Geohydrology of the Central Oahu, Hawaii, Ground-Water Flow System and Numerical Simulation of the Effects of Additional Pumping

By Delwyn S. Oki

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Conversion Factors

Multiply	By	To obtain
foot (ft)	0.3048	meter
foot per mile (ft/mi)	0.1894	meter per kilometer
foot per day (ft/d)	0.3048	meter per day
square foot per day (ft^2/d)	0.09290	square meter per day
foot per day per foot (ft/d)/ft	1	meter per day per meter
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon (gal)	0.003785	cubic meter
gallon per day (gal/d)	3.785	liter per day
million gallons (Mgal)	3,785	cubic meter
million gallons per day (Mgal/d)	0.04381	cubic meter per second
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
inch (in.)	25.4	millimeter
inch per year (in/yr)	2.54	centimeter per year

Water temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by using the equation:

$$°F = 1.8 \times °C + 32$$

Air temperature is given in degrees Fahrenheit (°F), which can be converted to degrees Celsius (°C) by using the following equation:

$$°C = (°F - 32) / 1.8$$

Abbreviations used in water quality descriptions:

mg/L, milligrams per liter

µS/cm, microsiemen per centimeter at 25° Celsius

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Abstract

A two-dimensional, finite-difference, ground-water flow model was developed for the central Oahu flow system, which is the largest and most productive ground-water flow system on the island. The model is based on the computer code SHARP which simulates both freshwater and saltwater flow. The ground-water model was developed using average pumping and recharge conditions during the 1950's, which was considered to be a steady-state period. For 1950's conditions, model results indicate that 62 percent (90.1 million gallons per day) of the discharge from the Schofield ground-water area flows southward and the remaining 38 percent (55.2 million gallons per day) of the discharge from Schofield flows northward. Although the contribution of recharge from infiltration of rainfall and irrigation water directly on top of the southern and northern Schofield ground-water dams was included in the model, the distribution of natural discharge from the Schofield ground-water area was estimated exclusive of the recharge on top of the dams.

The model was used to investigate the long-term effects of pumping under future land-use conditions. Future recharge was conservatively estimated by assuming no recharge associated with agricultural activities. Future pumpage used in the model was based on the 1995-allocated rates. Model results indicate that the long-term effect of pumping at the 1995-allocated rates will be a reduction of water levels from present (1995) conditions in all ground-water areas of the central Oahu flow system. In the Schofield ground-water area, model results indicate that water levels could decline about 30 feet from the 1995 water-level altitude of about 275 feet. In the remaining ground-water areas of the central Oahu flow system, water levels may decline from less than 1 foot to as much as 12 feet relative to 1995 water levels. Model results indicate that the bottoms of several existing deep wells in northern and southern Oahu extend below the model-calculated freshwater-saltwater interface location for the future recharge and pumping conditions.

Model results indicate that an additional 10 million gallons per day (beyond the 1995-allocated rates) of freshwater can potentially be developed from northern Oahu. Various distributions of pumping can be used to obtain the additional 10 million gallons per day of water. The quality of the water pumped will be dependent on site-specific factors and cannot be predicted on the basis of model results. If the additional 10 million gallons per day pumpage is restricted to the Kawailoa and Waialua areas, model results indicate that a regional drawdown (relative to the water-level distribution associated with the 1995-allocated pumping rates) of less than 0.6 foot can be maintained in these two areas. The additional pumping, however, would cause salinity increases in water pumped by existing deep wells. In addition, increases in salinity may occur at other wells in areas where the model indicates no significant problem with upconing.

INTRODUCTION

On the island of Oahu, Hawaii (fig. 1), the central Oahu ground-water flow system (fig. 2) (Hunt, 1996) is the largest and most productive flow system. The cen-

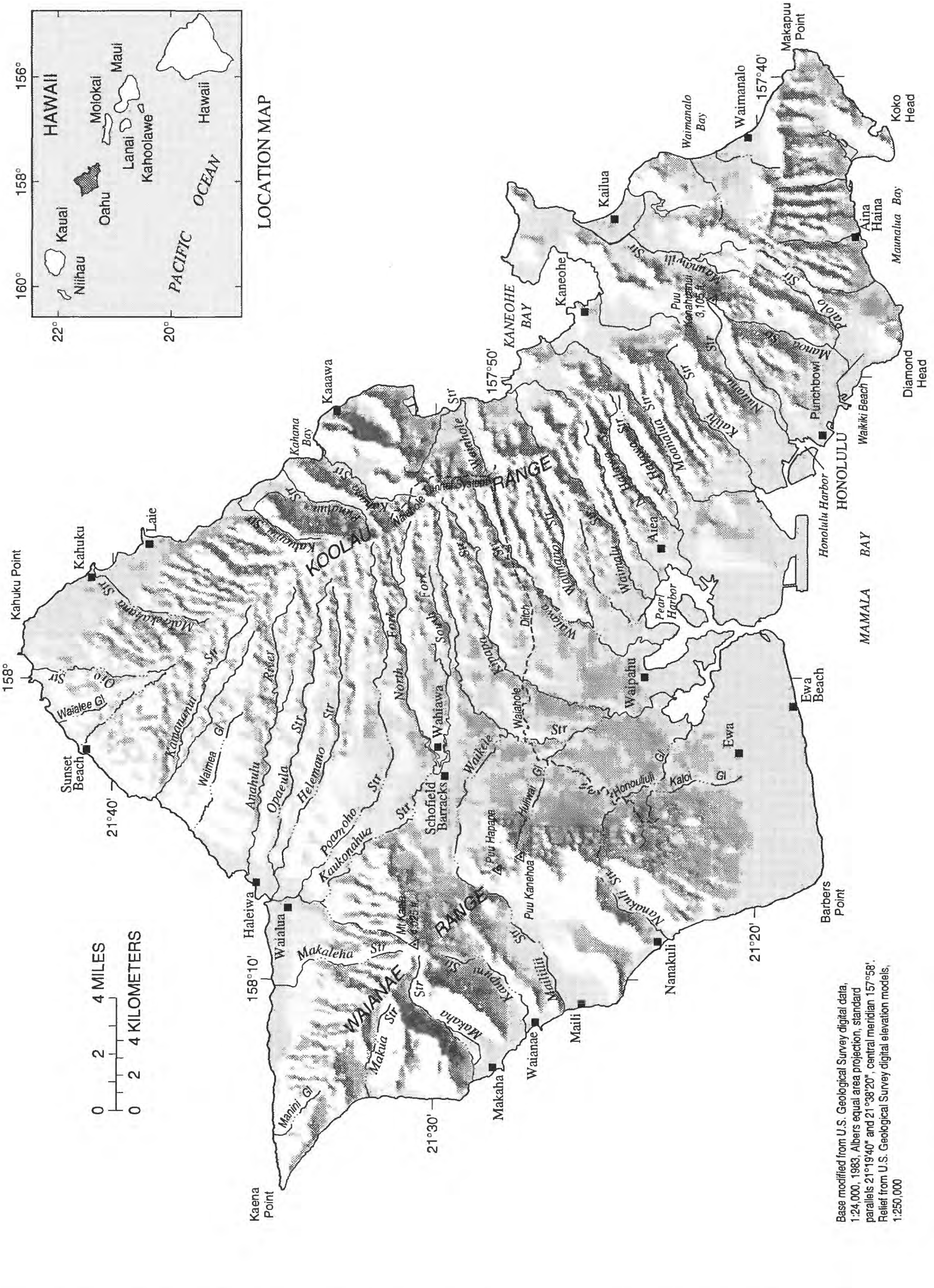


Figure 1. Geographic features, island of Oahu, Hawaii.

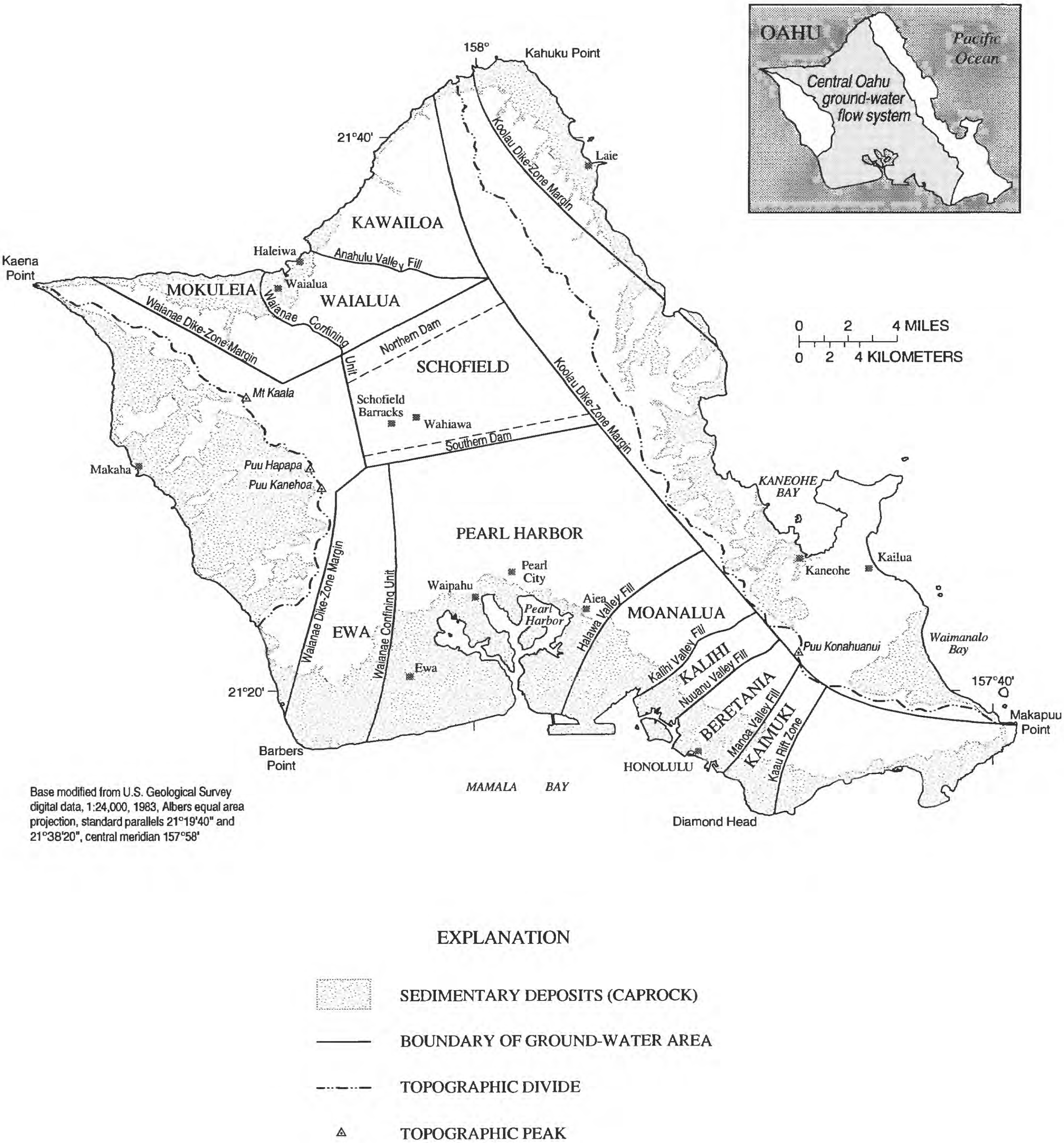


Figure 2. Ground-water areas within the central Oahu ground-water flow system, Oahu, Hawaii.

tral Oahu flow system is bounded on the east by the crest of the Koolau Range, on the southeast by the Kaau rift zone, on the south by the deposits and rocks that form a coastal caprock, on the west by the crest of the Waianae Range, and on the north by a coastal caprock, which generally thins toward the northeast. The Mokuleia, Waialua, and Kawailoa ground-water areas are in the northern part of the flow system, and the Ewa, Pearl Harbor, Moanalua, Kalihi, Beretania, and Kaimuki ground-water areas are in the southern part of the flow system. The Schofield ground-water area separates the northern and southern parts of the central Oahu flow system. For a mid-1980's land-use scenario, Shade and Nichols (1996) estimated that about 72 percent of the total ground-water recharge to the island of Oahu was from the central Oahu flow system. Since 1925, when reliable pumping records first became available, ground-water pumpage from the volcanic aquifers of the flow system has ranged from a low of 196 Mgal/d in 1927 to a high of 368 Mgal/d in 1977. During the 12-month period prior to July 1995, average pumpage from the volcanic aquifers of this flow system was about 198 Mgal/d (Neal Fujii, Commission on Water Resource Management, written commun., 1995).

As the population of Oahu increased from 21,275 in 1860 to 836,231 in 1990 (State of Hawaii, 1994), the demand for potable water also increased. Currently, operations associated with large- and small-scale agriculture, the military, golf courses and parks, resorts, and other industries compete for the finite water resources of the island. With this increased demand for ground water comes a need to better estimate ground-water availability on Oahu.

During the early stages of ground-water development on Oahu, the need to estimate ground-water availability was clearly recognized. In 1880, when the first flowing artesian well was drilled in the Beretania area of Honolulu, the freshwater head beneath the coastal caprock was about 42 ft above mean sea level (McCully, 1882). By 1900, freshwater head in the Beretania area had declined to 33 ft and by 1920, head had further declined to 26 ft above mean sea level. Because of this decline in head, some artesian wells ceased to flow, and other wells showed a reduction of flow or an increase in salinity. These factors led to the first attempts to estimate a sustainable yield for the area.

For periods of assumed zero recharge, McCombs (1927) estimated that a withdrawal of 42 Mgal/d would cause a head decline of 0.01 ft/d in the Beretania ground-water area. From 1906–26, the head in the area declined about 8 ft, which is equivalent to a rate of decline of about 0.0011 ft/d. Thus, McCombs suggested that during the period 1906–26, the withdrawals exceeded the sustainable yield by 4.6 Mgal/d. Because the average withdrawals during 1906–26 totaled 20 Mgal/d, and the estimated withdrawals in excess of the sustainable yield totaled 4.6 Mgal/d, McCombs concluded that the sustainable yield for the area was 15.4 Mgal/d. Kunesh (1929) estimated the sustainable yield for the Beretania area during 1928 to be 19 Mgal/d by equating sustainable yield with withdrawals for a period in which the head in the aquifer is exactly the same at the beginning as at the end. Stearns and Vaksvik (1935, p. 326), using the approach of Kunesh (1929) with more reliable withdrawal data and well casing leakage information, estimated the sustainable yield for the area to be 13.2 Mgal/d during 1929 and 1930. Using a multiple correlation analysis, Wentworth (1951) estimated the sustainable yield of the Beretania area to be 10.42 Mgal/d for an average head of 29.9 ft and 19.54 Mgal/d for a head of 22.3 ft. None of these sustainable yield estimates account for the effects of withdrawals from adjacent, hydrologically connected ground-water areas.

Numerous studies have been conducted to address the issue of ground-water availability for other areas within the central Oahu ground-water flow system. Some of these studies provide estimates of ground-water recharge from the plant root-zone system (Giambelluca, 1983; Shade and Nichols, 1996), and others consider hydrologic budgets that account for recharge, withdrawals, and natural ground-water discharge (Dale and Takasaki, 1976; Broadbent, 1980). More recent studies combine recharge estimates with analytical (Mink and others, 1988) or numerical (Eyre and Nichols, in press; Evans and others, 1995) ground-water flow models. Of the latter studies, none have considered the central Oahu flow system in its entirety.

In cooperation with the City and County of Honolulu Board of Water Supply, the U.S. Geological Survey (USGS) undertook an investigation of ground-water availability in northern Oahu. The primary area of concern includes the Mokuleia, Waialua, and Kawailoa ground-water areas (fig. 2). However, because the degree of hydrologic connection between these areas and the Schofield ground-water area was unknown, it was necessary to develop a ground-water model of the entire central Oahu flow system. The objectives of this study were to (1) obtain a better understanding of the central Oahu flow system, (2) estimate the distribution of flow from the Schofield ground-water area, and (3) determine the effects of additional pumping from northern Oahu.

Purpose and Scope

The purpose of this report is to describe (1) the geologic and hydrologic setting of the study area on the basis of available data and published information, (2) the numerical ground-water flow model developed, and (3) the results of model simulations to assess the effects of additional withdrawals, at rates in excess of 1995-allocated withdrawal rates, from northern Oahu.

Well-Numbering System

Wells mentioned in this report are numbered according to the State of Hawaii numbering system. Well numbers contain seven digits and are based on a latitude-longitude one-minute grid system. Well numbers are of the form:

a-bbcc-dd,

where:

a is the island code;

bb is the minutes of latitude of the southeastern corner of the one-minute grid;

cc is the minutes of longitude of the southeastern corner of the one-minute grid; and

dd is the sequential well number within the one-minute grid.

An island code of "3" is used for all wells on Oahu and is omitted in this report. The locations of all wells mentioned in this report are shown in figure 3, and the corresponding well numbers sorted in ascending order are listed in table 1.

Description of Study Site

Physical Setting

The island of Oahu, which has an area of 604 mi^2, is the third largest island of the State of Hawaii and is located between longitude 158°20′W and 157°35′W and between latitude 21°15′N and 21°45′N. The island is formed by the eroded remnants of the Waianae and Koolau shield volcanoes. The Waianae Range, which is the eroded remnant of the older Waianae Volcano, forms the western part of the island and has a peak altitude of 4,025 ft at Mount Kaala, the highest peak on Oahu. The younger Koolau Range forms the eastern part of Oahu and has a peak altitude of 3,105 ft at Puu Konahuanui. The central Oahu ground-water flow system lies between the crests of the Koolau and Waianae Ranges (fig. 1).

Land Use

Land use on Oahu is classified into conservation, urban, rural, and agricultural areas. The conservation areas have always been located primarily in the upper, high-rainfall areas of the Koolau and Waianae Ranges. The urban, rural, and agricultural areas are located near the coast and in the central saddle between the Waianae and Koolau Ranges. Before the 1879 discovery of artesian water on the dry southern coast of Oahu, urbanization on the island was restricted primarily to the Honolulu area and agriculture was mainly in the form of wetland crops, such as taro and rice, and small-scale farming. With the development of ground water, urbanization spread outward from Honolulu and large-scale agricultural operations were started. In 1880, there were 4.1 mi^2 planted in sugarcane by nine growers on Oahu (Stearns and Vaksvik, 1935). By 1900, there were 23.4 mi^2 planted in sugarcane on Oahu, and by 1937 this increased to 67.5 mi^2 (Vaksvik, 1939). In 1992, sugarcane was being grown on 35.2 mi^2 by two plantations (State of Hawaii, 1994). In October 1996, Waialua Sugar Company, the last remaining sugarcane plantation on Oahu, harvested its final crop. On Oahu, sugarcane was typically grown at altitudes of a few feet to about 900 ft. However, unirrigated sugarcane was cultivated at higher altitudes up to about 1,250 ft.

Pineapple cultivation is the other large-scale agricultural venture on Oahu. About 0.9 mi^2 of land were planted in pineapple in 1900, and this increased to about 23.4 mi^2 by 1937 (Vaksvik, 1939). In 1992, about 18.9 mi^2 were planted in pineapple (State of Hawaii, 1994). Pineapples are typically cultivated at altitudes of 300 to 1,400 ft, on lands above sugarcane irrigation ditches.

In recent years, the land-use pattern on Oahu has been marked by a gradual shift away from agricultural uses toward increased urbanization. For instance,

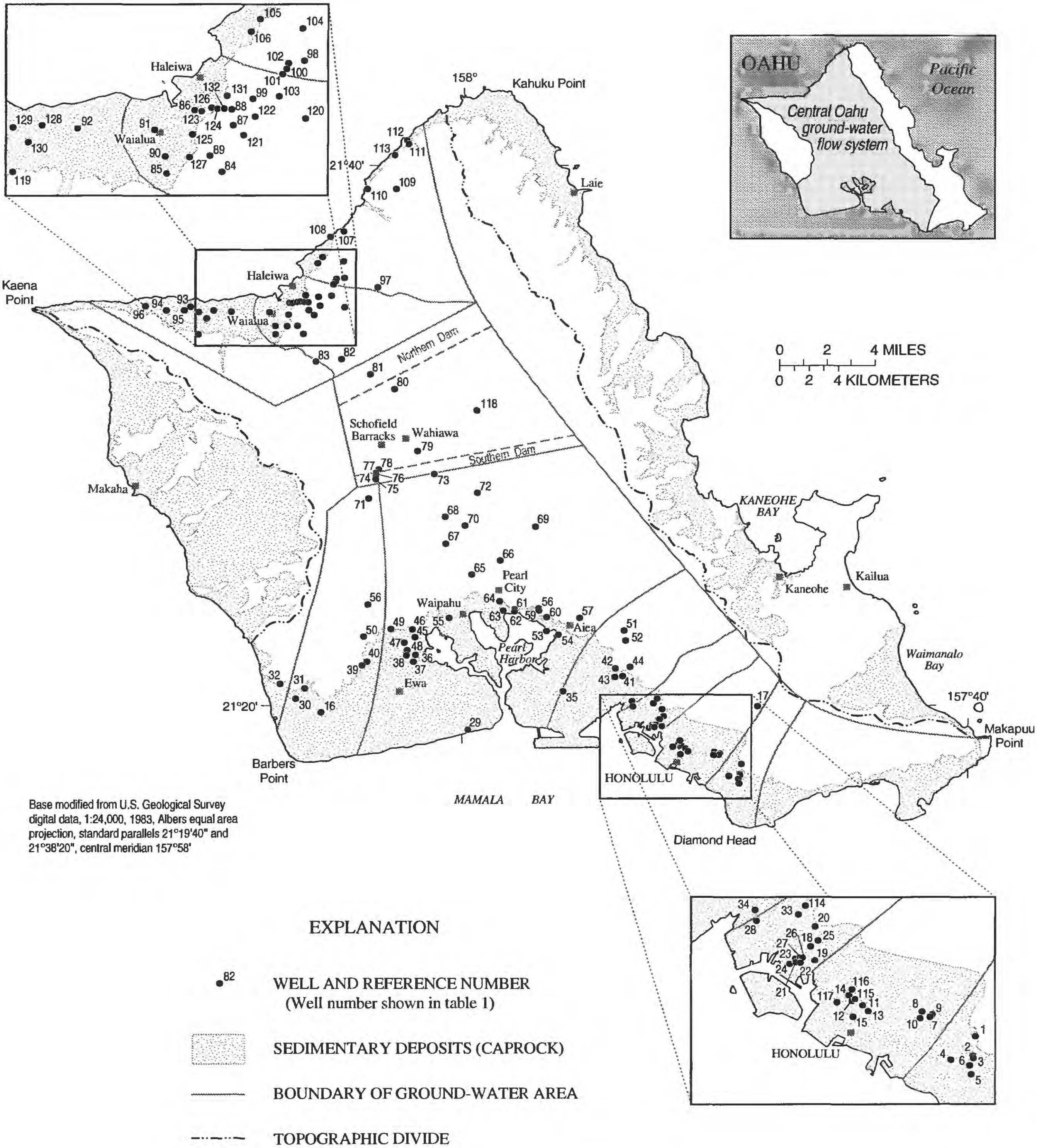


Figure 3. Well locations and reference numbers, central Oahu ground-water flow system, Hawaii.

Table 1. Wells in the central Oahu ground-water flow system, Hawaii

Well no.	Map no. (fig. 3)	Longitude	Latitude	Ground-water area
1748-01	1	157°48′54″W	21°17′50″N	Kaimuki
1748-03	2	157°48′58″W	21°17′27″N	Kaimuki
1748-11	3	157°48′58″W	21°17′27″N	Kaimuki
1749-11	4	157°49′23″W	21°17′23″N	Kaimuki
1749-16	5	157°49′02″W	21°17′09″N	Kaimuki
1749-18	6	157°49′00″W	21°17′15″N	Kaimuki
1849-01	7	157°49′50″W	21°18′12″N	Beretania
1849-05	8	157°49′58″W	21°18′16″N	Beretania
1849-11	9	157°49′47″W	21°18′13″N	Beretania
1850-13	10	157°50′00″W	21°18′10″N	Beretania
1851-02	11	157°51′07″W	21°18′24″N	Beretania
1851-12, -13, -24, -25, -31 to -35, -67	115	157°21′20″W	21°18′31″N	Beretania
1851-20	12	157°51′20″W	21°18′28″N	Beretania
1851-28	13	157°51′03″W	21°18′18″N	Beretania
1851-54	116	157°51′22″W	21°18′42″N	Beretania
1851-57	14	157°51′22″W	21°18′33″N	Beretania
1851-58	15	157°51′20″W	21°18′12″N	Beretania
1851-73	117	157°51′39″W	21°18′28″N	Beretania
1905-04	16	158°05′34″W	21°19′45″N	Ewa
1948-01	17	157°48′18″W	21°19′59″N	Beretania
1952-01	18	157°52′09″W	21°19′30″N	Kalihi
1952-03	19	157°52′06″W	21°19′16″N	Kalihi
1952-05	20	157°52′03″W	21°19′52″N	Kalihi
1952-11	21	157°52′22″W	21°19′15″N	Kalihi
1952-12	22	157°52′20″W	21°19′13″N	Kalihi
1952-13	23	157°52′24″W	21°19′16″N	Kalihi
1952-14	24	157°52′30″W	21°19′12″N	Kalihi
1952-15	25	157°52′00″W	21°19′36″N	Kalihi
1952-20	26	157°52′20″W	21°19′17″N	Kalihi
1952-21	27	157°52′22″W	21°19′17″N	Kalihi
1953-01	28	157°53′13″W	21°19′58″N	Kalihi
1959-05	29	157°59′47″W	21°19′07″N	Pearl Harbor
2006-01 to -11	30	158°06′36″W	21°20′16″N	Ewa
2006-12	31	158°06′15″W	21°20′38″N	Ewa
2007-01	32	158°07′12″W	21°20′50″N	not in a named area
2052-06	33	157°52′24″W	21°20′05″N	Kalihi
2052-10	114	157°52′15″W	21°20′15″N	Kalihi
2053-08	34	157°53′15″W	21°20′10″N	Moanalua
2056-03	35	157°56′01″W	21°20′33″N	Moanalua
2101-03	36	158°01′52″W	21°21′54″N	Pearl Harbor
2101-04	37	158°01′57″W	21°21′40″N	Pearl Harbor
2102-02, -04 to -22	38	158°02′12″W	21°21′52″N	Pearl Harbor
2103-01	39	158°03′57″W	21°21′32″N	Ewa
2103-02	40	158°03′46″W	21°21′38″N	Ewa
2153-02	41	157°53′37″W	21°21′06″N	Moanalua
2153-05	42	157°53′54″W	21°21′25″N	Moanalua
2153-06	43	157°53′56″W	21°21′05″N	Moanalua
2153-09	44	157°53′20″W	21°21′27″N	Moanalua
2201-03, -04, -07	45	158°01′53″W	21°22′34″N	Pearl Harbor
2201-10	46	158°01′58″W	21°22′50″N	Pearl Harbor
2202-03 to -14	47	158°02′18″W	21°22′20″N	Pearl Harbor
2202-15 to -20	48	158°02′12″W	21°22′04″N	Pearl Harbor
2202-21	49	158°02′50″W	21°22′52″N	Pearl Harbor
2203-01 to -06	50	158°03′54″W	21°22′34″N	Ewa
2253-01	51	157°53′34″W	21°22′48″N	Moanalua
2253-02	52	157°53′30″W	21°22′25″N	Moanalua
2256-04	53	157°56′38″W	21°22′47″N	Pearl Harbor
2256-10	54	157°56′11″W	21°22′38″N	Pearl Harbor
2300-10	55	158°00′30″W	21°23′17″N	Pearl Harbor
2303-06	56	158°03′46″W	21°23′47″N	Ewa
2355-01	57	157°55′20″W	21°23′16″N	Pearl Harbor
2356-02	58	157°56′57″W	21°23′37″N	Pearl Harbor
2356-45	59	157°56′56″W	21°23′34″N	Pearl Harbor
2356-47	60	157°56′38″W	21°23′17″N	Pearl Harbor
2357-10 to -12	61	157°57′56″W	21°23′35″N	Pearl Harbor
2357-13	62	157°57′56″W	21°23′33″N	Pearl Harbor

Table 1. Wells in the central Oahu ground-water flow system, Hawaii--Continued

Well no.	Map no. (fig. 3)	Longitude	Latitude	Ground-water area
2358-02	63	157°58′22″W	21°23′32″N	Pearl Harbor
2358-20	64	157°58′31″W	21°23′53″N	Pearl Harbor
2459-15	65	157°59′38″W	21°24′52″N	Pearl Harbor
2558-08	66	157°58′30″W	21°25′23″N	Pearl Harbor
2600-01	67	158°00′40″W	21°26′01″N	Pearl Harbor
2600-04	68	158°00′42″W	21°26′59″N	Pearl Harbor
2657-02	69	157°57′07″W	21°26′39″N	Pearl Harbor
2659-01	70	157°59′53″W	21°26′40″N	Pearl Harbor
2703-01	71	158°03′42″W	21°27′41″N	Ewa
2759-02	72	157°59′25″W	21°27′53″N	Pearl Harbor
2801-01	73	158°01′09″W	21°28′35″N	Pearl Harbor
2803-01	74	158°03′27″W	21°28′30″N	Schofield southern dam
2803-02	75	158°03′28″W	21°28′28″N	Schofield southern dam
2803-03	76	158°03′27″W	21°28′35″N	Schofield southern dam
2803-05	77	158°03′27″W	21°28′38″N	Schofield
2803-06	78	158°03′22″W	21°28′45″N	Schofield
2901-01 to -07, -10	79	158°01′48″W	21°29′27″N	Schofield
3059-02	118	157°59′25″W	21°30′56″N	Schofield
3102-01, -02	80	158°02′43″W	21°31′46″N	Schofield
3203-01	81	158°03′43″W	21°32′18″N	Schofield northern dam
3204-01	82	158°04′51″W	21°32′52″N	Waialua
3205-02	83	158°05′52″W	21°32′45″N	Mokuleia
3306-01 to -12	84	158°06′22″W	21°33′48″N	Waialua
3307-01 to -14	85	158°07′27″W	21°33′45″N	Waialua
3310-02	119	158°10′29″W	21°33′47″N	Mokuleia
3404-02	120	158°04′44″W	21°34′46″N	Waialua
3405-01, -02	121	158°05′56″W	21°34′28″N	Waialua
3405-03, -04	122	158°05′43″W	21°34′49″N	Waialua
3406-01	86	158°06′53″W	21°34′55″N	Waialua
3406-02	123	158°06′47″W	21°34′55″N	Waialua
3406-03	124	158°06′28″W	21°34′57″N	Waialua
3406-04	87	158°06′08″W	21°34′39″N	Waialua
3406-06	125	158°06′57″W	21°34′29″N	Waialua
3406-08	126	158°06′35″W	21°34′59″N	Waialua
3406-12	88	158°06′10″W	21°34′56″N	Waialua
3406-13	89	158°06′36″W	21°34′05″N	Waialua
3406-14, -15	132	158°06′21″W	21°34′58″N	Waialua
3407-01, -11, -12, -18, -19	127	158°07′01″W	21°34′05″N	Waialua
3407-04 to -06, -14, -15	90	158°07′28″W	21°34′02″N	Waialua
3407-07 to -10, -13, -16, -17, -20, -21	91	158°07′41″W	21°34′35″N	Waialua
3409-01, -13	128	158°09′54″W	21°34′39″N	Mokuleia
3409-16	92	158°09′11″W	21°34′36″N	Mokuleia
3410-01	129	158°10′28″W	21°34′36″N	Mokuleia
3410-03	130	158°10′10″W	21°34′21″N	Mokuleia
3410-08	93	158°10′49″W	21°34′46″N	Mokuleia
3411-01	94	158°11′46″W	21°34′39″N	Mokuleia
3411-04, -06 to -11, -13	95	158°11′02″W	21°34′39″N	Mokuleia
3412-01, -02	96	158°12′34″W	21°34′48″N	Mokuleia
3503-01	97	158°03′25″W	21°35′30″N	Kawailoa
3504-01	98	158°04′44″W	21°35′53″N	Kawailoa
3505-01 to -20	99	158°05′45″W	21°35′08″N	Waialua
3505-21	100	158°05′05″W	21°35′41″N	Waialua
3505-22	101	158°05′10″W	21°35′36″N	Waialua
3505-25	102	158°05′04″W	21°35′46″N	Kawailoa
3505-26	103	158°05′14″W	21°35′11″N	Waialua
3506-03, -04	131	158°06′16″W	21°35′11″N	Waialua
3604-01	104	158°04′46″W	21°36′26″N	Kawailoa
3605-01 to -23	105	158°05′37″W	21°36′36″N	Kawailoa
3605-25	106	158°05′47″W	21°36′23″N	Kawailoa
3704-01	107	158°04′48″W	21°37′34″N	Kawailoa
3705-01	108	158°05′17″W	21°37′22″N	Kawailoa
3902-01	109	158°02′42″W	21°39′09″N	Kawailoa
3903-01	110	158°03′51″W	21°39′08″N	Kawailoa
4002-01	111	158°02′14″W	21°40′49″N	Kawailoa
4002-02	112	158°02′17″W	21°40′57″N	Kawailoa
4002-06	113	158°02′46″W	21°40′24″N	Kawailoa

between 1968 and 1993, lands classified as urban on Oahu increased from 88.8 mi^2 (State of Hawaii, 1975) to 148.8 mi^2 (Oliver, 1995). The impetus for this trend is the continually increasing population on the island as well as the increased costs associated with maintaining large-scale sugarcane and pineapple operations, declining subsidies, and global competition. Lands formerly in sugarcane are expected to be used for diversified agriculture or converted to urban areas.

Climate

The climate of Oahu is characterized by mild temperatures, cool and persistent tradewinds, a rainy winter season from October through April, and a dry summer season from May through September (Blumenstock and Price, 1967). Climate is controlled primarily by topography and the location of the north Pacific anticyclone relative to the island. During the dry summer season the stability of the north Pacific anticyclone produces persistent northeasterly winds known locally as tradewinds. Summer tradewinds blow 80 to 95 percent of the time. During the rainy season migratory high-pressure systems often move past the Hawaiian islands resulting in less persistent tradewinds. Winter tradewinds blow 50 to 80 percent of the time. Southerly winds associated with low-pressure systems can bring heavy rains to the island. The dry coastal areas receive much of their rainfall as a result of these low-pressure systems.

Temperature

The mild temperatures around the State of Hawaii are attributed to the large heat capacity of the surrounding ocean. At the Honolulu International Airport, on the basis of data from 1961–90, the warmest month of the year is August, which has a mean temperature of 80.5°F, and the coolest month is February, which has a mean temperature of 72.0°F (Nullet and Sanderson, 1993). The small temperature difference between the warmest and coolest months is largely attributed to the buffering effect of the surrounding ocean, the persistence of the cool tradewinds, and the small variation in solar radiation (Blumenstock and Price, 1967).

For Hawaii, the average lapse rate, or decline of temperature with altitude, has been estimated to be 3.6°F per 1,000 ft below an altitude of 3,900 ft and 3.0°F per 1,000 ft above an altitude of 3,900 ft (Nullet and Sanderson, 1993). At an altitude of about 6,500 ft, a temperature inversion exists because of the compressional heating of subsiding air. As the warm subsiding air meets cooler air from below, a stable layer forms in which temperature increases with altitude. This inversion is associated with the general air-circulation pattern in the Pacific and affects climate at higher altitudes.

Rainfall

Rainfall on Oahu is characterized by maxima at high altitudes and steep spatial gradients (fig. 4). Maximum mean annual rainfall on Oahu is near the crest of the Koolau Range and exceeds 275 in. Over the Waianae Range, the maximum mean annual rainfall is about 80 in. near Mount Kaala. Near the coastal areas of southern and western Oahu, mean annual rainfall may be less than 25 in., and near the northern coast of the island in the vicinity of Waialua, mean annual rainfall is as low as 30 in. For comparison, mean annual rainfall over the open ocean is estimated to be between 21.7 in. and 27.6 in. (Elliot and Reed, 1984; Dorman and Bourke, 1979).

The spatial distribution of rainfall on Oahu is greatly affected by topography. The orientation of the Koolau Range is roughly perpendicular to the direction of the persistent northeasterly tradewinds, which makes the Koolau Range an effective barrier to air flow. Warm, moisture-laden air flowing over the ocean from the northeast is forced up the slopes of the Koolau Range. As the warm air is orographically lifted, cooling causes condensation and cloud formation. These clouds are responsible for the high mean annual rainfall totals measured near the crest of the Koolau Range. The rainfall maximum actually is located slightly leeward of the Koolau crest. This "has been attributed to the continuation of the upward air trajectory as it crests the ridge and its subsequent rapid downturning, which concentrates the release of raindrops in a zone slightly leeward of the summit" (Ramage, C.S., *in* Giambelluca and others, 1986, p. 16). Following its descent down the leeward slopes of the Koolau Range, the partially desiccated air is orographically lifted up the slopes of the Waianae Range, which results in a smaller rainfall maximum near Mount Kaala. Because air loses moisture as it flows over the Koolau and Waianae Ranges, the driest areas on Oahu are along the southern and western coasts. This is commonly known as the rain-shadow effect.

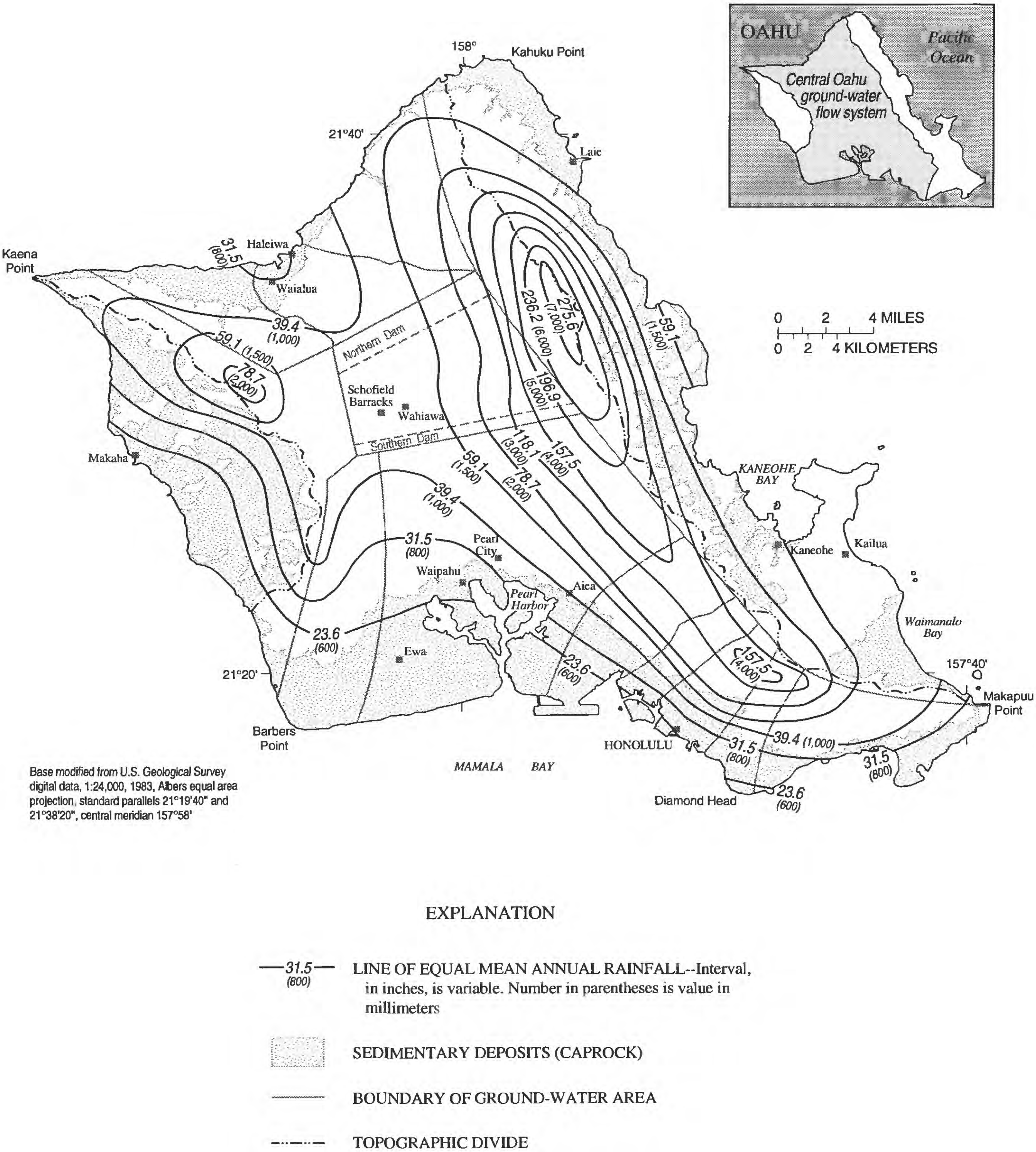


Figure 4. Mean annual rainfall, Oahu, Hawaii (modified from Giambelluca and others, 1986).

Evaporation

Over the open ocean, the estimated evaporation rate is about 65 in/yr (Seckel, 1962). Over the island of Oahu, pan evaporation minima exist at the higher altitudes of the Koolau and Waianae Ranges (fig. 5). Near the crest of the Koolau Range, mean annual pan evaporation may be as low as 20 in. Pan evaporation rates are highest along the southern coast of the island, and may exceed 90 in/yr.

As with rainfall, pan evaporation rates on Oahu are related to topography. At higher altitudes near the crests of the Koolau and Waianae Ranges, high humidity, low sunlight intensity caused by clouds, and cooler temperatures result in lower pan evaporation rates. Pan evaporation rates along the southern coast of Oahu exceed the open ocean rate because of positive heat advection (Ekern and Chang, 1985). Evaporation rates are highest during the dry summer season when maximum sunlight and tradewind flow also are highest (Ekern and Chang, 1985).

HYDROGEOLOGY

The island of Oahu is formed primarily by the shield-stage lavas of the older Waianae Volcano to the west and the younger Koolau Volcano to the east, and secondarily by preshield-, postshield-, and rejuvenated-stage volcanism (Langenheim and Clague, 1987). The central saddle area between the Waianae and Koolau Volcanoes was formed by lava flows from the Koolau Volcano banking up against and being deflected by the Waianae Volcano. Each volcano has two primary rift zones and a third lesser rift zone all emanating from a collapsed caldera (fig. 6). The rift zones are marked by numerous vertical to nearly vertical intrusive dikes (Takasaki and Mink, 1985). Coastal deposits, consisting of terrestrial and marine sediments and limestone reef deposits, form coastal plains in southern and northern Oahu.

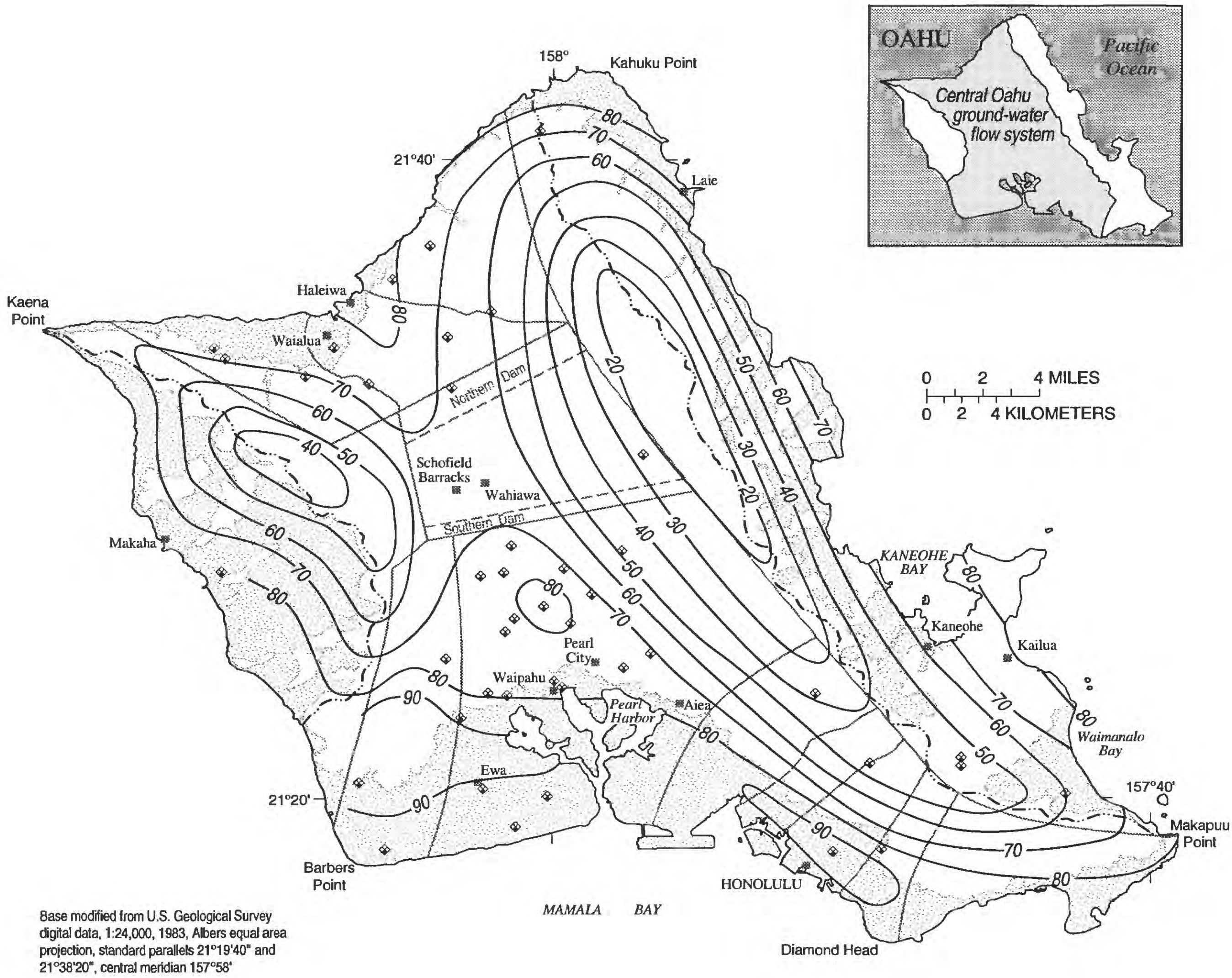
Extrusive Volcanic Rocks

Geology

Extrusive volcanic rocks consist mainly of lava flows that effused from fissures and vents. Lava flows associated with the flanks, rift zones, and calderas of the Waianae and Koolau Volcanoes form the bulk of the island of Oahu. Extrusive volcanic rocks also include pyroclastic material, such as ash, cinder, and tuff, which probably form less than 1 percent of the mass of a Hawaiian volcano (Wentworth and Macdonald, 1953).

Most lava flows emerge from fissures as pahoehoe, characterized by smooth, ropy surfaces, and can change to aa as they advance downslope. Aa flows consist of a massive central core typically sandwiched between rubbly clinker layers. Pahoehoe flows dominate near the rift zones of volcanoes, whereas aa flows dominate farther down the flanks. In the gulch at Kipapa Stream, 2 to 3 mi leeward of the Koolau rift zone, Mink and Lau (1980) found 50 to 70 percent of the rock consisted of aa. Wentworth and Winchell (1947) examined 2,000 ft of cores collected from drill holes 4 to 5 mi leeward of the Koolau rift zone and found about 75 percent aa flows.

The Waianae Volcano is made up of the Waianae Volcanics which include (1) the shield-stage lavas (Lualualei Member) of tholeiitic basalt (Sinton, 1986), (2) the transitional or late shield-stage lavas (Kamaileunu Member) of mainly tholeiitic basalt, alkalic basalt, hawaiite, and rare ankaramite (Sinton, 1986), (3) the postshield-stage lavas (Palehua Member) of hawaiite with minor alkalic basalt and mugearite (Sinton, 1986), and (4) the younger postshield-stage lavas (Kolekole Member) of alkalic basalt (Presley and others, 1997). The shield-stage lavas of the Lualualei Member form thin-bedded flows from 20- to 75-ft thick with dips of 4° to 14° (Stearns and Vaksvik, 1935). Potassium-argon dating of the Waianae Volcanics indicates an age of about 2.9 to 3.9 Ma (million years) corresponding to the Pliocene epoch (Doell and Dalrymple, 1973; Presley, 1994; Presley and others, 1997). Rocks of the Kolokole Member have an age of about 2.90 to 2.97 Ma, with a mean (nonweighted) age of 2.961 ± 0.03 Ma (Presley, 1994). The Kolekole Member was previously named the Kolekole Volcanics (Stearns, 1946; Sinton, 1986), and classified as the rejuvenated-stage alkalic lavas of the Waianae Volcano (Langenheim and Clague, 1987). On the basis of geochemical data and the nearly contemporaneous ages of the Palehua Member and Kolekole Volcanics, however, Presley and others (1997) suggested that the Kolekole Volcanics are not rejuvenated-stage lavas and do not represent a separate volcanic event from earlier postshield activity. Therefore, Presley and others (1997) reduced the rank of the Kolekole Volcanics to the Kolekole Member of the Waianae Volcanics.



EXPLANATION

—30— LINE OF EQUAL MEAN ANNUAL PAN EVAPORATION--Interval 10 inches

PAN-EVAPORATION STATION

SEDIMENTARY DEPOSITS (CAPROCK)

BOUNDARY OF GROUND-WATER AREA

TOPOGRAPHIC DIVIDE

Figure 5. Mean annual pan evaporation, Oahu, Hawaii (modified from Ekern and Chang, 1985).

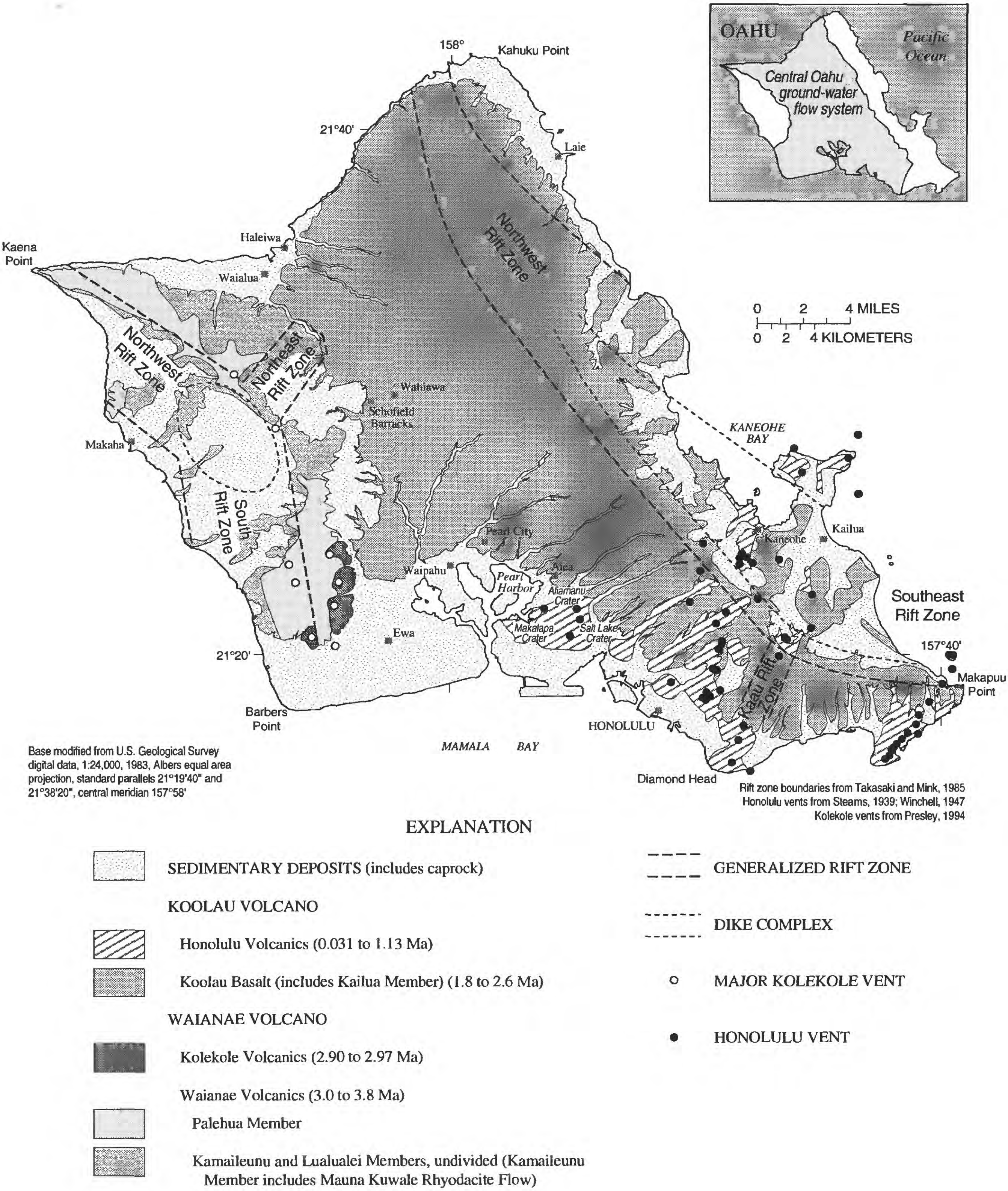


Figure 6. Generalized geology of Oahu, Hawaii (modified from Stearns and Macdonald, 1940; Stearns, 1946; Sinton, 1986; Langenheim and Clague, 1987).

Lavas of the younger Koolau Volcano are subdivided into the Koolau Basalt and the Honolulu Volcanics. The Koolau Basalt consists primarily of shield-stage tholeiitic basalt, and the rejuvenated-stage Honolulu Volcanics consist of alkalic basalt, basanite, and nephelinite to melilitite (Langenheim and Clague, 1987). Potassium-argon determinations of Koolau Basalt indicate an age of 1.8 to 2.6 Ma (Doell and Dalrymple, 1973). The Honolulu Volcanics were erupted from more than 50 vents, which are confined to the southeastern part of Oahu, and deposited on an already much-eroded, mature topography of the Koolau shield (Wentworth, 1951). The Honolulu Volcanics are most notably marked by tuff cones such as Diamond Head, Punchbowl, and Koko Head. However, the Honolulu Volcanics also consist of cinder cones, ash deposits, spatter cones, and lava flows. Potassium-argon dating of various Honolulu Volcanics indicates ages from 0.031 Ma (Gramlich and others, 1971) to 1.13 Ma (Lanphere and Dalrymple, 1980). Age dates for the same flow, however, may vary by an order of magnitude (Macdonald and others, 1983).

The shield-stage lavas of the Koolau Volcano are typically thin-bedded, with an average flow thickness of about 10 ft. Few soil or tuff layers interrupt the sequence of shield-stage lavas. Wentworth (1951) estimated that throughout the whole mass of the volcano, tuff lenses make up less than 1 or 2 thousandths of the whole section.

Koolau Basalt is separated from older Waianae Volcanics by an erosional unconformity. Stearns and Vaksvik (1935) suggested that the Waianae Range had a well-developed stream pattern prior to the formation of the central saddle because Koolau Basalt occupies a former amphitheater-headed valley between Mount Kaala and Puu Hapapa. Within the central saddle, dips of the Koolau Basalt are invariably less than 5° and rarely more than 3° (Stearns and Vaksvik, 1935, p. 34).

Hydraulic Conductivity

The permeability of the subaerial, shield-building lavas that form the primary aquifers of Oahu along the flanks of the Koolau and Waianae Volcanoes generally is high. The main elements of lava flows contributing to the permeability are (1) clinker zones associated with aa flows, (2) voids along the contact between flows, (3) cooling joints normal to flow surfaces, and (4) lava tubes associated with pahoehoe flows.

Mink and Lau (1980) suggested that the regional hydraulic conductivity of the volcanic aquifers, formed by flank lava flows dipping at 3° to 10°, lies in the range of 1,000 to 5,000 ft/d, with most values probably centering around 2,000 ft/d. Regional-scale estimates of hydraulic conductivity can be obtained by (1) analyzing regional drawdown caused by large pumping stresses, (2) examining the influence of ocean tides on inland water levels, or (3) using Darcy's law in conjunction with a known hydraulic gradient and ground-water flow rate. Numerical ground-water flow models can be used to estimate hydraulic conductivity and generally rely on one of the methods above. In addition to regional estimates of hydraulic conductivity, local-scale estimates can be obtained with aquifer tests using closely spaced wells, or laboratory tests of rock samples. Local-scale aquifer tests are distinguished from regional-scale aquifer tests by the distance over which drawdown is observed; for a local-scale test, drawdown typically is observed over tens to hundreds of feet from the pumped well, whereas drawdown in a regional-scale test may be observed over several thousands of feet. A summary of hydraulic conductivity estimates, and the methods used to determine them, for extrusive rocks of Oahu is shown in table 2.

Although the depth of the volcanic aquifers is not known, a reduction in permeability of the volcanic rocks may coincide with a measured seismic velocity discontinuity at an altitude of about -6,000 ft. Above an altitude of -6,000 ft, basalt has a seismic velocity of 11,500 to 13,800 ft/s, whereas below an altitude of -6,000 ft the seismic velocity is about 14,800 to 18,700 ft/s (Furumoto and others, 1970). Above an altitude of about -6,000 ft, Furumoto and others (1970) suggested that basalt lava flows retain much of their original structure, with dense layers alternating with clinker material. Below an altitude of -6,000 ft, the increase in seismic velocity may be associated with an increase in density. Assuming that Oahu has subsided about 6,000 ft, the change in seismic velocity of the basalt may coincide with the contact between subaerial and submarine lava flows.

Chemical weathering may greatly affect the hydrologic properties of the original basaltic material. Drill cores collected beneath pineapple fields of central Oahu near Mililani indicate the presence of saprolite, weathered rock retaining the structural and textural features of the parent material, to depths of at least 100 ft (Miller, 1987). Beneath stream channels, where water continu-

Table 2. Estimates of horizontal hydraulic conductivity for extrusive volcanic rocks, Oahu, Hawaii

Hydraulic conductivity (feet per day)	Ground-water area	Estimation method	Reference
[1]540	Mokuleia	Darcy's law	Rosenau and others, 1971
41,360	Waialua	Local aquifer test	Soroos, 1973, p. 225
1,600	Waialua	Regional aquifer test	Dale, 1978
655–2,317	Schofield	Local aquifer test	Soroos, 1973, p. 221–223
[2]1,500–4,500	Ewa	Numerical model	Eyre and Nichols, in press
71–85,120	Pearl Harbor	Local aquifer test	Soroos, 1973, p. 160–216
238–1,000	Pearl Harbor	Local aquifer test	Williams and Soroos, 1973, p. 27, 55
1,500	Pearl Harbor	Tidal response	Dale, 1974
1,500	Pearl Harbor	Darcy's law	Dale, 1974
1,561	Pearl Harbor	Regional aquifer test	Mink, 1980
1,300–1,500	Pearl Harbor	Numerical model	Liu and others, 1981
1,500	Pearl Harbor	Numerical model	Souza and Voss, 1987
[2]1,500–4,500	Pearl Harbor, Honolulu[3]	Numerical model	Eyre and Nichols, in press
484–738	Moanalua	Local aquifer test	Soroos, 1973, p. 158–159
473–1,616	Beretania	Local aquifer test	Soroos, 1973, p. 152–155
2,700	Beretania	Local aquifer test	Williams and Soroos, 1973, p. 137
3.5×10^{-5}	Beretania or Kalihi[4]	Permeameter, aa core	Ishizaki and others, 1967
1,504	Waialae	Darcy's law	Wentworth, 1938
1,818–3,516	Waialae	Regional aquifer test	Wentworth, 1938
44,346	Waialae	Local aquifer test	Soroos, 1973, p. 151

[1] Based on a reported transmissivity of 3 million gallons per day per foot and an assumed flow depth of 738 ft.
[2] 4,500 feet per day longitudinal to lava flow direction; 1,500 feet per day lateral to lava flow direction.
[3] Honolulu includes the Moanalua, Kalihi, Beretania, and Kaimuki ground-water areas.
[4] Exact location where aa core collected is not specified; possibly from Honolulu Volcanics.

ally percolates, depth of weathering may be considerably greater.

Weathered basalt generally has a much lower permeability than unweathered basalt. The reduction of permeability may be attributed to secondary mineralization which clogs the original open spaces, or clays and colloids that precipitate from percolating water (Mink and Lau, 1980). An injection test conducted in weathered basalt beneath Waiawa Stream valley yielded a hydraulic conductivity of 0.058 ft/d (R.M. Towill, 1978). On the basis of laboratory permeameter tests on core samples, Wentworth (1938) estimated the hydraulic conductivity of weathered basalt to be between 0.083 and 0.128 ft/d. Miller (1987) used the water-retention characteristics of core samples collected beneath pineapple fields of central Oahu to estimate the saturated hydraulic conductivity of saprolite and found values ranging from 0.0028 to 283 ft/d. The wide range of hydraulic-conductivity values estimated by Miller (1987) was attributed to the variability in macroporosity among samples.

Intrusive Volcanic Rocks

Geology

Intrusive volcanic rocks include those rocks, such as dikes and sills, which formed by magma that cooled below the ground surface. Dikes associated with the rift zones of the Waianae and Koolau Volcanoes are the dominant intrusive rocks on Oahu, and are most abundant within the central area of the rift zones. The locations and strikes of dikes on Oahu were mapped by Stearns (1939) and more recently by Takasaki and Mink (1985). Walker (1987) described in detail the intensity, widths, strikes, and dips of dikes of the Koolau Volcano. Walker determined that the dikes of the Koolau Volcano are systematically nonvertical and form complementary sets dipping 65° to 85° in opposite directions. The thickness of individual dikes generally is less than 10 ft.

The primary rift zones of the Waianae Volcano trend roughly northwest and south, and a third, subordinate rift zone trends northeast. The primary rift zones of the Koolau Volcano trend northwest and southeast, and a third, subordinate rift zone trends southwest. Rift zones marked by closely spaced, steeply dipping, subparallel dikes numbering in excess of 100 per mile are known as dike complexes (Stearns and Vaksvik, 1935; Wentworth, 1951). Within a dike complex the intrusions constitute at least 10 percent of the total rock volume (Takasaki and Mink, 1985). Marginal dike zones exist at the outer edges of the dike complex where the number of dikes is greatly reduced. Within the marginal dike zone, there are fewer than 100 dikes per mile and the dikes constitute less than 5 percent of the rock volume (Takasaki and Mink, 1985). Wentworth and Macdonald (1953) estimated that 200 dikes are needed to build 1,000 ft of a shield volcano.

Hydraulic Conductivity

Dikes on Oahu are hydrologically significant because of their low permeability. High-level ground water is impounded behind dikes to altitudes of about 1,000 ft within the rift zones of Oahu. The permeability of a dense basalt dike is affected by cooling joints perpendicular to the margins of the dike.

In general, the average hydraulic conductivity of a rift zone decreases as the number of dike intrusions within the rift zone increases. In addition, hydraulic conductivity is expected to be higher in a direction along the strike of the dikes rather than perpendicular to the strike. On the basis of a numerical model analysis, Meyer and Souza (1995) suggested that the average, effective hydraulic conductivity of a dike complex ranges from about 0.01 to 0.1 ft/d. These values reflect the influence of both the intrusive dikes as well as the extrusive lava between dikes. The hydraulic conductivity of the intrusive dike material was estimated to range from 10^{-5} to 10^{-2} ft/d (Meyer and Souza, 1995).

Old Alluvium

Geology

Wentworth (1951) classified the sedimentary rocks of Oahu into old, intermediate, and recent alluvial and marine formations. The sediments of greatest significance for this study are the old terrestrial sediments which formed during a period of extensive erosion that carved deep valleys in the original volcanoes.

Old alluvium consists of terrestrial sediments, varying in size from fine-grain particles to boulders, which have been weathered and compacted into a soft coherent mass (Wentworth, 1951). Old alluvium forms deposits in deeply incised valleys and beneath the coastal plain of Oahu and is hydrologically significant because of its low permeability. The low permeability of old alluvium is caused by a reduction of pore space from the volume increase associated with weathering as well as mechanical compaction (Wentworth, 1951).

