-water levels in the Schofield area are about 250 ft higher than those immediately north and south of the two barriers. Water is known to move north and south from the Schofield area although the exact quantities are unknown.

The study area for this report is contained entirely within the southern part of the central Oahu ground-water flow system. Ground water is found primarily as basal water in the highly permeable, thin-bedded basaltic lava flows of the Waianae and Koolau aquifers. Basal water refers to a body of freshwater that floats on seawater within the aquifers. The basal water table generally is flat and lies a few feet to tens of feet above sea level. The areal extent of basal water extends to the south Schofield barrier to the north, the Waianae rift zone to the west, and the Koolau rift zone to the east. To the southeast several valley-fill barriers cause abrupt discontinuities in water levels and act as partial barriers to flow. The Kaau rift zone, farther southeast, generally is assumed to be a nearly impermeable barrier. The erosional unconformity that divides the basalts of the Waianae aquifer from the Koolau aquifer represents an important geohydrologic boundary on the west side. The unconformity is a partial barrier to ground-water flow and separates the two aquifers in southern Oahu. To the south, the aquifers are confined by a thick, extensive low-permeability wedge of sediment (referred to as "caprock") that overlies the basalt along the southern coast. This unit is a barrier that inhibits the free discharge of freshwater to the ocean and the free flow of saltwater into the basaltic aquifer.

Distribution and Rates of Ground-Water Pumpage

The locations of 96 pumping sites containing 103 wells in southern Oahu that had pumping allocations in 1992 are shown in figure 4. Most ground-water pumpage in the study area is from wells that are located in clusters along the southern coast of Oahu at low altitudes and near the discharge end of the two aquifers. In addition, the greatest concentration of wells and of pumpage is in the western side of the Pearl Harbor area where development was primarily for agricultural use, and along the eastern half of the Pearl Harbor area where development was primarily for domestic supply. Mean annual pumpage for all of the southern Oahu study area for 1902 through 1990 is shown in figure 5. For convenience in discussing pumpage, the annual total has been broken down by the aquifers and areas shown in figure 4. Details of the pumping trends are discussed separately for the Koolau and Waianae aquifers in the following sections.

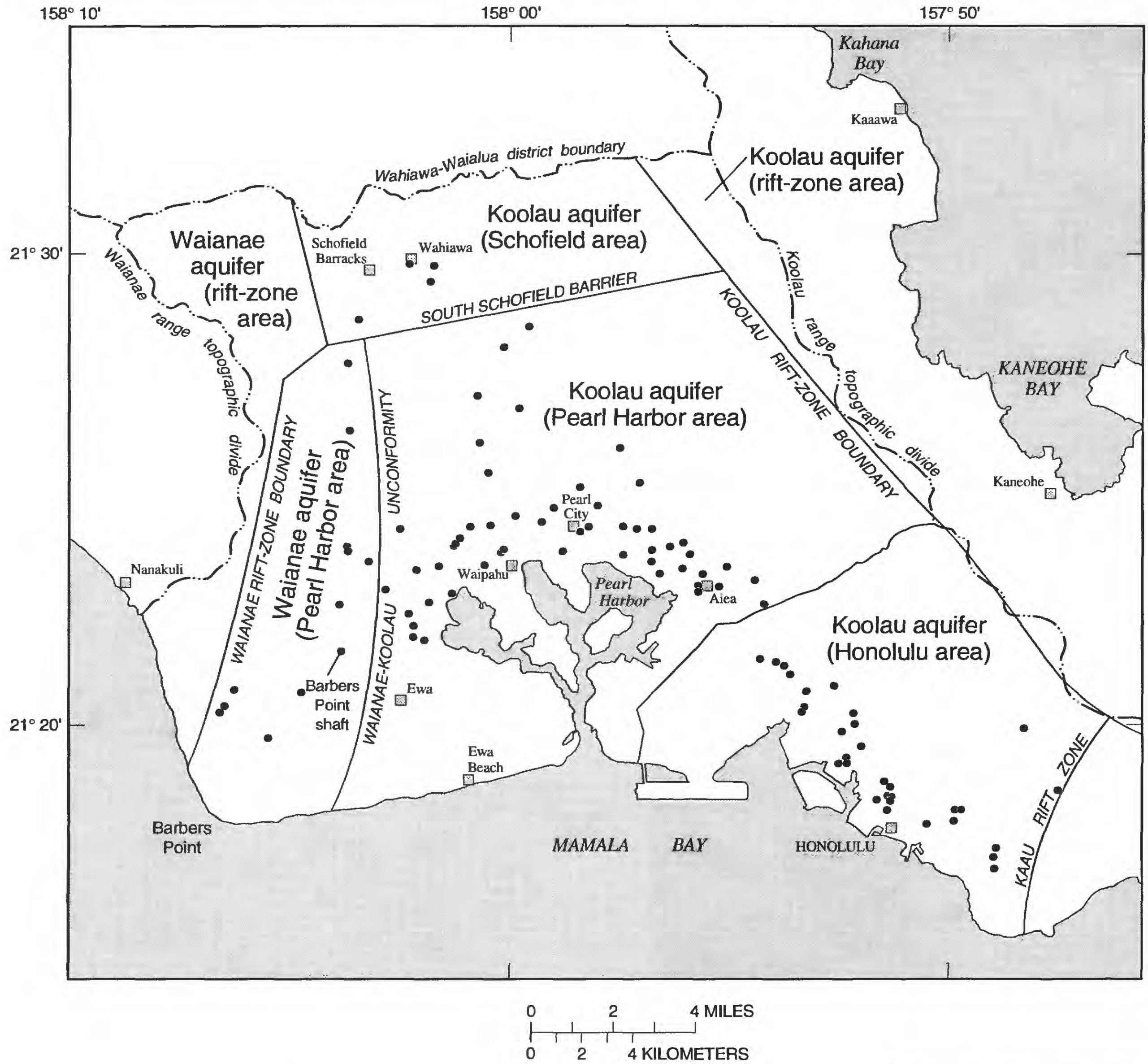
Koolau aquifer.--The withdrawal of ground water from the Koolau aquifer in southern Oahu increased from the early 1900's to the late 1970's, and most recently peaked at more than 290 Mgal/d in 1977 (fig. 5). Early development of ground water, from about 1900 through 1940, was mostly for agricultural supply and was concentrated in the western part of the Pearl Harbor area. After 1945, draft from the Koolau aquifer increased as a result of development and increased domestic demand. The sharpest increase was between 1960 and 1977. Since 1977, ground-water pumpage has declined because of a reduction of agricultural demand, which averaged about 205 Mgal/d in 1991. Most of the wells in southern Oahu are in the Pearl Harbor area of the Koolau aquifer (fig. 4), and, as shown in figure 5, the pumping history from this area dominates the long-term trends. Historically, the Honolulu part of the Koolau aquifer has followed the same pattern of pumpage, except for the decline in withdrawal after 1977. Since 1977, pumpage from the Honolulu area has remained steady.

Waianae aquifer.--The mean annual rates of ground-water withdrawal for the Waianae aquifer from 1905 through 1990 are shown in figures 5 and 6. Rates of ground-water withdrawal for selected individual wells or groups of wells are shown in figure 6. Until the last several years, most of the ground water pumped from the Waianae aquifer has been used to irrigate sugarcane. Sugar companies commonly have used manifolds to connect a group of wells within a small area to one large pump. Therefore, pump numbers such as Ewa pump 10 and Waipahu pump 5 are commonly referred to rather than individual well numbers.

Historically, the highest rates of ground-water production have been at two locations: in the southwestern part of the aquifer where the battery of wells at Ewa pumps 10, 11, and 12 is located (fig. 7), and in the more centrally located area where the battery of wells at Waipahu pump 5 is located. Ground water pumped at these two locations has represented 80 percent or more of the total pumpage from the aquifer for any given year. Some of the wells in these two areas are the deepest in the aquifer, reaching depths of about 240 ft below sea level.

Ground-water pumping began in 1905 at Waipahu pump 5 (fig. 6). The average annual rate of withdrawal from the pump was 7 Mgal/d. Pumpage from the Waianae aquifer remained below 10 Mgal/d until 1909 when the combined pumpage from Waipahu pump 5 and Ewa pump 10 (which came into use in 1908) exceeded 10 Mgal/d on an average annual basis. The average annual rate of withdrawal reached almost 20 Mgal/d in 1915. Annual withdrawal rates generally were within a few million gallons per day of this rate until 1939, after which withdrawal rates exceeded 20 Mgal/d in all but one year (1958) until 1983. Ground-water production from the aquifer began falling in 1981. In 1990, average annual ground-water production was below 10 Mgal/d for the first time since 1908. The period of highest ground-water pumpage was from 1966 through 1981 during which average annual ground-water withdrawal generally exceeded 30 Mgal/d.

Allocated pumpage.--Pumpage within a ground-water management area is allocated by the Hawaii Commission on Water Resource Management by assigning a water-use permit on a well-by-well basis. The 1995-allocated distribution for the Waianae aquifer is given in table 2 and well locations are shown in figure 7. Allocated rates of ground-water pumpage for the Waianae aquifer vary by year from 1989 through 1995 (table 3). The total allocated pumpage for the Waianae aquifer in 1992 was 18.267 Mgal/d. Allocation is scheduled to be reduced to 15.821 Mgal/d in 1995 after which rates stabilize through the year 2005. The reduction in allocated rates from 1990 through 1995 is a result of a reduction in allocation for agricultural purposes. Year-by-year allocated rates and the State of Hawaii's estimates for the aquifer's sustained yield for the period 1989 through 2005 are given in table 3.



EXPLANATION

• WELL WITH PUMPAGE ALLOCATED IN 1992

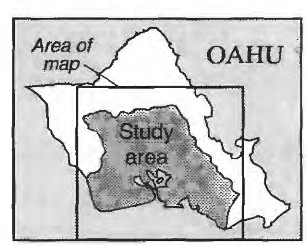


Figure 4. Aquifers and aquifer areas and locations of all wells with allocated pumpage in 1992 in southern Oahu, Hawaii.

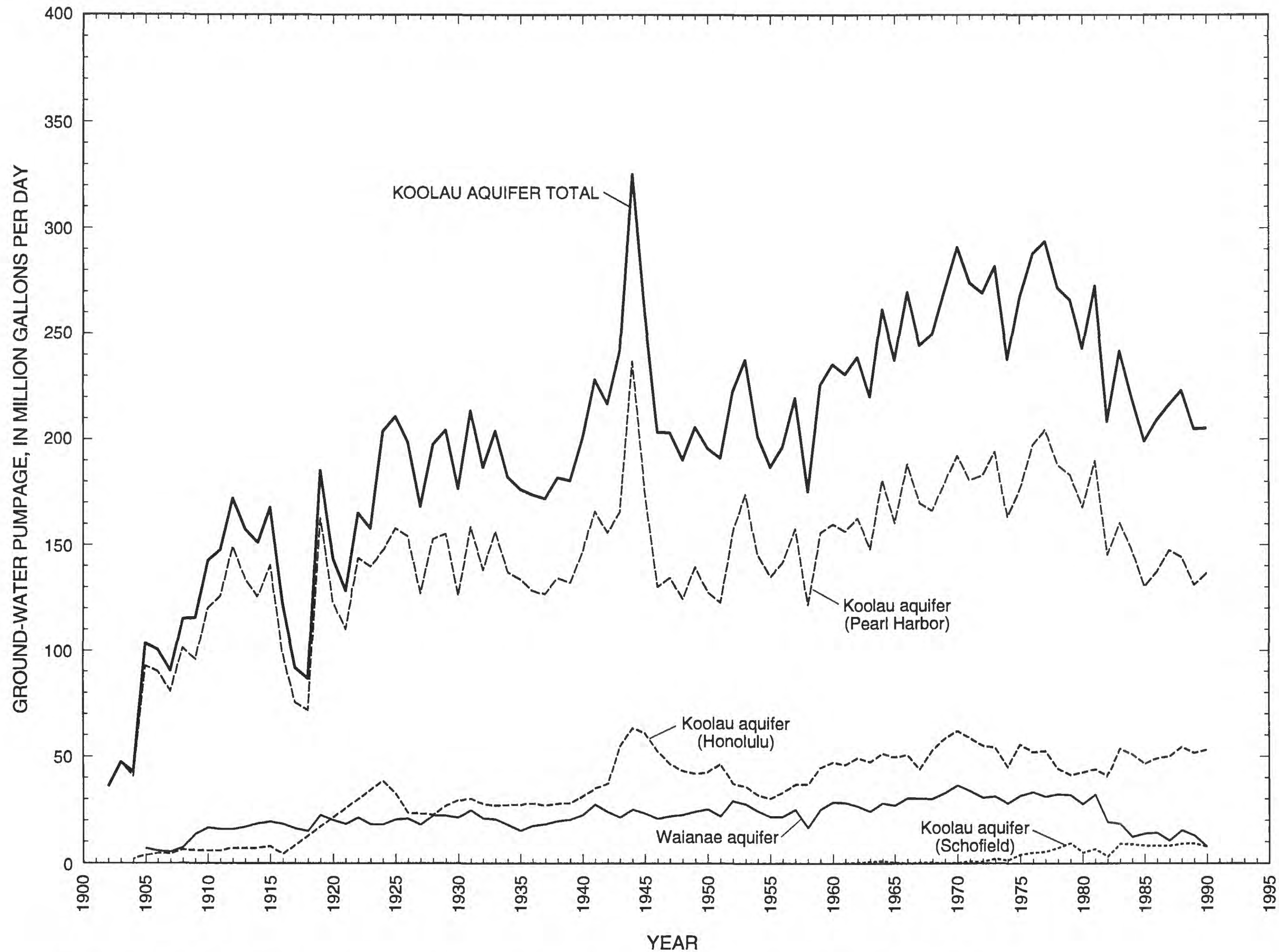


Figure 5. Mean annual ground-water pumpage in the Koolau and Waianae aquifers, southern Oahu, Hawaii, 1902–90.

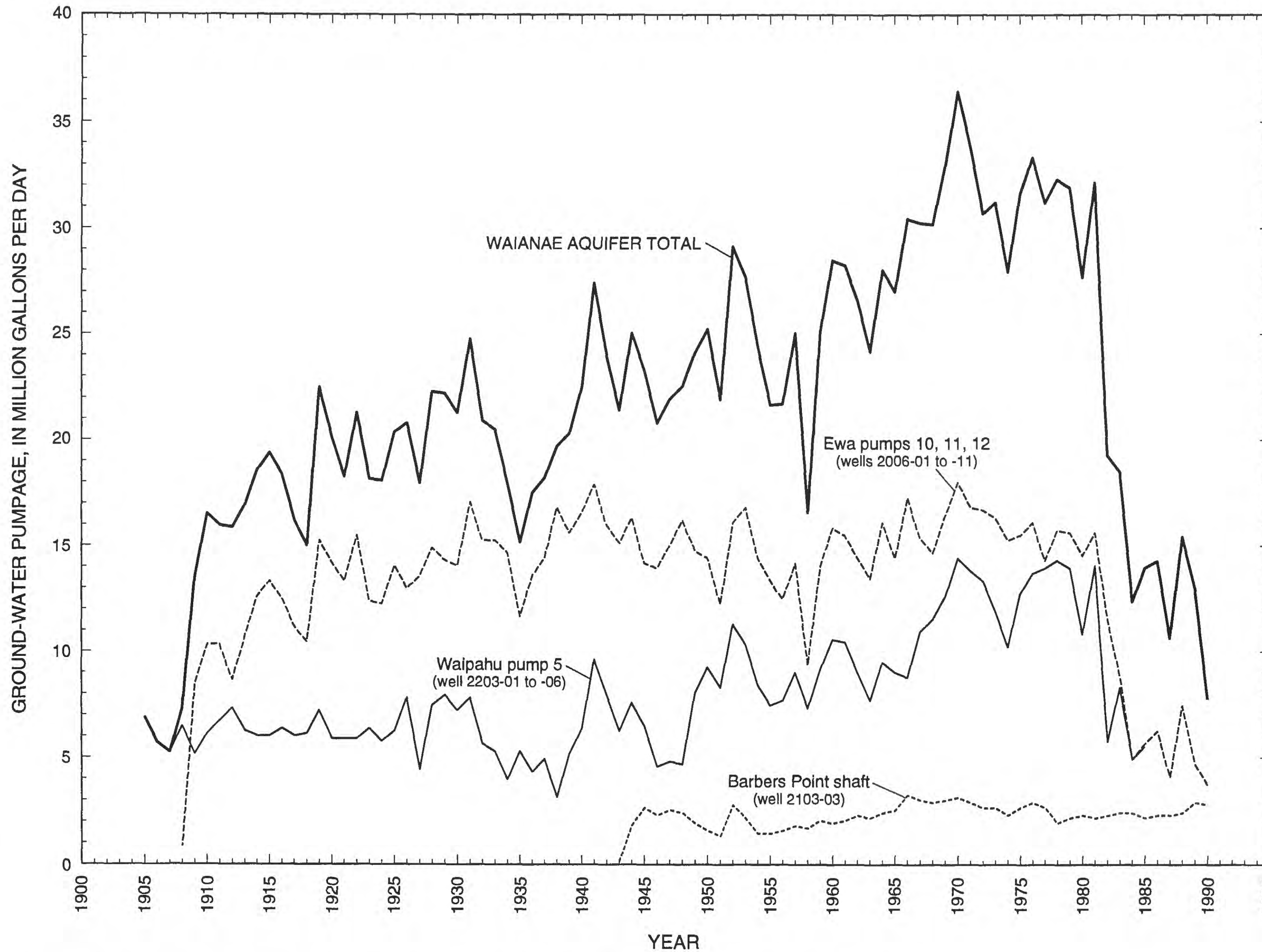
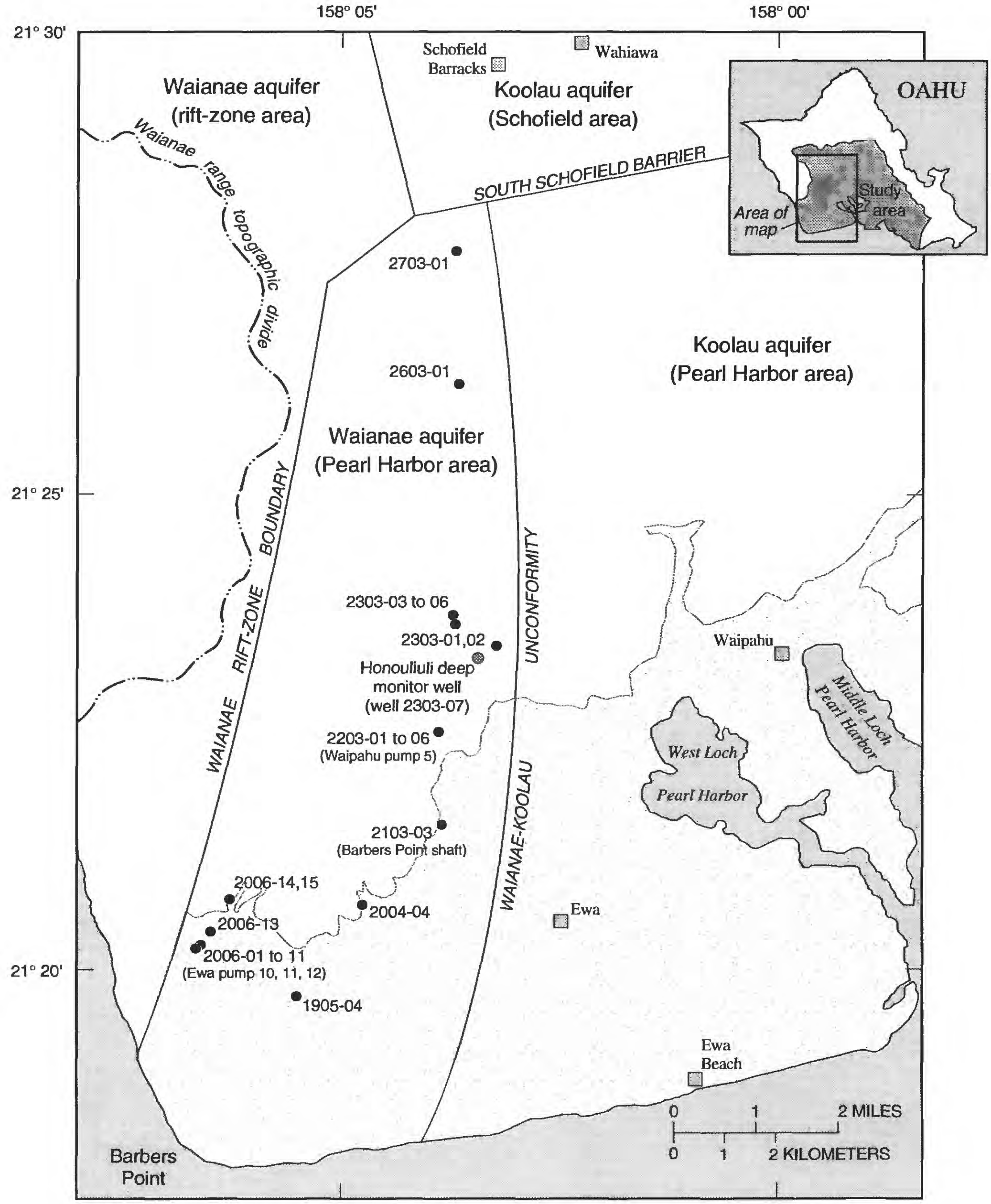


Figure 6. Mean annual ground-water pumpage in the Waianae aquifer, southern Oahu, Hawaii, 1902–90.



