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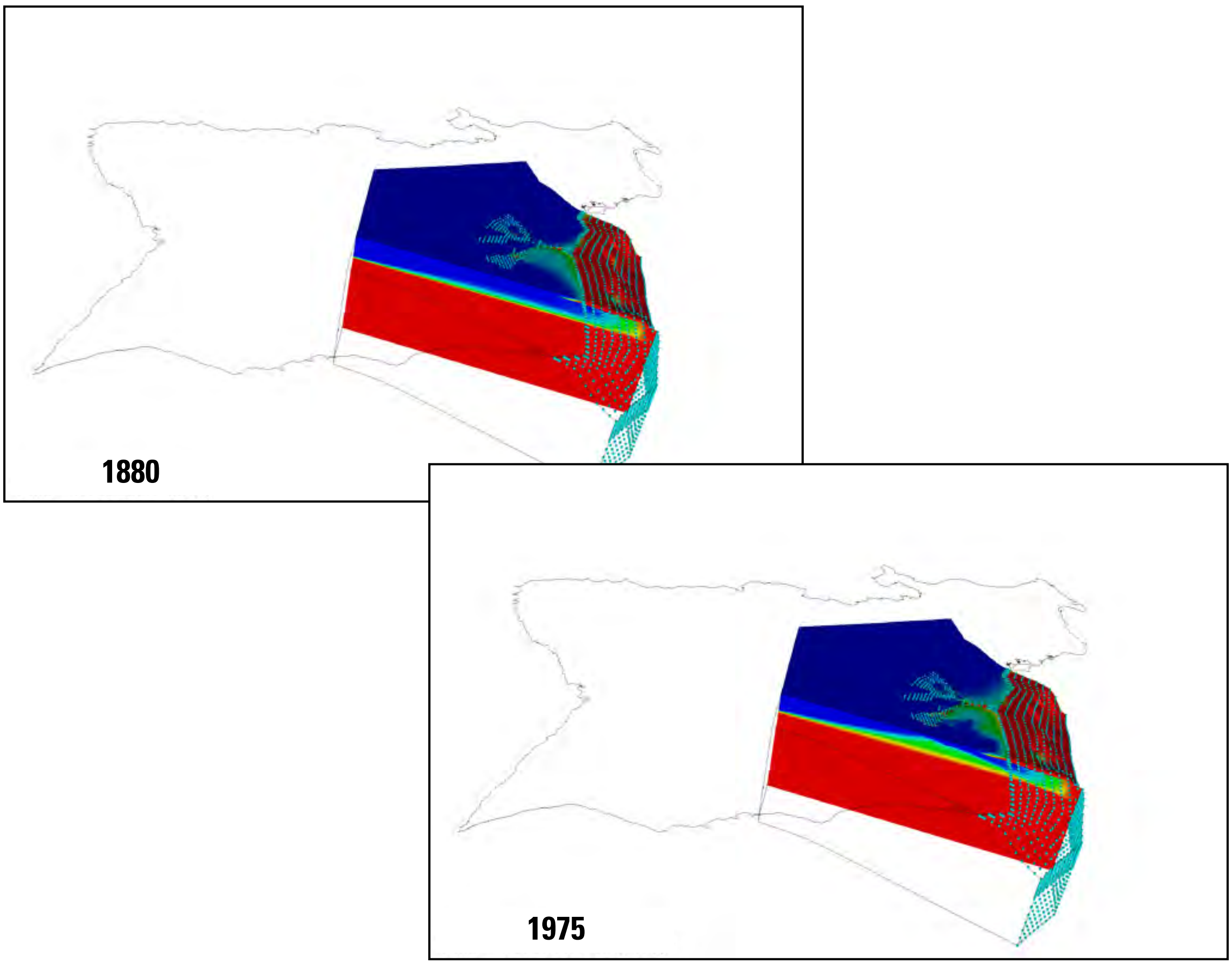
Numerical Simulation of the Effects of Low-Permeability Valley-Fill Barriers and the Redistribution of Ground-Water Withdrawals in the Pearl Harbor Area, Oahu, Hawaii



Scientific Investigations Report 2005-5253

U.S. Department of the Interior
U.S. Geological Survey

About the cover: The simulated distribution of salinity in the western part of the Pearl Harbor area is shown for predevelopment conditions (1880) and for the peak development period (1975), when the brackish-water transition zone rose in response to withdrawals.

Numerical Simulation of the Effects of Low-Permeability Valley-Fill Barriers and the Redistribution of Ground-Water Withdrawals in the Pearl Harbor Area, Oahu, Hawaii

By Delwyn S. Oki

Prepared in cooperation with the Honolulu Board of Water Supply

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U.S. Department of the Interior
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Gale A. Norton, Secretary

U.S. Geological Survey
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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per hour (in/h)	25.4	millimiter per hour (m/h)
inch per week (in/week)	25.4	millimeter per week (mm/week)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
	Pressure	
atmosphere, standard (atm)	101.3	kilopascal (kPa)
bar	100	kilopascal (kPa)
pound per square foot (lb/ft^2)	0.04788	kilopascal (kPa)
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Leakance	
foot per day per foot [(ft/d)/ft]	1	meter per day per meter
	Dynamic viscosity	
slug per foot per second (slug/ft/s)	47.88	pascal-sec (Pa-s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F–32)/1.8

Vertical coordinate information is referenced to mean sea level.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Numerical Simulation of the Effects of Low-Permeability Valley-Fill Barriers and the Redistribution of Ground-Water Withdrawals in the Pearl Harbor Area, Oahu, Hawaii

By Delwyn S. Oki

Abstract

The aquifer in the Pearl Harbor area of southern Oahu is the most heavily used aquifer in the State of Hawaii, producing more than 200 million gallons per day during the 1970s when sugarcane was actively cultivated, and more recently, about 100 million gallons per day during 2000. The aquifer has been divided by the State into three hydrologically connected management systems: the Ewa-Kunia system in the west, the Waipahu-Waiawa system in the middle, and the Waimalu system in the east. During some periods, reported withdrawals from the Waimalu management system have exceeded the State's sustainable-yield estimate for this system of 45 million gallons per day. This has led to concern regarding potential saltwater-intrusion effects associated with long-term withdrawals from the Waimalu management system.

In the Waimalu management system, water levels and salinity may be influenced by valley-fill barriers associated with existing stream valleys. Valley-fill barriers are formed by low-permeability valley-fill deposits and weathered volcanic rocks beneath the valley-fill deposits, and impede lateral ground-water movement. The State's sustainable-yield estimates for the Pearl Harbor area do not account for the hydrologic effects of these barriers.

The objectives of this study are to (1) obtain a better understanding of the hydrologic effects of valley-fill barriers in the Pearl Harbor area, Oahu, Hawaii, (2) determine the possible effects of valley-fill barriers on water levels and salinity in the Pearl Harbor area using a three-dimensional, density-dependent ground-water flow model, and (3) estimate the effects of redistributing existing withdrawals on the freshwater resource.

A numerical finite-element ground-water model capable of simulating variable-density flow was developed to meet the study objectives. The model mainly used published estimates for the permeability, storage, and dispersivity values, and simulated water levels and salinity profiles that generally were in agreement with measured water levels and salinity profiles from representative wells in the modeled area. Model sensitivity analyses of valley-fill-barriers indicated that simulated water levels and salinity can be affected by the depth and length of the hypothesized valley-fill barriers.

The model constructed for this study was used to simulate the hydrologic effects of redistributing withdrawals in the Pearl Harbor area by reducing withdrawals in the eastern part of the Waimalu area and increasing withdrawals farther to the west by an equal amount. Simulation results from selected scenarios of redistributed withdrawal indicate that: (1) redistributing withdrawal from Halawa Shaft (2354-01) or the Kalauao Wells (2355-09 to -14), near the eastern part of the Waimalu management system, to Pearl City III (2557-03), near the western part of the Waimalu management system, results in a thickening of the freshwater zone east of Waimalu Stream and a thinning of the freshwater zone west of Waimalu Stream; (2) redistributing withdrawal from Halawa Shaft to Pearl City III results in greater thickening of the freshwater in the eastern part of the Waimalu management system relative to redistributing an equal amount of withdrawal from the Kalauao Wells to Pearl City III; (3) the extent of freshwater thickening in the eastern part of the Waimalu management system caused by reducing withdrawal from the area is directly related to the amount of the reduction; (4) the zone where freshwater thickens in response to reducing withdrawal from a well is greatest downgradient from the well, between the well and the shore; and (5) valley-fill barriers can potentially reduce the zone where freshwater thickness increases in response to reduced withdrawals.

The numerical model developed for this study simulates regional water levels and salinity and may not accurately simulate salinity of water pumped from individual wells. Salinity of water pumped by a well may be controlled by local heterogeneities in the aquifer that are not represented in the model. The model has several other limitations for predictive purposes because of the various assumptions used and possible uncertainties in input data (for example, recharge, withdrawals, boundary conditions, and parameter values). Model reliability can be enhanced as our understanding of ground-water recharge, the distribution of model parameter values, and the geometry of the valley-fill barriers improves, and as numerical modeling technology improves.

Introduction

The aquifer in the Pearl Harbor area (fig. 1) of southern Oahu is the most heavily used aquifer in the State of Hawaii. In 1979, the Hawaii Board of Land and Natural Resources designated the Pearl Harbor area as a Ground-Water Management Area. With this designation, the State was authorized to protect the ground-water resource by managing ground-water withdrawals from the aquifer through a permitting process. For management purposes, the Hawaii Commission on Water Resource Management (CWRM) has divided the Pearl Harbor area into three hydrologically connected systems. From west to east, these management systems are the Ewa-Kunia system, the Waipahu-Waiawa system, and the Waimalu system (fig. 1).

During 2001, reported withdrawals from the Waimalu management system averaged 46.5 million gallons per day (Mgal/d) (unpub. data, Hawaii Commission on Water Resource Management). Ground-water withdrawal from the Waimalu management system was slightly higher than the CWRM sustainable-yield estimate of 45 Mgal/d for the area. This led to concern regarding potential saltwater-intrusion effects associated with long-term withdrawals from the Waimalu management system.

The aquifer in the Pearl Harbor area is formed mainly by gently dipping lava flows extending from land surface to thousands of feet below sea level, with a number of geologic barriers controlling regional ground-water flow. Volcanic rift zones contain thousands of nearly vertical, low-permeability dikes that cut across existing lava flows and impound water in numerous compartments (Takasaki and Mink, 1985). Low-permeability valley-fill deposits and weathered volcanic rocks beneath the valley-fill deposits impede ground-water movement and can create differences in ground-water levels on opposite sides of the valley. In the Waimalu management system, ground-water flow may be influenced by valley-fill barriers associated with existing stream valleys. The CWRM sustainable-yield estimate for this area does not account for the hydrologic effects of these barriers.

In cooperation with the City and County of Honolulu Board of Water Supply (BWS), the U.S. Geological Survey (USGS) undertook an investigation to evaluate the possible hydrologic effects of valley-fill barriers in the Pearl Harbor area. The objectives of this study are to (1) develop a better understanding of the hydrologic effects of valley-fill barriers in the Pearl Harbor area, (2) determine the possible effects of valley-fill barriers on water levels and salinity in the Pearl Harbor area, and (3) estimate the effects of redistributing existing withdrawals on the freshwater resource.

This report describes (1) information related to valley-fill barriers in the Pearl Harbor area, including water-level data collected as part of this study, (2) development of a numerical ground-water flow and transport model, and (3) results of model simulations to assess the hydrologic effects of low-permeability valley-fill barriers and the effects of redistributing withdrawals on water levels and salinity in the Waimalu management system of the Pearl Harbor area.

Acknowledgments.—The author is grateful to the Honolulu Board of Water Supply for providing invaluable data and access to monitor wells during the study. The cooperation of the Honolulu Board of Water Supply, Hawaii Commission on Water Resource Management, U.S. Navy Public Works Center, and U.S. Air Force (through their consultant URS Corp.) made it possible to conduct synoptic water-level surveys of the Pearl Harbor area in a timely manner. Paul R. Eyre of the U.S. Navy Public Works Center coordinated a shut down of the Waiawa Shaft to investigate water-level recovery on opposite sides of Waiawa Stream valley. Patrice Tottori Liu of Gentry Investment Properties facilitated access to a well on Gentry property for water-level-monitoring purposes, and Jeff A. Perreault (USGS) and Kenneth N. Natividad (USGS) helped in the collection of water-level data from selected wells. Finally, the author thanks Chien-Hwa (Max) Chen (USGS) for characterizing areas of pineapple and sugarcane cultivation for this study.

Setting

The island of Oahu (597 mi^2) is the third largest island of the State of Hawaii (Juvik and Juvik, 1998) and 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 (fig. 1). A gently sloping saddle, the Schofield Plateau, lies between the two mountain ranges.

The Pearl Harbor study area is in the southern part of Oahu's central corridor between the Koolau and Waianae Ranges (fig. 1). The study area is bounded on the northeast by the crest of the Koolau Range, on the southeast by the ridge (and flatter area near the coast) between South Halawa and Moanalua Stream valleys, on the south by the coast, on the west by the crest of the Waianae Range, and on the north by the approximate southern boundary of the Schofield ground-water area. The Schofield ground-water area is north of the Pearl Harbor area and is separated from the Pearl Harbor area by the southern Schofield ground-water dam, which is a natural feature of unknown structural origin (see for example Oki, 1998). The study area is formed by the Ewa-Kunia, Waipahu-Waiawa, and Waimalu aquifer-management systems defined by the CRWM (fig. 1). The management areas defined by the CWRM do not necessarily coincide with aquifer boundaries (Hunt, 1996). Thus, the boundaries of the study area do not coincide with hydrogeologic boundaries used in the numerical ground-water model in this study.

Topography within the Pearl Harbor study area ranges from a broad flat coastal plain to steep interior mountains. Topography of the island affects climate, which generally is characterized by mild temperatures, cool and persistent northeasterly trade winds, and large spatial variations in rainfall (fig. 2).

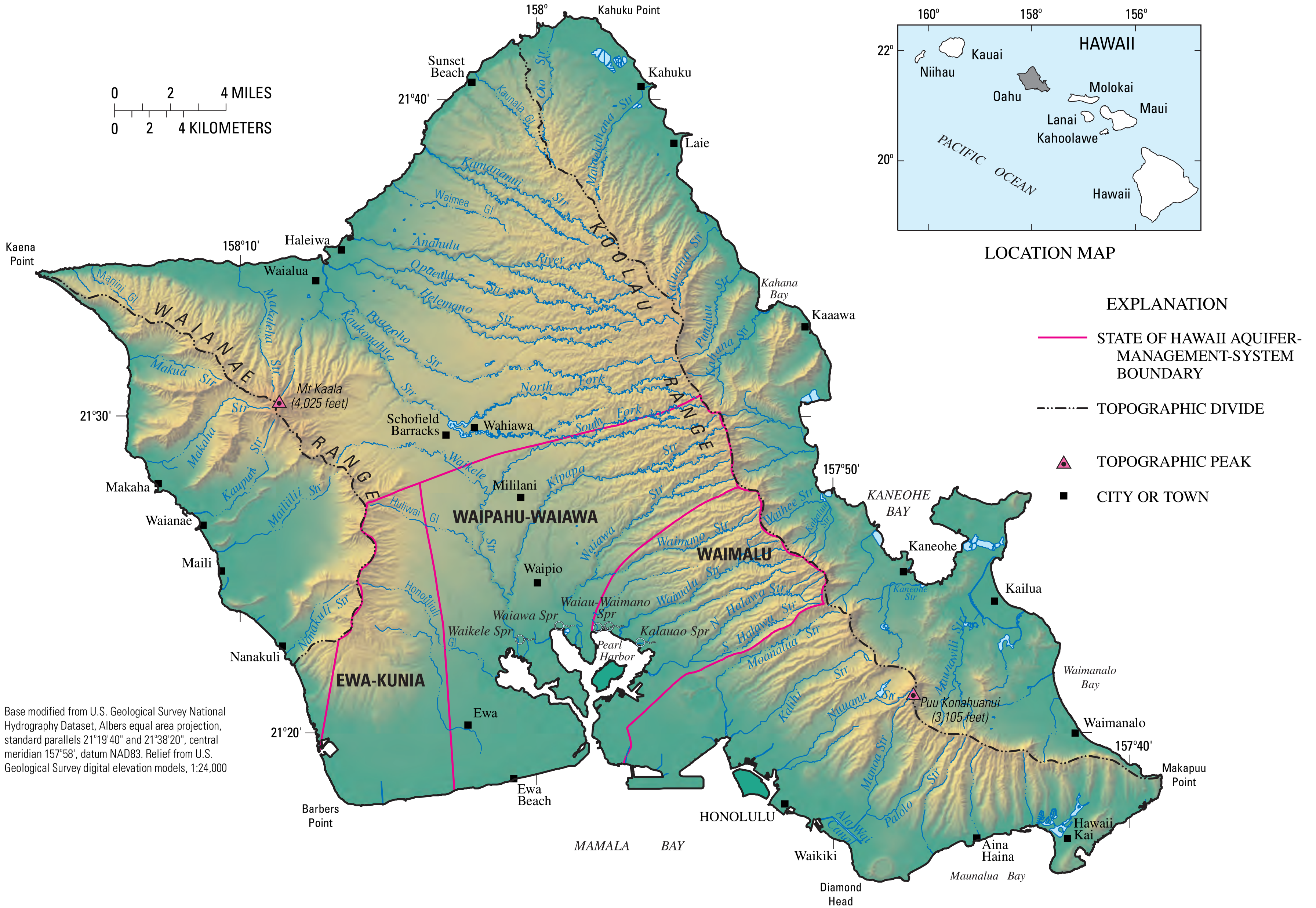


Figure 1. State of Hawaii aquifer-management systems (Ewa-Kunia, Waipahu-Waiawa, and Waimalu) in the Pearl Harbor area and other geographic features, Oahu, Hawaii.

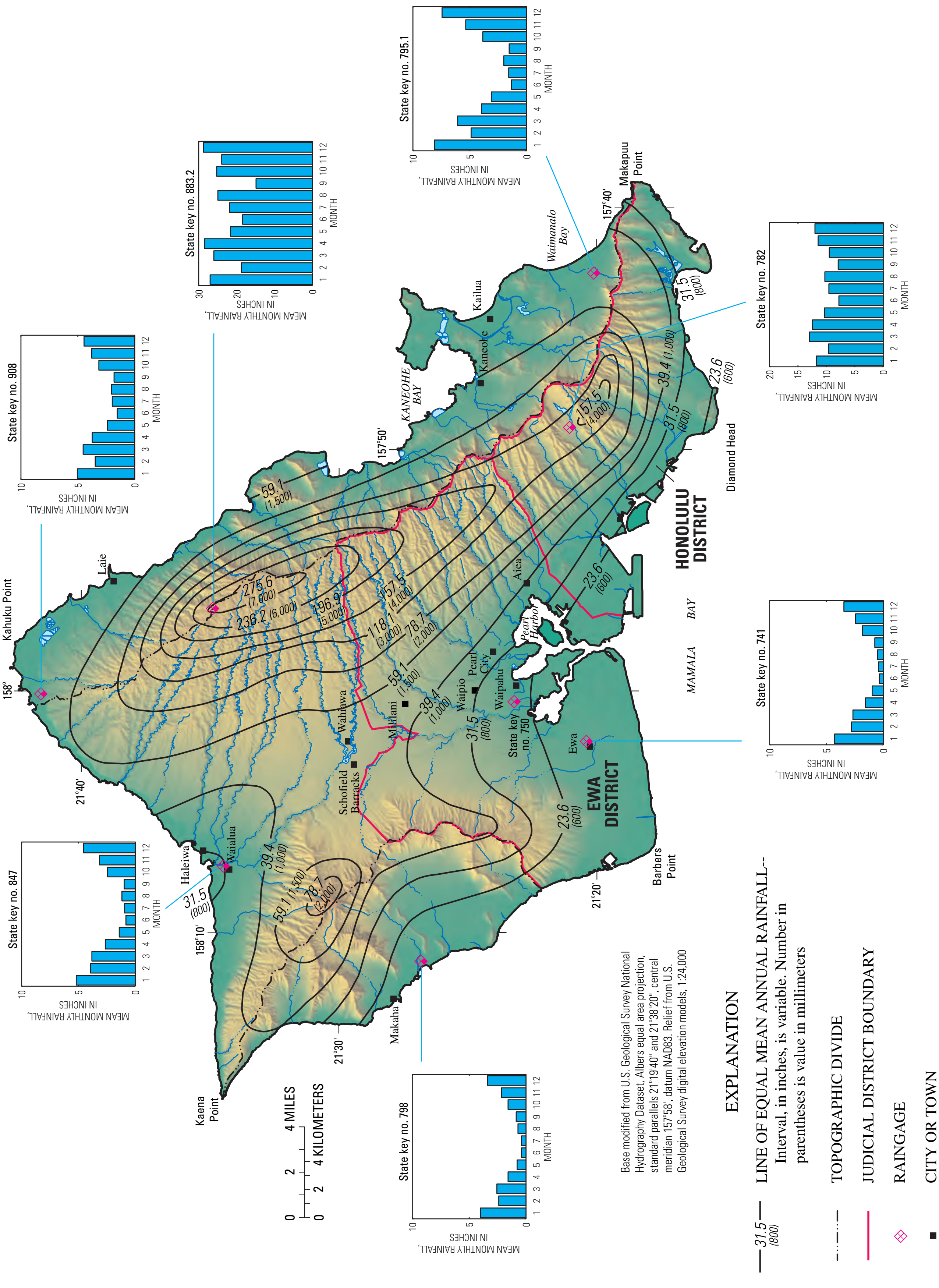


Figure 2. Mean annual rainfall, Oahu, Hawaii, and mean monthly rainfall at selected rain gages (modified from Giambelluca and others, 1986).

Land Use

Gently sloping areas in the central and southern parts of the Pearl Harbor area were used extensively for sugarcane cultivation that was made possible by the discovery of artesian ground water during 1879 beneath the dry, southwestern coastal plain. Following the 1995 closure of the last remaining sugarcane plantation in the Pearl Harbor area, much of the former sugarcane lands was urbanized or used for diversified agriculture.

During the 20th century, land-use patterns on Oahu reflected increases in population and decreases in large-scale agricultural operations over time. The resident population on Oahu increased from 58,504 in 1900, to 876,156 in 2000 (State of Hawaii, 2000). In 2000, about 72 percent of the State's population resided on Oahu, and more than 40 percent of the residents on Oahu were in the Honolulu District. In recent years, the population in the Ewa District (fig. 2) has increased significantly as large-scale agricultural operations in this area have been replaced by urban developments. Between 1980 and 2000, the resident population in the Ewa District increased 43 percent, from 191,051 to 272,328. For comparison, between 1980 and 2000, the population in the Honolulu District increased only 2 percent, from 365,048 to 372,279 (State of Hawaii, 2000).

Toward the latter part of the 20th century, the general trend of land use on Oahu shifted from large-scale plantation agriculture to urban land use and diversified agriculture. Although two large pineapple plantations continue to operate in central Oahu, some of the land previously used for pineapple cultivation in the Pearl Harbor area has been developed for urban uses. A description of land use on Oahu during 1998 is provided by Klasner and Mikami (2003).

Sugarcane Cultivation

Prior to 1879, lack of a reliable source of irrigation water precluded large-scale sugarcane cultivation in the Pearl Harbor area. The 1879 discovery of artesian ground water beneath the dry, southwestern coastal plain of Oahu made it possible for sugarcane cultivation to expand to the Pearl Harbor area. Areas of sugarcane cultivation varied over time (fig. 3) until 1995, when Oahu Sugar Company ceased operations.

In the Pearl Harbor area, sugarcane generally was grown at altitudes of a few feet to about 700 ft. Sugarcane cultivation practices varied among the plantations and were dependent on the variety of sugarcane as well as local field conditions. Sugarcane was grown year-round, and generally was harvested on a 2-yr crop cycle. A crop was initiated with the planting of sugarcane seeding stalks. One or two ratoon crops generally followed the initial crop. Prior to the 1970s, the main method of irrigation on Oahu was the furrow method, in which water was delivered to the fields through a system of ditches and in-field furrows. Fields generally were irrigated with the furrow method between 20 and 40 times over the 2-yr crop cycle, with each application requiring from 4 to 10 in. of water over the field (Yim and Dugan, 1975). Dale (1967) estimated that an average of about 112 in/yr of irrigation water was applied with the furrow method in southern Oahu between 1931 and 1965. Estimates of the irrigation efficiency (ratio of water volume used by the crop to water volume applied) for the furrow method range from about 0.3 to 0.7 (Dale, 1967; Fukunaga, 1978; Giambelluca, 1983; Mink, 1980; Nichols and others, 1996). Giambelluca (1983) estimated that ground-water recharge from furrow-irrigated sugarcane in the Pearl Harbor area averaged 87.3 in/yr, although Nichols and others (1996) estimated a much lower rate.