Hydraulic Conductivity

Wentworth (1938) estimated the hydraulic conductivity of three weathered alluvium samples with the use of a laboratory permeameter. Two of the samples had a hydraulic conductivity of less than 0.013 ft/d, and the third sample had a hydraulic conductivity of 1.08 ft/d. Eight samples classified as alluvium, without reference to weathering, produced a range of hydraulic conductivity from 0.019 to 0.37 ft/d (Wentworth, 1938).

Coastal Deposits

Geology

Deposits of terrestrial and marine sediments and reef limestones form a coastal plain of varying width along the shore of Oahu. The coastal plain extends more than 5 mi inland near Pearl Harbor and is less than 1,000 ft wide in parts of the north shore of the island. The onshore thickness of the coastal deposits is generally greatest at the coast and thins in an inland direction (Palmer, 1927; Palmer, 1946; Wentworth, 1951; Visher and Mink, 1964; Dale, 1978). In southern Oahu, the onshore coastal deposits are about 1,000-ft thick near the entrance to Pearl Harbor (Stearns and Chamberlain, 1967). Using well logs, well depths, and casing information, Palmer (1927, 1946) estimated structural contours for the top of the Koolau aquifer beneath the coastal deposits near Honolulu (fig. 7). Within the original channels of Manoa, Nuuanu, and Kalihi Stream valleys, the thickness of the coastal deposits likely exceeds 1,000 ft. In northern Oahu, the coastal deposits are about 500-ft thick near the coast in the Mokuleia ground-water area (Dale, 1978).

Gregory (1980) and Gregory and Kroenke (1982) used seismic reflection profiles to estimate the offshore sediment thickness above the volcanic rocks of southern Oahu. The sediments overlying the volcanic rocks off

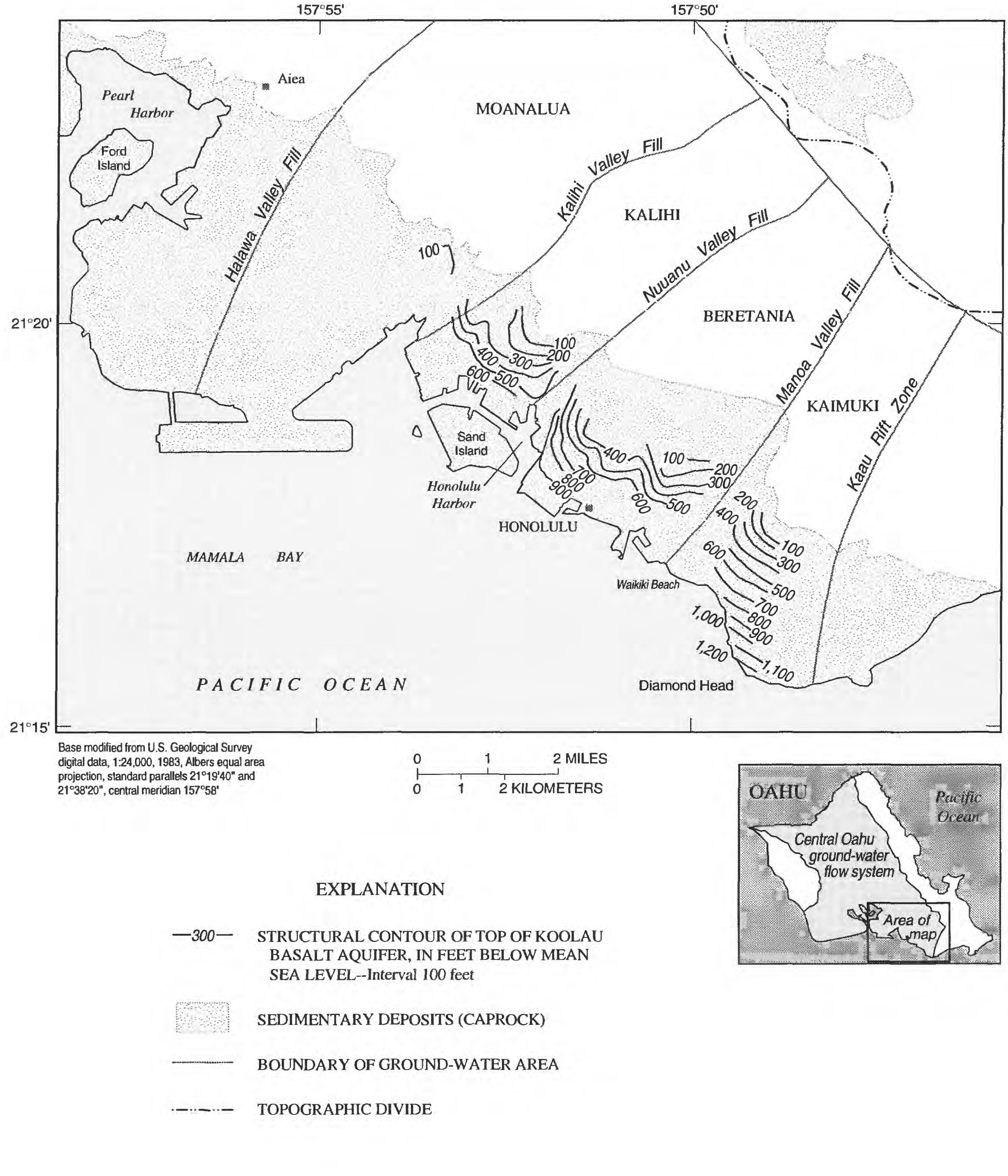


Figure 7. Structural contours of the top of the Koolau Basalt aquifer in the Honolulu area, Oahu, Hawaii (modified from Palmer, 1927, 1946).

southern Oahu are typically several hundred feet thick within about 10 mi of the coast. Off the northern coast of Oahu, no seismic reflection studies have been done that define the full thickness of the sediments overlying the volcanic rocks. Off the northern coast, coastal-deposit thickness can be estimated as the difference in altitude between the offshore-projected surface of the volcano and the measured bathymetry (see for example Pararas-Carayannis, 1965). Offshore from the Kawailoa ground-water area, the projected surface of the volcano can be obtained from measured dips of the lava flows. Offshore from the Mokuleia and Waialua ground-water areas, the surface of the volcano can be obtained by projecting slopes of the eroded volcanic-rock surface (Dale, 1978, fig. 5).

Hydraulic Conductivity

The weathered volcanic rocks, terrestrial and marine sediments, and reef limestone deposits which overlie Koolau Basalt and Waianae Volcanics form a caprock which impedes the seaward discharge of fresh ground water from the volcanic aquifers. Visher and Mink (1964) included terrestrial alluvium, marine sediments, calcareous reef deposits, pyroclastic rocks of the Honolulu Volcanics, and highly weathered basalt as part of the southern Oahu caprock. In addition to the caprock components of Visher and Mink (1964), massive aa cores or pahoehoe flows that are located near the coastal-discharge zones could also tend to impede the seaward discharge of fresh ground water. Visher and Mink (1964) suggested that although the permeability of the various components of the coastal caprock may vary widely, from low-permeability compacted old alluvium to cavernous limestone deposits, the overall effect of the caprock is one of low permeability.

The effective hydraulic conductivity of the caprock can be estimated by assigning representative hydraulic conductivity values to the individual layers within the caprock. Stearns and Chamberlain (1967) described core samples collected from a well (1959-05) that was drilled about 200 ft from the coast near the entrance to Pearl Harbor. The well penetrated 1,077.5 ft of caprock materials with aggregate thicknesses of about 544.5 ft of mud and weathered basalt, 103 ft of sand, gravel, and muddy limestone, and 430 ft of reef limestone. Assuming reasonable vertical hydraulic conductivity values of 0.01 ft/d for the mud and weathered basalt layers, 100 ft/d for the sand, gravel, and muddy limestone layers, and 3,000 ft/d for the limestone layers, an equivalent hydraulic conductivity for the entire 1,077.5-ft depth of the caprock is computed to be 0.02 ft/d. This estimate is largely controlled by the hydraulic-conductivity value assigned to the mud and weathered basalt layers.

Souza and Voss (1987) treated the caprock as a homogeneous and isotropic unit in a vertical cross-sectional model of the Pearl Harbor ground-water area. The hydraulic conductivity of the caprock was estimated to be about 0.15 ft/d (Souza and Voss, 1987).

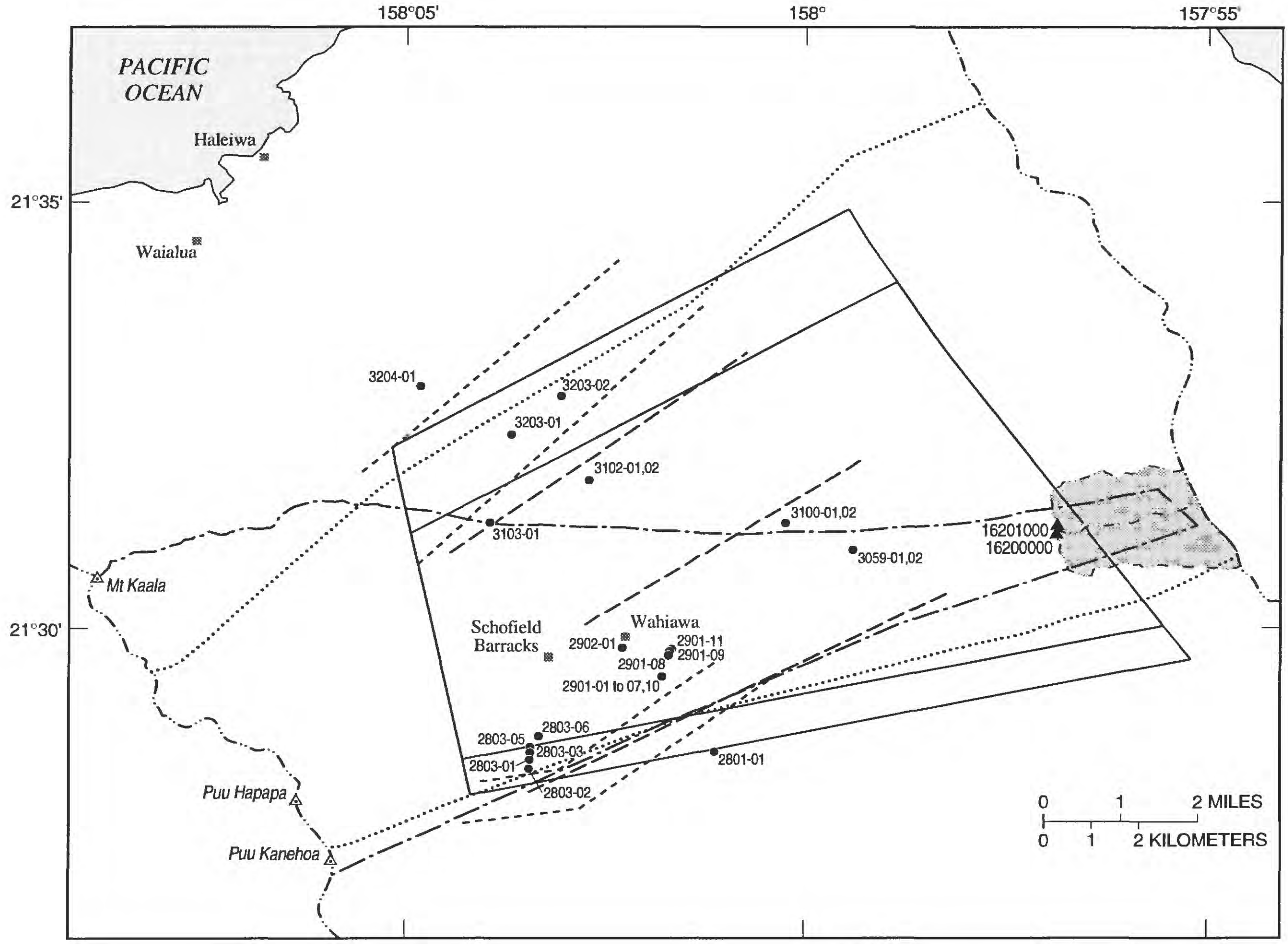
Geohydrologic Barriers

Northern and Southern Schofield Ground-Water Dams

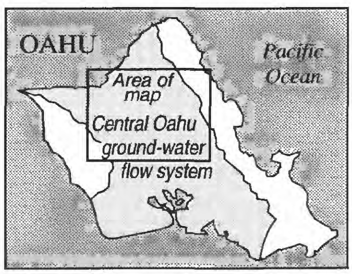
Before the first well was drilled in the Schofield ground-water area, it was estimated that water levels would be 30 to 50 ft above sea level in the area (Stearns, 1940; Palmer, 1956). Subsequently, in 1936, fresh ground water was found at an altitude of 276 ft in Schofield shaft 4 (well 2901-07), which was started at an altitude of 850 ft. Schofield shaft 4 was the first well drilled in the Schofield ground-water area. It was initially believed that the ground water was perched on ash or soil. However, in 1936 a diamond drill boring (well 2901-05) revealed no perching unit and penetrated saturated rocks to the bottom of the hole at an altitude of -21 ft (Stearns, 1940). Other wells drilled within the area have indicated continuous saturation to at least 120 ft below sea level.

The northern and southern boundaries of the Schofield ground-water area are formed by the northern and southern Schofield ground-water dams. The locations of the dams have been defined previously by several investigators (fig. 8; appendix A). The locations of the northern and southern Schofield dams defined by Dale and Takasaki (1976) are used in this study.

Although various hypotheses have been offered to explain the presence of the Schofield ground-water dams, their exact structural nature remains unknown. Stearns (1940) first suggested that the dams are formed by a few stray dikes striking westward from the main Koolau rift zone. Palmer (1955) interpreted several low mounds on the Schofield Plateau as "small lava shields" which may have been supplied with lava from dikes striking transverse to the main Koolau rift zone. Shettigara and Peterson (1985), using one- and two-dimen-



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 21°19'40" and 21°38'20", central meridian 157°58'



EXPLANATION

BOUNDARIES OF SCHOFIELD GROUND-WATER AREA

- Dale and Takasaki, 1976
- Swartz, 1939
- Broadbent, 1980
- Shettigara, 1985
- Mink and Lau, 1990

TOPOGRAPHIC DIVIDE

DRAINAGE BASIN

16201000 STREAM-GAGING STATION AND NUMBER

3204-01 WELL AND NUMBER

TOPOGRAPHIC PEAK

Figure 8. Previously delineated boundaries for the Schofield ground-water area, Oahu, Hawaii.

sional models to interpret their resistivity sounding and profile data, concluded that the ground-water dams were shallow dikes. The dikes making up the northern dam were estimated to be within 100 ft of the ground surface. Broadbent (1980) suggested that the dams are formed by buried ridges from the Waianae Range. Kauahikaua and Shettigara (1984) interpreted the same resistivity sounding data as Shettigara and Peterson (1985) and concluded that the dams are formed by buried Waianae ridges. Others have hypothesized that the dipping weathered zone between the Waianae Volcanics and Koolau Basalt within the valley between Mount Kaala and Puu Kanehoa of the Waianae Range may be responsible for high water levels within the Schofield area.

Although the geologic nature of the Schofield ground-water dams is not currently known, aquifer tests conducted during 1958 and 1959 (unpub. data USGS Hawaii District well files) using wells located within the southern dam provide some insight into the hydrogeologic characteristics of the dams. Starting on December 30, 1958, well 2803-02 was pumped at a rate of about 1,760 gal/min. Water levels were measured at well 2803-01, located about 200 ft from the pumped well. A semilogarithmic plot of drawdown as a function of time at the observation well, with time plotted on the logarithmic scale, shows changes in slope which are typically associated with ground-water barriers (fig. 9A). A second test, starting on March 18, 1959, also revealed the presence of ground-water barriers (fig. 9B). For the second test, well 2803-05 was pumped at a rate of about 1,700 gal/min and drawdown was measured at well 2803-03 located 500 ft away. Thus, these two aquifer tests indicate that the southern ground-water dam has a compartmental nature which could be related to dikes.

Waianae Confining Unit

Near the contact of the older Waianae Volcanics and younger Koolau Basalt, weathered Waianae Volcanics beneath the erosional unconformity and alluvium form a confining unit which impedes flow of freshwater and saltwater between the two volcanic aquifers. In southern Oahu, the Waianae confining unit separates the Ewa and Pearl Harbor ground-water areas. In central Oahu, the Waianae confining unit forms the western boundary of the Schofield ground-water area. In northern Oahu, the Waianae confining unit separates the Mokuleia and Waialua ground-water areas.

In southern Oahu, there is a drop in water level across the Waianae confining unit from the Pearl Harbor area to the Ewa area. Mink (1980) suggested that in 1879, prior to ground-water development, the water levels on the Pearl Harbor side of the confining unit were about 11 ft higher than on the Ewa side. By 1950, however, the water-level difference was reduced to about 2 to 3 ft. The confining unit separating the Ewa and Pearl Harbor areas dips at an angle of about 10° to the east. In plan view, the confining unit is represented as a line which corresponds to the location of the confining unit at sea level (fig. 2).

The western boundary of the Schofield ground-water area is located within the large valley between Mount Kaala and Puu Kanehoa and is formed by the weathered zone between older Waianae Volcanics and younger Koolau Basalt. Following its formation, the valley was filled with alluvium and Koolau Basalt. Because the slope of the original valley floor is unknown, it is difficult to establish the location of the western boundary of the Schofield area without well control or a surface geophysical investigation. Dale and Takasaki (1976, p. 16), however, estimated the location of the western boundary of the Schofield area as "a line corresponding to the subsurface slope of Waianae rocks at an altitude of 120 meters [394 ft]. The boundary is the inferred contact of the Koolau and Waianae rocks at this altitude." Although the location of the western boundary of the Schofield area is uncertain, no data currently exist to justify modification of Dale and Takasaki's boundary. Water levels in the Koolau Basalt of the Schofield area are about 275 ft above sea level. The water level in the Waianae Volcanics between the crest of the Waianae Range and the western boundary of the Schofield ground-water area is unknown and, consequently, the direction of ground-water flow across the western boundary of the Schofield area cannot be established.

In northern Oahu, the Waianae confining unit is at least partly responsible for the drop in water level from about 20 ft in the Mokuleia area to about 11 ft in the Waialua area. Although the Kaukonahua Stream valley fill and underlying weathered zone (see next section on valley-fill barriers) may be the effective barrier between the Mokuleia and Waialua areas at lower altitudes, at higher altitudes the valley fill and underlying weathered zone may not penetrate the water table. In fact, the water level in a well (3205-02) drilled at an altitude of about 590 ft on the northeast ridge above Kaukonahua Stream

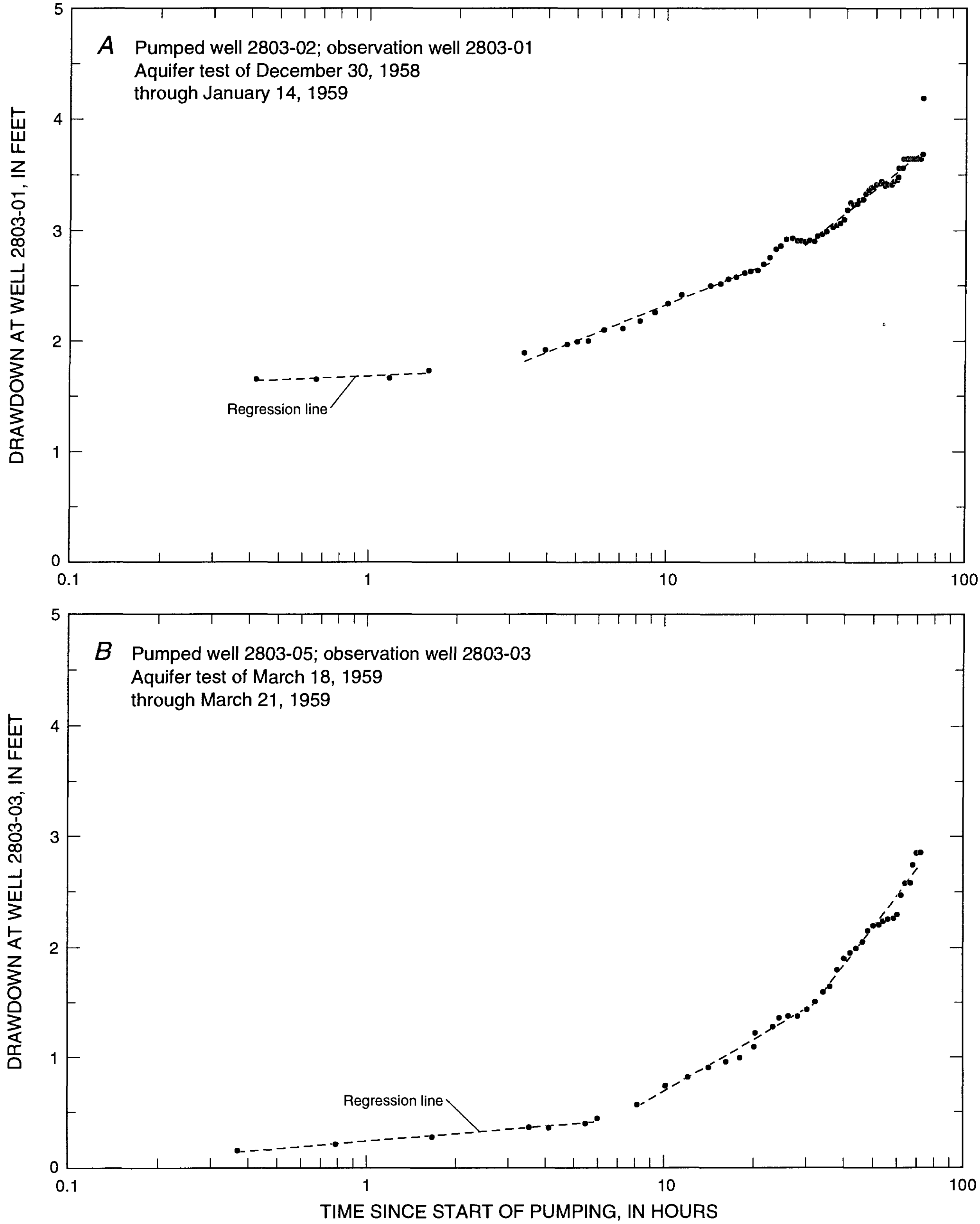


Figure 9. Drawdown as a function of time ***A***, at well 2803-01 during an aquifer test starting December 30, 1958; and ***B***, at well 2803-03 during an aquifer test starting March 18, 1959 (unpublished data from U.S. Geological Survey Hawaii District well files).

indicates that the valley fill and underlying weathered zone do not form an effective barrier near the well site. If the Kaukonahua Stream valley fill were the effective barrier at this location, then the well should be within the Waialua ground-water area and the water level in this well should be about 12 ft rather than 22.23 ft above sea level as measured on April 27, 1995. The water level in well 3205-02 is representative of water levels in the Mokuleia ground-water area. The geologic log indicates that well 3205-02 penetrated through the Waianae confining unit. Thus, in the vicinity of well 3205-02, the Waianae confining unit, and not the valley fill, represents the effective barrier between the Mokuleia and Waialua ground-water areas.

Valley-Fill Barriers

Following the shield stage of volcanic activity that formed the bulk of the Koolau Volcano, there was a period of extensive erosion during which valleys were deeply incised. The large valleys at Manoa, Nuuanu, and Kalihi Streams (fig. 1) probably did not form until after the island had subsided enough to allow significant rainfall to reach the leeward, southwestern slopes of the Koolau Volcano. The island of Oahu has probably subsided a total of 6,500 to 13,000 ft (2 to 4 km) since reaching the ocean surface (Moore, 1987). Assuming that the Koolau Volcano once stood 10,000 to 15,000 ft above sea level, which is above the temperature inversion at about 6,500 ft altitude, the original summit received less rainfall than the crest of the Koolau Range receives today. In addition, the original height of the Koolau Volcano created an effective barrier to the northeast tradewinds, thus limiting the amount of rainfall on the leeward side of the Koolau Range. Initially, rainfall on the leeward side infiltrated readily into the fresh, permeable lavas, and only a limited amount of runoff reached the coast. After the Koolau Volcano had subsided several thousand feet, rainfall and the rate of weathering on the leeward side increased. Rainfall on the leeward side of the Koolau Volcano may have also been enhanced by a prodigious landslide that took away the northeast flank of the volcano (Moore and others, 1989). As surface weathering ensued, runoff to the ocean increased, and thus, the rate of downward cutting of valleys on the leeward side of the Koolau Volcano also increased. It was during this period of extensive erosion that Palolo, Manoa, Nuuanu, and Kalihi Stream valleys of the Honolulu area were incised.

Following the period of extensive erosion, a rise in sea level resulted in valley alluviation. Toward the lower reaches of the valleys below an altitude of about 40 ft, valley-fill deposits consist of terrestrial sediments which interfinger with marine sediments and limestone units. The geologic sequence reflects changes in relative sea level associated with island subsidence and glacioeustatic sea-level fluctuations during the Pleistocene (Stearns and Chamberlain, 1967). Inland, above an altitude of about 40 ft, the base of the valley-fill material typically consists of highly weathered and compact old alluvium which is mantled with more recent, unconsolidated alluvium and colluvium. The old alluvium may be hundreds of feet thick at lower altitudes, but at altitudes above about 400 ft, old alluvium may be nonexistent.

In addition to visible submarine wave-cut notches around the island, wells drilled in Honolulu near stream mouths provide evidence for a lower base level than exists today. Palmer recognized reentrant forms (fig. 7) which represent the original, subaerially formed valley incisions. The reentrant near the mouth of Nuuanu Stream suggests that Nuuanu Stream valley was incised when base level was at least 800 ft lower than it is today. The valley likely was incised to a depth greater than 800 ft, however well coverage is insufficient to define the original valley cross section and maximum depth of incision.

The old alluvium filling valleys and the associated weathered zone beneath the original incisions form vertical barriers to ground-water flow. The near-continuous availability of water from streams may enhance weathering beneath stream channels. This weathering beneath stream channels may extend downward for hundreds of feet.

Within the central Oahu ground-water flow system, the valley fills that are considered effective barriers to fresh ground-water flow are the Manoa, Nuuanu, Kalihi, North Halawa, and Anahulu valley fills. Other valleys in the study area which are less deeply incised or which have less underlying weathering may be associated with less effective barriers to ground-water flow. Each of the main valley fills forms a vertical barrier between two adjacent ground-water areas (fig. 2). Within the volcanic aquifer, fresh ground-water levels on either side of a given valley-fill barrier generally differ by several feet. In northern Oahu, for example, ground-water levels in the Waialua area are about 4 to 6 ft higher than in the Kawailoa area to the north of the Anahulu valley-fill barrier. Although the valley-fill barriers impede the flow of fresh ground water between adjacent areas, flow of saltwater beneath the bottoms of these valley-fill barriers is generally unaffected.

Where the Honolulu Volcanics exist above the water table in the volcanic aquifer, they do not contribute to the overall effectiveness of the valley-fill barriers. Near the coast, the original valley incisions are obscured by hundreds of feet of sedimentary deposits that form a coastal plain. Estimates for the depths of the original valley incisions are provided in appendix B. Toward the heads of Manoa, Nuuanu, and Kalihi Stream valleys, stray dikes from the Koolau rift zone may contribute to the barrier effectiveness.

Dike Barriers

The ground-water areas of the central Oahu ground-water flow system extend to the outer edge of the marginal dike zones of the Koolau and Waianae Volcanoes. Wells are unavailable to accurately delineate the boundary between dike-impounded high-level ground water and the downgradient freshwater lenses. A transition zone may exist where water levels drop gradually from dike-impounded levels to lower levels associated with freshwater lenses as the dike intensity decreases away from the central rift area.

At the southeastern extent of the central Oahu flow system, the southwest rift zone of the Koolau Volcano marks the eastern boundary of the Kaimuki ground-water area. This rift zone coincides with the Kaau rift zone which is marked by numerous rejuvenated-stage vents of the Koolau Volcano, including Diamond Head. In addition, the Palolo valley-fill barrier may contribute to the barrier effectiveness (Wentworth, 1951). Water levels to the west of the barrier are more than 10 ft higher than in the adjacent ground-water area to the east.

At the southwestern extent of the central Oahu flow system, the south rift zone of the Waianae Volcano marks the western boundary of the Ewa ground-water area. Across the dike barrier, water levels drop from about 13 ft at well 2006-12 (T4) to about 4 ft at well 2007-01 (T5).

HYDROLOGY

Precipitation is the source of freshwater on Oahu. The precipitation either (1) runs off, (2) evaporates or is transpired by vegetation, or (3) recharges the ground-water system. Water that recharges the ground-water system flows from zones of higher to lower hydraulic head, as measured by water levels. Ground water is either withdrawn from wells or discharges to streams or the ocean.

Streams

Streams within the central Oahu ground-water flow system have steep gradients in the mountainous, high-rainfall areas and flat gradients near the coast. A few streams, including Manoa, Nuuanu, and Kalihi Streams, are perennial throughout their entire lengths. Most streams in the study area, however, are perennial only in the upper reaches where rainfall is persistent or where springs drain high-level ground water from dike compartments. Near the coast, below an altitude of about 20 ft, some streams are perennial because of spring discharge of ground water from the volcanic aquifer. Streams may be dry in their middle reaches because of diversions or infiltration into the underlying alluvium.

Streams on Oahu may gain water along some reaches and lose water along other reaches (Izuka, 1992). Although surface water and ground water may interact in the alluvium, streams cannot gain water from the volcanic aquifer where the stream bed is at a higher altitude than the water table in the volcanic aquifer. Beneath the stream bed, highly weathered old alluvium and weathered basalt impede the downward flow of water to the volcanic aquifer. Izuka (1992) suggested that these weathered materials may restrict the flow of ground water from the alluvium to the volcanic aquifer to small rates. Hirashima (1971a) estimated that dry-weather seepage from streambeds is about 0.04 Mgal/d per mile of stream.

Ground-Water Recharge

Numerous investigators have made estimates of ground-water recharge for parts or all of the central Oahu ground-water flow system (see for example Shade

Table 3. Regression equations relating recharge to rainfall, central Oahu, Hawaii
[From P.J. Shade, U.S. Geological Survey, written commun., 1992]

Land use	Regression equation for recharge and rainfall (inches per year)	Rainfall range	Coefficient of determination
Furrow-irrigated sugarcane	Recharge = 91.3	not applicable	not applicable
Pineapple	Recharge = 0.935 × Rainfall − 13.54	Rainfall > 14.5 in/yr	0.98
Urban, conservation, park, and mixed land use	Recharge = 0.846 × Rainfall − 43.035	Rainfall > 160 in/yr	0.95
	Recharge = 0.596 × Rainfall − 12.092	Rainfall ≤ 160 in/yr	0.89

and Nichols, 1996; Mink and others, 1988; Giambelluca, 1983; Mink, 1980; Broadbent, 1980; Dale, 1978; Dale and Takasaki, 1976; Rosenau and others, 1971). Giambelluca (1983) computed a detailed water balance for southern Oahu. On the basis of a daily water budget for the period 1946–75, Giambelluca (1983) estimated that recharge to the noncaprock areas of the Pearl Harbor-Honolulu basin was 332 Mgal/d. Shade and Nichols (1996) developed rainfall-recharge/land-cover relations on the basis of recharge estimates from Giambelluca (1983, 1986) for southern Oahu, and used these relations to estimate ground-water recharge for the entire central Oahu ground-water flow system. Predevelopment recharge and mid-1980's recharge to noncaprock areas of the central Oahu ground-water flow system were estimated to be 521 Mgal/d and 575 Mgal/d, respectively (Shade and Nichols, 1996).

The period 1950–59 is used to develop the ground-water flow model in the section of this report titled "Numerical Ground-Water Model of the Central Oahu Flow System." For this period, ground-water recharge to the volcanic aquifers of the central Oahu flow system was estimated in this study to be 623.4 Mgal/d. Giambelluca's (1983) estimates for the period 1950–59 were used in this study for the Beretania, Kalihi, Moanalua, Pearl Harbor, and Ewa ground-water areas and the southern part of the Schofield ground-water area. Detailed recharge estimates are not available for the other parts of the central Oahu flow system. Recharge for the Mokuleia, Waialua, Kawailoa, and Kaimuki ground-water areas and the northern part of the Schofield ground-water area was generated using regression equations relating recharge to rainfall (P.J. Shade, USGS, written commun., 1992) (table 3), in conjunction with rainfall and land-use distributions representative of average 1950's conditions (Harland Bartholomew and Associates, 1957). The rainfall-recharge-land cover relations developed by P.J. Shade (USGS, written commun., 1992) are based on recharge estimates from Giambelluca (1983, 1986) for southern Oahu, which has similar climate, topography, and soils as northern Oahu.

For areas in urban, conservation, park, and mixed land use, two regression equations relating recharge to rainfall were developed by P.J. Shade (USGS, written commun., 1992): one regression was developed for areas with annual rainfall greater than 160 in., and another regression was developed for areas with annual rainfall less than or equal to 160 in. (table 3, fig. 10). For areas in urban, conservation, park, and mixed land use, a single regression equation covering the entire range of mean annual rainfall values would tend to underestimate recharge in the high rainfall areas. For areas of pineapple cultivation, a single regression can be used to represent the relation between rainfall and recharge (table 3, fig. 10). For a given annual rainfall value, the regression equation for areas of pineapple cultivation predicts a higher recharge rate than the regression equation for areas with natural land cover. Relative to natural land cover, pineapple plants tend to enhance recharge by suppressing evapotranspiration (Giambelluca, 1983). For areas of furrow-irrigated sugarcane, recharge is not a function of rainfall because the fields are irrigated to maintain a relatively constant soil moisture. Recharge for areas of furrow-irrigated sugarcane was estimated to be 91.3 in/yr (P.J. Shade, USGS, written commun., 1992).

Shade and Nichols (1996) also developed regression equations, which were unavailable at the time this study began, relating rainfall and recharge for the central Oahu ground-water flow system. The regression equations developed by Shade and Nichols (1996) and those used in this study (P.J. Shade, USGS, written commun., 1992) were based on the same data which originated from Giambelluca (1983, 1986) and are therefore identical or very similar. The regression equation developed by Shade and Nichols (1996) for pineapple land use is identical to the equation used in this

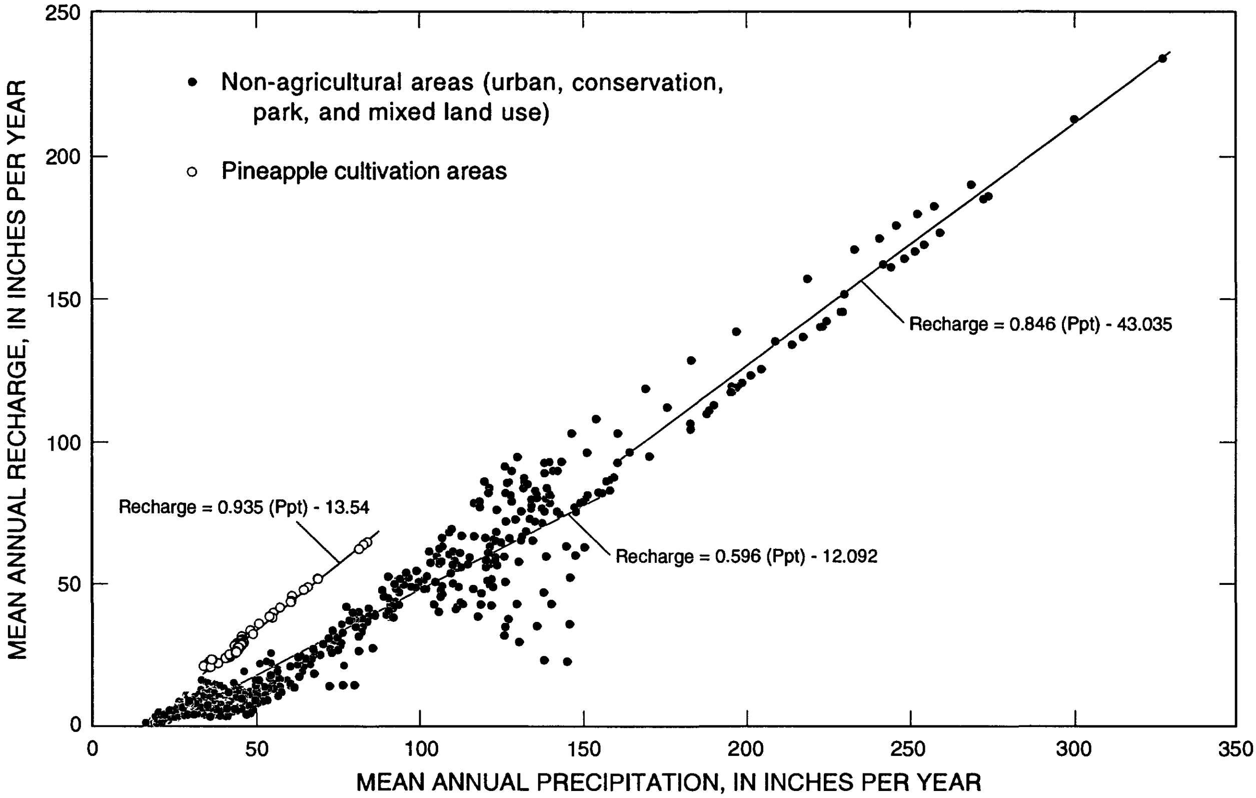


Figure 10. Relation between precipitation and estimated ground-water recharge for non-agricultural and pineapple land-use areas, central Oahu, Hawaii. Ppt, mean annual precipitation, in inches per year.

study. For non-agricultural areas, the difference between recharge estimated from the regression equations used in this study and recharge estimated by Shade and Nichols (1996) is small, less than 6 in/yr for mean annual rainfall between 20 and 300 in. For non-agricultural areas, recharge estimated from regression equations in this study may be up to 5.9 in/yr higher or 2.5 in/yr lower than recharge estimated by Shade and Nichols (1996), depending on the mean annual rainfall. The differences in recharge estimated by regression equations from P.J. Shade (USGS, written commun., 1992) and Shade and Nichols (1996) are well within the range of uncertainty associated with the estimates.

For this study, a recharge value of 91.3 in/yr, which is consistent with estimates by Giambelluca (1983), was used for furrow-irrigated sugarcane areas in northern Oahu. Shade and Nichols (1996) assumed a recharge rate of 87.3 in/yr for furrow-irrigated sugarcane in noncaprock areas, which is similar to the value used for this study. Shade and Nichols (1996) suggested, however, that Giambelluca (1983) may have overestimated recharge from irrigated sugarcane by a factor of two, and more investigations are needed to resolve the uncertainty in the sugarcane recharge estimate. For sugarcane land use, Giambelluca and others (1996) estimated that the uncertainty in recharge because of uncertainty in the water-budget model components is 49 percent of the mean. Nevertheless, for furrow-irrigated sugarcane areas, the recharge estimates from Giambelluca (1983) and the recharge estimates based on Giambelluca's work (P.J. Shade, USGS, written commun., 1992) represent the best available data and were therefore not adjusted for this study.

The regression equation for estimating recharge in nonagricultural areas receiving more than 160 in/yr rainfall (P.J. Shade, USGS, written commun., 1992) is based on results from Giambelluca (1983) who did not consider the high runoff areas near the eastern part of the Schofield ground-water area. The regression equation may overestimate recharge in these high runoff areas, and was therefore adjusted for this study. In these high runoff areas, greater than 50 percent of the annual rainfall runs off as streamflow. For the drainage basin of stream-gaging station 16200000 (fig. 8), the runoff-to-rainfall ratio was estimated to be 0.69 for the periods 1913–24, 1926–52, and 1960–74, and for the basin of gaging station 16201000 (fig. 8), the runoff-to-rainfall ratio was 0.53 for the periods 1913–24, 1926–32, and 1934–53 (Dale and Takasaki, 1976). For comparison, on the basis of 30 years of record for 1931–60, Hirashima (1971a) estimated that runoff is about 13 percent of average annual rainfall in the Pearl Harbor area. On the basis of data for 1957–59, Mink (1962) estimated that annual runoff is 13.6 to 25.4 percent of annual rainfall for the Kipapa basin. Dale and Takasaki (1976, p. 19) suggested that the high runoff-to-rainfall ratio in the Schofield area "is probably caused by high head and the rejection of recharge, as well as low rock permeability in the Koolau dike-impounded water body."

The regression equation relating recharge to rainfall for the eastern Schofield area where rainfall is in excess of 160 in/yr is

$$\text{Recharge} = 0.846 \times \text{Rainfall} - 43.035, \qquad (1)$$

in which both recharge and rainfall are in inches per year. Equation 1 is of the form

$$\text{Recharge} = (1 - r) \times \text{Rainfall} - \text{Evapotranspiration}, \qquad (2)$$

in which r represents the runoff-to-rainfall ratio. Thus, implicit in Shade's regression equation is a runoff-to-rainfall ratio of 0.154, and an evapotranspiration rate of 43.035 in/yr.

The regression equation developed by Shade is based on Giambelluca's (1983) results for 1946–75. To fill streamflow data gaps, Giambelluca used the model of Anderson and others (1966). This method also was used for this study to extend the records from stream gages 16200000 and 16201000 to the period 1946–75. The 1946–75 runoff-to-rainfall ratios for the drainage basins of gages 16200000 and 16201000 were estimated to be 0.59 and 0.42, respectively. The area-weighted runoff-to-rainfall ratio for the eastern Schofield area was computed to be 0.51.

The pan evaporation rate in the eastern Schofield area is about 20 in/yr (Ekern and Chang, 1985). If potential evapotranspiration is assumed to equal the pan evaporation rate, and if soil moisture is assumed to be nonlimiting, then actual evapotranspiration also will equal pan evaporation. Thus, given an evapotranspiration rate of 20 in/yr and a runoff-to-rainfall ratio of 0.51, equation 2 becomes

$$\text{Recharge} = 0.49 \times \text{Rainfall} - 20, \qquad (3)$$

in which recharge and rainfall are in inches per year. For the high-rainfall eastern Schofield area within the drainage basins of gages 16200000 and 16201000, recharge was estimated using equation 3 instead of equation 1.

Ground-Water Withdrawals

In general, ground-water pumpage in the central Oahu flow system is greatest in the Pearl Harbor area and smallest in the Mokuleia area. Ground water is withdrawn from vertical wells and infiltration tunnels primarily for agricultural, domestic, military, and industrial uses. Early records of withdrawals from 1879 to the mid-1920's are generally incomplete. The available histories of ground-water withdrawals from each of the ten ground-water areas of the central Oahu flow system are briefly described below.

Mokuleia Ground-Water Area

Pumping records for the Mokuleia area prior to 1924 appear to be incomplete. Ground-water withdrawals from the Mokuleia area are from both free-flowing and pumped wells. Since 1924, the reported annual mean pumpage has remained less than 6 Mgal/d (fig. 11). At times, however, the total withdrawal rate from pumped and free-flowing wells has exceeded 6 Mgal/d. Stearns and Vaksvik (1935, p. 375) estimated the total withdrawal rate to be 14 Mgal/d for 1933. On the basis of a single round of measurements, withdrawals from free-flowing wells in the Mokuleia area totaled 7.09 Mgal/d in January 1934 (Stearns and Vaksvik, 1938). It is unclear whether this represents the actual water use for January 1934 or whether this represents the potential free flow from the measured wells. Of the 21 wells which were reportedly free-flowing in 1934 (Stearns and Vaksvik, 1938), 17 were sealed by 1963. Only one

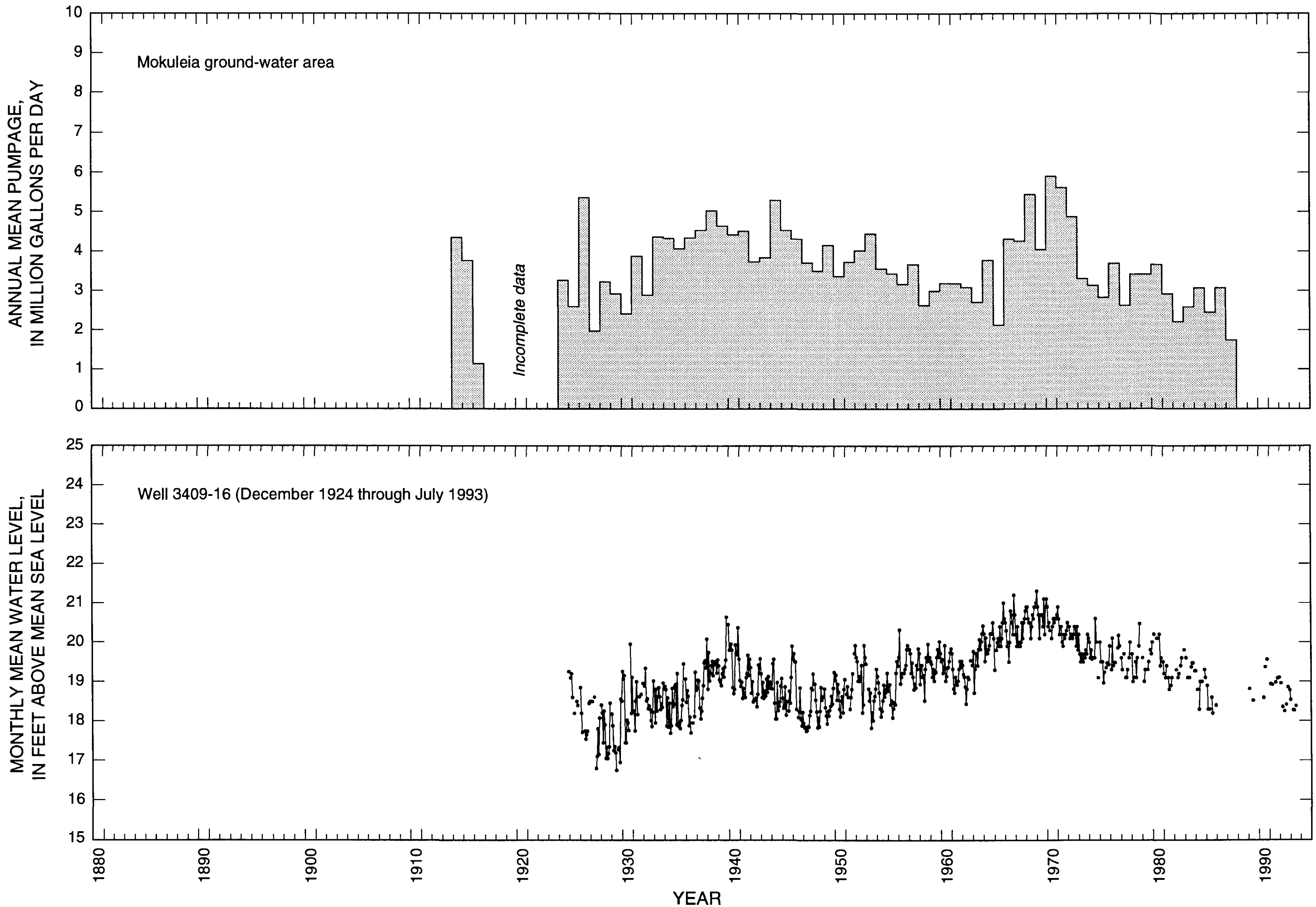


Figure 11. Annual mean pumpage from the Mokuleia ground-water area and monthly mean water levels at well 3409-16, Oahu, Hawaii.

continues to be used, for irrigation, and the remaining three serve as monitoring wells.

Waialua Ground-Water Area

Pumping records for the Waialua ground-water area prior to 1924 appear to be incomplete. Since 1924, reported annual mean pumpage has ranged from a low of 20.9 Mgal/d in 1958, the year of an industry-wide sugar strike, to a high of 51.2 Mgal/d in 1973 (fig. 12). Ground-water withdrawals from the Waialua area have been primarily from pumped wells for sugarcane cultivation.

Kawailoa Ground-Water Area

Pumping records for the Kawailoa ground-water area prior to 1927 appear to be incomplete. Since 1927, reported annual mean pumpage from the Kawailoa ground-water area has remained less than 9 Mgal/d (fig. 13). Reported annual mean pumpage has ranged from a low of 1.5 Mgal/d in 1936, to a high of 8.9 Mgal/d in 1970 (fig. 13). Most of the reported total pumpage from the Kawailoa ground-water area is from Waialua Sugar Company pump 4 (wells 3605-01 to -23).

Schofield Ground-Water Area

Since the first well was drilled in the Schofield area in 1936, annual pumpage from the area has generally been less than 10 Mgal/d, except during the period 1970–88 (fig. 14). In 1979, pumpage from the Schofield area peaked at 20.6 Mgal/d.

Ewa Ground-Water Area

Reported annual pumpage from the Ewa area generally increased from the early 1900's to a maximum annual pumpage of 35.8 Mgal/d in 1970 (fig. 15). Since 1981, reported pumpage from the Ewa area has generally decreased. Ground-water withdrawals from the Ewa ground-water area have been primarily from irrigation wells.

Pearl Harbor Ground-Water Area

Within the central Oahu flow system, withdrawals are greatest from the Pearl Harbor ground-water area. Ground-water withdrawals from the Pearl Harbor ground-water area are from pumped and free-flowing wells. In 1977, reported annual mean pumpage from the Pearl Harbor area reached a maximum of 205 Mgal/d (fig. 16). In addition to the reported pumpage, water is withdrawn from free-flowing artesian wells near the shore of Pearl Harbor. In 1911, measured withdrawal from 29 flowing artesian wells was 24.3 Mgal/d (Martin and Pierce, 1913). During 1928–30, the Honolulu Board of Water Supply made occasional discharge measurements at selected flowing artesian wells (Kunesh, 1931). Since 1965, withdrawals from flowing artesian wells near Pearl Harbor have been measured annually by the Honolulu Board of Water Supply. The discharge from these free-flowing wells is dependent on the artesian head in the aquifer. In May 1966, the Honolulu Board of Water Supply measured withdrawals of 20.75 Mgal/d from 31 free-flowing wells. Measured water levels in these wells ranged from 15.75 to 22.71 ft above mean sea level at the time of the discharge measurements. In 1969, one of the 31 measured free-flowing wells was sealed. In September 1973, total free flow from 30 of the 31 wells previously measured in May 1966 was only 5.92 Mgal/d, and measured water levels ranged from 10.75 to 11.34 ft above mean sea level at the time of the discharge measurements.

Moanalua, Kalihi, Beretania, and Kaimuki Ground-Water Areas

Pumping records appear to be incomplete for the Moanalua ground-water area prior to 1927, and for the Kalihi, Beretania, and Kaimuki areas prior to 1924. Reported pumpage from the Moanalua area increased from less than 1 Mgal/d in 1927 to a peak of 30.7 Mgal/d in 1945 (fig. 17). Since 1950, pumpage from the Moanalua area has ranged from 11.1 to 24.8 Mgal/d. Reported pumpage from the Kalihi area has ranged from 5.3 Mgal/d in 1925 to 15.4 Mgal/d in 1972 (fig. 18). Reported pumpage from the Beretania area has ranged from 7.4 Mgal/d in 1933 to 20.2 Mgal/d in 1970 (fig. 19). In the Kaimuki area, reported pumpage has been relatively steady and has not exceed 9 Mgal/d (fig. 20).

During the 1930's, combined pumpage from the four Honolulu ground-water areas ranged from about 27 to 30 Mgal/d (fig. 21). Total reported pumpage from the Honolulu areas increased during World War II to more than 63 Mgal/d in 1944. Since 1960, combined pumpage from the four Honolulu ground-water areas has ranged from about 40 to 60 Mgal/d. The pumpage totals do not include withdrawals from free-flowing artesian wells. In 1911, the total measured discharge from 35 flowing artesian wells in Honolulu was 30.8 Mgal/d (Martin and Pierce, 1913). The primary use of ground water from the Honolulu areas is for municipal purposes.

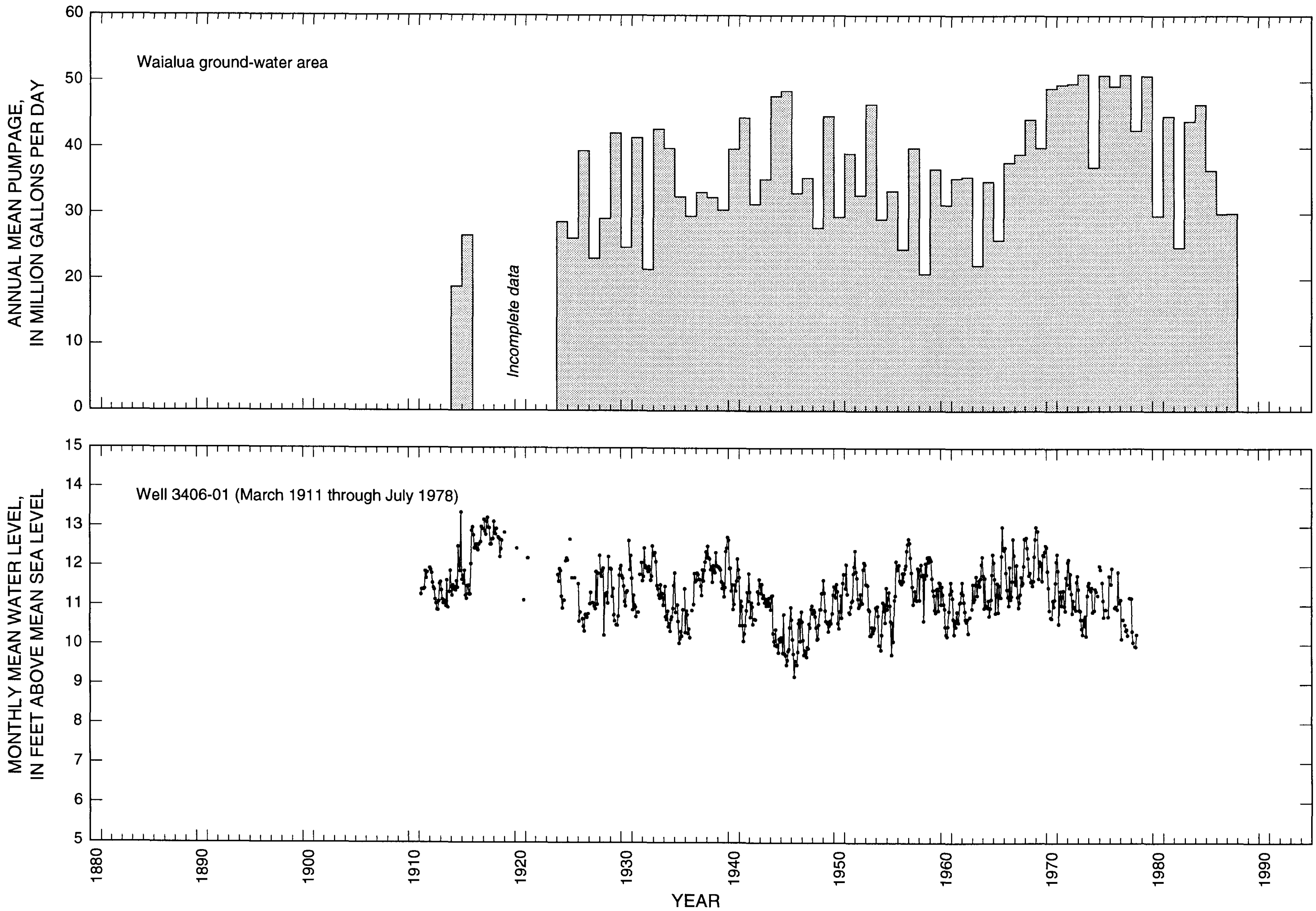


Figure 12. Annual mean pumpage from the Waialua ground-water area and monthly mean water levels at well 3406-01, Oahu, Hawaii.

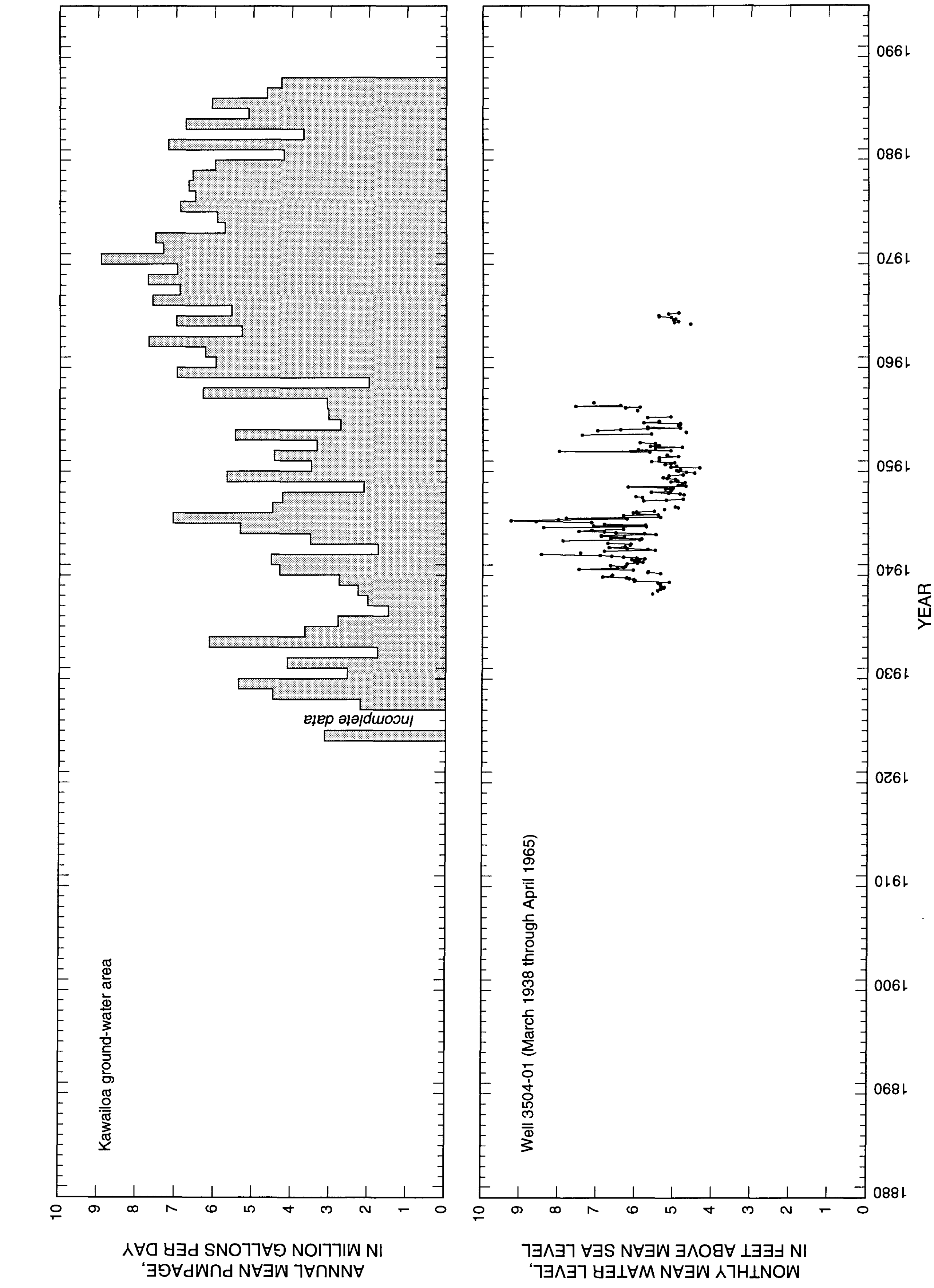


Figure 13. Annual mean pumpage from the Kawailoa ground-water area and monthly mean water levels at well 3504-01, Oahu, Hawaii.

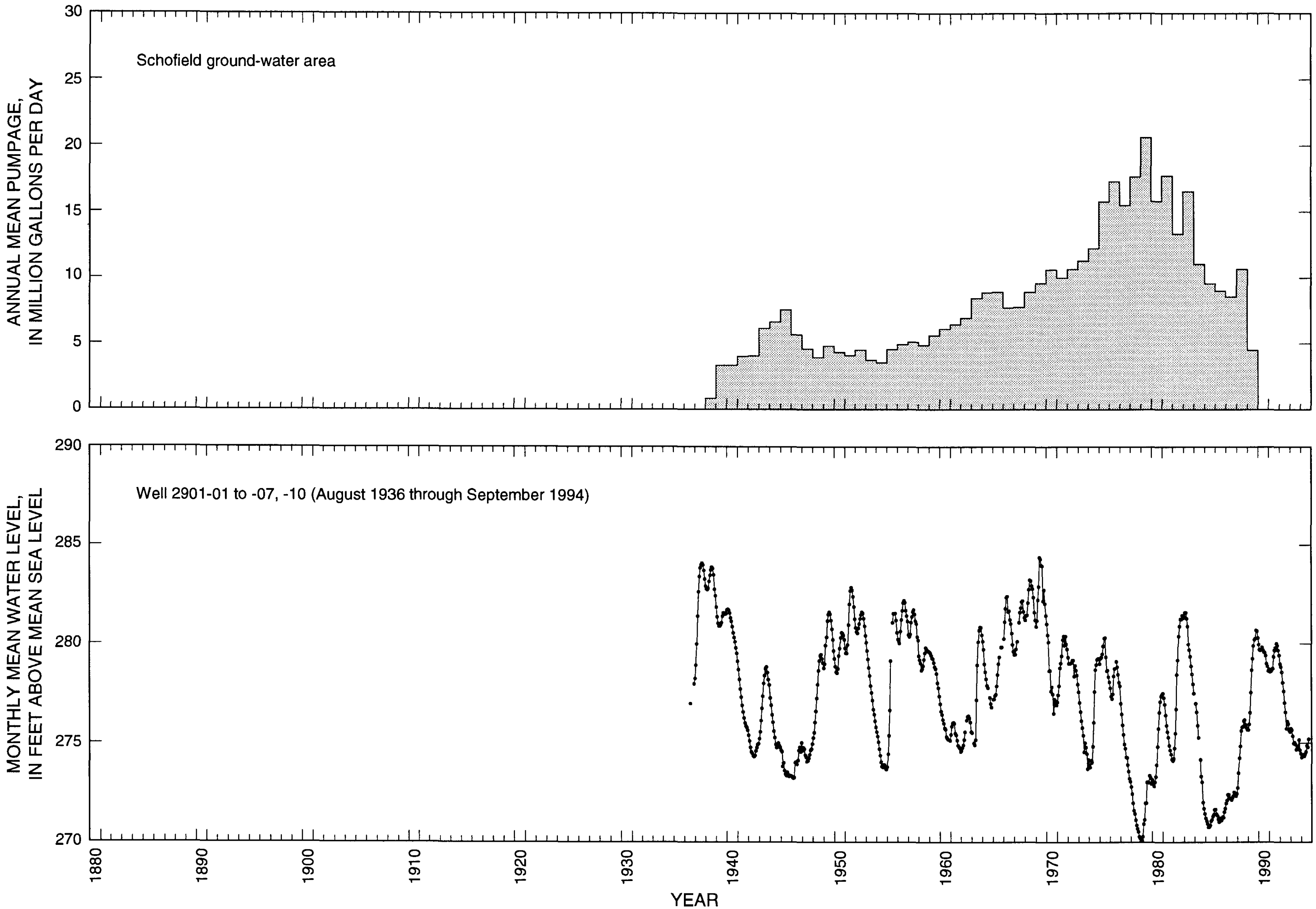


Figure 14. Annual mean pumpage from Schofield ground-water area and monthly mean water levels at wells 2901-01 to -07, -10, Oahu, Hawaii.