EXPLANATION

SEDIMENTARY DEPOSITS (CAPROCK)

2404-04 ● PUMPING WELL AND NUMBER

Figure 7. Waianae aquifer and locations of pumping wells (1990) and Honouliuli deep monitor well in southwestern Oahu, Hawaii.

Table 2. 1995-allocated ground-water pumpage for wells in the Waianae aquifer, Oahu Hawaii
[Data from Hawaii Commission on Water Resource Management; Mgal/d, million gallons per day]

Well	Other well designation	1995 allocation (million gallons per day)
2004-04	Makakilo	1.500
2006-14, -15	Makakilo nonpotable	1.000
2303-01, -02	Honouliuli 1 and 2	2.240
2303-03, -04	Honouliuli 3 and 4	2.240
2303-5	Honouliuli 5	1.120
2303-6	Honouliuli 6	1.120
2006-01-11	Ewa pumps 10, 11, 12	2.564
2203-01-06	Waipahu pump 5	0
2103-03	Barbers Point shaft	2.337
1905-04	State de-salt	1.000
2006-13	West Beach Golf Course	0.700
2603-01	Hawaii Country Club	[a]0.220
2703-01	Del Monte Kunia	[a]0.154
	Total............	16.195

[a]Located in Koolau aquifer by Hawaii Commission on Water Resource Management; is not included in table 3 allocation for 1995.

Table 3. Sustainable yield and allocated pumpage, Waianae aquifer, Oahu, Hawaii, 1989-2005
[Data from Hawaii Commission on Water Resource Management; values are in million gallons per day]

Year	Sustainable yield	Allocation
1989	23	17.237
1990	23	21.957
1991	20	19.347
1992	20	18.267
1993	20	18.267
1994	20	18.267
1995	20	15.821
1996	20	15.821
1997	20	15.821
1998	20	15.821
1999	20	15.821
2000	20	15.821
2001	20	15.821
2002	20	15.821
2003	20	15.821
2004	20	15.821
2005	20	15.821

A comparison of these allocations with historical distribution and rates of ground-water withdrawal indicates that the allocated pumpage is lower than average annual rates for most of the period of record from 1918 through 1992, and that the allocated pumpage is more evenly distributed through the aquifer than before. Historically, most of the water pumped from the Waianae aquifer has been from the southwestern part of the Pearl Harbor area at Ewa pumps 10, 11, and 12. Combined mean annual pumpage from these three pumps usually has exceeded 10 Mgal/d and has been as high as 18 Mgal/d. Pumpage at Ewa pump 10 in 1992 was 5.01 Mgal/d. In 1995, the allocation at Ewa pump 10 will be reduced to 2.6 Mgal/d. Allocations for Ewa pumps 11 and 12 are combined with Ewa pump 10. Pumpage at Waipahu pump 5 was the second highest in the aquifer for most of the period of record. For the last 35 years this pumpage usually has equaled or exceeded 8 Mgal/d and has been as high as 14 Mgal/d. Before 1992, the allocated pumpage for Waipahu pump 5 was 4.5 Mgal/d. In 1995, the allocation will be reduced to zero.

Ground-Water Levels

Ground-water levels have been measured nearly continuously at scattered locations throughout southern Oahu since the start of agricultural pumping in 1890. Locations of wells with water-level data discussed in the following sections are shown in figure 8 and well numbers are listed in table 4.

Koolau aquifer.--Ground-water levels in the Koolau aquifer have been declining since development began in the 1880's (Soroos and Ewart, 1979). Using five wells with long-term monthly measurements, Soroos and Ewart (1979) showed that average water levels in the Pearl Harbor area declined 0.09 ft/yr from about 1910 through 1979. For this study, water-level data for four of these wells have been updated and are shown in figure 9. Well 2300-10 has not been measured since 1978 because of inaccessibility. Data for this well were updated using water-level data from nearby wells to estimate the trend near well 2300-10 from 1978 to 1992. To extend the coverage of southern Oahu, additional water-levels for the Honolulu area (at well 1851-02) are also shown. Water levels fell to all-time lows in the late 1970's throughout the Koolau aquifer. As previously discussed, pumpage has declined as a result of reduced agricultural demand. In general the water levels have stabilized and have had no further downward trend in the data since 1970.

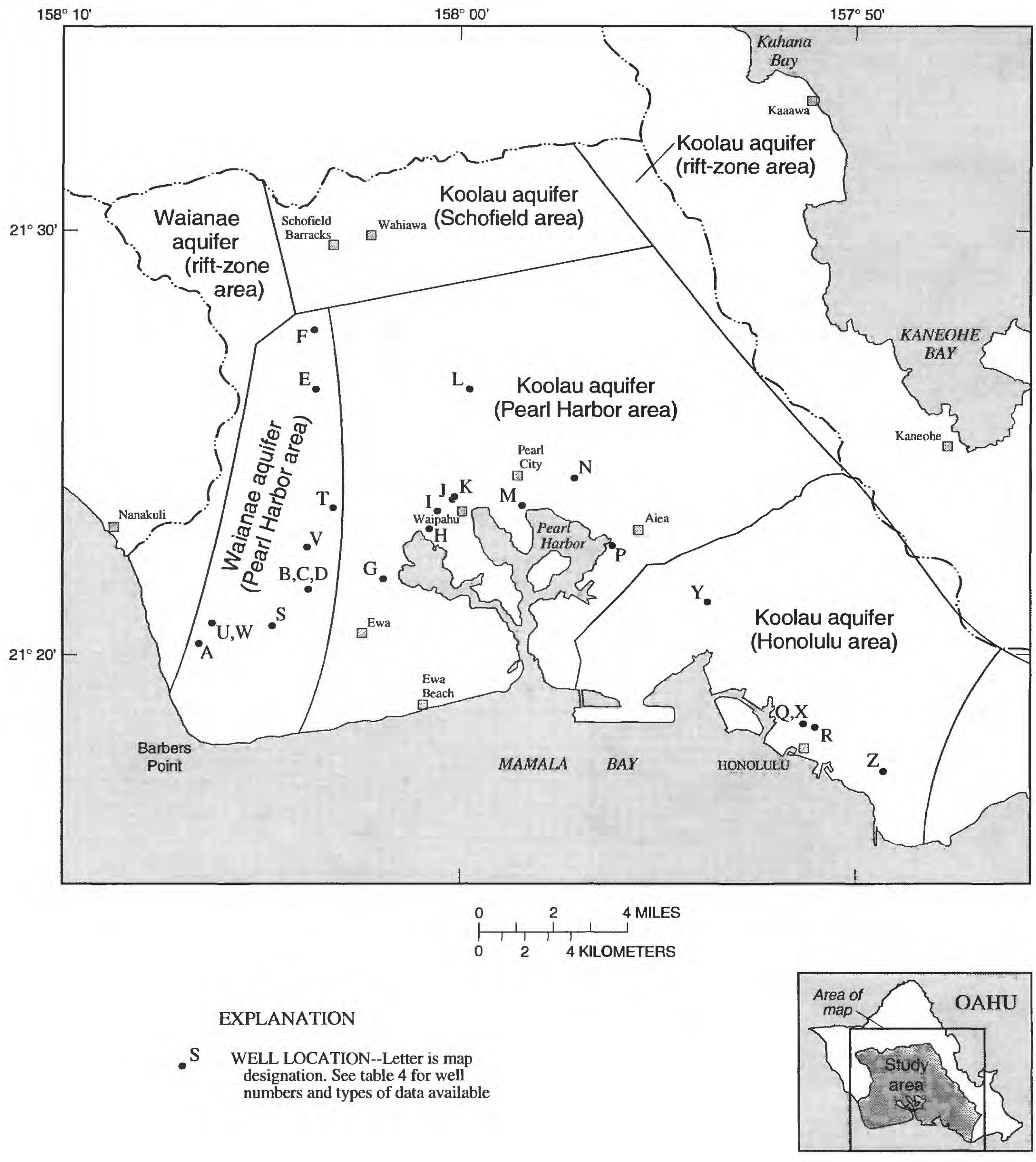


Figure 8. *Locations of selected wells and deep monitoring wells in southern Oahu, Hawaii, for which water-level or chloride-concentration data are available.*

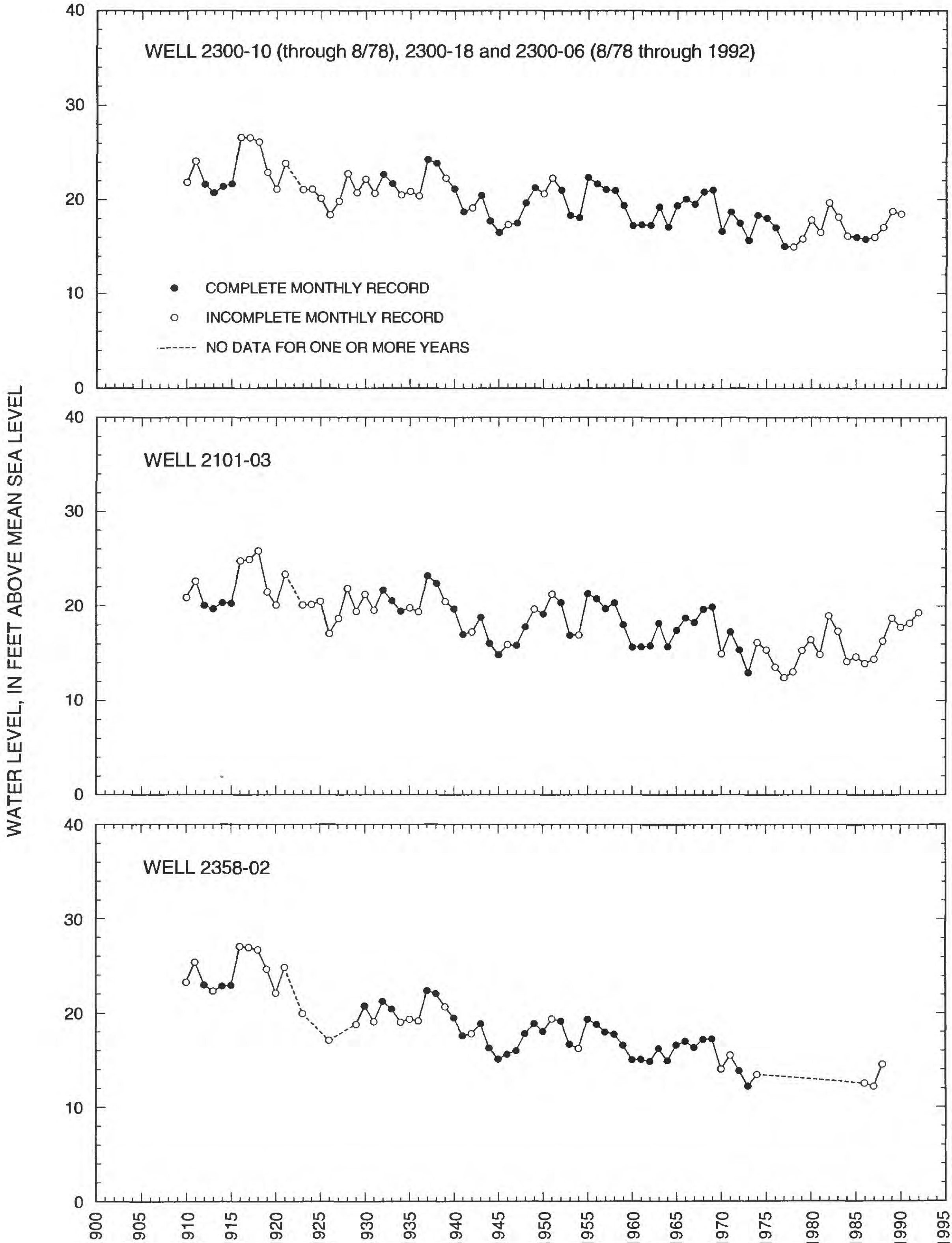


Figure 9. Annual mean water levels in selected wells in the Koolau aquifer, Oahu, Hawaii, for various periods of record, 1910-92.

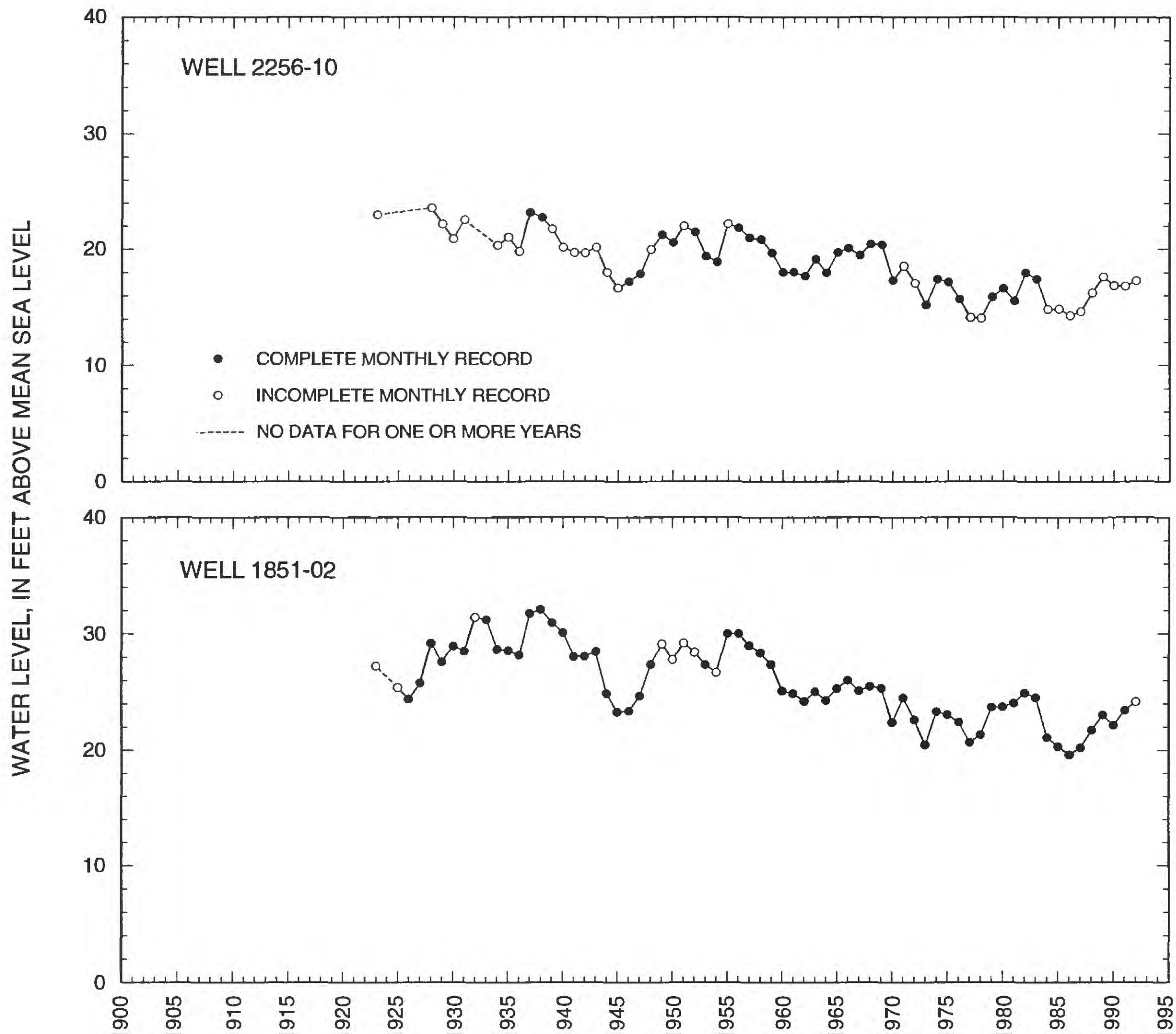


Figure 9. Annual mean water levels in selected wells in the Koolau aquifer, Oahu, Hawaii, for various periods of record, 1910-92--Continued.