Although overhead sprinkler systems were introduced on Oahu during the 1960s to improve irrigation efficiency (Hall, 1965), the drip-irrigation method began replacing the furrow method during the 1970s (Gibson, 1979). Estimates of the irrigation efficiency with the drip method range from about 0.80 to 0.95 (Fukunaga, 1978). The drip method uses lateral tubes with small emitters that are spaced to deliver water to the plants and maintain adequate soil moisture in the plant root zone. With the drip method, water was applied daily during peak-use periods at a rate of about 0.03 in/hr over a 12-hour period (Yamauchi and Bui, 1990). Irrigation generally was discontinued 2 to 3 months before harvest to enhance sugar storage in the plant (Yim and Dugan, 1975). Using recharge estimates from Giambelluca (1983), Shade and Nichols (1996) developed a relation between rainfall and recharge (both expressed in terms of in/yr) for drip-irrigated sugarcane in the Pearl Harbor area:

$$\text{Recharge (sugarcane, drip)} = 0.64 \cdot \text{Rainfall} + 11.1 \quad (1)$$

Pineapple Cultivation

During the 20th century, large-scale pineapple cultivation on the island mainly was in central Oahu on three plantations, although only two plantations remain as of 2005 (Dole Food Co., Inc. and Del Monte Corp.). Areas of pineapple cultivation in the Pearl Harbor area varied over time (fig. 3). Much of the land that previously was used for pineapple cultivation in the central part of the Pearl Harbor area now is used for other purposes, including urban developments.

Pineapples are grown year-round on Oahu, and fields are replanted every three to five years. The initial crop, which is harvested about 18 months after planting, is followed by one or two ratoon crops before the land is prepared for the next planting. Pineapples require much less water than sugarcane, and can be grown in areas of low to moderate rainfall with limited or no irrigation. Irrigation is applied using overhead sprinklers during periods of low rainfall or through drip-irrigation lines at the rate of about 0.25 in. per week (State of Hawaii, 1983). Most pineapples on Oahu have been cultivated in central Oahu at higher altitudes than areas of sugarcane cultivation.

Pineapple plants suppress evapotranspiration and enhance recharge relative to non-xerophytic plants. Using recharge

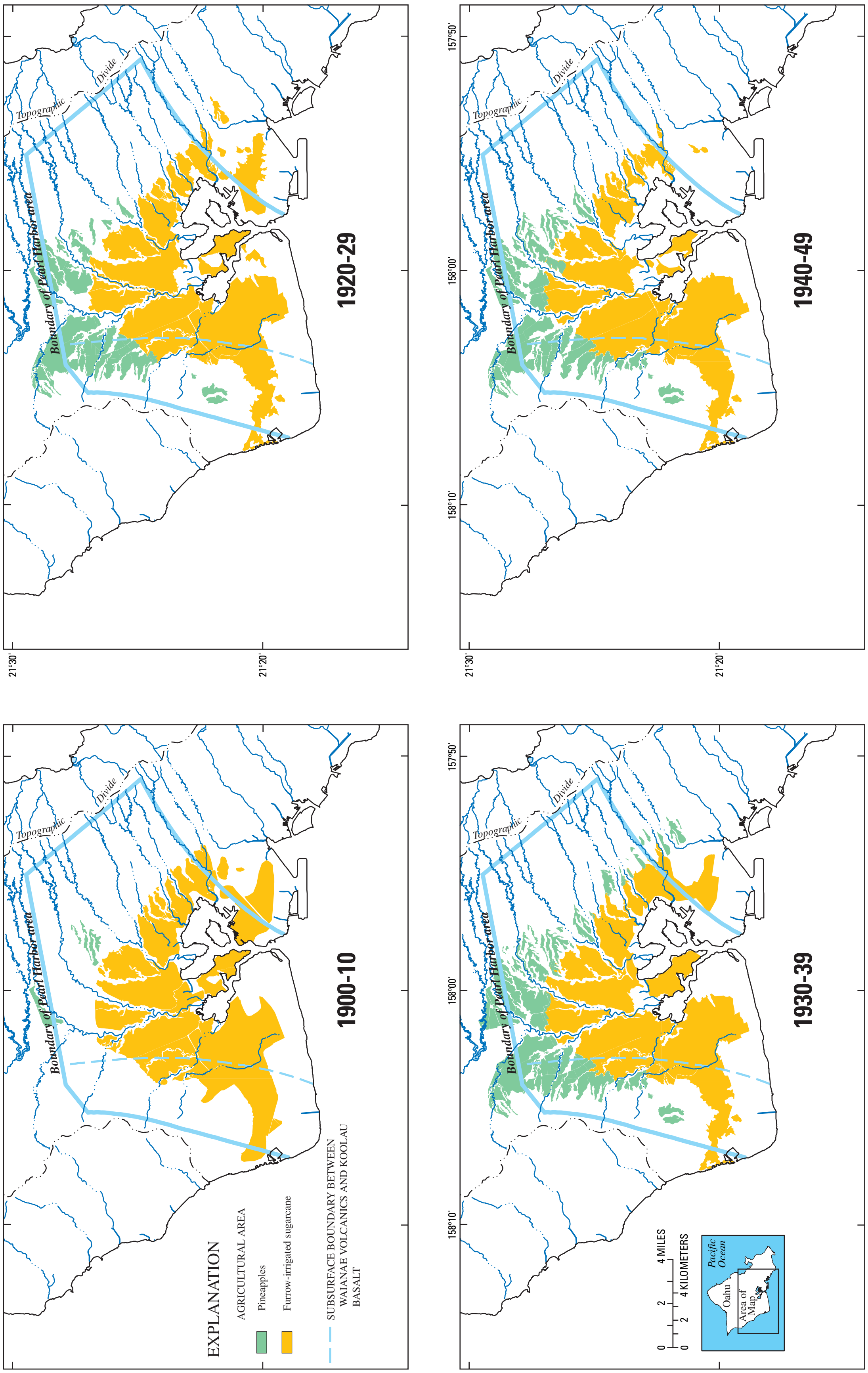


Figure 3. Areas of sugarcane and pineapple cultivation during selected periods from 1900 to 2000 in the Pearl Harbor area, Oahu, Hawaii.

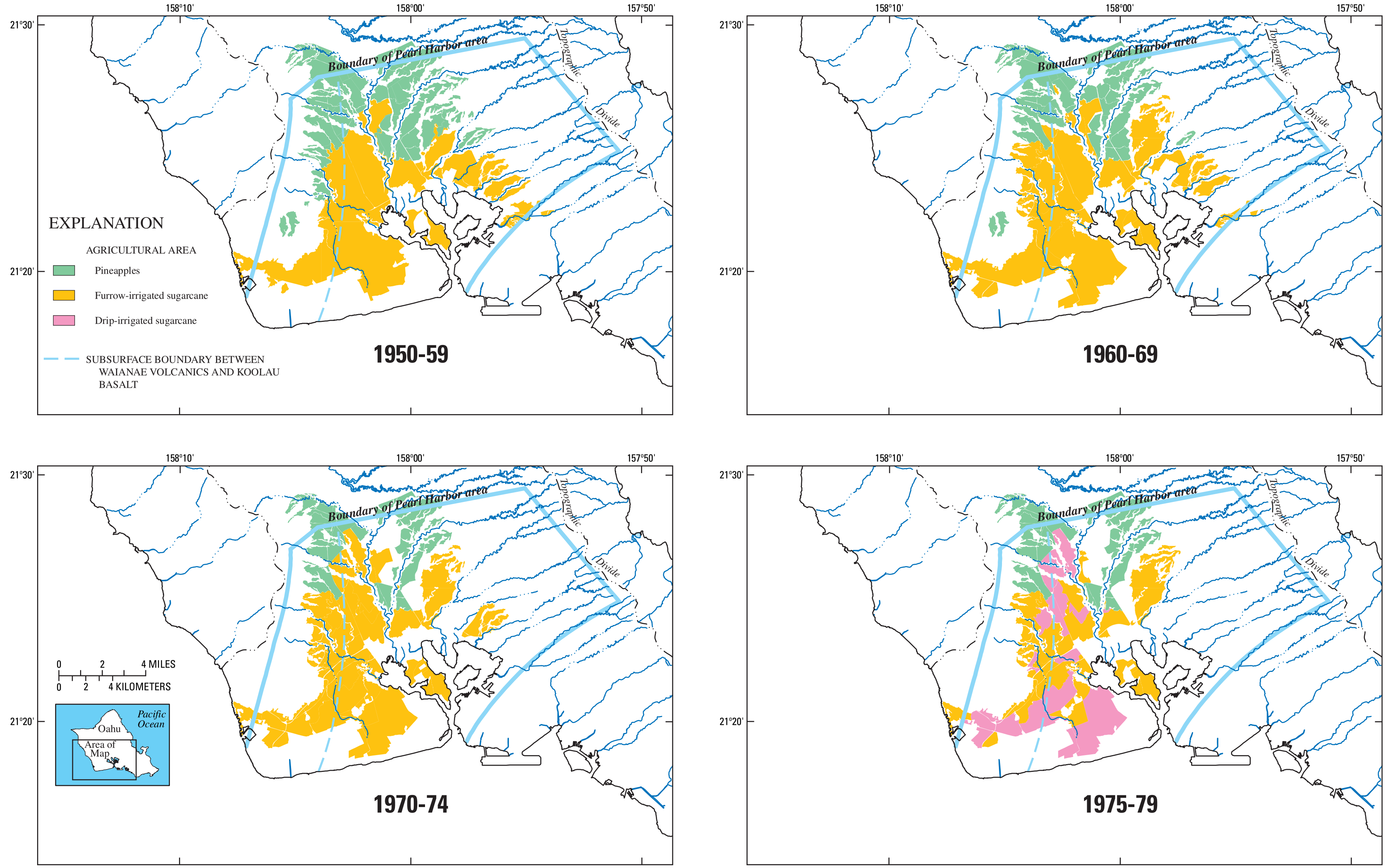


Figure 3. Areas of sugarcane and pineapple cultivation during selected periods from 1900 to 2000 in the Pearl Harbor area, Oahu, Hawaii—*Continued*.

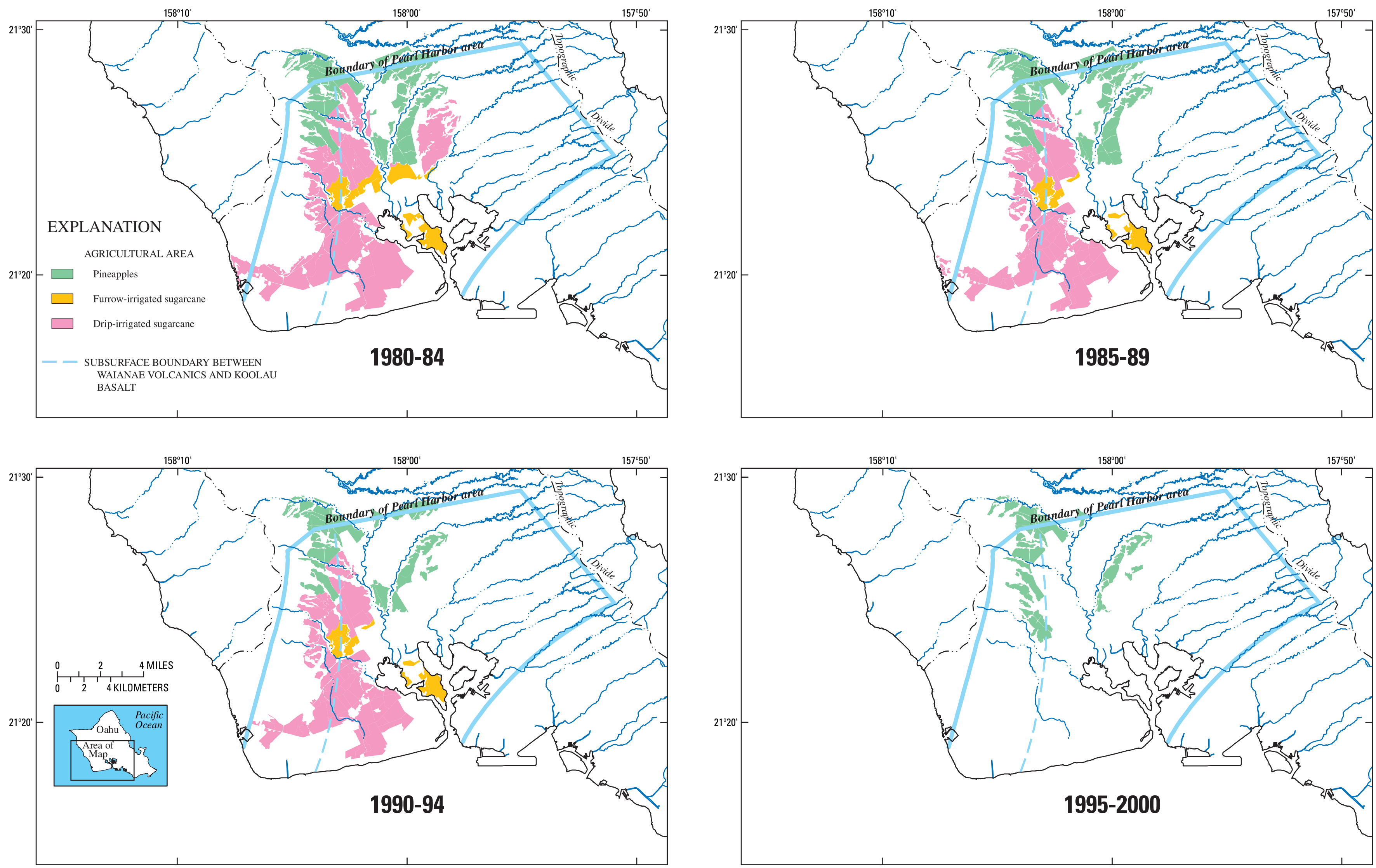


Figure 3. Areas of sugarcane and pineapple cultivation during selected periods from 1900 to 2000 in the Pearl Harbor area, Oahu, Hawaii—*Continued.*

estimates from Giambelluca (1983), Shade and Nichols (1996) developed a relation between rainfall and recharge (both expressed in terms of in/yr) for areas of pineapple cultivation in the Pearl Harbor area:

$$\text{Recharge (pineapple)} = 0.935 \cdot \text{Rainfall} - 13.54 \qquad (2)$$

Climate

Mild temperatures, cool and persistent northeasterly winds, a rainy season from October through April, and a dry season from May through September characterize the climate of Oahu (Blumenstock and Price, 1967; Sanderson, 1993). Topography and the location of the north Pacific anticyclone relative to the island primarily control the climate of Oahu. During the dry season, the stability of the north Pacific anticyclone produces persistent northeasterly winds, known locally as trade winds, that blow 80 to 95 percent of the time. During the rainy season, migratory weather systems often move past the Hawaiian islands, resulting in less persistent trade winds that 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 can receive most of their rainfall from these low-pressure systems. During heavy storms, 24-hour rainfall can exceed 10 in. over coastal areas and 20 in. over the mountainous interior of the Koolau Range (Giambelluca and others, 1984).

Rainfall

Rainfall on Oahu is characterized by maxima at high altitudes and steep spatial gradients (fig. 2). Maximum mean annual rainfall is near the topographic crest of the Koolau Range and exceeds 275 in. (Giambelluca and others, 1986). Over the Waianae Range, the maximum mean annual rainfall is about 80 in. near Mount Kaala. Over the southwestern coastal parts of the Pearl Harbor area, mean annual rainfall is less than 25 in. Mean annual rainfall changes significantly over short distances; on the Koolau Range, this change can be about 80 in. over a distance of one mile.

The windward (northeastern) side of the island is wettest. This pattern is controlled by the orographic lifting of moisture-laden northeasterly trade winds along the windward slope of the Koolau Range, which is oriented roughly perpendicular to the direction of the trade winds. The moisture-laden air mass cools as it ascends the slopes of the Koolau Range, resulting in condensation, cloud formation, and high rainfall near the crest of the Koolau Range. Following its descent along the leeward slopes of the Koolau Range, the partially desiccated air ascends the slopes of the Waianae Range, which results in a smaller rainfall maximum near Mount Kaala. Because the air loses moisture during its ascent over a mountain, the driest areas on Oahu are near the coast on the leeward (southwest) sides of the Koolau and Waianae Ranges. This is commonly known as the rain-shadow effect.

Pan Evaporation

Pan evaporation generally is the main measurement used in Hawaii to assess the amount of water loss by evapotranspiration, which is the loss of water to the atmosphere by the combination of transpiration of plants and direct evaporation from plant, land, and water surfaces. Evapotranspiration is a major component of the hydrologic budget on Oahu. In the Pearl Harbor area, for example, evapotranspiration was estimated to be greater than 50 percent of the total water (rainfall plus irrigation) falling on or applied to the ground surface during 1946-75 (Giambelluca, 1983).

Over Oahu, pan evaporation minima exist at the higher altitudes of the Koolau and Waianae Ranges (fig. 4). 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, where they may exceed 90 in/yr. For comparison, the computed evaporation rate over the open ocean is 65 in/yr (Seckel, 1962). As with rainfall, the spatial distribution of pan evaporation on Oahu is related to topography. At high altitudes (where sunlight intensity is reduced because of clouds, humidity is high, and temperatures are low), pan-evaporation rates are reduced to 30 percent of the open-ocean rate. Pan evaporation rates along the southern coast of Oahu exceed the open-ocean rate due to heat advection. Evaporation rates are highest during the drier summer months when maximum sunlight and trade-wind flow also are highest (Ekern and Chang, 1985).

Geology

The geology of Oahu has been described by numerous investigators (see for example Macdonald and others, 1983; Palmer, 1927; Palmer, 1946; Stearns, 1985; Stearns and Vaksvik, 1935; Wentworth, 1951; Wentworth and Winchell, 1947; Winchell, 1947). Stearns (1939) published a detailed geologic map of Oahu. Langenheim and Clague (1987) described the stratigraphic framework of volcanic rocks for the entire island of Oahu. Presley and others (1997) revised the stratigraphic nomenclature for Waianae Volcano. A brief description of the geologic setting of Oahu follows.

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). Each volcano has two primary rift zones and a third lesser rift zone, all emanating from a collapsed caldera (fig. 5). The primary rift zones of the Waianae Volcano trend roughly northwest and south, and the third, lesser rift zone trends northeast. The primary rift zones of the Koolau Volcano trend northwest and southeast, and the third, subordinate rift zone trends southwest. The rift zones are marked by numerous vertical to nearly vertical intrusive dikes (Takasaki and Mink, 1985; Walker, 1987).

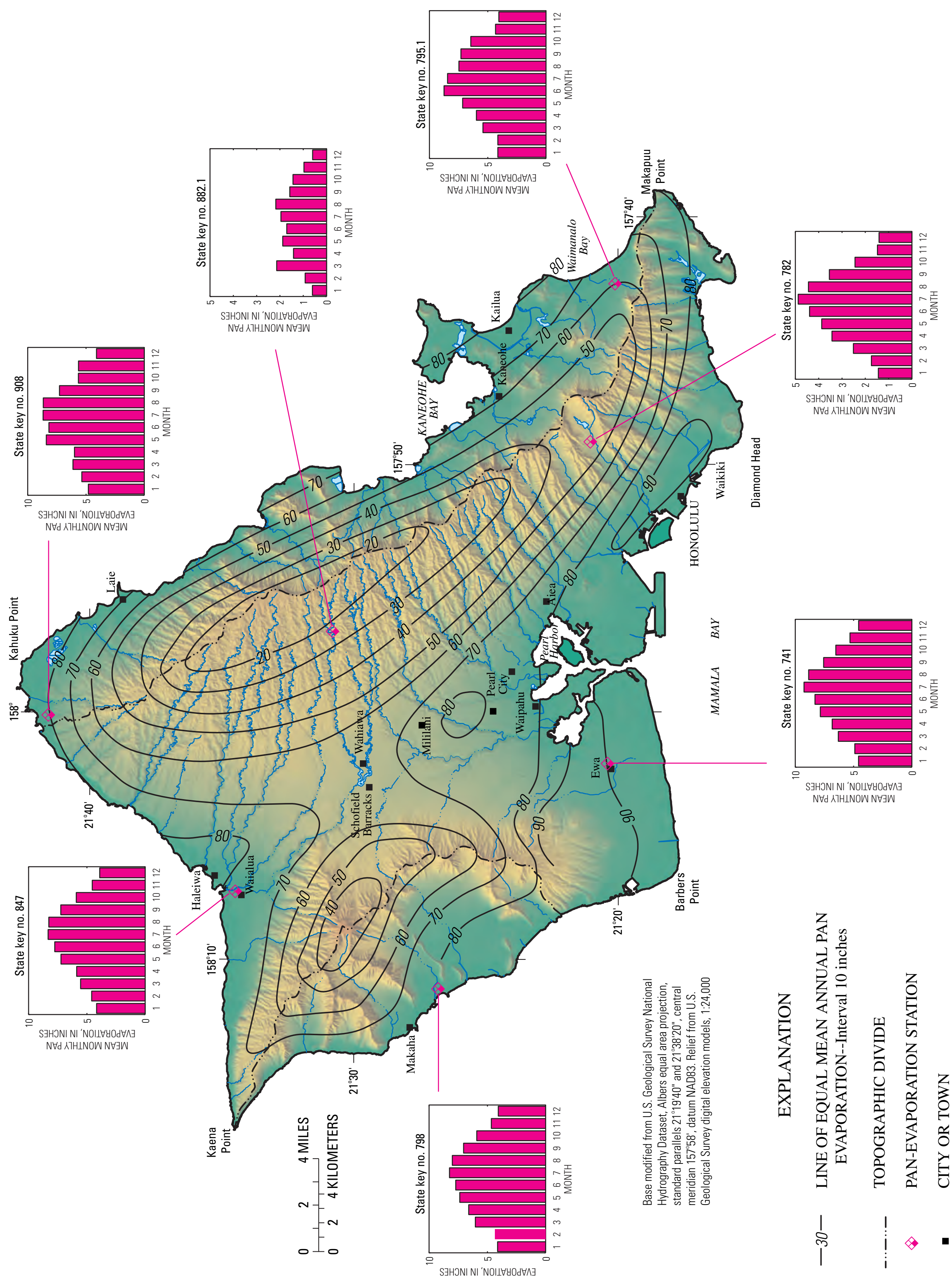


Figure 4. Mean annual pan evaporation, Oahu, Hawaii, and mean monthly pan evaporation at selected stations (modified from Ekern and Chang, 1985).

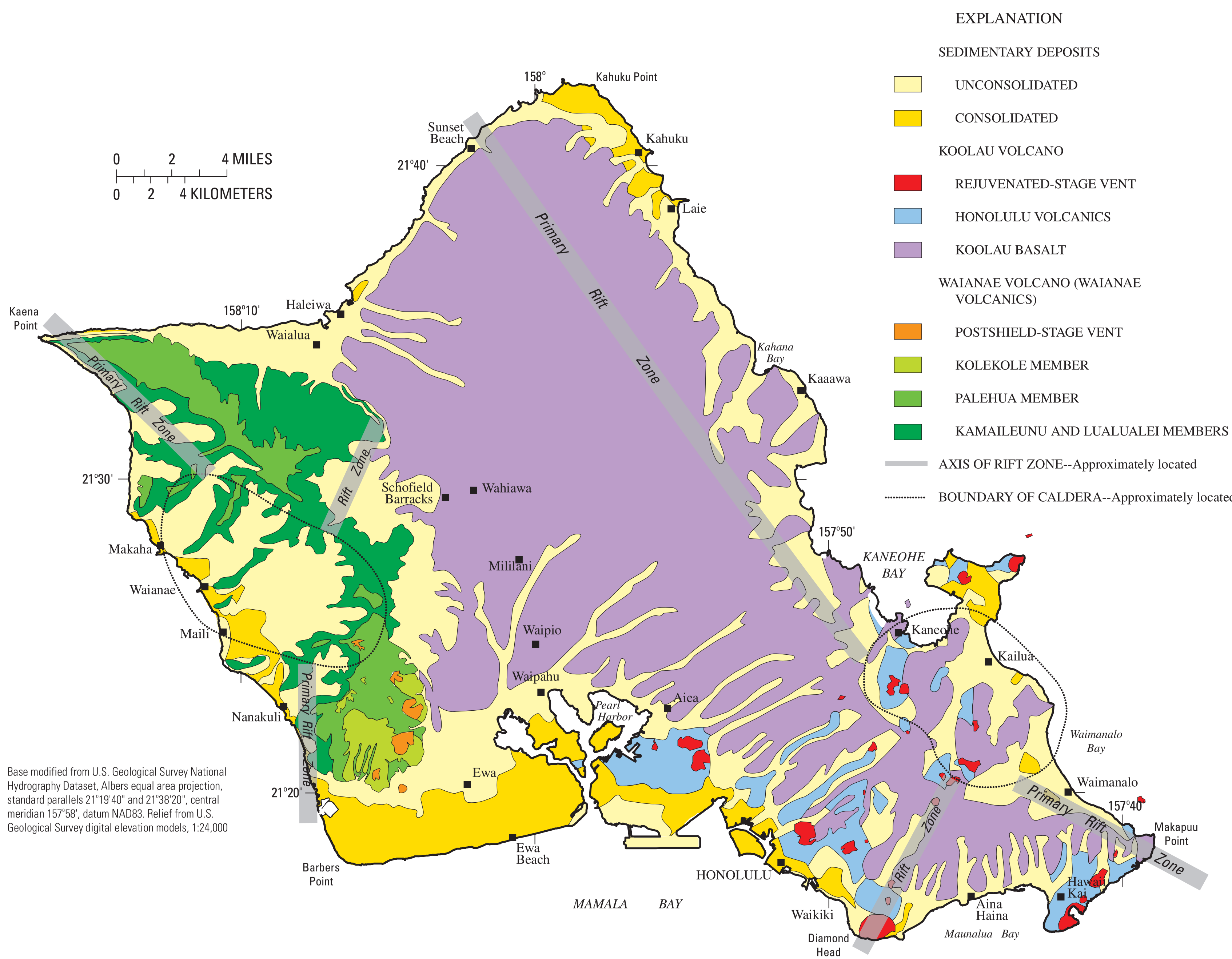


Figure 5. Generalized surficial geology, Oahu, Hawaii (modified from Stearns, 1939; Langenheim and Clague, 1987; Presley and others, 1997).