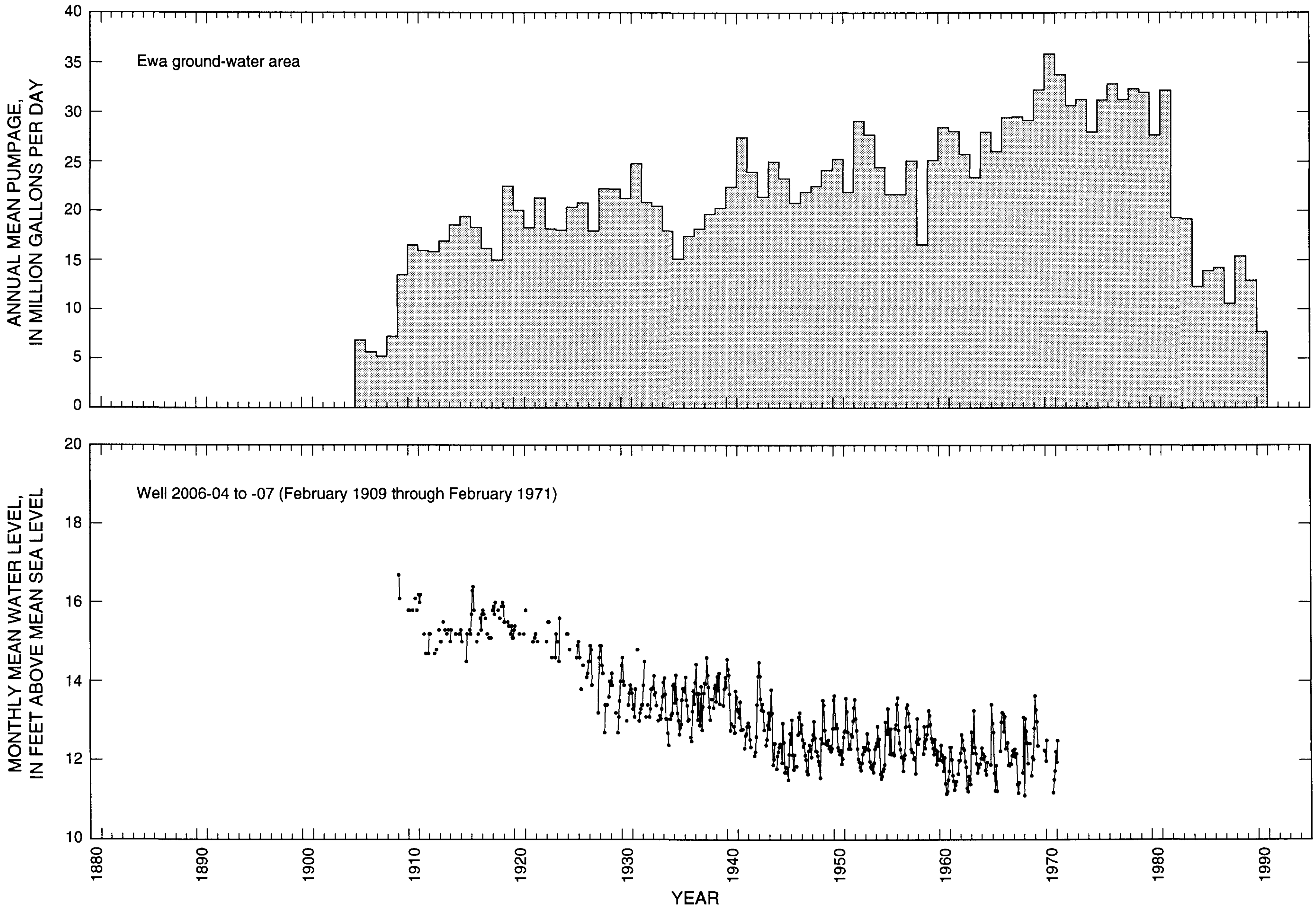


Figure 15. Annual mean pumpage from the Ewa ground-water area and monthly mean water levels at wells 2006-04 to -07, Oahu, Hawaii.

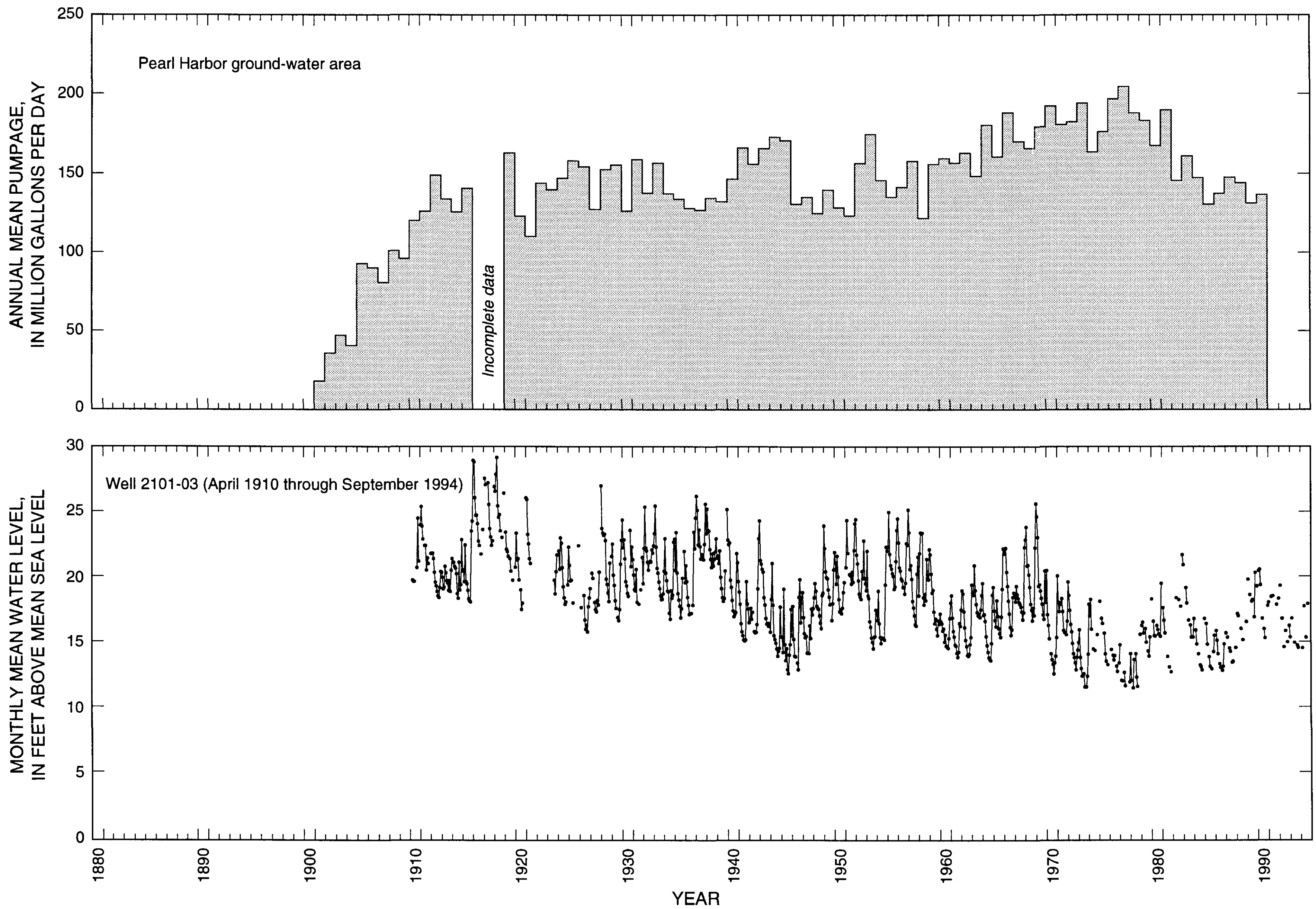


Figure 16. Annual mean pumpage (including flow from wells 2357-10 to -13) from the Pearl Harbor ground-water area and monthly mean water levels at wells 2101-03, 2300-10, and 2256-10, Oahu, Hawaii.

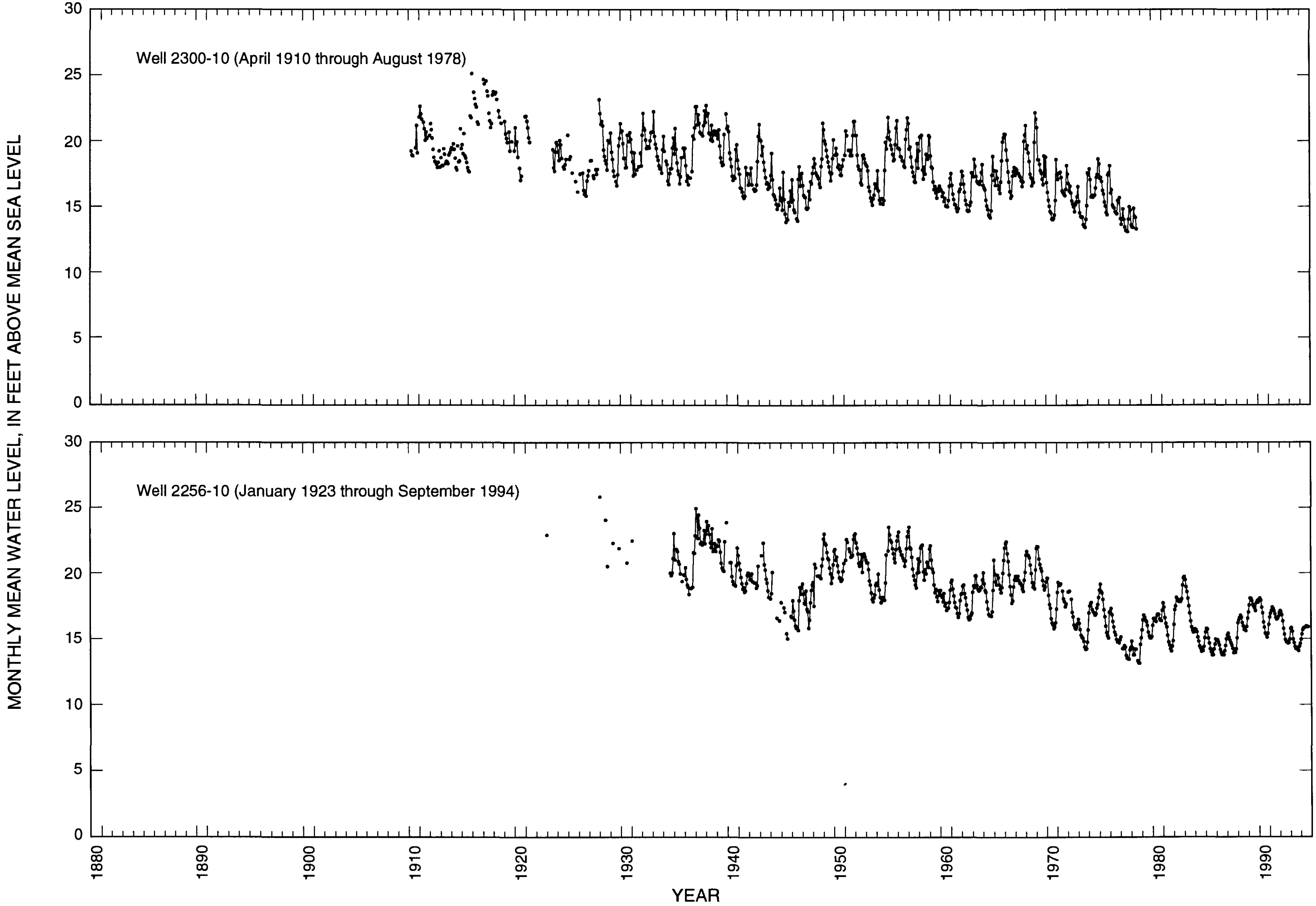


Figure 16. Annual mean pumpage (including flow from wells 2357-10 to -13) from the Pearl Harbor ground-water area and monthly mean water levels at wells 2101-03, 2300-10, and 2256-10, Oahu, Hawaii--*Continued.*

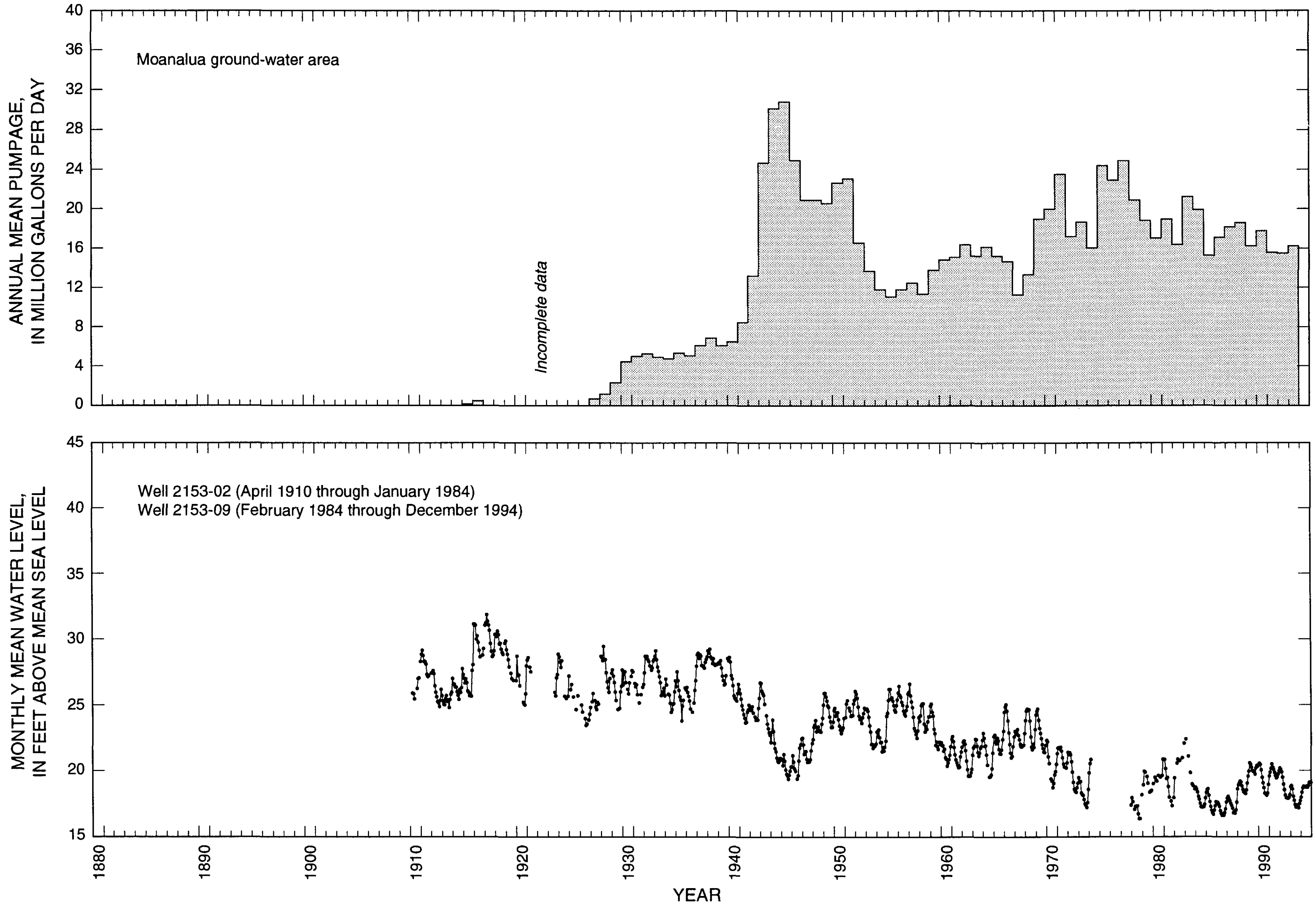


Figure 17. Annual mean pumpage and monthly mean water levels, Moanalua ground-water area, Oahu, Hawaii.

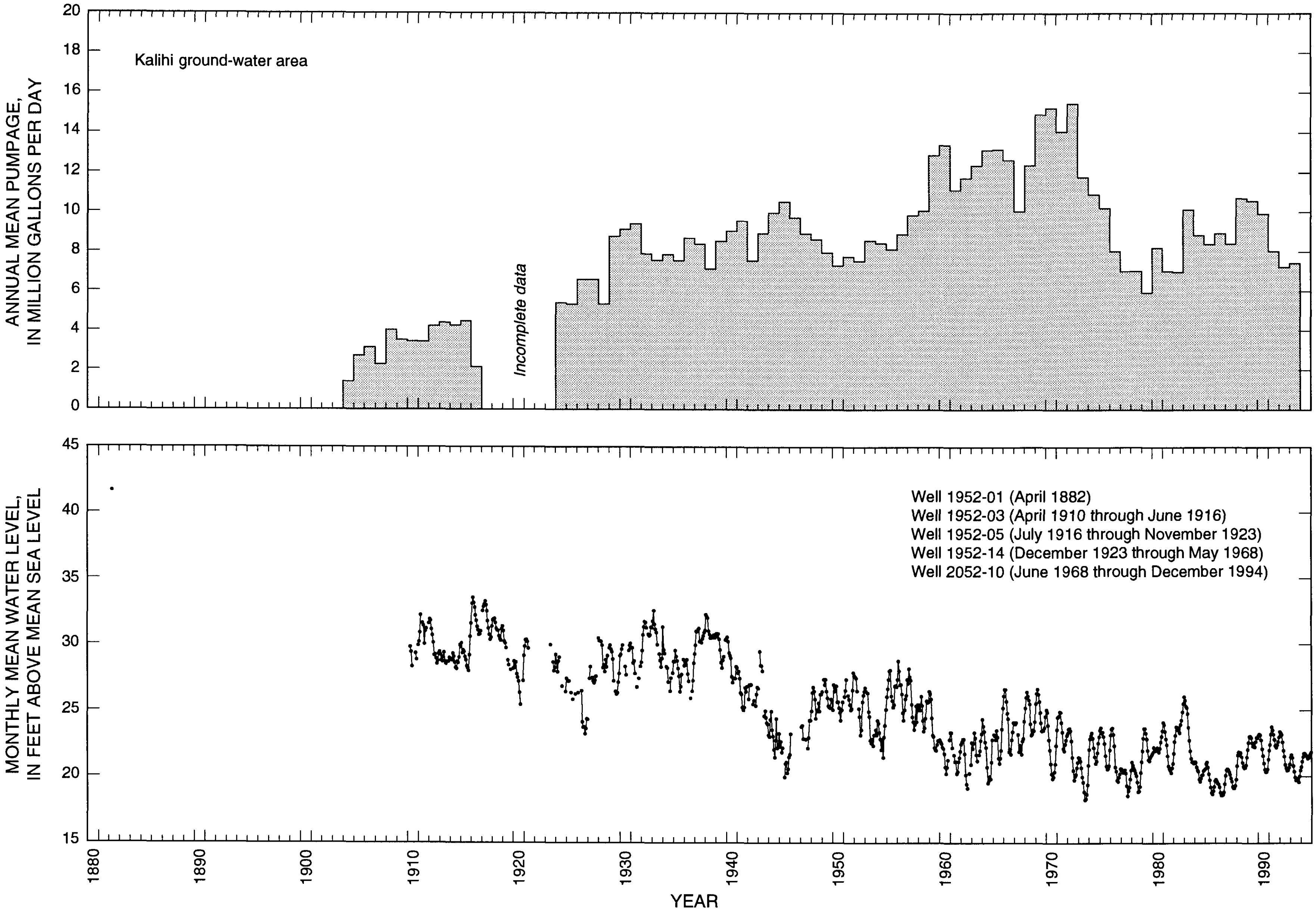


Figure 18. Annual mean pumpage and monthly mean water levels, Kalihi ground-water area, Oahu, Hawaii.

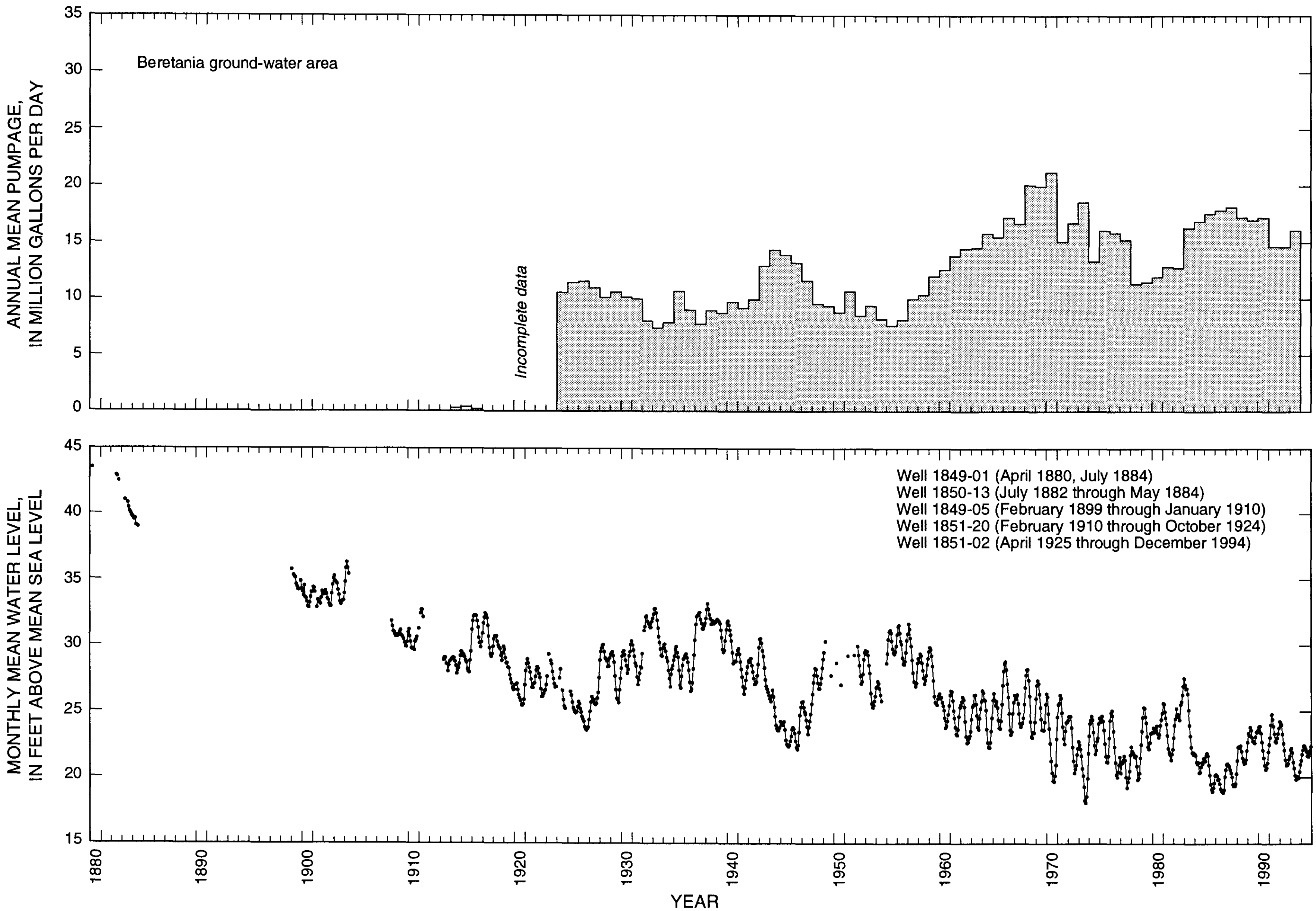


Figure 19. Annual mean pumpage and monthly mean water levels, Beretania ground-water area, Oahu, Hawaii.

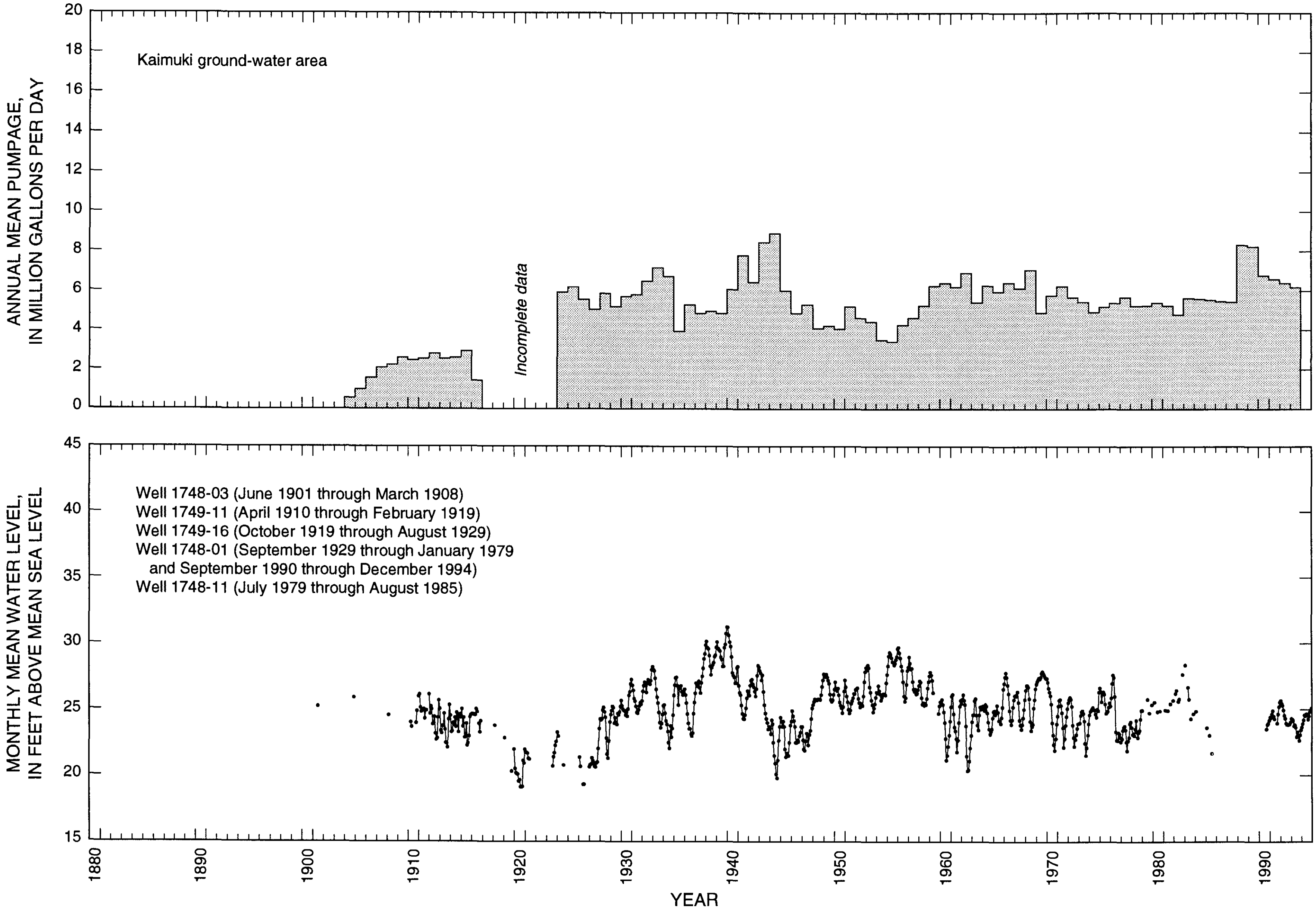


Figure 20. Annual mean pumpage and monthly mean water levels, Kaimuki ground-water area, Oahu, Hawaii.

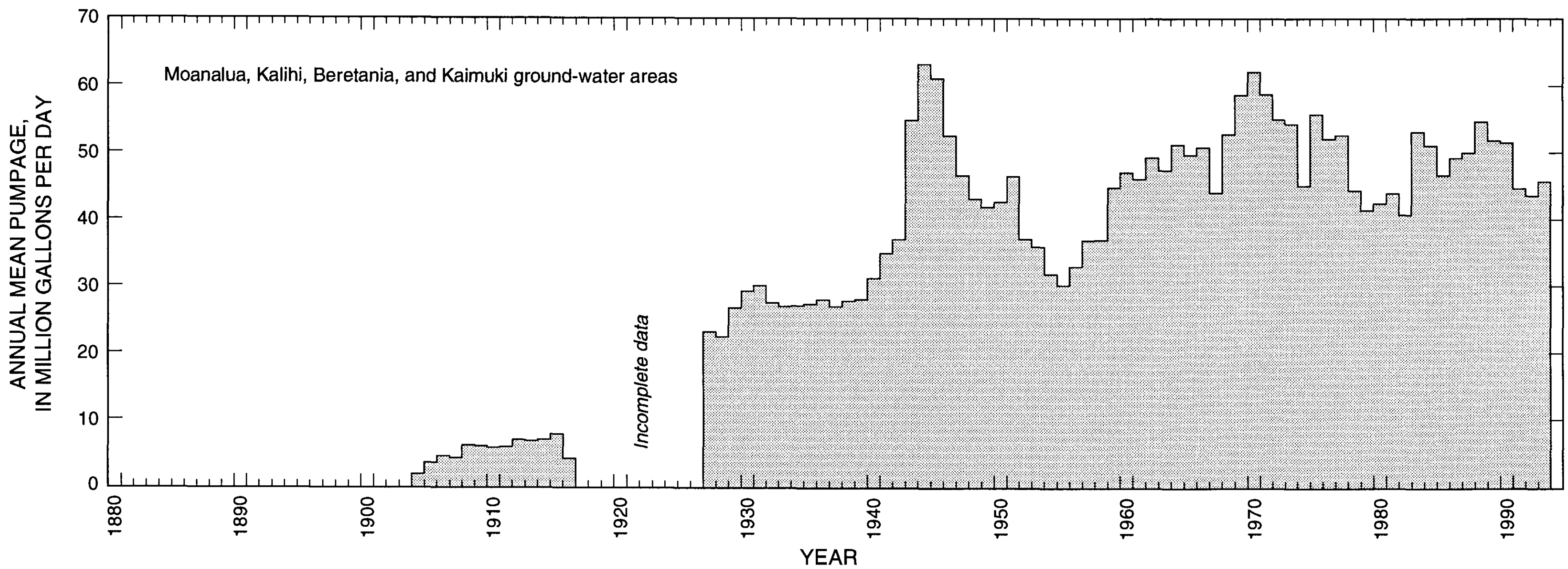


Figure 21. Combined annual mean pumpage from Honolulu (Moanalua, Kalihi, Beretania, and Kaimuki ground-water areas), Oahu, Hawaii.

Ground-Water Discharge by Springs

Ground-water discharge from the central Oahu flow system is in the form of seepage into stream channels, subaerial and submarine springs near the coast, and diffuse seepage into the caprock. The most notable group of springs exist near the shore of Pearl Harbor. On the basis of existing springflow measurements, Nichols and others (1996) estimated predevelopment discharge from the Pearl Harbor springs to be between 176 and 183 Mgal/d. Submarine discharge of freshwater through the caprock cannot be measured.

Northern Oahu

In northern Oahu, onshore coastal discharge of ground water from discrete springs and diffuse seeps is manifested in the form of marshes and channel flow from the marshes to the ocean. No published measurements of onshore coastal discharge are available for the Mokuleia ground-water area. In the Waialua ground-water area, Rosenau and others (1971) estimated that from 2 to 4 Mgal/d discharges in the coastal area as seepage into low-lying marshes or as springflow. By assuming total discharge at the marshes to be equal to the evaporation from an equivalent open body of water plus measured channel flow from the marshes to the ocean, Dale (1978) estimated ground-water discharge into marshes in the Waialua area to be 9.01 Mgal/d. Dale (1978) measured a combined total of 0.70 Mgal/d stream-channel seepage from Anahulu River and Opaeula, Helemano, Poamoho, and Kaukonahua Streams in the Waialua area. Rosenau and others (1971) estimated that about 3 Mgal/d discharges from springs on the south bank of the Anahulu River.

Schuyler and Allardt (1889, p. 30) measured discharge of 16 Mgal/d from springs east of what they named the Kawailoa River. Rosenau and others (1971) mentioned that freshwater springs have been reported offshore from the Kawailoa ground-water area, and that ground-water discharges to a large coastal swamp near the southwestern part of the area.

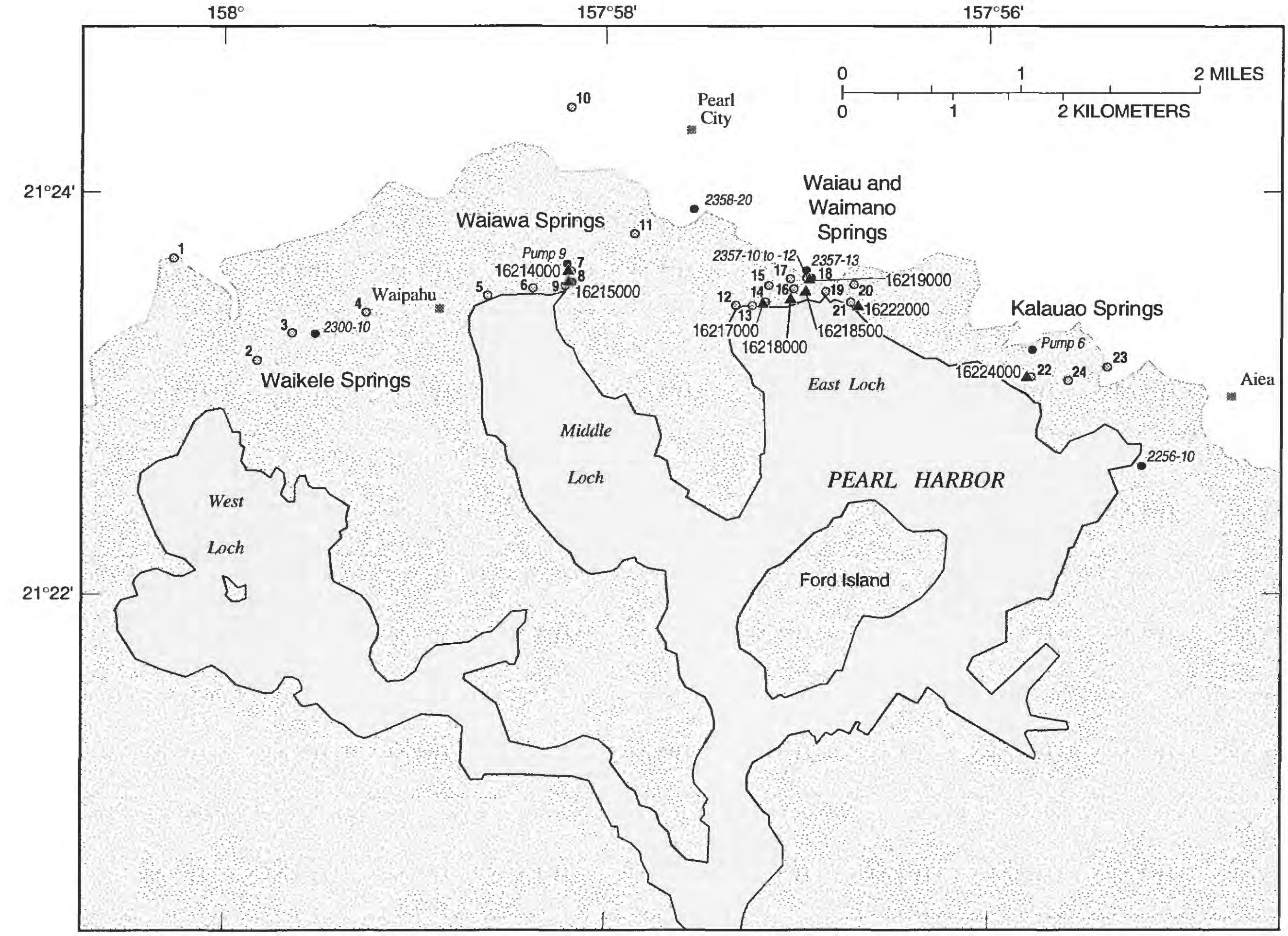
Pearl Harbor Springs

The Pearl Harbor springs consist of a group of springs near the inland margin of the caprock along the shore of Pearl Harbor. The five major springs have been named, from east to west, Kalauao, Waiau, Waimano, Waiawa, and Waikele Springs (fig. 22) and are described in detail by Visher and Mink (1964). Schuyler and Allardt (1889) reported that the largest flows were from a bluff at an altitude of 20 to 25 ft. The main spring discharge is from orifices where basalt is exposed in a break in slope of the land surface (Visher and Mink, 1964). Water also discharges as diffuse seeps where the caprock is thin or where erosion has exposed basalt. In addition, ground water discharges from the volcanic aquifer through alluvium into stream channels incised below the level of the existing head in the aquifer. Historically, the springflow was used for wetland crops such as rice. Spring discharge is currently used for watercress cultivation as well as for industrial purposes.

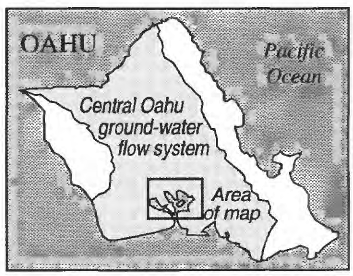
Discharge at these sites was first measured by Schuyler and Allardt (1889), who measured only the wasteflow not used for irrigation. The total discharge measured at seven locations was 75.05 Mgal/d, which represents a lower bound for the actual total Pearl Harbor springflow at the time because only the unused springflow was measured.

In 1911, miscellaneous measurements of springs at 11 locations around Pearl Harbor were made by the USGS (Martin and Pierce, 1913). The total measured spring discharge amounted to 47.95 Mgal/d. The measured discharge is not representative of the total flow from the Pearl Harbor springs because Kalauao Springs and other sites perhaps were not measured.

In 1927, the Honolulu Board of Water Supply initiated a program of measuring the discharge from the five major spring sites (Kunesh, 1929, 1931). Annual mean discharge for 1928–30 was computed from reported monthly discharge (Kunesh, 1931) and is presented in table 4. Starting in 1931, the USGS began establishing gaging stations to monitor flow from the Pearl Harbor springs. Discharge measurements for 1932 and 1933 (Stearns and Vaksvik, 1935) are shown in table 4. Reported discharge for 1928–30 at Waimano and Waikele (Kunesh, 1931) underestimated the actual total discharge at these sites (see discussion later in this section). Stearns and Vaksvik (1935) estimated the discharge from Waikele on the basis of the earlier measurements of Kunesh (1931). During 1931–67, the USGS maintained various gages to monitor the discharge from the Pearl Harbor springs. Since 1967, the USGS has made semiannual discharge measurements at 24 sites to monitor discharge from the Pearl Harbor springs.



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 21°19'40" and 21°38'20", central meridian 157°58'



EXPLANATION

16224000 ▲ STREAM-GAGING STATION AND NUMBER

11 ◎ SPRING MEASURING SITE AND NUMBER

2256-10 ● WELL OR PUMP AND NUMBER

SEDIMENTARY DEPOSITS (CAPROCK)

Figure 22. Location of Pearl Harbor springs measurement sites, and selected gaging stations, wells, and pumps, Oahu, Hawaii.

Table 4. Annual mean Pearl Harbor springs discharge, 1928–33, Oahu, Hawaii

[Data from Kunesh (1931) and Stearns and Vaksvik (1935); values in million gallons per day; est, estimated]

Year	Spring					Total
	Kalauao	Waiau	Waimano	Waiawa	Waikele	
1928	17.9	8.3	12.6	16.8	8.4	64.0
1929	17.5	6.1	16.2	14.3	7.1	61.2
1930	21.1	8.2	20.8	15.1	8.3	73.5
1932	21.8	8.7	31.7	15.2	8.0 (est)	85.4
1933	20.9	8.3	30.3	14.1	8.0 (est)	81.6

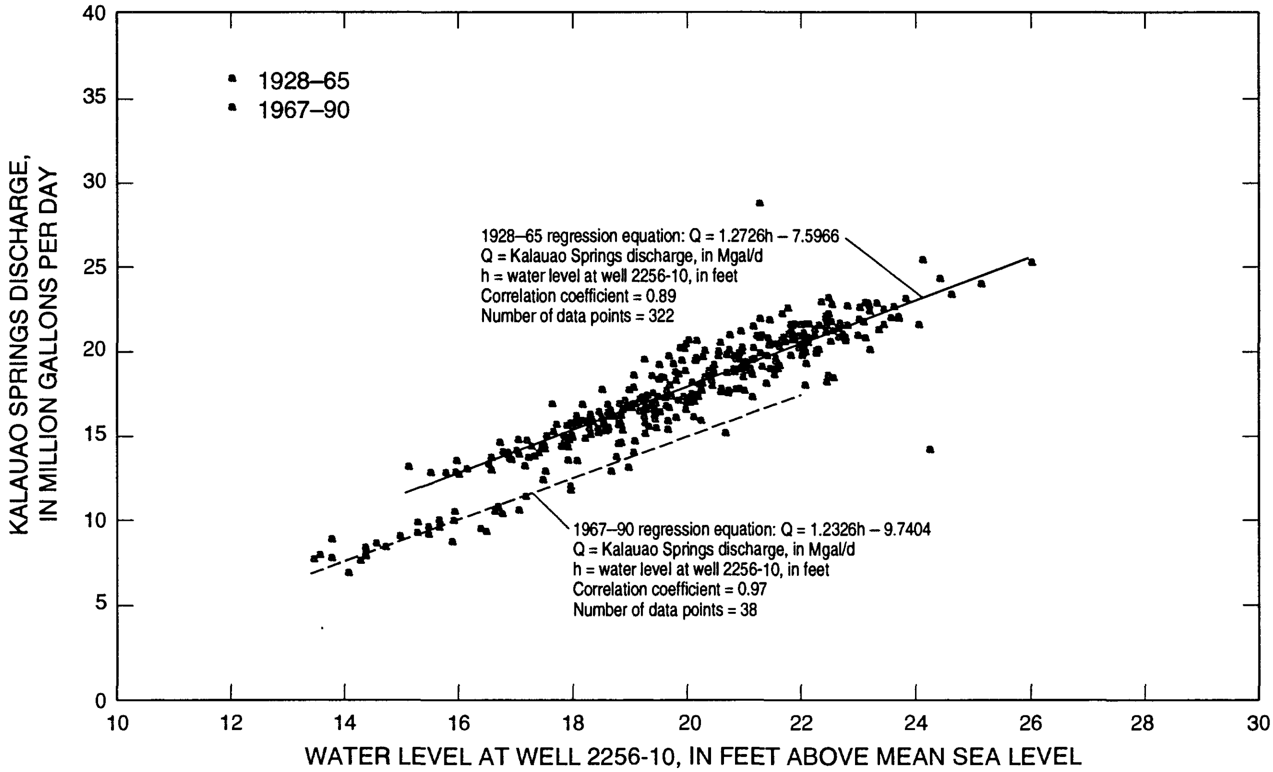


Figure 23. Relation of water level and discharge and linear regression lines for the Kalauao Springs, Pearl Harbor ground-water area, Oahu, Hawaii.

Kalauao Springs.--Between 1931 and 1965, the undiverted flow from Kalauao Springs was measured at USGS stream gage 16224000. Until 1965, Honolulu Plantation Company pump 6 diverted springflow above the measuring site. Thus, the pump 6 diversion must be added to the discharge measurements from gage 16224000 to reflect the Kalauao springflow. Since 1967, the USGS has measured the discharge at Kalauao Springs on a semiannual basis. The discharge at Kalauao Springs is a function of the freshwater head in the aquifer, as represented by the water level at well 2256-10 (fig. 23). Well 2256-10 is located about 4,000 ft from Kalauao Springs. The data shown in figure 23 represent all available water level-discharge pairs from 1928–90. Discharge at Kalauao Springs increases nearly linearly with water level within the range of discharge and water-level measurements shown in figure 23. The water-level discharge relation at Kalauao Springs shows a slight shift starting in 1967. This may reflect physical changes in the vicinity of the springs in the mid-1960's or changes in measuring technique. In addition to the discharge at Kalauao Springs, a small amount of channel seepage from Kalauao Stream has been measured by the USGS since 1967. This channel seepage is not included in the springflow data presented in figure 23.

Waiau and Waimano Springs.--Because of their proximity, Waiau and Waimano Springs are considered together in this report. Waiau and Waimano Springs discharge near the northwestern extent of East Loch and are located about 6,000 to 10,000 ft west of Kalauao Springs. During 1931–38, discharge from Waiau and Waimano Springs was measured at USGS stream gages 16217000, 16218000, 16218500, and 16222000. In 1938, the Hawaiian Electric Company began excavation of an infiltration tunnel (2357-13) at Waiau to meet condensing water needs for their power plant. Following completion of the tunnel in 1939, three artesian wells were drilled to augment the flow. Flow from these artesian wells (2357-10 to 12) goes directly into the infiltration tunnel. Discharge from the Hawaiian Electric Company tunnel was measured at USGS stream gage 16219000 starting in 1940. Average discharge at gage 16219000 during 1940–67 was about 11 Mgal/d. Although gages at Waiau and Waimano were maintained by the USGS during 1938–67, the total discharge from Waiau and Waimano cannot be estimated for this period because of incomplete data or unquantifiable diversions by Hawaiian Electric Company. Since 1967, the USGS has measured the discharge from Waiau and Waimano Springs on a semiannual basis. The combined discharge at Waiau and Waimano Springs is a function of the freshwater head in the aquifer, as represented by the water level at well 2256-10 (fig. 24). The data in figure 24 represent all available water level-discharge data pairs during 1928–37 and 1973–85. The combined discharge reflects a contribution from free-flowing artesian wells. The relation between water level and discharge for Waimano Springs alone, exclusive of Waiau Springs (fig. 25), seems to indicate that the data during 1928–30 (Kunesh, 1931) are not representative of the total discharge at Waimano Springs. In addition, discharge during the period 1928–30 does not seem to be correlated with water level at well 2256-10.

Waiawa Springs.--Waiawa Springs discharge in the vicinity of Middle Loch, about 6,000 ft west of Waimano Springs (fig. 22). Discharge measurements for Waiawa Springs during 1927–30 (Kunesh, 1931) include flow from the vicinity of USGS stream gage 16214000 which was established in 1931. Discharge data for gage 16214000 are available for 1931–64. These data must be corrected for diversions by Oahu Sugar Company pump 9 to reflect total spring discharge above gage 16214000. Additional flow from Waiawa Springs was measured at USGS gage 16215000. Data from USGS gage 16215000 are available for 1951–60. Since 1967, the USGS has measured discharge from Waiawa Springs on a semiannual basis. The data collected since 1967 reflect a better coverage of Waiawa Springs and also include a component of discharge of about 2 Mgal/d from nearby flowing artesian wells. The Waiawa Springs water-level/discharge relations for data from 1951–60 and 1967–90 (fig. 26) indicate that the 1951–60 data reflect an incomplete coverage of the total Waiawa Springs discharge. Visher and Mink (1964) seem to have based their estimate of Waiawa Springs discharge on data from gage 16214000. Thus, Visher and Mink (1964) underestimated the total discharge at Waiawa Springs.

Waikele Springs.--Waikele Springs discharge in the vicinity of Pearl Harbor's West Loch. Data to fully characterize the Waikele Springs discharge were first available in 1967. Discharge at Waikele Springs during 1967–90 is a function of the freshwater head in the aquifer, as represented by the water level at well 2256-10 (fig. 27). Between 1928 and 1932, the altitude of the

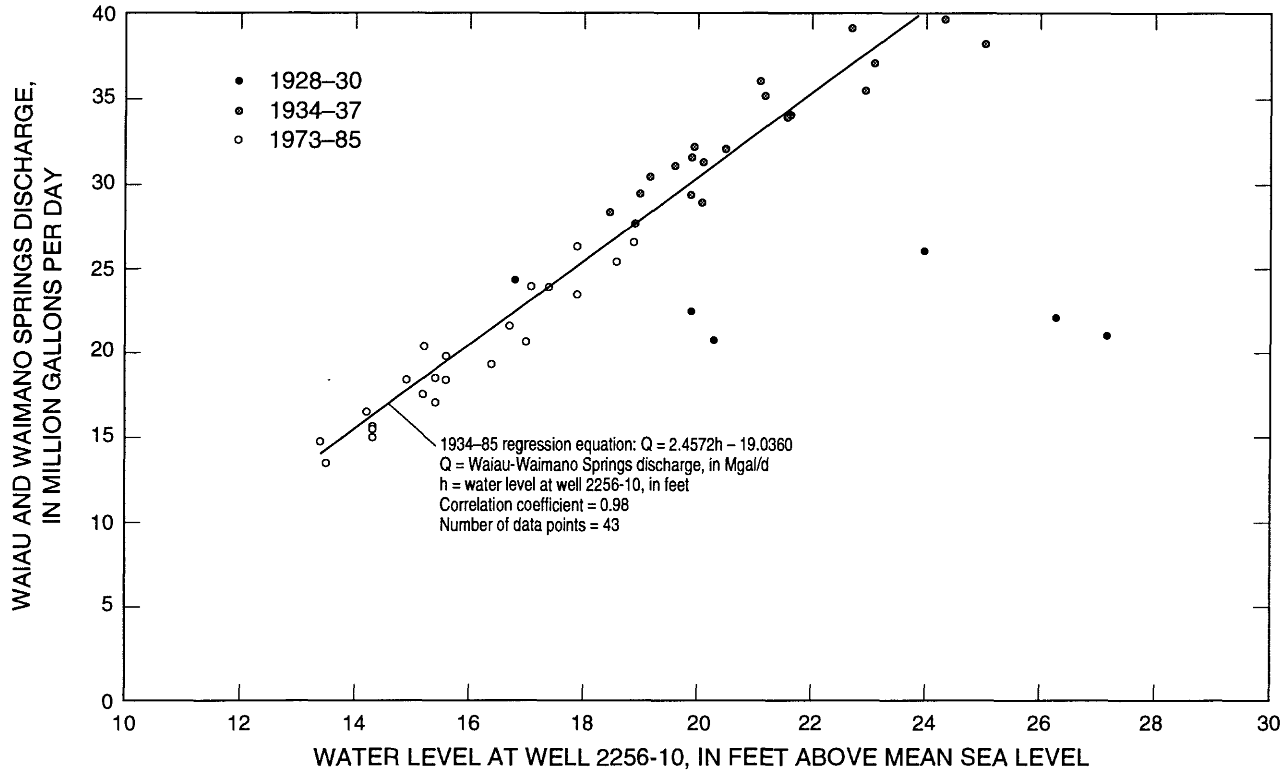


Figure 24. Relation of water level and discharge and linear regression line for the Waiau and Waimano Springs, Pearl Harbor ground-water area, Oahu, Hawaii.

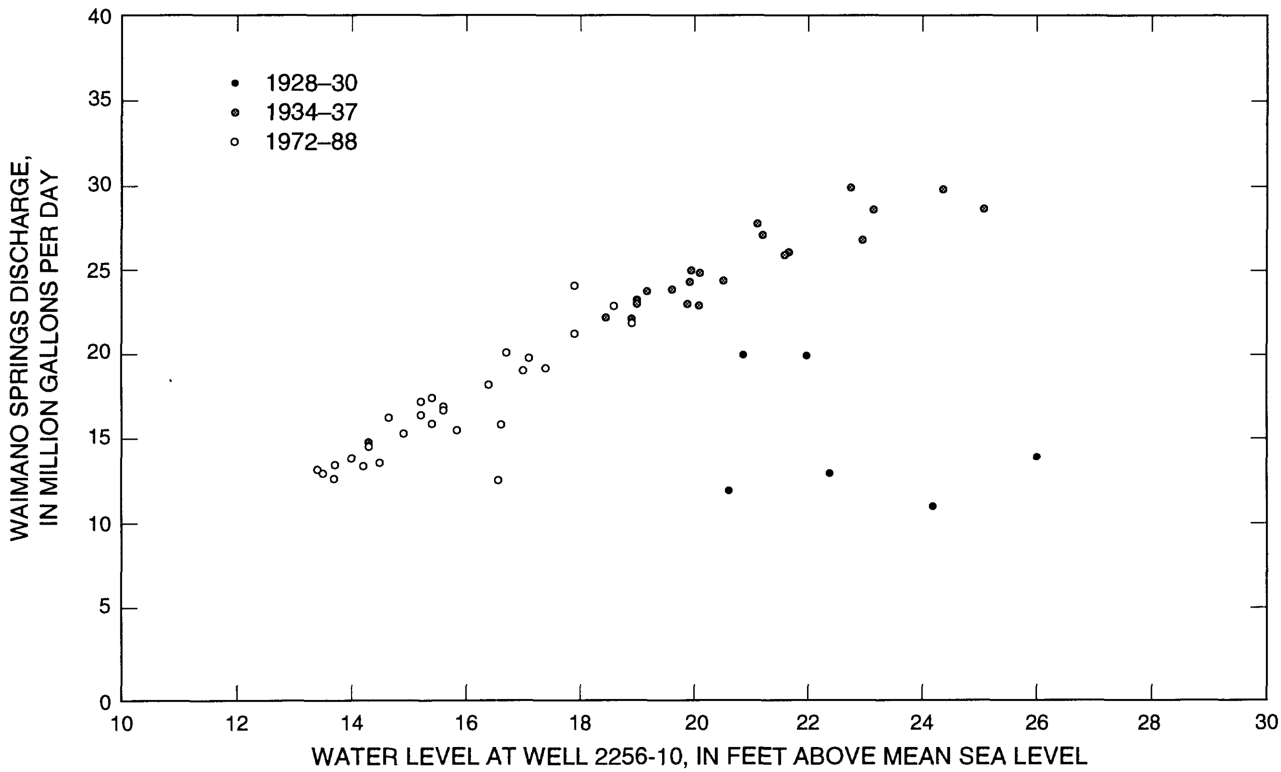


Figure 25. Relation of water level and discharge for the Waimano Springs, Pearl Harbor ground-water area, Oahu, Hawaii.

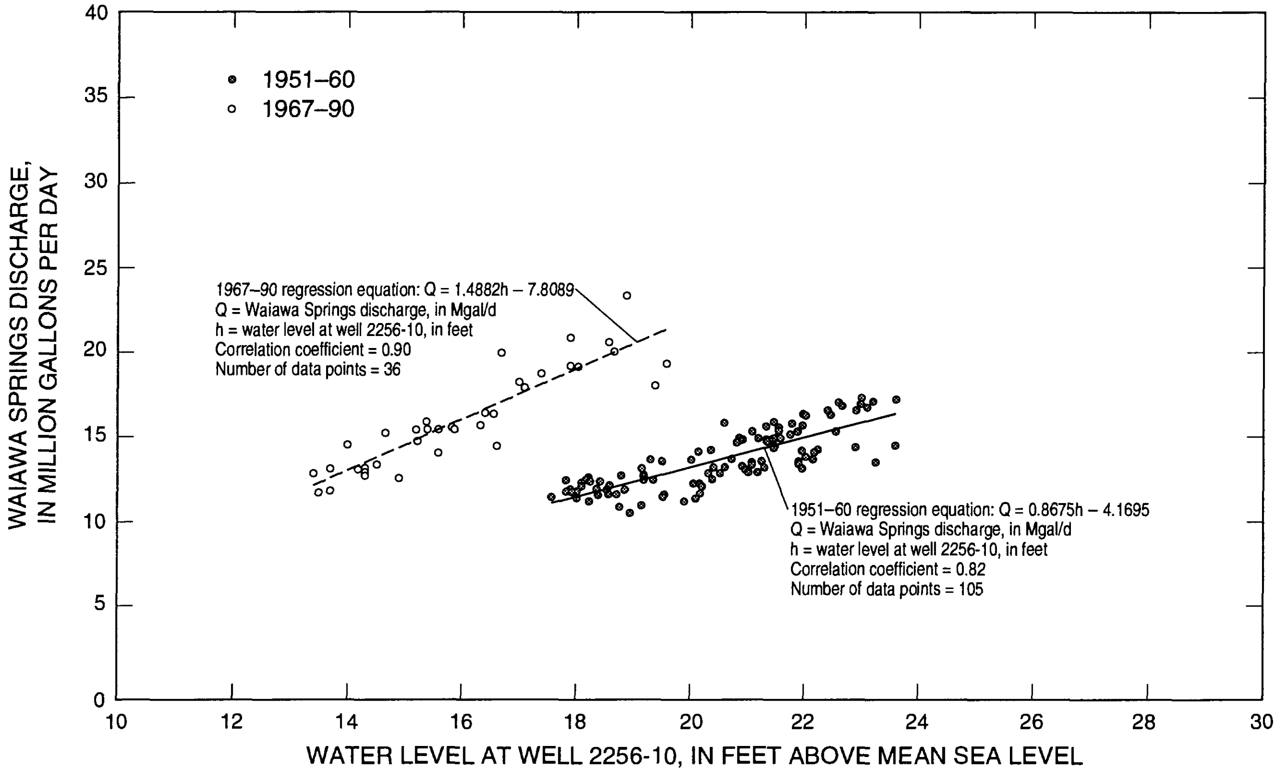


Figure 26. Relation of water level and discharge and linear regression lines for the Waiawa Springs, Pearl Harbor ground-water area, Oahu, Hawaii.

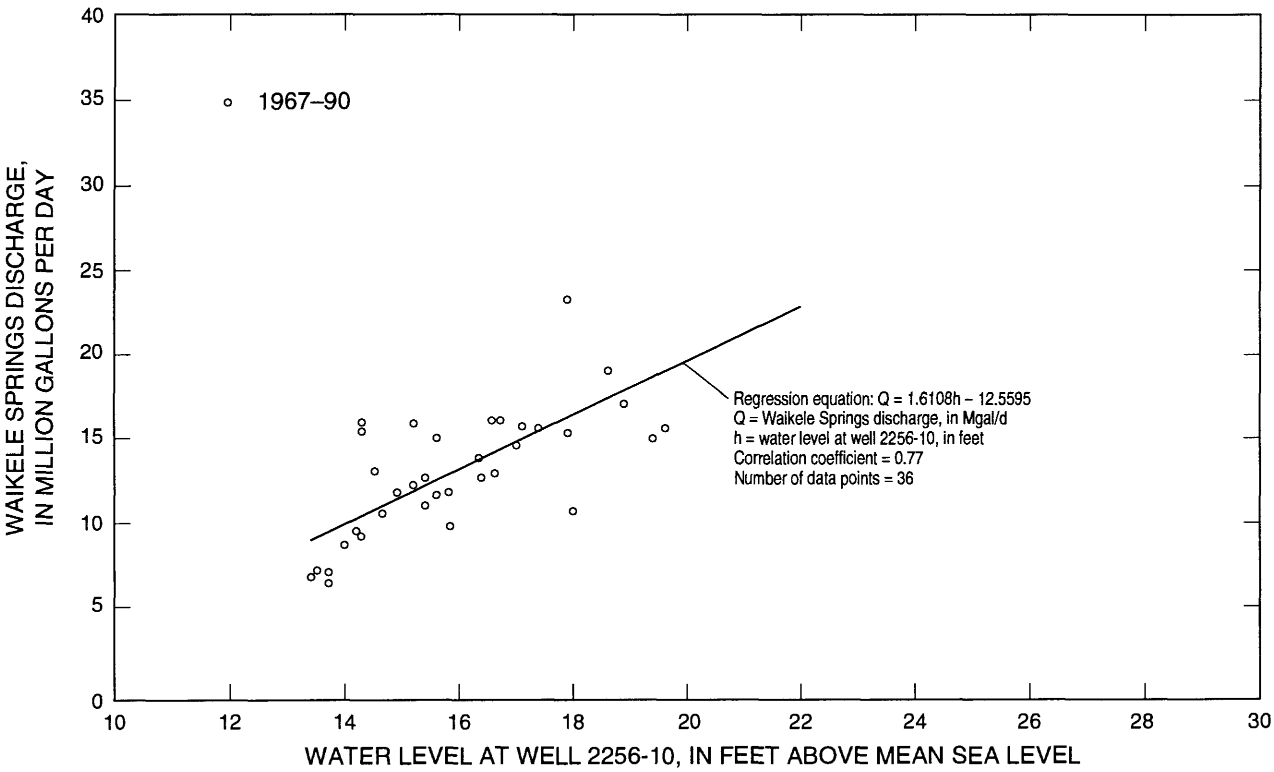


Figure 27. Relation of water level and discharge and linear regression line for the Waikele Springs, Pearl Harbor ground-water area, Oahu, Hawaii.

water level at well 2256-10 was about 22 ft, and the corresponding discharge at Waikele Springs was reported to be about 8 Mgal/d (Kunesh, 1931; Stearns and Vaksvik, 1935). Extrapolation of the data in figure 27 indicates that for a water level of 22 ft at well 2256-10, the discharge at Waikele Springs is expected to be in excess of 20 Mgal/d. Thus, the reported Waikele Springs discharge by Kunesh (1931) and Stearns and Vaksvik (1935) probably underestimated the total discharge.

Ground-Water Levels

Ground-water flow rates and directions are often inferred from ground-water levels. Ground-water levels also are an indicator of changes in recharge or withdrawals from the ground-water system, and can be an indicator of freshwater-lens thickness. The spatial and temporal distributions of water levels in the central Oahu flow system are described in this section by ground-water area.

Mokuleia Ground-Water Area

The first well drilled in the Mokuleia area was completed in 1881–82 (McCandless, 1936). Thrum (1889) stated that the maximum water level in wells in the Waialua district, which includes Mokuleia, was 21 ft. Of the 21 wells drilled before 1889 which are listed by Thrum (1889), 18 were located on what he termed the "Mokuleia Plains" and three were located in "Waialua." The "Mokuleia Plains" wells have depths ranging from 400 to 590 ft which are representative of wells drilled in the Mokuleia area through the thick coastal caprock. Thus, Thrum (1889) suggested that the maximum water level in the Mokuleia and Waialua ground-water areas did not exceed 21 ft above sea level.

The initial water level of 21 ft for the Waialua district was accepted by other investigators of the period (Andrews, 1909; Sedgwick, 1913). In 1936, however, 54 years after drilling the first well in the Mokuleia area, McCandless (1936) reported that the initial water level in the area was 30 ft above sea level. McCandless also states that diaries containing the details of the first series of artesian wells drilled in Hawaii were lost so that the recollection was based on memory. Thus, it is possible that the reported initial water level of 30 ft may be in error.

Recorded water-level measurements for wells in the Mokuleia area are unavailable prior to 1924. During the period 1924–93, water levels at well 3409-16 indicate a slight upward trend from 1924 to about 1970 (fig. 11). Since 1970, there has been a slight downward trend in water levels. The highest recorded water level at this well was 21.3 ft above mean sea level on January 16, 1969, and the lowest recorded water level was 16.75 ft above mean sea level on August 6, 1929. The annual difference between the wet season and dry season water levels at this well is about 1 ft.

Published water-level surveys for the Mokuleia area are available for September 22, 1934 (Stearns and Vaksvik, 1935, p. 266) and for January 1963 (Rosenau and others, 1971). Water levels in the Mokuleia area decrease from east to west. In 1995, water levels decreased from about 22.5 ft above mean sea level at well 3205-02 to about 16.5 ft above mean sea level toward the western extent of the area at well 3411-01. Wells 3205-02 and 3411-01 are about 6.7 mi apart. Thus, the magnitude of the hydraulic gradient in the Mokuleia area between these two wells is estimated to be 0.00017 ft/ft. Rosenau and others (1971) note that there is an 8-ft drop in head over a horizontal distance of about 5,000 ft at the western end of the Mokuleia ground-water area. The drop in head between wells 3411-01 and 3412-01 to -02 may indicate the presence of a barrier between these wells or may reflect the loss of head as water discharges vertically from the lens. The original depth of well 3411-01 is unknown but was sounded to 257 ft below sea level on September 2, 1994. Wells 3412-01 to -02 extend to a depth of 223 ft below sea level.

Waialua Ground-Water Area

The earliest recorded water level for the Waialua area is from 1911 at well 3406-01. Water levels at this well are available for 1911–78 (fig. 12). The highest recorded water level at well 3406-01 was 13.35 ft above mean sea level in December 1914, and the lowest recorded water level was 9.19 ft above mean sea level on April 24, 1946. Water levels at this well averaged about 11 ft, with seasonal fluctuations (difference between successive wet and dry season water levels) of about 1 ft.

Published water-level surveys for the Waialua ground-water area are available for 1930–34 (Stearns and Vaksvik, 1935, p. 266) and for November 22, 1974 (Dale, 1978). In 1995, measured water levels were about 10 to 11 ft above mean sea level at wells within 1.5 mi of the coast and about 12.5 ft above sea level at well 3204-01 located 3.9 mi from the coast. The water-level distribution within the Waialua area is affected by several agricultural pumping installations, the largest of which is capable of withdrawing 17 Mgal/d. In addition, the old alluvium filling the bottoms of Opaeula, Helemano, and Poamoho Stream valleys and the associated weathered zones beneath the valleys may act as partial barriers to ground-water flow which affect the spatial distribution of water levels within the area.

In 1993, a pair of observation wells was drilled to determine the freshwater vertical hydraulic gradient beneath the caprock in the Waialua area (Presley and Oki, 1996a). These wells were drilled about 6,000 ft from the coast through the caprock near the confluence of Helemano and Opaeula Streams. The first well has a screened interval between 271 and 291 ft below sea level. The second well, located about 30 ft away from the first well, has a screened interval between 68.5 and 78.5 ft below sea level. The artesian head in the deeper well is about 0.25 ft greater than the head in the shallow well which yields a vertical gradient at this site with a magnitude of about 0.001 ft/ft.