Table 4. Selected wells in southern Oahu, Hawaii, and types of data available

[--, not applicable]

Map designation (fig. 8)	Well no.	Old well number or other well designation
Wells with water-level data		
A	2006-04 to 07	Ewa pump 10
B	2103-01	T-19
C	2103-03	Barbers Point shaft
G	2101-03	--
I	2300-10	--
J	2300-18	--
M	2358-02	Waipahu monitor
P	2256-10	--
R	1851-02	--
V	2203-01 to 06	Waipahu pump 5
W	2006-12	T-4
Wells with chloride-concentration data		
A	2006-01 to 09	Ewa pumps 10, 11, 12
B	2103-01	T-19
D[1]	2103-04	--
E	2603-01	Hawaii Country Club
F	2703-01	Del Monte Kunia
G	2101-03	--
I	2300-10,12	--
L[1]	2659-01	Waipio monitor
M[1]	2358-02	Waipahu monitor
N[1]	2457-04	Punanani monitor
P	2256-10,12	--
Q[1]	1851-57	Beretania monitor
R	1851-34	--
S	2004-04	Makakilo
T	2303-01,02	Honouliuli 1 and 2
T[1]	2303-07	Honoluliuli monitor
V	2203-01	Waipahu pump 5
W	2006-12	T-4
Y[1]	2153-05	Moanalua monitor
Z[1]	1748-11	Kaimuki monitor
Z[1]	1749-22	Kaimuki High School

[1]Well designed to measure transition-zone chloride concentratiion

Waianae aquifer.--Locations for which water levels are available in the Waianae aquifer are limited, spatially and temporally. It is not possible to construct an accurate synoptic configuration of ground-water levels for any period of time, nor is it possible to determine the long-term trend in water levels over the entire aquifer. Ground-water levels in the Waianae aquifer have not been consistently monitored through time at any well since pumping started. Hydrographs are available for five wells and are shown in figure 10. Water levels for Ewa pump 10 extend for the longest time: from 1909 through 1971. Records for T-19 (well 2103-01) represent the second longest period, from 1953 through 1992, although there is no record for the period 1967 through 1971. Water levels were recorded for various lengths of time in Waipahu pump 5 (1926 through 1956), well T-4 (1953 through 1972) and Barbers Point shaft (1973 through 1985). In 1992 the only wells in which water levels were regularly measured were T-19, T-4, and T-20 (well 2103-02).

Regardless of their period of record, when the hydrograph for one well is overlayed on the hydrograph of another for overlapping time periods, the trend in water levels among all wells is consistent. Water levels at Ewa pump 10 were initially about 17 ft in 1909, one year after pumping began at Ewa pump 10 and four years after pumping began at Waipahu pump 5. In 1971, when the last measurement was made, the water level was about 12 ft. Water levels had fallen to near 12 ft in 1944, after which they stayed between 12 and 13 ft. Thus the 5 ft drop in water levels occurred between 1909 and 1944, although the drop was not continuous during this time period. The water level at T-19 usually was between 16 to just above 17 ft from 1953 through 1966 showing the same relatively stable trend shown in Ewa pump 10 during this time. The next period of record for this well begins in 1972. From 1972 through 1992, water levels have were mostly between 15 and 16 ft (1 ft lower than 1953 through 1966), although they rose from 15 to 16.5 ft since 1985.

Water levels in well T-4 are available for 1953 through 1971 and the hydrograph for this well reflects the same stable period shown at Ewa pump 10. Water-level data for Waipahu pump 5 are limited, but the data closely correspond to hydrograph trends at Ewa pump 10 for 1926 through 1957. Finally, the water-level data at Barbers Point shaft available from 1973 through 1986 show nearly the same changes as that of well T-19 for the same time. Given their physical proximity, this would be expected.

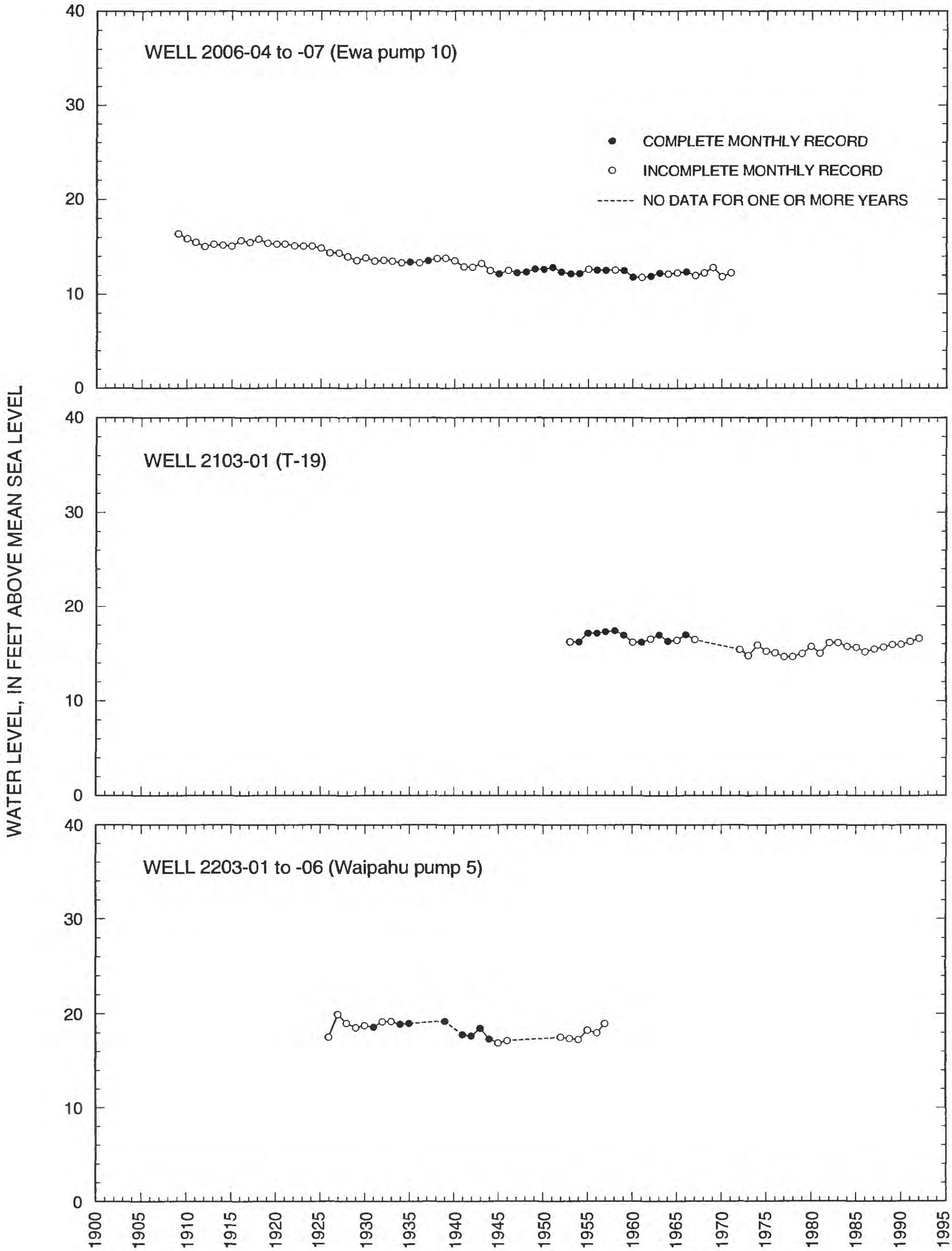


Figure 10. Annual mean water levels in selected wells in the Waianae aquifer, Oahu, Hawaii, for various periods of record, 1909-92.

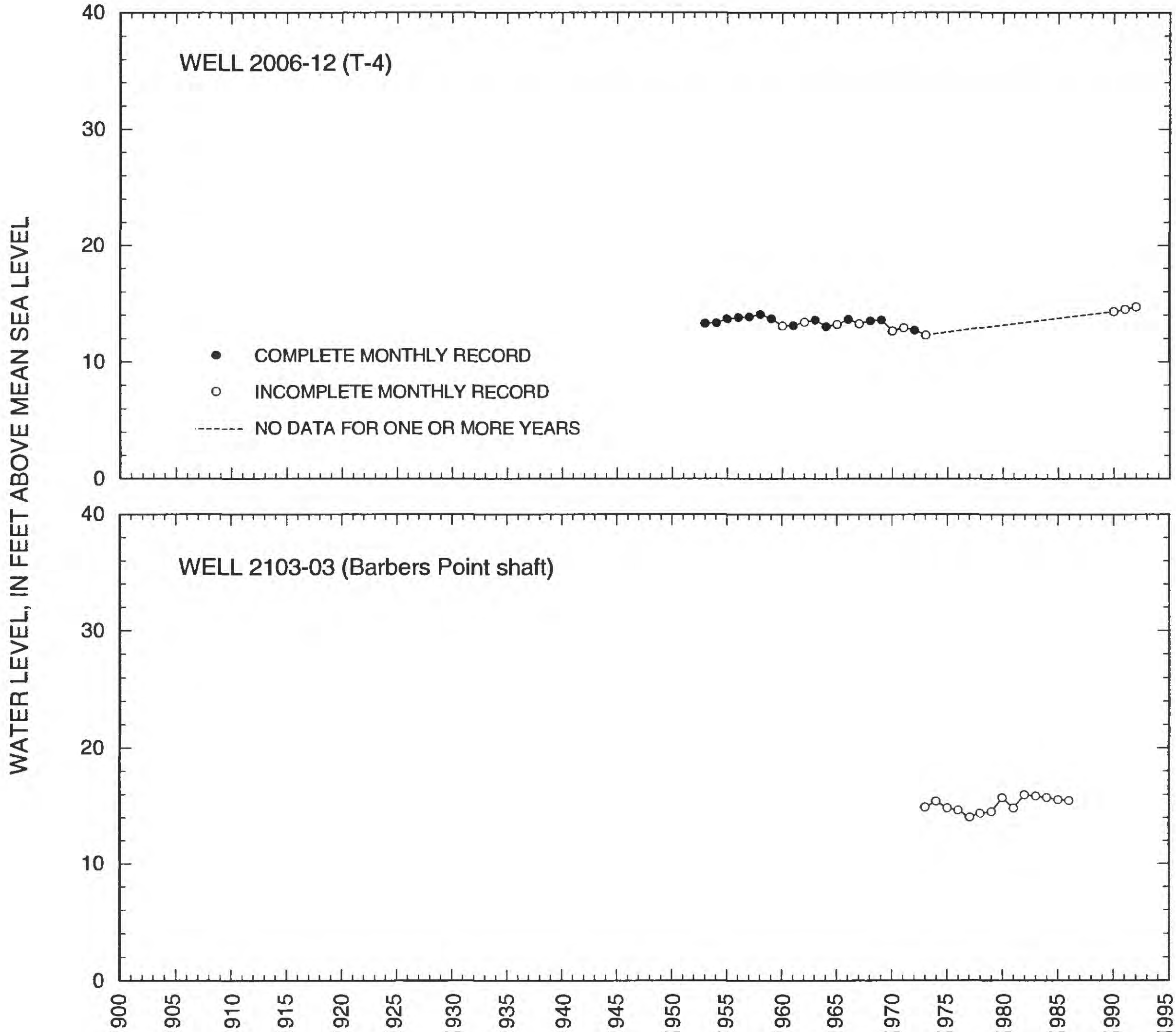


Figure 10. Annual mean water levels in selected wells in the Waianae aquifer, Oahu, Hawaii, for various periods of record, 1909-92--Continued.

The lowest ground-water level in the Waianae aquifer was that measured at Ewa pump 10 when the water level was between 12 and 13 ft during 1944 through 1971; however, water levels were below 12 ft for short periods during this time. The highest water levels were measured at T-19, more than 3 mi northwest of Ewa pump 10, were about 18 ft in 1957.

The rates of ground-water pumpage in the Waianae aquifer have not been uniformly distributed over space and time. However, the similarity of trends in the hydrographs, although for different periods of time, is significant. This indicates that the system, at least in the area of the wells just discussed, responds similarly to the magnitude of hydrologic stress that the aquifer has been subjected to.

Chloride-Concentration Data

Koolau aquifer.--In the Koolau aquifer, relatively long-term chloride-concentration data are available from five wells. Graphs of the annual means of monthly chloride concentrations of these wells are shown in figure 11. For this study, the data for these wells have been updated to about 1992. For those wells where data collection had stopped, data from nearby wells are used to estimate trends from the end of data collection to 1992.

Well 2101-03 shows no significant trends throughout the record. Well 2300-10 shows no significant trend; however, a slight continuing rise in chloride concentration is evident beginning in the 1950's. Well 2358-02 showed a significant rise in chloride concentrations from 1911 through 1970. However, the record since 1970 cannot be properly evaluated because of erratic data. Well 2256-10 shows no significant trends, although a slight rise since 1976 can be noted. Well 1851-34 also shows no significant trends throughout the record. A slight rise between 1960 and 1970 separates two stable periods in the record.

Waianae aquifer.--Nine locations in the Waianae aquifer have relatively long-term (10 years or more) records of chloride-concentration data (figs. 12 and 13. These locations are uniformly distributed throughout the aquifer, but other factors offset this potential advantage with regard to the scientific utility of the data. With the exception of two wells, T-19 and T-4, all of the data are from pumping wells (or as with the Ewa and Waipahu pumps, from a group of wells) with different rates of ground-water withdrawal and for which construction details, including well depth, are variable. Well T-19 near Barbers Point shaft is the only observation well in the Waianae aquifer for which ground-water levels and chloride concentrations are concurrently available. However, the period of time with concurrent data, 1953 through 1967, is limited. T-19 is a shallow well, which precludes obtaining information on the variation in chloride concentration with depth. Before the new observation well was drilled near Barbers Point shaft for this study, no site was available in the Waianae aquifer where profiles could be obtained of chloride concentrations as related to depth. Finally, the data collected at all of the nine sites were not collected at standard time intervals so that records are commonly incomplete.

Evaluating trends in chloride concentration in the aquifer from the available data at individual wells is difficult. Water from a single pumped well or from a group of wells with a single pump represents a composite sample of the water in the vicinity of that well or group of wells. Thus, the data, rather than representing a single point, represent the column of water being pumped. If pumping was at a constant rate, changes in chloride concentration of this water could provide valuable data on aquifer trends, assuming no other pumping affected the well. However, pumping has not been constant. Different pump rates draw water from different depths. Even shallow systems, such as the Barbers Point shaft, draw water from depth below the pumps. In addition, wells are affected by other pumping wells throughout the aquifer. Because of these problems, only the trend in chloride concentration at a well or pump can be described. In addition, the trend would indicate only local conditions and thus the data cannot be used to interpret aquifer trends away from the wells. Despite these limitations, some conclusions are possible. The two wells in the northern part of the Waianae aquifer (wells 2603-01 and 2703-01) have, for their respective periods of record, consistently shown chloride concentrations that are about 50 mg/L or less. Well 2703-01 was monitored from 1950 through 1977 and well 2603-01 has been monitored since 1972. The wells, at depths of 129 and 246 ft below the water table, respectively, are shallow relative to the estimated position of the freshwater-saltwater interface. The water produced from the wells probably represents some average of the column of water being pumped below the well. Thus, at least for their respective periods of record, chloride concentrations in the general vicinity of those wells probably were low.

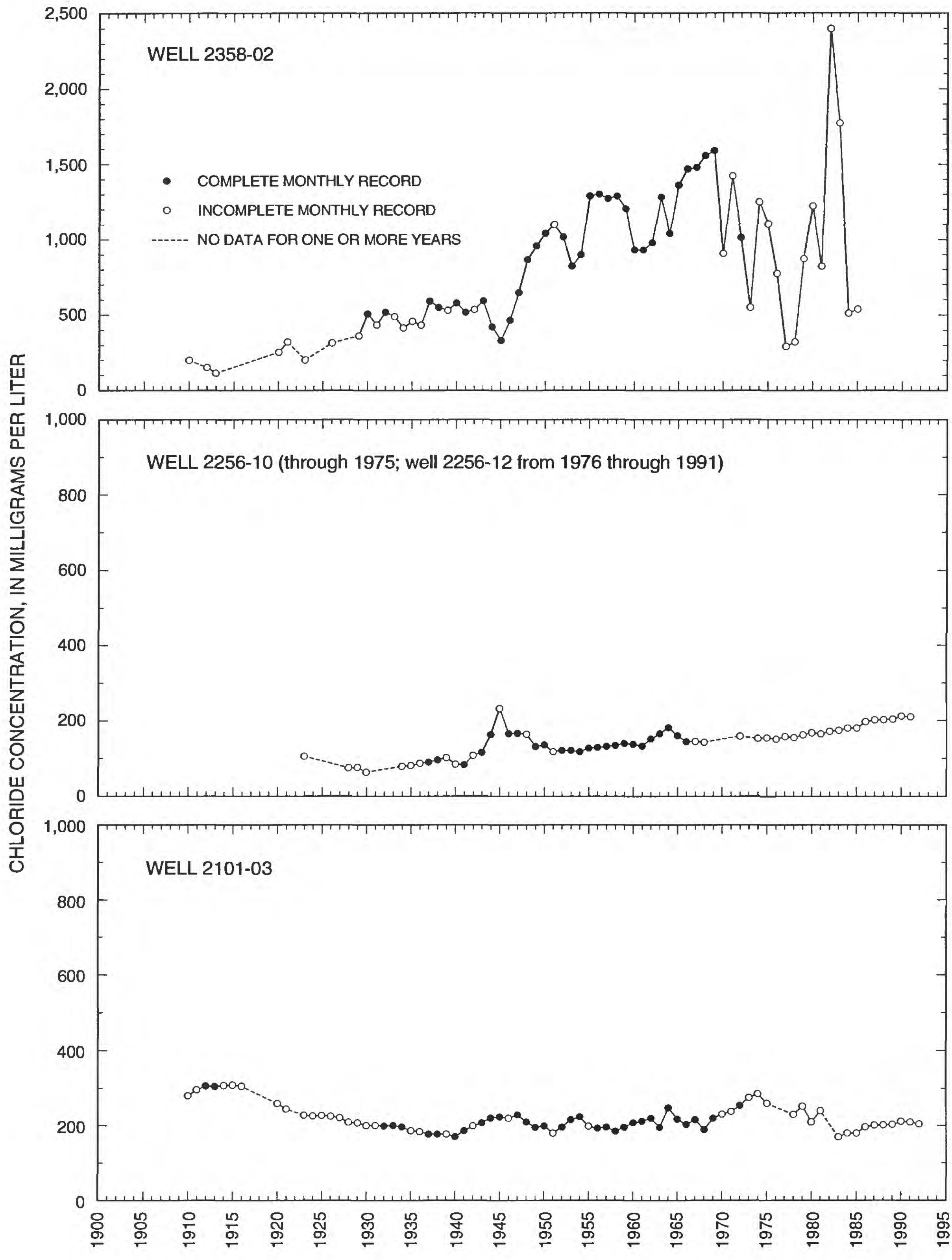


Figure 11. Annual mean chloride concentrationsof water in selected wells in the Koolau aquifer, Oahu, Hawaii, for various periods of record, 1910-92.