Waianae Volcano

The Waianae Volcano is made up of the Waianae Volcanics that includes (1) the shield-stage lavas (Lualualei Member) of tholeiitic basalt, (2) the transitional or late shield-stage lavas (Kamaileunu Member) of mainly tholeiitic basalt, alkalic basalt, hawaiite, and rare ankaramite, (3) the postshield-stage lavas (Palehua Member) of hawaiite with minor alkalic basalt and mugearite, and (4) the younger postshield-stage lavas (Kolekole Member) of alkalic basalt (Sinton, 1986; Presley and others, 1997). The lava flows from the shield-stage Lualualei Member are mainly thin-bedded pahoehoe, ranging in thickness from about 5 to 75 ft and averaging about 25 ft. Lava flows of the Lualualei Member typically have dips of 4–14°. Flows of the Kamaileunu Member are mainly pahoehoe and range in thickness from 10 to 120 ft, averaging about 40 ft. Flows of the Palehua Member are mainly aa and commonly have thicknesses ranging from 50 to 100 ft (Stearns and Vaksvik, 1935; Macdonald, 1940).

Potassium-argon dating of the Waianae Volcanics indicates an age of about 2.9 to 3.9 Ma, corresponding to the Pliocene epoch (Doell and Dalrymple, 1973; Presley, 1994; Presley and others, 1997). Exposed rocks of the Lualualei Member have ages of about 3.54 to 3.93 Ma, and exposed rocks of the Kamaileunu Member have ages of about 3.5 to 3.08 Ma (Guillou and others, 2000). Rocks of the Kolekole Member have an age of about 2.90 to 2.97 Ma (Presley and others, 1997).

Koolau Volcano

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 consists 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), corresponding to the Pliocene epoch. The lava flows from the shield-stage Koolau Basalt are typically thin-bedded, with an average thickness of about 10 ft, and dip 3 to 10 degrees (Stearns and Vaksvik, 1935). Few soil or tuff layers interrupt the sequence of shield-stage lavas. Wentworth (1951) estimated that throughout the volcano, tuff lenses make up less than 1 or 2 thousandths of the section.

During the shield stage, lava flowing westward from the Koolau Volcano was deflected northward and southward by the preexisting Waianae Volcano. The central saddle area between the two volcanoes was formed by Koolau Basalt banking up against and being deflected by the Waianae Volcano. Within the central saddle, dips of the Koolau Basalt are invariably less than 5 and rarely more than 3 degrees (Stearns and Vaksvik, 1935, p. 34).

The Honolulu Volcanics 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 is of limited areal extent and is most notably marked by tuff cones such as Diamond Head, Punchbowl, and Koko Head. However, the Honolulu Volcanics also consists 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) corresponding to the Pleistocene epoch. Age dates for the same flow, however, vary by an order of magnitude (Macdonald and others, 1983).

Volcanic-Rock Types

Volcanic rocks in Hawaii can be divided into three main groups on the basis of modes of emplacement: lava flows, dikes, and pyroclastic deposits. Lava flows that erupt from rift zones are either pahoehoe, which is characterized by smooth or ropy surfaces, or aa, which contains a massive central core sandwiched between rubbly clinker layers. Aa flows are typically more abundant at greater distances from eruptive centers (Lockwood and Lipman, 1987).

Dikes are thin, near-vertical sheets of massive rock that intrude existing rocks, such as lava flows. Dikes are commonly exposed by erosion within the rift zones of volcanoes, including the Waianae and Koolau Volcanoes (see for example Takasaki and Mink, 1985; Walker, 1987). In the central part of a rift zone, known as the dike complex, dikes may number as many as 1,000 per mile of distance and compose 10 percent or more of the total rock volume (Takasaki and Mink, 1985). The number of dikes decreases toward the outer edges of a rift zone. At the outer part of the rift zone, within the marginal dike zone, dikes usually constitute less than 5 percent of the total rock volume (Takasaki and Mink, 1985).

Pyroclastic rocks form by explosive volcanic activity and are deposited by transport processes related to this activity. Pyroclastic rocks, such as ash, cinder, and spatter, can be deposited during all of the subaerial stages of eruption and probably form less than 1 percent of the mass of a Hawaiian volcano (Wentworth and Macdonald, 1953).

Geologic Modification Processes

The volcanoes that formed Oahu have undergone significant modification by processes such as subsidence, weathering, erosion, and deposition. These processes have played an important role in defining the geohydrologic setting of the Pearl Harbor area.

Subsidence.—Subsidence of Oahu was contemporaneous with shield development. Moore (1987) estimated that most Hawaiian volcanoes have subsided 6,500 to 13,000 ft since reaching the ocean surface. Andrews and Bainbridge (1972) suggested that submarine valleys off the northeastern coast of Oahu were originally subaerial features that have drowned as the island subsided. Some of these submarine valleys can be traced to depths of at least 6,600 ft below sea level (Shepard and Dill, 1966), which may indicate that Oahu has subsided at least 6,600 ft relative to modern sea level. Hunt (1996) indicated that subsidence of Oahu occurred mainly prior to rejuvenated Koolau volcanism because Honolulu Volcanics either lies on or is intercalated only with the uppermost of the sedimentary units on the coastal plain.

Weathering and Erosion.—The processes of weathering and erosion contribute to the down-cutting of the original volcanic domes that formed Oahu. Although erosion can occur in the absence of weathering, weathering processes that break or soften rocks commonly enhance erosion.

Chemical weathering is the dominant weathering process on the island. Decomposition of rocks by chemical weathering is enhanced by high rainfall, abundant vegetation, and generally warm temperatures on Oahu. The effects of chemical weathering can extend to significant depths below the surface. The effects of chemical weathering proceed in a downward direction, resulting in a typical geologic profile consisting of several feet of soil and subsoil underlain by a few tens or hundreds of feet of saprolite, which is underlain by fresher volcanic rock. Saprolite is weathered rock retaining the structural and textural features of the parent rock. Hunt (1996) indicated that weathering intensity and saprolite thickness increase with rainfall, and estimated that saprolite is typically less than 100 ft thick in areas where rainfall is less than 50 in/yr and about 100 to 300 ft thick where rainfall is between 50 to 80 in/yr. Beneath stream channels, where percolating water is almost always present, depth of weathering may be considerably greater.

Erosion involves a group of processes that leads to the removal of earth materials from the surface. During the shield stage of volcanic activity, when the interval between successive lava flows is short, erosion of the land surface by streams likely is ineffective because the rocks generally are largely unaffected by weathering and highly permeable, and little rain runs off to the ocean. Following the shield stage of volcanic activity, however, during a period of volcanic quiescence, weathering of the land surface and erosion by streams can be significant. The rate of erosion by streams on Oahu has been estimated to range from about 1 to 6 in. per thousand years (Li, 1988). Erosion by streams has resulted in the formation of valleys that have been incised more than a thousand feet in the Koolau and Waianae Ranges. In general, the valleys in the Pearl Harbor area are in a youthful stage of dissection, and are narrow and V-shaped.

On Oahu, parts of the Waianae Volcano were eroded prior to being covered by Koolau Basalt. Thus, Waianae Volcanics is separated from Koolau Basalt 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 between the volcanoes because Koolau Basalt occupies a former amphitheater-headed valley.

Deposition.— Deposits of terrestrial and marine sediments and reef limestone form a coastal plain of varying width along the shore of Oahu. The coastal plain extends more than 5 mi inland near Pearl Harbor. The onshore thickness of the coastal deposits generally is greatest at the coast and thins in an inland direction (Palmer, 1927; Palmer, 1946; Wentworth, 1951; Visher and Mink, 1964; Dale, 1978). The sedimentary wedge is more than 1,000-ft thick along the southern coast near the entrance to Pearl Harbor.

Hydraulic Properties of the Rocks

The hydraulic properties of the various rock types control the ground-water flow system in the Pearl Harbor area. From a ground-water development standpoint, the main part of the ground-water flow system in the area exists in the dike-free volcanic rocks outside of the dike-intruded rift zones. Some rocks tend to impede the flow of ground water more than others, thereby creating barriers to flow.

Hydraulic Conductivity

Hydraulic conductivity is a quantitative measure of the capacity of a rock to transmit water. Hydraulic conductivity is the constant of proportionality in Darcy's law, which relates specific discharge (discharge per unit area) to the hydraulic gradient:

$$v = -K(\mathrm{d}h/\mathrm{d}l), \qquad (3)$$

where

v = specific discharge [LT^{-1}],
K = hydraulic conductivity [LT^{-1}], and
$\mathrm{d}h/\mathrm{d}l$ = hydraulic gradient [LL^{-1}].

Darcy's law generally is assumed to be applicable to regional ground-water flow analyses in Hawaii (see for example Souza and Voss, 1987; Oki, 1998; Gingerich and Voss, 2005).

The hydraulic conductivity of a rock can be qualitatively described by permeability. Permeability describes the ease with which fluid can move through rock. The permeability of volcanic rocks is variable and depends on many factors, including the mode of emplacement and amount of weathering. Lava chemistry and topography also can affect permeability. Thicker flows generally are less permeable and form highly viscous lava on flat topography (Gingerich and Oki, 2000).

Dike-Free Volcanic Rocks.—The permeability of the subaerial, shield-building, dike-free lava flows in the Pearl Harbor area 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 contacts between flows, (3) cooling joints normal to flow surfaces, and (4) lava tubes associated with pahoehoe flows. The regional horizontal hydraulic conductivity of the dike-free volcanic rocks generally ranges from hundreds to thousands of feet per day (Soroos, 1973; Mink and Lau, 1980; Hunt, 1996). Because of the high permeability of the dike-free volcanic rocks, horizontal water-table gradients in these rocks are small (on the order of 1 ft/mi). Horizontal hydraulic conductivity in the lava flows may be anisotropic—several times greater parallel to the lava flows than perpendicular to the flows (see for example Nichols and others, 1996).

In general, the vertical hydraulic conductivity of the dike-free lava flows may be hundreds of times less than the horizontal hydraulic conductivity. On the basis of a numerical-model analysis of the Pearl Harbor area, Souza and Voss (1987) estimated the ratio of horizontal to vertical hydraulic conductivity to be 200 to 1.

*Dikes.—*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. Although the thickness of individual dikes generally is less than 10 ft, dikes are hydrologically significant because of their low permeability and their impounding effect on ground water. Ground-water levels in parts of the rift zone of the Koolau Volcano may be as high as 1,000 ft above sea level.

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 lava flows 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).

*Weathering.—*Weathering reduces the permeability of all types of volcanic rocks. The reduction of permeability may be attributed to secondary mineralization that 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 Corporation, 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 was attributed to the variability in macroporosity among samples.

*Older Alluvium.—*Wentworth (1951) classified the sedimentary rocks of Oahu into older, intermediate, and recent alluvial and marine formations. The sediments of greatest hydrologic significance are the old terrestrial sediments, which were created during the period of extensive erosion that carved deep valleys in the original volcanoes. Older 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 older alluvium is caused by a reduction of pore space from the volume increase associated with weathering as well as mechanical compaction (Wentworth, 1951).

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 Sedimentary Deposits.—*The sedimentary deposits and underlying weathered volcanic rocks of the coastal plain form a low-permeability confining unit, called caprock, that overlies high-permeability volcanic rocks and impedes the seaward discharge of freshwater from the volcanic-rock aquifers. The caprock of southern Oahu includes terrestrial alluvium, marine sediments, calcareous reef deposits, pyroclastic rocks of the Honolulu Volcanics, and highly weathered basalt (Visher and Mink, 1964). In addition, massive aa cores or pahoehoe flows that are located near the coastal discharge zones also may impede the seaward discharge of fresh ground water. Although the permeability of the various components of the coastal caprock may vary widely, from low-permeability older alluvium and saprolite to cavernous limestone deposits with a hydraulic conductivity of thousands of feet per day, the overall effect of the caprock is one of low permeability (Visher and Mink, 1964). Souza and Voss (1987) modeled a vertical cross section of the Pearl Harbor ground-water area and estimated a caprock hydraulic conductivity of 0.15 ft/d (0.0457 m/d). In their analysis, Souza and Voss treated the caprock as a homogeneous and isotropic unit, although significant heterogeneity may exist (Oki and others, 1998).

Storage

The effective porosity and specific storage of the rocks forming an aquifer affect the timing of the water-level response to natural or human-induced changes. The effective porosity represents that part of the total rock porosity that contributes to flow, and specific storage is a measure of the compressive storage of the rocks and fluid. Small values of effective porosity or specific storage will cause a rapid water-level response to changes in pumping or recharge, whereas large values of effective porosity or specific storage will cause a slow water-level response.

Total porosity of a rock is the ratio of the volume of void spaces to the total rock volume. Pore spaces in a layered sequence of lava flows may result from (1) vesicles (small spaces formed by the expansion of gas bubbles during the solidification of cooling lava), (2) joints and cracks, (3) separations between lava flows, (4) void spaces between fragmented rock, including aa clinker, and (5) lava tubes. Total porosity of the volcanic rocks on Oahu has been measured at different spatial scales using rock samples (Wentworth, 1938; Ishizaki and others, 1967), borehole photographic logging

(Peterson and Sehgal, 1974), and density logs from gravity surveys in underground tunnels (Huber and Adams, 1971). Total porosity estimates for volcanic rocks of Oahu range from less than 5 to more than 50 percent. Low porosity values may be associated with massive features, including dense flows, aa cores, and dikes, and high values may be associated with aa clinker zones. Effective porosity, which includes only the hydraulically interconnected pore spaces, for the dike-free volcanic rocks of Oahu may be up to an order of magnitude less than total porosity.

Williams and Soroos (1973) analyzed aquifer-test data from wells in the Pearl Harbor area and estimated specific storage to range from about 10^{-4} to 10^{-7} ft^{-1}. Specific storage also may be estimated from the compressibilities of water and the rock matrix (see for example Freeze and Cherry, 1979).

$$S_f = \gamma_f (B + n\beta), \qquad (4)$$

where

S_f = freshwater specific storage [L^{-1}],
n = effective porosity of the rocks,
γ_f = freshwater specific weight [$ML^{-2}T^{-2}$],
B = compressibility of rock matrix [LT^2M^{-1}], and
β = compressibility of water [LT^2M^{-1}].

The compressibility of water is about 2.1×10^{-8} ft^2/lb (4.4×10^{-10} Pa^{-1}) (Freeze and Cherry, 1979), and the compressibility of the basaltic rock matrix in the Pearl Harbor area was estimated to be 1.2×10^{-7} ft^2/lb (2.5×10^{-9} Pa^{-1}) (Souza and Voss, 1987). The specific weight of freshwater is about 62.4 lb/ft^3. For an effective porosity of 0.02 the specific-storage value is about 7.5×10^{-6} ft^{-1}, and for an effective porosity of 0.2 the specific-storage value is about 7.8×10^{-6} ft^{-1}.

Dispersion Characteristics

Mixing of freshwater with underlying saltwater in an aquifer creates a transition zone of brackish water. The extent of mixing in an aquifer is dependent on factors including the ground-water velocity and the aquifer dispersivity, which has units of length. High values of dispersivity, all other factors being equal, result in greater mixing. Dispersivity values generally are larger in the (longitudinal) direction of flow relative to directions transverse to flow, and also may be controlled by aquifer anisotropy. Few reported dispersivity values are available for Oahu. Meyer and others (1974) estimated the dispersivity to be about 200 ft for the volcanic-rock aquifer in the Honolulu area, and this value likely represents a longitudinal dispersivity. Using a cross-sectional numerical model, Souza and Voss (1987) estimated the longitudinal and transverse dispersivities of the Pearl Harbor area to be 250 and 0.82 ft, respectively. Vertical discretization of the cross-sectional mesh was variable, and was finest (49 ft) where concentration gradients were greatest; horizontal discretization also was variable, and was finest (984 ft) near areas of converging flow.

Valley-Fill Barriers

Following the period of extensive erosion during which valleys were deeply incised, some valleys were filled in by marine and terrestrial sediments during a period when relative sea level was higher than it is today. The sedimentary deposits that filled stream valleys along with the weathered rock beneath the valley bottoms may extend below the ground-water table and generally have lower overall permeability than the main dike-free volcanic-rock aquifers of Oahu. Thus, these valley-fill features tend to act as barriers to ground-water flow.

Toward the lower reaches of the valleys, below an altitude of about 30 ft, valley-fill deposits may consist of terrestrial sediments that 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 30 ft, the base of the valley-fill material typically consists of highly weathered and compact older alluvium, which is mantled with more recent, unconsolidated alluvium and colluvium. Older 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). The older alluvium may be hundreds of feet thick at lower altitudes, but at altitudes above about 400 to 600 ft, older alluvium may be nonexistent.

Wells drilled in and near valley mouths provide evidence for a lower stream base level than exists today. For example, Palmer (1927, 1946) used information from wells to define structural contours for the top of the Koolau Basalt beneath the coastal sedimentary deposits in the Honolulu area (fig. 6), and identified reentrant forms that represent the original, subaerially formed valley incisions. The reentrant near the mouth of Nuuanu Stream valley suggests that this 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 across the valley mouth is insufficient to define the original valley cross section and maximum depth of incision. Within the original channels of Manoa, Nuuanu, and Kalihi Stream valleys of Honolulu, the thickness of the valley-fill deposits likely exceeds 1,000 ft. The valley-fill deposits and underlying weathered volcanic rock associated with Manoa, Nuuanu, and Kalihi Streams form effective valley-fill barriers that affect the movement of ground water in the Honolulu area. Water levels on opposite sides of valley-fill barriers in the Honolulu area have differed by several feet at times.

In the Pearl Harbor area, several valley-fill barriers, including those associated with the larger stream valleys of Kipapa and Waikele, Waiawa, Waimalu, and North Halawa Streams, may impede the flow of ground water. Measured water levels on opposite sides of the stream valleys in the Pearl Harbor area do not definitively indicate the presence of hydrologically effective valley-fill barriers such as those in the

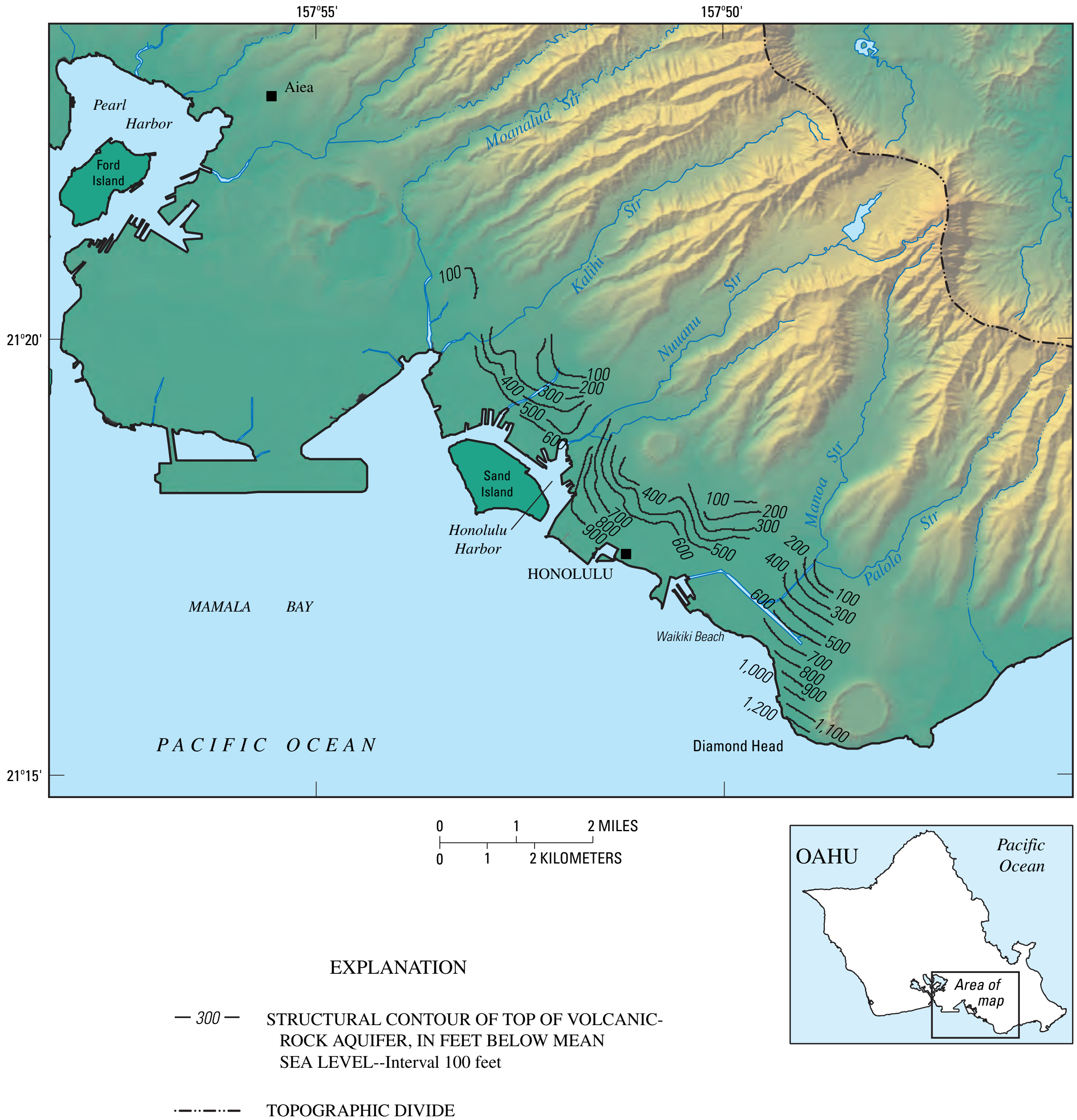


Figure 6. Structural contours of the top of the volcanic-rock aquifer in the Honolulu area, Oahu, Hawaii (modified from Palmer, 1927, 1946).

Honolulu area. The effectiveness of the valley-fill barriers in the Honolulu area may be related to the steeper topography and longitudinal slopes of the valleys in the Honolulu area relative to the Pearl Harbor area. The depths of the valley-fill barriers also likely are related to the availability of water that causes weathering below the stream channels, the location of the water table (and relative sea level), and the characteristics and structure of the rocks beneath the stream channels.

Drilling, geophysical, and hydrologic information from well 2401-01 (fig. 7), drilled about 600 ft downstream of the confluence of Kipapa and Waikele Streams to a depth of about 200 ft below mean sea level, indicates the presence of very weathered basalt, which grades into less weathered basalt, extending below sea level (Eyre, 1983). From aquifer-test analyses, Eyre (1983) estimated a hydraulic-conductivity value of about 50 ft/d for the volcanic rocks penetrated by the well.

In Waiawa Stream valley, a borehole log and geophysical information from resistivity and seismic surveys indicate the presence of a valley-fill barrier that partly penetrates the aquifer (R.M. Towill Corporation, 1978). Beneath the floor of Waiawa Stream valley is a sequence consisting of (1) an upper layer of soil and recent alluvium that is less than 10 ft thick, (2) older alluvium that is tens of feet thick in places, and (3) weathered basalt that becomes less weathered with depth. The weathered basalt beneath the studied site, which was at an altitude of about 190 ft, extends to a depth of 50 to 100 ft below sea level (fig. 8) (R.M. Towill Corporation, 1978), although subtle weathering effects that affect rock permeability may extend even deeper.

Waimalu Stream valley also may form a partially penetrating barrier to ground-water flow. Available drilling logs from wells in Waimalu Stream valley indicate the presence of sedimentary material and possibly weathered volcanic rocks to depths greater than 200 ft below mean sea level.

A valley-fill barrier formed beneath North Halawa Stream valley (Hunt, 1996) separates the Pearl Harbor area from the Moanalua ground-water area to the east. The alluvial and colluvial material that fills the bottom of the valley may penetrate below sea level (Izuka, 1992). In addition, weathered volcanic rocks may extend beneath the valley-fill material and impede the flow of ground water between the Moanalua and Pearl Harbor areas.

Effects of Valley-Fill Barriers on Water Levels

As part of this study, water levels from wells on opposite sides of Waiawa Stream valley were measured to determine if differences in water-level recovery associated with shutting off a large-capacity production well could be measured. The Waiawa Shaft (well 2558-10, fig. 7), which is located on the west side of Waiawa Stream valley, was shut off for a period of about 2 days. During the shut-off period, water was supplied by other sources several miles away from Waiawa Shaft.