Kawailoa Ground-Water Area

The first wells drilled in the Kawailoa area were at Waialua Sugar Company pump 4 (wells 3605-01 to -13) in 1900. (Note that 10 additional wells were drilled at pump 4 in 1955 so that the current State well numbers for pump 4 are 3605-01 to -23.) The earliest recorded water-level measurement for the Kawailoa area was 3.4 ft above mean sea level on April 9, 1930 at pump 4, located near the western extent of the Kawailoa area (Stearns and Vaksvik, 1938). The highest recorded water level at this well was 4.26 ft above mean sea level on October 8, 1930, and the lowest recorded water level was 1.97 ft above mean sea level on June 25, 1963. The lowest recorded water level was probably measured under pumping conditions when Waialua Sugar Company pump 4 was withdrawing 14 Mgal/d.

The earliest recorded water level at well 3504-01, located near the southern extent of the Kawailoa area, was 5.57 ft above mean sea level on March 26, 1938. Water-level measurements were collected from this well, which was cased with 0.75-in. pipe, between 1938 and 1965 (fig. 13). The lowest recorded water level was 4.36 ft above mean sea level on May 2, 1950, and the highest water level was 9.26 ft above mean sea level on April 2, 1945. The wide variations in water level at this well are likely not representative of conditions in the aquifer and may merely reflect rainfall or irrigation water from adjacent sugarcane fields affecting the water level in the well. Palmer (1958) suggests that the high measured water levels may be related to floods in the Anahulu River valley which recharge the Kawailoa ground-water area. Well 3504-01 was abandoned in 1967, and a search for the well in 1993 was unsuccessful. Later in 1993, well 3505-25 was drilled about 2,000 ft from the presumed location of well 3504-01. A digital recorder was installed to monitor water-level changes in well 3505-25 (fig. 28). Between July 1, 1994 and March 28, 1995, the water level at well 3505-25 remained between 4.5 and 5.5 ft above mean sea level.

Toward the northeastern extent of the Kawailoa area, a water level of 5.81 ft above mean sea level was measured at well 4002-02 on August 31, 1939. Subsequent water-level measurements at this well made between 1942 and 1964 have ranged from 2.74 to 3.50 ft above mean sea level.

In the Kawailoa area the coastal caprock is thin or nonexistent (Stearns and Vaksvik, 1935; Rosenau and others, 1971). Consequently, water levels are less than 6 ft above mean sea level, and more commonly less than 3 ft above sea level, at wells within a mile of the coast. At well 3503-01 (Presley and Oki, 1996b), located about 3.4 mi inland from the coast, measured water levels during 1995 were about 7.5 ft above mean sea level. The magnitude of the hydraulic gradient in the Kawailoa area between wells 3503-01 and 3505-25 is about 0.0003 ft/ft.

Schofield Ground-Water Area

Observation wells in the Schofield ground-water area are few so that the spatial distribution of water levels throughout the area is difficult to establish. Most of the observation wells are located in the western part of the Schofield area (Harding Lawson Associates, 1996). In general, it is expected that water levels are highest toward the eastern extent of the Schofield area, near the recharge area of the Koolau rift zone. Water levels decline from 275 ft above sea level in the Schofield area to 10 to 30 ft in the adjoining ground-water areas to the north and south. The northern and southern ground-water dams represent transition areas where water levels drop from 275 ft to 10 to 30 ft.

Water levels measured at Schofield shaft 4 (well 2901-07) have ranged from a low of 269.52 ft above sea

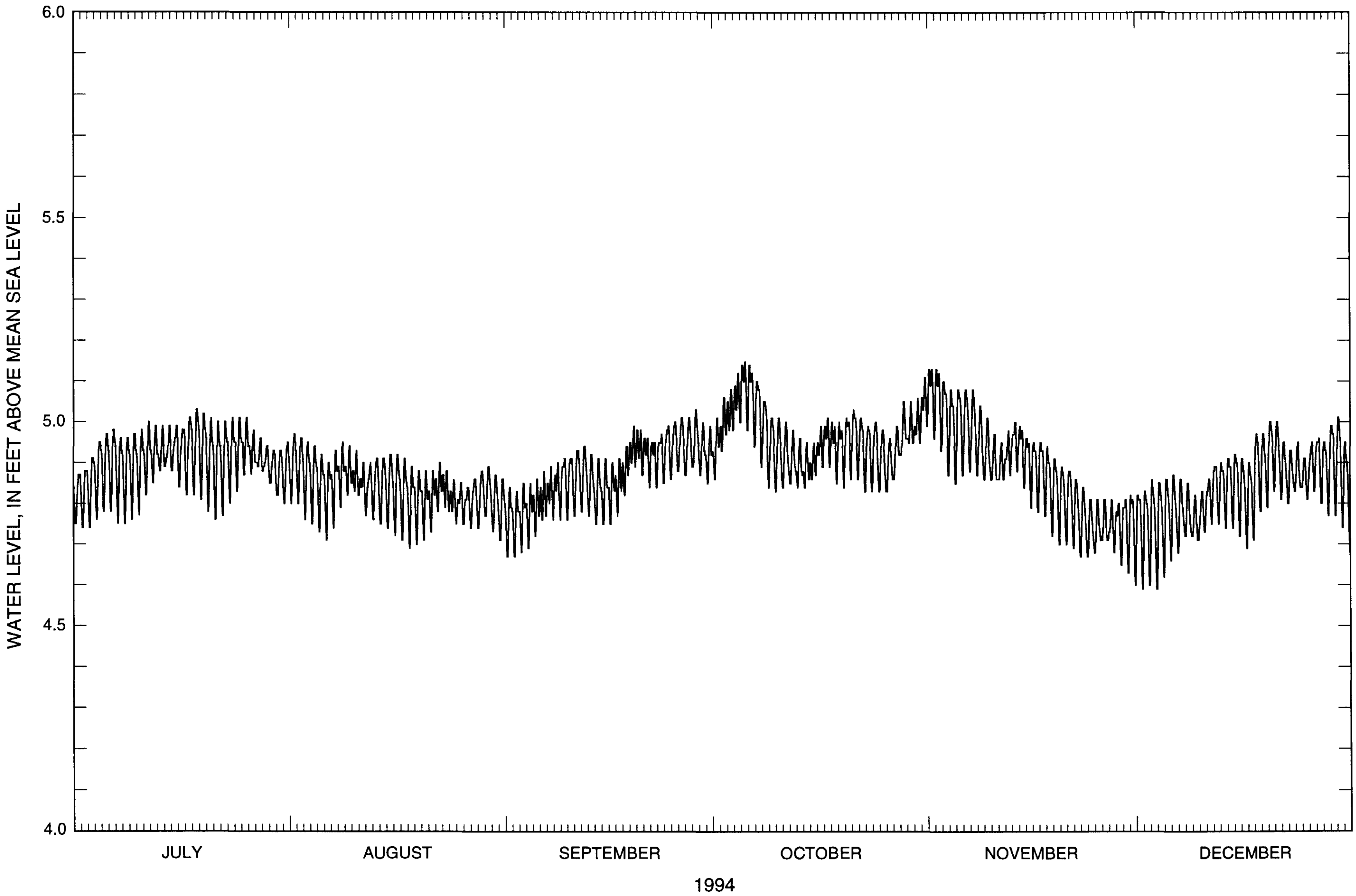


Figure 28. Water levels at North Lower Anahulu exploratory well 3505-25, Kawailoa ground-water area, Oahu, Hawaii.

level on December 5, 1978, to a high of 284.40 ft above sea level on May 12, 1969 (Matsuoka and others, 1995). Water levels in the Schofield area can change by as much as 7 ft within a year because of changes in recharge or pumpage (fig. 14).

Ewa Ground-Water Area

The first wells in the Ewa ground-water area of the Waianae aquifer were drilled in 1905 (wells 2006-01 to -07). The first reported water-level measurement for the Ewa area was 16.7 ft above mean sea level in February 1909 at wells 2006-01 to -07. Mink and others (1988, p. 31) suggested that the initial water level in the Ewa area was about 20 ft above mean sea level at the seaward extent of the volcanic aquifer beneath the Ewa Plain.

During 1909–45, water levels from wells 2006-04 to -07 declined at a rate of about 0.09 ft/yr (fig. 15). Since 1945, water levels have fluctuated about a mean value of about 12.5 ft above mean sea level. The seasonal fluctuation of water levels at this well is about 1 to 2 ft.

In the Ewa area, water levels measured between 1990 and 1994 are generally between 14 and 17 ft above sea level at wells located south of well 2303-06 (Matsuoka and others, 1995; unpub. data USGS Hawaii District well files). Reliable water levels at the inland extent of the Ewa area are unavailable to establish a current gradient.

Pearl Harbor Ground-Water Area

The first artesian well drilled on Oahu was in the Pearl Harbor area and was completed in 1879. The well (2101-04) was drilled toward the western extent of the Pearl Harbor area near West Loch. Thrum (1889) reported the original head in the southwestern part of the Pearl Harbor ground-water area to be 32 ft above sea level. Assuming a hydraulic gradient with a magnitude of 1 ft/mi, Mink (1980) estimated an initial water level of 39 ft at the inland extent of the Pearl Harbor area.

The history of water-level decline in wells in the Pearl Harbor area is well documented by other investigators (see, for example, Soroos and Ewart, 1979). Monthly mean water levels at wells in the western (well 2101-03), middle (well 2300-10), and eastern (well 2256-10) parts of the Pearl Harbor area show seasonal fluctuations as well as a long-term downward trend (fig. 16). Water levels are strongly influenced by a seasonal pumping pattern in the area. This effect is most pronounced at well 2101-03 which is located near several high-capacity agricultural pumping installations. Water levels at well 2101-03 have fluctuated 5 ft from successive dry and wet seasons.

Soroos and Ewart (1979) used a least squares analysis to estimate the rate of water-level decline in the Pearl Harbor area of 0.09 ft/yr during 1910–77. On the basis of an aquifer storage coefficient of 0.10 and the Ghyben-Herzberg principle, they then estimated the rate of water withdrawn from storage as 25 Mgal/d.

Ground water in the Pearl Harbor area of the Koolau aquifer is impounded behind the coastal caprock which is about 1,000 ft thick near the coast. Measured water levels in the Pearl Harbor area are lowest near large spring discharge sites along the shore of Pearl Harbor at the inland edge of the caprock. Water levels increase inland toward the recharge areas of the Koolau Range and the Schofield ground-water area. At well 2256-10 near East Loch and at well 2101-03 near West Loch, water levels in 1994 were about 16 ft above mean sea level. At well 2600-04, about 4.2 mi inland from Middle Loch, water levels in 1994 were about 20 ft above mean sea level (Matsuoka and others, 1995). Freshwater head maps for 1958 (Visher and Mink, 1964), 1971 (Dale and Ewart, 1971), and 1978 (Soroos and Ewart, 1979) are compiled by Soroos and Ewart (1979). In general, these maps show a uniform, regional decline in freshwater head of about 7 ft between 1958 and 1978.

Moanalua, Kalihi, Beretania, and Kaimuki Ground-Water Areas

The first well drilled in Honolulu was in the Beretania area and encountered flowing artesian conditions in April 1880. The water level at this well (1849-01) was reported by the owner to be 43.5 ft above mean sea level in April 1880. In the Kaimuki ground-water area to the east, the initial water level was reported to be about 35 ft above sea level (Larrison and others, 1917, p. 8). In the Kalihi ground-water area, the initial water level at well 1952-01 was 41.7 ft above sea level in April 1882. Larrison and others (1917, p. 8) suggest that the initial water level in the Moanalua ground-water area was about 37 ft above mean sea level in 1882. Using a correlation analysis, Mink (1980) concurred with the initial head of 37 ft for the Moanalua area. The initial water levels described above for the four Honolulu ground-water areas represent water levels from wells near the coast.

Because long-term records are unavailable at single wells, water-level histories for the Moanalua, Kalihi, Beretania, and Kaimuki areas (figs. 17–20) were culled from as many as five wells within a particular ground-water area. The overall water-level trends can be represented in this manner because water levels exhibit little spatial variation at wells near the coast within a particular Honolulu ground-water area.

Water levels in each of the four Honolulu ground-water areas have declined since the original measurements were made in the early 1880's (figs. 17–20). The declines in water levels have been caused by increased human-induced withdrawals from free-flowing and pumped wells. Water levels in the Moanalua area have declined from an estimated initial level of 37 ft in 1882 to about 18 to 20 ft in 1995. In the Kalihi area, water levels have declined from 41.7 ft in 1882 to about 20 to 22 ft in 1995. Water levels in the Beretania area show a long-term decline from an initial level of 43.5 ft in 1880 to about 20 to 25 ft above sea level in 1995. In the Kaimuki area, water levels declined from an initial level of 35 ft in the 1880's to about 25 ft by 1900, and since then, water levels in the Kaimuki area have fluctuated about a mean value of about 25 ft. On a seasonal basis, water-level fluctuations in the Honolulu ground-water areas are of the order of several feet.

The Honolulu Board of Water Supply has conducted simultaneous water-level surveys of Honolulu wells and published these in their annual reports. Results of water-level surveys from August 1932 (fig. 29) and May 1951 (fig. 30) indicate that within each of the Honolulu areas, water levels at observation wells located near the coast do not show a marked spatial variation. For this reason, Palmer (1927, p. 40) called each of these areas an isopiestic area, or area of equal artesian pressure. Within the Moanalua, Kalihi, Beretania, and Kaimuki areas of Honolulu, hydraulic gradients cannot be estimated from water-level measurements because of a lack of inland observation wells. On June 30, 1994, reported water levels from wells in the Kaimuki, Beretania, Kalihi, and Moanalua areas were 24.46, 20.03, 19.74, and 17.30 ft above mean sea level, respectively (Honolulu Board of Water Supply, 1994).

Coastal Caprock

Water levels in the coastal caprock are generally lower than those in the underlying volcanic aquifers, and ground water therefore discharges from the volcanic aquifers to the caprock. In southern Oahu, water levels within the uppermost unit of the coastal caprock are generally about 1 to 3 ft above mean sea level (Bauer, 1996). In northern Oahu, a thin body of fresh to brackish water, in which heads average 1 to 2 ft above mean sea level, exists in the limestone at the top of the caprock of the Mokuleia ground-water area (Rosenau and others, 1971).

Ground-Water Quality

The quality of the ground water in the central Oahu flow system has been documented by various investigators (Stearns and Vaksvik, 1935; Visher and Mink, 1964; Swain, 1973; Giambelluca and others, 1987). In terms of the major ions, chloride has typically been used as an indicator of saltwater intrusion. Since the early 1980's, ground-water contamination by organic chemicals has become a concern among water purveyors.

Lens Water Quality

In general, chloride concentrations of water from wells are expected to increase with depth, proximity to the coast, and pumping rate. Exceptions to this generalization, however, are known to exist. Under pumping conditions, many of the older, high-capacity irrigation wells drilled by sugarcane plantations pumped water with chloride concentrations exceeding 1,000 mg/L. Saltwater intrusion is a problem at these wells because of the great depth to which the wells were drilled and the high pumping rates. At some well fields, chloride concentrations of pumped water were reduced by backfilling the deeper wells (Stearns and Vaksvik, 1935).

To better understand conditions in the freshwater lenses of Oahu, the Honolulu Board of Water Supply established a program of monitoring the salinity profiles in deep wells that penetrate through the freshwater lens into the freshwater-saltwater transition zone. Borehole flow may affect the salinity profiles recorded in these deep monitor wells. Near the coast where ground water discharges, the hydraulic head decreases in an upward direction, which may cause upward flow within the borehole. Thus, the recorded salinity profile in a well near the coast may lead to an underestimate of the freshwater-lens thickness. Toward the inland, high recharge areas, the reverse situation may be true. That is, decreasing heads with depth may induce downward flow in the borehole. Thus, the recorded salinity profile

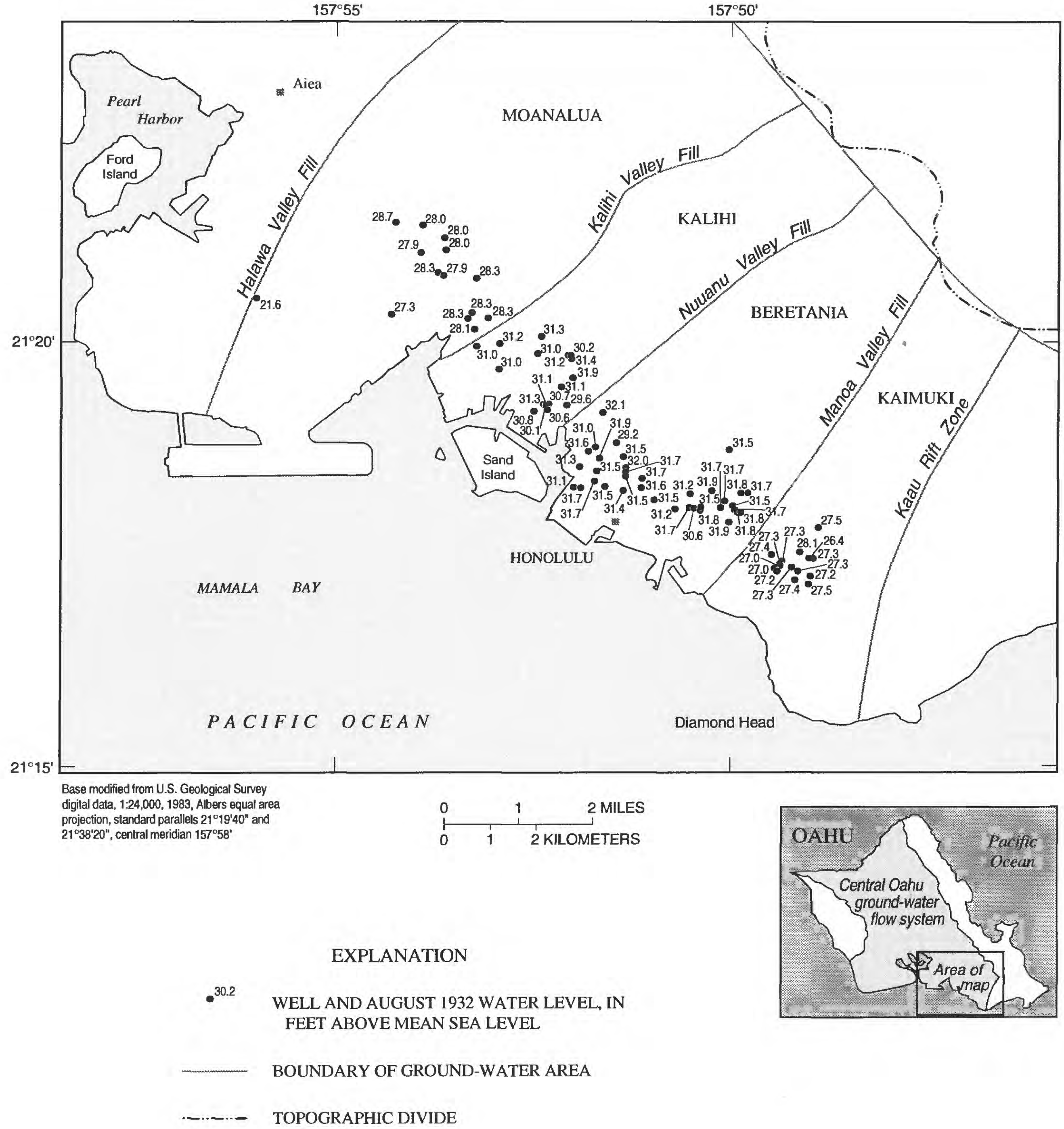


Figure 29. Measured water levels in Honolulu (Moanalua, Kalihi, Beretania, and Kaimuki ground-water areas) during August 1932, Oahu, Hawaii (from Board of Water Supply, 1933).

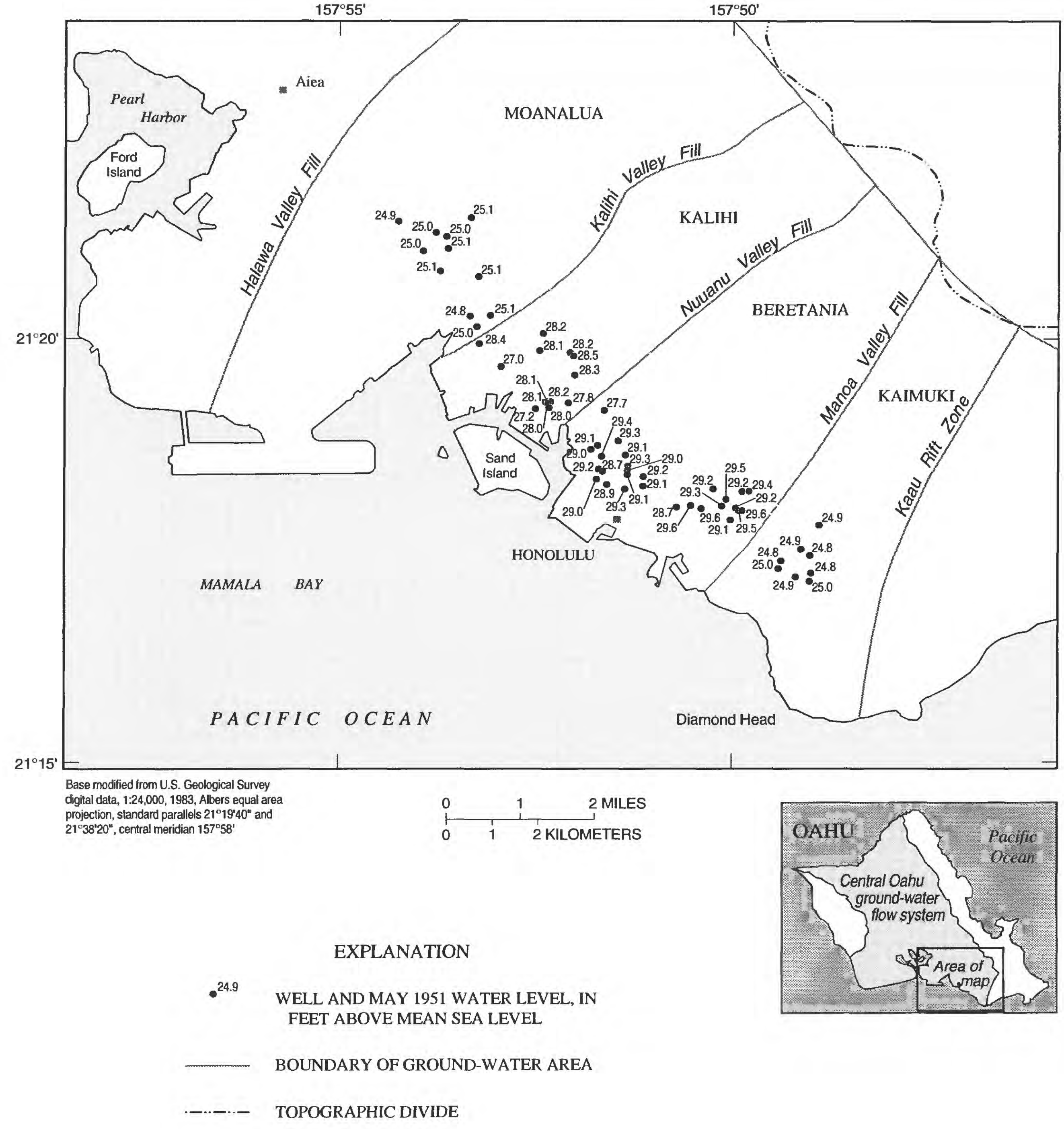


Figure 30. Measured water levels in Honolulu (Moanalua, Kalihi, Beretania, and Kaimuki ground-water areas) during May 1951, Oahu, Hawaii (from Board of Water Supply, 1953).

in deep wells located at inland recharge areas may lead to an overestimate of the freshwater-lens thickness. Most deep monitor wells on Oahu are located closer to the discharge areas of the aquifer than the high recharge areas, and thus provide conservative estimates of the freshwater lens thickness. Voss and Wood (1994) suggest that the scale of vertical disturbance by borehole flow is on the order of about 65 ft so that the salinity profiles obtained from deep monitor wells adequately describe the vertical distribution of fluid composition in the aquifer at larger scales.

In the Pearl Harbor ground-water area, the lens has a three-layered structure (Visher and Mink, 1964; Mink and others, 1988; Voss and Wood, 1994), which is indicated in specific-conductance and temperature logs measured on April 23, 1987 at the Waipio deep monitor well 2659-01 (fig. 31). The top of the lens is typically slightly warmer and saltier than the underlying freshwater core because of local recharge from irrigation return flow. The upper part of the lens, which is affected by irrigation return flow, is 100- to 300-ft thick and has a temperature of about 20° to 21°C. The freshwater core of the lens has a temperature of about 19.5° to 20°C and exists beneath the upper irrigation return zone. The freshwater core receives its recharge from the high-rainfall areas near the crest of the Koolau Range. Beneath the freshwater core, the water warms because of the natural geothermal gradient and salinity increases within the transition zone, ultimately nearing the concentration of seawater.

In 1994, deep monitor wells were completed in both the Waialua and Kawailoa ground-water areas of northern Oahu (Presley and Oki, 1996c; Presley and Oki, 1996d). The specific-conductance profile for the Kawailoa deep monitor well (3604-01) (fig. 32) indicates that the midpoint of the transition zone is at an altitude of about -190 to -200 ft. Using the Ghyben-Herzberg principle and a typical water level of about 4.25 ft for the Kawailoa well, the freshwater-saltwater interface is estimated to be at an altitude of -170 ft. Borehole flow can affect the specific-conductance profile and the water level in the well, and thus, can confound comparisons between the location of the transition-zone midpoint from a specific-conductance profile and the location of the freshwater-saltwater interface predicted by the Ghyben-Herzberg principle. The estimated thickness of the transition zone above the midpoint of the transition zone is about 130 ft (fig. 32).

For the Waialua area, the specific-conductance profile from the Twin Bridge Road deep monitor well (3406-12) (fig. 33) indicates that the midpoint of the transition zone is at an altitude of about -420 to -430 ft. Using the Ghyben-Herzberg principle and a typical water level of about 11.25 ft for the Twin Bridge Road well, the bottom of the lens is estimated to be at an altitude of -450 ft. The estimated thickness of the transition zone above the midpoint of the transition zone is about 100 ft (fig. 33).

Since the early 1980's, organic chemicals related to pineapple cultivation have been detected in ground-water samples from the Pearl Harbor and Ewa ground-water areas of southern Oahu and the Waialua and Kawailoa ground-water areas of northern Oahu. These chemicals include 1,2-dibromo-3-chloropropane (DBCP), 1,2-dibromoethane or ethylene dibromide (EDB), and 1,2,3-trichloropropane (TCP). Locations of contaminated well sites are highly correlated with areas of past and present pineapple cultivation (Oki and Giambelluca, 1987). EDB contamination on Oahu may also be linked to fuel pipeline leaks. Pineapple has not been cultivated in the Mokuleia ground-water area, and no pineapple-related contaminants have been detected in samples from wells in the Mokuleia area.

The herbicide atrazine, commonly used by sugarcane growers on Oahu, has been detected in ground-water samples from wells in or downgradient from areas previously used for sugarcane cultivation. Atrazine has been detected in ground-water samples from wells in the Pearl Harbor, Ewa, and Waialua ground-water areas (State of Hawaii, 1996). Pesticides such as chlordane and dieldrin have been detected in ground-water samples from wells in nonagricultural areas within the central Oahu flow system. In addition, solvents such as trichloroethylene (TCE) and tetrachloroethylene (PCE) have been detected in ground-water samples from the central Oahu flow system.

High-Level Water Quality

Water quality in the dike-impounded ground-water areas is generally excellent, with chloride concentrations less than 20 mg/L in the high-recharge areas. No contamination of dike-impounded ground water by organic chemicals is known to exist within the central Oahu flow system. Most areas contributing recharge to the high-level dike compartments are restricted conservation areas. This land-use zoning reduces the chance

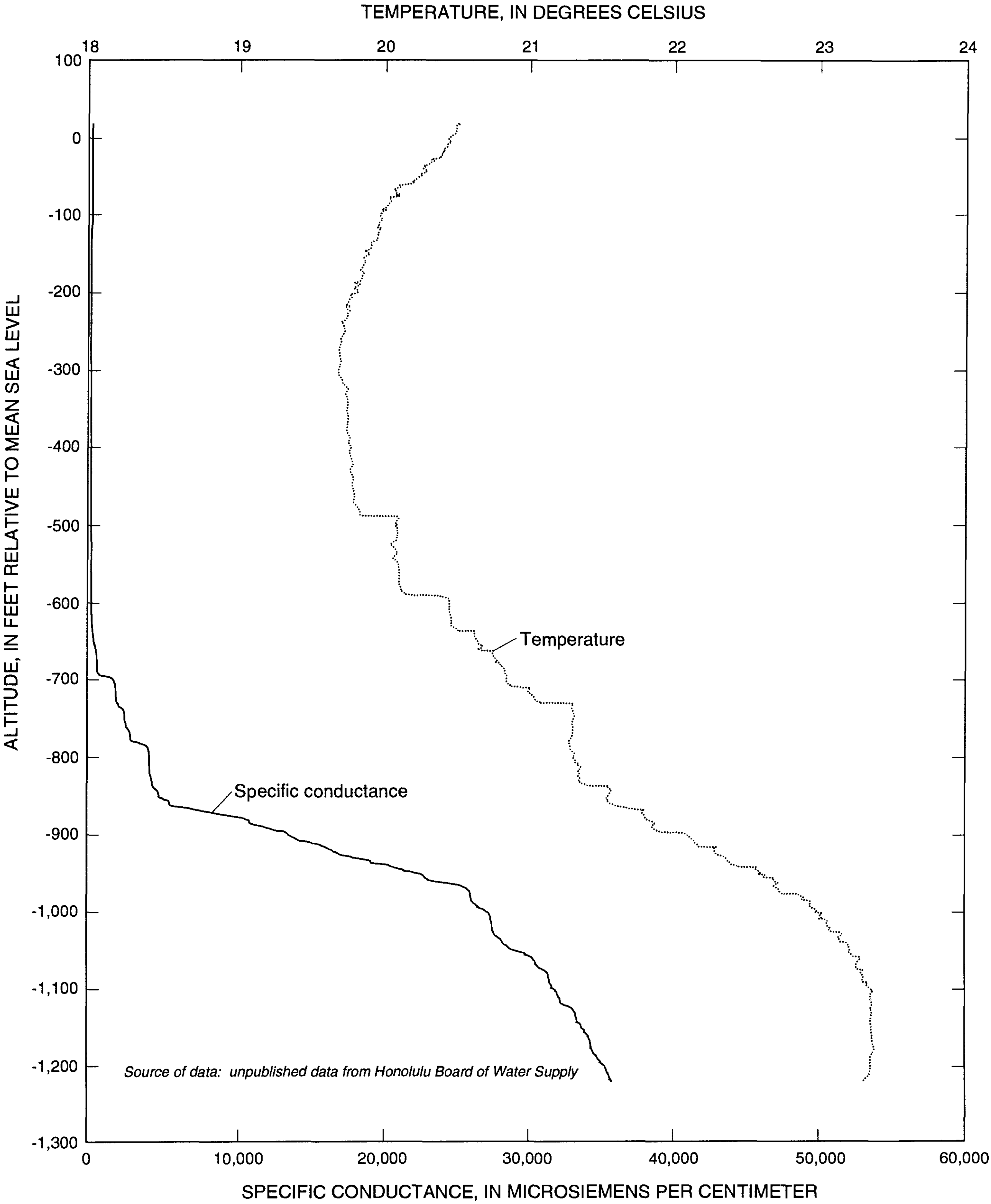


Figure 31. Specific-conductance and temperature profiles of April 23, 1987 for Waipio deep monitor well 2659-01, Pearl Harbor ground-water area, Oahu, Hawaii.

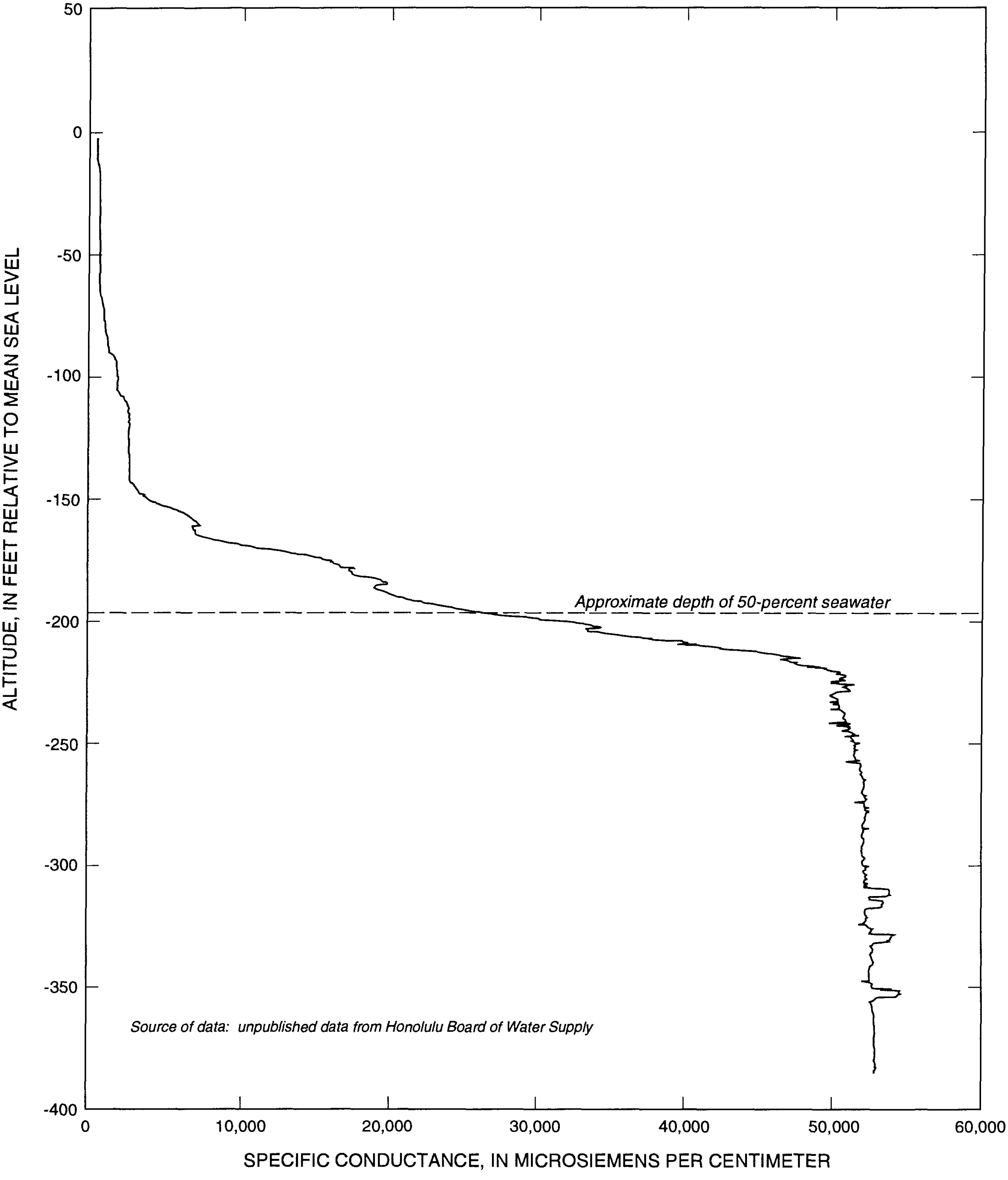


Figure 32. Specific-conductance profile of May 17, 1994 for Kawailoa deep monitor well 3604-01, Kawailoa ground-water area, Oahu, Hawaii.

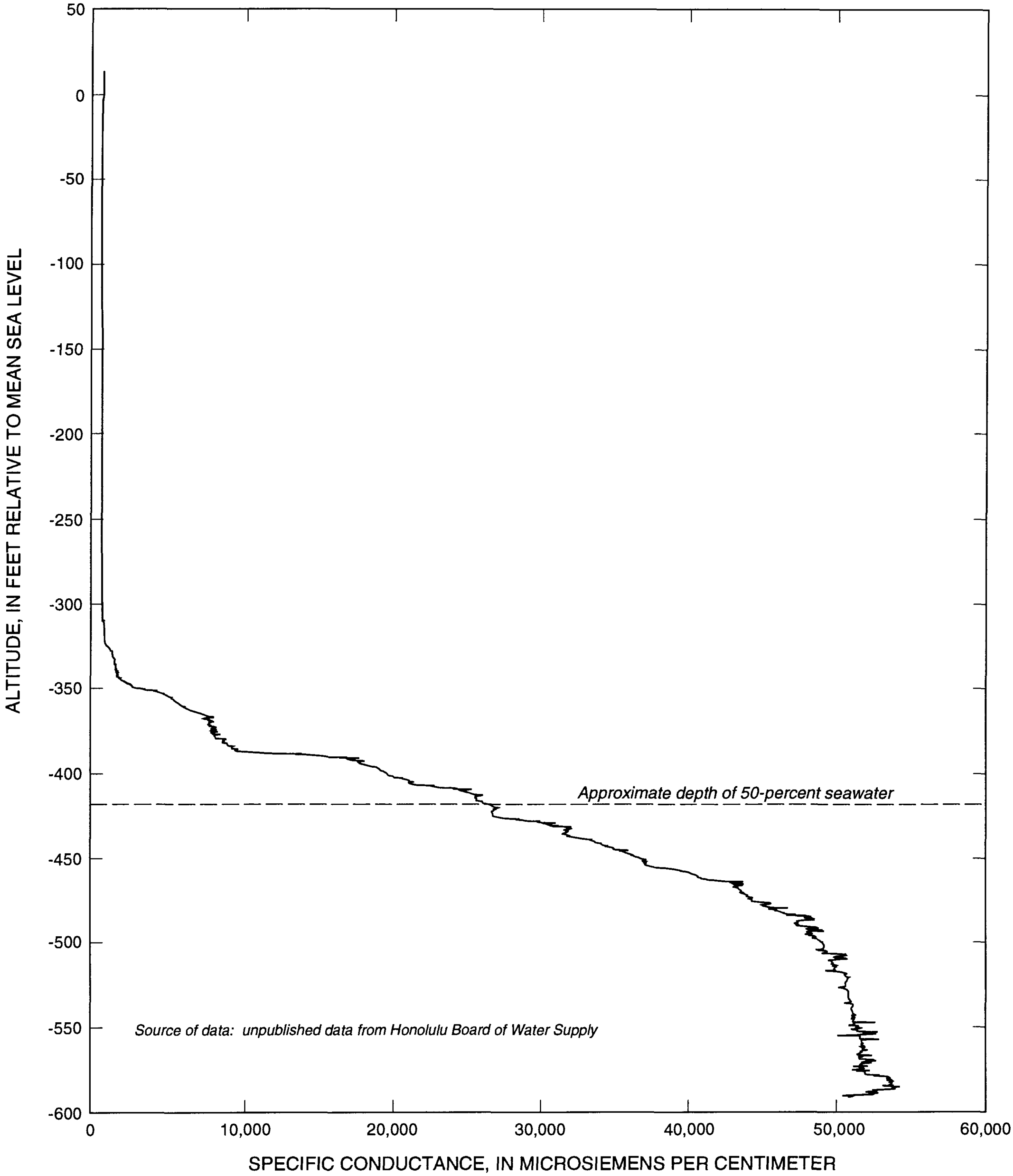


Figure 33. Specific-conductance profile of May 18, 1994 for Twin Bridge Road deep monitor well 3406-12, Waialua ground-water area, Oahu, Hawaii.

for contamination of the dike-impounded ground-water areas. Within the Schofield high-level ground-water area, contamination by TCE and PCE (Giambelluca and others, 1987) prompted the U.S. Environmental Protection Agency (USEPA) to place Schofield Barracks on the National Priorities List to determine the source of contamination.

Ground-Water Flow System

Ground-water recharge by direct infiltration of rainfall occurs over much of the island of Oahu. In the dry coastal areas, recharge rates are low except in areas that are irrigated. In areas where the volcanic aquifer is overlain by a coastal caprock, water that infiltrates the ground surface does not recharge the volcanic aquifer if the head in the aquifer is greater than the head in the caprock. Ground-water recharge is greatest in the inland, high-rainfall areas near the crests of the Koolau and Waianae Ranges.

Fresh ground water on Oahu occurs in two main forms: (1) as freshwater lenses floating on denser, underlying saltwater, and (2) as impounded high-level ground water. The latter form exists in the volcanic rift zones. In addition, ground water within the Schofield area can be classified as high-level ground water. Small quantities of perched water have been noted (Stearns and Vaksvik, 1935; State of Hawaii, 1983) but are not considered in this report.

Freshwater Lenses

Freshwater lenses are the primary source of ground water on Oahu and are developed by vertical wells and infiltration tunnels. A freshwater lens forms because of the density difference between fresh recharge water and underlying saltwater derived from the ocean. For hydrostatic conditions, the vertical thickness of the freshwater lens can be estimated by the Ghyben-Herzberg principle. If the specific gravities for freshwater and saltwater are assumed to be 1.000 and 1.025, respectively, then the Ghyben-Herzberg principle predicts that every foot of freshwater above sea level must be balanced by 40 ft of freshwater below sea level. The actual thickness of a freshwater lens is influenced by factors such as (1) the rate of ground-water recharge to the aquifer, (2) the amount of pumping, (3) the presence or absence of a coastal confining unit, and (4) the hydraulic properties of the aquifer.

The thickness of a freshwater lens increases as the rate of ground-water recharge increases, provided all other factors remain constant. The thickness of a freshwater lens decreases as the amount of pumping increases, provided all other factors remain constant.

The low-permeability coastal caprock along southern Oahu acts as a confining unit that impedes the discharge of fresh ground water from the aquifer as well as the inflow of saltwater into the aquifer. The southern Oahu caprock impounds freshwater behind it and, thus, freshwater heads are greater than they would be in the absence of a caprock. In the Beretania area of southern Oahu, where the caprock is several hundred feet thick, water levels in wells have exceeded 42 ft above mean sea level. In the Kawailoa area of northern Oahu, on the other hand, the coastal caprock is thin or nonexistent and, thus, freshwater heads are typically less than 3 ft near the coast.

The hydraulic conductivity of the aquifer also affects the thickness of the freshwater lens. The freshwater lens will be thicker in aquifers with lower hydraulic conductivities, provided all other factors remain constant.

Within the central Oahu flow system, a freshwater lens exists within the Ewa, Pearl Harbor, Moanalua, Kalihi, Beretania, and Kaimuki areas of southern Oahu and the Mokuleia, Waialua, and Kawailoa areas of northern Oahu. Water levels measured in wells within the freshwater lenses of the central Oahu flow system have short-term variations of a seasonal and daily time-scale superimposed on long-term variations. Long-term variations in water levels reflect overall changes in recharge and pumpage. On a seasonal time-scale, water levels respond to changes in pumpage. During the dry summer months when water demand is high, water levels tend to decline. Water levels typically recover during the wet winter months when ground-water pumpage is decreased. Water levels associated with freshwater lenses fluctuate on a daily time-scale because of tidal, barometric, and pumping influences.

High-Level Ground Water

Dike-impounded high-level ground water in the rift zones of the Waianae and Koolau Volcanoes is found where vertical and subvertical dikes cut through more permeable lava flows. The dikes form numerous compartments which are recharged by rainfall over the wet, mountainous regions of the island. These compartments can be saturated to altitudes of several hundred feet. Ground water from the high-level dike compartments contributes to the recharge of downgradient areas as underflow or discharges directly to the ocean. In addition, where erosion has cut into dike compartments, discharge of high-level ground water contributes to the base flow of streams.

The altitude to which water rises in the dike compartments is dependent primarily on (1) the recharge rate, (2) the intensity and orientation of dikes forming the compartments, and (3) the human-induced withdrawal rate from the dike compartments. In general, the altitude to which water rises is directly related to the recharge rate; greater recharge rates, all other factors remaining constant, result in higher water levels. Water also rises to greater levels where low permeability dikes are more prevalent and where dikes are oriented perpendicular to the preferred direction of ground-water flow. In the Waialee Gulch area of northern Oahu, where the rift zone extends to the coast and where dikes are oriented roughly perpendicular to the coast, ground water discharges directly to the ocean and water levels are only 10 to 20 ft above mean sea level.

In the rift zones of the Waianae and Koolau Volcanoes, numerous tunnels have been bored into the water-bearing dike compartments for water-development purposes. If allowed to flow unrestrained, these tunnels cause a dewatering of the dike compartments. Water levels decline to a new equilibrium altitude in response to this dewatering (Hirashima, 1971b). In addition to the reduction of ground water in storage within the dike compartments, withdrawals from high-level tunnels can cause a reduction in the base flow of nearby streams (Hirashima, 1962, 1963). A full description of the occurrence and development of dike-impounded ground water on Oahu is provided by Takasaki and Mink (1985).

In the Schofield ground-water area, geologic structures of an unknown origin impound ground water to an altitude of about 275 ft. No data exist to determine the depth to which volcanic rocks are saturated with freshwater in the rift zones or the Schofield ground-water area.

Regional Flow

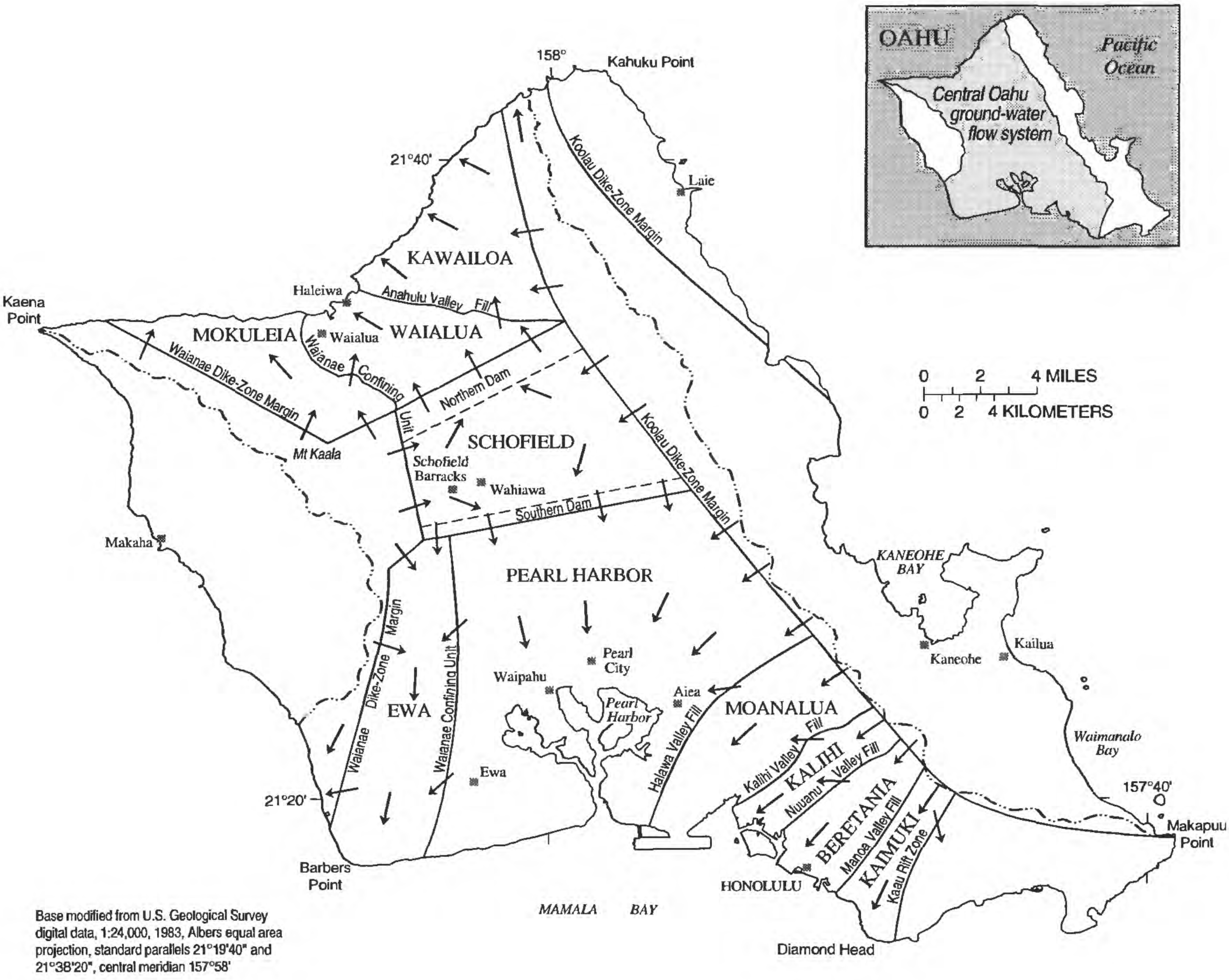
Regional ground-water flow directions drawn on the basis of water-level data, rainfall distribution, and topography, indicate that ground-water flows from the mountainous interior areas to coastal discharge areas (fig. 34). Ground water originating in the rift zones flows to (1) the Schofield ground-water area, (2) downgradient freshwater lenses, (3) springs where stream erosion has cut through dike compartments below the level of the water table, or (4) the ocean.

Ground water in the Schofield area that is not withdrawn by wells flows through either the northern or southern Schofield ground-water dams to downgradient freshwater lenses. A ground-water divide separating flow to the north and south exists within the Schofield area. A summary of previous estimates of flow from the Schofield ground-water area is provided in appendix C.

In northern Oahu, water levels are highest in the Mokuleia area and lowest in the Kawailoa area. Ground water may flow from the Mokuleia area into the adjoining Waialua area through the Waianae confining unit, and from the Waialua area to the adjoining Kawailoa area through, around the inland extent of, or beneath the Anahulu valley-fill barrier.

During the early stages of ground-water development in Honolulu, the water level was highest in the Beretania area. Thus, the ground-water divide separating flow to the east and west in Honolulu originally existed in the Beretania area. Water flowed from the Beretania area to the Kaimuki area in the east and to the Kalihi area in the west. In recent years, however, the water level in the Beretania area has declined to about the same level as in the Kaimuki area. Since the initial well was drilled in Honolulu, the water level in the Beretania area has generally remained higher than in the Kalihi area, which in turn has had a higher water level than the Moanalua area. Between adjacent Honolulu ground-water areas, ground water flows through, around the inland extent of, or beneath the valley-fill barriers. Ground water from the Kaimuki area flows through the Kaau rift-zone barrier to the east. Ground water from the Moanalua area flows to the Pearl Harbor area to the west.

Ground water in the Pearl Harbor area generally flows from inland areas to springs near the inland margin of the caprock. Ground water also flows to the Ewa ground-water area through the Waianae confining unit. Ground water flows to the Ewa area from (1) the Waianae rift zone, (2) the Schofield ground-water area, and (3) the Pearl Harbor ground-water area. Discharge from the Ewa area is in the form of (1) ground-water withdrawals from wells, (2) diffuse flow into the coastal



EXPLANATION

———	BOUNDARY OF GROUND-WATER AREA
—··—··—	TOPOGRAPHIC DIVIDE
⟵	GENERALIZED DIRECTION OF GROUND-WATER FLOW

Figure 34. Regional ground-water flow pattern for the volcanic aquifers of the central Oahu ground-water flow system, Hawaii.

caprock, and (3) flow through the rift-zone barrier at the southwestern extent of the area.

Within the volcanic aquifers of the Mokuleia, Waialua, Kawailoa, Ewa, Pearl Harbor, and Honolulu ground-water areas, the ground-water flow system is composed of a freshwater lens overlying a zone of transition to a saltwater body. The source of freshwater forming the lenses within the volcanic aquifers is ground-water recharge from (1) upgradient high-level ground-water areas, (2) infiltration of rainfall, and (3) irrigation return flow. The aquifers are unconfined in the inland areas. Fresh ground water flows from the inland, unconfined areas toward coastal discharge areas. The volcanic aquifers are generally confined near the coast by a caprock that impedes the seaward discharge of fresh ground water. The caprock extends far offshore, beyond the seaward extent of the freshwater lenses, and impedes the landward flow of seawater into the volcanic aquifers. A saltwater circulation system exists beneath the freshwater lenses. Saltwater flows landward in the deeper parts of the aquifers, rises, and then mixes with fresher water. This mixing creates a freshwater-saltwater transition zone. The generalized freshwater and saltwater flow patterns within the volcanic aquifers are shown in figure 35.

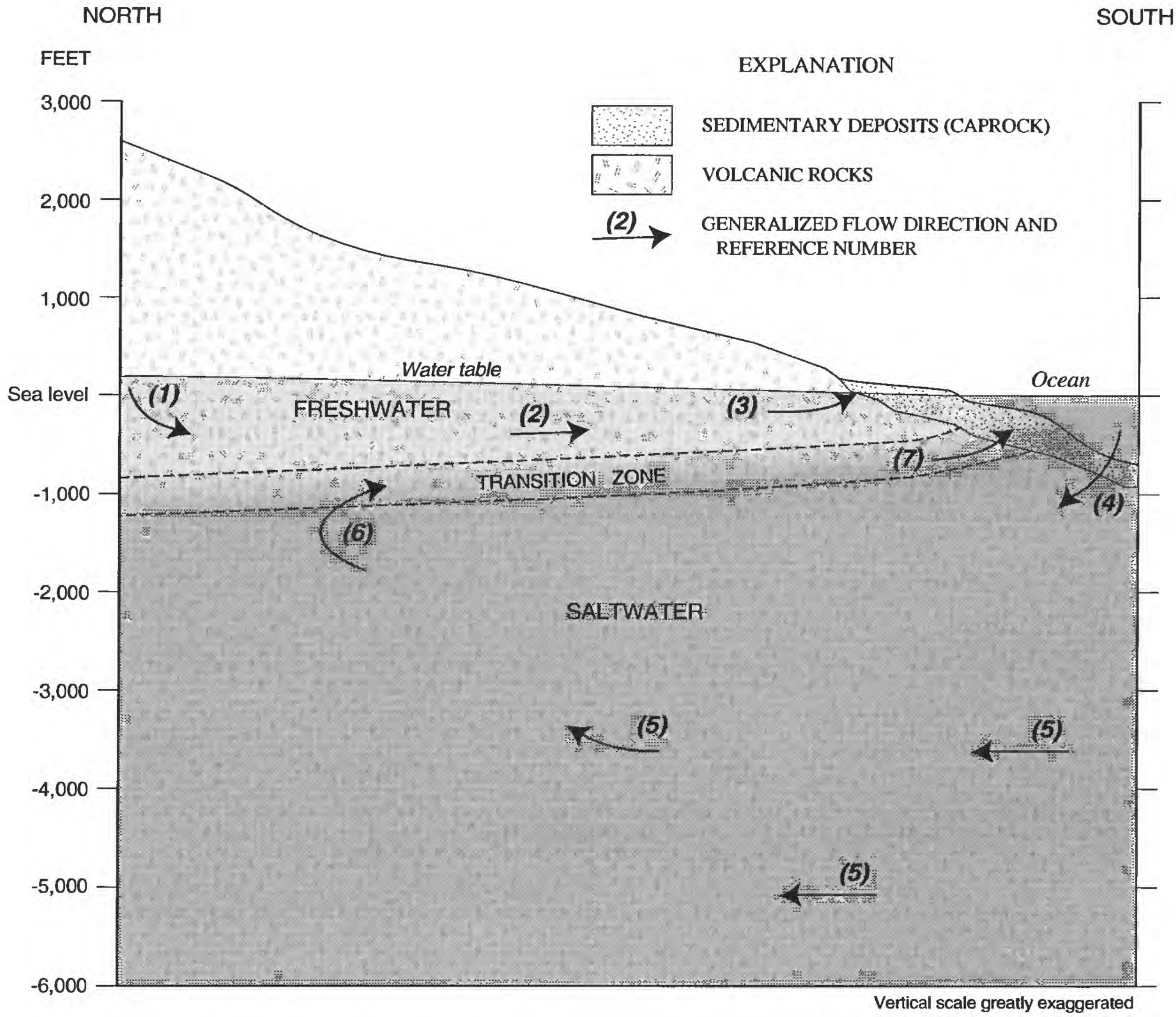
NUMERICAL GROUND-WATER MODEL OF THE CENTRAL OAHU FLOW SYSTEM

A two-dimensional, areal ground-water flow model using a modified version (see appendix D) of the computer code SHARP (Essaid, 1990) was developed to simulate steady-state ground-water flow in the central Oahu ground-water flow system. SHARP is a quasi-three-dimensional finite-difference code that simulates both freshwater and saltwater flow in layered aquifer systems. SHARP treats freshwater and saltwater as immiscible fluids separated by a sharp interface. In reality, a diffuse transition zone exists between the freshwater and underlying saltwater. The position of the surface of 50 percent seawater salinity, however, is approximated by the sharp interface position. The model of the central Oahu ground-water flow system accounts for spatially varying hydraulic characteristics of the geologic materials, ground-water withdrawals, and recharge.

Model Construction

The ground-water flow model of the central Oahu flow system was developed to simulate ground-water levels for the period 1950–59. The hydraulic characteristics were varied in the model to obtain acceptable agreement between average measured water levels during 1950–59 and model-calculated water levels. The period 1950–59 was selected for steady-state simulation because throughout most of the central Oahu flow system, pumping rates and water levels remained relatively steady during the decade of the 1950's. Mink (1980) suggests that for the Pearl Harbor region, near-equilibrium conditions persisted between 1946 and 1959. Eyre and Nichols (in press) used the 1950's period to develop a model of the southern part of the central Oahu flow system. The Mokuleia ground-water area shows a slight upward trend in water levels toward the latter half of the 1950's. However, in the Mokuleia area, the 1950's is one of the steadiest periods of record.

Average 1950's water levels were computed for 41 wells in the central Oahu flow system (table 5). (For well 2703-01 listed in table 5, a likely range for the average 1950's water level was identified. Data from this well are discussed in the subsection on the "Ewa Ground-Water Area" in the section titled "Estimation of Hydraulic Conductivity.") Twenty of the 41 wells are in the Pearl Harbor area, whereas only one well was available in the Kawailoa area. In general, only data from wells with at least 80 monthly water-level measurements were used to ensure satisfactory representation of the 1950's conditions. However, for some areas where data are insufficient, wells with fewer than 80 monthly measurements were considered. In the Pearl Harbor and Ewa areas, five of the wells considered have fewer than 50 monthly measurements during the 1950's (table 5). At these sites, missing data in the 1950's were generated by correlation with nearby wells in the same ground-water area. For each of these wells, the average measured 1950's water level based on fewer than 50 monthly measurements compared favorably with the average 1950's water level for the complete 1950's data set, with both measured and generated data. Thus, for those five wells with fewer than 50 monthly water-level measurements during the 1950's, the average measured water levels were considered representative of the period.



Reference number and description of ground-water flow:

(1) The source of freshwater forming the lenses within the volcanic aquifers is ground-water recharge from rainfall and irrigation return flow. In the inland recharge areas where the aquifers are unconfined, fresh ground water has a predominantly downward flow component.

(2) Fresh ground water in the volcanic aquifers moves from inland recharge areas toward coastal discharge areas. Between the recharge and discharge areas, flow is predominantly horizontal.

(3) The volcanic aquifers are confined by the sedimentary caprock that impedes the seaward discharge of fresh ground water from the volcanic aquifers. Near the coast, fresh ground water flows upward in the volcanic aquifers toward the caprock.

(4) The landward inflow of seawater into the volcanic aquifers is impeded by the sedimentary caprock.

(5) Saltwater within the volcanic aquifers also is derived from the ocean from deep circulation in the volcanic rocks.

(6) A saltwater circulation system exists beneath the freshwater lens. Saltwater flows landward in the deeper parts of the aquifers, rises, and then mixes with fresher water. This mixing creates a freshwater-saltwater transition zone.

(7) The mixed water within the transition zone and freshwater *(3)* flow from the volcanic aquifers into the caprock.

Figure 35. Generalized ground-water flow pattern in the volcanic rocks, Oahu, Hawaii (adapted from Souza and Voss, 1987).

Table 5. Average 1950's water levels at wells in the central Oahu ground-water flow system, Oahu, Hawaii

[--, standard deviation not computed from air-line measurements]

Ground-water area	Well no.	Grid cell (row, column) (fig. 36)	Number of monthly water-level measuremsnts during 1950's	Average 1950's water level (feet above mean sea level)	Standard deviation of measurements (fset)
Kaimuki	1748-01	68, 37	115	26.7	1.3
Kaimuki	1749-18	69, 36	106	26.8	1.4
Beretania	1849-11	66, 35	103	28.7	1.6
Beretania	1851-02	65, 33	92	28.5	1.7
Beretania	1851-28	66, 33	118	28.2	1.7
Kalihi	1952-14	63, 31	116	25.2	1.7
Kalihi	2052-06	61, 32	107	27.0	1.5
Moanalua	2153-02	58, 31	118	24.0	1.3
Moanalua	2153-09	58, 31	120	24.0	1.2
Moanalua	2253-02	55, 31	102	23.7	1.4
Pearl Harbor	2101-03	52, 19	117	19.5	2.5
Pearl Harbor	2201-03, -04, -07	51, 20	84	20.1	2.4
Pearl Harbor	2201-10	51, 20	120	20.1	2.4
Pearl Harbor	2202-03 to -08	51, 19	83	20.4	2.3
Pearl Harbor	2202-21	50, 18	99	20.2	2.4
Pearl Harbor	2256-04	53, 27	107	20.8	1.4
Pearl Harbor	2256-10	54, 27	117	20.7	1.5
Pearl Harbor	2300-10	50, 22	117	20.5	2.1
Pearl Harbor	2355-01	53, 29	113	20.9	1.5
Pearl Harbor	2356-02	51, 27	116	19.9	1.5
Pearl Harbor	2356-45	51, 27	118	18.6	1.1
Pearl Harbor	2356-47	52, 27	81	16.7	1.2
Pearl Harbor	2358-02	51, 25	117	18.0	1.5
Pearl Harbor	2358-20	50, 25	120	19.2	1.6
Pearl Harbor	2459-15	48, 24	119	23.1	2.5
Pearl Harbor	2558-08	48, 25	108	23.1	2.1
Pearl Harbor	2600-01	47, 22	43	25.8	2.2
Pearl Harbor	2657-02	47, 28	45	26.9	1.8
Pearl Harbor	2759-02	45, 25	47	30.4	2.7
Pearl Harbor	2801-01	42, 23	19	27.9	1.7
Schofield	2901-07	37, 22	117	279.3	2.4
Ewa	2006-01 to -11	54, 12	115	12.7	0.5
Ewa	2006-12	53, 13	84	13.7	0.5
Ewa	2103-01	52, 16	120	17.0	0.7
Ewa	2103-02	52, 17	120	17.2	0.7
Ewa	2203-01	50, 17	45	17.8	0.7
Ewa	2703-01	43, 19	119	22.2–25	--
Mokuleia	3409-16	18, 14	115	19.1	0.5
Mokuleia	3410-08	17, 12	118	17.7	0.6
Waialua	3406-01	19, 17	118	11.3	0.6
Waialua	3406-04	20, 18	120	11.4	0.5
Kawailoa	3504-01	18, 21	48	5.6	0.8

Predevelopment conditions were not used to estimate the hydraulic conductivity values for two main reasons: (1) predevelopment water levels are not known with certainty throughout the entire central Oahu ground-water flow system, and (2) the hydraulic characteristics of the caprock for predevelopment conditions may not be relevant to subsequent development conditions. Initial heads are known for most of southern Oahu near the coast. However, initial heads for inland areas of southern Oahu and for most of northern Oahu are not known with certainty. Even if a model is capable of satisfactorily simulating predevelopment conditions, the model may not be valid for subsequent development periods because of human-induced changes to the hydraulic characteristics of the caprock. Since 1879, hundreds of artesian wells have been drilled through the coastal caprock into the underlying volcanic rocks. Some of these wells flowed freely at rates in excess of 1 Mgal/d. Although many of these old wells have been sealed, the effectiveness of the seals cannot be determined. The amount of subsurface leakage through old, rusted casings of improperly sealed, lost, or unreported wells cannot be quantified. Given that artesian wells may flow in excess of 1 Mgal/d at the ground surface, subsurface leakage at lower altitudes may be significant. Stearns and Vaksvik (1935, p. 331) estimate that subsurface leakage from a faulty casing may be as high as 0.75 Mgal/d. The hydraulic characteristics of the caprock from predevelopment times to the present may differ so that a model capable of simulating predevelopment conditions may not accurately reflect the ground-water system as it exists today.