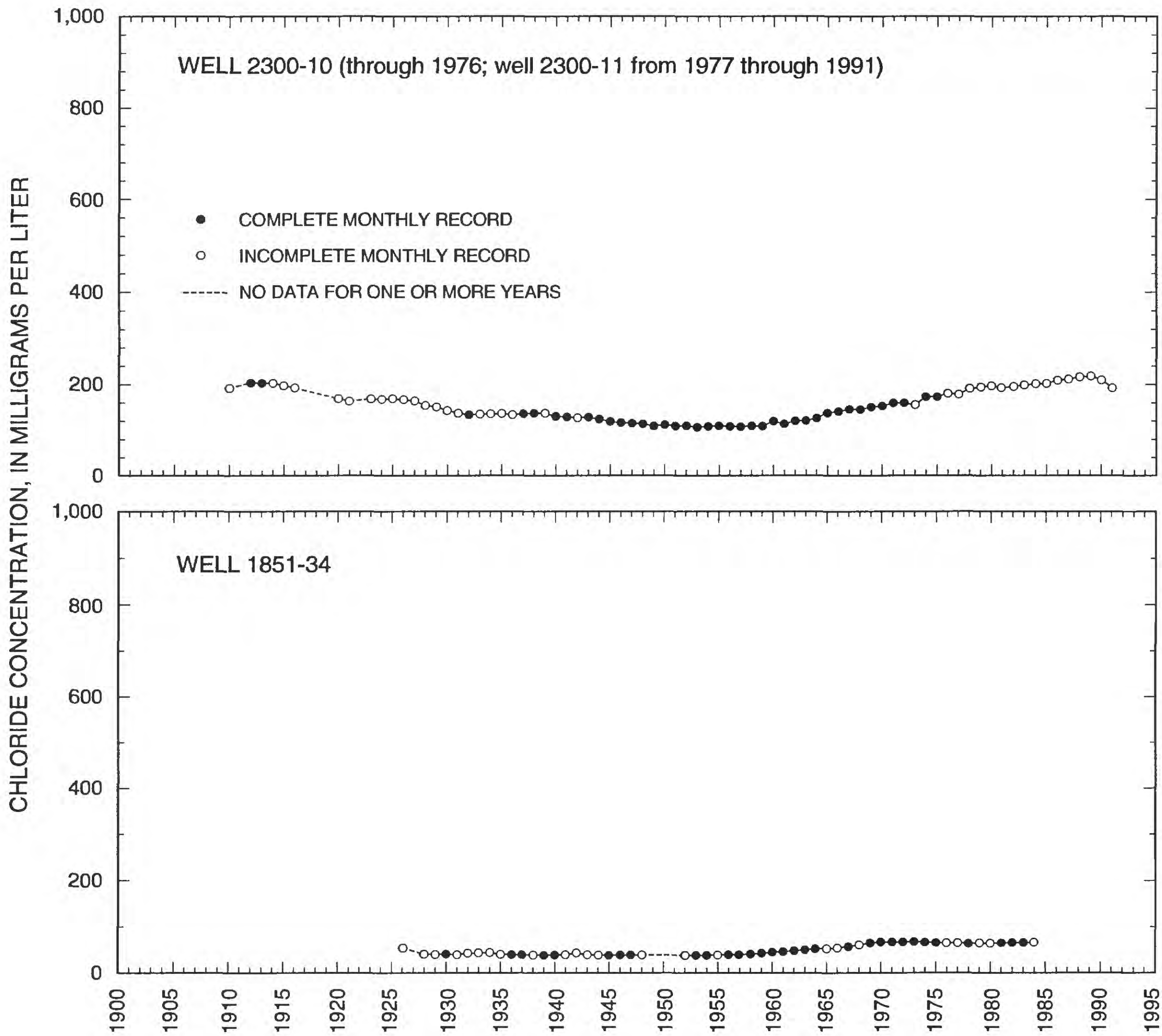


Figure 11. Annual mean chloride concentrationsof water in selected wells in the Koolau aquifer, Oahu, Hawaii, for various periods of record, 1910-92--Continued.

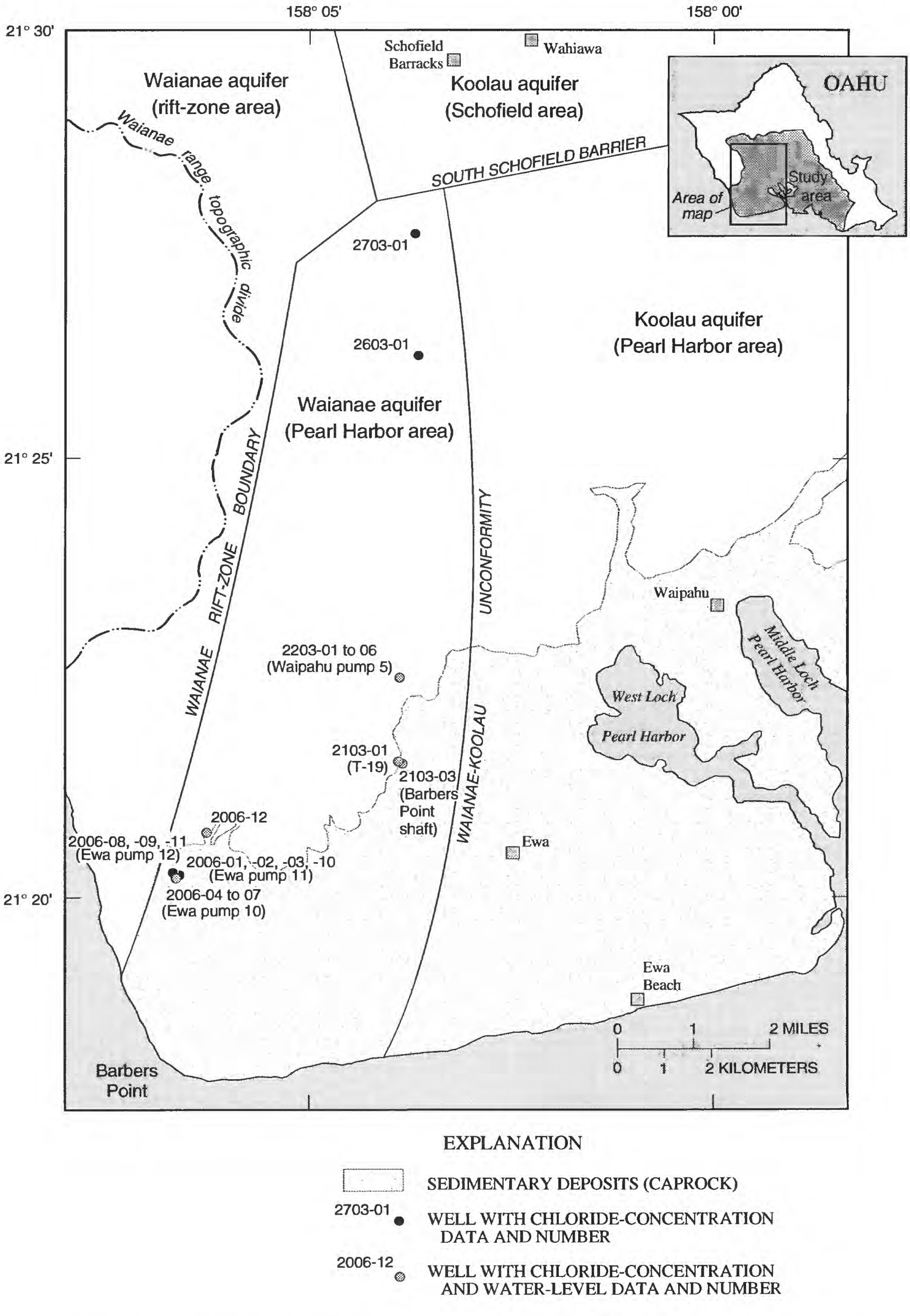


Figure 12. Waianae aquifer and locations of wells with long-term (10 years or more) chloride-concentration and water-level data in southwestern Oahu, Hawaii.

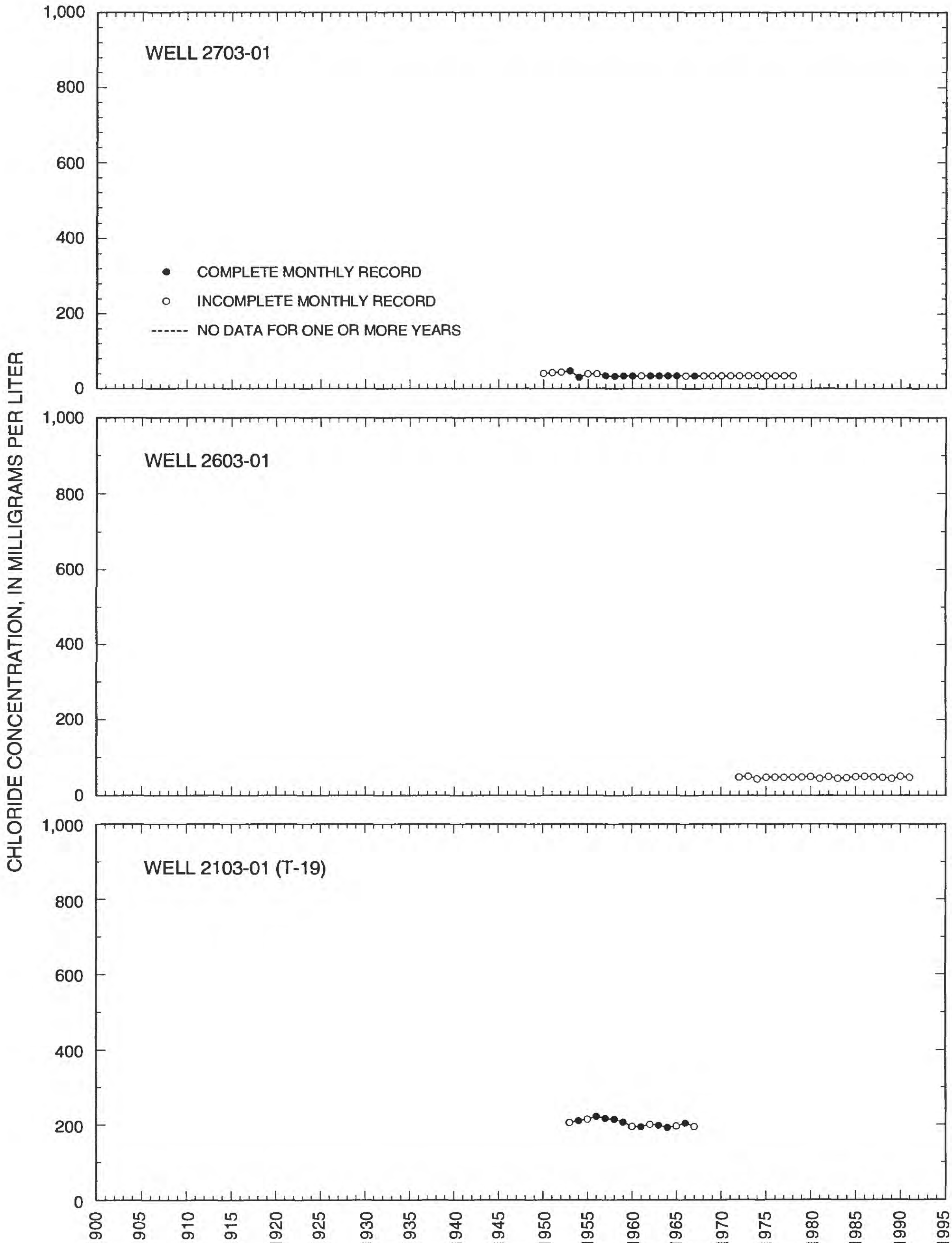


Figure 13. Annual mean chloride concentrations of water in selected wells in the Waianae aquifer, Oahu, Hawaii, for various periods of record, 1901-92.

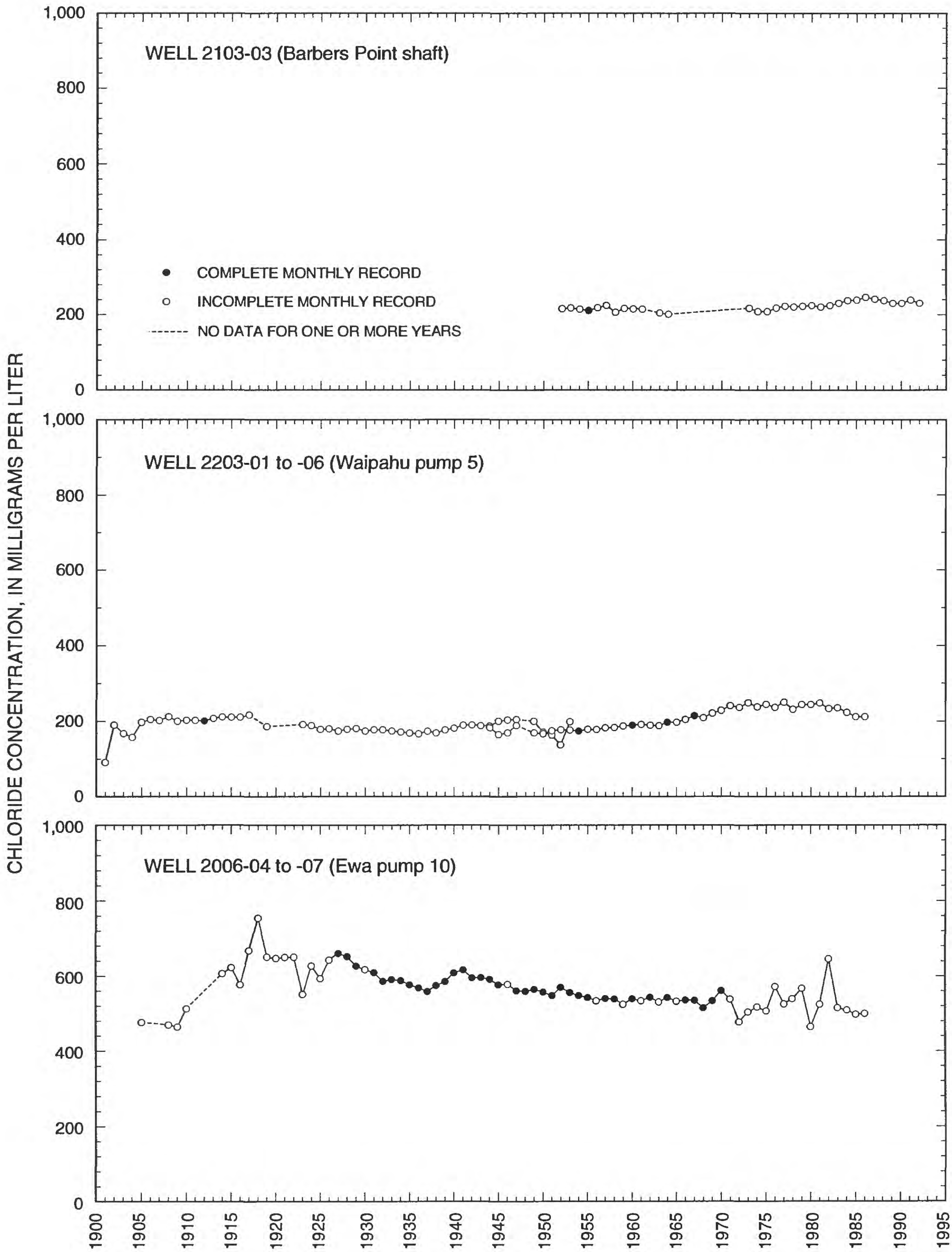


Figure 13. Annual mean chloride concentrations of water in selected wells in the Waianae aquifer, Oahu, Hawaii, for various periods of record, 1901-92--Continued.

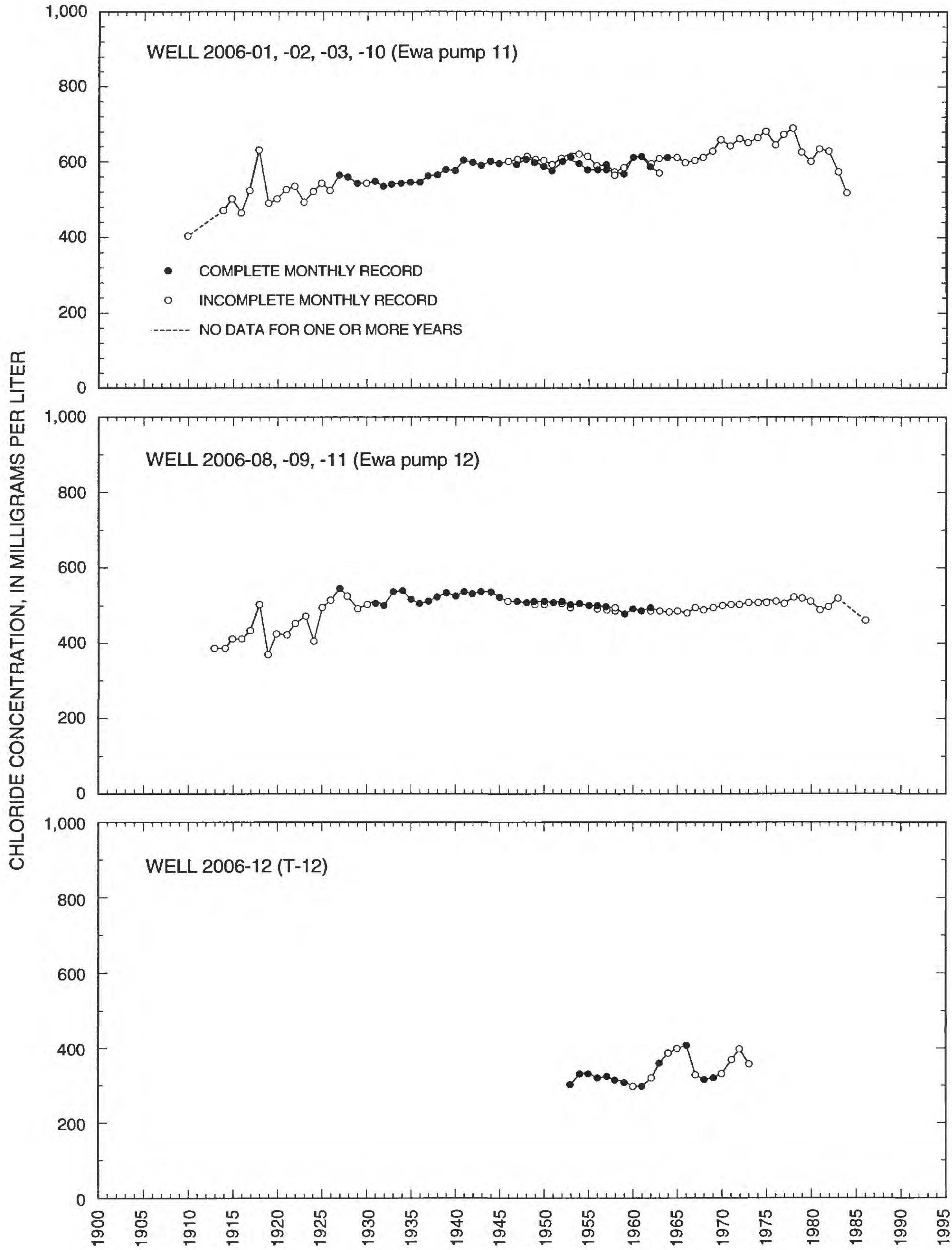


Figure 13. Annual mean chloride concentrations of water in selected wells in the Waianae aquifer, Oahu, Hawaii, for various periods of record, 1901-92--Continued.