Waiawa Shaft is a Maui-type shaft (Stearns and Vaksvik, 1935) that consists of a 30-degree inclined shaft, which originates at a land-surface altitude of about 140 ft near the western valley wall within Waiawa Stream valley and leads down to a pump room at an altitude of about 30 ft, a sump excavated beneath the pump-room floor to about 20 ft below mean sea level, and a 1,700-ft long infiltration tunnel extending generally northward from the sump. Waiawa Shaft has a large-capacity infiltration tunnel and is capable of withdrawing greater than 15 Mgal/d partly by skimming water from the top of the freshwater lens. The infiltration tunnel is 12 ft wide by 12 ft high near its entrance, which has an invert altitude of about 4 ft below mean sea level, and tapers to about 7 ft wide by 10 ft high near its terminus, which has an invert altitude of about 4 ft above mean sea level (Oki and others, 1990).

During the week prior to the 2-day shut-off of Waiawa Shaft in February 2005, withdrawal from Waiawa Shaft was steady at about 10 Mgal/d. Rainfall during February 15 through 25, 2005 at a rain gage near Mililani was 0.19 in. (National Weather Service, 2005), which is unlikely to have affected ground-water levels much. Water levels were monitored at wells 2659-04 and 2459-26 on the west side of Waiawa Stream valley, and at well 2557-04 on the east side of the valley (fig. 7). During the 2-day period when Waiawa Shaft was shut off, water levels on each side of Waiawa Stream valley appeared to recover, although the measured recoveries are somewhat obscured by the hydrologic effects of barometric (atmospheric) pressure (fig. 9).

Barometric pressure at a particular site is determined by the weight of the air column above that site. Pressure changes at a site are caused by dynamical (air motion) and thermal (temperature) effects that change the weight of the air column above the site. Variations of barometric pressure can occur over time scales ranging from seconds to several years. Over short time scales of seconds to minutes, sensitive barometers may measure high-frequency pressure variations caused by local gusts of wind. On a weekly to annual time scale, migratory low- or high-pressure systems can cause relatively large pressure variations (in excess of 0.3 ft of water) over a region. In Hawaii, barometric pressure at the surface shows a marked semidiurnal variation which is attributed to absorption of radiation by water vapor and ozone in the upper atmosphere (Whiteman and Bian, 1996; Chapman and Lindzen, 1970). Unlike tidal phenomena, the semidiurnal variation in barometric pressure is not purely sinusoidal in nature. The amplitude of the semidiurnal barometric-pressure variation at surface sites in Hawaii is typically about 0.05 ft of water.

The effects of barometric pressure on measured water levels were removed using a one-dimensional numerical model that accounts for air flow in the unsaturated zone, vertical flow of water in the aquifer, and vertical loading of the aquifer (Oki, 1997). The one-dimensional numerical model removes low-frequency barometric-pressure effects as well as the semidiurnal barometric-pressure effects on water levels. The semidiurnal variations in water levels caused by barometric-pressure changes are generally a few hundredths of a foot in amplitude, and are greater in well 2659-04 (which has the greatest depth to water of the three wells) than in wells 2459-26 or 2557-04.

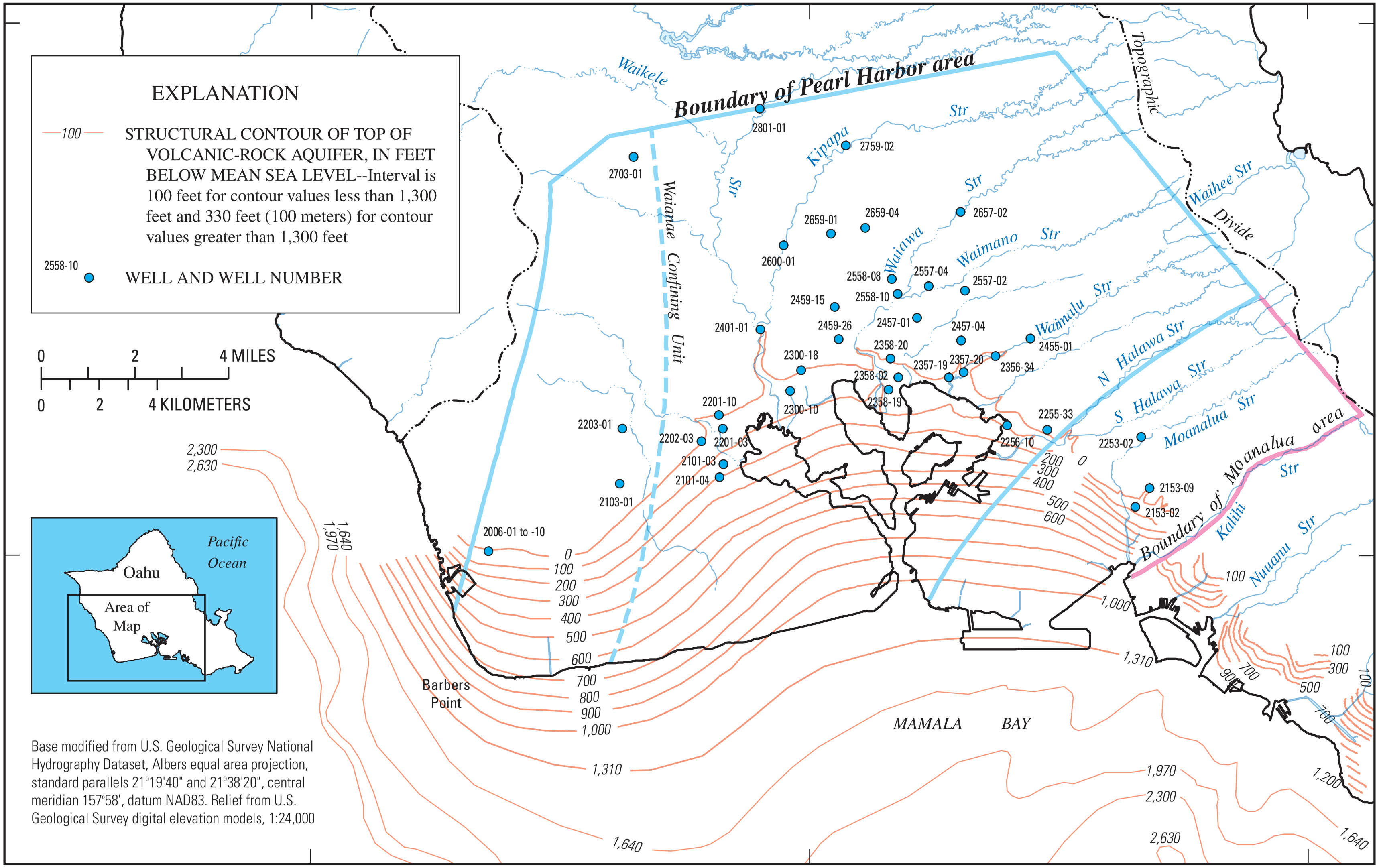


Figure 7. Selected wells with water-level, salinity, or geologic information used in this study, and structural contours of the top of the volcanic-rock aquifer in the Pearl Harbor area, Oahu, Hawaii. Structural contours modified from Palmer (1946), Wentworth (1951), Visher and Mink (1964), and Gregory (1980).

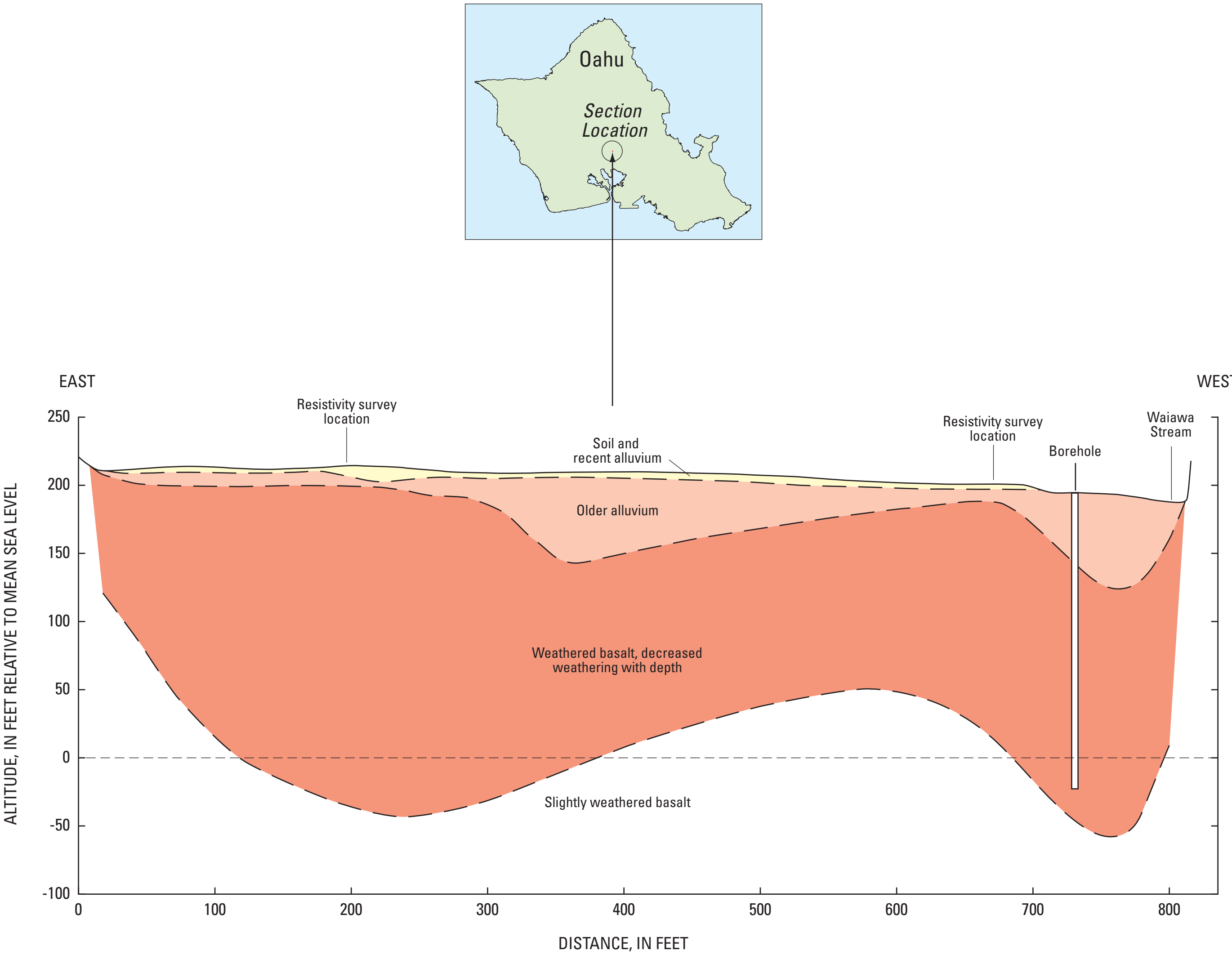


Figure 8. Cross section of Waiawa Stream valley, Oahu, Hawaii (modified from R.M. Towill Corporation, 1978).

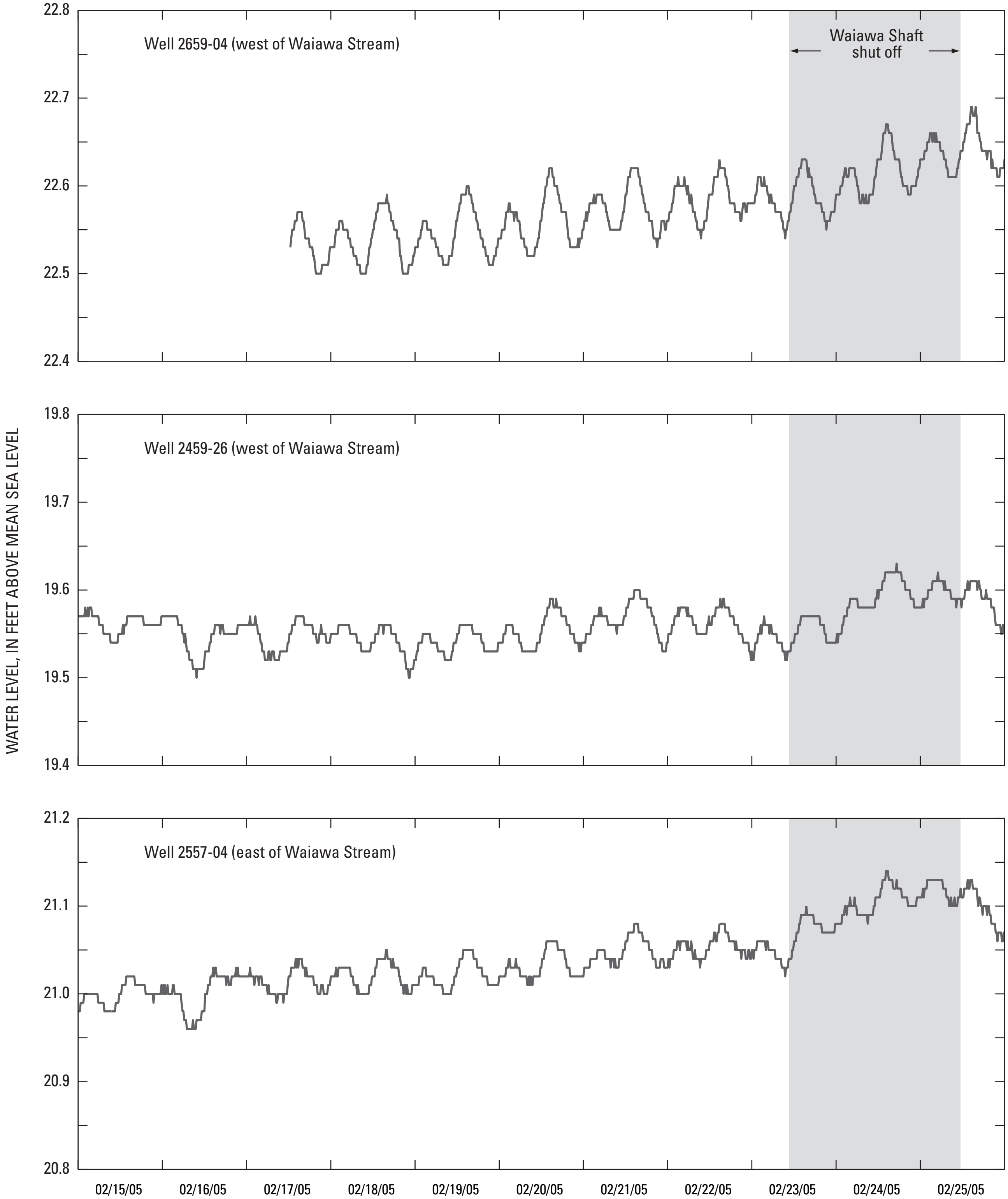


Figure 9. Measured water levels in wells near the Waiawa Shaft (2558-10), which was shut off during February 23-25, 2005, Pearl Harbor area, Oahu, Hawaii. Shaded area represents shut-off period.

The resulting water levels with barometric-pressure effects removed indicate a recovery on the east side of Waiawa Stream valley (well 2557-04) (fig. 10). (The recovery associated with shutting off Waiawa Shaft also is indicated in wells 2659-04 and 2459-26 on the west side of Waiawa Stream valley, although the water levels in these wells with barometric-pressure effects removed are not shown.) Thus, on the basis of water-level information, the Waiawa valley-fill barrier is not a totally effective hydrologic barrier in the vicinity of Waiawa Shaft. Ground-water withdrawal from the western side of Waiawa Stream valley measurably affects water levels on the eastern side of the valley because the ground-water pressure reduction caused by withdrawal is propagated either beneath or through the valley-fill barrier.

Ground-Water Flow System

The most important source of fresh ground water on Oahu is from the freshwater lens in dike-free volcanic rocks in the Pearl Harbor area (fig. 11). The main ground-water system in the Pearl Harbor area consists of a lens-shaped freshwater body, an intermediate transition zone of brackish water, and underlying saltwater. Several geologic features form boundaries of the freshwater-lens system of the Pearl Harbor area or impede the flow of ground water within the system. Features that form boundaries of the freshwater-lens system include dikes and the southern Schofield ground-water dam; features that may impede flow within the system include valley-fill barriers, the coastal caprock that thickens in a seaward direction, and the Waianae confining unit that separates Waianae Volcanics and Koolau Basalt.

Freshwater Lens

The freshwater lens in the Pearl Harbor area forms because of the density difference between freshwater and underlying saltwater. For hydrostatic conditions, the depth at which the brackish water in the transition zone has a salinity about 50 percent that of ocean water is sometimes estimated from the Ghyben-Herzberg principle (see for example Freeze and Cherry, 1979). The Ghyben-Herzberg principle describes a freshwater-saltwater relation for conditions in which the two fluids do not mix (no transition zone) and freshwater flow is horizontal. For these conditions, the freshwater-lens thickness below sea level is directly proportional to the height of the top of the freshwater above sea level. In principle, at a place where the water table stands 1 foot above sea level, for example, 40 feet of freshwater will be below sea level, and the freshwater lens will thus be 41 feet thick. This relation exists because ocean water is about one-fortieth denser than freshwater. In the dike-free volcanic rocks of the Pearl Harbor area, mixing of freshwater with underlying saltwater creates a brackish-water transition zone that may be hundreds of feet thick. (For the purposes of this report, brackish water is considered to be water with salinity that ranges from greater than 2 percent to less than 100 percent ocean-water salinity.)

The water table in the dike-free volcanic rocks is less than a few tens of feet above sea level. In general, the altitude of the water table in the dike-free volcanic rocks is lowest near the coast and increases in an inland direction at a rate of about 1 ft/mi, although local variations may exist near areas of converging flow caused by springs and pumping from wells. Within the dike-free volcanic rocks, freshwater generally flows from inland areas to coastal discharge areas (fig. 12). Although freshwater flow is predominantly horizontal in the dike-free volcanic rocks, the flow may have an upward component in some areas. For example, freshwater may flow upward to sites of discharge near the land surface at the Pearl Harbor springs. Within the uppermost limestone unit in the caprock, the water table generally is less than a few feet above sea level.

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 caprock of southern Oahu extends offshore, beyond the seaward extent of the freshwater lens. The freshwater-lens system in the dike-free volcanic rocks is mainly unconfined inland from the caprock. Within the caprock, highly permeable limestone units may be confined by low-permeability sedimentary deposits, although the uppermost limestone unit of the caprock is unconfined and contains brackish water (see for example Bauer, 1996; Oki and others, 1998).

A saltwater-circulation system exists beneath the freshwater lens. Saltwater flows landward in the deeper parts of the aquifer, rises, and then mixes with seaward-flowing fresher water (fig. 12). This mixing creates the brackish-water transition zone.

Recharge

Recharge to the freshwater-lens system in the Pearl Harbor area is from infiltration of rainfall and irrigation water, and discharge from upgradient ground-water bodies. Upgradient ground-water bodies that recharge the freshwater-lens system of the Pearl Harbor area include the Koolau and Waianae rift zones, the Schofield ground-water area, and the Moanalua ground-water area (fig. 11). Oki (1998) estimated that during the 1950s, about 62 percent of the discharge from the Schofield ground-water area flowed toward the Pearl Harbor area, with the remaining 38 percent flowing northward.

Shade and Nichols (1996) developed regression equations relating rainfall and recharge in the Pearl Harbor area using water-budget information from Giambelluca (1983, 1986) (table 1). Shade and Nichols used these regression equations to estimate the distribution of recharge in the Pearl Harbor area for predevelopment conditions, and indicated that total predevelopment recharge to the Pearl Harbor area was about 280 Mgal/d (including recharge from the rift zones and the Schofield ground-water area) (fig. 13). The adjacent Moanalua

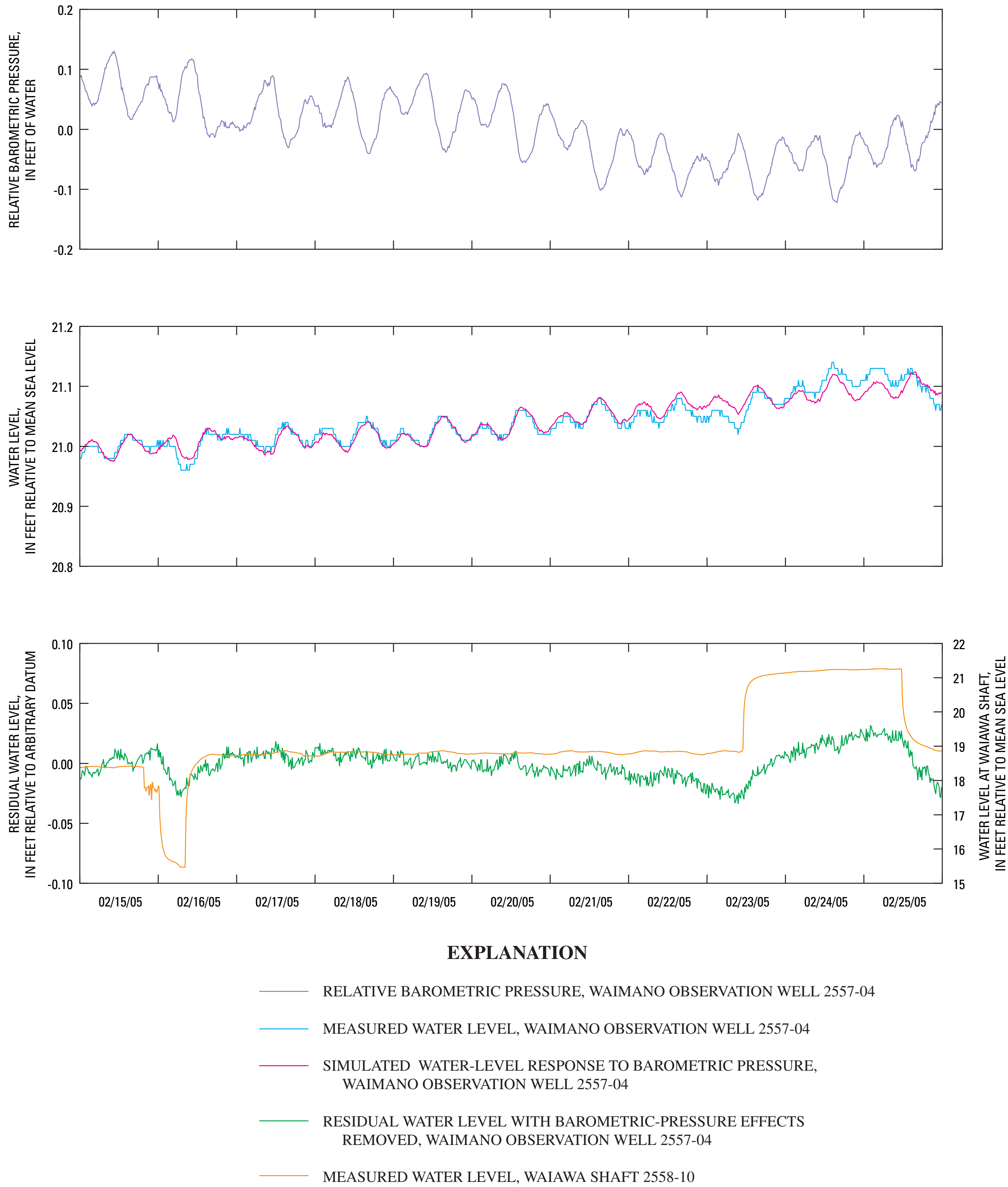


Figure 10. Measured and simulated barometric-pressure response in Waimano observation well 2557-04, Oahu, Hawaii, during February 15, 2005 through February 25, 2005. Barometric-pressure response was simulated with a pneumatic diffusivity of 1.0×10^{8} ft^2/d, vertical hydraulic conductivity of 10 ft/d, specific storage of 1.0×10^{-5} ft^{-1}, loading efficiency of 0.5, and specific yield of 0.5.