Model Grid

The model grid used in this study consists of 80 rows and 42 columns and is oriented N 14° W with a geographic origin (lower left-hand corner) at longitude 158°10′33″W and latitude 21°01′51″N (fig. 36). The model grid covers the entire central Oahu study area and extends several miles offshore to include the entire zone where fresh ground water discharges to the ocean. Grid discretization is finest near the Schofield ground-water dams where hydraulic gradients are steepest, and coarsest offshore, toward the northwestern and southeastern ends of the grid.

Representation of the Physical System

Grid cells used to represent the ground-water barriers, which separate the 10 ground-water areas of the central Oahu ground-water flow system, are shown in figure 36. The Waianae confining-unit barrier represents the zone, formed by weathered volcanic rocks and alluvium, between Waianae Volcanics and Koolau Basalt. Although the confining unit dips at an angle of only 10° it extends throughout the freshwater-lens thickness and impedes ground-water flow between the Waianae and Koolau aquifers. In this study, the Waianae confining unit is represented in the two-dimensional model as a barrier to horizontal flow with a zone of reduced hydraulic conductivity. The Schofield ground-water dams are assumed to fully penetrate the aquifer and are also represented as zones of reduced hydraulic conductivity.

In the two-dimensional model, valley-fill barriers may be represented in two main ways. First, the thicknesses of those grid cells used to represent the barrier can be reduced by reducing the altitudes of the tops of the cells. The hydraulic conductivity of the cells can then be assigned the same value as the surrounding volcanic aquifer. In this way, the valley-fill material and associated weathered zone are not simulated, only the underlying aquifer is represented. A reduction in cell thickness reduces the transmissivity in the valley-fill cells, creating an impediment to ground-water flow in the model. The second method is to assume that the barriers are fully penetrating by reducing the hydraulic conductivity of the valley-fill cells. For this study, a combination of the two methods was used. That is, in addition to lowering the tops of grid cells representing the valley-fill barrier, the hydraulic conductivity of the valley-fill barrier cells was reduced.

The bottom of the grid was assigned an altitude of -6,000 ft to coincide with an assumed aquifer bottom (Souza and Voss, 1987) and a seismic velocity discontinuity (Furumoto and others, 1970).

Boundary Conditions

SHARP supports three types of boundary conditions: (1) specified head, (2) specified flow (which includes no flow), and (3) head-dependent discharge. Although specified-head cells were used in preliminary submodels representing parts of the central Oahu flow system (see section titled "Estimation of Hydraulic Conductivity"), specified-head cells were not used in the final model of the entire central Oahu flow system.

The outer rows and columns of the grid represent no-flow boundaries in the SHARP code. Because simulation of water levels in the rift zones was beyond the scope of this study, the rift-zone margins bounding the modeled part of the central Oahu flow system were treated as no-flow boundaries (fig. 37). Although the grid cells for the rift zones were treated as no-flow cells, recharge over the rift zones was included in the model by adding it to the recharge in the first active cells at the outer margins of the rift zones. Eastward discharge from the Kaimuki ground-water area through the Kaau rift zone and westward discharge from the Ewa area through the south rift zone of the Waianae Volcano are precluded in the model because of the no-flow assumption.

Freshwater flow and saltwater flow through the coastal caprock were modeled using a head-dependent discharge boundary condition (fig. 37). The rate of freshwater discharge, Q, is linearly related to the head in the aquifer according to the equation

$$Q = (K/b)Ah - (K/b)Ah_o, \qquad (4)$$

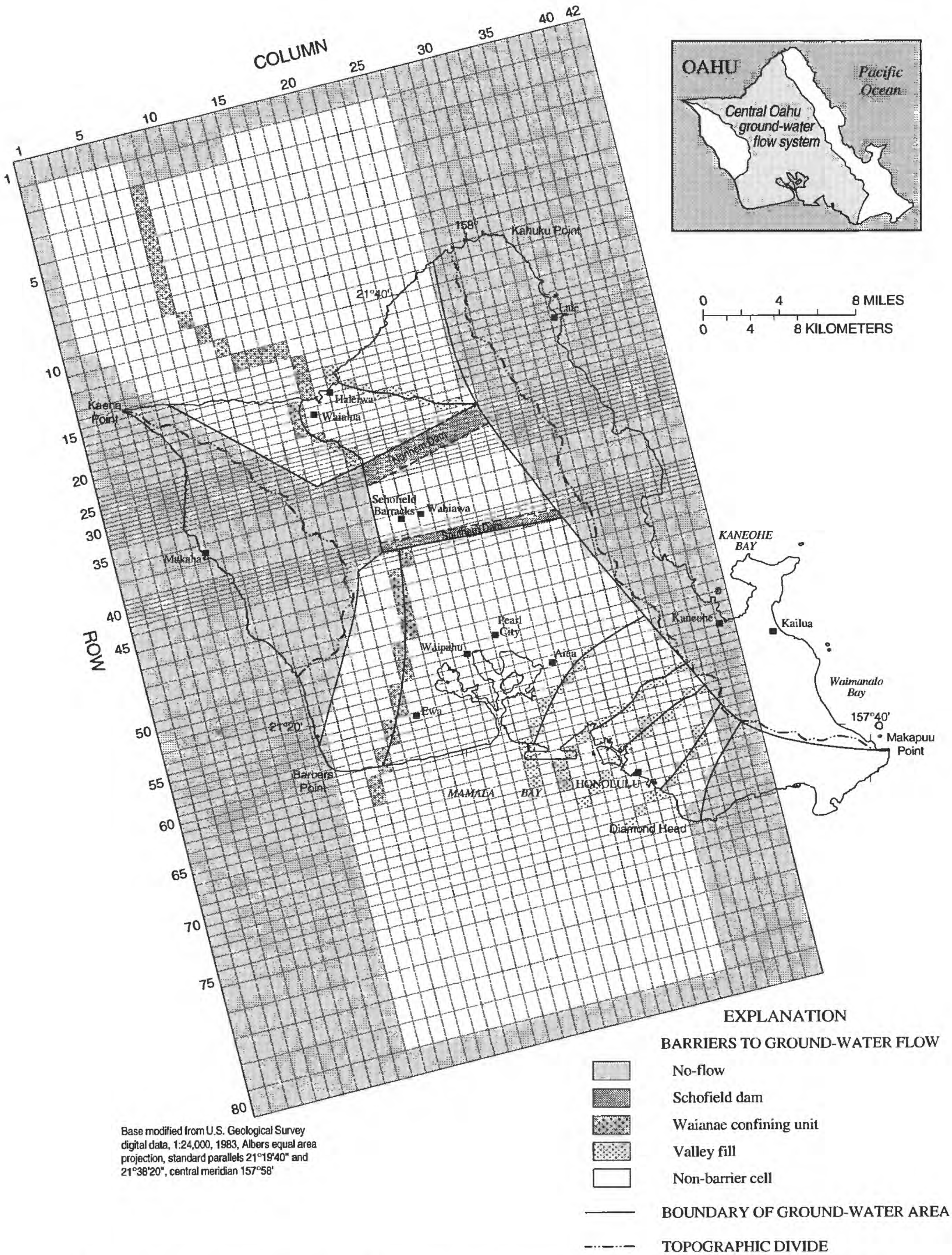


Figure 36. Barriers to ground-water flow used in the model grid for the central Oahu ground-water flow system, Hawaii.

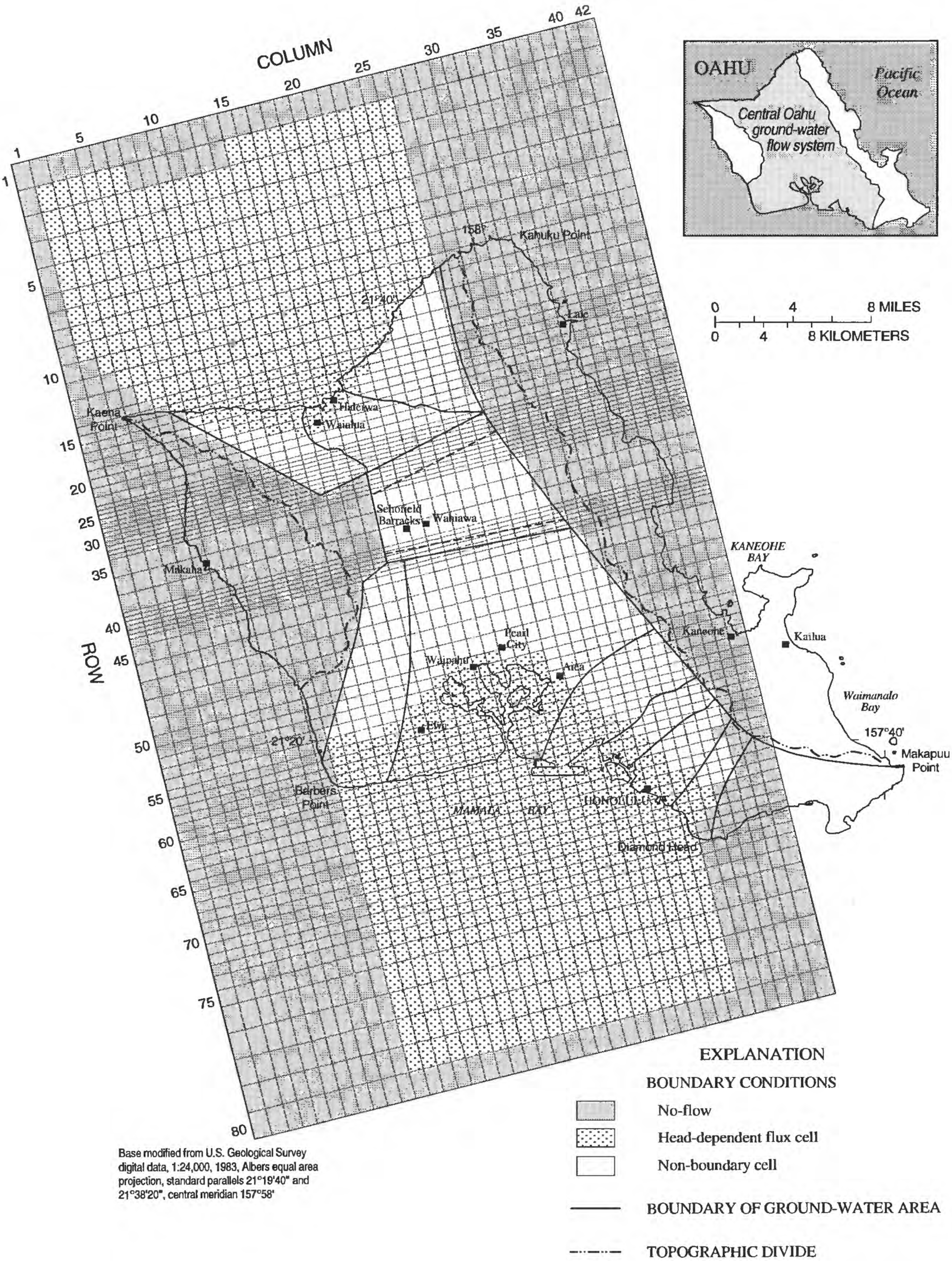


Figure 37. Boundary conditions used in the model grid for the central Oahu ground-water flow system, Hawaii.

where: K is the vertical hydraulic conductivity of the confining unit [L/T],
b is the thickness of the confining unit [L],
A is the area of the grid cell [L^2],
h is the head in the aquifer beneath the confining unit [L], and
h_o is the head overlying the confining unit [L].

The vertical hydraulic conductivity of the confining unit divided by the thickness of the confining unit forms a lumped parameter known as the leakance.

For southern Oahu, onshore caprock thickness was estimated from the studies of Palmer (1927, 1946), Wentworth (1951), Visher and Mink (1964), and Gregory (1980), and the onshore thickness of the northern Oahu caprock was estimated from Dale (1978). For southern Oahu, Gregory (1980) estimated the offshore caprock thickness on the basis of seismic reflection profiles. In northern Oahu, there is no published information to estimate caprock thickness offshore. Off the northern coast, coastal-deposit thickness can be estimated as the difference in altitude between the offshore-projected eroded surface of the volcano and the measured bathymetry. The bathymetry and caprock thickness used in the model grid are shown in figures 38 and 39, respectively.

The head overlying the confining unit, h_o, was assumed to be 2 ft for all onshore areas except in the Kawailoa ground-water area where h_o was assumed to be 0 ft. Water levels of about 2 ft above mean sea level are typically found in shallow wells drilled in the southern Oahu caprock and in the caprock of the Mokuleia and Waialua areas. For the Kawailoa ground-water area, h_o was assumed to be 0 ft because water levels near the coast may be less than 2 ft. For offshore cells, the head overlying the confining unit was assumed to be equal to the freshwater equivalent head of the saltwater column above the submerged caprock. For offshore cells, the freshwater equivalent head is computed from the equation

$$h_o = -Z(\gamma_s - \gamma_f)/\gamma_f, \qquad (5)$$

where: Z is the bathymetry or altitude of the ocean floor [L],
γ_f is the specific gravity of freshwater, and
γ_s is the specific gravity of saltwater.

Using specific gravities of 1 and 1.025 for freshwater and saltwater, respectively, equation (5) reduces to

$$h_o = -Z/40. \qquad (6)$$

Inland of the caprock, at cells not representing the valley-fill barriers that penetrate the aquifer, unconfined, water-table conditions were simulated.

The Pearl Harbor springs were also modeled using linear, head-dependent discharge relations in the form of equation 4. Although the actual relations may not remain linear for extreme values of head, the relations are approximately linear within the range of available data. The regression equations in figures 23, 24, 26, and 27 were used to model the Pearl Harbor springs. At Waiawa, Waiau-Waimano, and Waikele Springs, however, the regression equations were modified to reflect head changes at wells closer to the respective spring sites. For Waiawa and Waiau-Waimano Springs, discharge was related to the head at well 2358-20, and for Waikele Springs, discharge was related to the head at well 2300-10. The model values used to simulate discharge at the Pearl Harbor springs for 1950's conditions are given in table 6.

Recharge

Average annual recharge to the central Oahu flow system during the 1950's was estimated to be 623.4 Mgal/d (table 7). Recharge is greatest near the margin of the Koolau rift zone and in areas of sugarcane cultivation (fig. 40).

Recharge for grid cells representing the Waianae confining unit was set to zero. The volume of recharge lost from these cells was assigned to adjacent cells on the eastern side of the confining unit. This reassignment of water assumes that recharge over the confining unit is more likely to flow into the Koolau aquifer rather than through the weathered zone into the Waianae aquifer.

For cells in which the valley-fill barriers are assumed to penetrate the volcanic aquifer, the aquifer is confined and recharge for these cells is ignored by the model. For some of these cells, however, the valley occupies only a fraction of the area of the cell. In these cases, recharge to the cell was distributed to the two cells on either side of the valley.

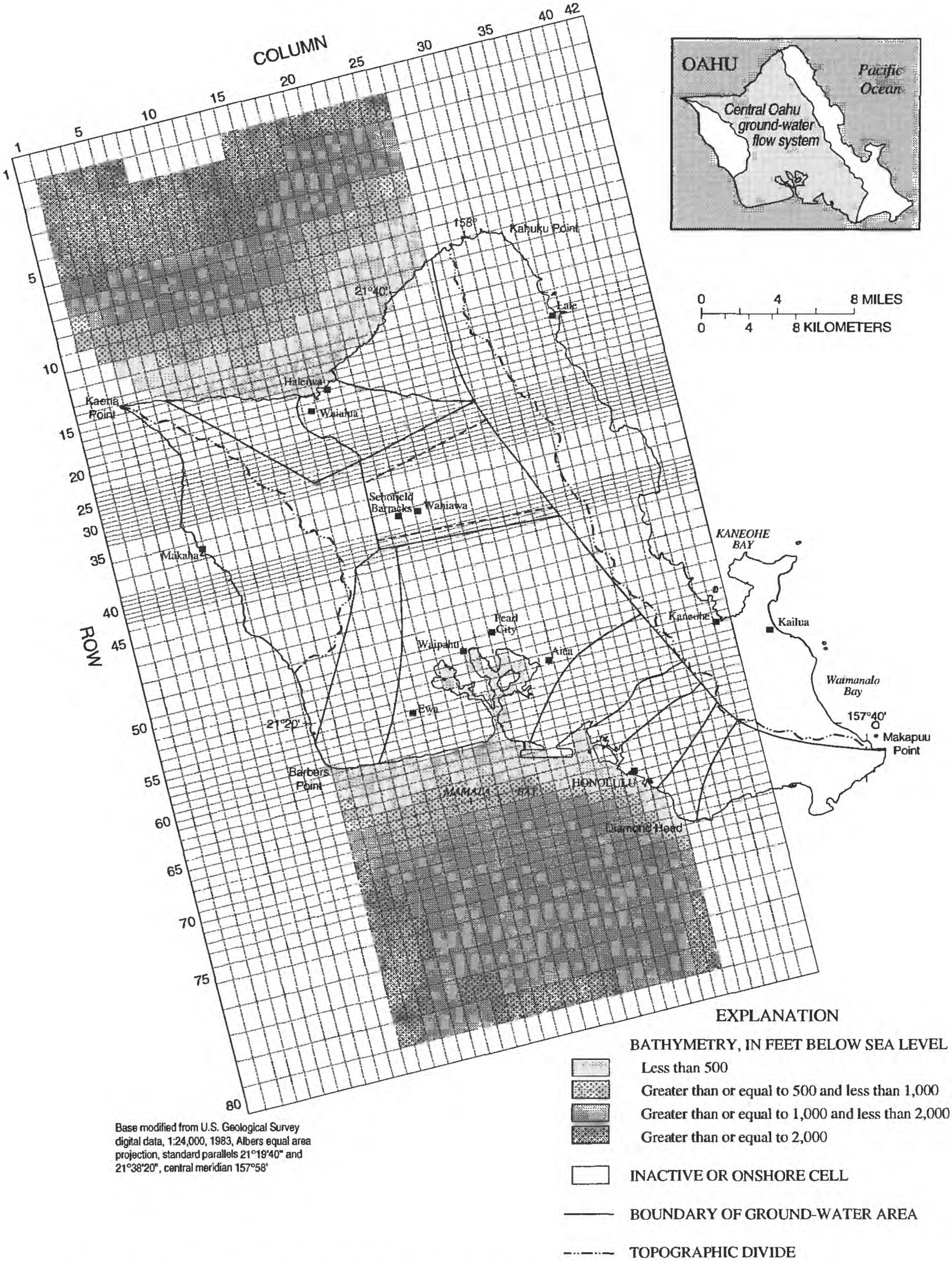


Figure 38. Bathymetry used in the model grid for the central Oahu ground-water flow system, Hawaii.

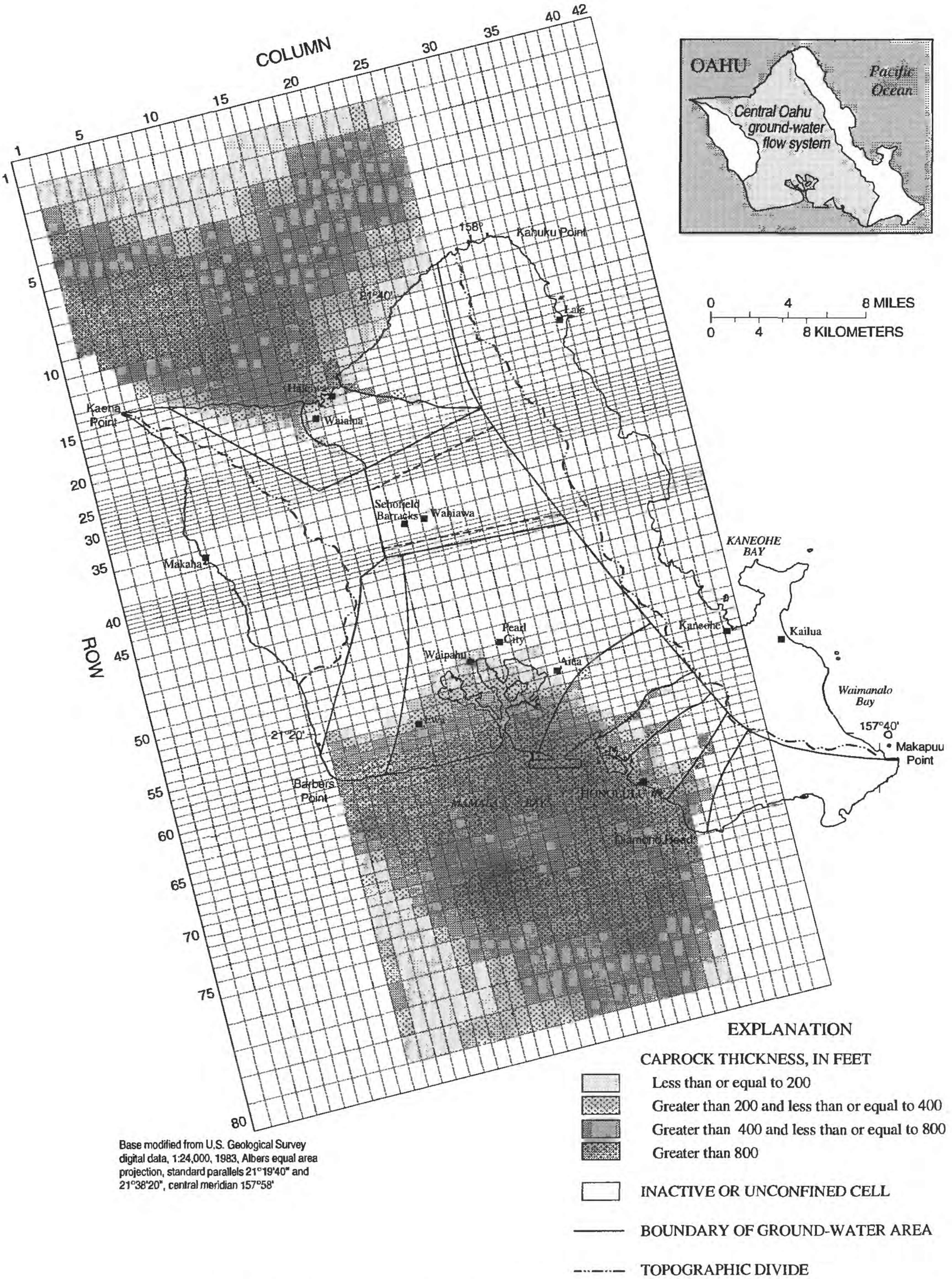


Figure 39. Caprock thickness used in the model grid for the central Oahu ground-water flow system, Hawaii.

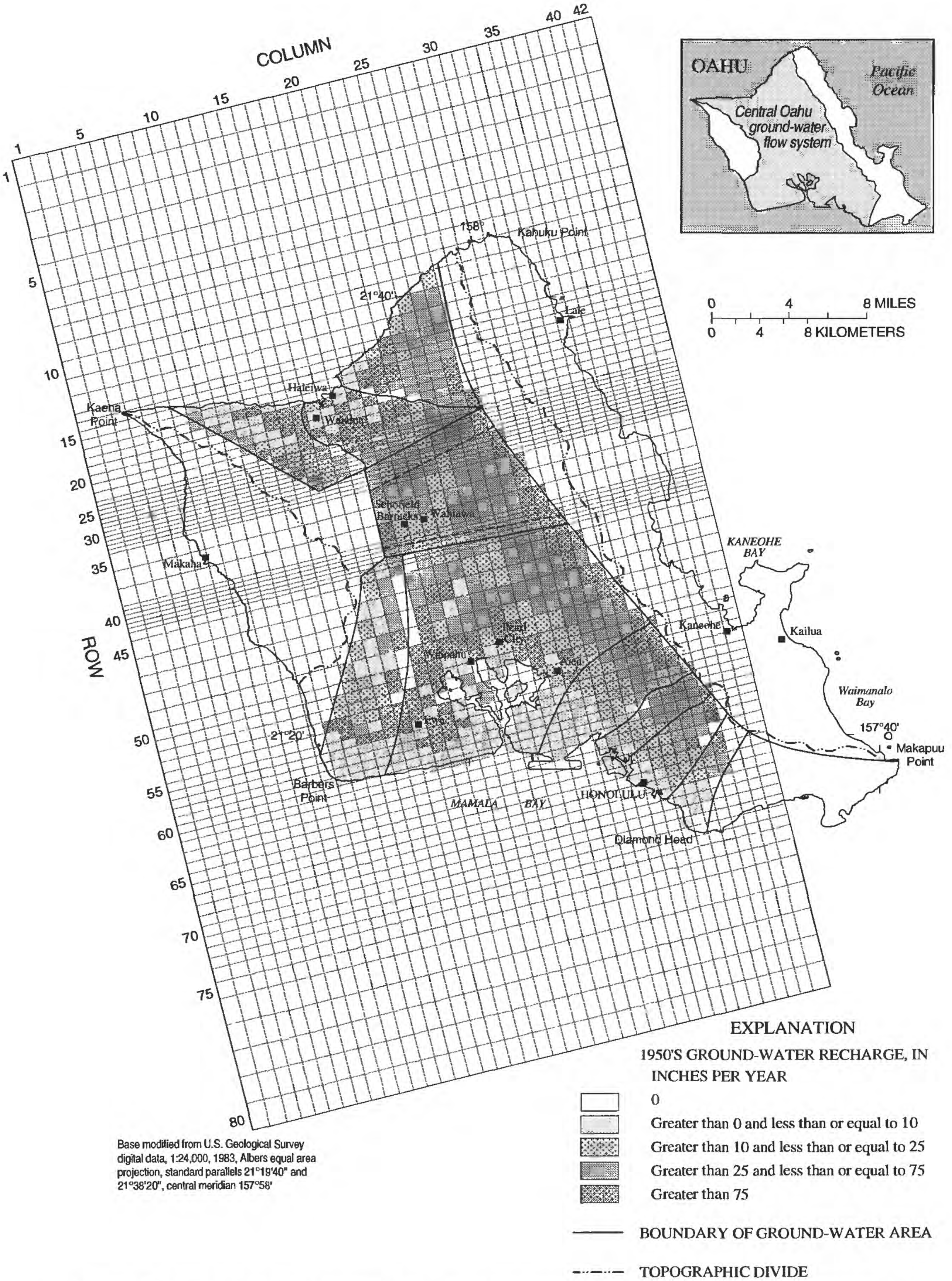


Figure 40. Distribution of 1950's ground-water recharge used in the model grid for the central Oahu ground-water flow system, Hawaii.

Table 6. Pearl Harbor springs model input values for 1950's conditions, Oahu, Hawaii

Spring	Cell row, column (fig. 36)	Leakance, K/b (1/year)	Head, h_0 (feet)
Kalauao	52, 27	5.178	5.969
Waiau-Waimano	51, 25	9.342	5.288
Waiawa	50, 24	5.658	2.613
Waikele	50, 21	5.574	5.786

Table 7. Average 1950's recharge, pumpage, and model-calculated natural discharge for the volcanic aquifers of the central Oahu ground-water flow system, Hawaii

[Mgal/d, million gallons per day]

	Northern Oahu, including northern Schofield dam	Schofield ground-water area	Southern Oahu, including southern Schofield dam	Total
Recharge (Mgal/d)	163.9	149.9	309.6	623.4
Pumpage (Mgal/d)	40.9	4.6	194.3	239.8
Model-calculated natural discharge (Mgal/d)	178.2	55.2 to north 90.1 to south	205.4	

With a few modifications, recharge between the crests of the Waianae Range and the Koolau Range west of the Kaau rift zone was assumed to contribute to the central Oahu flow system. The high-level ground-water areas between the crests of the ranges and the outer margins of the rift zones were not modeled in this study. Most of the recharge in these areas, however, was assumed to contribute to the downgradient areas of the central Oahu flow system. In the Koolau Range and most of the Waianae Range, recharge in the rift zones was assumed to enter the modeled area by flowing perpendicular to the rift-zone boundary. In the Waianae rift zone at the western extent of the Schofield ground-water area, recharge over Waianae Volcanics was assumed to contribute to the Ewa and Mokuleia ground-water areas, and recharge over areas mapped as alluvium (Takasaki, 1971) was assumed to enter the Schofield ground-water area. For areas mapped as alluvium, it is assumed that Koolau Basalt filled the valleys between Mount Kaala and Puu Kanehoa and underlies the surficial alluvium.

Recharge estimates from Giambelluca (1983) and P.J. Shade (USGS, written commun., 1992) are based on the amount of water that percolates beyond the plant root zone. However, not all of the water percolating beyond the plant root zone enters the central Oahu ground-water flow system. Some of the estimated recharge from the high-level dike compartments between the Waianae and Koolau crests discharges directly to the ocean and some discharges to the opposite side of the crests to areas outside of the central Oahu flow system. Areas where recharge from the high-level dike compartments between the Koolau and Waianae crests does not enter the central Oahu flow system are described below. A summary of the affected cells is given in table 8.

Southern Waianae Range.--For the southern part of the Waianae Range, it was estimated that about 5.0 Mgal/d of the recharge between the crest and the eastern margin of the south rift zone of the Waianae Volcano discharges to the ocean without entering the Ewa ground-water area. Water levels at wells 2006-12 and 2007-01 indicate that ground water flows westward across the rift-zone margin. Thus, recharge over the southern extent of the Waianae Range, between the crest of the range and the eastern margin of the south rift zone, is assumed to remain to the west of the Ewa area.

Northern Koolau Rift Zone.--At the northern extent of the Koolau Range, dike-impounded ground-water discharges directly to the ocean without contributing to the Kawailoa ground-water area. Takasaki and Mink (1985) estimate the total northward discharge to the ocean from the rift zone to be about 20 Mgal/d. Because the Koolau crest is near the center of the rift

Table 8. Model grid cells between the Waianae and Koolau Range crests that do not contribute recharge to the central Oahu ground-water flow system, Hawaii

Area	Cell (row, column) (fig. 36)
Southern Waianae rift zone	(49, 11), (49, 12), (50, 11), (50, 12), (51, 11), (51, 12), (52, 11), (52, 12), (53, 11), (54, 11)
Northern Koolau rift zone	(10, 27), (11, 27), (12, 27), (12, 28), (13, 27), (13, 28), (14, 27), (14, 28), (15, 27),(15, 28), (16, 27), (16, 28), (17, 29)
Leeward Koolau rift zone	(35, 32), (40, 33), (41, 33), (42, 33), (43, 33), (44, 33), (47, 34), (50, 36), (51, 37)

zone in northern Oahu, direct discharge to the ocean is assumed to be about 10 Mgal/d from each side of the crest. For 1950's conditions, the amount of recharge in the study area that discharges directly to the ocean at the northern extent of the Koolau rift zone is estimated to be 10.5 Mgal/d.

Windward Valleys.--The Waiahole tunnel system consists of five tunnels excavated into the Koolau rift zone between Waiahole and Kahana Stream valleys on the windward (northeastern) side of the Koolau crest (Takasaki and Mink, 1985). The tunnels are connected by a ditch system and water collected from the windward side of the Koolau crest by the Waiahole system is delivered to the southwestern, leeward side through the trans-Koolau tunnel. The five tunnels were completed between 1915 and 1929, and one of the tunnels was extended in 1963 (Takasaki and Mink, 1985). The Waiahole tunnel system drains about 28 Mgal/d from the rift zone. About 5 Mgal/d of the total flow is discharged by gravity directly into the trans-Koolau tunnel from the leeward side of the crest. Furthermore, Mink and others (1988) reason that the Waiahole system must drain additional water from the leeward side of the crest because there is not enough rainfall within the windward drainage area of the Waiahole system to account for the total flow. The equilibrium base flow of the tunnel system is not appreciably different from the sum of the base flows of streams on the windward side of the Koolau crest before tunnel construction (Takasaki and Mink, 1985, p. 29). Thus, data from the Waiahole tunnel system suggests that streams on the windward side of the Koolau crest can drain ground water from the leeward side of the crest.

Recharge in cells located on the leeward side of the crest, at the edges of windward valley reentrants (table 8), was assumed to drain to the windward side of the crest. The rationale behind this decision was that where the windward valleys have formed large reentrants, they have cut deeply into the dike complexes allowing impounded water to drain into the valleys. The total reduction of recharge caused by leeward rift-zone recharge draining to the windward side of the crest is estimated to be about 18.2 Mgal/d for the 1950's period. It should be noted that water diverted by the Waiahole tunnel system re-enters the central Oahu ground-water flow system by irrigation water in the recharge model.

Pumpage

Ground-water pumpage from the central Oahu flow system during the 1950's was estimated from existing records in USGS Hawaii District data files. Well depths were determined from the summary of Miyamoto and others (1986) and USGS well files. Where more than one well occupies a single cell, a flow-weighted average well depth was used. The distribution of 1950's pumpage by grid cell is shown in figure 41. A summary of the pumpage is provided in table 7. The average 1950's pumpage of 239.8 Mgal/d represents 38 percent of the recharge for the same period.

Water Properties

The specific gravities of freshwater and saltwater were assumed to be 1.0 and 1.025, respectively. Hydraulic conductivity is dependent on fluid viscosity which is in turn a function of temperature and, to a lesser extent, pressure and salinity. Freshwater and saltwater dynamic viscosities at 20°C are 2.09×10^{-5} $lb \cdot s/ft^2$ (Freeze and Cherry, 1979) and 2.24×10^{-5} $lb \cdot s/ft^2$ (Weast and others, 1989), respectively. The specific gravity and viscosity values were assumed to remain constant for all simulations.

Estimation of Hydraulic Conductivity

The hydraulic conductivities that must be estimated include the horizontal hydraulic conductivities of the aquifers and the barriers, and the vertical hydraulic

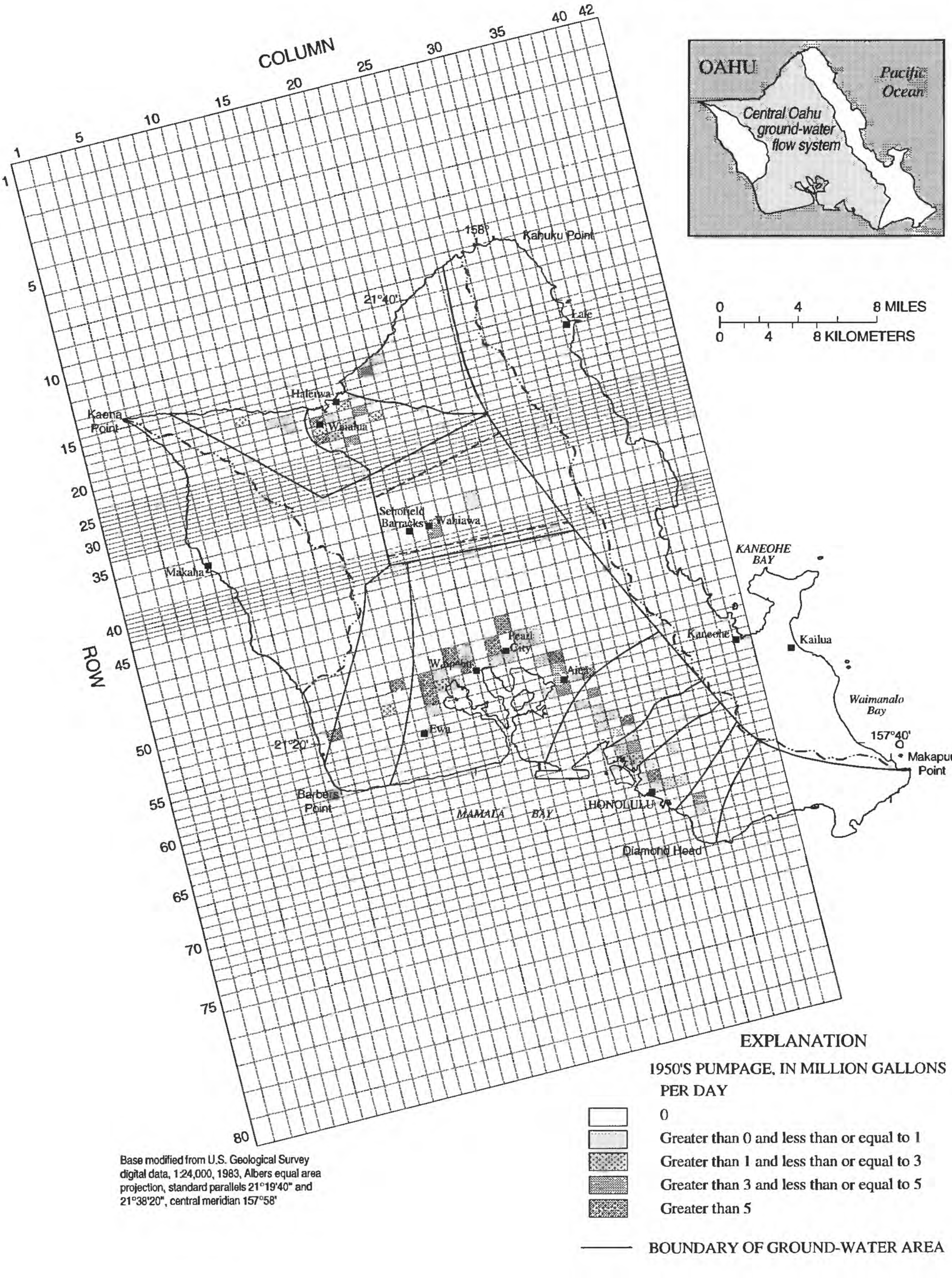


Figure 41. Distribution of 1950's pumping rates used in the model grid for the central Oahu ground-water flow system, Hawaii.

conductivity of the coastal caprock. There are a total of ten ground-water areas and nine ground-water barriers within the central Oahu flow system. In addition, the caprock vertical hydraulic conductivity must be estimated for nine of the ten ground-water areas in the study area. If the hydraulic conductivities of the ten ground-water areas are allowed to be anisotropic, then there are a total of 38 independent hydraulic-conductivity values which must be estimated.

Given the large number of hydraulic-conductivity values that must be estimated in the model, it is likely that different hydraulic-conductivity distributions can be used in a model to produce equally acceptable model-calculated water levels. This non-unique nature of the model led to the imposition of simplifying assumptions and a parsimonious approach for estimating the hydraulic-conductivity distribution. To reduce the number of hydraulic conductivity values requiring estimation, homogeneous and isotropic conditions were assumed where possible. The parsimonious approach involved modeling individual ground-water areas prior to modeling the central Oahu flow system in its entirety. A brief summary of the five modeling steps used to estimate the hydraulic-conductivity distribution is provided below.

1. The part of the model grid containing the Mokuleia ground-water area was first isolated to estimate three hydraulic conductivities: (1) a horizontal hydraulic conductivity of 1,500 ft/d for the Waianae aquifer in the Mokuleia ground-water area, (2) a horizontal hydraulic conductivity of 1.5 ft/d for the Waianae confining unit separating the Mokuleia and Waialua ground-water areas, and (3) a vertical hydraulic conductivity of 0.10 ft/d for the caprock along the coast of the Mokuleia area.
2. The part of the model grid containing the Ewa ground-water area was next isolated to estimate four hydraulic conductivities: (1) a horizontal hydraulic conductivity of 1,500 ft/d for the Waianae aquifer in the Ewa ground-water area, (2) a horizontal hydraulic conductivity of 1.5 ft/d for the Waianae confining unit separating the Ewa and Pearl Harbor ground-water areas, (3) a horizontal hydraulic conductivity of 0.5 ft/d for the part of the southern Schofield dam separating the Ewa and Schofield ground-water areas, and (4) a vertical hydraulic conductivity of 0.15 ft/d for the caprock along the coast of the Ewa area.
3. The part of the model grid containing the Kawailoa ground-water area was next isolated to estimate ranges of values for three hydraulic conductivities: (1) the horizontal hydraulic conductivity of the Koolau aquifer in the Kawailoa ground-water area, (2) the vertical hydraulic conductivity of the caprock along the coast of the Kawailoa area, and (3) the horizontal hydraulic conductivity of the Anahulu valley-fill barrier separating the Kawailoa and Waialua ground-water areas. The method used to represent the Anahulu valley-fill barrier was established during this step of the modeling process. Final values for the hydraulic conductivities of the Kawailoa ground-water area, however, were not established during this step because of the need to model the Waialua and Kawailoa areas simultaneously to ensure that proper water levels could be simulated in both areas.
4. The part of the model grid containing the Kaimuki, Beretania, and Kalihi ground-water areas was next isolated to estimate ranges of values for three hydraulic conductivities: (1) the horizontal hydraulic conductivity of the Koolau aquifer in the Kaimuki, Beretania, and Kalihi ground-water areas, (2) the vertical hydraulic conductivity of the caprock along the coast of the Kaimuki, Beretania, and Kalihi areas, and (3) the horizontal hydraulic conductivity of the Manoa, Nuuanu, and Kalihi valley-fill barriers. The method used to represent the valley-fill barriers was established during this step of the modeling process. Final values for the hydraulic conductivities of the Kaimuki, Beretania, and Kalihi ground-water areas, however, were not established during this step because of the need to model these three areas with the Moanalua area simultaneously.
5. Values estimated from steps 1 and 2, and the ranges of values estimated from steps 3 and 4 were used to estimate the final distribution of hydraulic conductivities. A trial-and-error procedure was used to determine the final values for 12 hydraulic conductivities (table 9): (1) the

Table 9. Final freshwater model hydraulic-conductivity values based on 1950's simulation period, central Oahu ground-water flow system, Hawaii

	Hydraulic conductivity (feet per day)
Aquifar hydraulic conductivity	
Mokuleia area	1,500
Waialua area	7,500
Kawailoa area	7,500
Schofield area	1,500
Ewa area	1,500
Pearl Harbor area	1,500 and 4,500
Moanalua area	1,500
Kalihi area	1,500
Beretania area	1,500
Kaimuki area	1,500
Barrier hydraulic conductivity	
Northern Waianae confining unit	1.5
Southern Waianae confining unit	1.5
Schofield northern ground-water dam	1.17
Schofield southern ground-water dam	0.5
Anahulu Valley Fill	1,000
Halawa Valley Fill	1,500
Kalihi Valley Fill	30
Nuuanu Valley Fill	30
Manoa Valley Fill	30
Caprock vertical hydraulic conductivity	
Mokuleia area	0.10
Waialua area	0.25
Kawailoa area	10
Ewa area	0.15
Pearl Harbor area	0.10
Moanalua area	0.02
Kalihi area	0.02
Beretania area	0.02
Kaimuki area	0.02

horizontal hydraulic conductivity of the Koolau aquifer in the Waialua and Kawailoa ground-water areas, (2) the horizontal hydraulic conductivity of the Koolau aquifer in the Schofield ground-water area, (3) the horizontal hydraulic conductivity of the Koolau aquifer in the Pearl Harbor ground-water area, (4) the horizontal hydraulic conductivity of the Koolau aquifer in the Moanalua, Kalihi, Beretania, and Kaimuki ground-water areas, (5) the horizontal hydraulic conductivity of the northern Schofield ground-water dam, (6) the horizontal hydraulic conductivity of the Anahulu valley-fill barrier, (7) the horizontal hydraulic conductivity of the Halawa valley-fill barrier, (8) the horizontal hydraulic conductivity of the Kalihi, Nuuanu, and Manoa valley-fill barriers, (9) the vertical hydraulic conductivity of the caprock along the coast of the Waialua area, (10) the vertical hydraulic conductivity of the caprock along the coast of the Kawailoa area, (11) the vertical hydraulic conductivity of the caprock along the coast of the Pearl Harbor area, and (12) the vertical hydraulic conductivity of the caprock along the coast of the Moanalua, Kalihi, Beretania, and Kaimuki areas.

The five steps summarized above are described in detail in the next sections of this report.

Mokuleia Ground-Water Area

The part of the model grid containing the Mokuleia ground-water area was isolated to estimate the values of the three hydraulic conductivities relevant to that area (fig. 42). Specifically, it was desired to estimate (1) the horizontal hydraulic conductivity of the Waianae aquifer in the Mokuleia ground-water area, (2) the horizontal hydraulic conductivity of the Waianae confining unit separating the Mokuleia and Waialua ground-water areas, and (3) the vertical hydraulic conductivity of the caprock along the coast of the Mokuleia area. The horizontal hydraulic conductivity of the Waianae confining unit was estimated by varying the hydraulic conductivity of the Waianae confining unit cells and maintaining a specified-head boundary on the Waialua (eastern) side of the barrier. The specified head values on the Waialua (eastern) side of the Waianae confining unit ranged from 11 ft near the coast to 12.5 ft at the inland extent of the Waialua area. The specified-head cells were assigned a horizontal hydraulic conductivity value of 7,500 ft/d. Horizontal hydraulic-conductivity values of 0, 1.5, 15, and 150 ft/d for the Waianae confining unit, horizontal hydraulic-conductivity values of 500; 1,500; and 3,000 ft/d for the Waianae aquifer, and vertical hydraulic conductivity values from 0.01 to 0.5 ft/d for the caprock were tested. The various combinations of Waianae confining unit, Waianae aquifer, and caprock hydraulic-conductivity values were examined to determine which combination of values best simulated measured average water levels at two Mokuleia observation wells.

The model-calculated water levels at wells 3409-16 (fig. 43) and 3410-08 (fig. 44) vary as a function of

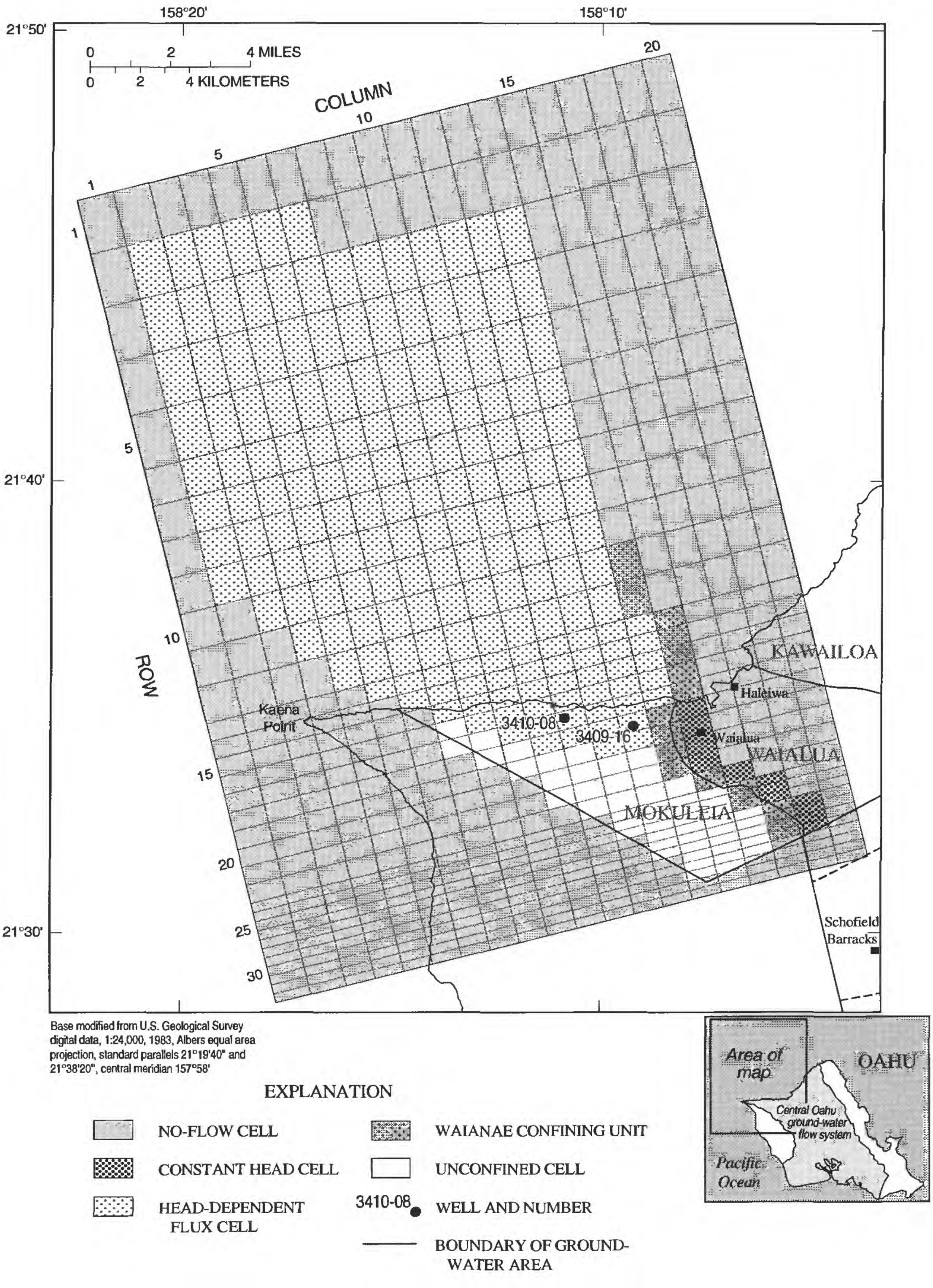


Figure 42. Model grid for the Mokuleia ground-water area of the central Oahu ground-water flow system, Hawaii.

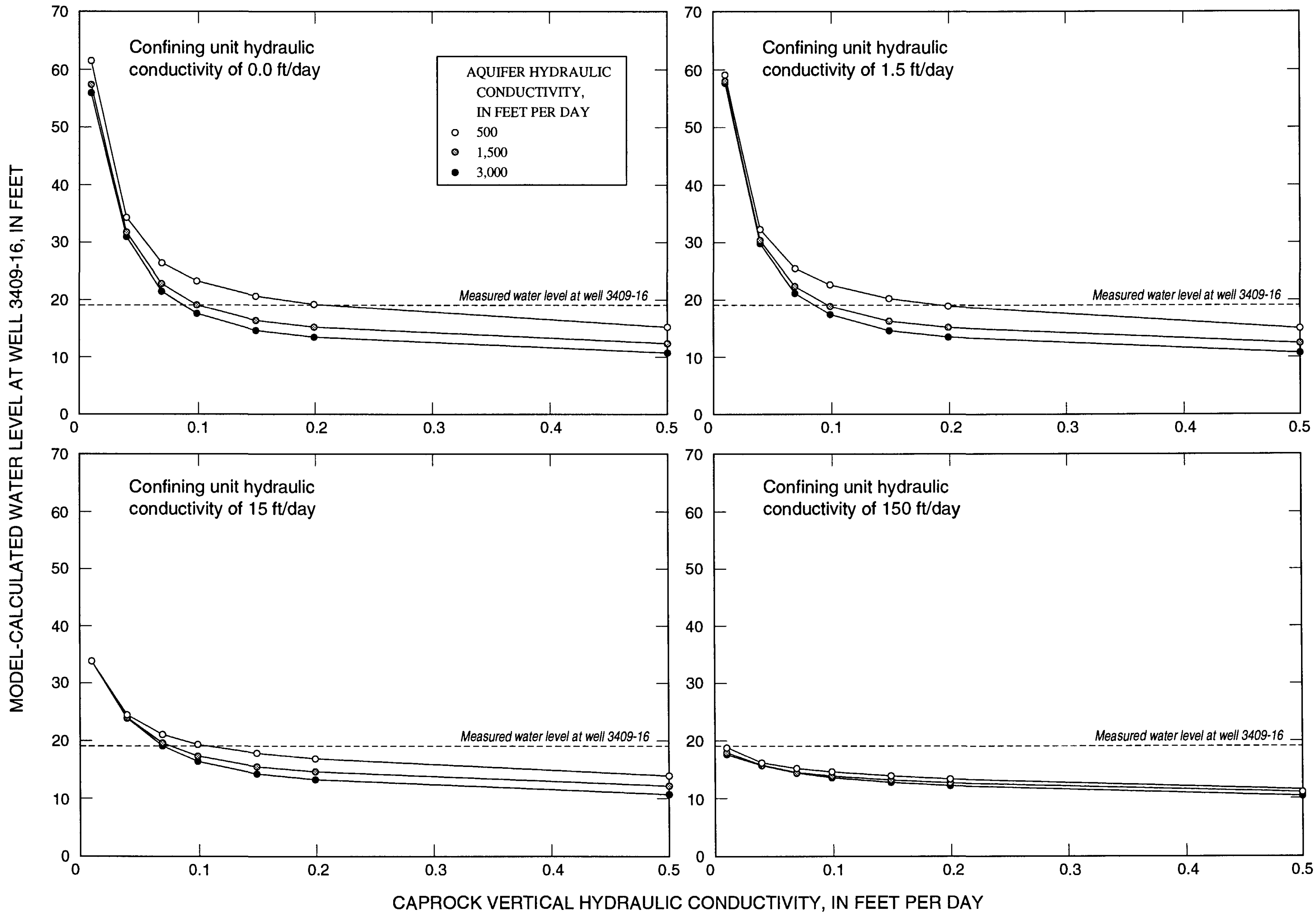


Figure 43. Model-calculated water levels at well 3409-16 as a function of aquifer, caprock, and Waianae confining unit hydraulic conductivity values, Mokuleia ground-water area, Oahu, Hawaii.

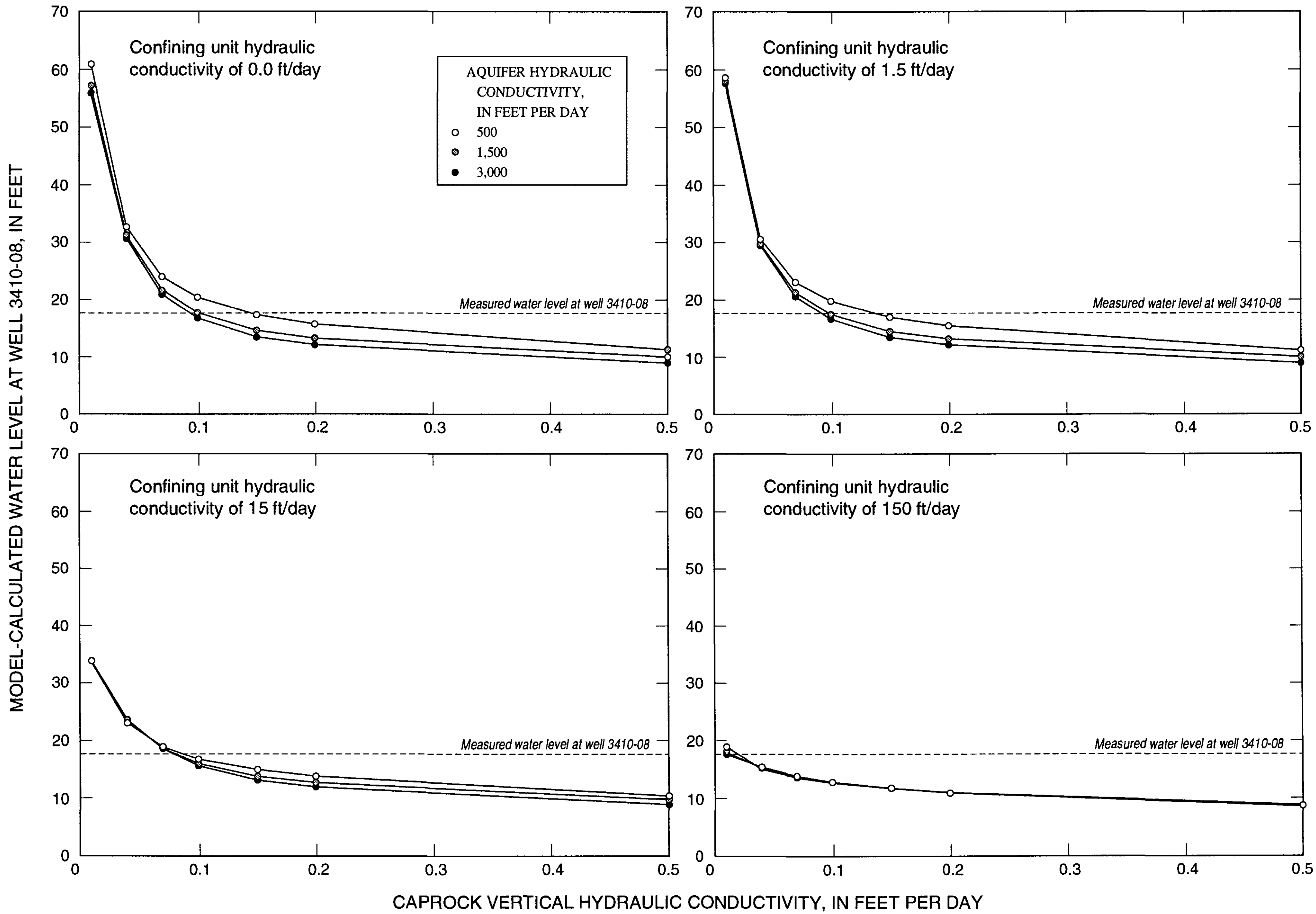


Figure 44. Model-calculated water levels at well 3410-08 as a function of aquifer, caprock, and Waianae confining unit hydraulic conductivity values, Mokuleia ground-water area, Oahu, Hawaii.

the assigned caprock vertical hydraulic conductivity value for particular horizontal hydraulic-conductivity values for the Waianae aquifer and Waianae confining unit. Average 1950's water levels at wells 3409-16 and 3410-08 were 19.1 and 17.7 ft, respectively. For well 3409-16, the intersection of each curve with the horizontal line at 19.1 ft (fig. 43) yields the best value of caprock vertical hydraulic conductivity for the given horizontal hydraulic-conductivity values for the Waianae aquifer and Waianae confining unit represented by the curve. Similarly, for well 3410-08, the intersection of each curve with the horizontal line at 17.7 ft (fig. 44) yields the best value of caprock vertical hydraulic conductivity for the given horizontal hydraulic-conductivity values for the Waianae aquifer and Waianae confining unit represented by the curve.

The sum of the absolute error between model-calculated and measured water levels also varies as a function of the assigned caprock vertical hydraulic conductivity value for particular horizontal hydraulic-conductivity values for the Waianae aquifer and Waianae confining unit (fig. 45). Lowest absolute error values are obtained with a horizontal hydraulic conductivity of 1,500 ft/d for the Waianae aquifer, a vertical hydraulic conductivity of 0.1 ft/d for the caprock, and a horizontal hydraulic conductivity of 0 or 1.5 ft/d for the Waianae confining unit (fig. 45). Because it is unlikely that the Waianae confining unit is impermeable, a horizontal hydraulic-conductivity value of 1.5 ft/d was selected for use in the final model.

Ewa Ground-Water Area

The part of the model grid containing the Ewa ground-water area (fig. 46) was isolated in a manner similar to the Mokuleia area. For the Ewa area, the four hydraulic conductivities to be estimated include (1) the horizontal hydraulic conductivity of the Waianae aquifer in the Ewa area, (2) the vertical hydraulic conductivity of the caprock that impedes coastal discharge from the Ewa area, (3) the horizontal hydraulic conductivity of the Waianae confining unit separating the Ewa and Pearl Harbor ground-water areas, and (4) the horizontal hydraulic conductivity of the part of the southern Schofield ground-water dam that separates the Schofield and Ewa ground-water areas. Flow between the Pearl Harbor and Ewa ground-water areas was simulated by maintaining specified-head cells on the Pearl Harbor (eastern) side of the Waianae confining unit. The specified head values on the Pearl Harbor (eastern) side of the Waianae confining unit ranged from 17.5 ft near the coast to 27.5 ft near the southern Schofield ground-water dam by assuming a hydraulic gradient with a magnitude of about 1 ft/mi. Flow across the southern Schofield ground-water dam into the Ewa area was simulated by maintaining a specified head of 279 ft in cells on the northern side of the southern dam. The specified-head cells were assigned a horizontal hydraulic conductivity value of 4,500 ft/d. (Note that flow across the barriers is controlled mainly by the low hydraulic conductivity of the barrier cells and, thus, model results are not significantly affected by the hydraulic conductivity value assigned to the non-barrier specified-head cells within the range of 1,500 to 4,500 ft/d.) A summary of the hydraulic-conductivity values used in the Ewa area simulations is given in table 10.

Data from four primary well sites in the Ewa area, wells 2006-01 to -11, 2006-12, 2103-01, and 2203-01 to -06 (table 5), were used to estimate the hydraulic-conductivity values. Because of the coarse nature of the model grid, well 2103-02 of the Ewa area actually falls within a cell used to represent the Waianae confining unit. Thus, data from well 2103-02 were not used. However, data from well 2103-01, located about 1,200 ft southwest of well 2103-02, were used to estimate the hydraulic-conductivity values.