Barbers Point shaft and observation well T-19 are shallow, penetrating about 20 ft and 10 ft below the water table, respectively. Chloride concentrations were measured at T-19 from 1955 through 1966. Chloride concentrations in this well were between 200 and 250 mg/L. Chloride concentrations at Barbers Point shaft are available for most of the time between 1952 through 1992. In general, chloride concentrations have ranged between 200 and 250 mg/L with the data showing a small upward trend to 250 mg/L during the last 17 years. Eyre (1987) concluded that the background chloride concentration of water in the aquifer near the shaft is about 200 to 220 mg/L, and that chloride concentrations above background result from ground-water recharge derived from the irrigation water applied to the sugarcane fields in the area of the shaft. The shallowness of the infiltration gallery at the shaft, about 20 ft below the water table, and the altitude of the water table in the shaft (between 14 and 17 ft above mean sea level) strongly supports Eyre's conclusion that chloride concentrations at the shaft are more a result of salty recharge water rather than upward movement of the transition zone.

Chloride concentrations in Waipahu pump 5, located north and upgradient of the shaft and in an area where water is used to irrigate sugarcane, were first measured in 1901 at 91 mg/L. The next measurement in 1902 was just below 200 mg/L. Chloride concentrations fluctuated about the 200 mg/L level until about 1946 when a gradual rise in chloride concentrations began. Concentrations peaked in 1973 at about 250 mg/L. Chloride concentrations remained close to 250 mg/L until 1982 after which they started to decrease. This decrease occurred at the same time as a decrease in pumpage at Waipahu pump 5.

Chloride concentrations in Ewa pump 10, in the southwestern part of the aquifer and downgradient of the shaft, have been as high as 750 mg/L in 1918 and as low as 420 mg/L in 1909 and 1980. For the period from 1927 through 1970, where the record is most complete, chloride concentrations generally fell from a high of about 650 mg/L in 1927 to a low of nearly 500 mg/L in 1967.

Chloride-concentration data for Ewa pump 11 are available from 1910 through 1982. Initial concentrations were about 600 mg/L. The level fluctuates until 1966, after which a rise occurs to a high of 680 mg/L in 1978. Values generally decrease after 1978 reaching 525 mg/L in 1982.

Records for chloride concentrations in Ewa pump 12 begin in 1913 when the concentrations were just below 400 mg/L. Small upward and downward trends exist in the data, but for the most part, chloride-concentration values range between 400 to 500 mg/L. A general downward trend exists in the data from about 1944 through 1959. A small upward trend has occurred from about 1968 through 1983.

Two conclusions can be made about the significance of chloride concentrations measured during various time periods at Waipahu pump 5 and at Ewa pumps 10, 11, and 12, the two areas of greatest ground-water withdrawal. One, regardless of trends, the chloride concentration of the water being pumped and applied to the sugarcane fields was relatively high, ranging from about 450 to 750 mg/L in the area irrigated by the Ewa pumps, and from about 175 to 250 mg/L in the area irrigated by the Waipahu pumps. Two, different areas of the aquifer have different trends of chloride concentrations, ranging from that at Ewa pump 10, which underwent a decline in chloride concentrations over most of its period of record, to that at Waipahu pump 5, which had long periods of relatively stable chloride-concentrations and a relatively long 27-year period of a gradual increase. Because chloride concentrations can be affected by pumping at other wells, and because ground-water pumpage from the total area generally was stable or increased over most of the period of record, it is apparent that there is not a direct correlation between chloride-concentration trends in wells and total ground-water pumpage.

FRESHWATER-SALTWATER TRANSITION ZONE IN SOUTHERN OAHU

Fresh ground water in southern Oahu is underlain by saltwater at depth. Beneath the freshwater a transition zone exists where the salinity of the water gradually increases from freshwater to seawater with increasing depth in the aquifer. As a result of density differences, freshwater floats on the underlying seawater. The ground-water modeling used in this report and discussed in the next section uses a sharp interface as an approximation of diffuse transition zone. A sharp interface assumes that all the water above the interface is fresh and all that below is seawater. A ground-water model with a sharp interface is a useful hydrologic tool because the interface calculated by the model is the point in the actual flow system represented by about 50-

percent freshwater and 50-percent saltwater, and is easily measured where deep monitor wells are located.

The entire transition zone from freshwater to seawater includes all water with a chloride concentration between 250 mg/L and about 19,600 mg/L. Through the transition zone, the density of the mixed water also ranges from that of freshwater (about 1.000 gm/cm^3) to that of seawater (about 1.025 gm/cm^3). On the basis of this density difference, freshwater may be assumed to extend below sea level to a depth 40 times the water level above sea level. This is referred to as the Ghyben-Herzberg relation (Bear, 1979, p. 560). In practice, the depth defined by the Ghyben-Herzberg relation approximates the mid-point of the transition zone (Lau, 1962). The mid-point of the transition zone is at a chloride concentration of about 9,800 mg/L. Thus, the upper transition zone includes water with a chloride concentration between about 250 and 9,800 mg/L.

The Ghyben-Herzberg relation assumes a hydrostatic equilibrium between the freshwater and saltwater. In the aquifer, ground water is in motion and where there is significant vertical flow, the Ghyben-Herzberg relation may underestimate or overestimate the depth to a sharp interface.

Available Data

Field data describing the distribution of salinity in the transition zone in southern Oahu are relatively scarce. Available data consist primarily of profiles of fluid resistivity as a function of depth in observation wells that are deep enough to penetrate through the freshwater core to saltwater. Data obtained from deep monitor wells by the Honolulu Board of Water Supply have shown that continuous salinity profiles in an open borehole provide the most reliable and usable information on the transition zone (Lao, 1975). This technique has been used successfully since 1969, but at few sites. In 1992, nine deep monitoring wells in southern Oahu penetrated into the transition zone (fig. 8): Four in the Honolulu area, three in the Pearl Harbor area, and two in the Waianae area. A new monitor well (well 2103-04) near Barbers Point shaft constructed for this study penetrated to the top of the transition zone.

Thickness of the Transition Zone

Salinity profiles from all of the deep monitoring wells provide useful estimates of the thickness of the transition zone. Because the profile is obtained in an open well bore, there is the possibility of water flowing up and down the well and mixing waters of different salinity. In fact, vertical flow is known to occur in the open boreholes of two of the deep monitor wells. Sensitive flow-meter measurements at wells 2659-01 and 2358-02 have shown that small, but measurable, vertical flow occurs up and down multiple intervals in a single well (C.I. Voss, U.S. Geological Survey, written commun., 1992). The movement of water can be directly correlated with abrupt changes in salinity and temperature of the well water, as well as with changes in lava-flow structure as indicated by subsurface mapping (Multhaup and others, in press). Although water is flowing up and down the well, the intervals between where water enters the well bore and where it leaves is relatively short, about 50 ft or less. The mixing of water with different salinities in the well because of this flow is limited to these short sections, causing the stepwise character of salinity curve (fig. 14). Because of flow that can occur anywhere in the well, the depth to a particular salinity value may be shifted by tens of feet. This characteristic of the conductivity log limits the accuracy of determining point values of salinity with depth. However, the general distribution of salinity in the well profile is not affected.

As previously described, the upper transition zone includes water with a chloride concentration between about 250 and 9,800 mg/L. However, in many aquifers in dry areas freshwater at and below the water table may have chloride concentrations of 400 to 500 mg/L or more because of irrigation-return water or sea spray (Eyre, 1987), and the top of this upper zone is less precisely defined. The freshest water at the top of the lens may vary with depth or be near or above potable limits entirely. The top may have a range of salinity, from 50 to 500 mg/L. For this report, the top is considered to be the first sharp increase in salinity above that of the freshwater core salinity.

Five of the deep monitor wells in southern Oahu have data on the transition zone (fig. 12). Salinity profiles for these wells are shown in figures 14 through 17. The thickness of the upper part of the transition zone ranges from about 150 to 200 ft in the Honolulu area and about 250 to 325 ft in the Pearl Harbor area. The thickness of the top of the transition zone in the Ewa area is about 300 ft.

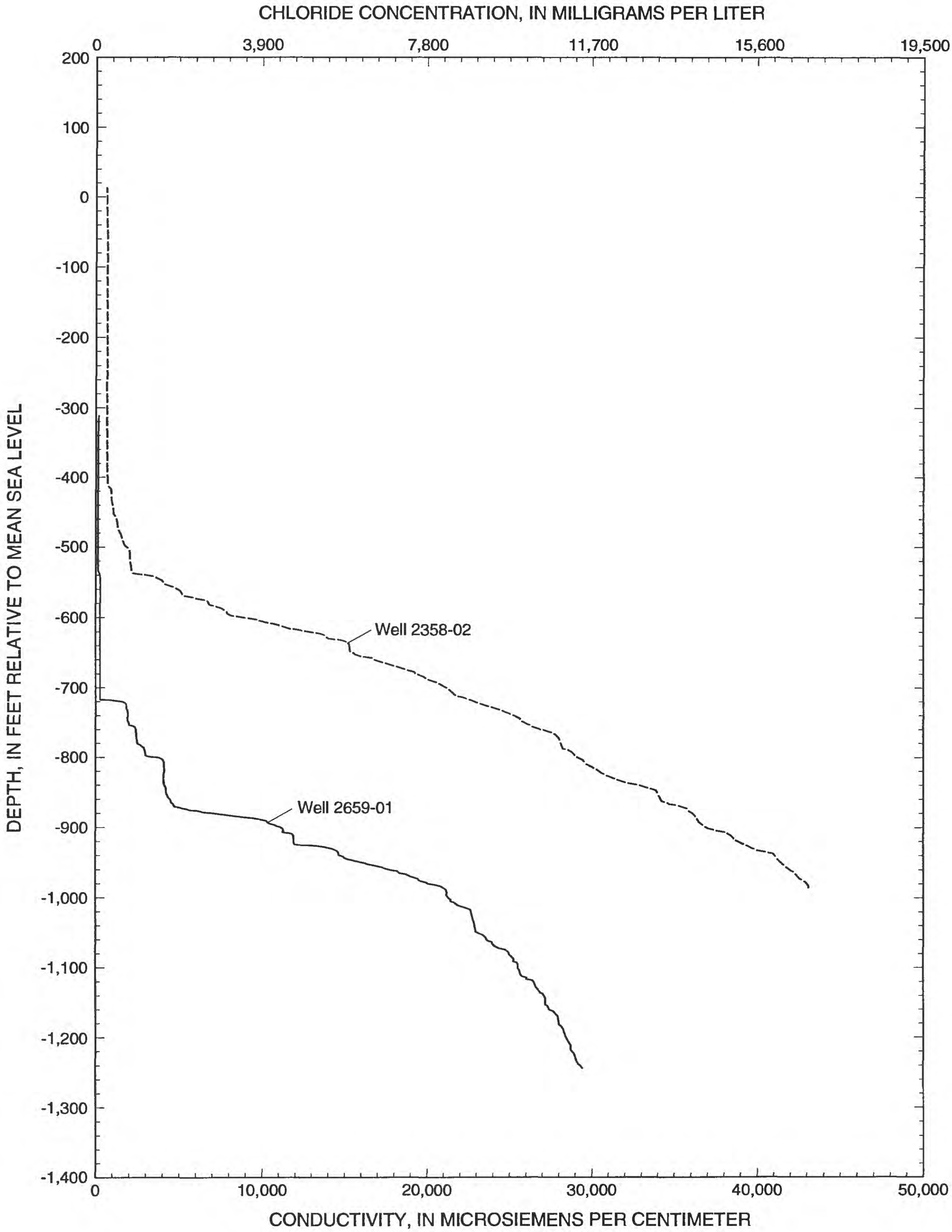


Figure 14. Vertical salinity profiles from deep monitor wells 2358-02 and 2659-01, Oahu, Hawaii.

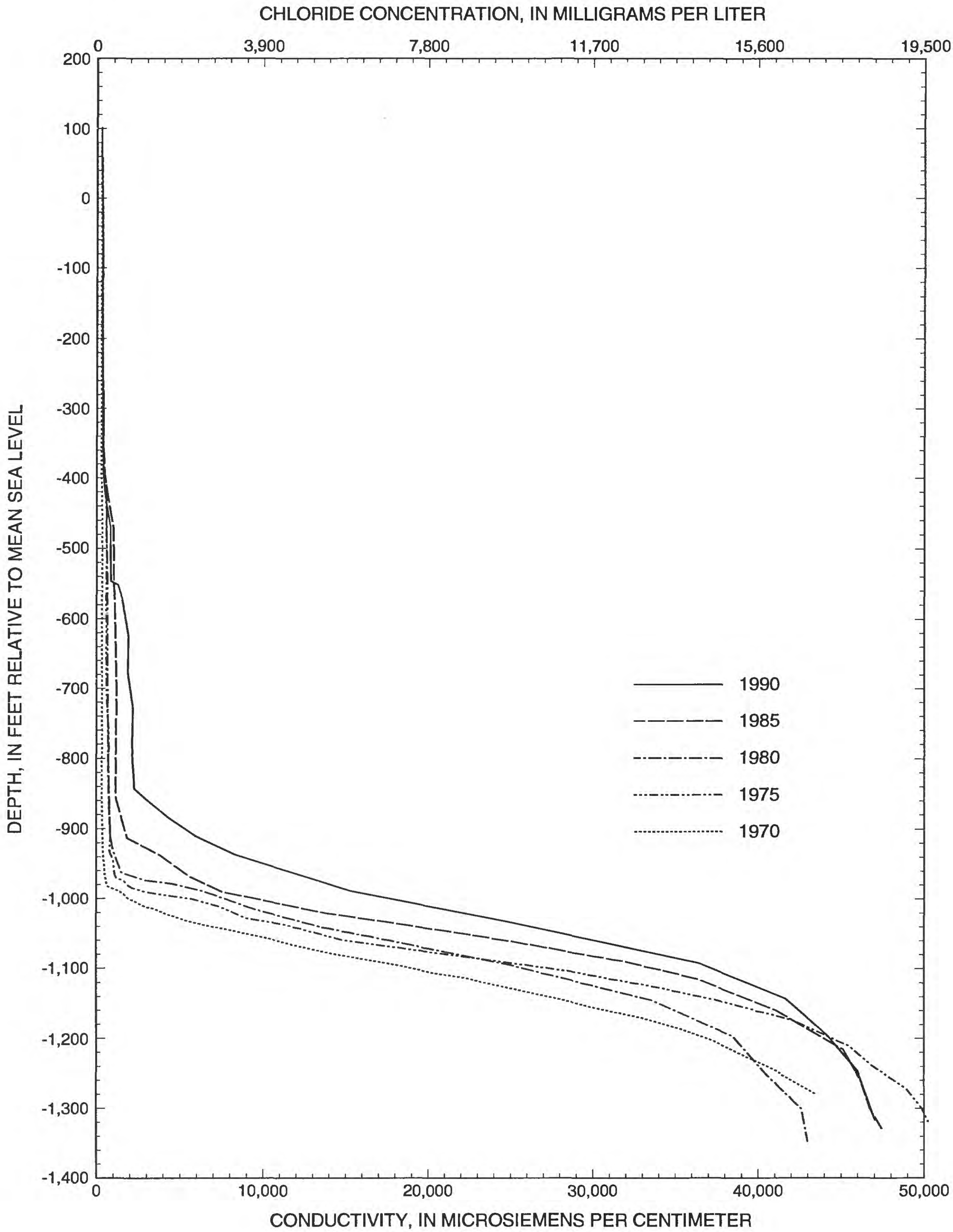


Figure 15. Vertical salinity profiles of deep monitor well 1851-57, Oahu, Hawaii.

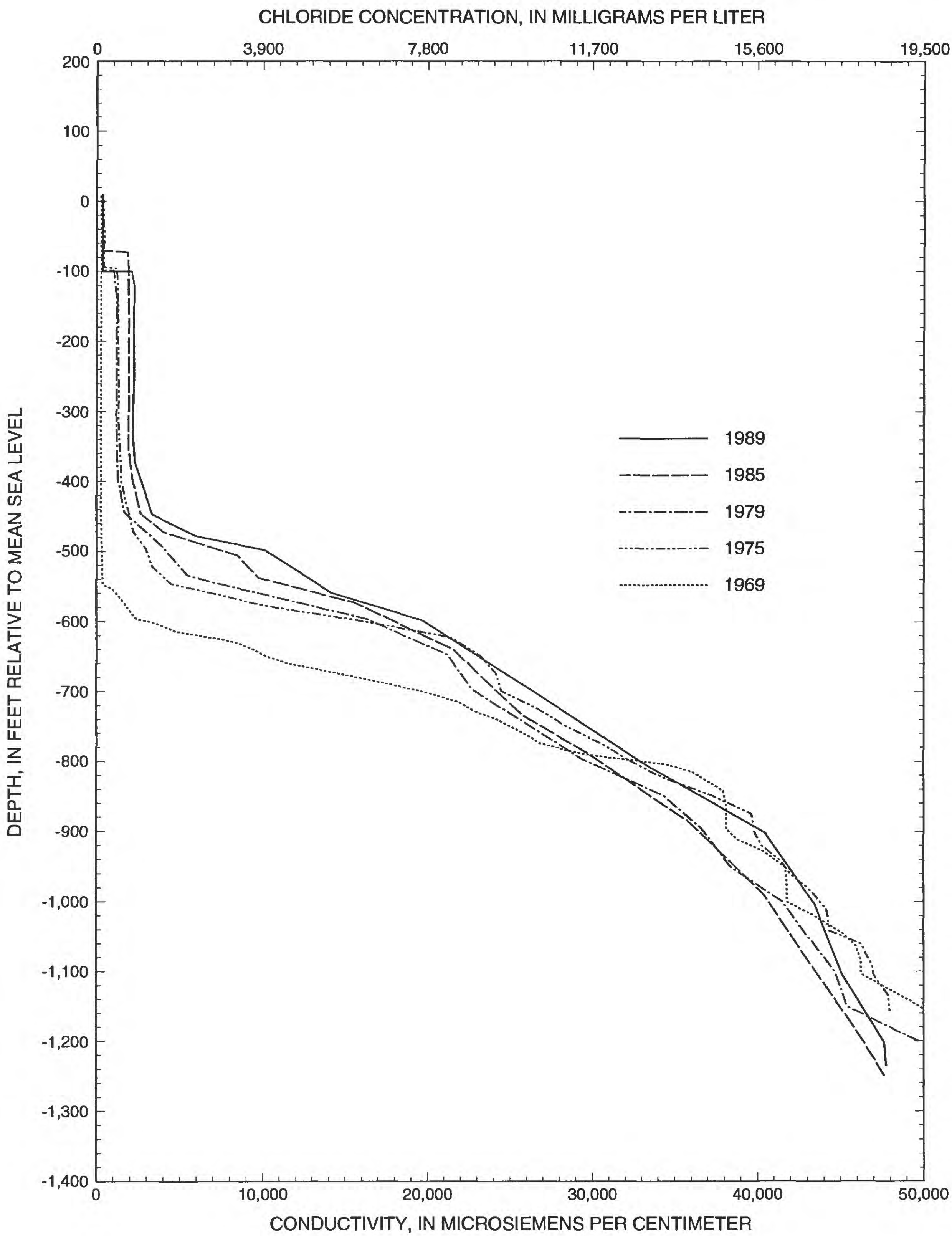


Figure 16. Vertical salinity profiles of deep monitor well 2457-04, Oahu, Hawaii.