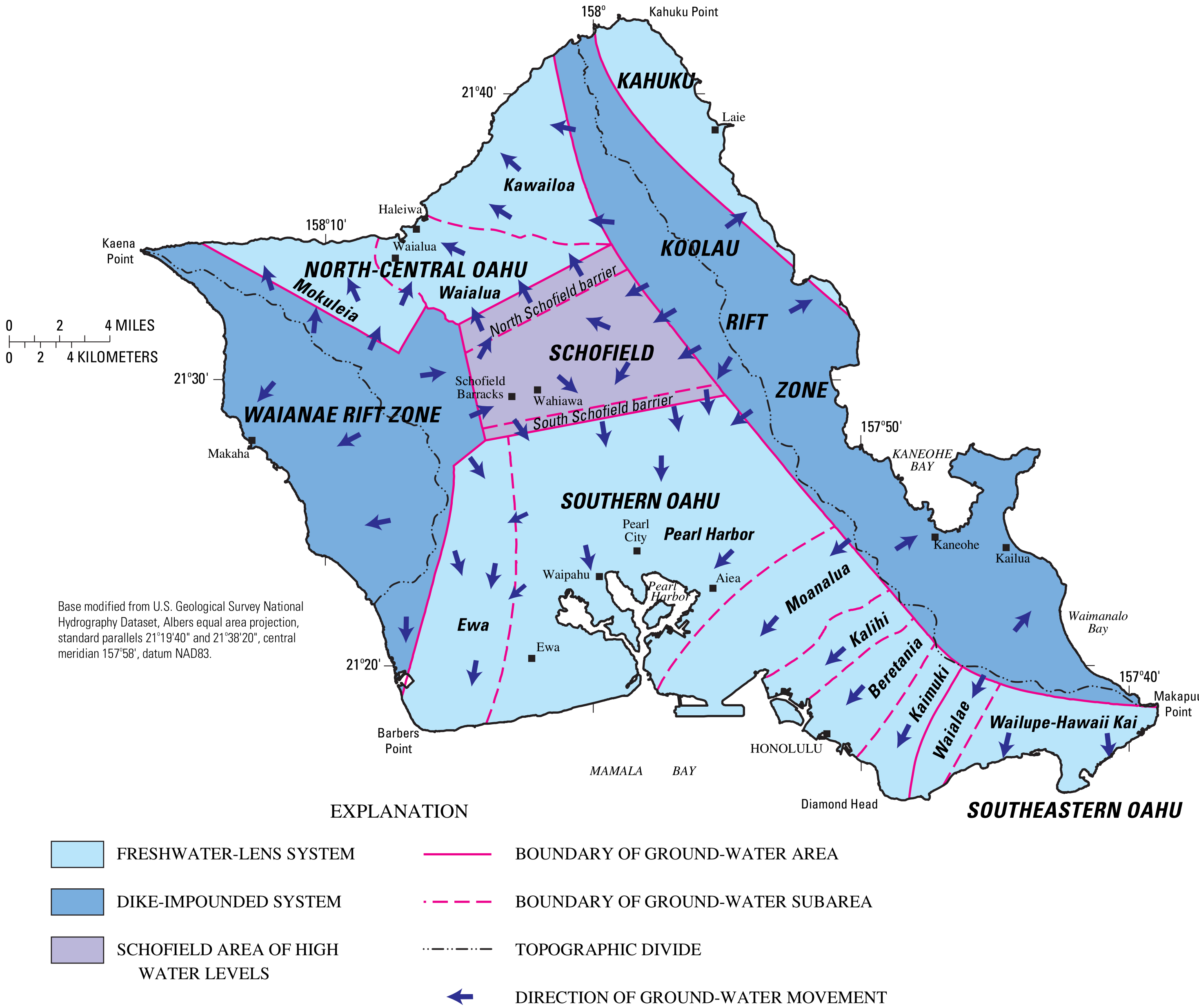


Figure 11. Ground-water areas and generalized directions of ground-water movement, Oahu, Hawaii.

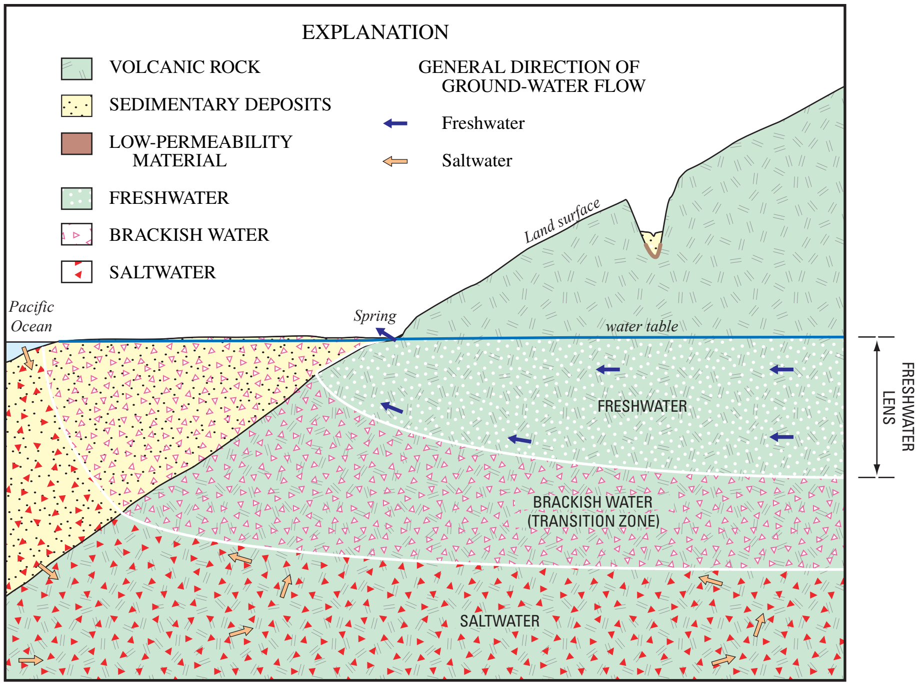


Figure 12. Generalized cross section of ground-water flow in the Pearl Harbor area, Oahu, Hawaii.

Table 1. Relations between annual rainfall and annual recharge for different land uses, Pearl Harbor area, Oahu, Hawaii (Shade and Nichols, 1996).

Land use	Relation[1]	Coefficient of determination, r^2	Range of annual rainfall for indicated relation, in inches
Predevelopment (before 1880)	Recharge = 0.06p + 3.4	0.09	20-43
	Recharge = 0.78p – 28.0	0.93	43-95
	Recharge = 0.60p – 15.0	0.24	95-152
	Recharge = 0.89p – 56.0	0.91	> 152
Development (after 1880)			
Non-agricultural	Recharge = 0.41p – 5.7	0.57	14-60
	Recharge = 0.78p – 28.0	0.93	60-95
	Recharge = 0.60p – 15.0	0.24	95-152
	Recharge = 0.89p – 56.0	0.91	> 152
Pineapple	Recharge = 0.935p – 13.54	0.98	> 15
Sugarcane (drip)	Recharge = 0.64p + 11.1	0.89	> 0

[1]Recharge is in inches per year; p is rainfall, in inches per year.

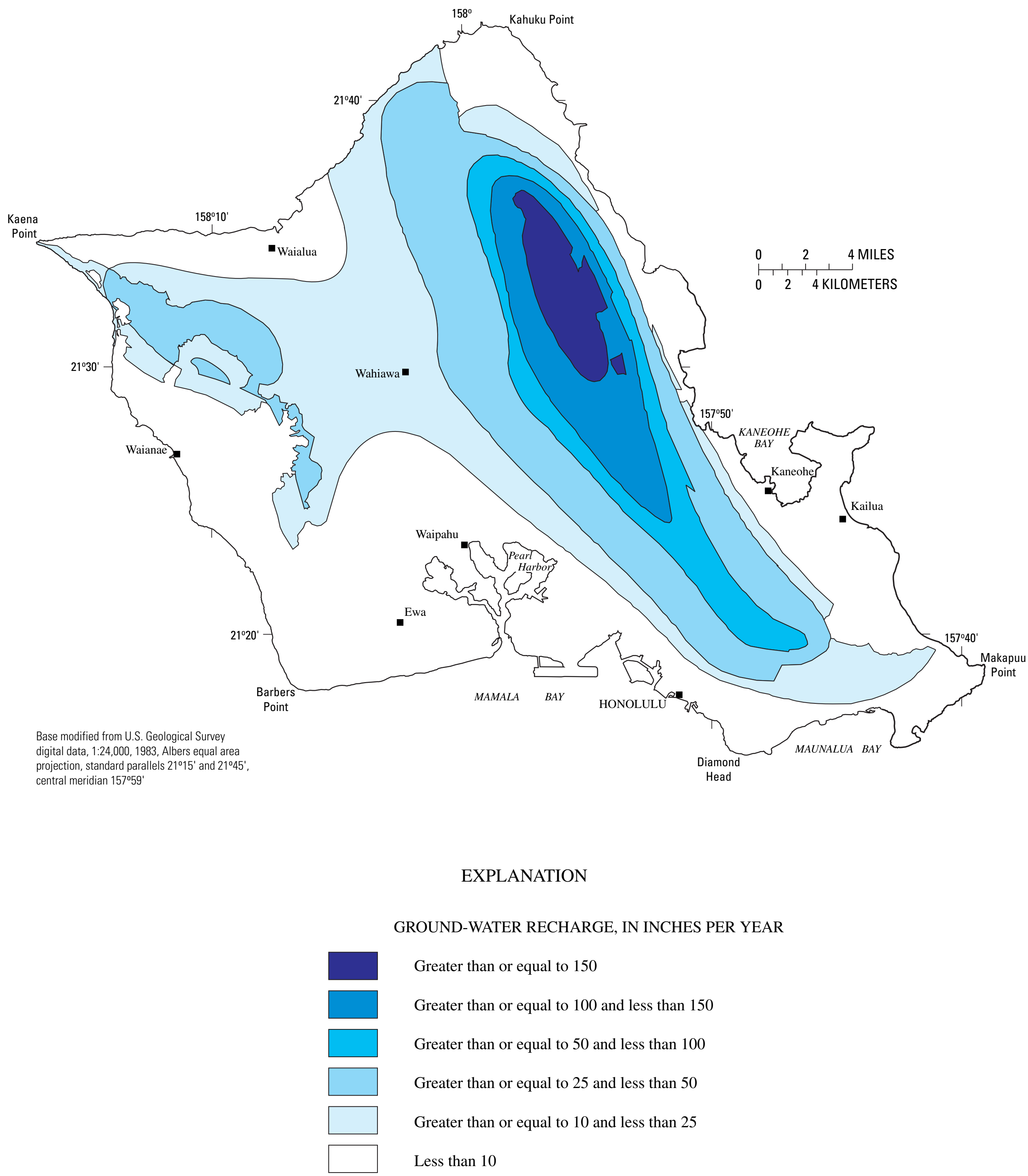


Figure 13. Distribution of ground-water recharge for predevelopment land use, Oahu, Hawaii (modified from Shade and Nichols, 1996).

ground-water area to the east of the Pearl Harbor area received about 28 Mgal/d recharge for predevelopment conditions.

Since about 1900, land use in the Pearl Harbor area has undergone significant changes (see for example Oki and Brasher, 2003), and these changes have had an effect on the hydrologic budget of the area. Irrigation on large-scale sugarcane plantations and suppressed evapotranspiration associated with pineapple plants generally have resulted in increased recharge relative to predevelopment conditions. Variations in rainfall (fig. 14) also have affected the amount of recharge in the Pearl Harbor area over time. During the 1940s and late 1970s, rainfall was less than average, whereas during the 1960s rainfall was above average (fig. 14). During the 1950s, rainfall was near the long-term average.

Relations from Shade and Nichols (1996) (table 1) were used in this study to estimate recharge from rainfall for different time periods and land uses. Estimated recharge over time was used as input to the numerical ground-water model described later in this report.

Discharge

Discharge from the Pearl Harbor area is in the form of ground-water withdrawals from pumped wells, discharge to onshore springs inland from Pearl Harbor, and diffuse seepage through the caprock to Pearl Harbor and the ocean. Withdrawals from pumped wells and discharge from the Pearl Harbor springs have been measured, although records are incomplete for some time periods and locations. Diffuse seepage through the caprock has not been measured.

Withdrawals from Wells

Withdrawals from drilled wells in the Pearl Harbor area began following the 1879 discovery of free-flowing artesian water in the southwestern part of the area. Early records of withdrawals are not available, but withdrawals were probably about 5 Mgal/d during the 1880s (Mink, 1980). Records of withdrawals from the volcanic-rock aquifer from 1890 to about 1920 are incomplete, although information is available for when wells were drilled. After about 1920, records of withdrawals from the volcanic-rock aquifers in the Pearl Harbor area are more complete.

During the early period of ground-water development, most of the water was used for sugarcane cultivation. For this study, sugarcane-plantation withdrawals from individual well fields during the early period of development from 1890 to about 1920 were estimated if data were not available. Withdrawals from individual well fields for early periods when data were unavailable were estimated from either (1) a linear-regression equation relating annual rainfall from a nearby rain gage (State key number 741 or 750) and annual withdrawal from the well field during a period for which data were available, or (2) the average annual withdrawal rate from the well field during a subsequent period for which data were available. The latter method was used for cases in which the correlation coefficient of the relation between annual rainfall and annual withdrawal rate was between about 0.6 and –0.6. Estimated annual withdrawals for a well were disaggregated into monthly withdrawals using mean ratios of monthly-to-annual withdrawal from the same well for a subsequent period with available data. Estimated withdrawal rates also were adjusted proportionally to account for the number of wells existing in the well field during the estimation period relative to when data were available.

Ground-water withdrawals from the volcanic rocks of the Pearl Harbor area (including the Ewa-Kunia, Waipahu-Waiawa, and Waimalu management systems) increased after about 1895 as areas used for sugarcane cultivation expanded. From 1910 through 1939, average withdrawal was about 157 Mgal/d (fig. 15). During the war years 1940 through 1945, average withdrawal increased to about 191 Mgal/d. From 1946 through 1959, average withdrawal decreased to about 158 Mgal/d, which was about the same as the pre-war average. During the 1960s, average withdrawal increased to 184 Mgal/d, and during the 1970s, average withdrawal increased further to 224 Mgal/d. After the 1970s, average withdrawal began to decline. From 1996 through 2001, following the closure of the last remaining sugarcane plantation in the area in 1995, average ground-water withdrawal from the Pearl Harbor area was 104 Mgal/d. Much of the reduction in ground-water withdrawal after 1980 was from the western part of the Pearl Harbor area, in the Waipahu-Waiawa management system (fig. 15).

Ground-water withdrawals from the coastal caprock mainly are from the upper-limestone unit of the caprock. Prior to the closure of Oahu Sugar Co., most of the withdrawals from the caprock were for irrigation of sugarcane. Since the closure of Oahu Sugar Co., ground water from the caprock has mainly been used for landscape and golf-course irrigation and industrial purposes.

Pearl Harbor Springs

The Pearl Harbor springs consist of a group of springs inland from the shore of Pearl Harbor near the inland margin of the caprock. The five major springs have been named, from east to west, Kalauao, Waiau, Waimano, Waiawa, and Waikele Springs (fig. 1) 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 about 20 to 25 ft. Visher and Mink (1964) indicated that the main spring discharges are from areas where volcanic rocks are exposed at a break in slope of the land surface. Water also discharges as diffuse seeps where the caprock is thin, where erosion has exposed the volcanic rocks, and through alluvium into stream channels incised below the level of the existing head in the aquifer. Historically, the spring discharge was used for wetland crops such as rice. The discharge is currently used for watercress cultivation as well as for industrial purposes.

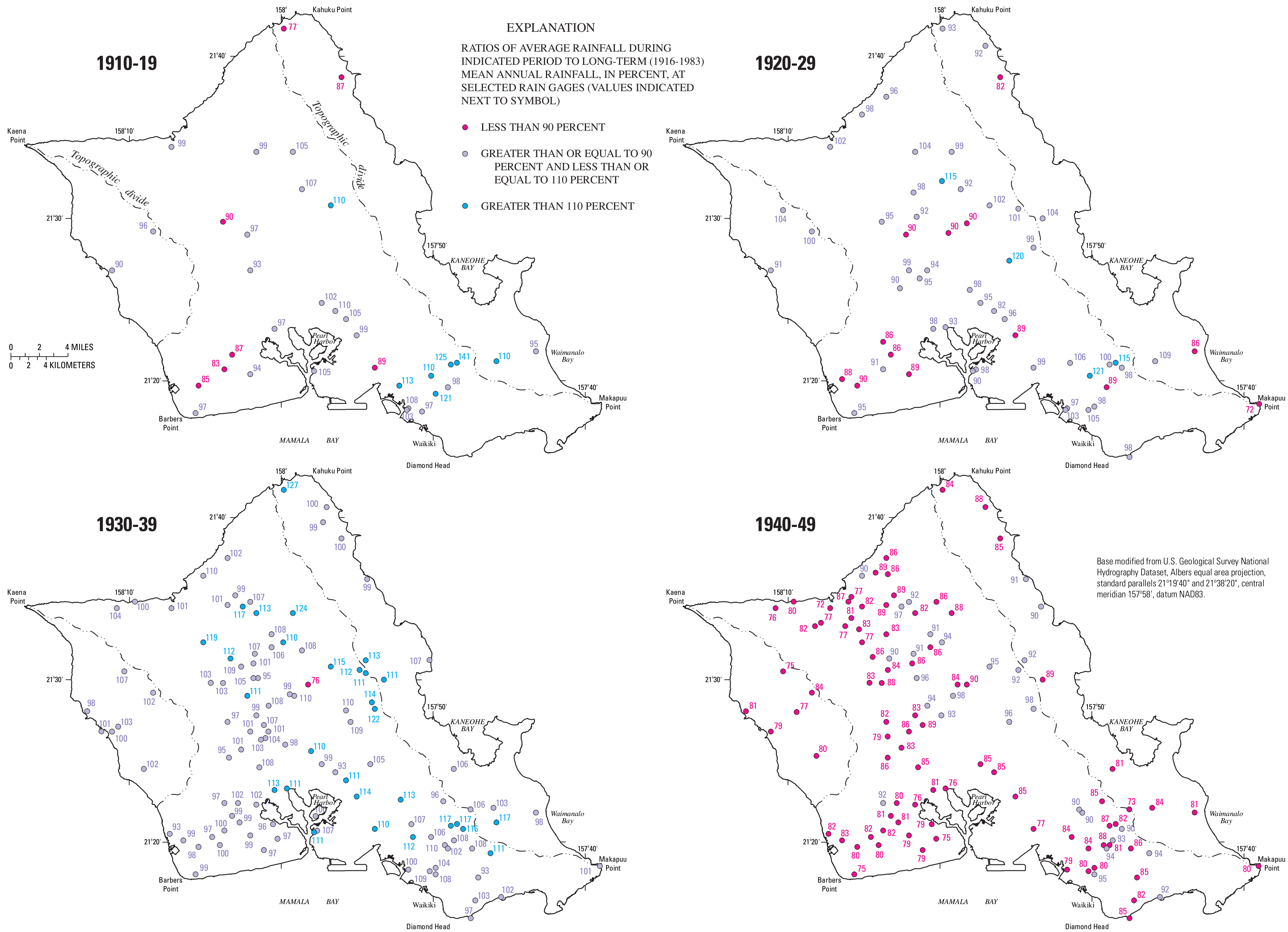


Figure 14. Ratios of mean annual rainfall during selected periods to long-term (1916-83) mean annual rainfall (Giambelluca and others, 1986), Oahu, Hawaii.

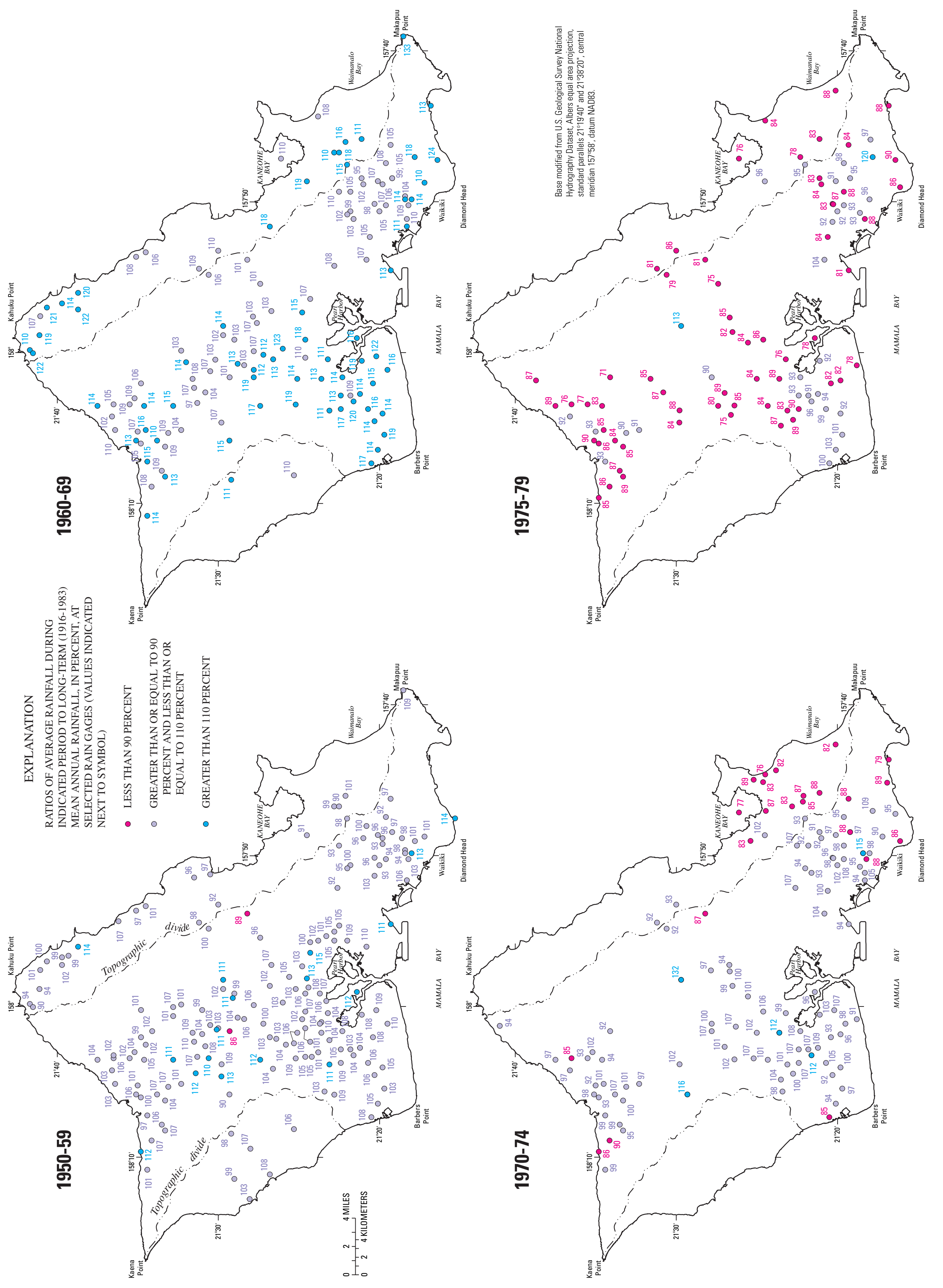


Figure 14. Ratios of mean annual rainfall during selected periods to long-term (1916-83) mean annual rainfall (Giambelluca and others, 1986), Oahu, Hawaii—*Continued.*

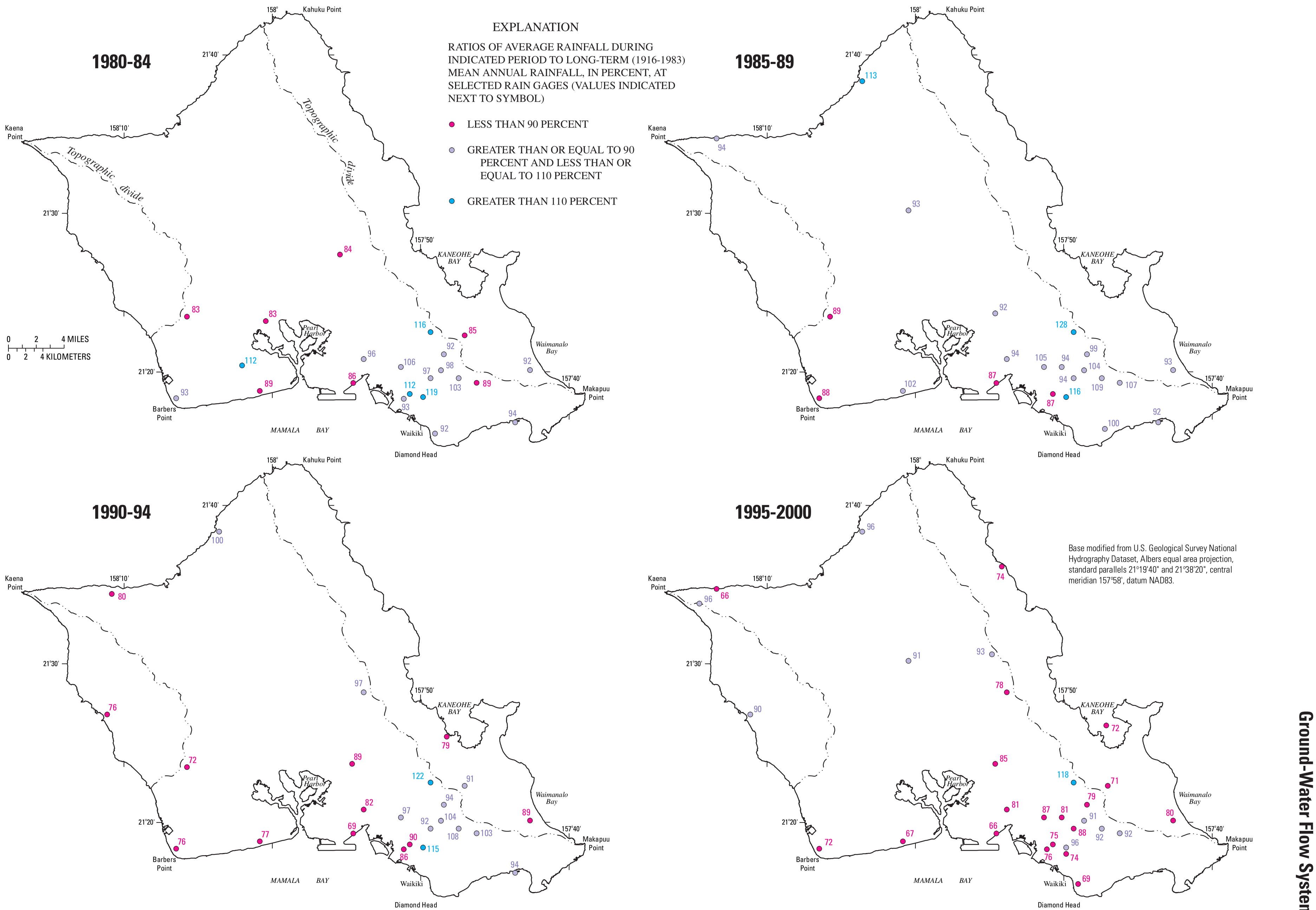


Figure 14. Ratios of mean annual rainfall during selected periods to long-term (1916-83) mean annual rainfall (Giambelluca and others, 1986), Oahu, Hawaii—*Continued.*