The Del Monte Kunia well 2703-01 is located toward the northern, inland extent of the Ewa ground-water area and provides an important constraint on the hydraulic gradient. However, during the 1950's, water levels were measured at this well using an air line which has limited accuracy and precision. On the basis of reported air-line measurements, the average 1950's water level was 22.2 ft at well 2703-01. Prior to the 1950's, water-level measurements at well 2703-01 were made in January, February, and November 1947 with a tape or wire device. The average of the three 1947 measurements at well 2703-01 is 24.2 ft. At wells 2103-02 and 2006-01 to -11 in the Ewa area, the ratios of average 1947 water levels to average 1950's water levels range from 0.97 to 0.99. At these same wells, the ratios of the average 1947 water levels from the months of January, February, and November to the average 1950's water levels range from 0.99 to 1.02. On the basis of the minimum and maximum 1947 to 1950's water-level ratios of 0.97 and 1.02, respectively, the average 1950's water level at well 2703-01 is estimated to be between 24.9 (=24.2/0.97) and 23.7 (=24.2/1.02) ft. Thus, for the Del Monte Kunia well 2703-01, the model-calculated

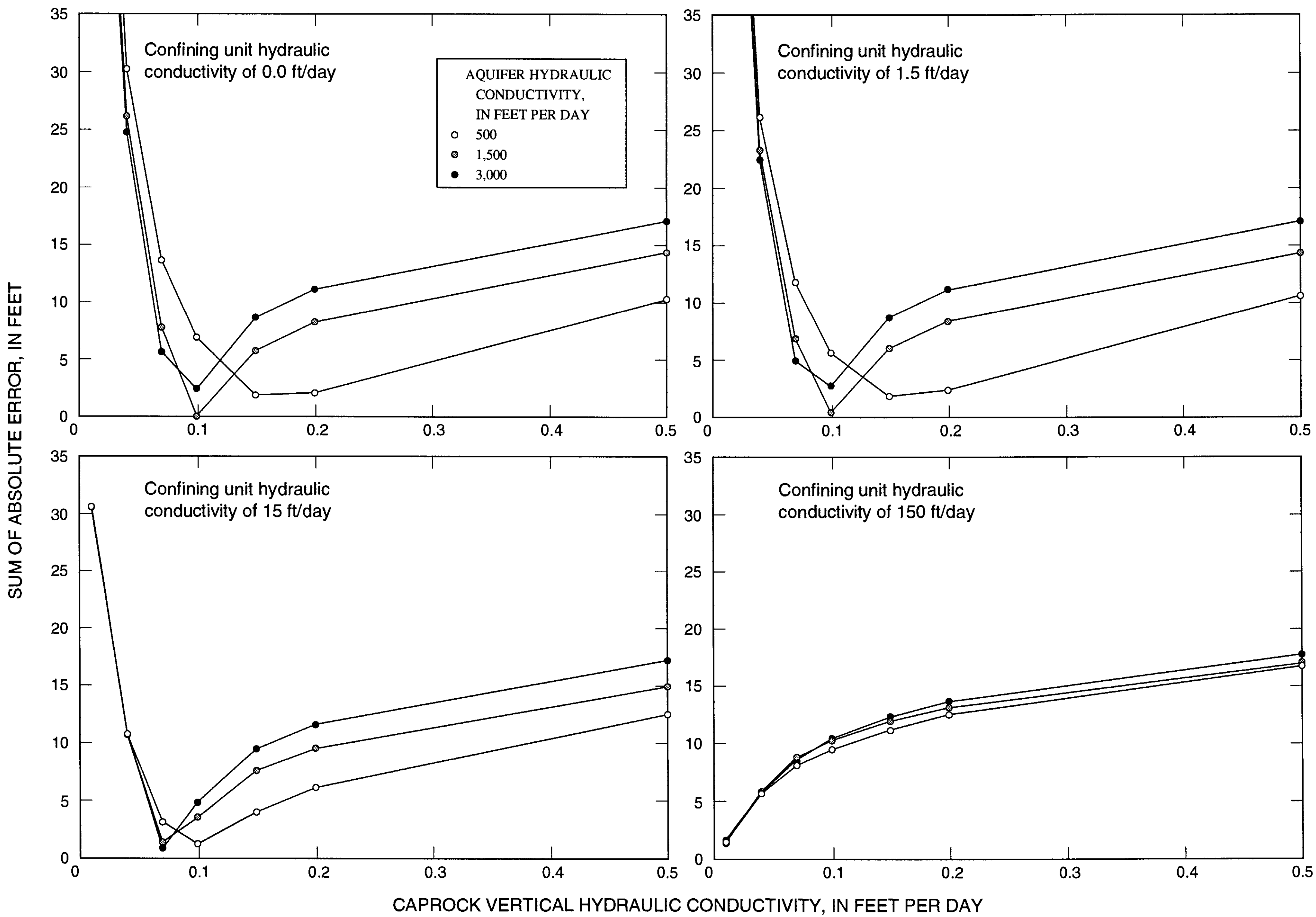
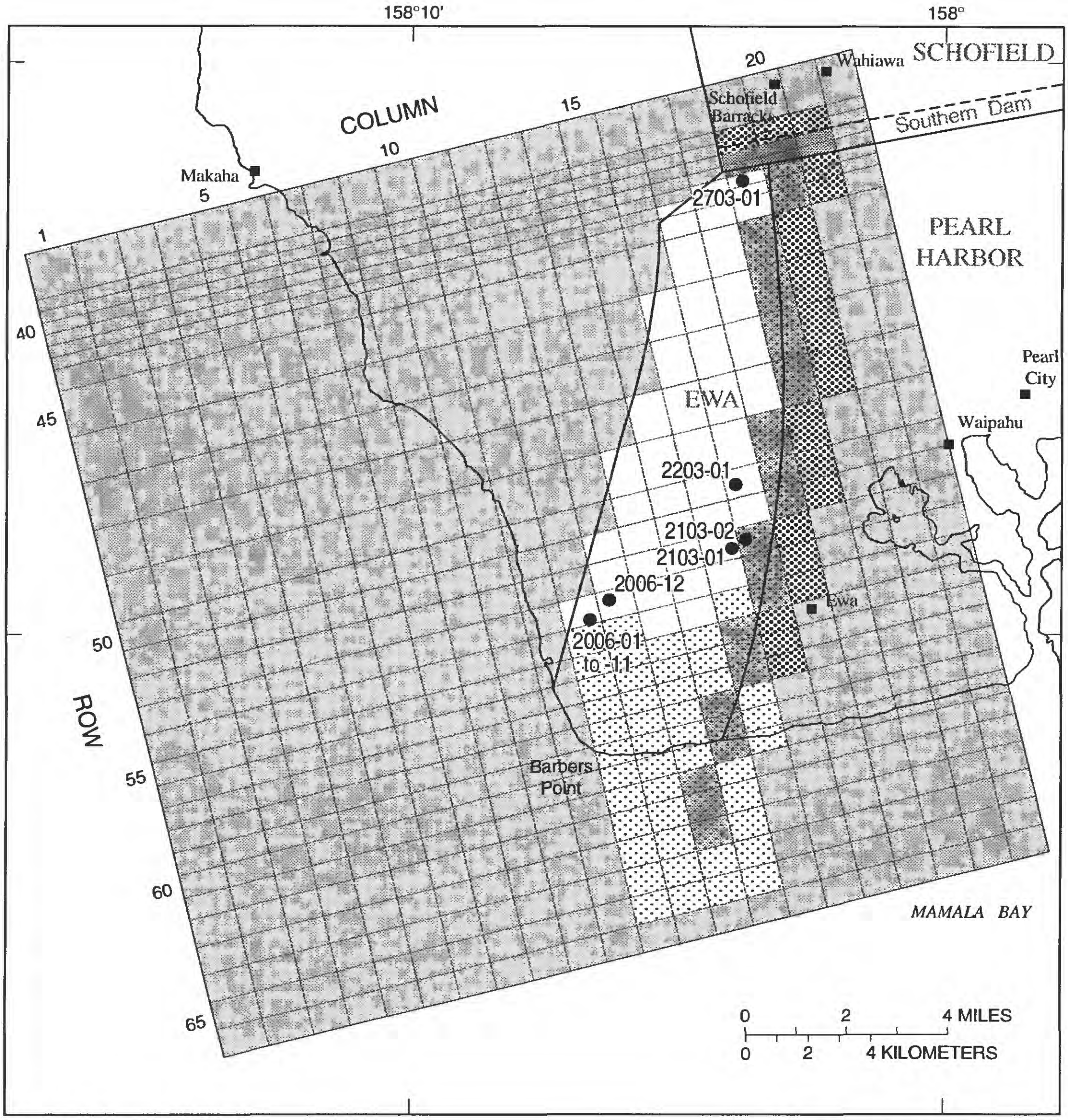
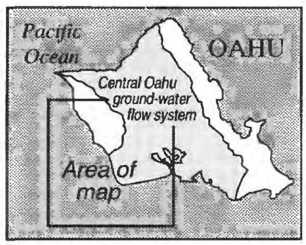


Figure 45. Sum of absolute error as a function of aquifer, caprock, and Waianae confining unit hydraulic conductivity values, Mokuleia ground-water area, Oahu, Hawaii.



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 21°19'40" and 21°38'20", central meridian 157°58'



EXPLANATION

- NO-FLOW CELL
- CONSTANT HEAD CELL
- HEAD-DEPENDENT FLUX CELL
- SCHOFIELD SOUTHERN DAM
- WAIANAE CONFINING UNIT
- UNCONFINED CELL
- 2203-01 WELL AND NUMBER
- BOUNDARY OF GROUND-WATER AREA

Figure 46. Model grid for the Ewa ground-water area of the central Oahu ground-water flow system, Hawaii.

Table 10. Hydraulic-conductivity values tested for the Ewa ground-water area simulations, Oahu, Hawaii
[ft/d, feet per day]

Simulation series (fig. 47)	Waianae confining unit (ft/d)	Waianae volcanic aquifer (ft/d)	Southern Schofield ground-water dam (ft/d)	Ewa caprock vertical hydraulic conductivity (ft/d) values tested for the specified Waianae confining unit, Waianae aquifer, and southern Schofield dam hydraulic conductivities
1	0.0	500	0.0	0.01, 0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
2	0.0	500	0.2	0.01, 0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
3	0.0	500	0.4	0.01, 0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
4	1.5	500	0.0	0.01, 0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
5	1.5	500	0.2	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
6	1.5	500	0.4	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
7	1.5	500	0.6	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
8	1.5	500	0.8	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
9	15	500	0.0	0.01, 0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
10	15	500	0.2	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
11	15	500	0.4	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
12	15	500	0.6	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
13	15	500	0.8	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
14	150	500	0.0	0.01, 0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
15	150	500	0.2	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
16	150	500	0.4	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
17	150	500	0.6	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
18	150	500	0.8	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
19	1.5	1,500	0.0	0.01, 0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
20	1.5	1,500	0.2	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
21	1.5	1,500	0.4	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
22	1.5	1,500	0.6	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
23	1.5	1,500	0.8	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
24	15	1,500	0.0	0.01, 0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
25	15	1,500	0.2	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
26	15	1,500	0.4	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
27	15	1,500	0.6	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
28	15	1,500	0.8	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
29	150	1,500	0.0	0.01, 0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
30	150	1,500	0.2	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
31	150	1,500	0.4	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
32	150	1,500	0.6	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
33	150	1,500	0.8	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
34	1.5	3,000	0.2	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
35	1.5	3,000	0.4	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
36	1.5	3,000	0.6	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
37	1.5	3,000	0.8	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
38	15	3,000	0.2	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
39	15	3,000	0.4	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
40	15	3,000	0.6	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
41	15	3,000	0.8	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
42	75	3,000	0.2	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
43	75	3,000	0.4	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
44	75	3,000	0.6	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
45	75	3,000	0.8	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
46	150	3,000	0.2	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
47	150	3,000	0.4	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
48	150	3,000	0.6	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75
49	150	3,000	0.8	0.05, 0.10, 0.15, 0.20, 0.25, 0.35, 0.75

1950's water level should be between a low of 22.2 ft from the air-line measurements, and a high of about 25 ft from the 1947 taped water-level measurements.

For each set of Waianae aquifer, Waianae confining unit, and southern dam horizontal hydraulic-conductivity values tested (which corresponds to a single row in table 10), a best value for the vertical hydraulic conductivity of the caprock was established for each of the four primary well sites (fig. 47). (The simulation series represented in figure 47 correspond to the series numbers listed in table 10.) The mean and standard deviation of the four caprock vertical hydraulic conductivity values were then computed for each set of Waianae aquifer, Waianae confining unit, and southern dam hydraulic conductivity values tested. A computed standard deviation of zero for the caprock vertical hydraulic conductivity corresponds to a perfect fit between measured and model-calculated water levels at the four well sites. Low standard deviations generally correspond to better simulations. However, this may not be true if, for a given set of Waianae aquifer, Waianae confining unit, and southern dam hydraulic conductivity values, the model is insensitive to the caprock vertical hydraulic conductivity.

The selection of final hydraulic-conductivity values for the Ewa area was based on two main criteria. The first criterion to evaluate model performance was the error between model-calculated and measured water levels at the four well sites. For each simulation series (table 10), the error between model-calculated and measured water levels at the four well sites was estimated using the mean of the four best caprock vertical hydraulic-conductivity values (fig. 47).

The second criterion which was used to evaluate model performance was the range of caprock vertical hydraulic conductivity values necessary to establish water levels of 22.2 to 25 ft at the Del Monte Kunia well 2703-01. For each set of Waianae aquifer, Waianae confining unit, and southern dam horizontal hydraulic-conductivity values, the mean of the best caprock vertical hydraulic conductivity values, corresponding to the four well sites, was compared to the range of caprock vertical hydraulic conductivity values necessary to establish water levels of 22.2 to 25 ft at the Del Monte Kunia well 2703-01. Using the mean of the best caprock hydraulic-conductivity values from the four well sites, those simulation series in table 10 that did not produce water levels between 22.2 and 25 ft at well 2703-01 were rejected. These rejected series are shown in figure 47 with dashed vertical lines. Acceptable series, from the standpoint of producing an acceptable water level at well 2703-01, are shown in figure 47 with solid vertical lines.

Smallest errors between measured and model-calculated water levels are obtained using aquifer horizontal hydraulic conductivity values of 1,500 and 3,000 ft/d. However, for an aquifer horizontal hydraulic conductivity of 3,000 ft/d, the Waianae confining unit must be assigned a hydraulic conductivity value of 150 ft/d (fig. 47). A Waianae confining unit hydraulic conductivity value of 150 ft/d would probably not produce the 11-ft head difference between the Pearl Harbor and Ewa ground-water areas estimated for predevelopment conditions (P.R. Eyre, USGS, oral commun., 1995). On the basis of the criteria above, a horizontal hydraulic conductivity value of 1,500 ft/d was selected for the Waianae aquifer in the Ewa area. This value is the same as that selected for the Waianae aquifer in the Mokuleia area. The caprock for the Ewa area was estimated to have a vertical hydraulic conductivity of about 0.15 ft/d. The Waianae confining unit and the southern Schofield ground-water dam were assigned horizontal hydraulic-conductivity values of 1.5 and 0.5 ft/d, respectively. The horizontal hydraulic conductivity of the Waianae confining unit was assigned the same value in both northern and southern Oahu.

Kawailoa Ground-Water Area

The part of the model grid containing the Kawailoa ground-water area (fig. 48) was isolated to estimate the caprock vertical hydraulic conductivity and aquifer horizontal hydraulic conductivity for the Kawailoa area, and to examine the effects of different representations of the Anahulu valley-fill barrier. Data are insufficient to estimate the spatial distribution of average 1950's water levels for the Kawailoa area. Water levels were measured frequently at well 3504-01 during the 1950's, but, as discussed previously, the data may not accurately reflect conditions in the freshwater lens. A few scattered water-level measurements were made in wells located near the coast (table 11). However, these wells do not provide an adequate spatial coverage of the area.

Since 1950, annual mean pumpage in the Kawailoa ground-water area has remained below 10 Mgal/d. This pumpage represents less than 20 percent of the natural ground-water recharge to the Kawailoa area after accounting for recharge from the upgradient Koolau rift

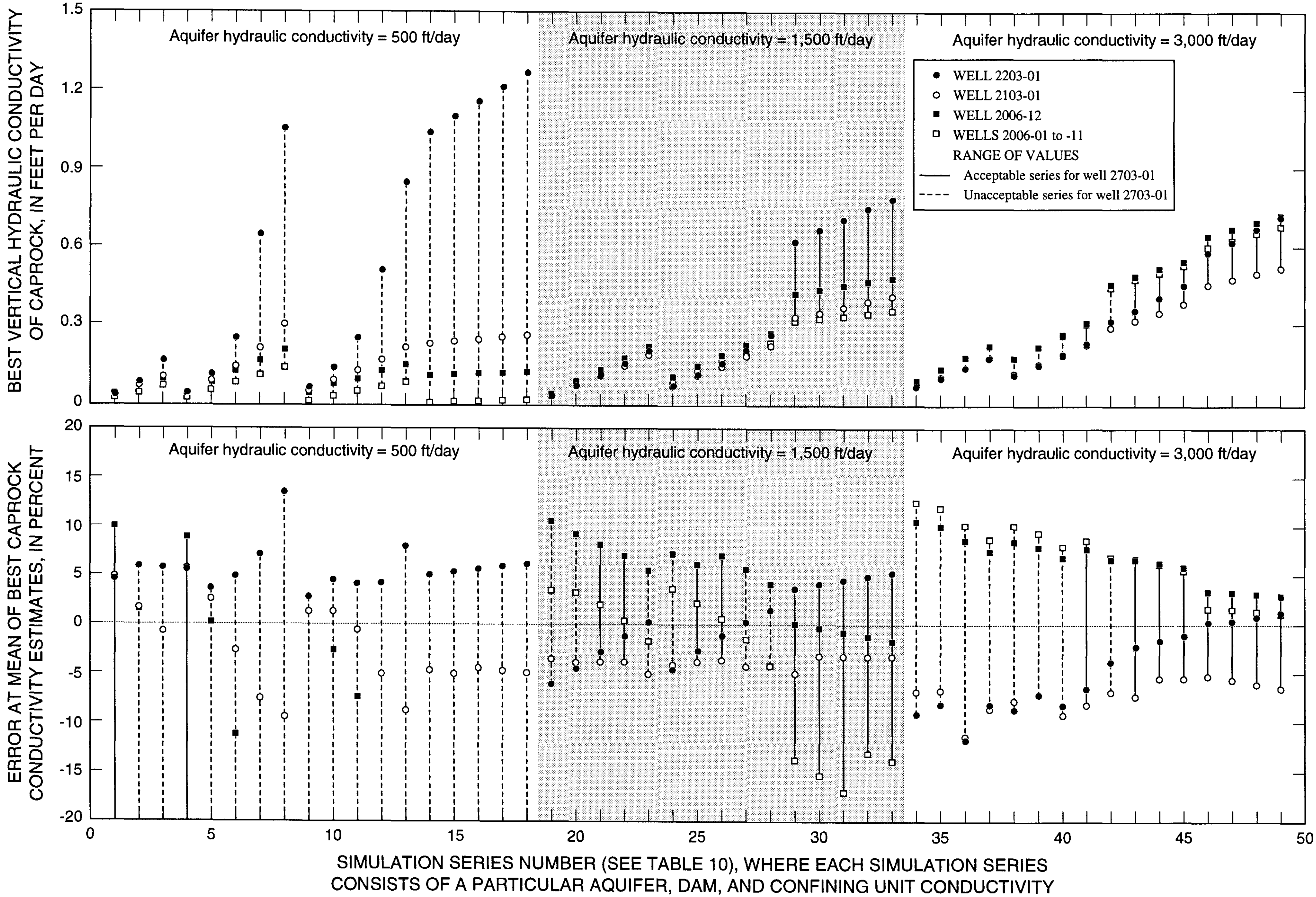


Figure 47. Best caprock hydraulic conductivity (top) and error (bottom) estimates for the simulation series of the Ewa ground-water area model. See table 10 for a summary of the aquifer, dam, and Waianae confining unit conductivities used in each simulation series. Errors below -20 percent not depicted in bottom graph.

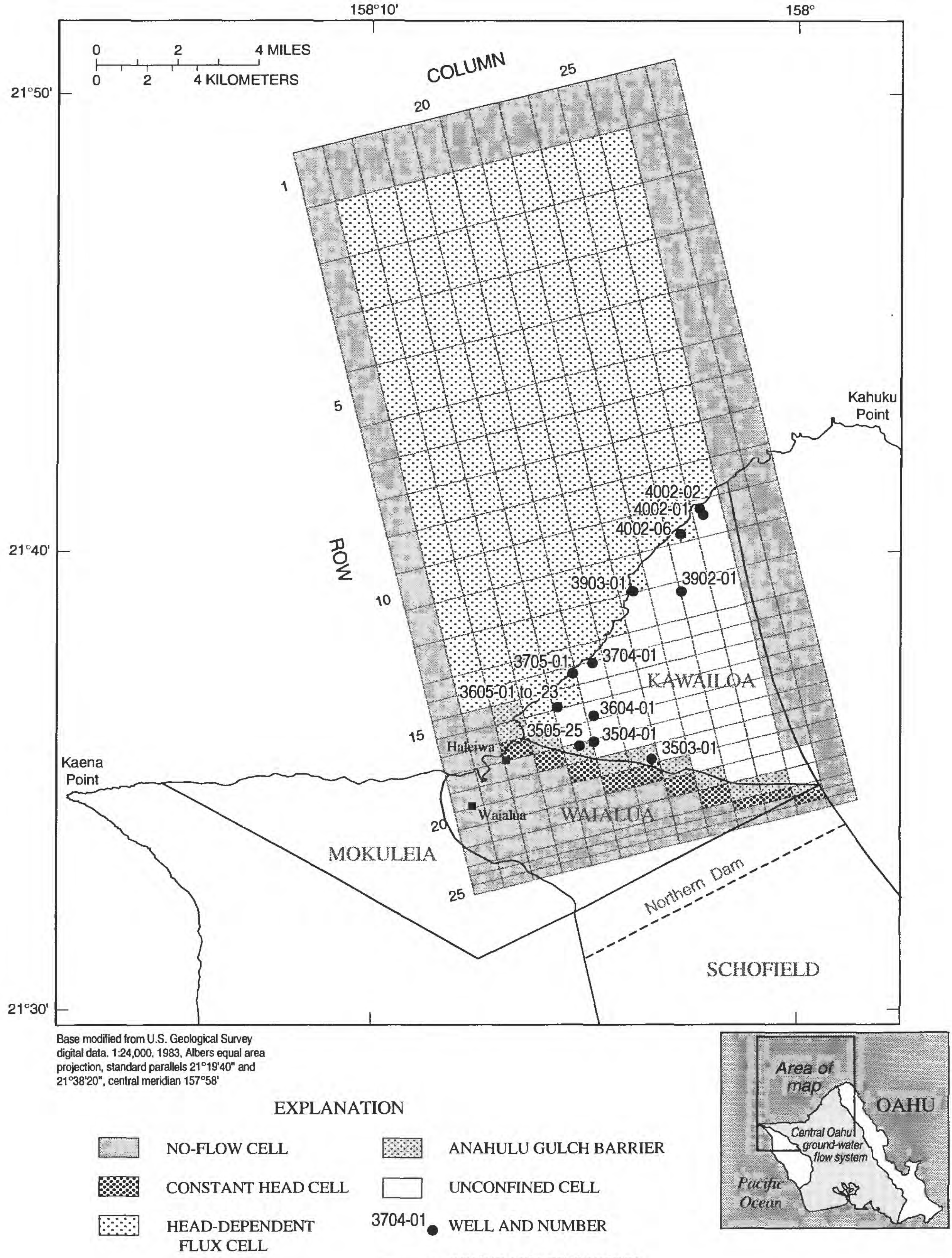


Figure 48. Model grid for the Kawailoa ground-water area of the central Oahu ground-water flow system, Hawaii.

Table 11. Water-level measurements for wells in the Kawailoa ground-water area during the 1950's, Oahu, Hawaii
[Data from U.S. Geological Survey, Hawaii District well files]

Well no.	Water level (feet above mean sea level)	Date measured
3605-18	4.32	Nov. 7, 1955
3605-19	4.38	Nov. 7, 1955
3605-20	4.45	Nov. 7, 1955
3605-21	4.53	Nov. 7, 1955
3605-22	4.50	Nov. 7, 1955
3605-23	4.45	Nov. 7, 1955
3704-01	2.3–2.8	Mar. 1956
3705-01	2.24	Feb. 27, 1958
3902-01	2.83	May 1, 1956
3902-01	2.83	Oct. 11, 1956
3902-01	2.94	Nov. 5, 1956
3902-01	2.60	June 5, 1957
3902-01	2.87	Sept. 10, 1957
3902-01	2.60	Aug. 20, 1958
3903-01	2.15	Aug. 2, 1956
3903-01	1.42	Aug. 22, 1956
4002-01	2.84	Jan. 19, 1955
4002-01	3.19	Sept. 4, 1957
4002-01	3.29	Aug. 4, 1958
4002-02	1.62	Jan. 9, 1955
4002-06	2.09	Jan. 22, 1956

zone (Shade and Nichols, 1996). The 10 Mgal/d pumpage is an even smaller fraction of the total recharge to the Kawailoa area after accounting for irrigation return flow and ground-water flow from the Waialua area to the Kawailoa area. Thus, it is reasonable to assume that water levels in the Kawailoa area have not changed significantly since the 1950's. At well 3605-23 of Waialua Sugar Company pump 4, the measured water level in 1955 was 4.45 ft. For this study, a water-level recorder was installed at well 3605-25, located about 400 ft away from well 3605-23, and was maintained from January 1994 to April 1995. The average water level at well 3605-25 was about 4.25 ft during this period. Thus, present water levels in the Kawailoa area are probably representative of conditions during the 1950's. Current water levels at wells 3503-01, 3505-25, and 3604-01 were used to supplement the existing data from the 1950's.

The Anahulu valley-fill barrier was initially modeled as a partially penetrating barrier by lowering the tops of grid cells used to represent the barrier. In this way, the valley-fill material and associated weathered zone were not simulated, only the underlying aquifer was represented. The depth of penetration of the barrier is unknown, but was estimated by assuming the barrier to be effective at an altitude of -300 ft near well 3503-01. Water levels at well 3503-01 in the Kawailoa ground-water area are about 4 ft lower than water levels in the adjacent Waialua ground-water area. The head drop from the Waialua ground-water area to the Kawailoa ground-water area is assumed to be caused by the Anahulu valley-fill barrier separating the two areas. Near well 3503-01 the barrier is assumed to extend to the bottom of the freshwater lens of the Kawailoa ground-water area. The bottom of the barrier was projected upstream and downstream assuming a 5 percent slope, and these altitudes were used to represent the top of the aquifer for grid cells representing the barrier. Ground-water flow across the barrier from the Waialua area was simulated by maintaining specified-head cells on the Waialua (southern) side of Anahulu River valley. The specified head values ranged from 10.75 ft near the coast to 12.75 ft at the inland extent of the Waialua area. The specified-head cells for the Waialua ground-water area were assigned a horizontal hydraulic conductivity equal to the value assigned to the Kawailoa ground-water area. At the inland extent of the Anahulu barrier, a single cell from the northern Schofield dam was assigned a head of 125 ft. The specified-head cell for the northern Schofield dam was assigned a horizontal hydraulic conductivity of 1.2 ft/d.

The bottom of the projected Anahulu valley-fill barrier was estimated to be above the water table at the inland cells used to represent the barrier. Thus, in the model, ground water at the inland extent of the Waialua area was initially allowed to flow into the Kawailoa area without being affected by the valley-fill barrier. Simulations using this configuration did not produce the desired head drop across the barrier. Thus, in addition to lowering the tops of grid cells representing the valley-fill barrier, the horizontal hydraulic conductivity of the Anahulu valley-fill barrier cells, including those cells which extend to the northern Schofield dam, was reduced. The effect of the barrier was tested using horizontal hydraulic-conductivity values of 1, 10, 100, and 1,000 ft/d. Horizontal hydraulic-conductivity values of 1,500; 5,000; and 10,000 ft/d were used for the Koolau aquifer in the Kawailoa ground-water area. The vertical hydraulic conductivity value of the caprock in the Kawailoa area was varied from 0.2 to 100 ft/d.

All simulations using an aquifer horizontal hydraulic conductivity value of 1,500 ft/d produced hydraulic gradients that are steeper than expected for the Kawailoa area. Thus, all simulations using an aquifer horizontal hydraulic conductivity value of 1,500 ft/d were rejected. The remaining combinations of hydraulic-conductivity values that produced reasonable results were retained for further analysis using the complete central Oahu flow-system grid. Final hydraulic-conductivity values were estimated using the complete central Oahu flow-system grid to ensure that proper water levels could be simulated in both the Kawailoa and Waialua areas. The number of potential combinations of hydraulic-conductivity values requiring consideration in the final model was greatly reduced, however, by isolating the Kawailoa ground-water area from the other parts of the main grid.

Kaimuki, Beretania, and Kalihi Ground-Water Areas

The part of the main model grid containing the Kaimuki, Beretania, and Kalihi ground-water areas (fig. 49) was isolated in a manner similar to that done for the Kawailoa area. A series of simulations was run to determine how to represent the valley-fill barriers in the model and to establish initial estimates for the caprock vertical hydraulic conductivity and aquifer horizontal hydraulic conductivity. The Moanalua area was not included in this analysis because the Halawa valley-fill barrier is assumed to be a less effective barrier than the valley-fill barriers to the east. North Halawa Stream valley is in a more youthful stage of dissection than the larger Honolulu valleys to the east and was thus considered separately. For all three isolated Honolulu areas, a single value for aquifer horizontal hydraulic conductivity was used, and a single value for caprock vertical hydraulic conductivity was used. Flow from the Kalihi area to the Moanalua area was simulated by maintaining specified-head cells on the Moanalua (western) side of the Kalihi valley-fill barrier. The specified head values ranged from 23 ft near the coast to 29 ft at the inland extent of the Moanalua area. The specified-head cells for the Moanalua ground-water area were assigned a horizontal hydraulic conductivity value equal to the value assigned to the Kaimuki, Beretania, and Kalihi ground-water areas.

The valley-fill barriers were initially modeled as partially penetrating barriers by lowering the tops of grid cells used to represent the barriers. In this way, the valley-fill material and associated weathered zone were not simulated, only the underlying aquifer was represented. In the model, the Nuuanu and Kalihi valley-fill barriers do not penetrate the aquifer at the edge of the rift zone of the Koolau Volcano, but the Manoa valley-fill barrier was extended to the edge of the rift zone because dikes and high-level water do exist at the head of the valley. Simulation of flow in the rift zone was beyond the scope of the study. Thus, cells at the head of Manoa Stream valley were inactivated. Recharge in these cells was input to the adjacent, downgradient cells of the grid.

As with the Kawailoa area, little success was obtained with model runs using partially penetrating barriers that do not remain effective toward the heads of the valleys. Thus, in addition to reducing the cell thicknesses, the horizontal hydraulic conductivity of the valley-fill barrier cells, including those cells which extend to the margin of the Koolau rift zone, was reduced. A limited series of runs was made to bracket the aquifer, caprock, and valley-fill barrier hydraulic conductivity values. All combinations using horizontal hydraulic-conductivity values of 1,500 and 4,500 ft/d for the aquifer, horizontal hydraulic-conductivity values of 1, 10, and 100 ft/d for the valley-fill barriers, and vertical hydraulic-conductivity values of 0.01, 0.05, 0.1, and 0.5 ft/d for the caprock, were tested. Final hydraulic-conductivity values for the Kaimuki, Beretania, and Kalihi areas were estimated using the entire central Oahu flow-system grid as described in the next section. This was necessary because it was desired to maintain a common aquifer horizontal hydraulic conductivity value and a common caprock vertical hydraulic conductivity value for the Kaimuki, Beretania, Kalihi, and Moanalua ground-water areas of Honolulu.

Final Estimation of Hydraulic Conductivity

Final freshwater hydraulic-conductivity values established by trial and error are given in table 9. For the final model, the hydraulic-conductivity values previously established for the Mokuleia and Ewa areas were retained. The offshore configuration of the Waianae confining unit in northern Oahu was adjusted slightly for the final model by extending the barrier to the edge of the model grid. This offshore adjustment only affects model results if saltwater flow is important, and thus the overall results previously described for the Mokuleia ground-water area simulations remain unchanged.

Although the western end of the southern Schofield ground-water dam may have different

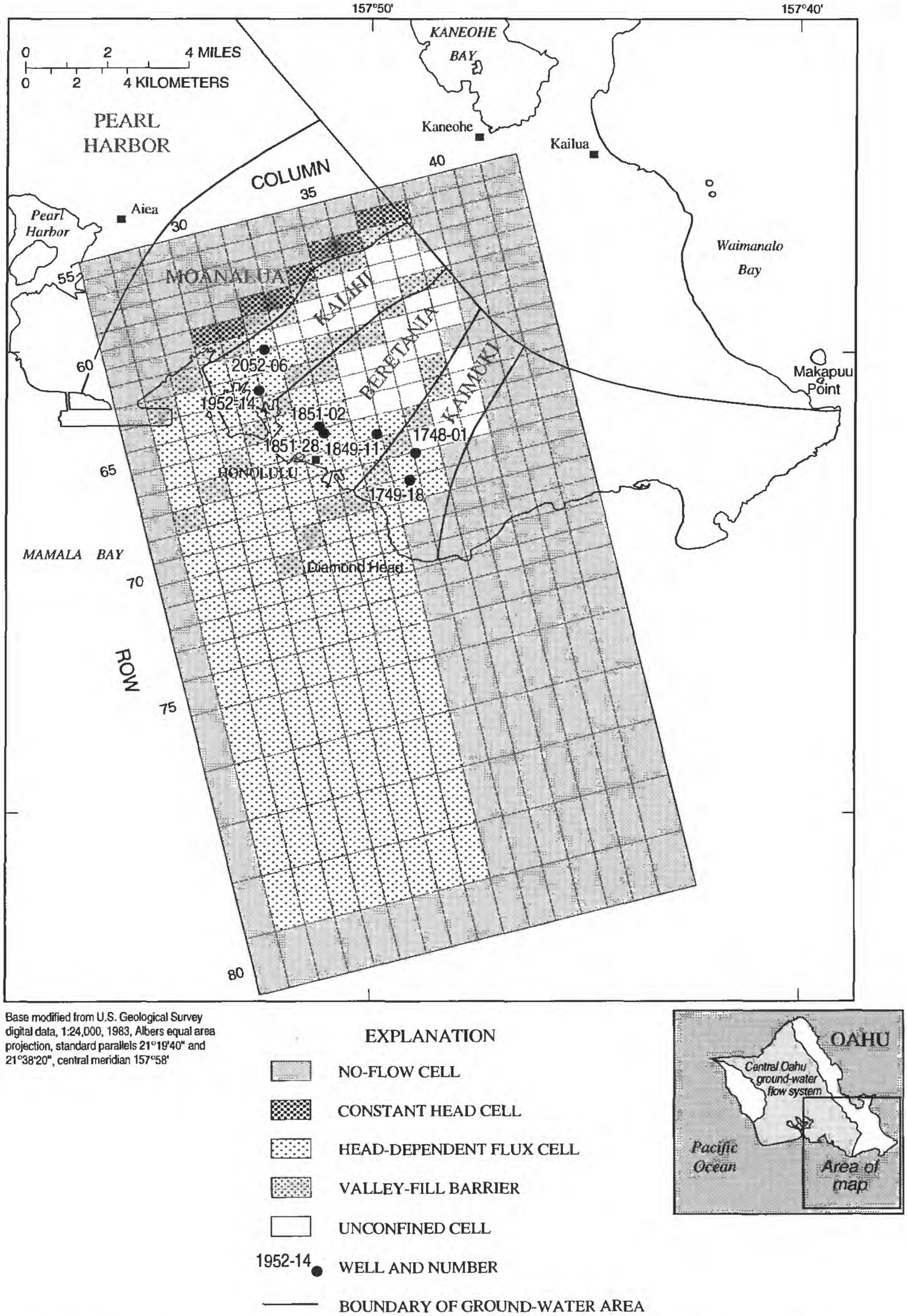


Figure 49. Model grid for the Kalihi, Beretania, and Kaimuki ground-water areas of the central Oahu ground-water flow system, Hawaii.

hydraulic characteristics than the eastern end of the dam, no evidence exists to quantify any variation in hydraulic conductivity. Thus, the horizontal hydraulic conductivity of the southern dam established during simulation of the Ewa area was used for the entire length of the dam extending eastward to the Koolau rift zone. Having established the horizontal hydraulic conductivity of the southern dam, the horizontal hydraulic conductivity of the northern dam was readily estimated from simulations because a head of about 279 ft must be maintained in the Schofield ground-water area and discharge in excess of withdrawals from this area is assumed to flow entirely through the two dams. The final horizontal hydraulic-conductivity values used for the southern and northern ground-water dams were 0.5 and 1.2 ft/d, respectively. These horizontal hydraulic-conductivity values correspond to leakance values of about 0.0002 per day for both the northern and southern dams. The dam leakance is computed by dividing the horizontal hydraulic conductivity by the assumed width of the dam.

The valley-fill barriers were modeled by lowering the tops of grid cells used to represent the barriers and reducing the horizontal hydraulic conductivity of the valley-fill barrier cells. With the exception of Halawa valley-fill barrier, all valley-fill barriers were extended headward to the inland extent of the ground-water areas being separated. For the Waialua and Kawailoa areas, a single horizontal hydraulic-conductivity value was used for the aquifer; the caprock vertical hydraulic conductivity, however, was allowed to differ between areas. For the Kaimuki, Beretania, Kalihi, and Moanalua areas of Honolulu, a single value for aquifer horizontal hydraulic conductivity was used, and a single value for caprock vertical hydraulic conductivity was used. In all ground-water areas, aquifer horizontal hydraulic conductivity was initially assumed to be homogeneous and isotropic. However, use of anisotropic conditions for the Pearl Harbor area improved model results.

In the Pearl Harbor area, simulation results were improved by using horizontal hydraulic-conductivity values of 4,500 ft/d in the direction of the short side of the grid (roughly east-west) and 1,500 ft/d in the orthogonal direction. A higher hydraulic conductivity in the east-west direction reduced the hydraulic gradient along the shore of Pearl Harbor from East Loch to West Loch.

In the model the horizontal hydraulic conductivity of the Waianae aquifer remains constant in northern and southern Oahu, but the horizontal hydraulic conductivity of the Koolau aquifer varies considerably from north to south. In northern Oahu, horizontal hydraulic conductivity of the Koolau aquifer is estimated to be 7,500 ft/d, whereas for southern Oahu horizontal hydraulic conductivity is between 1,500 and 4,500 ft/d. The value of 7,500 ft/d was necessary to maintain proper hydraulic gradients in the Waialua and Kawailoa areas. The lower horizontal hydraulic-conductivity value used for the southern part of the Koolau aquifer may be related to weathering. From a geomorphic standpoint, northern Oahu is in a more youthful stage of dissection than the Honolulu area of southern Oahu. Thus, the lavas of northern Oahu may be less weathered at depth than the lavas of southern Oahu. Palmer (1955) suggests that the northern Oahu lavas are from a younger episode of eruptions than the lavas of the Honolulu area, but no age dates are available to confirm this hypothesis.

Model-Calculated Water Levels

Model-calculated water levels are in general agreement with measured water levels (figs. 50, 51). Model-calculated water levels at 23 of the 40 usable sites listed in table 5 are within 1 ft of the target values. Considering 40 of the 42 sites listed in table 5, the average, average-absolute, and root-mean-square of the differences between measured and model-calculated water levels were 0.75 ft, 1.20 ft, and 1.64 ft, respectively. Two of the sites, wells 2703-01 and 2103-02, were not considered in computing the model errors. (At well 2703-01, water levels were measured with an air line and are not considered reliable. Well 2103-02 is in the Ewa ground-water area. However, in the model well 2103-02 lies in a cell representing the Waianae confining unit.) The largest model errors are in the vicinity of the Pearl Harbor springs where vertical hydraulic gradients are likely large. A comparison between measured and model-calculated freshwater-saltwater interface locations cannot be made because of a lack of transition-zone data from the 1950's.

It should be emphasized that different hydraulic-conductivity distributions can be used to produce equally acceptable model-calculated water levels if some of the constraints adopted for this study are relaxed. These model constraints include: (1) the horizontal hydraulic conductivity of each Schofield dam was assumed to be constant along the entire length of the dam, (2) the same isotropic aquifer horizontal

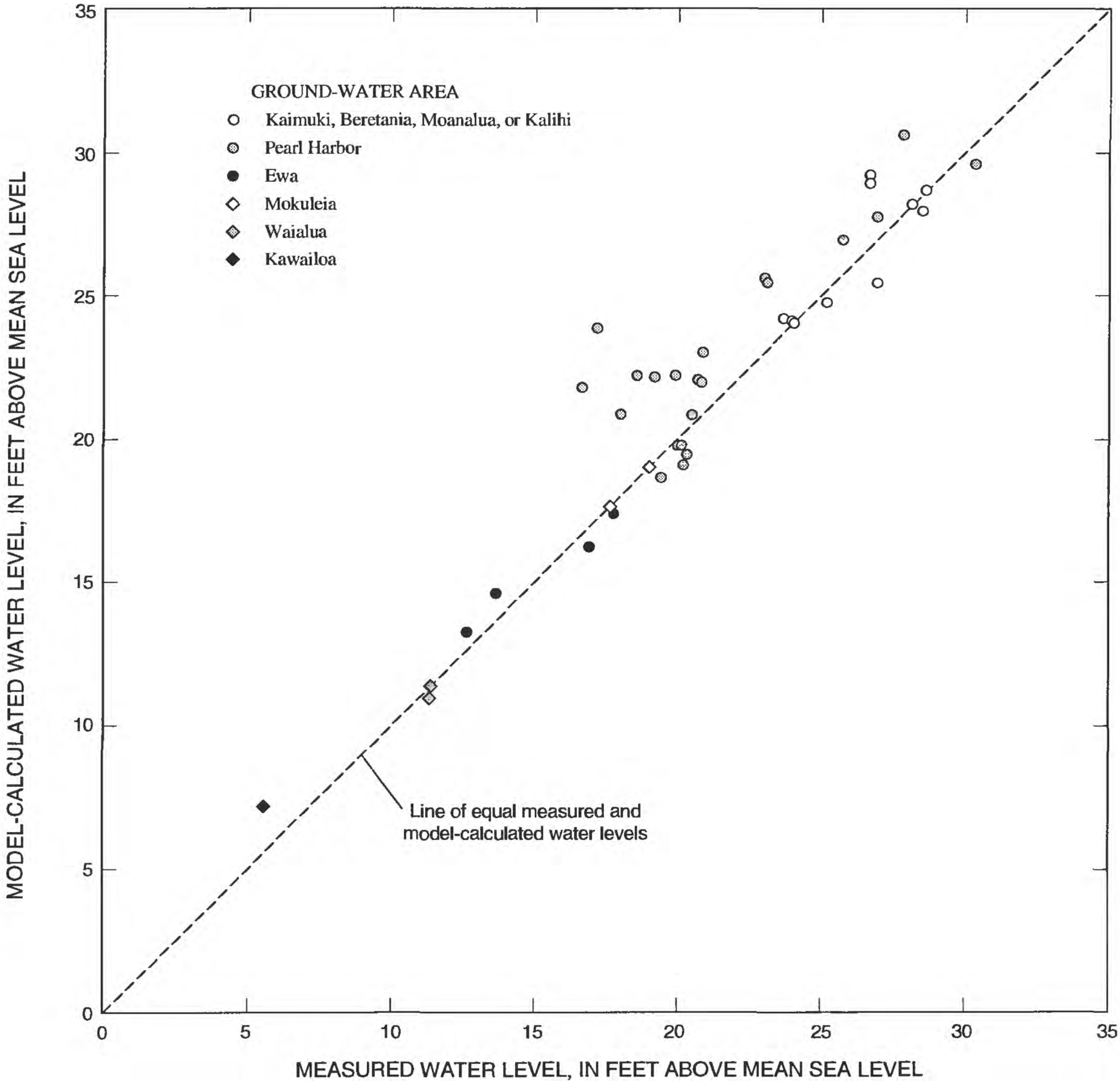
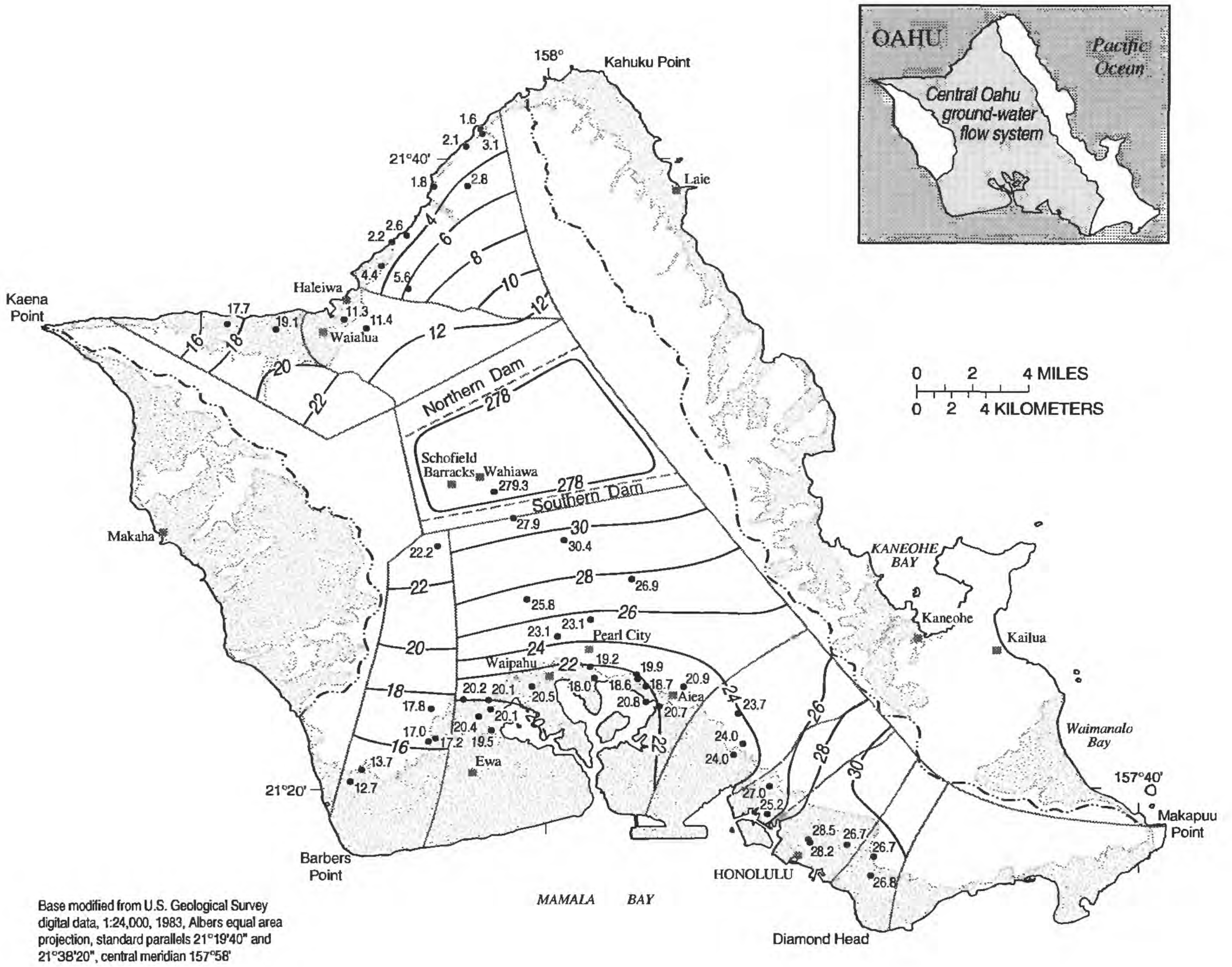


Figure 50. Scattergram of model-calculated steady-state and measured water levels at selected wells used in the 1950's model for the central Oahu ground-water flow system, Hawaii.



EXPLANATION

—22— LINE OF EQUAL MODEL-CALCULATED 1950's WATER LEVEL--Interval, in feet, is variable. Datum is mean sea level

30.4 • WELL AND MEASURED WATER LEVEL, IN FEET ABOVE MEAN SEA LEVEL

SEDIMENTARY DEPOSITS (CAPROCK)

BOUNDARY OF GROUND-WATER AREA

TOPOGRAPHIC DIVIDE

Figure 51. Model-calculated and measured water levels in the central Oahu ground-water flow system for average 1950's conditions, Hawaii.

hydraulic-conductivity value was used for the Waialua and Kawailoa ground-water areas, (3) the same isotropic aquifer horizontal hydraulic-conductivity value was used for the Moanalua, Kalihi, Beretania, and Kaimuki ground-water areas, (4) the same caprock vertical hydraulic-conductivity value was used for the Moanalua, Kalihi, Beretania, and Kaimuki ground-water areas, (5) in general, recharge in the rift zones was assumed to enter the modeled area by flowing perpendicular to the rift-zone boundary, (6) in general, the crests of the Koolau and Waianae Ranges were assumed to coincide with ground-water divides, and (7) the central Oahu ground-water flow system was assumed to be separated from the other flow systems of the island by impermeable barriers. The assumptions adopted for this study were designed to produce the simplest model capable of reproducing measured 1950's water levels in the central Oahu ground-water flow system.

Model-Calculated Ground-Water Discharge

The estimated discharges through the southern and northern Schofield dams are 90.1 and 55.2 Mgal/d, respectively (table 7). Thus, about 62 percent of the discharge from the Schofield ground-water area flows southward and the remaining 38 percent of the discharge from Schofield flows northward. Although the contribution of recharge from infiltration of rainfall and irrigation water directly on top of the southern and northern Schofield ground-water dams was included in the model, the distribution of natural discharge from the Schofield ground-water area was estimated exclusive of the recharge on top of the dams. If infiltration directly on top of the southern and northern dams is included in the computation of the distribution of discharge from the Schofield ground-water area, it is estimated that, for 1950's conditions, 104.1 Mgal/d discharges to the south and 79.4 Mgal/d discharges to the north.

Under natural conditions, in the absence of human activity, a ground-water system will typically approach a steady-state condition with the natural discharge rate equal to the average recharge rate. If water is withdrawn from the aquifer at a constant rate, the ground-water system will eventually reach a new steady-state condition with lower heads and a reduced natural discharge rate equal to the average recharge rate minus the withdrawal rate. This latter situation is reflected in the steady-state water-budget summary of table 7. Natural discharge from the central Oahu ground-water flow system is in the form of springs and flow through the caprock near the coast. Model results indicate that the average 1950's coastal discharge from northern and southern Oahu is 383.6 Mgal/d. For steady-state conditions, this natural discharge rate is equal to the recharge rate of 623.4 Mgal/d minus the withdrawal rate of 239.8 Mgal/d.

EFFECTS OF PROPOSED WITHDRAWALS

To determine the long-term effects of future withdrawals on ground-water levels in the central Oahu flow system, additional steady-state simulations were run using the final hydraulic-conductivity values (table 9) estimated from 1950's conditions. The water level-discharge relation for Kalauao Springs, however, was updated to reflect a change in conditions at the site since the mid 1960's. At Kalauao Springs, the water level-discharge relation for the period 1928–65 differs from the water level-discharge relation for the period 1967–90 (fig. 23).

A base-case scenario was simulated in which future recharge was conservatively estimated by assuming no agricultural activities within the study area and future withdrawals were assumed to be equal to the allocated withdrawal rates as of September 1, 1995. This base-case scenario was used as a reference for computing water-level drawdown from six different proposed withdrawal scenarios.

Simulation of Base-Case Future Conditions

For the base-case simulation, recharge from irrigation return water was assumed to be zero. Recharge was computed using the regression equations developed by P.J. Shade (USGS, written commun., 1992) in conjunction with long-term average rainfall (Giambelluca and others, 1986) and a non-agricultural land-use distribution. The regression equation for the eastern part of the Schofield ground-water area was modified to reflect a high runoff-to rainfall ratio of 0.51. In addition, about 28.0 Mgal/d recharge occurring between the crests of the Koolau and Waianae Ranges within the central Oahu flow system was assumed to discharge from the central Oahu flow system without entering any of the modeled ground-water areas (see previous discussion in the "Recharge" subsection of the "Model Construction" section of this report). The grid cells (table 8) that do not

Table 12. Future recharge without agriculture and 1995-allocated pumping rates for the volcanic aquifers of the central Oahu ground-water flow system, Hawaii

[Pumpage data from the State of Hawaii Commission on Water Resource Management; Mgal/d, million gallons per day]

Area	Recharge (Mgal/d)	1995-allocated pumpage (Mgal/d)
Northern Oahu, including Schofield northern dam	108.4	57.1
Schofield ground-water area	142.1	16.8
Southern Oahu, including Schofield southern dam	211.6	229.9
Total	462.1	303.8

contribute recharge to the modeled part of the central Oahu flow system are for areas near (1) the southern part of the Waianae Range, (2) the northern part of the Koolau Range, and (3) the windward, northeastern valleys.

The distribution of recharge by grid cell is shown in figure 52. Total recharge within the modeled area was estimated to be 462.1 Mgal/d. For comparison, total recharge during the 1950's was estimated to be 623.4 Mgal/d.The reduction in recharge from 1950's conditions is because of the elimination of agricultural activities and associated irrigation return water for the conservative future recharge scenario. Given the uncertain future of agriculture on Oahu, the conservative recharge scenario adopted for this study represents a plausible recharge condition.

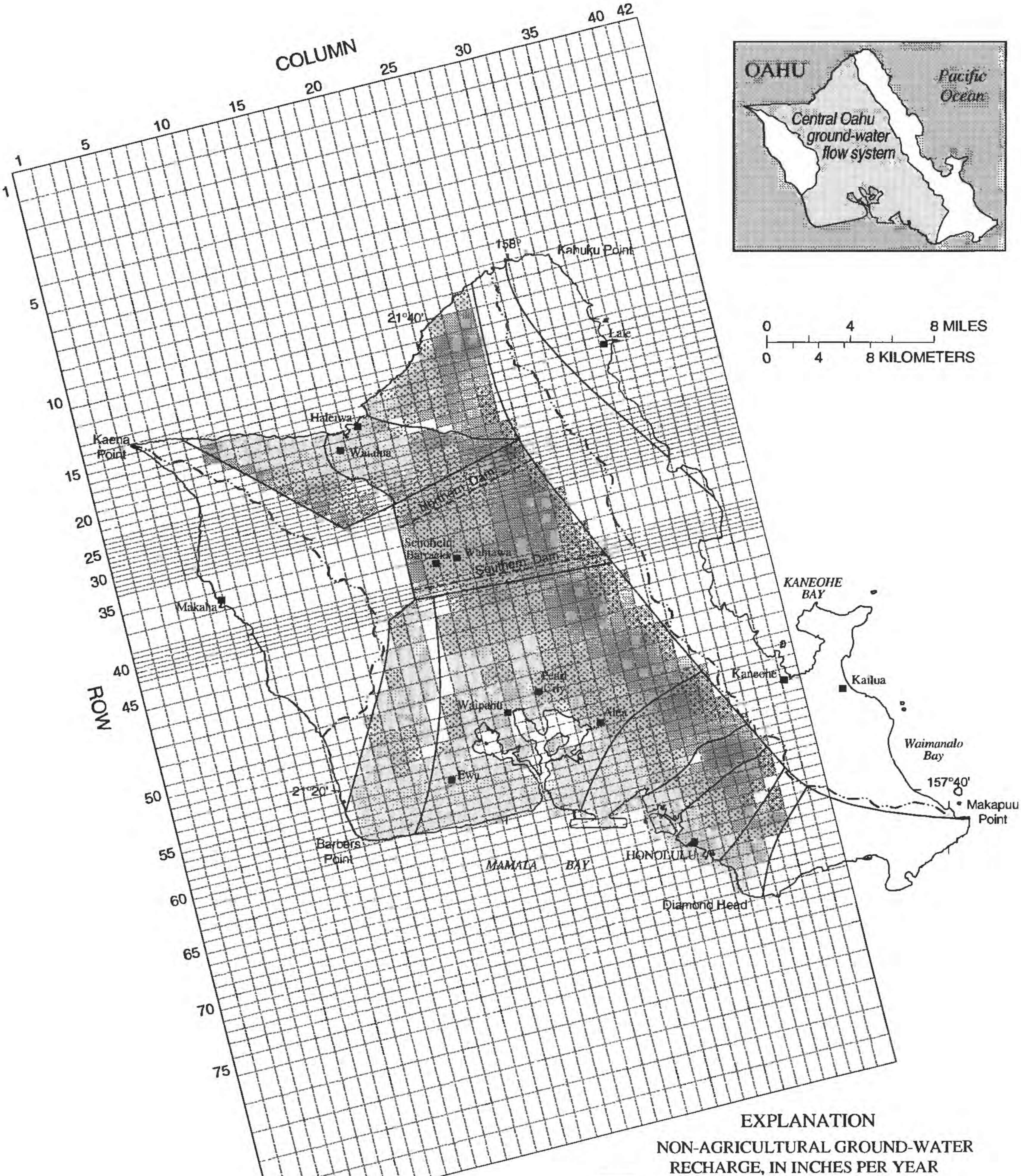
The allocated withdrawal rates as of September 1, 1995 were used for the base-case simulation. The pumping allocations were provided by the State of Hawaii Commission on Water Resource Management (W.R. Hardy, oral commun., 1995). The distribution of 1995-allocated pumpage by grid cell is shown in figure 53. Total 1995-allocated pumpage from the volcanic aquifers of the central Oahu flow system is 303.8 Mgal/d. For comparison, the average reported pumpage from the volcanic aquifers during the 12-month period prior to July 1995 was about 198 Mgal/d (Neal Fujii, Commission on Water Resource Management, written commun., 1995).

A summary of the distribution of withdrawals and recharge in the modeled area for the base-case simulation is shown in table 12. The combination of recharge and withdrawal conditions simulated in the base case represents an extreme condition, because the future recharge scenario does not include any irrigation return water from agricultural activities but the 1995-allocated pumpage includes 108 Mgal/d originally allocated to two sugar companies which ceased operations in the mid 1990's.

Results from the base-case simulation indicate that model-calculated steady-state water levels in all ground-water areas are lower than measured water levels from 1995 (fig. 54). In the Schofield ground-water area, the model-calculated water level for the base-case simulation is about 246 ft, which is lower than the measured water level in 1995 of 275 ft. In the other ground-water areas, model-calculated water levels are several feet lower than measured water levels from 1994 and 1995 (table 13).

For the base-case simulation, the model-calculated freshwater-saltwater interface rises above the bottoms of the deeper wells in the study area. Total model-calculated saltwater withdrawal from affected wells is about 15.7 Mgal/d (table 14), which leaves 288.1 Mgal/d total withdrawal from above the model-calculated interface position (table 15). Of the 15.7 Mgal/d withdrawn from below the model-calculated interface position, about 4.9 Mgal/d is from the northern Oahu ground-water areas. Affected wells in the Mokuleia and Waialua areas (fig. 54) are deep irrigation wells which were drilled around the turn of the century. The single affected well in the Kawailoa area is a privately owned well near the coast.

Model results from the base-case simulation indicate that discharge from the Schofield area is 48.3 Mgal/d to the north and 77.0 Mgal/d to the south (table 15). Although the contribution of recharge from infiltration of rainfall directly on top of the southern and northern Schofield ground-water dams was included in the base-case simulation, the distribution of natural discharge from the Schofield ground-water area was estimated exclusive of the recharge on top of the dams. Using the conservative future recharge and 1995-allocated pumping distributions, 39 percent of the discharge



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 21°19'40" and 21°38'20", central meridian 157°58'

EXPLANATION

NON-AGRICULTURAL GROUND-WATER RECHARGE, IN INCHES PER YEAR

- 0
- Greater than 0 and less than or equal to 10
- Greater than 10 and less than or equal to 25
- Greater than 25 and less than or equal to 75
- Greater than 75

—— BOUNDARY OF GROUND-WATER AREA

-··-··- TOPOGRAPHIC DIVIDE

Figure 52. Distribution of future recharge without agriculture used in the model grid for the central Oahu ground-water flow system, Hawaii.

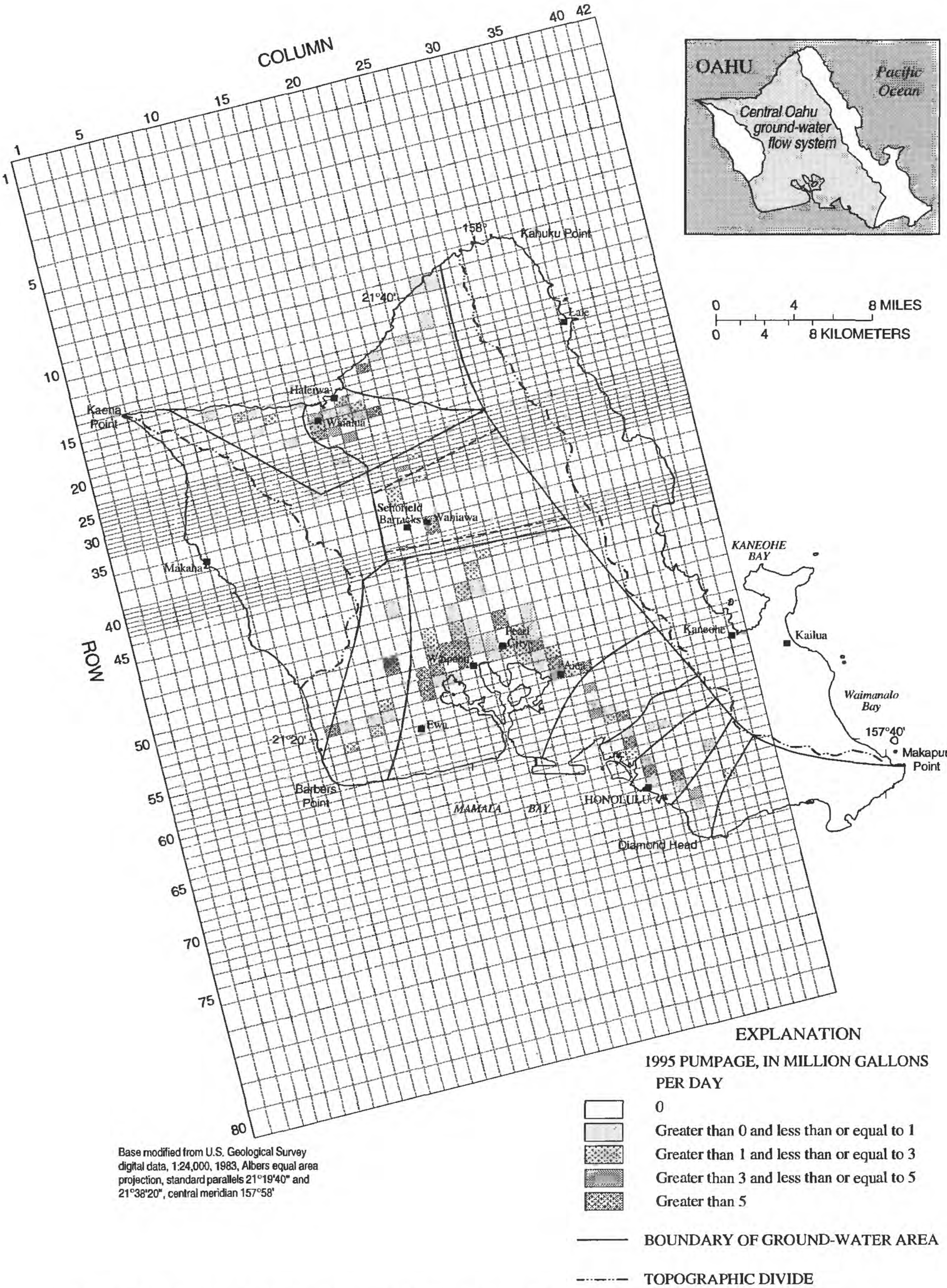
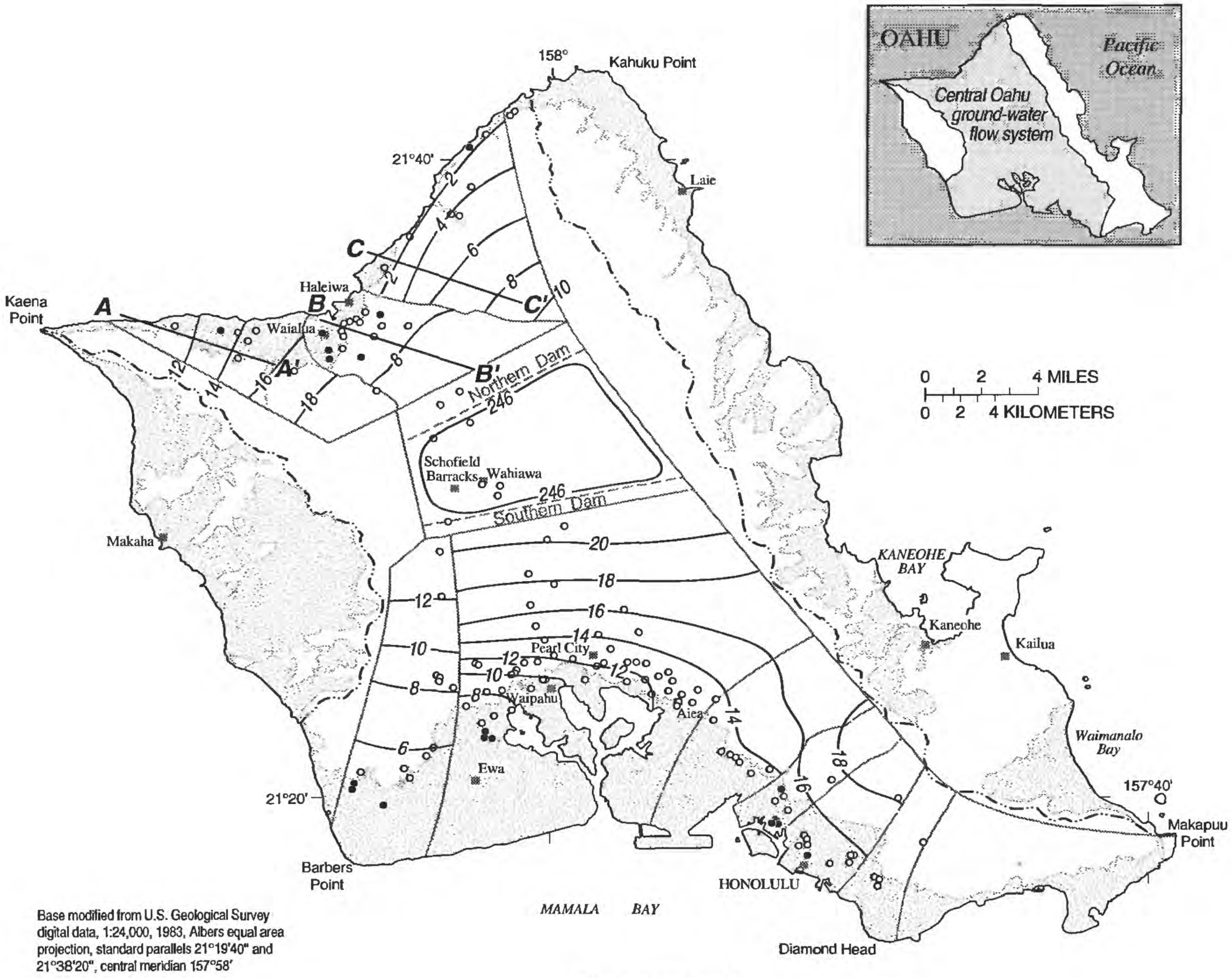


Figure 53. Distribution of 1995-allocated pumping rates used in the model grid for the central Oahu ground-water flow system, Hawaii.