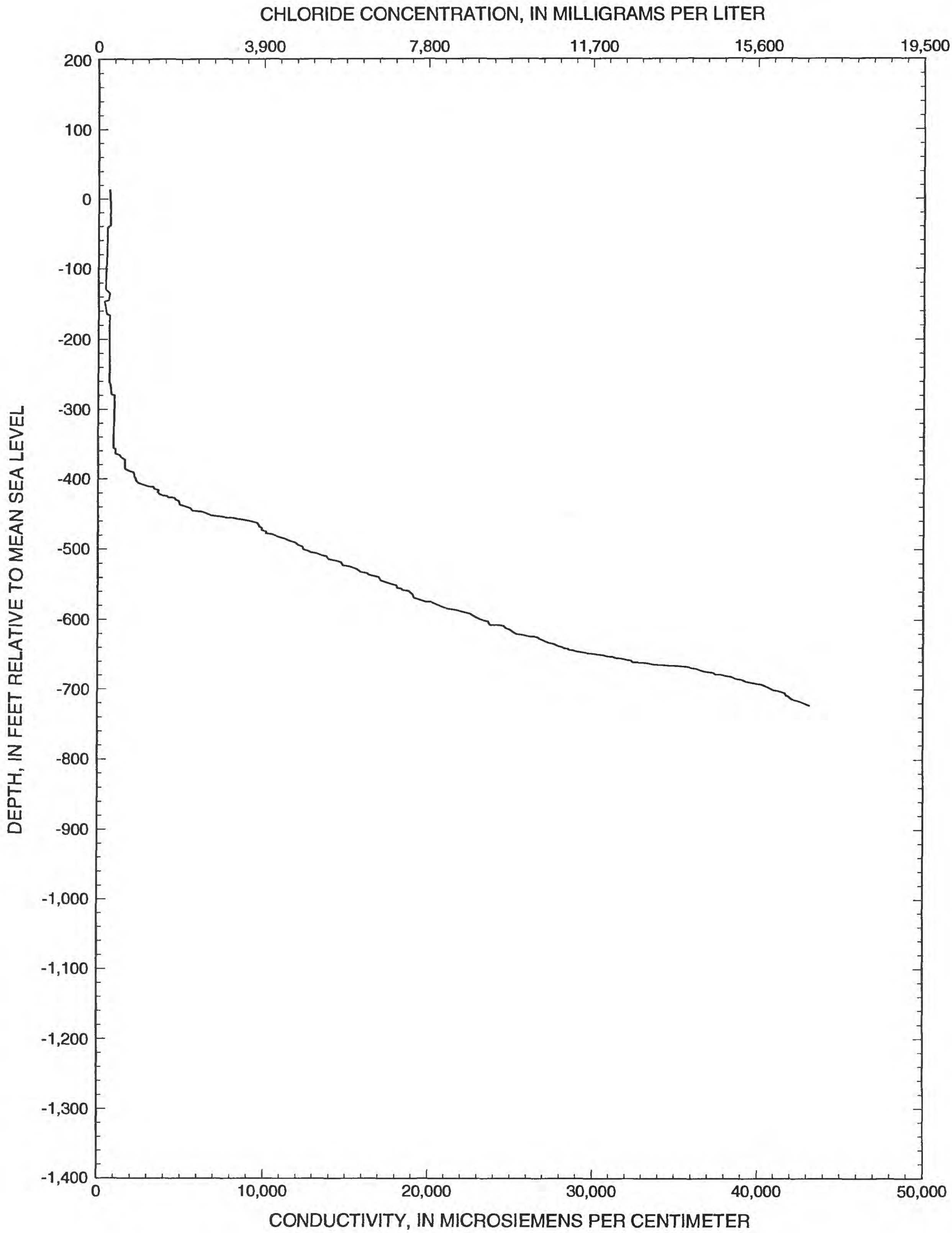


Figure 17. Vertical salinity profile from Honouliuli deep monitor well (well 2303-07), September 19, 1992, Oahu, Hawaii (modified from Nance, 1993).

The preceding analysis is based on the assumption that the salinity profiles logged in the wells are representative of the salinity of water in the surrounding aquifer. However, each well is open to the aquifer for the entire depth below the water table, providing an open conduit through the pre-existing aquifer layers. If vertical hydraulic gradients exist in the aquifer, water will flow vertically within the well bore, entering from aquifer zones with greater hydraulic head and exiting to zones with lesser head. If ground-water flow in the aquifer is predominantly horizontal and vertical flow in the well bore is inconsequential, the salinity profile in the well can be expected to correspond closely to the salinity profile in the aquifer. However, vertical flow in the well could be of sufficient magnitude to distort the salinity profile and thickness of the transition zone in the well bore from that in the aquifer.

The deep monitor wells in southern Oahu are located between 1 and 6 mi from discharge at the shoreline or springs around Pearl Harbor, and near these wells the dominant direction of ground-water movement is expected to be horizontal. As a result, vertical flow in the aquifer, and thus in the test wells, would not be significant. If vertical flow does occur, it would most likely be upward because of the well's proximity to the shoreline where freshwater begins to discharge upward into the ocean. Upward flow within the well bore would tend to bring saltwater to higher altitudes in the well bore than exist in the aquifer. Accordingly, the salinity profile as logged in the well bore would be displaced upward by some unknown amount. Thus the well-bore salinity profile would indicate that the top of the transition zone is shallower than it actually is in the aquifer.

Movement of the Transition Zone

Vertical salinity profiles from two of the deep monitor wells with the longest records are shown in figures 15 and 16. Well 1851-57 is located in the Honolulu area and well 2457-04 is located in the eastern part of the Pearl Harbor area. These wells have been logged quarterly for about 20 years and have provided information on changes in the thickness and depth of the transition zone in these areas. As shown in figures 18 and 19, the transition zone in southern Oahu moved progressively upward from 1969 through 1990. In both wells, the transition zone has moved about 150 ft in 20 years. The movement is approximately consistent with a decline in water level of about 5 ft during the same period of time (figs. 18 and 19).

NUMERICAL MODEL

Southern Oahu Ground-Water Model

The effects on the regional ground-water system in southern Oahu from increased pumpage at Barbers Point shaft were estimated by a numerical model developed for the Oahu Regional Aquifer Systems Analysis (RASA) study (Eyre and Nichols, in press). The RASA study used the two-dimensional areal ground-water model, AQUIFEM-SALT (Voss, 1984), which simulates an aquifer containing a freshwater body that freely floats on seawater. The model simulates water-level changes in, and movement of, only the freshwater in an aquifer system that can contain freshwater and saltwater. To account for a dispersed freshwater-saltwater transition zone, a sharp interface approximation in the model represents the location in the transition zone represented by 50-percent freshwater and 50-percent seawater. The interface position is determined by hydrostatic equilibrium between freshwater and saltwater.

The modeled area, finite-element mesh, boundaries, and source-sink locations are the same as those used by the RASA model. For a complete description of these features and other information in the construction details of the model refer to Eyre and Nichols (in press). The model is bounded by the Waianae Range topographic divide to the west, the Wahiawa-Waialua district boundary to the north, which is an approximate topographic divide, the Koolau Range topographic divide to the east, and the Kaau rift zone to the southeast. The southern boundary is at an arbitrary location about 3 to 4 mi off the southern coast of Oahu (fig. 20).

The modeled area is divided into the distinct but hydrologically connected areas identified in figure 4. Barriers between these areas include the Waianae-Koolau unconformity, the southern Schofield dam, and the valley-fill barrier west of Honolulu. Each of these barriers is represented in the model as an area of low permeability that restricts ground-water movement.

Water is introduced into the model as ground-water recharge distributed areally over the modeled area. Recharge was calculated from a land-use based water budget by Giambelluca (1986). Water discharges from the model through simulated springs, the caprock, and through simulated wells. The caprock is modeled as a leaky layer covering the basalt aquifers along the southern coast.

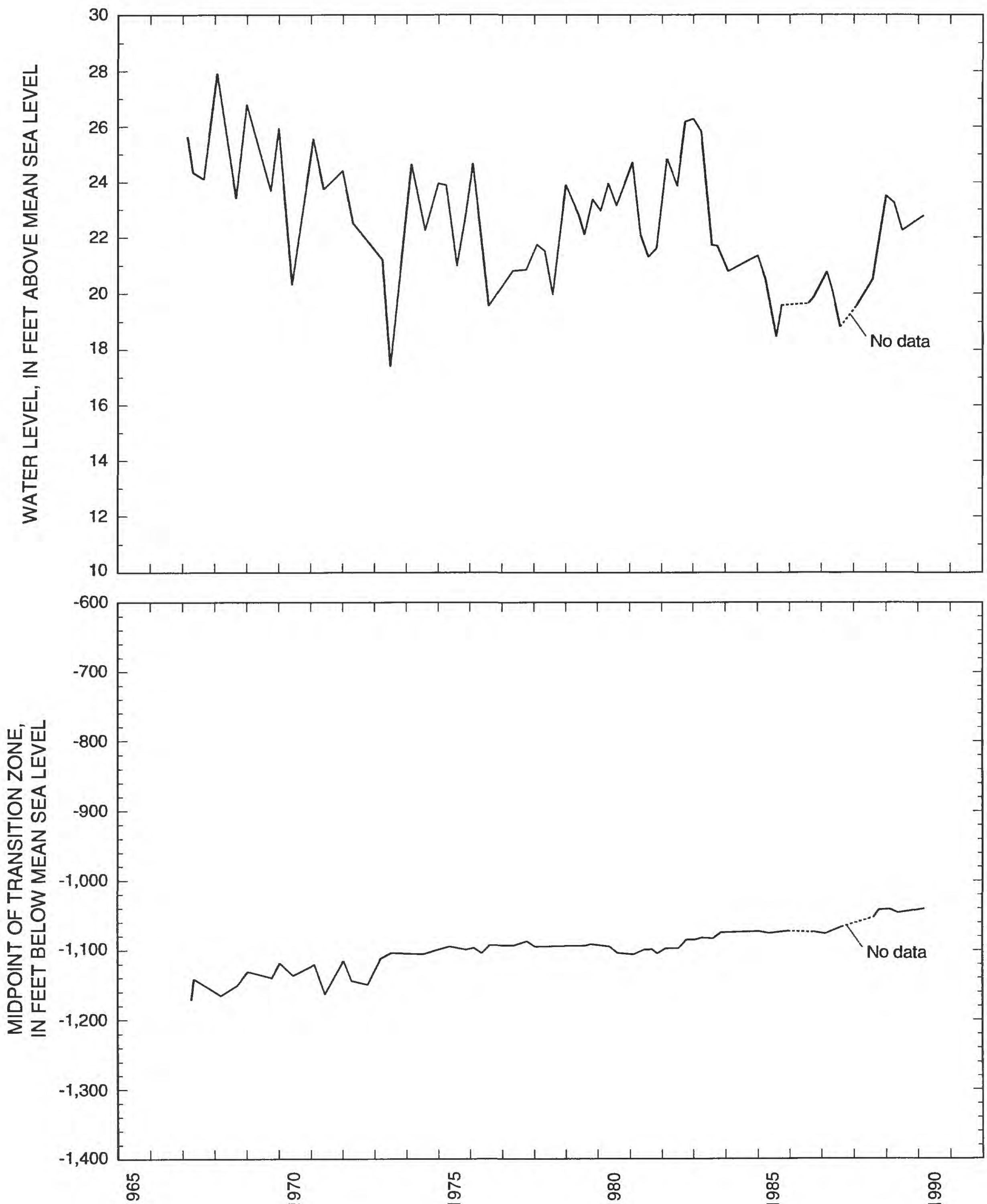


Figure 18. Water levels and depth of the midpoint of the transition zone with time for deep monitor well 1851-57, Oahu, Hawaii, 1967-90.

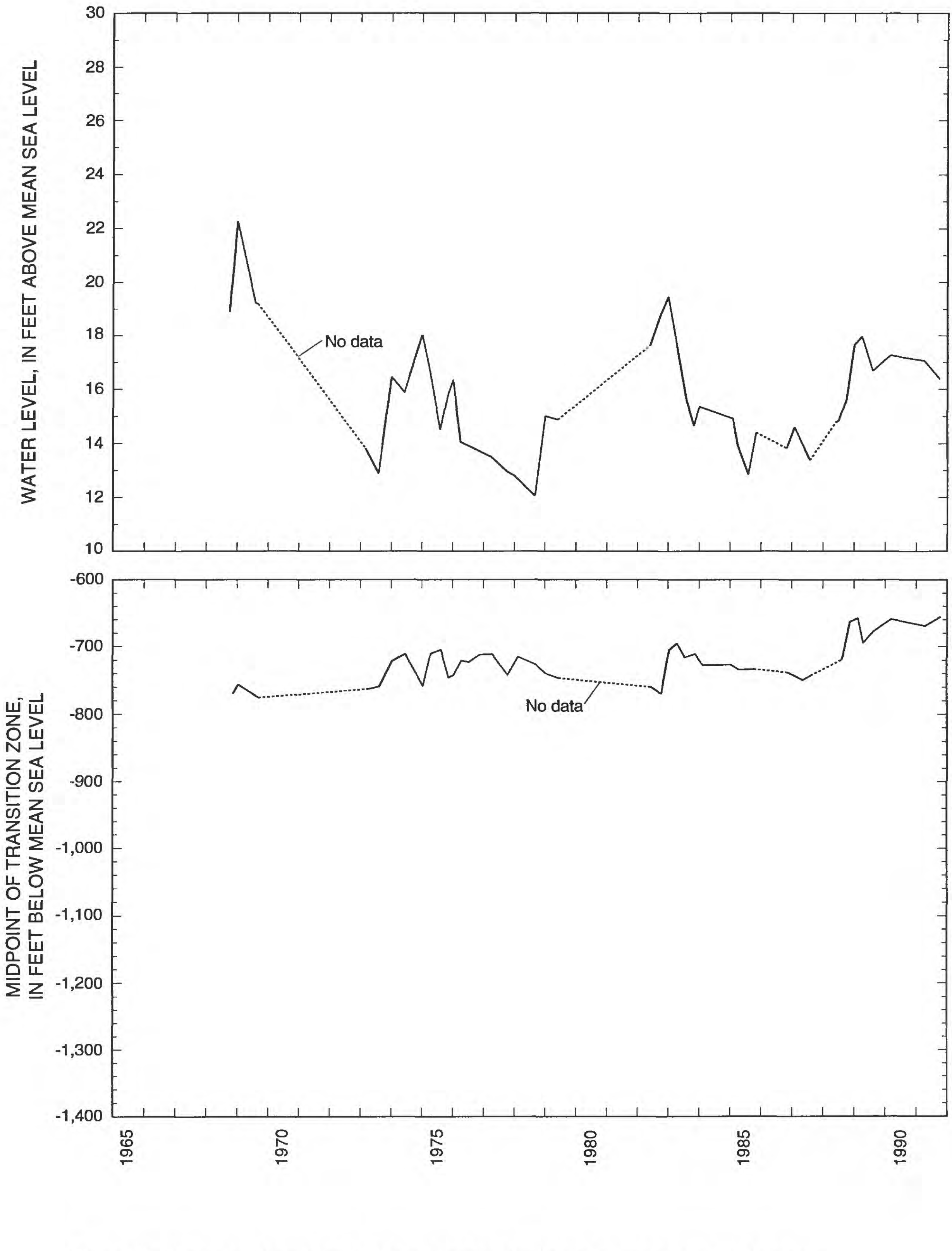


Figure 19. Water levels and depth of the midpoint of the transition zone with time for deep monitor well 2457-04, Oahu, Hawaii, 1968-91.

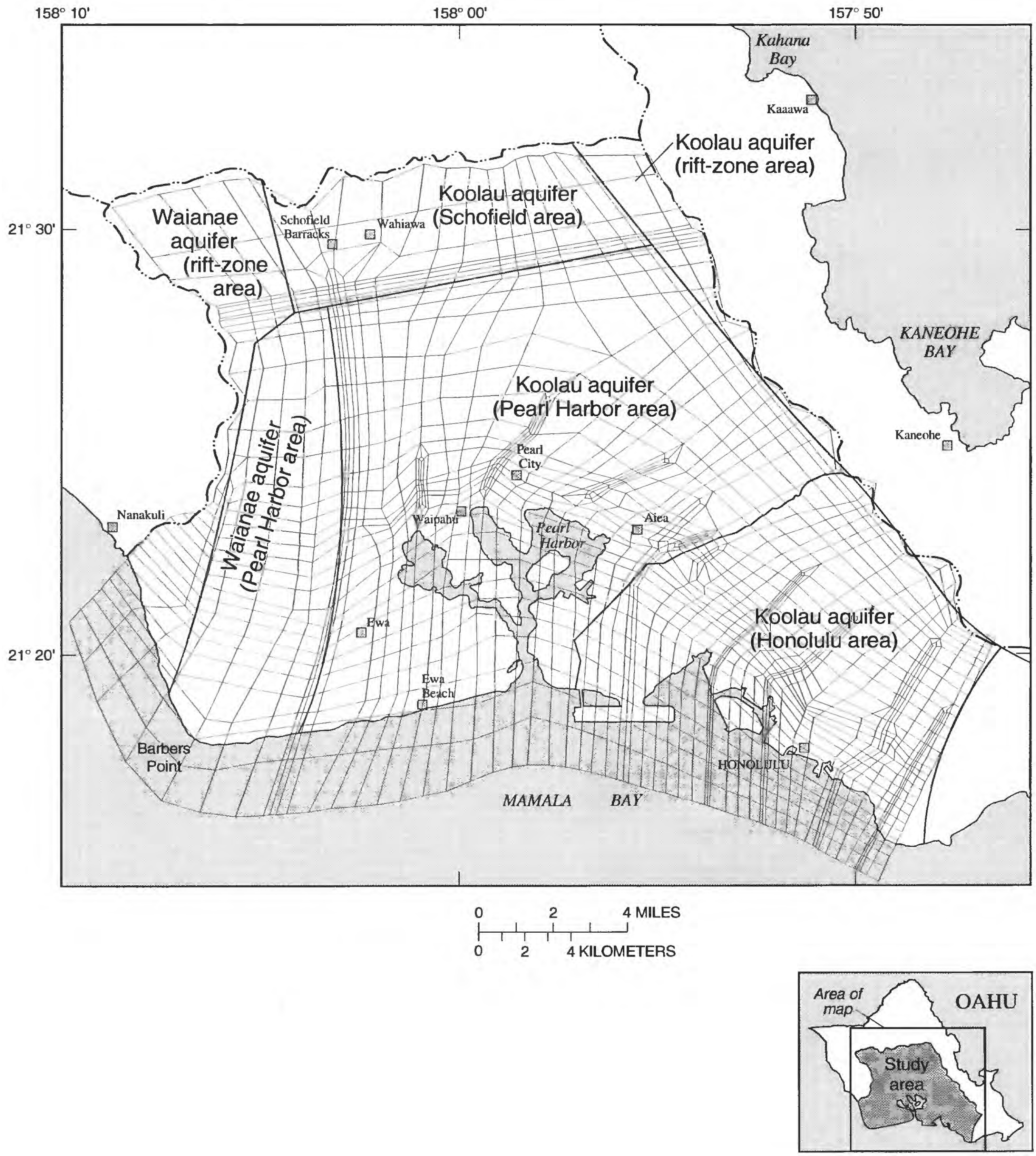


Figure 20. Boundaries and grid of the southern Oahu ground-water mode (from Eyre and Nichols, in press).