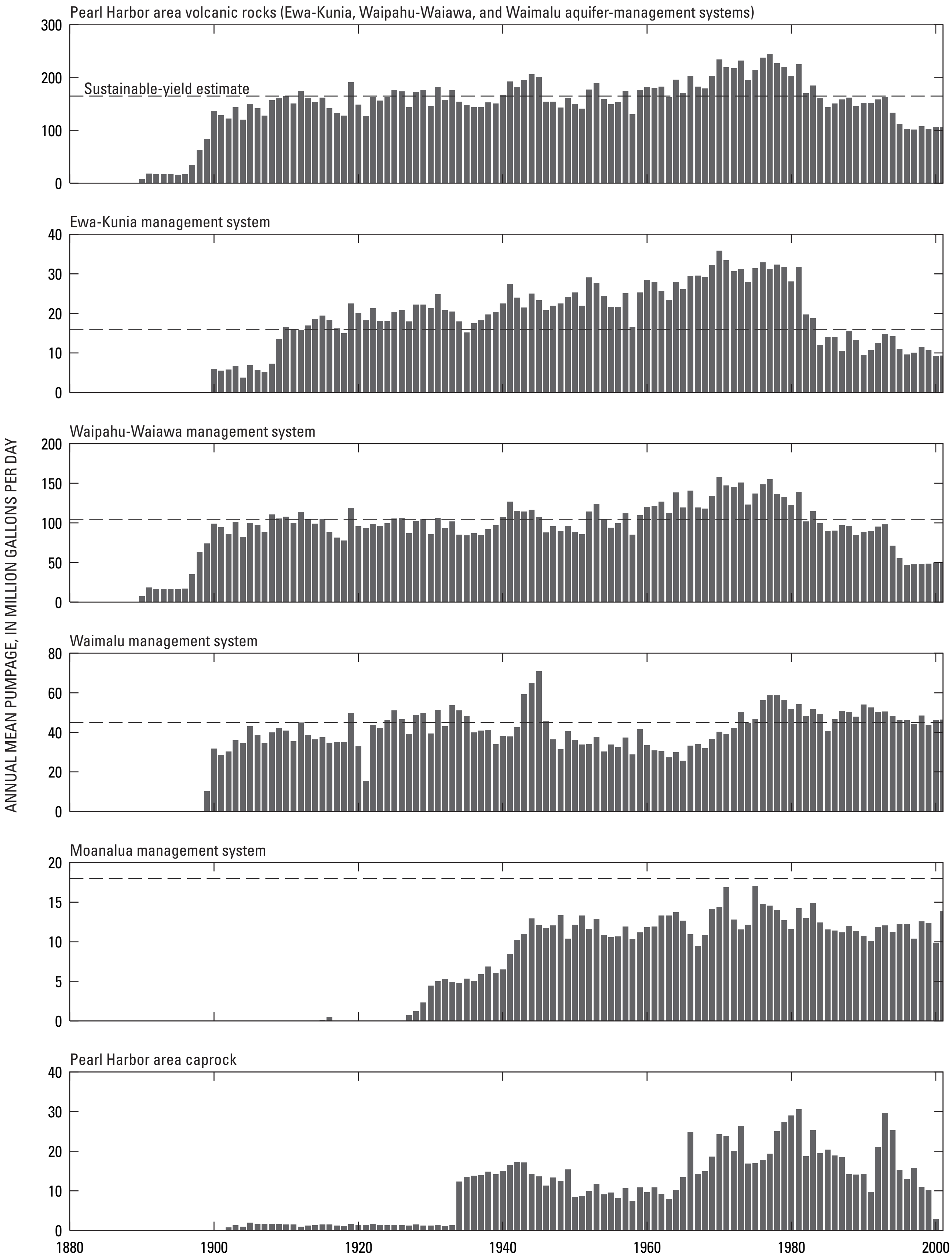


Figure 15. Ground-water withdrawals from the Pearl Harbor and Moanalua areas, Oahu, Hawaii. Sustainable-yield values (as of 2005) are from the Hawaii Commission on Water Resource Management.

Schuyler and Allardt (1889) described the first known measurements of discharge from the Pearl Harbor springs and reported that discharge measured at seven locations totaled about 75 Mgal/d. These first known measurements of discharge from the springs represent a lower bound for the total discharge at the time because only the unused flow was measured.

In 1911, miscellaneous measurements of springs at 11 locations near Pearl Harbor were made by the USGS (Martin and Pierce, 1913). The total measured spring discharge was about 48 Mgal/d, which is not representative of the total flow because not all known springs were 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). Measured annual mean discharge from the Pearl Harbor springs was about 64, 61, and 74 Mgal/d during 1928, 1929, and 1930, respectively. However, reported discharge from Waikele and Waimano springs during 1928 to 1930 (Kunesh, 1931) underestimated the total discharge at these sites (Oki, 1998).

Starting in 1931, the USGS began establishing gaging stations to measure flow from the Pearl Harbor springs. Annual mean discharge from the springs was about 85 and 82 Mgal/d during 1932 and 1933 (Stearns and Vaksvik, 1935), respectively, but these values include estimated discharge from Waikele springs based on the incomplete measurements from Kunesh (1931).

During 1931 to 1967, the USGS maintained gaging stations to measure discharge from the Pearl Harbor springs. Since 1967, the USGS has made semiannual discharge measurements at 20 to 24 sites near Pearl Harbor to monitor discharge from the springs (see for example Taogoshi and others, 2001).

Discharge from the Pearl Harbor springs is directly dependent on the head in the aquifer; discharge is high when head in the aquifer is high, and discharge is low when head in the aquifer is low. Soroos and Ewart (1979) indicated that a linear relation exists between head (as measured by the water level in a monitor well) and total spring discharge. Oki (1998) used available data to develop linear-regression equations for each of the major spring areas relating discharge and ground-water level (table 2). These relations were developed for conditions when water levels at well 2256-10 were between about 13 and 24 ft for Kalauao, Waiau, and Waimano springs, and between about 13 and 20 ft for Waiawa and Waikele springs.

Water Levels

Ground-water flow directions commonly are inferred from ground-water levels measured in wells. 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. In the Pearl Harbor area, ground-water levels vary spatially (both horizontally and vertically) and temporally.

In general, measured water levels in the Pearl Harbor area are lowest near the Pearl Harbor springs 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 (Visher and Mink, 1964; Dale and Ewart, 1971; Soroos and Ewart, 1979). On October 31, 2002 and May 15, 2003, ground-water-level surveys were made in the Pearl Harbor area. Agencies participating included the USGS, BWS, CWRM, U.S. Air Force (through their consultant, URS Corporation), and U.S. Navy (U.S. Geological Survey, 2003). Water levels measured on October 31, 2002 ranged from 13.6 to 20.4 ft above mean sea level. Water levels measured on May 15, 2003 ranged from 13.1 to 19.7 ft above mean sea level. In general, measured water levels were lowest near the southeastern and southwestern parts of the Pearl Harbor area and were highest in the inland, northern part of the area (fig. 16). Water levels in the Waianae Volcanics (west of the Waianae confining unit) generally are lower than water levels in Koolau Basalt because recharge to the Waianae Volcanics is relatively low.

The magnitude of the horizontal hydraulic gradient varies spatially and generally is on the order of 0.0002 ft/ft (about 1 ft/mi). Near areas of converging flow, such as near the Pearl Harbor springs, the horizontal hydraulic gradient may exceed 0.0002 ft/ft.

Table 2. Relations between discharge at the Pearl Harbor springs and water level measured at well 2256-10, Oahu, Hawaii (Oki, 1998).

Spring	Relation[1]	Coefficient of determination, r^2
Waikele	Discharge = 1.6108h – 12.5595	0.59
Waiawa	Discharge = 1.4882h – 7.8089	0.81
Waimano-Waiau	Discharge = 2.4572h – 19.0360	0.96
Kalauao	Discharge = 1.2726h – 7.5966	0.79

[1]Discharge is in million gallons per day; h is the water level, in feet above mean sea level, at well 2256-10.

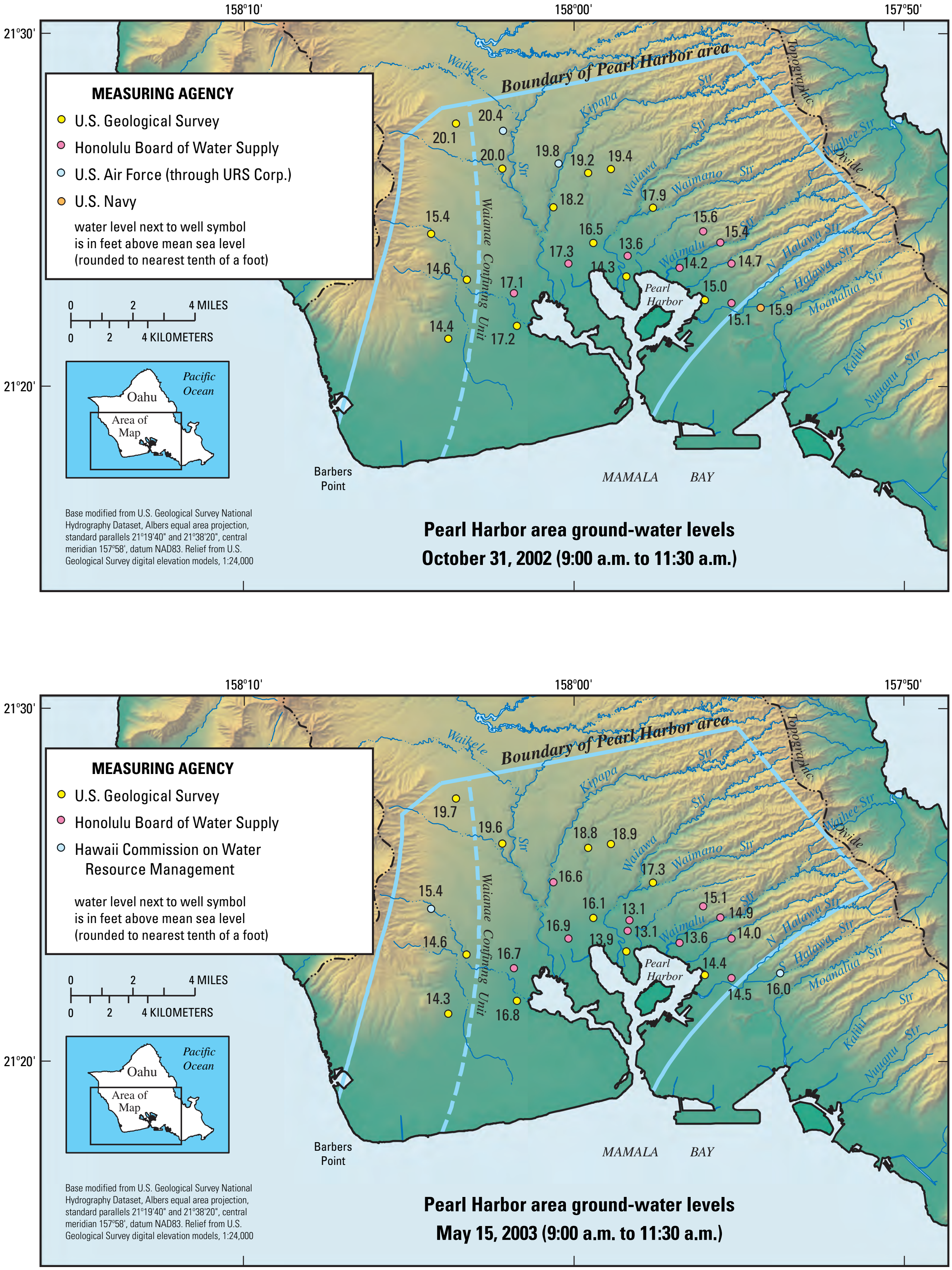


Figure 16. Water-level surveys of October 31, 2002 and May 15, 2003, Pearl Harbor area, Oahu, Hawaii.

Near inland recharge areas, heads in the aquifer may decrease with depth, whereas near coastal discharge areas heads in the aquifer may increase with depth. Although limited information is available to quantify the magnitude of the vertical hydraulic gradient in the Pearl Harbor area, information from a pair of wells near a discharge area in northern Oahu indicates that the vertical hydraulic gradient near the wells is about 0.001 ft/ft (Oki, 1998).

The first successful artesian well drilled on Oahu was in the Pearl Harbor area and was completed in 1879. The well (2101-04) was drilled near the southwestern part of the Pearl Harbor area near West Loch. Thrum (1889) reported the original head in the southwestern part of the Pearl Harbor area to be 32 ft above mean sea level, although it is unclear whether this head is representative of an average head during predevelopment times or whether it reflects a particular wet or dry period. Assuming a hydraulic gradient of 0.0002 ft/ft and a head of 32 ft near Pearl Harbor, Mink (1980) estimated an inland predevelopment water level of 39 ft above mean sea level near the boundary between the Pearl Harbor and Schofield ground-water areas.

The history of water-level decline in wells in the Pearl Harbor area is well documented (see for example Soroos and Ewart, 1979). Water levels measured in wells in the area indicate seasonal variations and a long-term downward trend (fig. 17). Historically, water levels were strongly affected by the seasonal pattern of ground-water withdrawals by sugarcane plantations. This effect is evident at well 2101-03, which is near several high-capacity agricultural wells. Measured water levels in well 2101-03 varied by 5 ft between dry and wet seasons when sugarcane was being cultivated. Soroos and Ewart (1979) used a linear-regression analysis to estimate a 0.09 ft/yr rate of water-level decline in the Pearl Harbor area during 1910-77. The water-level decline was caused by the increased ground-water withdrawals from the aquifer over time, and also may reflect a downward trend in rainfall over time (Oki, 2005).

Salinity

Salinity is one of the main factors controlling ground-water availability in the Pearl Harbor area. In general, the salinity of water withdrawn from wells in the area is expected to increase with depth, proximity to the coast, and withdrawal rate, although exceptions to this generalization are known to exist. Many of the older, high-capacity irrigation wells drilled by sugarcane plantations produced water with a salinity exceeding 5 percent that of ocean water. Saltwater intrusion is a problem at these wells because of the great depth to which the wells were drilled and the high withdrawal rates. At some well fields, salinity of pumped water was reduced by backfilling the deeper wells (Stearns and Vaksvik, 1935).

To better understand conditions in the freshwater-lens systems on Oahu, the BWS established a program of monitoring the salinity profiles in deep open boreholes that fully penetrate the freshwater lens. Salinity profiles generally are measured in terms of fluid conductivity. For this study, ocean water was assumed to have a fluid conductivity of 50,000 microsiemens per centimeter, which is near the maximum value measured in deep boreholes. Measured fluid-conductivity values were divided by 50,000 microsiemens per centimeter to obtain salinity in terms of percent of ocean-water salinity.

Measured salinity profiles provide an indication of the volume of freshwater in the aquifer. Collection of salinity profiles over time provides an indication of the changes in freshwater volume. In the Pearl Harbor area, numerous deep wells have been drilled for the purpose of monitoring salinity profiles. Although many of these wells were drilled within the past several years, a few deep monitor wells were drilled more than 15 years ago. In general, salinity profiles collected from the older deep monitor wells indicate a rise of the top of the brackish-water transition zone and a reduction of freshwater thickness over time (fig. 18). Decreased salinity over time measured in some wells (compare profiles from 1990 and 2001 for well 2457-04 in fig. 18) may be related to reduced withdrawals, logging-equipment changes, or changing borehole-flow conditions.

Salinity profiles from deep open boreholes may be affected by flow within the borehole (Paillet and others, 2002). Borehole flow can be caused by both natural and withdrawal-induced vertical-head differences in the aquifer. Head may increase with depth in the aquifer near coastal discharge areas and near partially penetrating pumped wells, and increasing head in the aquifer with depth may lead to upward flow within an open borehole. Upward borehole flow may cause saltwater to flow upward in the borehole, which in turn may lead to an underestimate of the freshwater-lens thickness based on the recorded salinity profile. In areas where head decreases with depth, downward borehole flow may occur and lead to an overestimate of the freshwater-lens thickness based on the recorded salinity profile.

Temperature

Ground-water temperatures in the Pearl Harbor area generally range from about 19 to 25 degrees Celsius and are highest near the top and bottom of measured temperature profiles. Water temperatures at the top of the freshwater lens generally are slightly warmer than temperatures in the underlying freshwater because of local recharge from irrigation-return flow. Beneath the warm upper zone, water temperatures in the main part of the freshwater body are cooler because recharge originates from cooler high altitudes. Beneath the main freshwater body, water warms with depth because of the natural geothermal gradient.

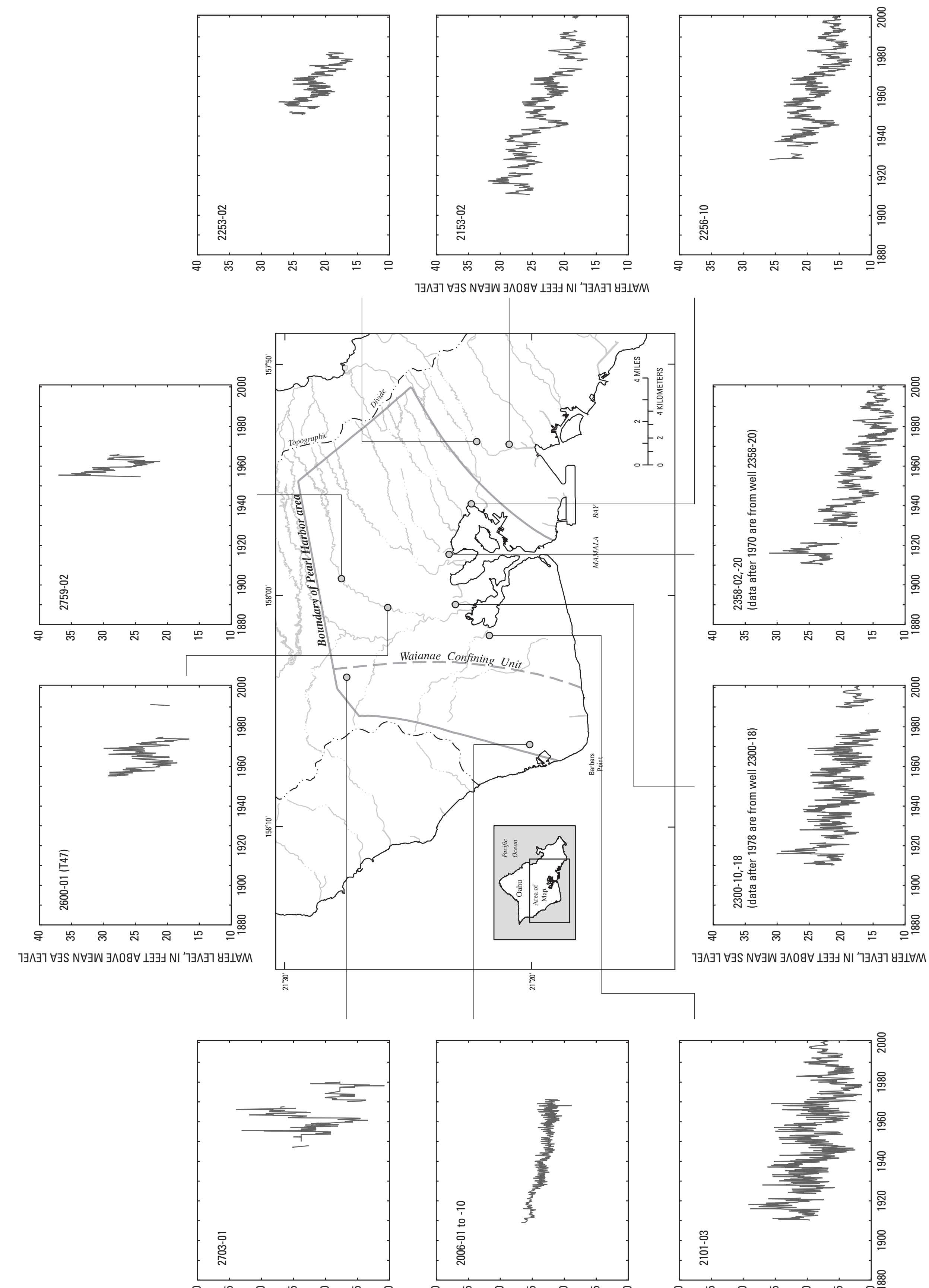


Figure 17. Measured water levels in selected wells in the Pearl Harbor area, Oahu, Hawaii.

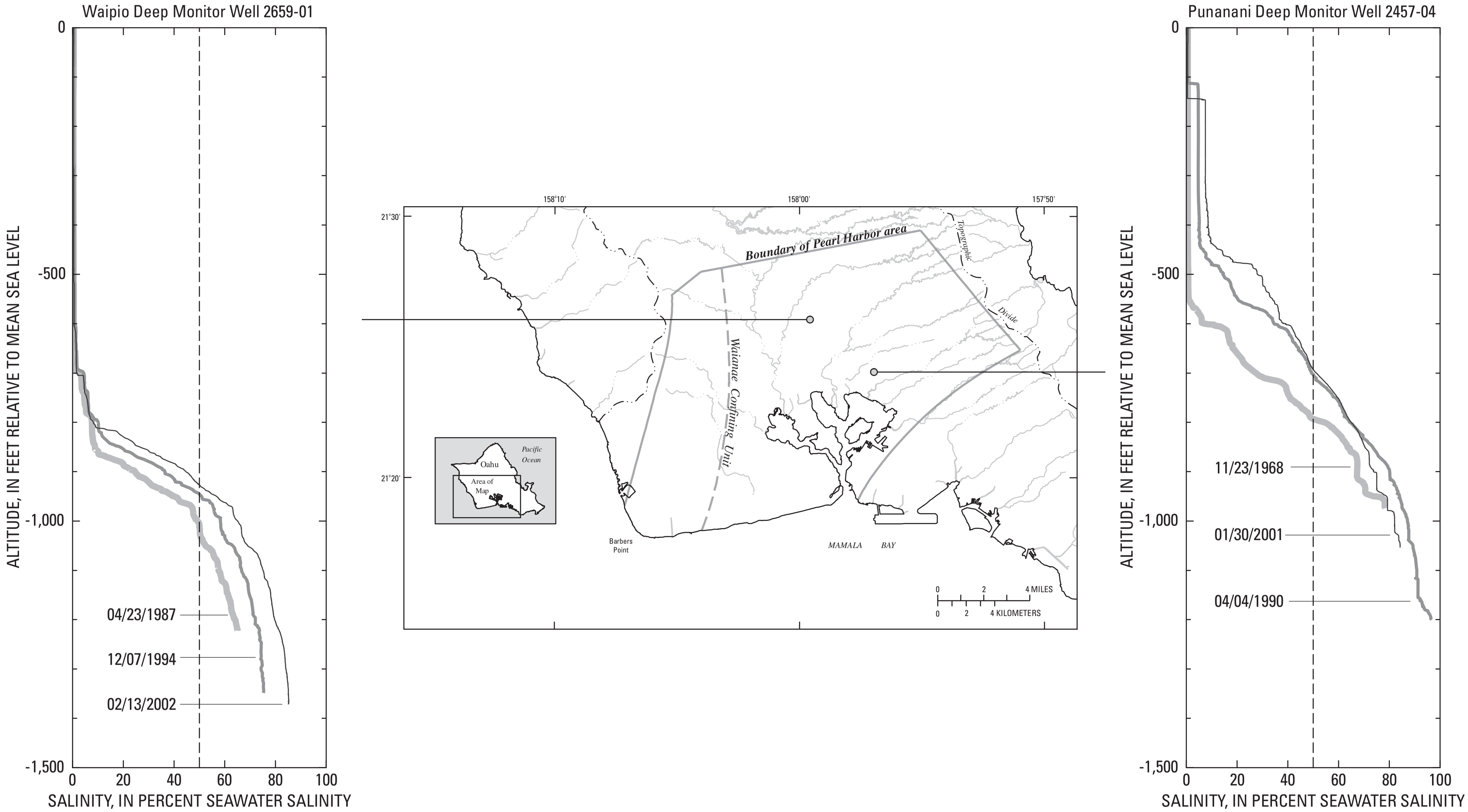


Figure 18. Measured salinity profiles in selected wells in the Pearl Harbor area, Oahu, Hawaii. (Salinity profiles from Honolulu Board of Water Supply.)