EXPLANATION

—22— LINE OF EQUAL MODEL-CALCULATED WATER LEVEL
Interval, in feet, is variable. Datum is mean sea level

○ PUMPED WELL WITH 1995 ALLOCATION

● PUMPED WELL WITH 1995 ALLOCATION--Extends below model-calculated interface

SEDIMENTARY DEPOSITS (CAPROCK)

A——A' LINE OF SECTION

BOUNDARY OF GROUND-WATER AREA

TOPOGRAPHIC DIVIDE

Figure 54. Model-calculated water-level contours in the central Oahu ground-water flow system assuming a non-agricultural recharge scenario and pumpage at the 1995-allocated rates, Hawaii.

Table 13. Water levels at selected wells in the central Oahu ground-water flow system during the 1990's, Hawaii

Ground-water area	Well no.	Measured water level (feet above mean sea level)	Date measured	Reference for measured water level	Model-calculated water level (feet above meen sea level) for 1995-allocated pumpage
Mokuleia	3205-02	22.23	Apr. 27, 1995	unpub. data USGS well files	18.5
Mokuleia	3411-01	16.72	Apr., 28, 1995	unpub. data USGS well files	12.0
Waialua	3204-01	11.93	Sept. 1, 1995	unpub. data USGS well files	8.6
Waialua	3406-13	11.20	May 31, 1995	unpub. data USGS well files	6.7
Waialua	3505-26	10.06	May 30, 1995	unpub. data USGS well files	7.6
Kawailoa	3503-01	7.18	Apr. 7, 1995	unpub. data USGS well files	7.1
Kawailoa	3505-25	4.41	May 30, 1995	unpub. data USGS well files	3.8
Kawailoa	3605-25	4.14	Apr. 10, 1995	unpub. data USGS well files	2.6
Schofield	2901-07	275.25	Sept. 1, 1994	Matsuoka and others, 1995	246.1
Ewa	2103-01	14.86	Sept. 23, 1994	Matsuoka and others, 1995	5.8
Pearl Harbor	2101-03	17.89	Sept. 19, 1994	Matsuoka and others, 1995	6.0
Pearl Harbor	2256-10	15.96	Sept. 30, 1994	Matsuoka and others, 1995	12.0
Pearl Harbor	2600-04	20.66	Sept. 8, 1994	Matsuoka and others, 1995	17.9
Moanalua	2153-05	19.08	Sept. 30, 1994	Matsuoka and others, 1995	13.4

Table 14. Wells in the central Oahu ground-water flow system that extract saltwater on the basis of simulation of 1995-allocated pumping rates and non-agricultural recharge scenario, Hawaii

Ground-water area	Cell (row, column) (fig. 36)	Well	Altitude of well bottom (feet)	Total simulated pumping rate (million gallons per day)	Model-calculated saltwater extraction rate (million gallons per day)
Mokuleia	17, 11	3411-04, -06 to -11, -13	-507	2.55	0.022
Waialua	19, 16	3407-07 to -10, -13, -16, -17, -20, -21	-236	4.63	0.32
Waialua	19, 19	3505-01 to -20	-315	1.55	0.93
Waialua	20, 16	3407-04 to -06, -14, -15	-288	2.33	0.73
Waialua	21, 16	3307-01 to -14	-292	8.82	2.2
Waialua	22, 18	3306-01 to -12	-330	5.00	0.72
Kawailoa	10, 25	4002-06	-77	0.005	0.005
Ewa	53, 12	2006-01 to -11	-120	5.71	1.7
Ewa	55, 13	1905-04	-320	1.00	1.0
Pearl Harbor	52, 19	2102-02, -04 to -22; 2202-15 to -20	-429	9.53	4.3
Kalihi	63, 31	1952-14	-678	2.50	2.5
Kalihi	63, 32	1952-11 to -13, -15, -20, -21	-574	2.27	0.93
Beretania	65, 33	1851-12, -13, -24, -25, -31 to -35, -67; 1851-54, -73	-575	7.27	0.20
Beretania	66, 33	1851-58	-714	0.10	0.10

Table 15. Model-calculated water-budget components for the central Oahu, Hawaii, ground-water flow system using future recharge without agriculture and 1995-allocated pumping rates

[Mgal/d, million gallons per day]

	Northern Oahu, including northern Schofield dam	Schofield ground-water area	Southern Oahu, including southern Schofield dam	Total
Recharge (Mgal/d)	108.4	142.1	211.6	462.1
[1]Pumpage (Mgal/d)	52.1	16.8	219.2	288.1
Natural discharge (Mgal/d)	104.6	48.3 to north 77.0 to south	69.4	

[1]Includes only pumpage from above the model-calculated interface

from Schofield is to the north and the remaining 61 percent is to the south. This distribution of Schofield discharge is similar to the distribution, estimated for the 1950's period, of 38 percent to the north and 62 percent to the south.

Although the conditions represented in the base case are extreme, the results of the simulation are nevertheless informative and relevant. Model results indicate that long-term pumping at the 1995-allocated rates may cause saltwater contamination problems to occur at many wells within the central Oahu ground-water flow system. In addition to the wells at which the model-calculated freshwater-saltwater interface rises above the bottom of the well, increases in salinity may occur at wells in areas where the model indicates no significant problem with upconing. The model developed for this study is based on a sharp interface approach and therefore cannot be used to predict the distribution of salinity within the freshwater-saltwater transition zone or the quality of water pumped from a given well.

Simulation of the Hydrologic Effects of Additional Withdrawals

The Honolulu Board of Water Supply is currently attempting to develop additional ground water on Oahu to meet expected future demands and is considering developing an additional 10 Mgal/d from the northern Oahu ground-water areas. On the basis of the existing sustainable yield estimates for northern Oahu (appendix E), additional ground water may be available in the Mokuleia and Kawailoa areas. The regional hydrologic effects of additional ground-water development in northern Oahu were assessed in six scenarios (table 16) in which 10 Mgal/d was added to the 1995-allocated pumping rates represented in the base case.

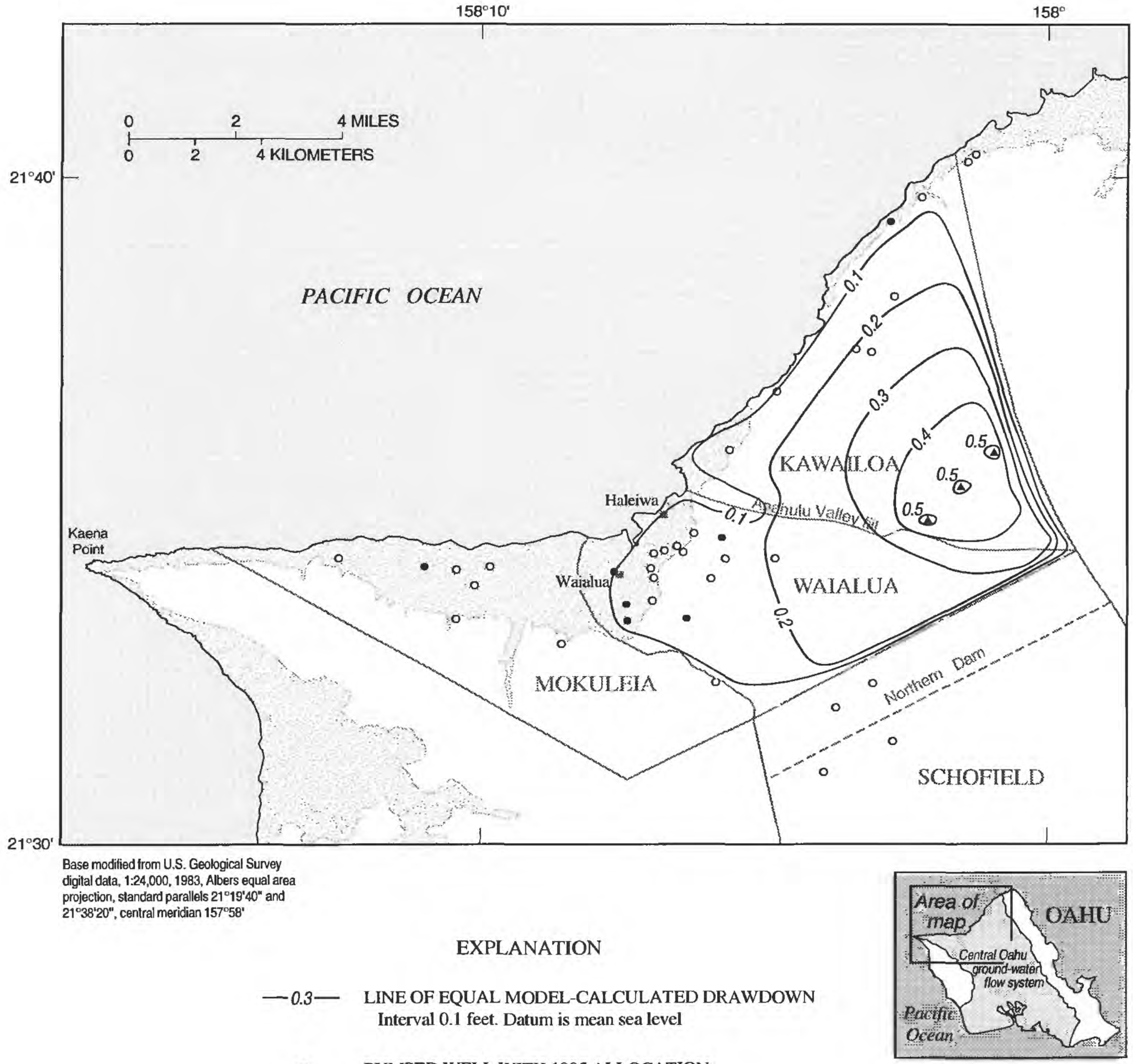
Table 16. Distribution of 10 million gallons per day pumping in northern Oahu, Hawaii, beyond the 1995-allocated pumping rates

	Ground-water area	Cell (row, column) (fig. 36)	Pumping rate (million gallons per day)
Scenario 1	Kawailoa	18, 26	3.33
	Kawailoa	19, 25	3.33
	Kawailoa	20, 24	3.33
Scenario 2	Waialua	22, 23	3.33
	Waialua	24, 21	3.33
	Waialua	25, 19	3.33
Scenario 3	Kawailoa	18, 26	2.5
	Kawailoa	20, 24	2.5
	Waialua	22, 23	2.5
	Waialua	24, 21	2.5
Scenario 4	Mokuleia	20, 13	2.5
	Mokuleia	21, 14	2.5
	Waialua	22, 23	2.5
	Waialua	24, 21	2.5
Scenario 5	Kawailoa	18, 26	2
	Kawailoa	20, 24	2
	Waialua	22, 23	2
	Waialua	24, 21	2
	Mokuleia	20, 13	1
	Mokuleia	21, 14	1
Scenario 6	Kawailoa	17, 25	3.33
	Kawailoa	18, 24	3.33
	Kawailoa	19, 23	3.33

Scenario 1--10 Mgal/d from Upper Kawailoa

In scenario 1, the additional 10 Mgal/d pumpage was equally distributed to three cells of the model grid toward the inland extent of the Kawailoa area. The model-calculated drawdown, relative to the base-case simulation, is 0.4 to 0.5 ft in the Kawailoa area in the vicinity of the added pumping (fig. 55). The model-calculated cone of depression resulting from the additional pumping extends beyond the boundaries of the Kawailoa ground-water area. In the Waialua area, maximum model-calculated drawdown, relative to the base-case simulation, is about 0.3 ft near the Anahulu valley-fill barrier. Reduction of natural discharge caused by the additional pumping is manifested as drawdown of a few hundredths of a foot near the coast in the Kawailoa and Waialua areas. Model-calculated drawdown in the Schofield and Mokuleia ground-water areas does not exceed 0.01 ft. In all scenarios, model-calculated drawdown south of the Schofield area does not exceed 0.001 ft.

Model results indicate that in the Kawailoa area, the freshwater-saltwater interface rises about 16 to 20 ft, relative to the base-case simulation, in response to the additional pumping (fig. 56). In the Waialua area, the model-calculated interface position rises about 12 ft. Model results indicate that no additional wells in the central Oahu flow system withdraw water from the saltwater zone as a result of the 10 Mgal/d pumpage from the upper Kawailoa area. However, for wells which already withdraw saltwater (table 14), increased contri-



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 21°19'40" and 21°38'20", central meridian 157°58'

EXPLANATION

—0.3— LINE OF EQUAL MODEL-CALCULATED DRAWDOWN Interval 0.1 feet. Datum is mean sea level

o PUMPED WELL WITH 1995 ALLOCATION

• PUMPED WELL WITH 1995 ALLOCATION--Extends below model-calculated interface

▲ LOCATION OF SIMULATED ADDITIONAL PUMPING FOR SCENARIO 1

SEDIMENTARY DEPOSIT (CAPROCK)

BOUNDARY OF GROUND-WATER AREA

Figure 55. Model-calculated drawdown (relative to the base-case simulation with 1995-allocated pumping rates and no recharge from agriculture) caused by 10 million gallons per day additional pumpage in the upper Kawailoa ground-water area (scenario 1), Oahu, Hawaii.

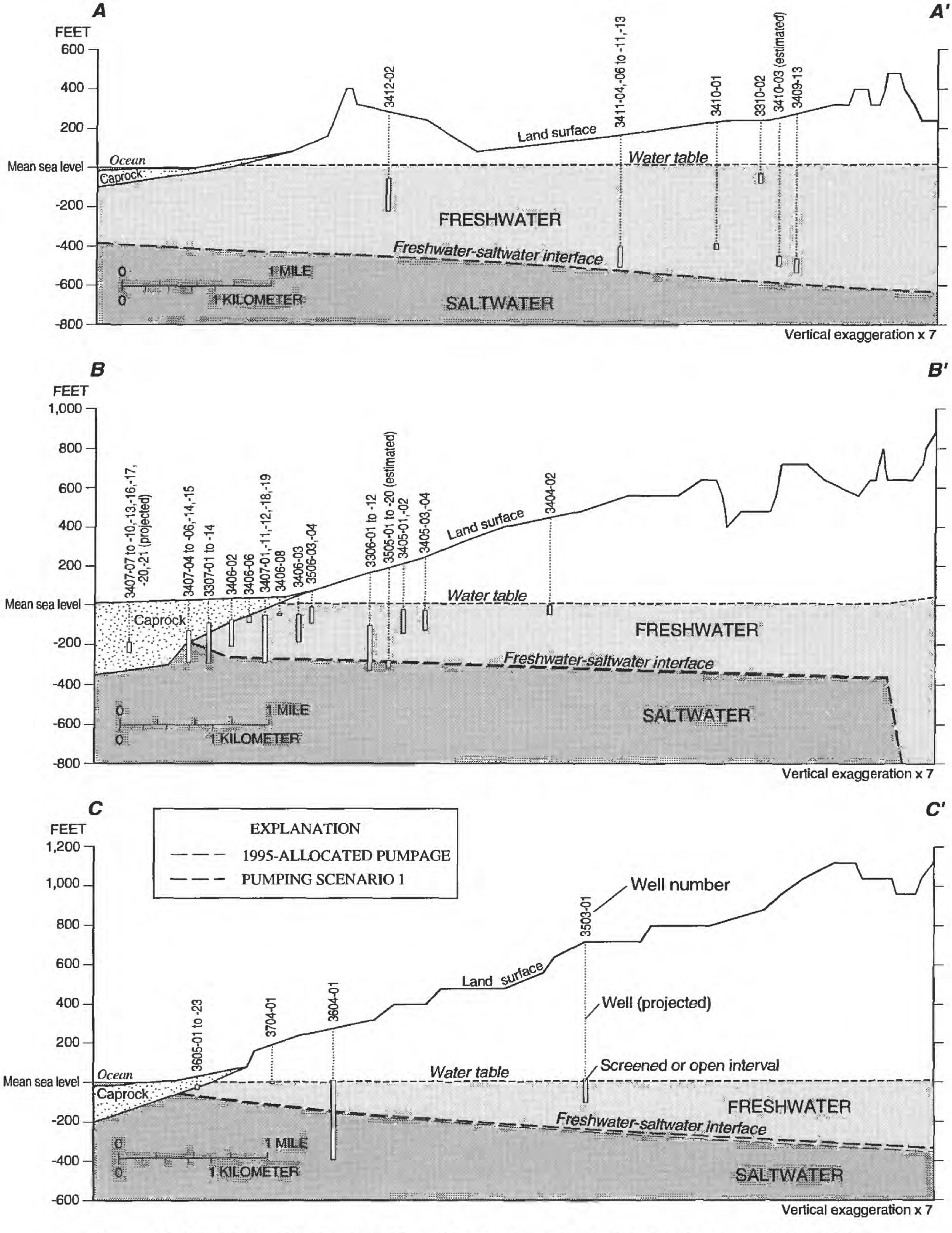


Figure 56. Model-calculated water table and freshwater-saltwater interface before and after adding 10 million gallons per day additional pumpage in the upper Kawailoa ground-water area (scenario 1) for sections in the, ***A-A'***, Mokuleia ground-water area; ***B-B'***, Waialua ground-water area; and ***C-C'***, Kawailoa ground-water area, Oahu, Hawaii (trace of sections shown in fig. 54).

Table 17. Model-calculated water-budget components for the central Oahu ground-water flow system using future recharge without agriculture, Hawaii
[Mgal/d, million gallons per day]

	Northern Oahu, including northern Schofield dam	Schofield ground-water area	Southern Oahu, including southern Schofield dam	Total
Recharge (Mgal/d)	108.4	142.1	211.6	462.1
Pumping scenario 1				
[1]Pumpage (Mgal/d)	60.8	16.8	219.2	296.8
Natural discharge (Mgal/d)	95.9	48.3 to north; 77.0 to south	69.4	
Pumping scenario 2				
[1]Pumpage (Mgal/d)	58.3	16.8	219.2	294.3
Natural discharge (Mgal/d)	98.4	48.3 to north; 77.0 to south	69.4	
Pumping scenario 3				
[1]Pumpage (Mgal/d)	59.7	16.8	219.2	295.7
Natural discharge (Mgal/d)	97.0	48.3 to north; 77.0 to south	69.4	
Pumping scenario 4				
[1]Pumpage (Mgal/d)	58.8	16.8	219.2	294.8
Natural discharge (Mgal/d)	97.9	48.3 to north; 77.0 to south	69.4	
Pumping scenario 5				
[1]Pumpage (Mgal/d)	59.6	16.8	219.2	295.6
Natural discharge (Mgal/d)	97.1	48.3 to north; 77.0 to south	69.4	
Pumping scenario 6				
[1]Pumpage (Mgal/d)	61.0	16.8	219.2	297.0
Natural discharge (Mgal/d)	95.7	48.3 to north; 77.0 to south	69.4	

[1] Includes only pumpage from above the model-calculated interface

butions from the saltwater zone are expected because of the interface rise. Model results indicate that total withdrawal from above the interface is 296.8 Mgal/d (table 17) and total withdrawal from below the interface is 17.0 Mgal/d. Of the 17.0 Mgal/d withdrawn from below the interface, 6.3 Mgal/d is from wells in northern Oahu.

Scenario 2--10 Mgal/d from Upper Waialua

In pumping scenario 2, the 10 Mgal/d additional pumpage was equally distributed to three cells of the model grid toward the inland extent of the Waialua area. The model-calculated drawdown, relative to the base-case simulation, is about 0.6 ft in the Waialua area in the vicinity of the added pumping (fig. 57). The model-calculated cone of depression resulting from the pumpage added to the 1995 allocations extends beyond the boundaries of the Waialua ground-water area. In the Kawailoa area, maximum drawdown is about 0.3 ft near the Anahulu valley-fill barrier. Model-calculated drawdown, relative to the base-case simulation, in the Mokuleia ground-water area is less than 0.01 ft, and model-calculated drawdown in the Schofield area does not exceed 0.02 ft.

Model results indicate that in the Kawailoa area, the freshwater-saltwater interface rises about 12 ft, relative to the base-case simulation, in response to the additional pumping (fig. 58). In the Waialua area, the model-calculated interface position rises about 24 ft. Model results indicate that no additional wells in the central Oahu flow system withdraw water from the saltwater zone as a result of the 10 Mgal/d additional pumpage. However, for wells which already withdraw saltwater (table 14), increased contributions from the saltwater zone are expected because of the interface rise. Model results indicate that total withdrawal from above the interface is 294.3 Mgal/d (table 17) and total withdrawal from below the interface is about 19.5 Mgal/d. Of the 19.5 Mgal/d withdrawn from below the interface, 8.8 Mgal/d is from wells in northern Oahu.

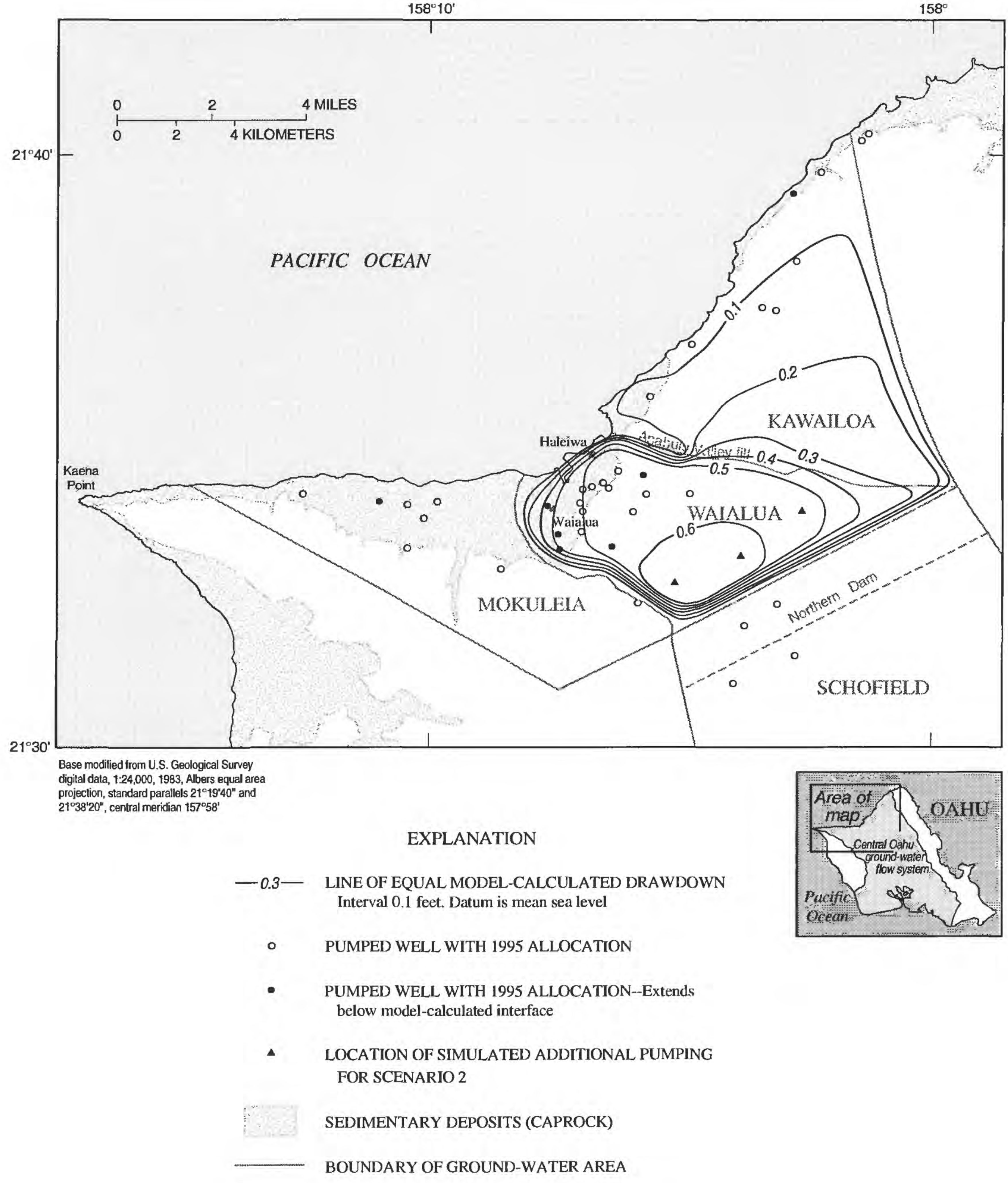


Figure 57. Model-calculated drawdown (relative to the base-case simulation with 1995-allocated pumping rates and no recharge from agriculture) caused by 10 million gallons per day additional pumpage in the upper Waialua ground-water area (scenario 2), Oahu, Hawaii.

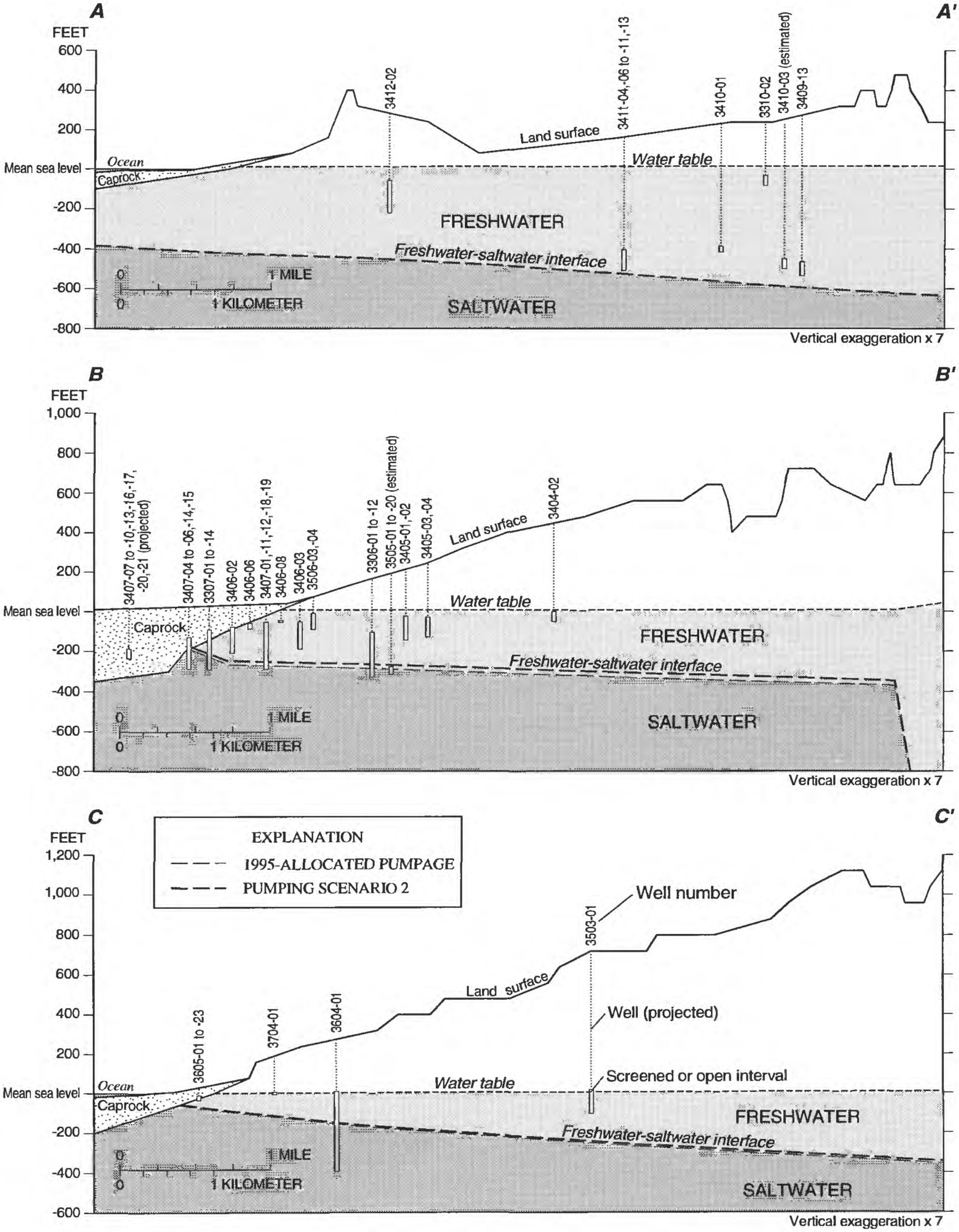


Figure 58. Model-calculated water table and freshwater-saltwater interface before and after adding 10 million gallons per day additional pumpage in the upper Waialua ground-water area (scenario 2) for sections in the, ***A-A'***, Mokuleia ground-water area; ***B-B'***, Waialua ground-water area; and ***C-C'***, Kawailoa ground-water area, Oahu, Hawaii (trace of sections shown in fig. 54).

Scenario 3--5 Mgal/d from Upper Waialua; 5 Mgal/d from Upper Kawailoa

In pumping scenario 3, the 10 Mgal/d additional pumpage was equally distributed to the Kawailoa and Waialua ground-water areas. Toward the inland extent of the Kawailoa area, 5 Mgal/d pumpage was equally distributed to two cells of the model grid. Similarly, toward the inland extent of the Waialua area, 5 Mgal/d pumpage was equally distributed to two cells. Maximum model-calculated drawdown, relative to the base-case simulation, in both ground-water areas is 0.3 to 0.4 ft in the vicinity of the added pumping (fig. 59). The cone of depression extends beyond the boundaries of the Waialua ground-water area. The model-calculated drawdown in the Mokuleia area is less than 0.01 ft, and drawdown in the Schofield area does not exceed 0.02 ft.

Model results indicate that in the Kawailoa and Waialua areas, the freshwater-saltwater interface rises about 12 to 16 ft, relative to the base-case simulation, in response to the additional pumping (fig. 60). In the Mokuleia area, there is no notable rise in the interface. Model results also indicate that no additional wells in the central Oahu flow system withdraw water from the saltwater zone as a result of the 10 Mgal/d pumpage from the upper Kawailoa and Waialua areas. However, for wells which already withdraw saltwater (table 14), increased contributions from the saltwater zone are expected because of the interface rise. Model results indicate that total withdrawal from above the interface is 295.7 Mgal/d (table 17) and total withdrawal from below the interface is about 18.1 Mgal/d. Of the 18.1 Mgal/d withdrawn from below the interface, 7.4 Mgal/d is from wells in northern Oahu.

Scenario 4--5 Mgal/d from Upper Waialua; 5 Mgal/d from Mokuleia

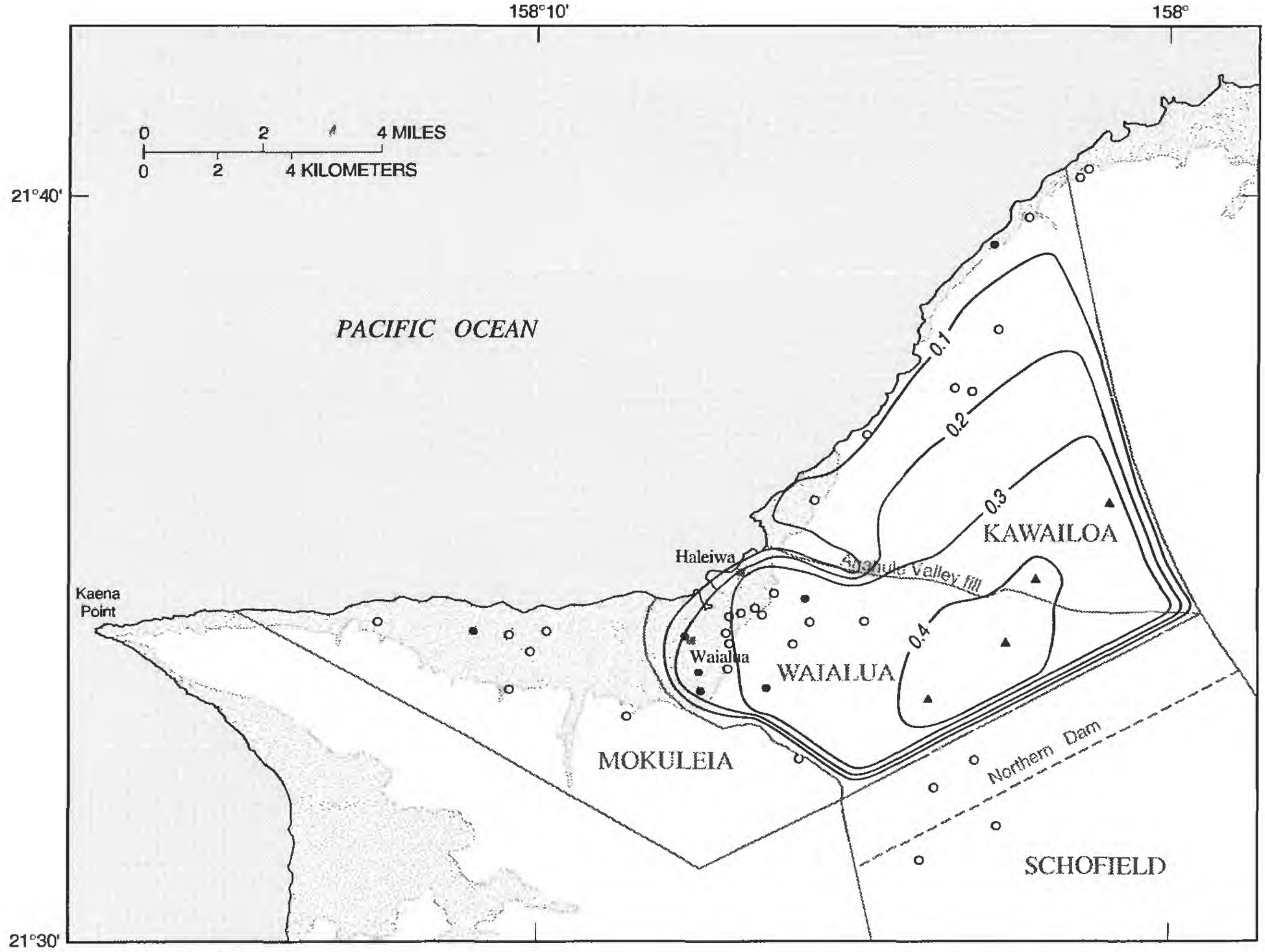
In pumping scenario 4, the 10 Mgal/d additional pumpage was equally distributed to the Mokuleia and Waialua ground-water areas. Toward the inland extent of the Waialua area, 5 Mgal/d pumpage was equally distributed to two cells of the model grid. Similarly, in the central part of the Mokuleia area, 5 Mgal/d pumpage was equally distributed to two cells of the grid. In the Waialua area, maximum drawdown, relative to the base-case simulation, is about 0.3 ft (fig. 61). The model-calculated cone of depression extends into the Kawailoa area, where drawdown is less than about 0.2 ft. In the Mokuleia area, maximum drawdown is about 2.3 ft in the vicinity of the added pumping. The cone of depression caused by the additional pumping also extends into the Schofield area, where drawdown does not exceed 0.01 ft.

Model results indicate that in the Kawailoa area, the freshwater-saltwater interface rises less than about 8 ft, relative to the base-case simulation, in response to the additional pumping (fig. 62). In the Waialua area, the model-calculated interface position rises about 12 ft. In the Mokuleia area, the model-calculated interface rises about 80 ft in response to the additional pumping. This interface rise causes the bottom of one additional existing well in the Mokuleia area to be below the interface. Model results indicate that total withdrawal from above the interface is 294.8 Mgal/d (table 17) and total withdrawal from below the interface is about 19.0 Mgal/d. Of the 19.0 Mgal/d withdrawn from below the interface, 8.3 Mgal/d is from wells in northern Oahu.

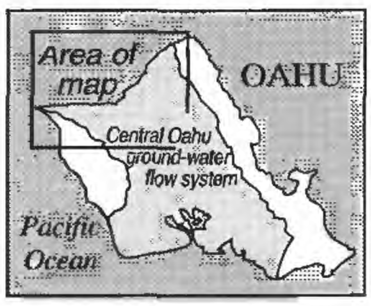
Scenario 5--Distributed Pumpage from Mokuleia, Waialua, and Kawailoa

In pumping scenario 5, the 10 Mgal/d additional pumpage was distributed to the Mokuleia, Waialua, and Kawailoa ground-water areas at rates of 2, 4, and 4 Mgal/d, respectively. In the central part of the Mokuleia area, 2 Mgal/d pumpage was equally distributed to two cells of the model grid. In both the Waialua and Kawailoa areas, 4 Mgal/d pumpage was equally distributed to two cells. Maximum drawdown, relative to the base-case simulation, in the Waialua and Kawailoa areas is about 0.3 ft (fig. 63). In the Mokuleia area, maximum drawdown is about 0.8 ft in the vicinity of the added pumping. The cone of depression caused by the additional pumping extends into the Schofield area, where drawdown does not exceed 0.01 ft.

Model results indicate that in the Kawailoa and Waialua areas, the freshwater-saltwater interface rises about 12 ft, relative to the base-case simulation, in response to the additional pumping (fig. 64). In the Mokuleia area, the model-calculated interface rises about 32 ft in response to the additional pumping. Model results indicate that no additional wells in the central Oahu flow system withdraw water from the saltwater zone as a result of the additional 10 Mgal/d pumpage from the Kawailoa, Waialua, and Mokuleia areas. However, for wells which already withdraw saltwater (table 14), increased contributions from the saltwater zone are expected because of the interface rise. Model



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 21°19'40" and 21°38'20", central meridian 157°58'



EXPLANATION

—0.3— LINE OF EQUAL MODEL-CALCULATED DRAWDOWN Interval 0.1 feet. Datum is mean sea level

o PUMPED WELL WITH 1995 ALLOCATION

• PUMPED WELL WITH 1995 ALLOCATION--Extends below model-calculated interface

▲ LOCATION OF SIMULATED ADDITIONAL PUMPING FOR SCENARIO 3

SEDIMENTARY DEPOSITS (CAPROCK)

BOUNDARY OF GROUND-WATER AREA

Figure 59. Model-calculated drawdown (relative to the base-case simulation with 1995-allocated pumping rates and no recharge from agriculture) caused by 5 million gallons per day additional pumpage in the upper Kawailoa ground-water area and 5 million gallons per day additional pumpage in the upper Waialua ground-water area (scenario 3), Oahu, Hawaii.

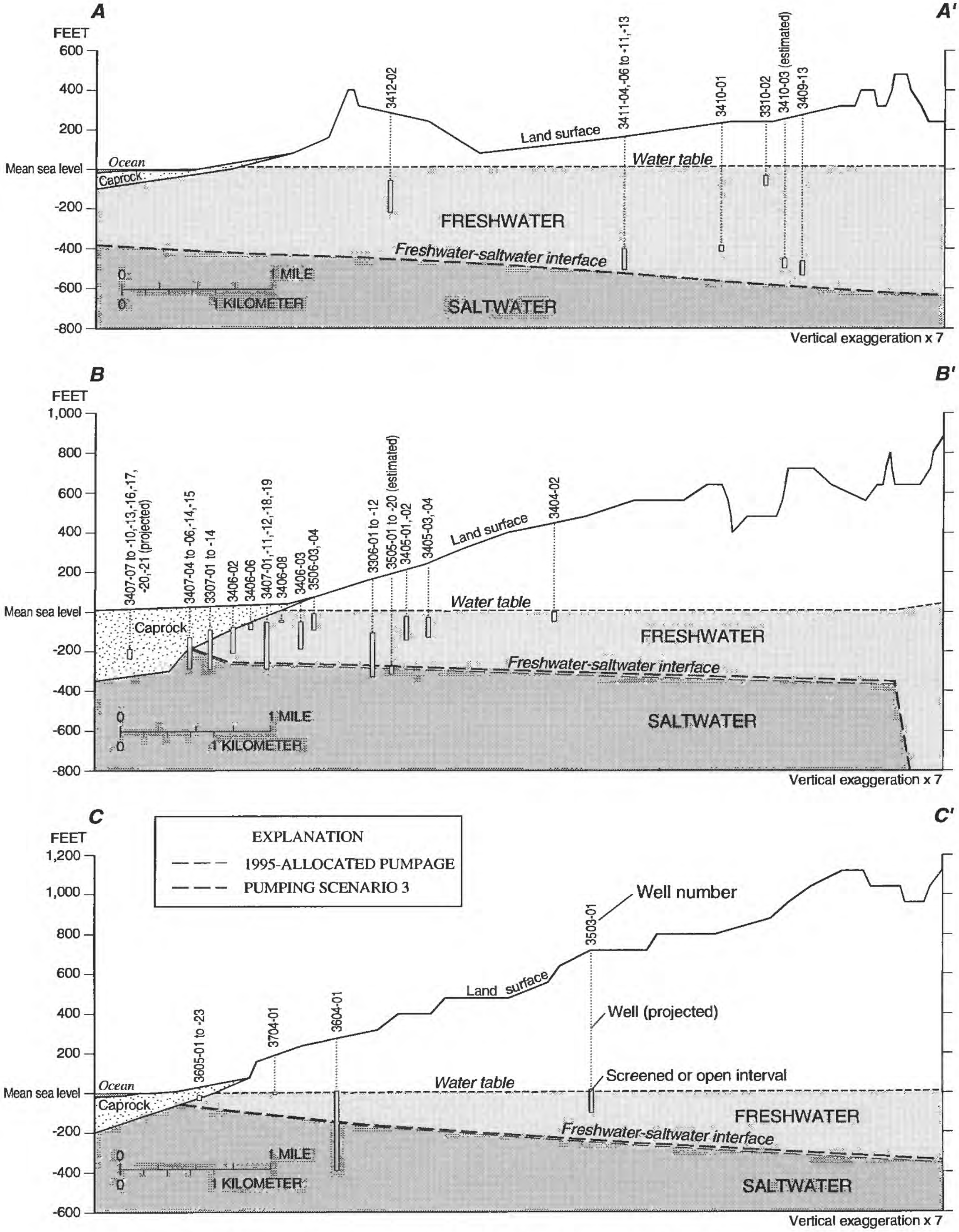
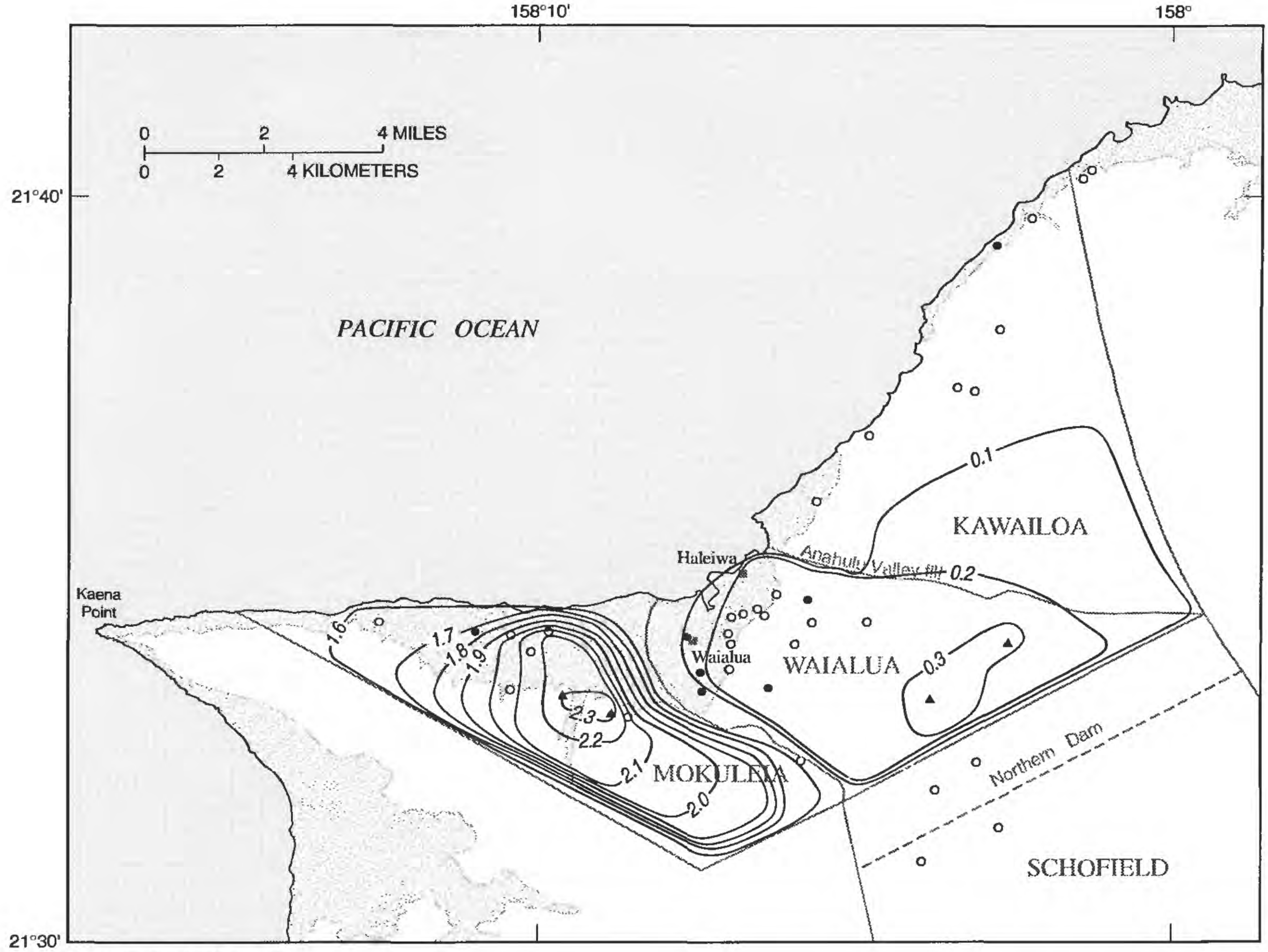
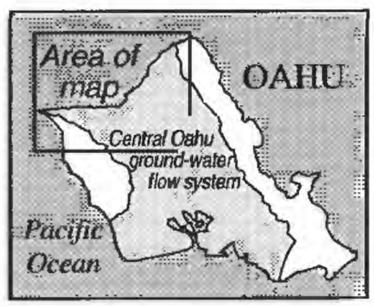


Figure 60. Model-calculated water table and freshwater-saltwater interface before and after adding 5 million gallons per day additional pumpage in the upper Kawailoa ground-water area and 5 million gallons per day additional pumpage in the upper Waialua ground-water area (scenario 3) for sections in the, ***A-A'***, Mokuleia ground-water area; ***B-B'***, Waialua ground-water area; and ***C-C'***, Kawailoa ground-water area, Oahu, Hawaii (trace of sections shown in fig. 54).



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 21°19'40" and 21°38'20", central meridian 157°58'



EXPLANATION

—0.3— LINE OF EQUAL MODEL-CALCULATED DRAWDOWN
Interval, in feet, is variable. Datum is mean sea level

o PUMPED WELL WITH 1995 ALLOCATION

• PUMPED WELL WITH 1995 ALLOCATION--Extends below model-calculated interface

▲ LOCATION OF SIMULATED ADDITIONAL PUMPING FOR SCENARIO 4

SEDIMENTARY DEPOSITS (CAPROCK)

BOUNDARY OF GROUND-WATER AREA

Figure 61. Model-calculated drawdown (relative to the base-case simulation with 1995-allocated pumping rates and no recharge from agriculture) caused by 5 million gallons per day additional pumpage in the upper Waialua ground-water area and 5 million gallons per day additional pumpage in the upper Mokuleia ground-water area (scenario 4), Oahu, Hawaii.

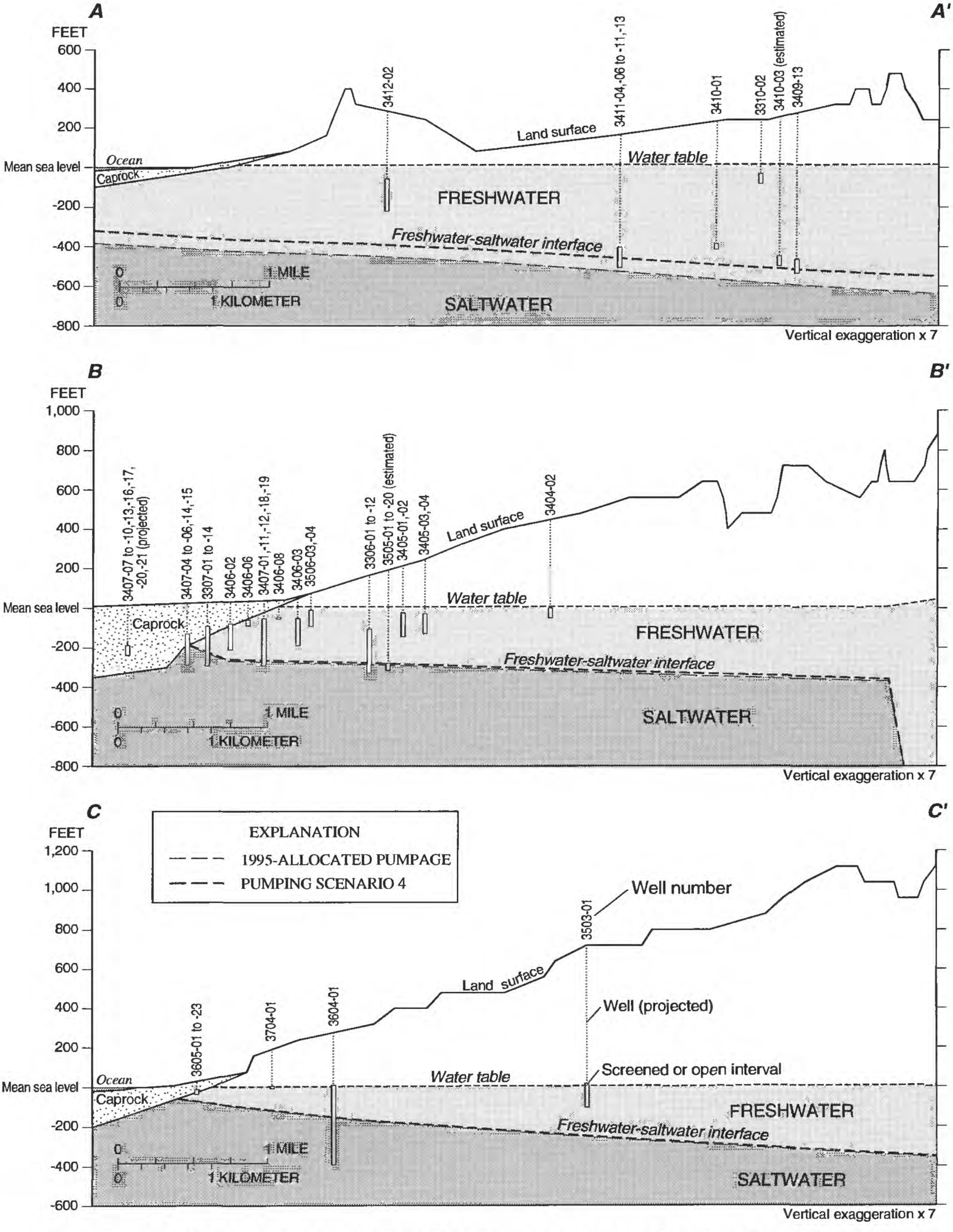
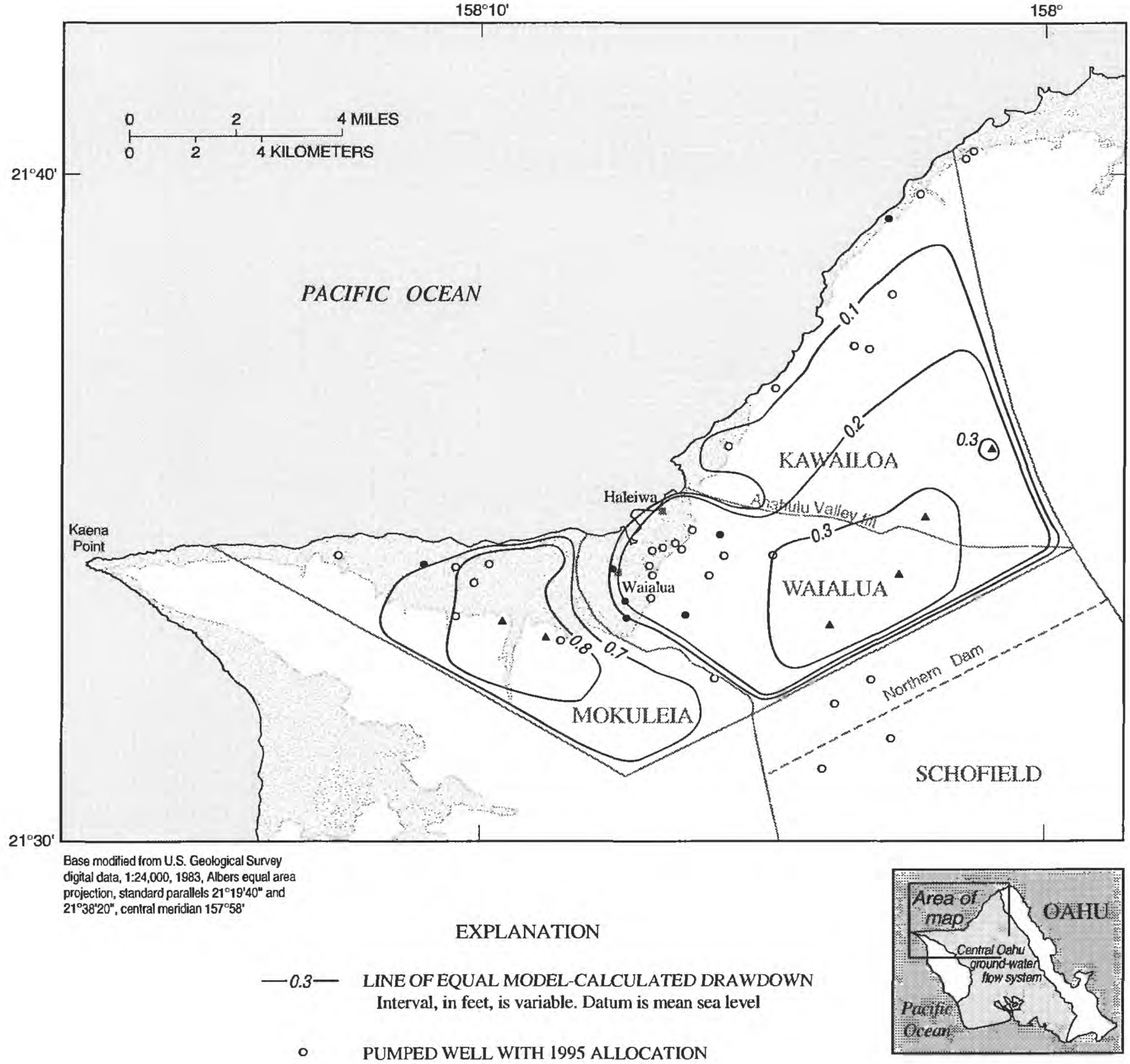


Figure 62. Model-calculated water table and freshwater-saltwater interface before and after adding 5 million gallons per day additional pumpage in the upper Waialua ground-water area and 5 million gallons per day additional pumpage in the Mokuleia ground-water area (scenario 4) for sections in the, ***A-A'***, Mokuleia ground-water area; ***B-B'***, Waialua ground-water area; and ***C-C'***, Kawailoa ground-water area, Oahu, Hawaii (trace of sections shown in fig. 54).



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 21°19'40" and 21°38'20", central meridian 157°58'

EXPLANATION

—0.3— LINE OF EQUAL MODEL-CALCULATED DRAWDOWN Interval, in feet, is variable. Datum is mean sea level

○ PUMPED WELL WITH 1995 ALLOCATION

● PUMPED WELL WITH 1995 ALLOCATION--Extends below model-calculated interface

▲ LOCATION OF SIMULATED ADDITIONAL PUMPING FOR SCENARIO 5

SEDIMENTARY DEPOSITS (CAPROCK)

BOUNDARY OF GROUND-WATER AREA

Figure 63. Model-calculated drawdown (relative to the base-case simulation with 1995-allocated pumping rates and no recharge from agriculture) caused by 4 million gallons per day additional pumpage in the upper Kawailoa ground-water area, 4 million gallons per day additional pumpage in the upper Waialua ground-water area, and 2 million gallons per day additional pumpage in the upper Mokuleia ground-water area (scenario 5), Oahu, Hawaii.

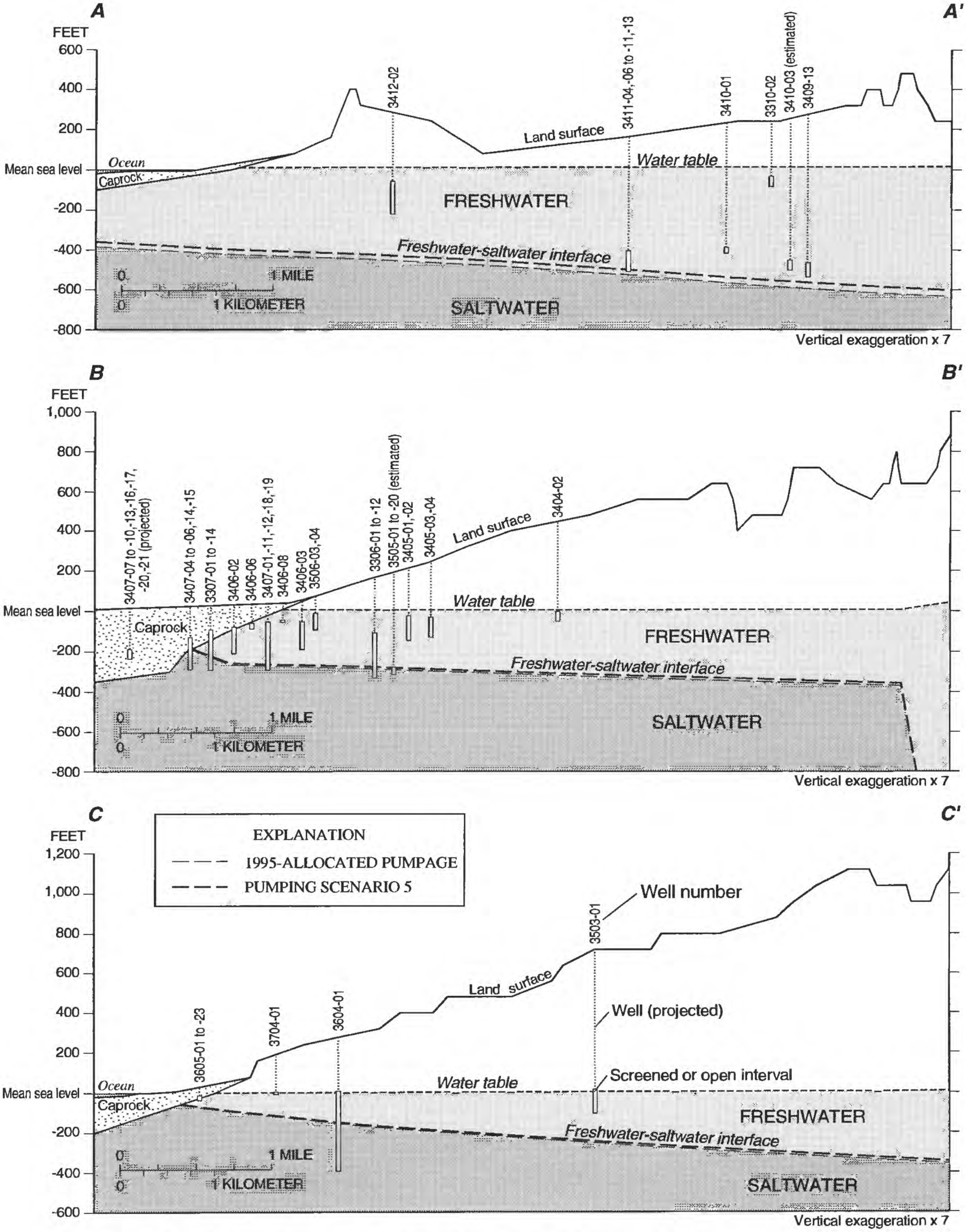


Figure 64. Model-calculated water table and freshwater-saltwater interface before and after adding 4 million gallons per day additional pumpage in the upper Kawailoa ground-water area, 4 million gallons per day additional pumpage in the upper Waialua ground-water area, and 2 million gallons per day additional pumpage in the Mokuleia ground-water area (scenario 5) for sections in the, ***A-A'***, Mokuleia ground-water area; ***B-B'***, Waialua ground-water area; and ***C-C'***, Kawailoa ground-water area, Oahu, Hawaii (trace of sections shown in fig. 54).

results indicate that total withdrawal from above the interface is 295.6 Mgal/d (table 17) and total withdrawal from below the interface is about 18.2 Mgal/d. Of the 18.2 Mgal/d withdrawn from below the interface, 7.5 Mgal/d is from wells in northern Oahu.

Scenario 6--10 Mgal/d from Middle Kawailoa

Pumping scenario 6 is similar to scenario 1 except that the 10 Mgal/d additional pumping was assumed to occur at lower altitudes, closer to the discharge boundary. The pumpage was equally distributed to three cells of the model grid toward the middle part of the Kawailoa area. The model-calculated drawdown, relative to the base-case simulation, is about 0.4 ft in the Kawailoa area in the vicinity of the added pumping (fig. 65). The cone of depression resulting from the pumpage added to the 1995 allocations extends beyond the boundaries of the Kawailoa ground-water area. In the Waialua area, maximum drawdown is about 0.2 ft near the Anahulu valley-fill barrier. Model-calculated drawdown in the Schofield ground-water area to the south and the Mokuleia ground-water area to the west does not exceed 0.01 ft.

Model-calculated drawdown in scenario 6 is slightly less than model-calculated drawdown in scenario 1 because of the proximity of the simulated withdrawals to the coast. The drawback of placing the wells at lower altitudes is that the freshwater lens thins in the seaward direction. Thus, the probability of saltwater contamination is increased as the wells are placed at lower altitudes.

Model results indicate that in the Kawailoa area, the freshwater-saltwater interface rises about 16 ft, relative to the base-case simulation, in response to the additional pumping, and in the Waialua area the model-calculated interface position rises about 8 ft (fig. 66). Model results indicate that no additional wells in the central Oahu flow system withdraw water from the saltwater zone as a result of the 10 Mgal/d pumpage from the upper Kawailoa area. However, for wells which already withdraw saltwater (table 14), increased contributions from the saltwater zone are expected because of the interface rise. Model results indicate that total withdrawal from above the interface is 297.0 Mgal/d (table 17) and total withdrawal from below the interface is about 16.8 Mgal/d. Of the 16.8 Mgal/d withdrawn from below the interface, 6.1 Mgal/d is from wells in northern Oahu.

MODEL LIMITATIONS

The model developed for this study simulates regional water levels and freshwater-saltwater interface locations, but cannot be used to simulate local-scale water-level drawdown or upconing in the vicinity of pumped wells. Water-level drawdown in the immediate vicinity of partially penetrating pumped wells may be much greater than simulated. Similarly, the freshwater-saltwater interface beneath pumped wells is subject to local upconing, and increases in salinity may be measured at wells in areas where the model indicates no significant problem with upconing. The model has several other limitations for predictive purposes because of the various assumptions used and possible errors in input data. These limitations are discussed below.