Modification of the Regional Aquifer Systems Analysis (RASA) Model

The original RASA model was calibrated to hydrologic conditions that existed before ground-water development and also to the distribution and rate of pumpage during the 1950's (Eyre and Nichols, in press). For this study, the distribution and rate of pumpage simulated in the model was initially that for the 1995 allocation as set by the State Commission on Water Resource Management (table 5). Accordingly, ground-water recharge rates were revised on the basis of anticipated land-use changes described below. The model was allowed to reach steady-state conditions with this pumpage after which changes in ground-water levels and corresponding changes in the freshwater-saltwater interface were evaluated by simulating an increase in pumpage at Barbers Point shaft of 2 Mgal/d.

Pumpage changes.--Pumpage data used in this study are based on the allocated distribution and rates of ground-water withdrawals for southern Oahu for 1995. These pumping rates were selected as best representing current and near-future conditions because they account for a reduction in agricultural demand and a scheduled reduction in allocations through 1995. Table 2 provides specific information relative to this withdrawal for the Waianae aquifer at locations shown in figure 7. All of the scheduled decreases in water allocation between 1988 through 1995 occur in agricultural pumpage, which results in a significant reduction in land under irrigated agricultural production. These changes will also have a significant effect on recharge estimates for the aquifer.

Recharge changes.--Recharge rates for the original RASA model were calculated by Giambelluca (1986) using a water-balance model with variable land-use parameters. Recharge calculations included three major land-use scenarios; undisturbed landscape (predevelopment), extensive agriculture, and extensive urban development. Recharge is derived from precipitation alone in the predevelopment, and from precipitation plus irrigation-return water during the 1950's. On the basis of the water balance, the combined effects of agricultural land use increased recharge by 34 percent more than the natural rate during the 1950's; however, urban development did not change recharge by more than a few percent. To account for the planned reduction in irrigation through 1995 the component of recharge from irrigation-return water to the aquifer had to be reduced. Because actual land-use changes are difficult to predict, the recharge scenario for predevelopment conditions was used. This scenario assumes no lands under agricultural production, and has the effect of reducing the irrigation-return component of recharge to zero, thus providing a conservative estimate of recharge.

RESULTS OF NUMERICAL SIMULATION

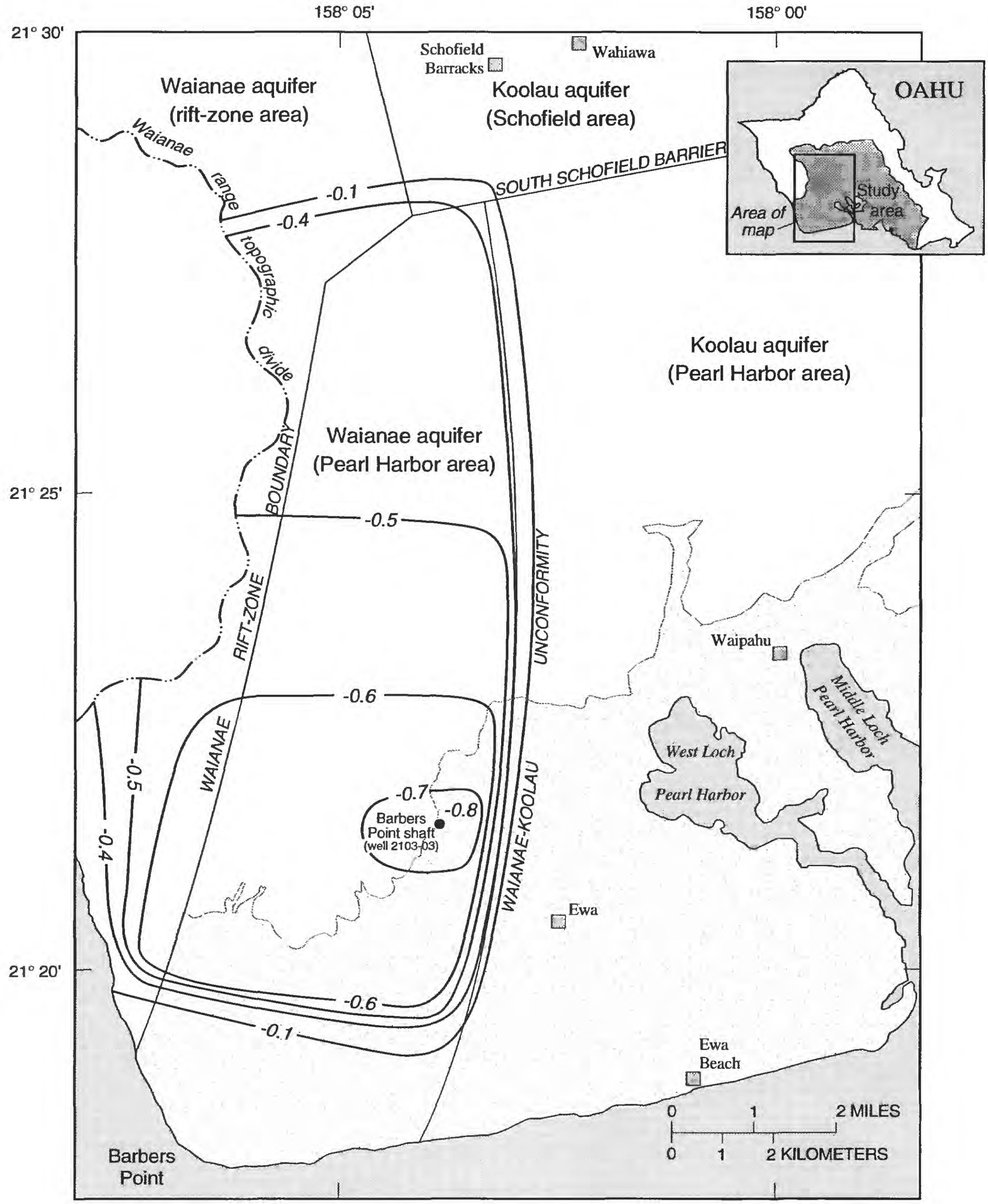
Changes in ground-water levels and the position of the freshwater-saltwater interface resulting from increasing the pumpage at Barbers Point shaft from its allocated rate of 2.334 Mgal/d to 4.334 Mgal/d was done in a two-step process. First, the 1995-allocated distribution and rates of ground-water pumpage were simulated by the model until steady-state conditions were reached. Second, simulated ground-water pumpage at Barbers Point shaft was increased from 2.334 Mgal/d to 4.334 Mgal/d, and the model was allowed to reach a new equilibrium. Ground-water levels estimated by the model and the position of the freshwater-saltwater interface obtained from the second simulation were subtracted from those for the first simulation to obtain regional changes as a result of increasing pumpage.

Changes in Ground-Water Levels

Declines in ground-water levels estimated by the model that result from increasing pumpage by 2 Mgal/d above 1995-allocated rates at Barbers Point shaft are shown in figure 21. As can be seen, estimated declines range from about 0.8 ft near the shaft to 0.4 ft at the northern part of the aquifer and 0.6 ft at the southernmost extent of the freshwater lens. Model-estimated declines greater than 0.1 ft do not cross the Waianae-Koolau unconformity. Furthermore, declines estimated by the model of about 0.1 ft occur across the southern Schofield barrier. Declines in water levels estimated by the model reach the western boundary of the Waianae aquifer, where the dikes of the Waianae rift zone terminate the aquifer. The estimated declines in ground-water levels throughout the aquifer are small compared with the thickness of the freshwater lens and these declines would not be expected to affect the yields of other wells in terms of quantity. The chloride concentration of the water produced could increase, however, if the transition zone rises into a well or wells.

Table 5. Values used in the simulation for 1995-allocated pumpage for wells in southern Oahu, Hawaii
[Data from Hawaii Commission on Water Resource Management; Mgal/d, million gallons per day]

Well	Node	1995-allocated pumpage (Mgal/d)	Well	Node	1995-allocated pumpage (Mgal/d)
1748-03	771	4.000	2300-11	798	0.680
1749-18	702	0.043	2300-20	798	0.400
1749-19	770	0.336	2301-01 to -10	1015	1.151
1750-09	637	0.020	2301-11 to -20	1011	4.000
1847-01	1286	1.310	2301-21 to -32	933	5.594
1849-07	766	0.001	2301-27, -32	933	5.594
1849-10	907	0.142	2301-34 to -37	1010	6.610
1849-13	907	7.000	2302-01, -02	931	4.357
1851-07	763	0.040	2303-01, -02	1081	2.240
1851-12	764	7.000	2303-03, -04	1158	2.240
1851-20	695	0.020	2303-05	1158	1.120
1851-26	636	0.060	2303-06	1158	1.120
1851-54	831	0.237	2354-01	1187	11.320
1851-58	831	0.100	2355-03, -05	1033	0.790
1851-73	517	0.030	2355-06, -07	1033	1.030
1905-04	359	1.000	2355-09 to -14	1032	11.750
1948-01	1836	0.700	2356-49, -50	950	0.080
1952-06	689	6.220	2356-54	1182	0.222
1952-11	572	2.000	2356-55, -56	1107	1.100
1952-12	572	0.244	2356-58, -59	956	1.990
1952-14	513	2.500	2356-70	876	0.100
1952-15	759	0.024	2357-23, -24	873	1.110
2004-04	596	1.500	2358-49	805	0.003
2006-01 to -03, -10	417	2.564	2400-01 to -04	1016	6.000
2006-13	417	0.700	2400-05, -06	1015	2.100
2006-14, -15	535	1.000	2402-01, -02	1086	2.710
2052-07	898	0.229	2456-01-03	1177	1.500
2052-08	972	8.110	2457-01 to -03	1175	2.190
2052-12	825	1.000	2457-05, -06, -09 to -12	1176	11.970
2053-05	684	0.139	2457-13 to -15	1176	1.890
2053-09	625	0.082	2458-01	1024	1.320
2053-10	819	1.035	2458-03, -04	1102	0.310
2101-01	602	0.110	2459-19, -20	1019	0.630
2102-02, -04 to -22	602	2.502	2459-21	869	0.006
2103-03	715	2.337	2500-01, -02	1240	2.000
2153-02	818	0.021	2557-01, -02	1248	0.136
2153-07	817	0.609	2557-03	1309	0.500
2153-10	891	3.790	2558-10	1244	14.977
2154-01	816	0.346	2600-02	1015	0.100
2201-14	664	0.003	2600-03	1407	1.550
2202-03 to -14	720	6.615	2603-01	1355	0.220
2202-15 to -20	661	6.011	2659-02, -03	1365	0.850
2202-21	856	10.769	2703-01	1442	0.154
2254-01	887	4.659	2800-01, -02	1451	2.980
2255-32	957	0.697	2803-05	1692	2.121
2255-35, -36	957	0.906	2859-01, -02	1492	1.900
2255-36	957	0.788	2901-02 to -04	1741	5.700
2255-37 to -39	957	1.000	2901-08, -09, -11	1741	3.270
2300-07 to -09	729	9.000	2902-01	1740	1.000



EXPLANATION

SEDIMENTARY DEPOSITS (CAPROCK)

—*-0.1*— LINE OF EQUAL ESTIMATED CHANGE IN WATER LEVEL--Estimated change is for 1995-allocated pumpage in the Waianae aquifer plus 2 million gallons per day above allocated at Barbers Point shaft from water level estimated for 1995-allocated pumpage in the Waianae aquifer. Interval, in feet, is variable

Figure 21. Simulated change in water level estimated for 1995-allocated pumpage in the Waianae aquifer plus 2 million gallons per day above allocated at Barbers Point shaft from water level estimated for 1995-allocated pumpage in the Waianae aquifer, Oahu, Hawaii.

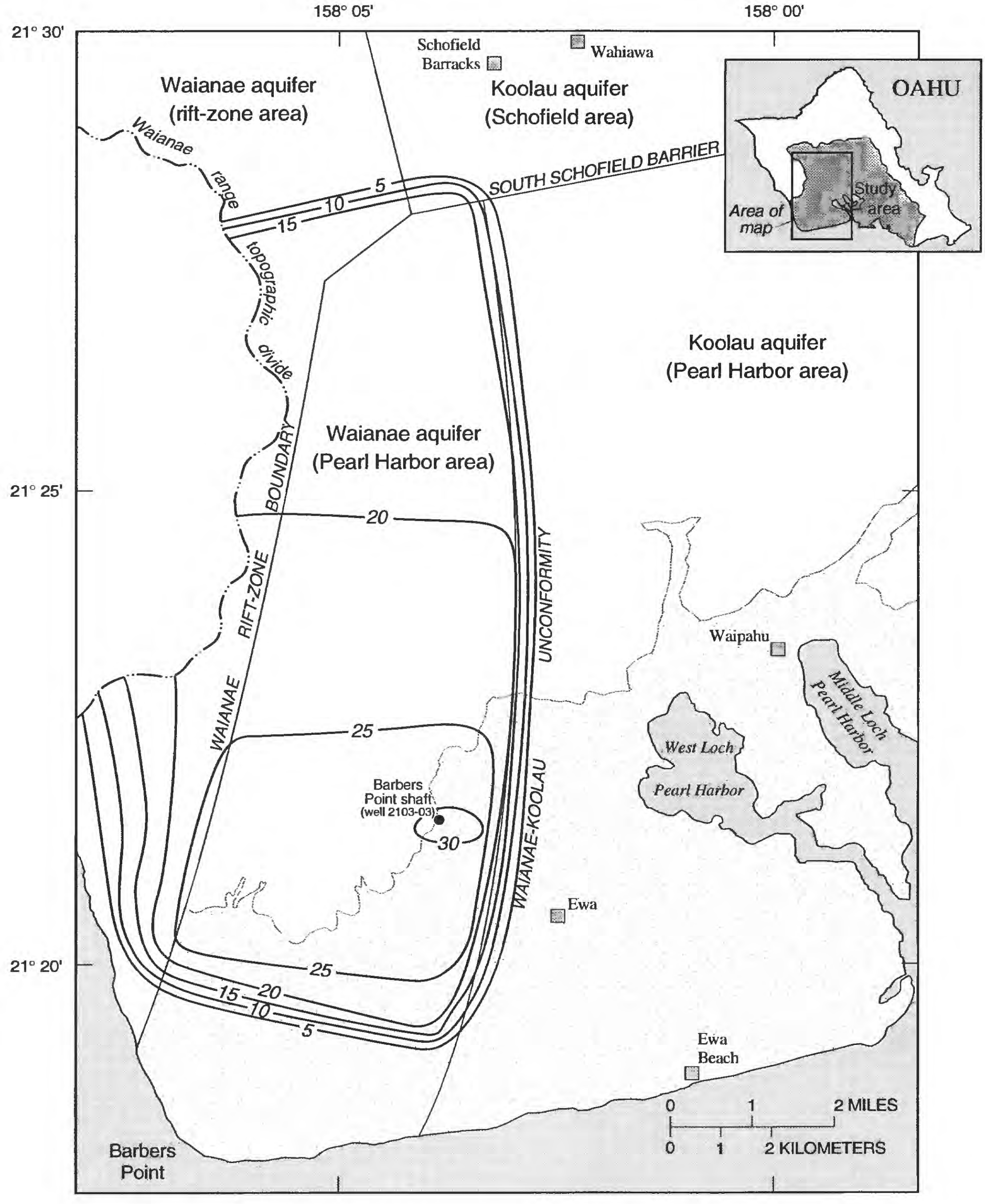
Changes in the Freshwater-Saltwater Interface

The model-estimated rise in the freshwater-saltwater interface induced by the increase in pumpage at Barbers Point shaft is shown in figure 22. Because declines in ground-water levels estimated by the model greater than 0.1 ft were limited to the Waianae aquifer, corresponding rises in the interface are similarly limited. Model-estimated rises range from a high of 30 ft near the shaft to about 20 to 15 ft near the caprock and the Schofield barrier, respectively. As with ground-water levels, movement estimated by the model of the interface near the shaft is not indicative of what would actually occur in the shaft.

The model also estimates the steady-state configuration of the freshwater-saltwater interface relative to mean sea level. Figure 23 shows the model-estimated position of the interface in the Waianae aquifer resulting from pumping at allocated rates plus 2 Mgal/d more than the allocated rate at the shaft. Figure 24 is a section along the long, north-south, axis of the aquifer. As shown in the section, the model-estimated interface is at depths ranging from 500 to 860 ft below mean sea level from south to north in the aquifer. The position of the interface for allocated pumpage is shown in figure 24 also. The two interfaces roughly parallel each other with the altitude between them varying by about 20 to 30 ft. Data discussed previously indicate that the transition zone could be expected to have moved upward in a similar manner. Depths of screened intervals of selected wells in the Waianae aquifer are projected on the section in figure 24. Construction details for all the wells in the aquifer are shown in table 6. Bottoms of pumping wells range from 244 ft below to 4 ft above mean sea level.

Field data on the transition zone in southern Oahu indicate that the thickness of the upper part of the transition zone in the Waianae aquifer is about 300 ft. Using this value for the upper transition-zone thickness, freshwater thicknesses above the top of the transition zone can be calculated at about 200 ft in the southern part of the Waianae aquifer, 275 ft near Barbers Point shaft, and 600 ft in the northern part of the aquifer for the condition of allocated pumpage plus an additional 2 Mgal/d at the shaft. Such a calculation should be considered as a rough estimate of the actual thickness of the freshwater above the transition zone. The freshwater thickness shown in figure 24 should be used as a general guide to the relative depth of the transition zone among the wells in the Waianae aquifer. To be more precise, more definitive information is needed on actual transition-zone thickness in the Waianae aquifer.

Many of the wells in the southern part of the aquifer are constructed to depths of 100 ft or more below sea level so that these wells potentially could be affected by saltwater intrusion. Toward the middle and northern parts of the aquifer, however, the extent of freshwater above the transition zone becomes sufficiently great to indicate that a combination of well depths and pumping rates that would preclude saltwater intrusion is potentially possible.