Simulation of Ground-Water Flow

Several numerical models have been developed to simulate ground-water flow in the Pearl Harbor area. These models include two-dimensional areal models that treat the interface between freshwater and saltwater as a sharp interface (Liu and others, 1981; Essaid, 1990; Nichols and others, 1996; Oki, 1998), two-dimensional cross-section models that simulate the brackish-water transition zone (Souza and Voss, 1987), and most recently, a three-dimensional model capable of simulating the brackish-water transition zone (Gingerich and Voss, 2005). The model developed for this study also is a three-dimensional model capable of simulating the brackish-water transition zone and incorporates hydrogeologic features (valley-fill barriers, an upper-limestone unit in the caprock, onshore discharge at the Pearl Harbor springs, and a weathered surface separating Waianae Volcanics and Koolau Basalt) that were not represented in the model developed by Gingerich and Voss (2005).

The model code used for this study was SUTRA (version 2D3D.1) (Voss and Provost, 2003), modified to account for water-table storage (Gingerich and Voss, 2005) through the specific yield of the aquifer. SUTRA is a finite-element code that simulates fluid movement and the transport of dissolved substances in a ground-water system. SUTRA (version 2D3D.1) is capable of simulating three-dimensional, variable-density ground-water flow and solute transport in heterogeneous anisotropic aquifers. Model construction was facilitated using a graphical user interface (SutraGUI) (Winston and Voss, 2003) capable of reading geographic information system (GIS) spatial data.

Construction of the Model

The numerical model of ground-water flow and transport in the Pearl Harbor area was developed to simulate ground-water levels and brackish-water transition-zone movement within the freshwater-lens system during the period 1880 through 2000, and incorporated time-varying recharge and withdrawals. Hydraulic characteristics used to construct the model were based mainly on previous estimates (R.M. Towill Corporation, 1978; Souza and Voss, 1987; Oki and others, 1998; Oki, 1998). In some cases, hydraulic-characteristic values were varied in the model to obtain better agreement between simulated and measured water levels and measured salinity profiles. Transient simulations of the Pearl Harbor area from 1880 through 2000 were initiated with the hydrologic system in a steady-state, predevelopment condition.

Model Mesh

The model mesh used for this study consists of 306,432 nodes and 292,875 elements, covers the entire freshwater-lens system in the Pearl Harbor area as well as the Moanalua ground-water area to the east, and extends several miles offshore to include the zone where fresh ground water discharges to the ocean (fig. 19). The model mesh excludes dike-intruded areas between the margins of the rift zones and the topographic crests of the Koolau and Waianae Ranges, although recharge within these excluded areas is included in the model and is assumed to contribute to the freshwater-lens system.

The modeled domain extends to 5,906 ft below mean sea level to coincide with an assumed aquifer bottom (Souza and Voss, 1987) and a seismic velocity discontinuity (Furumoto and others, 1970). Node spacing is variable in both the vertical and horizontal directions and is finest in the upper part of the aquifer and near areas of ground-water discharge. Onshore, the vertical spacing between nodes varies from 33 ft within the top 1,969 ft of the aquifer to 492 ft within the bottom 2,953 ft of the modeled domain; offshore, the vertical spacing between nodes is dependent on the bathymetry within the top 1,969 ft of the aquifer, but is the same as the onshore spacing within the bottom 3,937 ft of the modeled domain (fig. 20).

Boundary Conditions

The lateral extent of the model domain is defined by vertical boundaries that are either no-flow, recharge, or specified-pressure boundaries. The southeastern boundary is formed by the valley-fill barrier associated with Kalihi Stream valley and is treated as a no-flow boundary in the model. The western, northern, and northeastern boundaries are formed, respectively, by the southern rift zone of the Waianae Volcano, the southern Schofield ground-water dam, and the northwest rift zone of the Koolau Volcano. Recharge from upgradient areas is allowed to enter the western, northern, and northeastern boundaries between altitudes of -3 ft and -984 ft (fig. 19). Below altitudes of -984 ft, the western, northern, and northeastern boundaries are no-flow boundaries.

The offshore, vertical southern boundary of the model domain is a specified-pressure (hydrostatic ocean-water) boundary condition. Pressure at each node along the offshore vertical southern boundary is equal to the pressure of a column of ocean water extending from the node to sea level. Water may either enter or exit the flow system across the vertical southern boundary of the model. Water entering at the vertical southern boundary has salinity equal to that of ocean water, and water exiting at the southern boundary has salinity equal to that in the adjacent aquifer.

The top of the offshore model domain is defined by the ocean-bottom bathymetry (U.S. Army Corps of Engineers, 2000; U.S. Geological Survey, 2002) and is a specified-pressure (hydrostatic ocean-water) boundary condition. Ocean water may enter the model domain at the top boundary in offshore areas or water from the aquifer may exit at the top boundary in offshore areas.

The top of the onshore model domain is assumed to be at sea level. Although the top water-table boundary in onshore areas is truncated at sea level, the overall aquifer transmissivity is underestimated by less than 1 percent by this assumption. The bottom of the model is assumed to be a no-flow boundary.

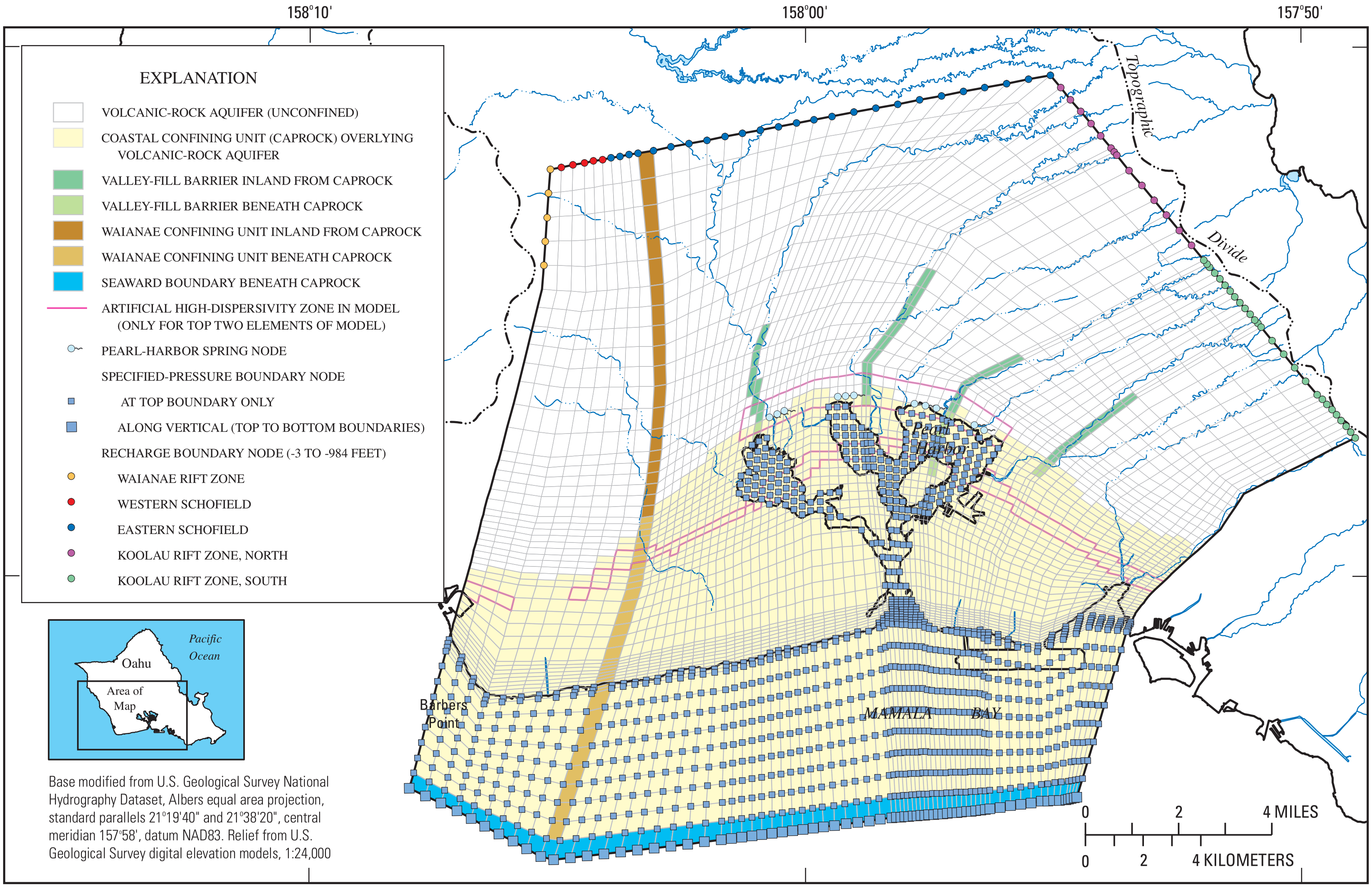


Figure 19. Model boundary conditions and other features for the vertically aligned mesh, Pearl Harbor area, Oahu, Hawaii. A hydrostatic seawater boundary condition is used for the uppermost offshore nodes and all nodes along the southern vertical boundary of the mesh.

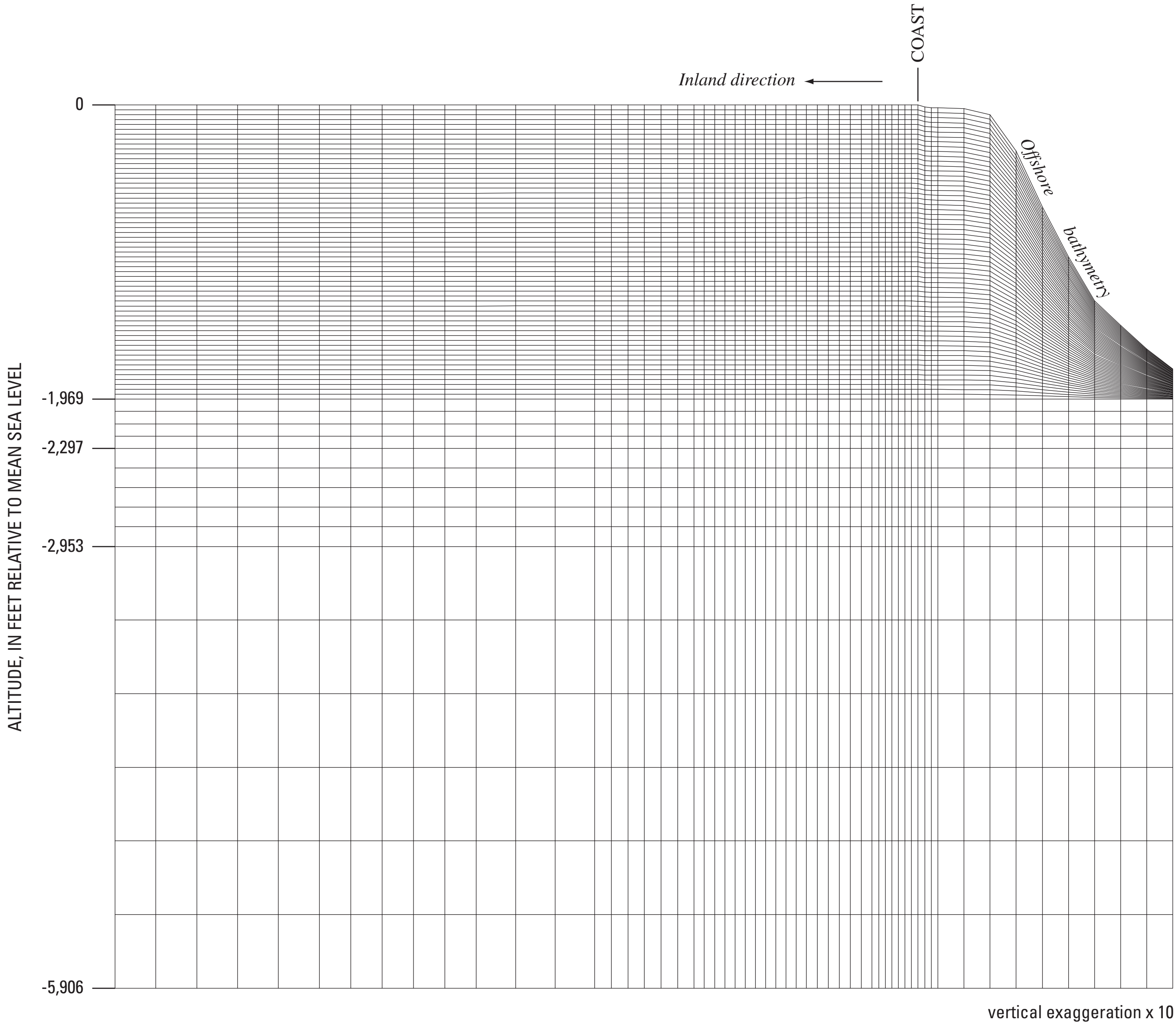


Figure 20. Vertical cross section (western edge) of model mesh for the Pearl Harbor area, viewed from west to east.

Initial Conditions

Initial conditions for the transient simulation from 1880 through 2000 were estimated from a steady-state simulation using predevelopment recharge (Shade and Nichols, 1996) and zero withdrawals. Predevelopment recharge of 307 Mgal/d was used in the model. Simulated predevelopment discharge from the Pearl Harbor springs was about 137 Mgal/d.

Representation of Hydrogeologic Features

Several hydrogeologic features of low permeability relative to the main aquifer were represented in the model. Valley-fill barriers associated with Kipapa, Waiawa, Waimalu, and North Halawa Stream valleys were represented as partially penetrating, vertical, low-permeability zones. The depth of penetration of the valley-fill barriers is uncertain because of a paucity of available information. Depths of the valley-fill barriers were estimated at selected locations and interpolated or extrapolated at other sites. The valley-fill barrier depths described in this section represent the base-case valley-fill barriers in the model.

On the basis of available information from well 2401-01, weathered volcanic rocks may extend about 100 ft below mean sea level in Waikele Stream valley, about 600 ft downstream from the confluence of Waikele and Kipapa Streams at a channel altitude of about 100 ft (Eyre, 1983). Data are unavailable to define the bottom of the Kipapa valley-fill barrier seaward or inland of well 2401-01. For the model, the Kipapa valley-fill barrier was extended seaward of well 2401-01, using a bottom altitude of -100 ft to where the contact between the caprock and volcanic rocks also is 100 ft below mean sea level. The bottom of the Kipapa valley-fill barrier was extended inland, with an estimated slope of 3 percent, to where the bottom of the barrier was at sea level.

On the basis of available well logs, the bottom of the Waiawa valley-fill barrier was estimated to extend to 65 ft below mean sea level near the shore of Middle Loch of Pearl Harbor (fig. 21). At a channel altitude of 200 ft, the alluvium was estimated to be 65 ft thick, extending to an altitude of 135 ft, and underlain by 200 ft of weathered basalt (R.M. Towill Corporation, 1978). Thus, the bottom of the Waiawa valley-fill barrier was estimated to be at an altitude of -65 ft where the channel altitude is 200 ft (fig. 21). Inland from where the channel altitude is 200 ft and between channel altitudes of 100 and 200 ft, the bottom of the Waiawa valley-fill barrier was assumed to have a slope of 3 percent. The Waiawa valley-fill barrier was extended inland to where the bottom of the barrier was at sea level.

On the basis of available well logs, the bottom of the Waimalu valley-fill barrier was estimated to extend to about 330, 260, and 200 ft below mean sea level near wells 2357-19, 2357-20, and 2356-34, respectively (fig. 22). Seaward of well 2357-19, the bottom of the Waimalu valley-fill barrier was assumed to be 330 ft below mean sea level to where the contact between the caprock and volcanic rocks also is 330 ft below mean sea level. Inland of well 2356-34, the bottom of the Waimalu valley-fill barrier was extrapolated using a slope of 3 percent to where the bottom of the barrier was at sea level.

Izuka (1992) estimated the bottom of the alluvium filling Halawa Stream valley to be near sea level at a channel altitude of about 150 ft. Weathered basalt was assumed to extend 200 ft beneath the alluvium. Thus, the bottom of the North Halawa valley-fill barrier was estimated to be at an altitude of -200 ft where the channel altitude is 150 ft. Seaward of where the channel altitude is 150 ft, the bottom of the North Halawa valley-fill barrier was assumed to be 200 ft below mean sea level to where the contact between caprock and volcanic rocks also is 200 ft below mean sea level. Inland of where the channel altitude is 150 ft, the North Halawa valley-fill barrier was extrapolated using a slope of 3 percent to where the bottom of the barrier was at sea level.

In the model, the volcanic-rock aquifer is unconfined in areas that are not beneath valley-fill barriers or the coastal confining unit (caprock). The caprock was represented as a seaward-thickening wedge with geometry defined by published structural contours (Palmer, 1946; Wentworth, 1951; Visher and Mink, 1964; Gregory, 1980) that were modified using additional logs from more recently drilled wells (fig. 7). A high-permeability upper-limestone unit within the low-permeability caprock was defined on the basis of existing structural contours (Camp Dresser and McKee, 1994) that were extrapolated offshore and to the east.

Although the Waianae confining unit separating Waianae Volcanics from Koolau Basalt follows the weathered, dipping surface of the Waianae Volcano, this confining unit was represented as a partially penetrating, vertical, low-permeability zone in the model, extending down to an altitude of -2,953 ft. The representation of the Waianae confining unit in the model is simplified because of uncertainties in the geometry and barrier effectiveness at depth.

Recharge

Recharge enters the model at the top, water-table boundary in onshore areas and along parts of the western, northern, and northeastern boundaries. Recharge from the western, northern, and northeastern boundaries enters the model between altitudes of -3 ft and -984 ft relative to mean sea level.

Recharge was estimated as a function of rainfall and land use (table 1). For predevelopment conditions, a piecewise linear model relating annual rainfall and annual recharge (Shade and Nichols, 1996) along with the distribution of long-term average annual rainfall (Giambelluca and others, 1986) was used to estimate the spatial distribution of average recharge over the modeled area. Recharge in the non-modeled, dike-intruded areas between the model boundaries and the crests of the Koolau and Waianae Ranges was estimated using values from Shade and Nichols (1996). Recharge entering the northern model boundary through the southern Schofield groundwater dam was estimated to be 106 Mgal/d (Oki, 1998; Shade

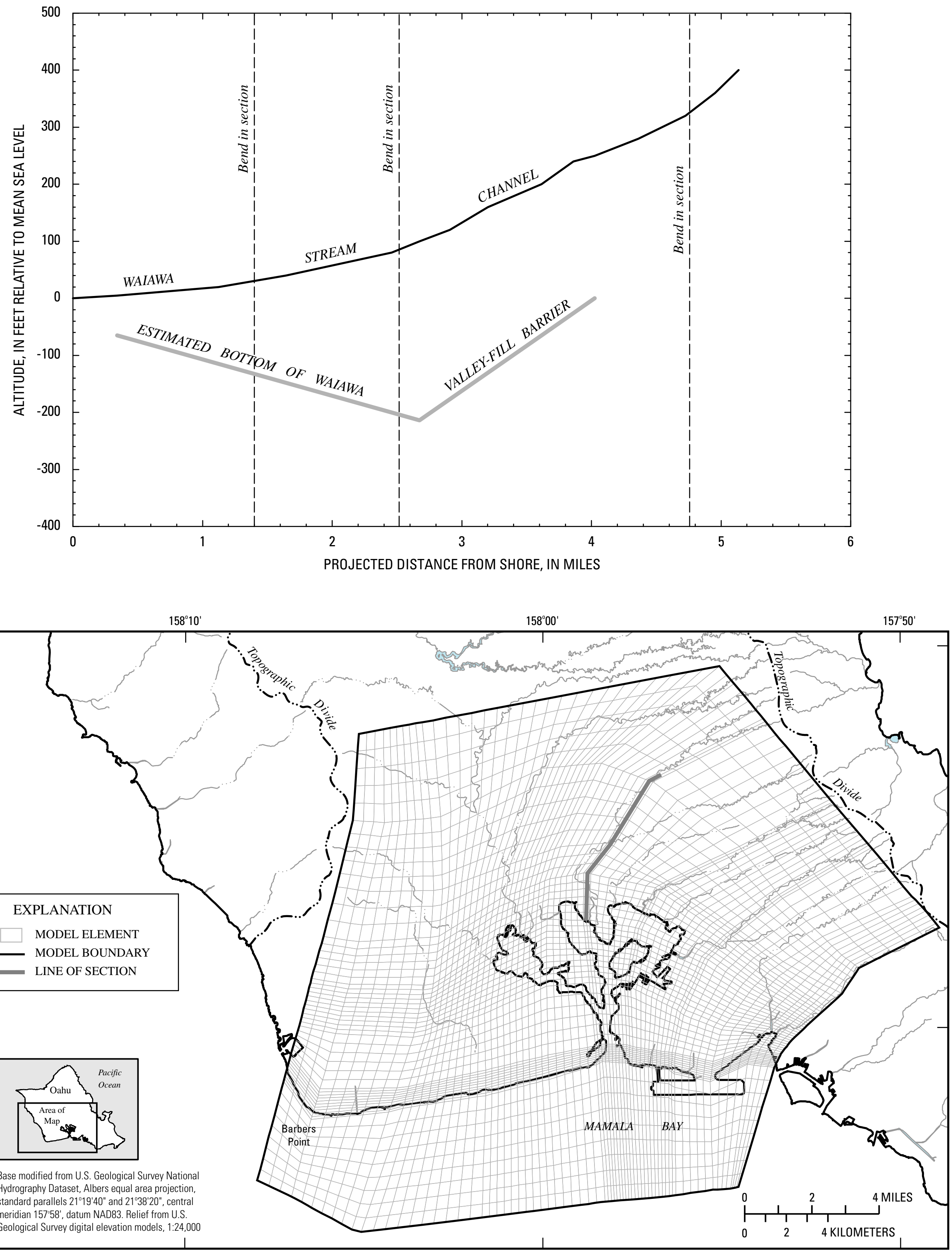
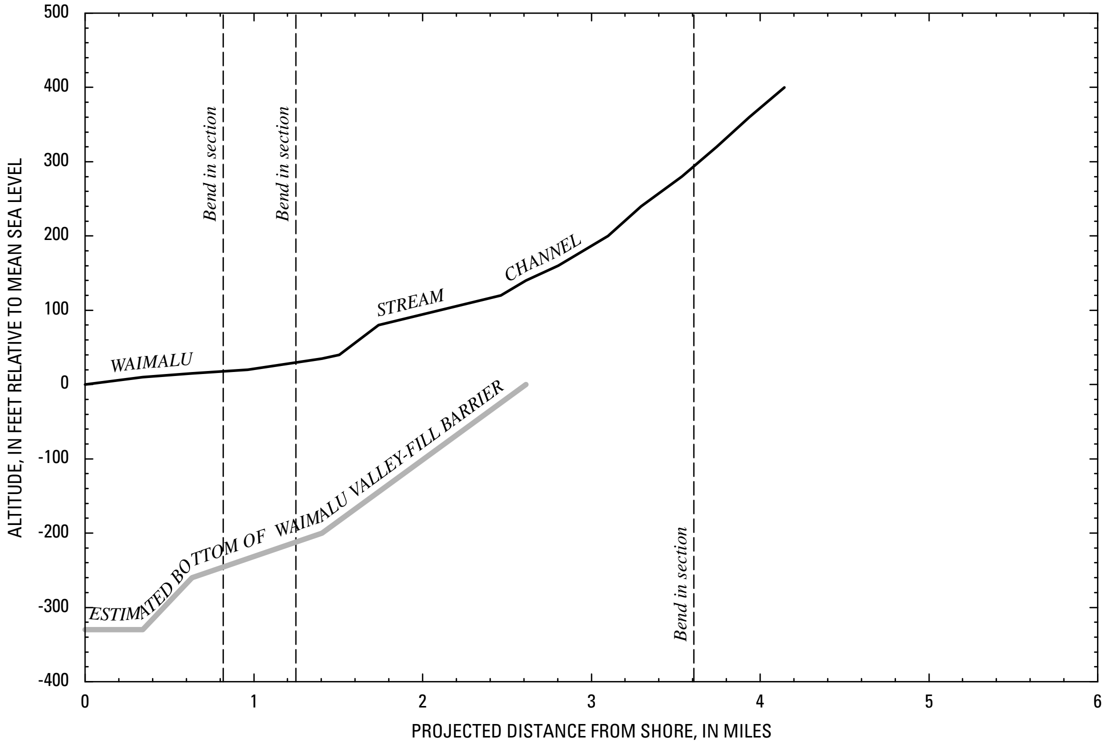


Figure 21. Profile of Waiawa Stream channel and estimated bottom of valley-fill barrier, Pearl Harbor area, Oahu, Hawaii.