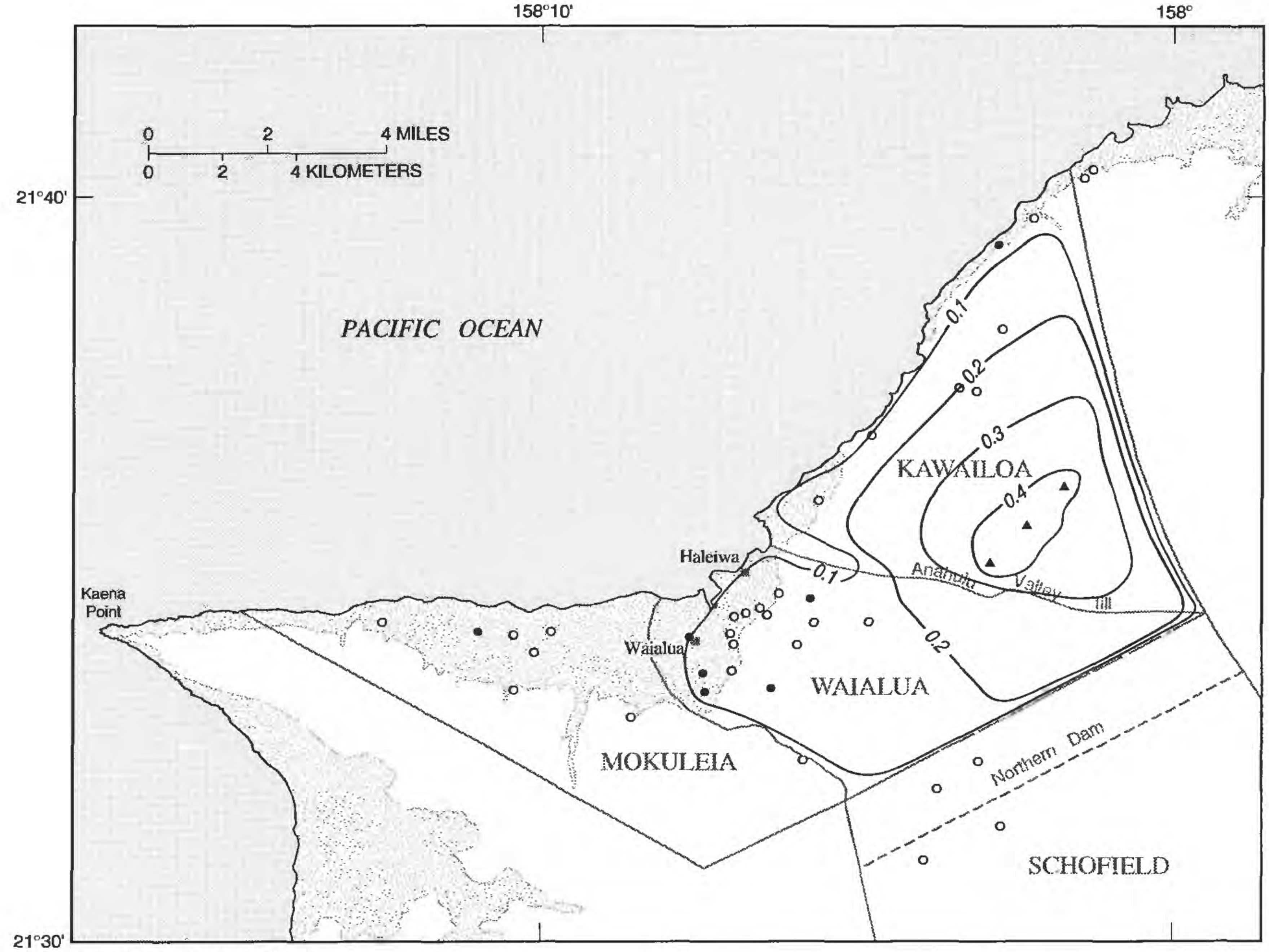
Steady-State Assumption

For this study, it was assumed that the 1950's represented a steady-state period for the purpose of estimating the hydraulic-conductivity distribution. Time series of pumpage, rainfall, and ground-water levels generally do not show any significant upward or downward trends during the 1950's. For some ground-water areas of the central Oahu flow system, such as the Kawailoa ground-water area, this steady-state assumption is reasonable since pumpage and recharge conditions were relatively steady for several decades prior to the 1950's. In general, however, the central Oahu ground-water flow system may have been adjusting during the 1950's to antecedent conditions. Thus, the steady-state assumption may limit the accuracy of the estimated hydraulic-conductivity distribution.

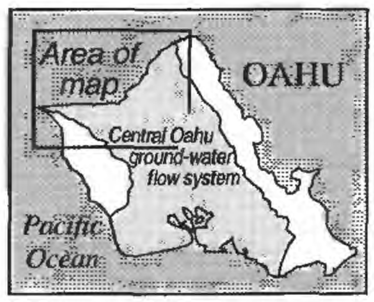
The steady-state model developed for this study is not suitable for transient predictions. Although the model can be used to evaluate the long-term hydrologic effects for steady pumping and recharge conditions, model calibration to transient conditions is needed before the model can be used for transient predictions.

Sharp Interface Assumption

The model developed for this study cannot be used to simulate local upconing in the vicinity of pumped wells. In addition, because the model is based on a sharp interface approach, it is not capable of predicting the distribution of salinity within the freshwater-saltwater



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 21°19'40" and 21°38'20", central meridian 157°58'



EXPLANATION

—0.3— LINE OF EQUAL MODEL-CALCULATED DRAWDOWN Interval 0.1 feet. Datum is mean sea level

o PUMPED WELL WITH 1995 ALLOCATION

• PUMPED WELL WITH 1995 ALLOCATION--Extends below model-calculated interface

▲ LOCATION OF SIMULATED ADDITIONAL PUMPING FOR SCENARIO 6

SEDIMENTARY DEPOSITS (CAPROCK)

BOUNDARY OF GROUND-WATER AREA

Figure 65. Model-calculated drawdown (relative to the base-case simulation with 1995-allocated pumping rates and no recharge from agriculture) caused by 10 million gallons per day additional pumpage in the middle Kawailoa ground-water area (scenario 6), Oahu, Hawaii.

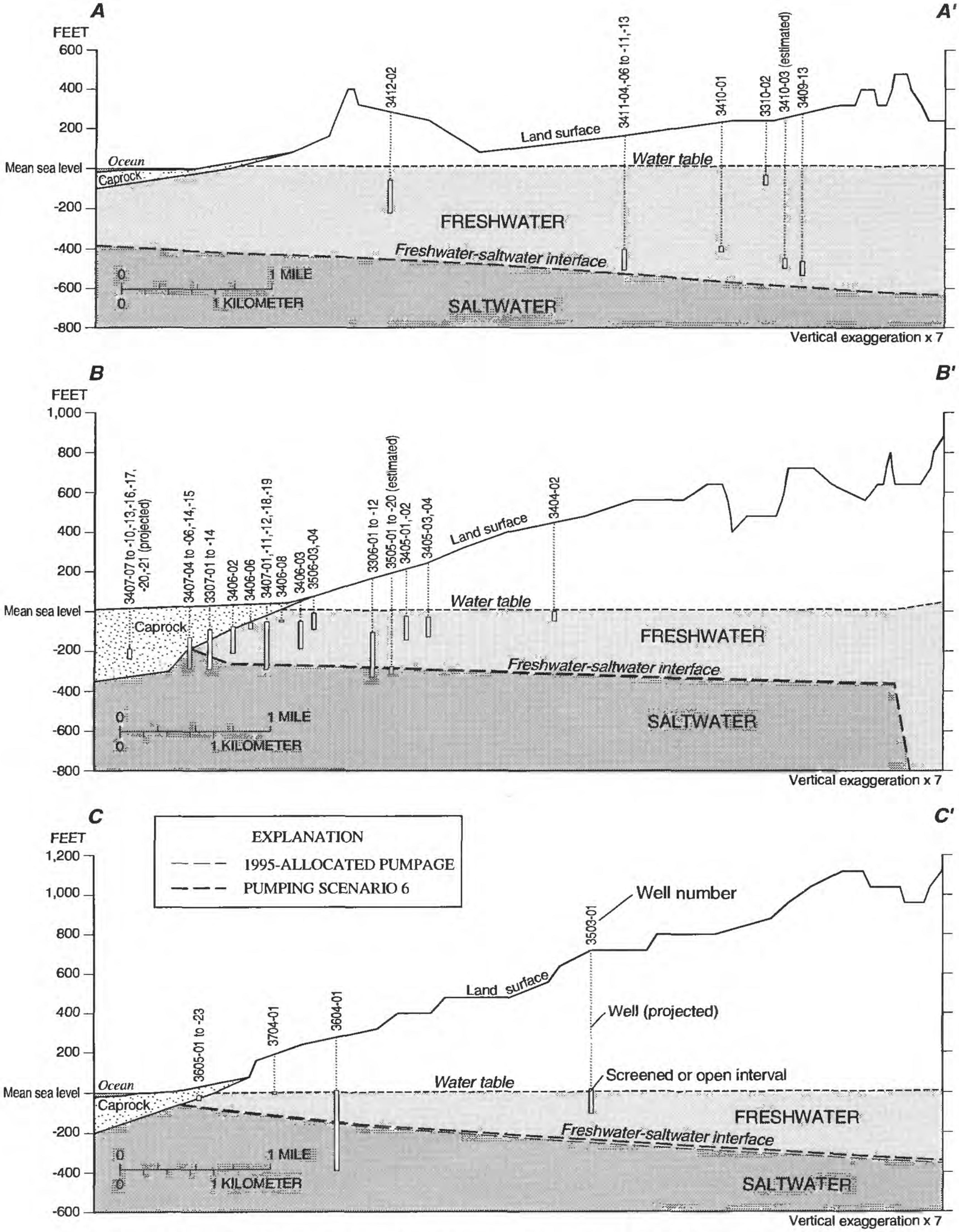


Figure 66. Model-calculated water table and freshwater-saltwater interface before and after adding 10 million gallons per day additional pumpage in the middle Kawailoa ground-water area (scenario 6) for sections in the, ***A-A'***, Mokuleia ground-water area; ***B-B'***, Waialua ground-water area; and ***C-C'***, Kawailoa ground-water area, Oahu, Hawaii (trace of sections shown in fig. 54).

transition zone or the quality of water pumped from a given well. In the model, the amount of freshwater and saltwater extracted from a well is linearly apportioned according to the proportion of the screened (or open) interval of the well that exists in the freshwater and saltwater zones. Thus, wells that are screened or open entirely above the model-calculated interface are assumed to extract only freshwater. In reality, water withdrawn from wells screened within the upper part of a lens, where chloride concentrations are less than 250 mg/L, may have chloride concentrations exceeding 250 mg/L depending on factors such as (1) withdrawal rate, (2) distance from the bottom of the well to the freshwater-saltwater transition zone, (3) the hydraulic characteristics of the aquifer, and (4) the presence or absence of salty irrigation return water at the top of the lens.

For a well with half its screened interval above the model-calculated interface and half its screened interval below the model-calculated interface, the SHARP model assigns half the total pumpage to the freshwater zone and half to the saltwater zone. This may not accurately reflect the actual pumping distribution from a well because highly permeable clinker zones in either the freshwater or saltwater part of the aquifer may contribute most of the water to a well.

Input Data Errors

The model developed for this study is limited by the accuracy of the pumpage data and recharge estimates used. Because pumpage at the high-capacity irrigation wells was typically estimated on the basis of electricity usage rather than with flow meters, there may be some unquantifiable error in the pumpage values used as input to the model. Errors associated with the recharge estimates used as input to the model will affect the estimated distribution of hydraulic-conductivity values. Giambelluca and others (1996) estimated that, in central Oahu, recharge uncertainty, caused by recharge model component uncertainties, is 49 percent of the mean for sugarcane and 59 percent of the mean for pineapple.

Boundary Conditions

In the model, eastward discharge from the Kaimuki ground-water area through the Kaau rift zone and westward discharge from the Ewa area through the south rift zone of the Waianae Volcano are assumed to be zero. Although there is likely some flow across these rift-zone barriers, the amount cannot be quantified without expanding the modeled area beyond the boundaries of the central Oahu flow system.

The interaction between surface water and ground water is handled indirectly in the model. Near the coast, head-dependent discharge of ground water to streams is subsumed by discharge into the caprock. In the mountainous inland regions, discharge of high-level, dike-impounded ground water into streams is accounted for in the water budget model as runoff (Giambelluca, 1983). In the middle reaches of streams, there is assumed to be no interaction between ground water in the volcanic aquifer and surface water.

Anisotropy

Model errors for the Pearl Harbor ground-water area were reduced by assuming that the horizontal hydraulic conductivity of the aquifer is anisotropic. The principal directions of anisotropy in the SHARP model coincide with the orientation of the grid. That is, for a given cell of the grid, the horizontal hydraulic conductivity may vary in the orthogonal directions corresponding to the cell boundaries. Throughout the central Oahu study area, the direction of maximum horizontal hydraulic conductivity is probably in the direction of the lava flows, whereas the direction of minimum horizontal hydraulic conductivity is perpendicular to the direction of the lava flows. These directions may vary from one location to another. Thus, for the Pearl Harbor area, the true principal directions of anisotropy are better represented in some areas of the model than in others. The other ground-water areas of the central Oahu flow system were satisfactorily represented with an isotropic horizontal hydraulic-conductivity model. It should be noted, however, that the orientation of the model grid precluded the use of an anisotropic horizontal hydraulic conductivity representation for many of these ground-water areas.

Two-Dimensional Approximation

Although the SHARP model is capable of quasi-three-dimensional simulations, the central Oahu flow system was simulated with a two-dimensional areal model. The two-dimensional nature of the model has several limitations: (1) because the model assumes horizontal flow, vertical gradients near the recharge and discharge areas of the flow system and vertical gradients near pumped wells cannot be represented; (2) the sloping Waianae confining unit must be represented as a vertical feature that is a barrier to horizontal flow; (3) ground-water flow beneath and through the partially penetrating valley-fill barriers cannot be simultaneously simulated; and (4) the Schofield dams are represented as fully penetrating barriers. Each of these limitations is discussed below.

Horizontal-Flow Assumption

Beneath the caprock of the Waialua ground-water area, the freshwater vertical gradient in the volcanic aquifer has a magnitude of about 0.001 ft/ft. Assuming a freshwater lens thickness of 450 ft for the Waialua area, the vertical head difference between the bottom and top of the lens would be 0.45 ft based on an average vertical hydraulic gradient magnitude of 0.001 ft/ft. Thus, for the Waialua ground-water area, the vertically averaged freshwater head may differ from the actual head, as measured by a piezometer, by a few percent near the discharge zone.

Stearns and Vaksvik (1935, p. 257) presented data to establish a vertical gradient at well 2153-06 in the Moanalua area. During drilling, the artesian head at this well increased from 17.7 ft just below the sedimentary deposits at an altitude of -122 ft, to 22 ft at an altitude of about -150 ft. Near the top of the aquifer, which may be slightly weathered, the magnitude of the vertical hydraulic gradient in the Moanalua area was about 0.15 ft/ft. Between altitudes of about -182 and -226 ft, the artesian head at well 2153-06 increased from 24.6 to 24.96 ft, which corresponds to a vertical hydraulic gradient magnitude of 0.008 ft/ft. The final well depth was at an altitude of -265 ft and the corresponding artesian head was 25.36 ft. At greater depths, the magnitude of the average vertical hydraulic gradient likely decreases. Assuming an average vertical hydraulic gradient magnitude of 0.008 ft/ft and a freshwater lens thickness of 1,025 ft for the Moanalua area, the vertical head difference between the bottom and top of the lens near the discharge zone would be about 8 ft. Thus, for the Moanalua area, the vertically averaged freshwater head may differ from the actual head, as measured by a piezometer, by more than 15 percent.The measured vertical hydraulic gradient in the Moanalua area is greater than the vertical gradient measured in the Waialua area. This difference could be caused by a greater natural discharge rate or a lower vertical hydraulic conductivity in the Moanalua area relative to the Waialua area.

Vertical hydraulic gradients also exist near the recharge areas of the aquifer and beneath pumped wells, but insufficient data are available to quantify these gradients. A three-dimensional model is needed to represent the vertical hydraulic gradients in the recharge and discharge areas and beneath pumped wells.

Waianae Confining Unit

The Waianae confining unit dips about 10° away from the Waianae Volcano. In a two-dimensional areal model, this dipping unit is represented as a vertical barrier that fully penetrates the aquifer. In the model, the onshore location of this barrier is assumed to be at the sea-level contact between Waianae Volcanics and Koolau Basalt (fig. 2). Although a two-dimensional model can properly simulate the hydraulic gradient across the confining unit, the effects of the two-dimensional representation of the confining unit cannot be fully quantified without developing a three-dimensional model of the system.

Valley-Fill Barriers

Partially penetrating valley-fill barriers are formed by both low permeability alluvium within the valley incision and weathered volcanic rocks beneath the original valley incision that extend into the volcanic aquifer. Ground water may flow beneath or through the valley-fill barriers, but because the valley-fill barriers are less permeable than the volcanic aquifer a head drop of several feet typically exists across the barriers. The magnitude of the hydraulic gradient across the Anahulu valley-fill barrier is about 0.004 ft/ft, which is an order of magnitude greater than the regional hydraulic gradient of about 0.0002 ft/ft associated with the ground-water areas of the central Oahu flow system. Partially penetrating valley-fill barriers are best represented using a three-dimensional model in which the valley-fill barriers are treated as low-conductivity cells for the entire depth of the valley plus the distance of weathering beneath the valley bottom. In a three-dimensional model, cells beneath the valley-fill barrier bottoms would retain the hydraulic properties of the volcanic aquifer.

In the two-dimensional model developed for this study, the valley-fill barriers were represented by reducing the relevant cell thicknesses. In addition, the hydraulic conductivity of the valley-fill cells also was reduced to provide the necessary head drop across the barriers. In the model, freshwater discharge from the aquifer into the valley fill cannot be represented where the tops of the valley-fill cells are located beneath the freshwater-saltwater interface. This effect may be a problem where the head in the volcanic aquifer exceeds the head in the alluvium within the original valley incisions. Generally, this condition is expected to exist at lower altitudes near the coast where ground water can flow into the coastal caprock. Although fresh ground water cannot discharge from those cells in which the cell top is below the freshwater-saltwater interface, freshwater can discharge from adjacent cells through the modeled caprock.

Schofield Ground-Water Dams

Dale and Takasaki (1976) suggested that discharge from the Schofield area is partly by flow through the dams and partly by spilling over the tops of the dams. In a two-dimensional model, the spill-over phenomenon cannot be simulated. Given the uncertain nature of the ground-water dams at present, the effects of this limitation on model results cannot be fully determined.

SUMMARY AND CONCLUSIONS

The central Oahu ground-water flow system is the largest and most productive flow system on Oahu. The central Oahu flow system is bounded on the east by the crest of the Koolau Range, on the southeast by the Kaau rift zone, on the south by the deposits and rocks that form a coastal caprock, on the west by the crest of the Waianae Range, and on the north by a coastal caprock, which generally thins toward the northeast. The Mokuleia, Waialua, and Kawailoa ground-water areas are in the northern part of the flow system, and the Ewa, Pearl Harbor, Moanalua, Kalihi, Beretania, and Kaimuki ground-water areas are in the southern part of the flow system. The Schofield ground-water area separates the northern and southern parts of the central Oahu flow system. The northern and southern boundaries of the Schofield ground-water area are formed by geologic structures of unknown origin and are known as the Schofield ground-water dams.

The Waianae confining unit separates the Waianae and Koolau aquifers of Oahu. The Mokuleia and Ewa ground-water areas are in the Waianae aquifer, and the remaining ground-water areas of the central Oahu flow system are in the Koolau aquifer. In southern Oahu, the ground-water areas of the Koolau aquifer are separated from each other by valley-fill barriers.

In 1879, the first well was drilled in the central Oahu flow system along the dry southern coast of the island just west of Pearl Harbor. The successful development of artesian water at this well paved the way for large-scale agricultural activities and expanded urbanization throughout Oahu. Reported ground-water pumpage from the central Oahu flow system increased from zero prior to 1879 to 196 Mgal/d in 1927. In 1977, annual pumpage peaked at 368 Mgal/d. During the 12-month period prior to July 1995, average pumpage from the volcanic aquifers of the flow system was about 198 Mgal/d.

In response to ground-water withdrawals, water levels in some ground-water areas have been lowered more than 20 ft below their initial (about the year 1880) levels. In the Beretania area of Honolulu, for instance, the initial water level was about 42 ft above mean sea level. During the 1970's when ground-water pumpage in the Beretania area was greatest, water levels less than 20 ft above mean sea level were measured.

With increased ground-water withdrawals, ground-water discharge has decreased. The Pearl Harbor springs represent the most notable ground-water discharge from the central Oahu flow system. Discharge at these springs is directly related to the head in the aquifer as measured by water levels in nearby wells. At Kalauao Springs, which are the easternmost of the Pearl Harbor springs, discharge has ranged from as low as 12.5 Mgal/d when head at well 2256-10 was about 15 ft above mean sea level, to as high as 25 Mgal/d when head at well 2256-10 was about 26 ft above mean sea level.

In 1995, the State of Hawaii Commission on Water Resource Management authorized a total of 303.8 Mgal/d pumpage from the volcanic aquifers of the central Oahu flow system. Although ground water is no longer required for sugarcane cultivation on Oahu, the demand for ground water remains high because of the needs associated with increased urbanization and diversified agriculture.

To assess the effects of different future pumping scenarios in northern Oahu, a two-dimensional, finite-difference ground-water flow model was developed for the central Oahu flow system which contains the most productive ground-water areas of the island. The model uses the computer code SHARP (Essaid, 1990) which simulates flow of both freshwater and saltwater. The SHARP model treats freshwater and saltwater as immiscible fluids separated by a sharp interface. The sharp interface corresponds roughly to the surface of 50-percent seawater salinity within the transition zone between freshwater and saltwater.

For this study, the hydraulic-conductivity distribution was estimated using average 1950's water levels. For the 1950's, average recharge to the central Oahu ground-water flow system was estimated to be about 623.4 Mgal/d and average pumpage was 239.8 Mgal/d. For 1950's conditions, model results indicate that 62 percent (90.1 Mgal/d) of the discharge from the Schofield ground-water area flows southward and the remaining 38 percent (55.2 Mgal/d) of the discharge from Schofield flows northward. Although the contribution of recharge from infiltration of rainfall and irrigation water directly on top of the southern and northern Schofield ground-water dams was included in the model, the distribution of natural discharge from the Schofield ground-water area was estimated exclusive of the recharge on top of the dams.

The model was used to investigate the long-term effects of pumping under non-agricultural land-use conditions. A base-case simulation was run in which conservative future recharge and 1995-allocated pumping rates were considered. The conservative future recharge used in the base-case simulation was estimated for urban, conservation, park, and mixed land uses without agriculture to be about 462.1 Mgal/d. Future pumpage used in the base-case simulation was based on the 1995-allocated rates and totaled about 303.8 Mgal/d.

Model results from the base-case simulation indicate that the long-term effect of pumping at the 1995 allocated rates will be a reduction, relative to 1995 conditions, of water levels in all ground-water areas of the central Oahu flow system. In the Schofield ground-water area, water levels decline about 30 ft from the 1995 level of 275 ft. In the remaining ground-water areas of the central Oahu study area, water levels may decline by less than 1 ft to as much as 12 ft relative to 1995 water levels. Using conservative recharge conditions and the 1995-allocated pumpage, the model-calculated interface rises above the bottoms of several deep existing wells in northern and southern Oahu.

Although the conditions represented in the base case are extreme, the results of the simulation are nevertheless informative and relevant. Model results indicate that long-term pumping at the 1995-allocated rates may cause saltwater contamination problems to occur at many wells within the central Oahu ground-water flow system. In addition to the wells at which the model-calculated freshwater-saltwater interface rises above the bottom of the well, increases in salinity may occur at wells in areas where the model indicates no significant problem with upconing. The model developed for this study is based on a sharp interface approach and therefore cannot be used to predict the distribution of salinity within the freshwater-saltwater transition zone or the quality of water pumped from a given well.

To determine the effects of additional pumping in northern Oahu, six pumping scenarios were tested. In each scenario, 10 Mgal/d additional withdrawal was added to the pumping distribution represented in the base case. The scenarios differ only in the spatial distribution of the additional pumping. Model results indicate that an additional 10 Mgal/d of freshwater can potentially be withdrawn in northern Oahu but would cause increased saltwater intrusion at some existing deep wells. In addition, increases in salinity may occur at other wells in areas where the model indicates no significant problem with upconing. Different distributions of pumping can be used to obtain the additional 10 Mgal/d. The quality of the water pumped will be dependent on site-specific factors and cannot be predicted on the basis of model results.

If the 10 Mgal/d additional pumpage is limited to the Waialua and Kawailoa ground-water areas, model-calculated regional drawdown, relative to the base-case simulation, in these two areas is less than about 0.6 ft. The cone of depression extends beyond the boundaries of these areas. In the adjoining Mokuleia and Schofield ground-water areas, model-calculated drawdown, relative to the base-case simulation, is no more than about 0.01 ft. Additional 10 Mgal/d pumpage in the Kawailoa or Waialua areas will not cause any additional wells to withdraw water from below the model-calculated interface position. The actual quality of water pumped from existing wells, however, cannot be predicted on the basis of model results.

Pumping an additional 2 Mgal/d in the middle part of the Mokuleia area may cause a rise of the interface, relative to the base-case simulation, of about 32 ft in the vicinity of the added pumping. If the additional Mokuleia pumpage is 5 Mgal/d, a drawdown of about 2.3 ft, corresponding to an interface rise of about 80 ft, may occur near the pumping sites.

Because the Kawailoa area has low water levels and a thin freshwater lens, any additional withdrawals near the coast in the Kawailoa area may result in saltwater intrusion. Development toward the inland extent of the Kawailoa area may have an advantage because (1) the freshwater lens is thicker and (2) pineapple-related contaminants in the ground water may be absent. Development in the Waialua area is also possible. However, several wells in the Waialua area have already tested positive for DBCP and TCP so that additional groundwater development in this area may require costly treatment processes. Although organic contaminants have not been detected in the Mokuleia area, long-term pumpage of a few million gallons per day above the 1995-allocated rates from this area may cause saltwater intrusion problems at existing wells.

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APPENDIX A. BOUNDARIES OF THE SCHOFIELD GROUND-WATER AREA

In 1938, an electrical resistivity survey using the Lee Partitioning Method was conducted to determine the extent of the high-level water in the Schofield area (Swartz, 1939, 1940). This method was found to be suitable for detecting the transition between freshwater and underlying saltwater. Within the Schofield area, the resistivity measurements failed to detect underlying saltwater because of the great thickness of the freshwater zone. Swartz (1939) estimated the locations of the northern and southern boundaries of the Schofield ground-water area (fig. 8) using the geophysical survey results. To the north of the delineated northern boundary, Swartz also delineated a transition area between the high-level water of Schofield and the lower water levels associated with the Waialua area. Swartz did not attempt to delineate the dams beyond his resistivity survey area. Although presumably based on the same data, the boundaries presented by Swartz (1940) differ slightly from those of Swartz (1939).

Dale and Takasaki (1976), utilizing information from wells drilled since the study of Swartz (1939), refined the boundaries of the Schofield ground-water area and the associated ground-water dams (fig. 8). The northern boundary was delineated between wells 3102-01 and 3203-01. The measured water level in well 3102-01 was 269.63 ft above sea level in September 1973; in well 3203-01, the water level measured with an air line was 121 ft above sea level in November 1974. The northern boundary was oriented in the same direction as presented by Swartz (1940). The southern boundary was placed 500 ft south of well 2803-06, which had a measured water level of 272.04 ft above sea level in March 1962, and was drawn through the midpoint of a line connecting Schofield shaft 4 and well 2801-01, located in the Pearl Harbor area. The last known water-level measurement for well 2801-01 was 26.18 ft above sea level in August 1958. Dale and Takasaki (1976) placed the southern boundary for the Schofield area north of well 2803-02, which had a measured water level of 187.47 ft in August 1963. This well has a transitional water level between the Schofield and the Pearl Harbor areas. Dale and Takasaki (1976) estimated the width of the southern Schofield ground-water dam to be about 5,200 ft using available water-level data. They suggested that the width of the northern dam should be greater than the width of the southern dam based on a hydrologic analysis which indicated that most of the ground water from Schofield flows southward to the Pearl Harbor area. This conclusion is based on the assumption that the northern and southern dams have about the same transmissivity. Dale and Takasaki (1976) extended the dams in a northeasterly direction to the Koolau rift zone, and in a southwesterly direction to the contact between Koolau Basalt and Waianae Volcanics at an altitude of 390 ft (120 m).

Broadbent's (1980) theory for the evolution of the Schofield ground-water area and the locations of the ground-water dams involved the formation of a graben along the eastern Waianae rift zone that defined a drainage basin between Mount Kaala and Puu Kanehoa of the Waianae Range. According to Broadbent, the northern ground-water dam is the buried northern ridge of the valley formed between Mount Kaala and Puu Hapapa of the Waianae Range (fig. 8). Broadbent's (1980) southern ground-water dam is the southern ridge of the valley between Puu Hapapa and Puu Kanehoa of the Waianae Range (fig. 8). Broadbent suggested that (1) the southern ridge has subsided to a greater extent than the northern ridge, and (2) the northern ridge forms the ground-water divide between the Waialua and Pearl Harbor areas. Toward the Koolau Range in the east, Broadbent's northern and southern ground-water dams converge (fig. 8).

Shettigara (1985), Shettigara and Peterson (1985), and Shettigara and Adams (1989) used 19 Schlumberger resistivity soundings and three gradient profiles to determine the locations of the northern and southern boundaries of the Schofield ground-water area. According to the investigators, the southern boundary strikes N64°E, and the northern boundary strikes N54°E. However, on the basis of figure 7.25 of Shettigara (1985), the southern and northern boundaries appear to strike at N56°E and N47°E, respectively. Shettigara's boundaries presented in figure 8 are based on figure 7.25 of Shettigara (1985). The northern boundary of Shettigara (1985), Shettigara and Peterson (1985), and Shettigara and Adams (1989) is about 5,200 ft north of the transition-zone limit of Swartz (1939). No attempt was made to extend the dams beyond the area of the geophysical survey.

The locations of the northern and southern Schofield ground-water dams of Takasaki (1977), Mink and Sumida (1984), and Mink and Lau (1990) are generally in agreement with the boundaries delineated by

Dale and Takasaki (1976). Takasaki (1977), however, extended the northern and southern boundaries of his Schofield geohydrologic unit eastward to the crest of the Koolau Range. Mink and Sumida (1984) and Mink and Lau (1990) extended the northern and southern boundaries of the Schofield area westward to the crest of the Waianae Range. In a more recent classification scheme, Hunt (1996) basically retained the boundaries of Dale and Takasaki (1976) for the Schofield ground-water area.

APPENDIX B. DEPTH OF VALLEY INCISIONS

The Manoa, Nuuanu, Kalihi, North Halawa, and Anahulu valley-fill barriers (fig. 2) impede the flow of fresh ground-water between ground-water areas on either side of the barriers. The channel incision depths of the valley-fill barriers are estimated below on the basis of geologic logs and assumed channel slopes. The depths of the valley-fill barriers are needed to properly describe the geometry of the ground-water system.

Stream channel cutting is directly related to stream velocity, which in turn is affected by base-level changes. A rise in base level, either because of sea-level rise from glacial melting or from island subsidence, results in smaller stream gradients and increased alluviation. A lower base level results in increased stream gradients and thus increased rate of downcutting (Macdonald and others, 1983). Lower regional base levels existed during glacial periods as a result of eustatic sea-level changes. For example, in the past 12,000 years, sea level was 350 ft below present sea level (Stearns, 1978). In addition, local base-level changes can result from alluviation, landslides, or valley-filling lavas.

The slope of an ancient stream channel is difficult to reconstruct on the basis of current topography because base level at the time of stream cutting is not precisely known. The stream channel gradient is greater than the slope of the original volcanic shield toward the inland areas. However, as the stream approaches the ocean, the channel gradient is probably less than the slope of the original surface. Where a stream discharges into the ocean at the lip of a sea cliff, the above assumption may not hold and, in fact, the stream channel may have a greater slope than the original lava flows. Between the coast and the steep inland areas of the geologically younger islands of Hawaii, the stream channel slope is about the same as the original volcanic shield slope. The original shield slope can be used to estimate the slope of ancient stream channels in the middle reaches of streams on Oahu.

On the basis of the maximum seaward extent at salients along existing topographic contours, the ancient surface of the Koolau shield can be approximated. For the Honolulu area, salients along the 200-, 600-, 1,000-, and 1,400-ft contours were identified to estimate the original surface. Between the reconstructed 200-ft and 1,400-ft contours, the slope of the original surface appears to be between about 10 to 14 percent (6 to 8°). The reconstructed 200-ft and 1,000-ft contours indicate that the slope of the original surface was between about 12 and 18 percent (7 and 10°). As an average, the slope of the original surface appears to be about 14 percent (8°). This is considerably greater than the typical dip of 5° for the basalt flows in the area (Stearns and Vaksvik, 1935, p. 23). In any event, it seems reasonable to assume that the average slope of the original surface was between about 9 and 14 percent (5 and 8°).

Manoa Valley.--The valley fill and underlying weathered zone associated with Manoa Stream form a barrier separating the Kaimuki ground-water area to the east from the Beretania ground-water area to the west. At well 1948-01, located in Manoa Stream valley at an altitude of about 384 ft, 4.2 mi inland from the coast, weathered basalt or old alluvium was encountered at the bottom of the hole at an altitude of -406 ft. On the basis of structural contours for the top of the volcanic aquifer, the minimum depth of incision near the coast is 400 ft below sea level (fig. 7). Wells are unavailable to precisely determine the original depth of incision near the coast. However, the depth of incision is estimated below on the basis of assumed channel slopes. As a first approximation, linear segments are used to estimate the original channel profile.

Above well 1948-01, the present channel slope is computed to be 33 percent between the 1,000-ft and 2,000-ft contours, and 11 percent between the 400-ft and 600-ft contours. Assuming an average channel slope of 22 percent, and assuming that continuous bedrock exists at the 800-ft contour, which represents the highest extent of alluvium as mapped by Stearns (1939), the original valley bottom at well 1948-01 can be estimated. The 800-ft contour in the stream channel is 4,300 ft inland from the well. Thus, the valley bottom near well 1948-01 is estimated to be at 146 ft below sea level. On the basis of this estimate, the weathered zone beneath the valley bottom is at least 260 ft thick.

Lacking any information to project the channel slope downstream from well 1948-01, it was assumed that the original channel slope was equal to the original slope of the volcanic shield of about 9 percent. The 9 percent channel gradient was extended down to a depth of 1,300 ft below present sea level. Beyond this depth, a reduced channel gradient of 2 percent was used to a depth of 2,300 ft below sea level, which corresponds to the offshore basement shelf indicated by Gregory (1980). Using these channel projections, the depth of the original Manoa Stream valley incision at the coast near Waikiki extends to a depth of 1,480 ft below sea level. The adjacent ridges near the coast, as indicated by the structural contours shown in figure 7, were at least 580 ft above the valley bottom.

Nuuanu Valley.--The valley fill and underlying weathered zone associated with Nuuanu Stream form a barrier separating the Beretania ground-water area to the east and the Kalihi ground-water area to the west. On the basis of nine diamond drill holes, Wentworth (1951, fig. 11) constructed a geologic section across Nuuanu Stream valley at a stream channel altitude of about 850 ft, 4.2 mi inland from Honolulu Harbor. The geologic section shows the original channel being incised to an altitude of 385 ft. Near the diamond drill holes, the valley is currently filled with Honolulu Volcanics and alluvium to about 850 ft above mean sea level.

Structural contours for the top of the volcanic aquifer near the mouth of Nuuanu Stream indicate a reentrant at a depth of 900 ft below sea level (fig. 7). This depth represents the minimum depth of incision because wells are unavailable to precisely delineate the original channel incision. Assuming a 9 percent original channel slope from Wentworth's (1951) drill holes in Nuuanu Stream valley to a depth of 1,300 ft below sea level, and a 2 percent slope thereafter, the original valley bottom is estimated to be at 1,340 ft below sea level at Honolulu Harbor. The adjacent ridges near the coast, as indicated in figure 7, were at least 440 ft above the valley bottom.

Kalihi Valley.--The valley fill and underlying weathered zone associated with Kalihi Stream form a barrier separating the Kalihi ground-water area to the east and the Moanalua ground-water area to the west. A series of diamond drill holes was completed in 1949 in Kalihi Stream valley (Wentworth, 1951). Geologic logs of these drill holes and a geologic section across the valley, located at an altitude of about 650 ft, 4.5 mi inland from the coast, were made available by the Honolulu Board of Water Supply. The data indicate an original channel bottom at an altitude of about 300 ft. Near the diamond drill holes, the valley is currently filled with Honolulu Volcanics and alluvium to an altitude of about 650 ft. Assuming a 9 percent original channel gradient from the diamond drill holes to a depth of 1,300 ft below sea level, and a 2 percent channel slope thereafter, the original valley bottom is estimated to be at 1,480 ft below sea level at the coast.

To accurately define the depth of the valley incision, a transect across the valley consisting of many closely spaced wells is required. This is necessary because the walls of the original valley may have been extremely steep, resulting in a very narrow channel incision. Evidence for the narrowness of the valley barrier is provided by wells 1953-01 and 2053-08, located in the Kalihi and Moanalua ground-water areas, respectively. Although these wells are located only about 1,300 ft apart, they belong to separate ground-water areas on the basis of measured water levels in the wells.

North Halawa Valley.--The valley fill and underlying weathered zone associated with North Halawa Stream form the barrier separating the Moanalua area to the east and the Pearl Harbor area to the west. Although South Halawa Stream valley may also contribute to the barrier effectiveness, Eyre (P.R. Eyre, U.S. Geological Survey, written commun., 1991, *in* Hunt, 1996) reasoned that North Halawa Stream valley shows a greater degree of erosion and is therefore the more appropriate choice for the barrier between the Moanalua and Pearl Harbor areas. In addition, well 2253-01 drilled in South Halawa Stream valley at an altitude of about 256 ft shows no evidence of extensive weathering. Water levels at this well, drilled to an altitude of -19 ft, were typical of the volcanic aquifer.

The original course of North Halawa Stream was altered by eruptions at Makalapa, Aliamanu, and Salt Lake Craters (fig. 6). These Honolulu vents diverted the southerly flow of North and South Halawa Streams westward into Pearl Harbor. Although well control is limited, the original North Halawa Stream valley incision, which forms the barrier between the Moanalua and Pearl Harbor areas, was likely located in the vicinity of well 2056-03. Because of a paucity of data for North

Halawa Stream valley, the original channel incision was assumed to be similar in nature to Kalihi Stream valley.

Anahulu Gulch.--The valley fill and underlying weathered zone associated with the gulch at Anahulu River form the barrier separating the Kawailoa and Waialua ground-water areas of northern Oahu. The water-level drop across the barrier is about 4 to 6 ft, with the higher water level in the Waialua area to the south of the barrier. Two wells (3505-21 and 3505-22) were drilled in Anahulu Gulch approximately 1.5 mi inland from the mouth of Anahulu River. Well 3505-21, drilled north of the river, yielded little water at a depth of 246 ft below sea level, and was backfilled in 1952. The well was still in weathered material or alluvium at the final depth of 246 ft below sea level, and the water level was about 3 ft above sea level. After abandoning well 3505-21, a second well (3505-22) was drilled on the south side of Anahulu River about 600 ft southwest of the first well. Well 3505-22 was drilled through alluvium and weathered basalt to a depth of 227 ft below sea level. Measured water levels in this well are typical of the Waialua ground-water area. The ground-water barrier separating the Waialua and Kawailoa areas must be between well 3505-22 and the northern wall of the gulch which is less than 700 ft away. The barrier, consisting of old alluvium and weathered basalt, near well 3505-22 is thus fairly narrow (less than about 700 ft wide). A third well (3505-25) drilled in 1993 on the northern facet above Anahulu Gulch within 1,300 ft of well 3505-22 has water levels typical of the Kawailoa ground-water area.

During 1967 and 1968, seven foundation test borings were drilled about 2,000 ft from the coast for a proposed bridge over Anahulu River (State of Hawaii, 1967; State of Hawaii, 1968a, b). Two borings were drilled south of the river within 50 ft of the south river bank, two borings were drilled in the center of the river channel, and two borings were drilled north of the river within 50 ft of the north river bank. The remaining test boring was drilled about 300 ft north of the north river bank. The borings extend to depths of 34 to 89 ft below sea level and, as indicated in the boring logs (State of Hawaii, 1968a, b), end in slightly weathered basalt. The boring logs seem to indicate that the channel incision near the mouth of Anahulu River does not extend more than about 80 ft below sea level. On the basis of measured water levels from other wells in the Waialua and Kawailoa ground-water areas, however, the Anahulu valley-fill barrier is effective in the vicinity of the test borings. Thus, weathering beneath the original incision may contribute to the barrier effectiveness. Alternatively, the original valley incision may lie north of where Anahulu River currently flows and may be deeper than indicated by the test borings. Indeed, the test borings which indicate the greatest depth of alluvium actually lie north of the current north river bank. Furthermore, the measured artesian head in a bore hole drilled within the river channel was at an altitude of about 8.4 ft, which is higher than measured water levels in the Kawailoa ground-water area. Thus, water-level information also indicates that the original valley incision may lie north of where the river currently flows. Given the uncertainty associated with the location of the original valley incision, the test borings for the bridge may underestimate the depth of the original incision.

To determine the inland extent of the Anahulu valley-fill barrier, well 3503-01 was drilled on the northern ridge above the gulch at a distance of about 3.4 mi from the coast (Presley and Oki, 1996a). Water levels measured in well 3503-01 are about 7.5 ft above sea level, which indicates that the Anahulu valley-fill barrier is effective at this distance inland from the coast. If the barrier were ineffective, the water level would be expected to be closer to Waialua area water levels, which are estimated to be greater than 12 ft above sea level at this distance from the coast.

Dale (1978) extended the Anahulu valley-fill barrier to the inland extent of mapped alluvium within the gulch at a channel altitude of about 400 ft. At this point, which is about 5,000 ft inland from well 3503-01, Dale (1978) suggested that the Anahulu valley-fill barrier meets the northern dam of the Schofield ground-water area. Wells are unavailable to confirm this assumption. Stray dikes from the Koolau rift zone may also contribute to the effectiveness of the barrier at the inland extent of the Kawailoa and Waialua ground-water areas.

The ridges adjacent to Anahulu Gulch have slopes of about 5 percent. If it is assumed that continuous bedrock exists at a channel altitude of 400 ft and the original channel incision had a slope of about 5 percent, the bottom of the original channel can be projected downstream. Using these projection estimates, the channel incision is expected to be at an altitude of -350 ft near wells 3505-21 and 3505-22. Weathering beneath the channel bottom may extend the barrier effectiveness downward an additional 150 ft or more (R.M. Towill, 1978). However, the projected channel will not provide an effective barrier at the upstream site near well 3503-01. Thus, it is assumed that beneath Anahulu Gulch near well 3503-01 the barrier extends down to an altitude of -300 ft, which corresponds to the Ghyben-Herzberg interface location for a 7.5-ft head. From there, the valley-fill barrier is projected in the downstream and upstream directions using a 5-percent gradient.

APPENDIX C. PREVIOUS ESTIMATES OF GROUND-WATER FLOW FROM THE SCHOFIELD GROUND-WATER AREA

Dale and Takasaki (1976) were the first investigators to directly address the apportionment of recharge from the Schofield ground-water area. On the basis of equations relating direct stream runoff with mean annual rainfall, and median annual pan evaporation with mean annual rainfall, Dale and Takasaki (1976) estimated that recharge to the Schofield area was 126 Mgal/d. Dale and Takasaki (1976) estimated that a total of 118 Mgal/d, which represents the difference between the total recharge and the ground-water withdrawals, discharges through either the northern or southern Schofield dams. The apportionment of this net recharge from Schofield was estimated on the basis of an analysis of the steady-state outflow from the Pearl Harbor and Waialua areas. Dale and Takasaki (1976) concluded that the Pearl Harbor area requires routing of 115 Mgal/d from Schofield, whereas the Waialua area requires routing of 18 Mgal/d from Schofield. In their steady-state analysis, Dale and Takasaki (1976) assumed that ground-water discharge from the Pearl Harbor and Waialua areas consisted only of pumping and measurable spring discharge exclusive of subsurface and submarine discharge. The discrepancy between the estimated 118 Mgal/d net recharge and the 133 Mgal/d routed to the north and south was attributed to measurement errors or faulty assumptions.

Broadbent (1980) suggested that the ground-water divide between the Waialua and Pearl Harbor areas consists of the buried northern ridge of the valley formed between Mount Kaala and Puu Hapapa of the Waianae Range. This divide corresponds to the northern boundary of Broadbent's Schofield ground-water area (figs. 8 and C1). Broadbent (1980) assumed that recharge to the Schofield ground-water area, as defined by his boundaries, drains southward into the Pearl Harbor area. Because Broadbent's (1980) hydrologic boundaries differ from those of Dale and Takasaki (1976), comparisons between hydrologic budgets are difficult.

Rosenau and others (1971) estimated ground-water recharge from infiltration of rainfall to be 225 Mgal/d in their north-central Oahu study area, which is "bounded by the crest of the Koolau Range and the drainage basin of Kamananui Stream on the east, by the crest of the Waianae Range on the west, by the ocean on the north, and by the summit of the Schofield Plateau in the area of Wahiawa and Schofield Barracks on the south" (Rosenau and others, 1971, p. D3). Recharge was estimated for steady-state conditions by subtracting runoff and evapotranspiration from mean annual rainfall. Rosenau and others (1971) implicitly assumed that none of the recharge flowed toward the south to the Pearl Harbor area. Recharge within the boundaries of their north-central Oahu study area was assumed to discharge as pumping from within the area or as springflow and subsurface flow along the northern coast of Oahu. Because the southern boundary of the study area used by Rosenau and others (1971) was just north of the southern Schofield ground-water dam (fig. 8), most of the recharge over the Schofield ground-water area was thus assumed to drain northward. The southern boundary of their study is apparently formed by the surface-water drainage divide of the Schofield Plateau (fig. C1).

Turnbull and others (1994) used stable and radioactive isotopes to evaluate the regional ground-water flow pattern in the Schofield ground-water area. On the basis of isotope data, Turnbull and others (1994) suggested that the ground-water divide between the Waialua and Pearl Harbor areas is just south of the North Fork of Kaukonahua Stream (fig. C1). Although Turnbull and others (1994) did not present any flow estimates, their ground-water divide lies south of the divide presented by Broadbent (1980). Thus, results from Turnbull and others (1994) indicate that a greater proportion of water originating from the Schofield area flows northward than that suggested by Broadbent (1980).

Eyre and Nichols (in press) assumed that the Wahiawa-Waialua district boundary represents the approximate location of the ground-water divide separating water moving either to the north or south (fig. C1). For predevelopment conditions, Eyre and Nichols (in press) estimated that 87.9 Mgal/d flows southward from the Schofield ground-water area. For average 1950's condi-

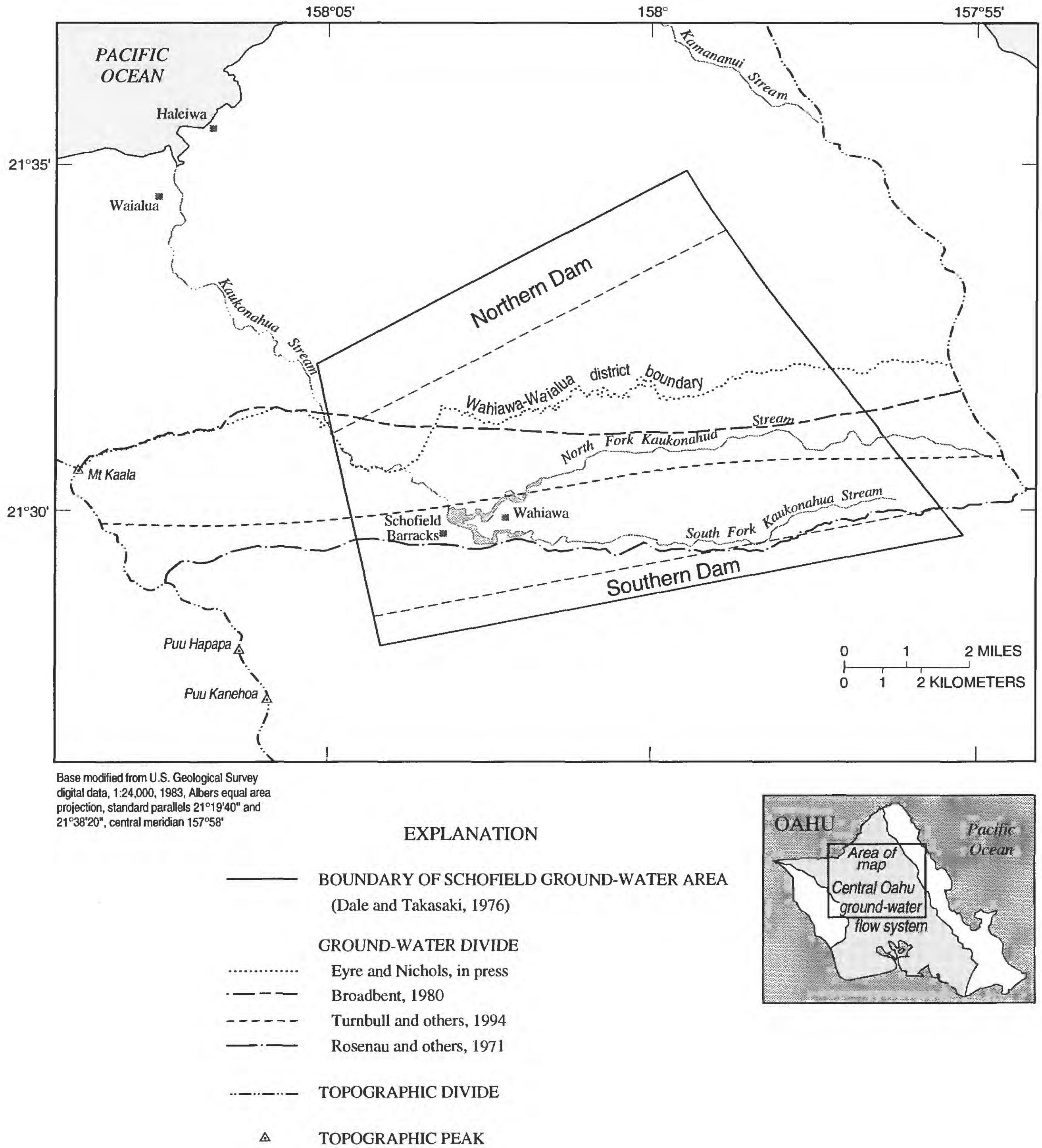

Figure C1. Previously estimated locations of the ground-water divide for the Schofield ground-water area, Oahu, Hawaii.

Table C1. Distribution of recharge to the north and south of the Schofield ground-water divide, Oahu, Hawaii

Ground-water divide	Basis for establishing location of ground-water divide	Recharge, in million gallons per day	
		North of divide	South of divide
Rosenau and others, 1971	surface-water drainage	141	9
Broadbent, 1980	geologic structure	89	61
Turnbull and others, 1994	chemical isotopes	113	37
Eyre and Nichols, in press	topographic divide	75	75

tions, the southward discharge from Schofield was estimated to be 88.6 Mgal/d.

It should be noted that ground-water divides may shift in response to changes in recharge or withdrawals. However, a comparison of the recharge within the Schofield ground-water area to the north and south of each divide shown in figure C1 can be made. Recharge was estimated for 1995 land-use conditions using regression equations relating recharge to rainfall (see the "Ground-Water Recharge" subsection of the "Hydrology" section). The estimated 1995 recharge to the Schofield ground-water area, exclusive of the northern and southern dams, is about 150 Mgal/d. The distribution of recharge to the north and south of each divide shown in figure C1 is given in table C1. The amount of recharge south of the divide ranges from 6 percent (Rosenau and others, 1971) to 50 percent (Eyre and Nichols, in press) of the total recharge to the Schofield area.

Evans and others (1995) constructed a three-dimensional, finite-element model for the Waialua, Schofield, and Pearl Harbor ground-water areas within the central Oahu flow system. Recharge and discharge from the modeled area were represented with specified-head boundary conditions. Ground water from the Schofield area was assumed to flow over the northern and southern ground-water dams into the adjoining Waialua and Pearl Harbor areas, respectively. This spill-over conceptualization was modeled "by warping the mesh over the dams" (Evans and others, 1995, p. 258). No explicit mention was made of the proportion of water from the Schofield area which flows north and south. However, Evans and others (1995) utilized the ground-water flow paths of Turnbull and others (1994) as part of their model calibration.

Mink and others (1988) computed by analytical equation the total natural ground-water flow, free of irrigation return water, for the Pearl Harbor area to be 206 Mgal/d. Under predevelopment conditions, recharge from infiltration of rainfall for the Pearl Harbor area was computed to be 144 Mgal/d. The 62 Mgal/d difference between the total flow (206 Mgal/d) and the recharge from infiltration of rainfall (144 Mgal/d) was attributed primarily to underflow from the Schofield ground-water area and secondarily to underflow from the Moanalua area. For the Ewa area of southern Oahu, Mink and others (1988) computed the total natural ground-water flow to be 22 Mgal/d. Giambelluca (*in* Mink and others, 1988) estimated predevelopment recharge from infiltration of rainfall in the Ewa area to be 8 Mgal/d. Thus, Mink and others (1988) estimated that 14 Mgal/d entered the Ewa area as ground-water underflow from the Schofield and Pearl Harbor areas under predevelopment conditions. For predevelopment conditions, Mink and others (1988) suggested that a maximum of 76 Mgal/d moved southward from the Schofield ground-water area. Toward the high recharge area of the Koolau Range, the southern boundary for the Schofield area used by Mink and others (1988) is north of the southern dam used in this study. Thus, the southward flow from Schofield estimated by Mink and others (1988) is lower than what would be estimated using the Schofield boundaries of this study.

Liu and others (1981) used a single-fluid, finite-difference ground-water flow model to simulate conditions within the Pearl Harbor and Ewa ground-water areas. The model used by Liu and others (1981) assumes that the location of the sharp interface between the freshwater and saltwater adjusts instantaneously to changes in freshwater head. Total natural recharge, exclusive of irrigation return flow, to the Pearl Harbor and Ewa areas was considered to be 210 Mgal/d. In addition, 15 Mgal/d inflow was assumed to originate from the Moanalua area to the east. Although Liu and others (1981) stated that inflow from the Schofield ground-water area to the Pearl Harbor and Ewa areas was modeled using a specified-flow boundary condition, the amount of inflow assumed is not reported. The Schofield contribution was included in the 210 Mgal/d natural recharge estimate.

The initial estimate for sustainable yield for the Schofield area was 15 Mgal/d (State of Hawaii, 1979). The estimated sustainable yield for the Schofield area is small relative to the ground-water flow rate through the area because excessive pumping from the Schofield area would reduce the recharge to the downgradient ground-water areas. The State of Hawaii Commission on Water Resource Management currently regulates water use in the Schofield area on the basis of a sustainable yield estimate of 23 Mgal/d.

APPENDIX D. MODIFICATIONS TO THE SHARP MODEL

For this study, two modifications were made to the SHARP model (Essaid, 1990). Both modifications are related to the tracking of the interface tip and toe and were necessary to achieve a satisfactory mass balance.

SHARP assigns a code to each cell of the grid on the basis of the thicknesses of the freshwater and saltwater zones within the cell. A cell is desisgnated as "F," "M," or "S" depending on whether it is a freshwater, mixed, or saltwater cell, respectively. In its unmodified form, SHARP assigns a code of "F" to cells in which the thickness of the saltwater zone is less than or equal to 1 percent of the total cell thickness contributing to flow. SHARP assigns a code of "S" to cells in which the thickness of the freshwater zone is less than or equal to 1 percent of the total cell thickness contributing to flow. Cells not meeting the criteria for an "F" or "S" designation are assigned a code of "M." The code assignment determines whether the interface tip or toe will be projected into adjacent cells. That is, the interface tip will only be projected from an "F" or "M" cell into an "S" cell, and the interface toe will only be projected from an "S" or "M" cell into an "F" cell. For cases in which the aquifer is thick and the freshwater lens is thin, the code designations may result in a premature truncation of the lens. For this study, SHARP was modified to assign a code of "F" to cells in which the thickness of the saltwater zone is less than or equal to 0.1 percent of the total cell thickness contributing to flow and a code of "S" to cells in which the thickness of the freshwater zone is less than or equal to 0.1 percent of the total cell thickness contributing to flow. The modified lines (TC 650 and TC 710) of the code are shown at the bottom of the page.

The second modification to SHARP involves the assignment of the area of a cell contributing to either freshwater or saltwater vertical flow. Because the position of the interface tip or toe may not necessarily coincide with a cell boundary, SHARP incorporates a tracking algorithm to project the interface tip or toe into adjacent cells. The tip is linearly projected, on the basis of the interface slope, until the top of the aquifer is intersected, and the toe is linearly projected until the bottom of the aquifer is intersected. For areal models, the interface is projected in both the x- and y-directions. In the code, the variables FXN and FYN represent the interface tip projection distances in the x- and y-directions, respectively. SXN and SYN represent the interface toe projection distances in the x- and y-directions, respectively. FXN and SXN are expressed as a fraction of the cell length in the x-direction, and FYN and SYN are expressed as a fraction of the cell length in the y-direction. Essaid (1990) computes the areas contributing to freshwater and saltwater leakage across the top of a

---

Line TC 650 modified from

```
IF((ZINT(I,J,K)-ZBOT(I,J,K)).LE.(.01*THICK))THEN
```

to

```
IF((ZINT(I,J,K)-ZBOT(I,J,K)).LE.(.001*THICK))THEN
```

Line TC 710 modified from

```
ELSE IF((ZTOP(I,J,K)-ZINT(I,J,K)).LE.(.01*THICK))THEN
```

to

```
ELSE IF((ZTOP(I,J,K)-ZINT(I,J,K)).LE.(.001*THICK))THEN
```

model layer on the basis of values of FXN, FYN, SXN, and SYN. The variable FAREA is used to represent the fraction of the cell area contributing to freshwater leakage, and the variable SAREA is used to represent the fraction of the cell area contributing to saltwater leakage.

In the original SHARP code, whenever FXN is equal to 1.0, FAREA is assigned the same value as FYN. In some situations, this could lead to an underestimation of FAREA and an underestimation of freshwater leakage. In the original code, whenever FYN is equal to 1.0, FAREA is assigned the same value as FXN, and this may lead to an underestimate for FAREA. In a similar way, the original SHARP code may underestimate SAREA.

For situations in which the horizontal flow component is predominantly in one direction, the following modifications are unnecessary. However, when the horizontal flow component is not strictly one-dimensional in nature, as in the model developed for this study, the following modifications may improve the model-calculated mass balance. The modified lines (TC 6090, TC 6110, TC 6240, and TC 6260) of the code are shown at the bottom of the page.

With these modifications, whenever FXN or FYN are equal to 1.0, FAREA is computed from equations 34 and 35 of Essaid (1990, p. 25). Similarly, whenever SXN or SYN are equal to 1.0, SAREA is computed from equations 36 and 37 of Essaid (1990, p. 25).

To determine the effects of the modifications, example 1 from Essaid (1990, p. 57–77) was tested using the modified version of SHARP. Although example 1 is a two-dimensional areal problem, simulated flow is predominantly in one direction. For this example, the modified version of SHARP produces freshwater heads that average 0.04 ft lower than heads produced by the unmodified code. The largest freshwater head difference was 0.12 ft.

Line TC6090 modified from

```
IF(FXN(I,J,K).EQ.0.0.OR.FXN(I,J,K).EQ.1.0)THEN
```

to

```
IF(FXN(I,J,K).EQ.0.0)THEN
```

Line TC6110 modified from

```
ELSE IF(FYN(I,J,K).EQ.0.0.OR.FYN(I,J,K).EQ.1.0)THEN
```

to

```
ELSE IF(FYN(I,J,K).EQ.0.0)THEN
```

Line TC6240 modified from

```
IF(SXN(I,J,K).EQ.0.0.OR.SXN(I,J,K).EQ.1.0)THEN
```

to

```
IF(SXN(I,J,K).EQ.0.0)THEN
```

Line TC6260 modified from

```
ELSE IF(SYN(I,J,K).EQ.0.0.OR.SYN(I,J,K).EQ.1.0)THEN
```

to

```
ELSE IF(SYN(I,J,K).EQ.0.0)THEN
```

Table E1. Sustainable yield estimates and allocations for ground-water areas of the central Oahu ground-water flow system, Hawaii

[Data from State of Hawaii Commission on Water Resource Management (Neal Fujii, written commun., 1995); Mgal/d, million gallons per day]

Ground-water area	Sustainable yield (Mgal/d)	1995 allocation (Mgal/d)	1995 actual ground-water use (Mgal/d)[1]
Mokuleia	12	6.6	1.7
Waialua	40	39.3	20.2
Kawailoa	39	6.3	2.6
Schofield with dams	23	21.6	10.7
Ewa	20	19.1	9.8
Pearl Harbor	164	158.2	111.7
Moanalua	18	18.6	11.6
Kalihi	9	13.0	7.8
Beretania	15	15.3	16.4
Kaimuki	5	5.7	5.5
Total	345	304	198

[1]1995 water use is based on a 12-month average for the period from July 1994 through June 1995

APPENDIX E. PREVIOUS ESTIMATES OF GROUND-WATER AVAILABILITY IN NORTHERN OAHU

The State of Hawaii Commission on Water Resource Management regulates water use in the central Oahu flow system on the basis of sustainable yield estimates from an analytical model developed by Mink (1980). The sustainable yield estimates for ground-water areas in the central Oahu flow system are listed in table E1 (State of Hawaii, 1992).

Mokuleia Ground-Water Area

On the basis of a single round of well discharge measurements in January 1934, Stearns and Vaksvik (1935) estimated the average daily withdrawal for 1933 in the Mokuleia area to be 14 Mgal/d. Stearns and Vaksvik (1935, p. 375) noted that the head in the Mokuleia area was not declining in the years prior to 1934 and concluded that the sustainable yield of the area had probably not been reached.

The initial estimate for sustainable yield for the Mokuleia area was between 15 and 25 Mgal/d (State of Hawaii, 1979). The lower bound was based on the ground-water withdrawal rate of 15 Mgal/d in 1930, and the upper bound was estimated on the basis of ground-water flow computations (K.J. Takasaki *in* Dale, 1987).

On the basis of two different computation methods, Dale (1987) estimated recharge to the Mokuleia area to be between 13 and 20 Mgal/d. Pumpage from the Mokuleia area was about 4 Mgal/d, primarily from Waialua Sugar Co. pump 5 (3411-04, -06 to -11, -13). Dale suggested that an additional 10 Mgal/d probably could be pumped from wells located toward the eastern extent of the Mokuleia area without adversely affecting water quality at Waialua Sugar Co. pump 5. The State of Hawaii Commission on Water Resource Management regulates water use in the Mokuleia area on the basis of a sustainable yield estimate of 12 Mgal/d.

Waialua Ground-Water Area

Stearns and Vaksvik (1935, p. 328) were the first to place a lower bound on the sustainable yield from the Waialua area. They noted that head in the Waialua area did not decline from 1911 to 1934 and concluded that the average pumpage of 33 Mgal/d was not causing an over-withdrawal on the system.

Using Dale and Takasaki's (1976) previous estimate of 18 Mgal/d for flow from the Schofield area to the Waialua area, Dale (1978) computed the total ground-water flow through the Waialua area. On the basis of pre-1974 land-use conditions, Dale (1978) estimated that the Waialua area receives 35 Mgal/d recharge from infiltration of rainfall and irrigation return flow. Thus, the total flow through the Waialua area based on the sum of the inflow terms was estimated to be 53 Mgal/d. As a check on this estimate, Dale (1978) also estimated the total outflow from the Waialua area. Total outflow, consisting of pumpage, spring discharge, and outflow to the adjacent Kawailoa ground-water area, was estimated to be 55 Mgal/d. Average pumpage was 36 Mgal/d, discharge through the caprock was estimated to be 10 Mgal/d, and flow from the Waialua area to the Kawailoa area was estimated to be 9 Mgal/d. The State of Hawaii Commission on Water Resource Management regulates water use in the Waialua area on the basis of a sustainable yield estimate of 40 Mgal/d.

Kawailoa Ground-Water Area

Ground-water development in the Kawailoa area has been limited because of the thin freshwater lens in this area. However, existing wells typically are located near the coast where water levels are only a few feet above mean sea level. Toward the inland extent of this area, water levels are greater than 7 ft above mean sea level. The State of Hawaii Commission on Water Resource Management regulates water use in the Kawailoa area on the basis of a sustainable yield estimate of 39 Mgal/d. Annual average ground-water pumpage from this area historically has been less than 10 Mgal/d.