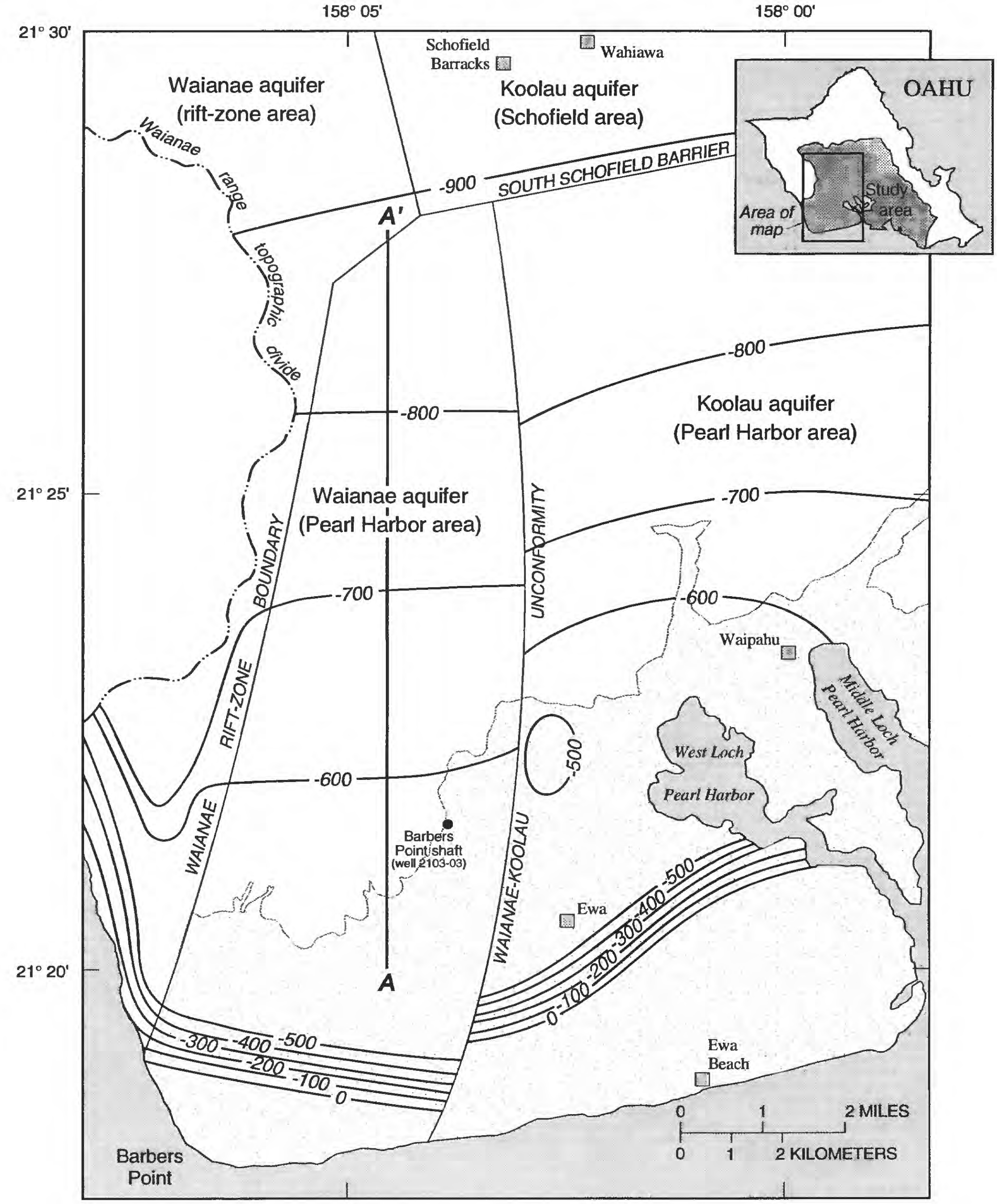


EXPLANATION

SEDIMENTARY DEPOSITS (CAPROCK)

—20— LINE OF EQUAL ESTIMATED RISE IN ALTITUDE OF FRESHWATER-SALTWATER INTERFACE--Estimated change is for 1995-allocated pumpage in the Waianae aquifer plus 2 million gallons per day above allocated at Barbers Point shaft from water level estimated for 1995-allocated pumpage in the Waianae aquifer. Interval 5 feet

Figure 22. Simulated change in altitude of freshwater-saltwater interface estimated for 1995-allocated pumpage in the Waianae aquifer plus 2 million gallons per day above allocated at Barbers Point shaft from altitude estimated for 1995-allocated pumpage in the Waianae aquifer, Oahu, Hawaii.



EXPLANATION

SEDIMENTARY DEPOSITS (CAPROCK)

—*-200*— LINE OF EQUAL ESTIMATED ALTITUDE OF FRESHWATER-SALTWATER INTERFACE--Estimate is for 1995-allocated pumpage in the Waianae aquifer plus 2 million gallons per day above allocated at Barbers Point shaft. Interval 100 feet. Datum is mean sea level

— LINE OF SECTION

Figure 23. Simulated altitude of freshwater-saltwater interface estimated for 1995-allocated pumpage in the Waianae aquifer plus 2 million gallons per day above allocated at Barbers Point shaft, Oahu, Hawaii.

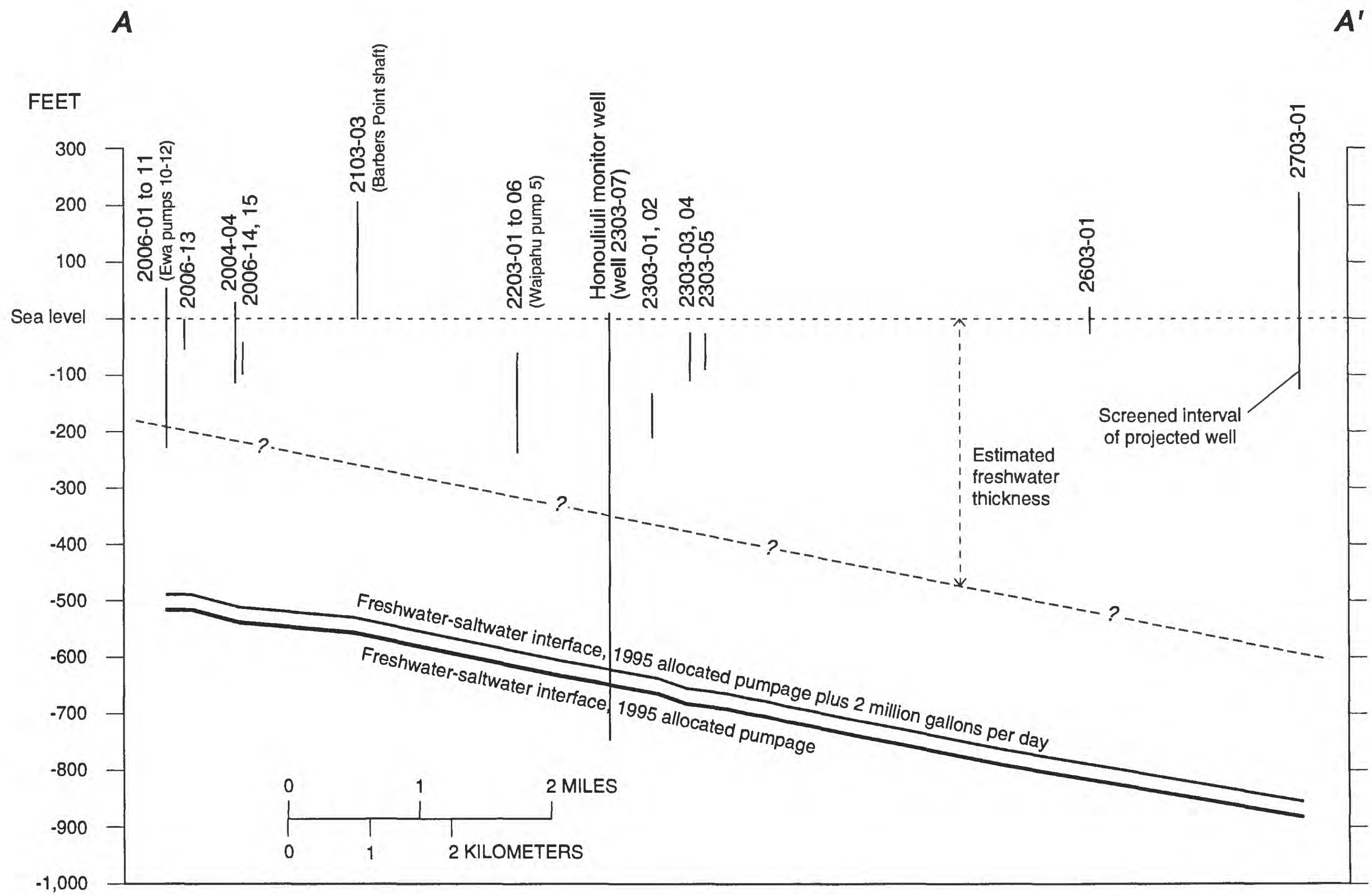


Figure 24. Hydrologic section through Waianae aquifer showing estimated freshwater-saltwater interface and depth of screened intervals of selected wells. Line of section ***A-A'*** shown in figure 23; well locations are shown in figure 7.

Table 6. Construction details and water levels for wells in the Waianae aquifer, Oahu, Hawaii

[Data from Hawaii Commission on Water Resource Management, Ground Water Index/Summary, February 26, 1991 (unpublished); values are in feet, datum is mean sea level; --, no data; DOWALD, Hawaii Division of Water and Land Development]

Well	Owner	Date drilled	Total depth	Top of well	Bottom of solid casing	Bottom of perforated casing	Bottom of well	Initial water level	1990 water level
1905-01	Campbell Estate	1957	50	18	15	--	-32	1.3	--
1905-02	Campbell Estate	1957	90	62	59	--	-28	2.1	--
1905-03	Hawaiian Telephone Inc.	1966	70	56	--	--	-14	2.3	--
1905-04	State DOWALD	1987	380	--	--	--	--	--	15.21
1905-05	State DOWALD	1987	80	--	--	--	--	--	15.21
2004-01	U.S. Navy	1933	147	89	-7	-13	-58	19.2	--
2004-02	Campbell Estate	1937	200	174	7	--	-26	14	--
2004-03	U.S. Navy	1941	190	175	-7	--	-15	16.7	--
2004-04	Honolulu Board of Water Supply	1981	268	141	-47	--	-127	14.9	--
2005-01	Pacific Concrete Quarry	1971	142	120	15	0	-22	22	14.98
2006-01	Oahu Sugar	1908	--	41	--	--	--	13	14.4
2006-02	Oahu Sugar	1908	282	41	-21	--	-241	13	14.4
2006-03	Oahu Sugar	1908	--	41	--	--	--	13	14.4
2006-04	Oahu Sugar	1908	155	41	--	--	-114	16.7	14.4
2006-05	Oahu Sugar	1908	165	41	--	--	-124	16.7	14.4
2006-06	Oahu Sugar	1908	165	41	--	--	-124	16.7	14.4
2006-07	Oahu Sugar	1908	--	41	--	--	--	16.7	14.4
2006-08	Oahu Sugar	1913	--	41	--	--	--	15	14.4
2006-09	Oahu Sugar	1913	--	41	--	--	--	15	14.4
2006-10	Oahu Sugar	1923	160	41	-19	--	-119	13	14.4
2006-11	Oahu Sugar	1923	160	41	-16	--	-119	15	14.4
2006-12	Honolulu Board of Water Supply	1938	150	138	30	--	-12	17	14.46
2006-13	West Beach Estate	1986	120	58	0	--	-62	13	14.53
2006-14	Honolulu Board of Water Supply	1988	285	179	-49	--	-106	--	14.51
2006-15	Honolulu Board of Water Supply	1988	300	195	-49	--	-105	14.3	14.51
2103-01	U.S. Navy	1942	206	210	193	--	4	--	16.2
2103-02	U.S. Navy	1942	137	140	131	--	3	--	--
2103-03	U.S. Navy	1943	204	200	--	--	-4	--	--
2103-04	U.S. Navy	1992	490	145	-90	-345	-345	14	--
2104-01	Pacific Rock Quarry	1976	176	125	-15	-35	-51	--	--
2203-01	Oahu Sugar	--	213	19	-69	--	-194	19.6	--
2203-02	Oahu Sugar	--	158	19	-69	--	-139	19.6	--
2203-03	Oahu Sugar	--	263	19	-69	--	-244	19.6	--
2203-04	Oahu Sugar	--	233	19	-69	--	-214	19.6	--
2203-05	Oahu Sugar	--	246	19	-69	--	-227	19.6	--
2203-06	Oahu Sugar	--	197	19	-69	--	-178	19.6	--
2303-01	Honolulu Board of Water Supply	1986	625	412	-138	--	-213	16	--
2303-02	Honolulu Board of Water Supply	1987	610	411	-139	--	-199	16	16.58
2303-03	Ewa Water Development Inc.	1987	534	419	-31	--	-115	17	16.33
2303-04	Ewa Water Development Inc.	1988	555	421	-34	--	-134	12.2	--
2303-05	Ewa Water Development Inc.	1989	545	432	-33	--	-113	16	16.65
2303-06	Ewa Water Development Inc.	1989	535	432	-23	--	-103	17.4	--
2303-07	Ewa Water Development Inc.	1992	1,050	300	17	-750	-750	--	--
2603-01	Hawaii Country Club	1961	991	745	19	-32	-246	23.6	--
2703-01	Del Monte	1946	976	847	221	-129	-129	24.9	--

SUMMARY AND CONCLUSIONS

The effect on the regional ground-water system of southern Oahu from increased pumpage at Barbers Point shaft was estimated by a numerical ground-water model developed for the Oahu Regional Aquifer Systems Analysis (RASA) study. The RASA model was updated by revising pumpage and ground-water recharge data. Pumpage data used in the new simulations are based on allocated pumping rates for 1995 as set by the State Commission on Water Resource Management. These pumping rates were selected as best representing near-future conditions because of a reduction in agricultural demand and a scheduled reduction in allocations through 1995. Recharge in the new simulations was adjusted for changing irrigation practices. It is expected that a reduction in irrigation will reduce that component of recharge from irrigation-return water to the aquifer. To provide a conservative estimate of the changes, the irrigation-return component of recharge was reduced to zero.

From results of numerical simulations, regional ground-water levels are estimated to decline about 0.4 to 0.7 ft in the Waianae aquifer in southern Oahu as a result of increasing pumpage in Barbers Point shaft by 2 Mgal/d above the allocated rate of 2.337 Mgal/d. The corresponding rise of the freshwater-saltwater interface, as a result of ground-water-level declines, is estimated to be about 20 to 30 ft. Greatest drawdowns in water level and induced rise in the interface would be expected near the shaft. Model estimates also indicate that changes in ground-water levels greater than about 0.1 ft do not extend across either the Waianae-Koolau unconformity or the southern Schofield barrier. In addition, the estimated declines in ground-water levels throughout the aquifer are small compared with the thickness of the freshwater lens and these declines would not be expected to affect the yields of other wells in terms of quantity. On the basis of numerical simulation, Barbers Point shaft can sustain a withdrawal rate of 4.34 million gallons per day without adversely affecting wells in the Waianae aquifer.

The model-estimated position of the freshwater-saltwater interface ranges from 500 to 860 ft below sea level in the southern and northern parts of the aquifer, respectively, and about 540 ft below sea level at the shaft. The thickness of the transition zone above the interface in the Waianae aquifer is about 300 ft. Therefore, the freshwater lens would remain about 240 ft thick below the shaft. Because of the lack of knowledge on the depth and thickness of the transition zone in the Waianae aquifer, these values can be considered an estimate of the actual thickness of freshwater above the transition zone throughout the aquifer.

Chloride concentrations in water pumped at Barbers Point shaft during 1992 were about 240 mg/L. This relatively high concentration probably results directly from recharge water that has high chloride concentrations rather than from saltwater intrusion by upward movement of the transition zone. Rainfall and irrigation for sugarcane crops are the sources of ground-water recharge. The estimated background chloride concentration is 200 to 220 mg/L because of the low rainfall and the contamination of recharge water from natural salt accumulation in the soil. The chloride concentrations above background are believed to be a result of irrigation-return water that has chloride concentrations estimated at 400 to 500 mg/L. Reductions in the allocated rates of pumping scheduled through 1995 are a result of reduced use of ground water for sugarcane irrigation near the shaft and in the southern part of the aquifer. A reduction in irrigation is expected to reduce recharge to the aquifer from irrigation-return water, as well as reduce chloride concentrations throughout the Waianae aquifer. As a result of these combined effects, chloride concentrations of water pumped from the Barbers Point shaft are anticipated to decrease, although the length of time required for this lowering is unknown.

REFERENCES CITED

Eyre, P.R., 1987, Source of salts in the Waianae part of the Pearl Harbor aquifer near Barbers Point water tunnel, Oahu, Hawaii: U.S. Geological Survey Water-Resources Investigations Report 87-4247, 48 p.

Eyre, P.R., and Nichols, W.D., in press, Regional analysis of the southern Oahu ground-water flow system, Hawaii: U.S. Geological Survey Open-File Report 94-513.

Giambelluca, T.W., 1986, Land-use effects on the water balance of a tropical island: National Geographic Research, v. 2, no. 2, p 125-151.

Hunt, C.D., Jr., Ewart, C.J., and Voss, C.I., 1988, Region 27, Hawaiian Islands, chap. 30 of Back, William, Rosenshein, J.S., and Seaber, P.R., eds., Hydrogeology: Boulder, Colorado, Geological Society of America, The Geology of North America, v. O-2.

Lao, Chester, 1975, Behavior of basal water sources as interpreted from periodic logging of deep monitoring wells: Water Resources Seminar Series No. 8, University of

Hawaii, Honolulu, Hawaii, 18 p.
Mink, J.F., 1980, State of the groundwater resources of southern Oahu: Honolulu Board of Water Supply, Honolulu, Hawaii, 83 p.
Mink, J.F., Yuen, G.A.L., and Chang, J.Y.C., 1988, Review and re-evaluation of groundwater conditions in the Pearl Harbor Groundwater Control Area, Oahu, Hawaii: Honolulu, Hawaii, George A.L. Yuen and Associates, Inc., 95+ p.
Multhaup, R.A., Voss, C.I., and Souza, W.R., in press, Subsurface mapping of basalts based on petrographic characterization of cuttings from borehole drilling on Oahu, Hawaii: U.S. Geological Survey Water-Resources Investigations Report 89-4181.
Nance, Tom, 1993, Results of an extended pump test at Honouliuli wells I and II: Honolulu, Hawaii, Water Resource Engineering, 18 p., 1 app. [Available from Ewa Plain Water Development Corporation, 828 Fort Street Mall - Suite 500, Honolulu, HI 96813]
Prickett, T.A., 1967, Designing pumped well characteristics into electric-analog models: Ground Water, v. 5, no 4, p. 38-46.
Soroos, R.L., and Ewart, C.J., 1979, Ground-water status report, Pearl Harbor area, Hawaii, 1978: U.S. Geological Survey Water-Resources Investigations Report 79-1542, 3 sheets.
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.
Voss, C.I., 1984, AQUIFEM-SALT, A finite-element model for aquifers containing a seawater interface: U.S. Geological Survey Water-Resources Investigations Report 84-4263, 37 p.
Wentworth, C.K., 1951, Geology and ground-water resources of Honolulu-Pearl Harbor area, Oahu, Hawaii: Honolulu Board of Water Supply, Honolulu, Hawaii, 111 p.