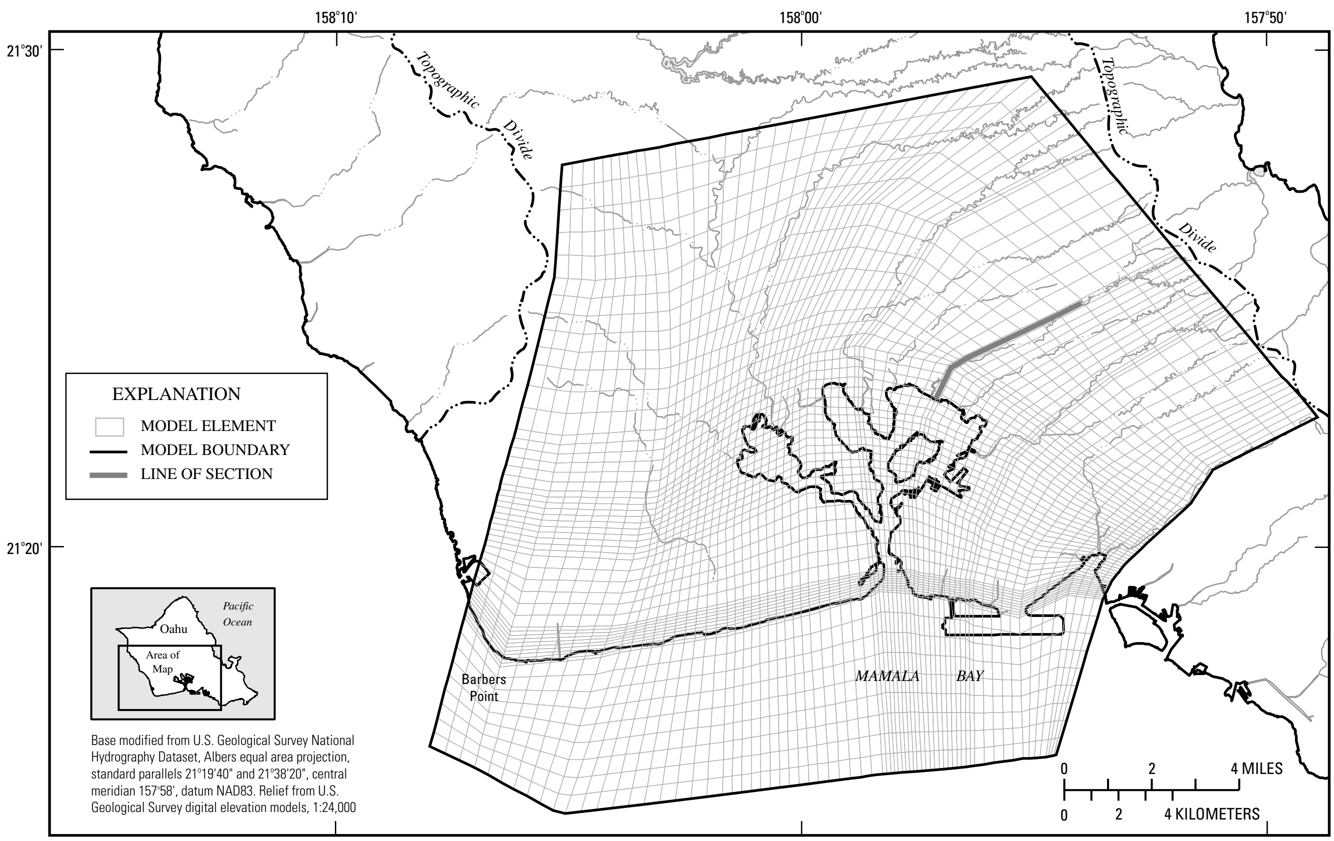


Figure 22. Profile of Waimalu Stream channel and estimated bottom of valley-fill barrier, Pearl Harbor area, Oahu, Hawaii.

and Nichols, 1996). Estimated total predevelopment recharge in the modeled area was 307 Mgal/d (table 3).

The distributions of recharge for individual 5- to 20-year periods from 1880 through 2000 were estimated using the distributions of land use (fig. 3) and rainfall (fig. 14) during each period in conjunction with equations relating annual rainfall and annual recharge for different land uses (Shade and Nichols, 1996). Annual rainfall during a particular period was estimated from the long-term annual rainfall (fig. 2) (Giambelluca and others, 1986) multiplied by the ratio of annual rainfall during the period to the long-term annual rainfall. For each model node, ratios of annual rainfall during selected periods to the long-term annual rainfall (fig. 14) were determined using the ratio from the nearest rain gage with a computed ratio for the period. Land use at each node was assumed to be representative of the land use for the immediate area surrounding the node.

For furrow-irrigated sugarcane areas, recharge was estimated by adding a fraction of the applied irrigation water (table 4) to the estimated non-agricultural recharge rate. For this study, it was assumed that 30 percent of the applied irrigation water in furrow-irrigated sugarcane fields contributed to recharge, which is lower than some previous estimates but consistent with the estimate from Nichols and others (1996).

For each selected time period, recharge entering the model domain from the western, northern, and northeastern boundaries was determined by multiplying the predevelopment recharge value by an average ratio (determined from nearby rain gages with available data) of annual rainfall during the period to the long-term annual rainfall. Estimated recharge in the modeled area for individual 5- to 20-year periods during 1880 through 2000 ranged from 261 Mgal/d (1995-2000) to 424 Mgal/d (1930-1939) (table 3). Estimated recharge is greatest near high-rainfall areas, although irrigation associated with sugarcane cultivation and evapotranspiration suppression associated with pineapple cultivation locally modify this general recharge distribution.

Withdrawal

Reported or estimated monthly withdrawals from wells during 1890 through 2000 were simulated in the numerical model (Appendix A). Reported withdrawals were compiled from published records (Stearns and Vaksvik, 1935; Stearns, 1940), information contained in U.S. Geological Survey files (unpub. data, USGS Pacific Islands Water Science Center data files), and a CWRM digital database (unpub. data, 2002). The small amount of estimated withdrawal prior to 1890 (Mink, 1980) was not simulated in the transient model, which has little effect on the long-term transient response of the system.

Withdrawal wells (fig. 23) were represented in the model by the nearest vertical column of nodes to the withdrawal well. Within the nearest vertical column of nodes from a pumped well, only those nodes corresponding to the interval of the well open to the aquifer (appendix B) were used to simulate withdrawal. Withdrawal from the aquifer was assumed to be uniform within the interval of the well open to the aquifer. Withdrawals from Maui-type shafts with large-capacity infiltration tunnels generally were represented in the model by a single node, although some infiltration tunnels were represented by more than one node to improve model stability. In the model, withdrawals were not simulated from the top layer of nodes to avoid assigning both recharge and pumpage at the same node in SutraGUI (Winston and Voss, 2003).

Discharge from the Pearl Harbor springs was simulated in the model from selected nodes at the top of the model domain (fig. 19). Recharge from nodes used to represent the Pearl Harbor springs was set to zero. Discharge from the Pearl Harbor springs was simulated as a function of the simulated head at well 2256-10 according to relations from Oki (1998) (table 2). Because of the lack of information on discharge from the Pearl Harbor springs during the entire period from 1880 through 2000, it was necessary to apply the relations in table 2 beyond the range of water levels used to develop the relations.

Water Properties

For all model simulations, water was assigned a fluid compressibility of 2.14×10^{-8} ft^2/lb (4.47×10^{-10} Pa^{-1}) and dynamic viscosity of 2.1×10^{-5} slug/(ft•s) [0.001kg/(m•s)]. Viscosity is a property of a fluid that measures its resistance to deformation (flow). Dynamic viscosity is the ratio of shear stress (shear force per unit area) to velocity gradient.

Solute concentrations in the model are expressed as a mass fraction: mass of total dissolved solids (TDS) per unit mass of fluid. Freshest water was assigned a TDS concentration of zero and 100 percent saltwater was assigned a TDS concentration of 0.0357 kg/kg. The density of water was assumed to increase linearly with salinity from 62.42 lb/ft^3 (1,000 kg/m^3) for freshwater to 63.98 lb/ft^3 (1,024.99 kg/m^3) for saltwater.

Molecular diffusion of a solute is driven by concentration gradients in the fluid and may take place in the absence of ground-water flow. Molecular diffusion of a solute in a fluid is characterized by the molecular diffusivity. In the model, molecular diffusivity was assigned a value of 1.1×10^{-8} ft^2/s (1.0×10^{-9} m^2/s).

Aquifer Properties

For this study, aquifer properties generally were assigned values based on published estimates. Solid-matrix compressibility was assigned a value of 1.2×10^{-7} ft^2/lb (2.5×10^{-9} Pa^{-1}) (Souza and Voss, 1987). For the volcanic-rock aquifers, effective porosity values used in the model were 0.04 (east of Waiawa Stream) and 0.1 (west of Waiawa Stream). The effective porosity values used in the model are within the range of previously estimated values (Mink, 1980; Souza and Voss, 1987) and are lower in the east than west to improve the match between measured and simulated salinity profiles. For the upper-limestone unit, effective porosity was assigned a

Table 3. Estimated ground-water recharge used in construction of the numerical model of the Pearl Harbor area, Oahu, Hawaii during selected periods.

[Mgal/d, million gallons per day]

Period	Recharge, in Mgal/d							Pumpage, in Mgal/d
	Top boundary[1]	Waianae rift zone[2]	Western Schofield[2]	Eastern Schofield[2]	Koolau rift zone[2], north	Koolau rift zone[2], south	Total	
Predevelopment	175	1.9	0.6	106	23	0.8	307	0
1880-1889	175	1.9	0.6	106	23	0.8	307	0
1890-1899	175	1.9	0.6	106	23	0.8	307	29
1900-1909	229	1.9	0.6	106	23	0.8	361	139
1910-1919	258	1.8	0.6	115	23	0.8	390	156
1920-1929	256	1.9	0.6	104	23	0.8	386	160
1930-1939	282	2.0	0.6	113	26	0.8	424	156
1940-1949	224	1.6	0.5	97	21	0.6	345	176
1950-1959	245	2.0	0.6	109	21	0.7	378	160
1960-1969	267	2.2	0.7	113	24	0.9	407	184
1970-1974	232	2.1	0.7	112	21	0.8	368	220
1975-1979	183	1.7	0.5	97	19	0.7	302	229
1980-1984	194	1.9	0.6	106	23	0.9	326	189
1985-1989	202	1.9	0.6	99	23	1.0	327	152
1990-1994	187	1.9	0.6	103	22	0.9	316	152
1995-2000	142	1.8	0.6	98	18	0.9	261	105

[1]Includes recharge over the volcanic-rock aquifer, coastal caprock, valley-fill barriers, and Waianae confining unit.

[2]Recharge boundary shown in figure 19.

Table 4. Estimated areas and irrigation rates for furrow-irrigated sugarcane fields in the Pearl Harbor area, Oahu, Hawaii during selected time periods.

[Mgal/d, million gallons per day]

	Area, in square miles	Irrigation rate, in Mgal/d	Irrigation rate, in inches per year
Predevelopment	0	0	0
1880-1899	0	0	0
1900-1909	48.8	155	67
1910-1919	48.8	185	80
1920-1929	45.2	208	97
1930-1939	43.8	222	106
1940-1949	38.7	215	117
1950-1959	33.4	187	118
1960-1969	38.1	184	102
1970-1974	36.2	189	110
1975-1979	18.6	not estimated[1]	112
1980-1984	4.3	not estimated[1]	112
1985-1989	2.6	not estimated[1]	112
1990-1994	2.6	not estimated[1]	112
1995-2001	0	0	0

[1]Irrigation rate for furrow-irrigated sugarcane fields was not estimated from water-use information because of uncertainty in distribution of water used for furrow- and drip-irrigated sugarcane. Irrigation rate for furrow-irrigated sugarcane fields estimated from the time-weighted average value during 1940 to 1974.

value of 0.2, and for all other rock types effective porosity was assigned a value of 0.1.

For all rock types, the transverse dispersivity was assigned a value of 0.82 ft (0.25 m) (Souza Voss, 1987) (table 5). For the volcanic-rock aquifers, longitudinal dispersivity was assigned a value of 250 ft (76 m) in the horizontal direction (corresponding to the major and semi-major axes of the permeability tensor) (Souza and Voss, 1987) and 25 ft (7.6 m) in the vertical direction (corresponding to the minor axis of the permeability tensor). For the upper-limestone unit of the caprock, longitudinal dispersivity was assigned a value of 250 ft (76 m) in the horizontal direction and 25 ft (7.6 m) in the vertical direction (Oki and others, 1998). For the low permeability features in the model (valley-fill barriers, Waianae confining unit, and caprock exclusive of the upper-limestone unit), longitudinal dispersivity was assigned a value of 10 ft (3 m) (Oki and others, 1998).

To enhance numerical stability near the discharge zones of the Pearl Harbor springs and near the inland contact between the upper-limestone unit and low-permeability part of the caprock, zones of high dispersivity were created within the top 66 ft (top two elements) of the model. These zones were created by trial and error to eliminate numerical problems that result in unrealistic solute-concentration distributions. Within these zones of high dispersivity, longitudinal dispersivity values were increased by a factor of 3 relative to the values for the volcanic rocks and upper-limestone unit. Although these high-dispersivity zones may a have local effect on the salinity distribution by enhancing mixing, they do not affect the regional distribution of salinity in the aquifer at depth.

The hydraulic-conductivity values for some geologic features, including the upper-limestone unit of the caprock (2,500 ft/d horizontal; 25 ft/d vertical), the Waianae confining unit (10 ft/d horizontal), and valley-fill barriers (0.058 ft/d), were estimated on the basis of published information (Camp Dresser and McKee, 1994; Oki and others, 1998; Oki, 1998; R.M. Towill Corporation, 1978) and were not varied in the model. Souza and Voss (1987) assigned a leakance of 1.25 $\times 10^{-3}$ d^{-1} for the elements at the seaward end of their mesh to control the ease with which saltwater enters and exits the flow system. For this study, the hydraulic conductivity at the seaward end of the mesh was assigned a value that resulted

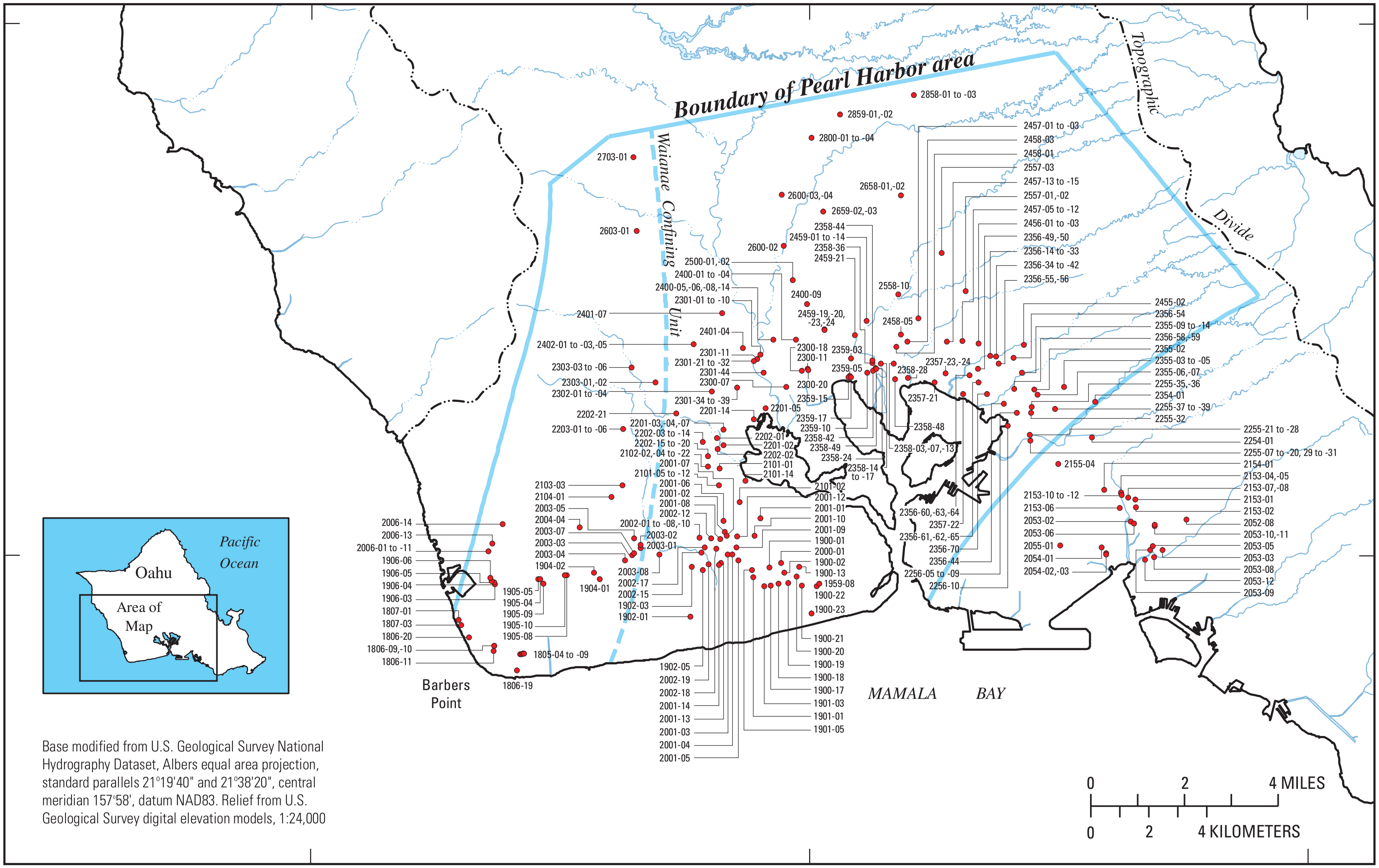


Figure 23. Selected withdrawal wells used in construction of the numerical model of the Pearl Harbor area and the Moanalua ground-water area, Oahu, Hawaii.

Table 5. Aquifer-property values used in the construction of the numerical ground-water model of the Pearl Harbor area, Oahu, Hawaii.

[ft, feet; ft/d, feet per day; ft^2/lb, feet squared per pound]

Parameter	Estimated value		
Hydraulic conductivity (ft/d)	**Vertical**	**Horizontal, transverse**	**Horizontal, longitudinal**
Volcanic-rock aquifer	7.5	1,500[1]	4,500[2]
Caprock[3], upper-limestone unit	25	2,500	2,500
Caprock[3], low-permeability unit			
Above Waianae Volcanics	0.3	0.3	0.3
Above Koolau Basalt, west of Waiawa Stream	0.01	0.01	0.01
Above Koolau Basalt, east of Waiawa Stream	0.6	0.6	0.6
Valley-fill barriers	0.058	0.058	0.058
Waianae confining unit	7.5	10	10
Seaward boundary below caprock (last row of elements)	7.5	30	30
Dispersivity (ft)	**Transverse**	**Longitudinal, minimum[4]**	**Longitudinal, middle and maxmum[5]**
Volcanic-rock aquifer	0.82	25	250
Caprock, upper-limestone unit	0.82	25	250
Caprock, low-permeability unit	0.82	10	10
Valley-fill barriers	0.82	10	10
Waianae confining unit	0.82	10	10
Seaward boundary below caprock (last row of elements)	0.82	25	250
High-dispersivity zones	0.82	75	750
Porosity (and specific yield)			
Upper limestone unit	0.2		
Volcanic-rock aquifer, east of Waiawa Stream	0.04		
All other rocks	0.1		
Solid-matrix compressibility (ft^2/lb)	1.2×10^{-7}		

[1]The transverse direction represents the direction transverse to the general lava-flow direction.

[2]The longitudinal direction represents the general lava-flow direction.

[3]In the model, the caprock is represented by an upper-limestone unit and a low-permeability unit with hydraulic-conductivity values that vary spatially depending on whether the caprock overlies Waianae Volcanics or Koolau Basalt, and whether the caprock over Koolau Basalt is east or west of Waiawa Stream.

[4]The longitudinal, minimum dispersivity is the longitudinal dispersivity for flow in the direction of the minimum (vertical) hydraulic conductivity.

[5]The longitudinal, middle dispersivity is the longitudinal dispersivity for flow in the direction of the middle (horizontal transverse) hydraulic conductivity. The longitudinal, maximum dispersivity is the longitudinal dispersivity for flow in the direction of the maximum (horizontal longitudinal) hydraulic conductivity.

in a leakance about one order of magnitude higher than the value used by Souza and Voss as this tended to produce a better overall match between simulated and measured water levels and salinity profiles. Within the lochs of Pearl Harbor, a layer of sedimentary material (typically about 33-ft or 1-element thick) was assumed to overlie the upper-limestone unit and was assigned the same hydraulic-conductivity value as the underlying low-permeability caprock beneath the upper-limestone unit.

Different distributions of hydraulic-conductivity values for the volcanic-rock aquifers and low-permeability part of the caprock were used in the model to match measured water levels and salinity profiles from selected wells in the study area. Hydraulic-conductivity values used in the model ranged from 0.01 ft/d for parts of the caprock to 4,500 ft/d for the volcanic-rock aquifers (table 5). Horizontal hydraulic-conductivity values for the volcanic-rock aquifers in the model were 4,500 ft/d in the assumed direction of the surficial lava flows (approximately perpendicular to the existing topographic contours), and 1,500 ft/d in the lateral direction. Vertical hydraulic conductivity of the volcanic-rock aquifers in the model was 7.5 ft/d (Souza and Voss, 1987).

Evaluation of Simulated Transient Conditions 1880-2000

Water Levels.—Simulated water levels generally are in agreement with measured water levels from representative wells in the modeled area (fig. 24). Measured and simulated water levels decline regionally until the late 1970s. In the western part of the Koolau Basalt aquifer, near well 2101-03, measured and simulated water levels increase after the late 1970s in response to reduced withdrawals for sugarcane irrigation in the area. The water-level recovery after the late 1970s is less pronounced in the eastern part of the Koolau Basalt aquifer (well 2256-10), mainly because withdrawals in the eastern part of the aquifer did not change as much as those in the western part, where most of the wells used for sugarcane irrigation were located.

Because recharge in the transient model was averaged over periods ranging from 5 to 20 years, interannual variations in water levels caused by interannual variations in recharge were not represented by the model. Some interannual variability in water levels was represented, however, because of variations in withdrawal.

Within the Koolau Basalt aquifer of the Pearl Harbor area, simulated water levels west of Kipapa Stream generally are low and simulated water levels east of Waiawa Stream generally are high relative to measured water levels. The model underestimates, by about 4 ft, the reported predevelopment head near well 2101-03 of 32 ft above mean sea level (fig. 24). During the 1950s, a period for which the spatial distribution of water levels is relatively well-characterized by available data, average simulated water levels generally are within a few feet, and sometimes within a foot, of measured water levels (fig. 25).

Some of the discrepancy between measured and simulated water levels can be attributed to uncertainties in the estimated distribution of hydraulic properties in the model. In addition, some of the discrepancy may be related to factors including: (1) the reported predevelopment head may be from a period with climatic conditions that are not representative of long-term conditions, (2) the estimated distributions of recharge for different time periods are uncertain, (3) the reported ground-water withdrawal information may be inaccurate, (4) the hydraulic characteristics of the caprock may have changed over time because of the drilling of numerous artesian wells, which flowed freely at the surface and may have leaked in the subsurface.

Pearl Harbor Springs Discharge.—Discharge from the Pearl Harbor springs was modeled as a function of head at well 2256-10 (table 2). During the period from about 1970 to the early 1980s, simulated discharge from the Pearl Harbor springs was in general agreement with measured discharge (fig. 26). After the early 1980s, however, simulated spring discharge generally was higher than measured discharge. After the early 1980s, simulated spring discharge is high mainly because simulated water levels at well 2256-10 are higher than measured water levels.

Salinity profiles.—Prior to about 2000, salinity profiles from deep monitor wells in the study area were limited to only a few wells, including wells at Waipahu (2300-18), Waipio (2659-01), and Punanani (2457-04). The BWS periodically logs these wells to measure changes in salinity profiles over time. In general, measured salinity profiles indicate a rise in the brackish-water transition zone over time, and simulated salinity profiles are consistent with this trend (fig. 27). The shapes of the simulated salinity profiles also generally are consistent with the measured profiles. At the Waipahu deep monitor well (2300-18), simulated and measured depths where salinity is 50 percent that of ocean water are within about 50 feet of each other. At the Punanani deep monitor well (2457-04), which is toward the eastern part of the Pearl Harbor area, simulated and measured depths where salinity is 50 percent that of ocean water may differ by as much as 200 ft.

Some of the discrepancy between measured and simulated salinity profiles can be attributed to (1) uncertainties in the estimated distribution of hydraulic properties in the model, (2) borehole flow (Paillet and others, 2002), and (3) additional factors described above for simulated water levels.

Simulation of the Effects of Valley-Fill Barriers on Water Levels and Salinity

Model sensitivity to the geometry of the valley-fill barriers was tested using four additional, hypothetical valley-fill barrier configurations: (1) no barriers; (2) base-case barriers deepened by 200 ft, extended inland using a 3 percent slope,

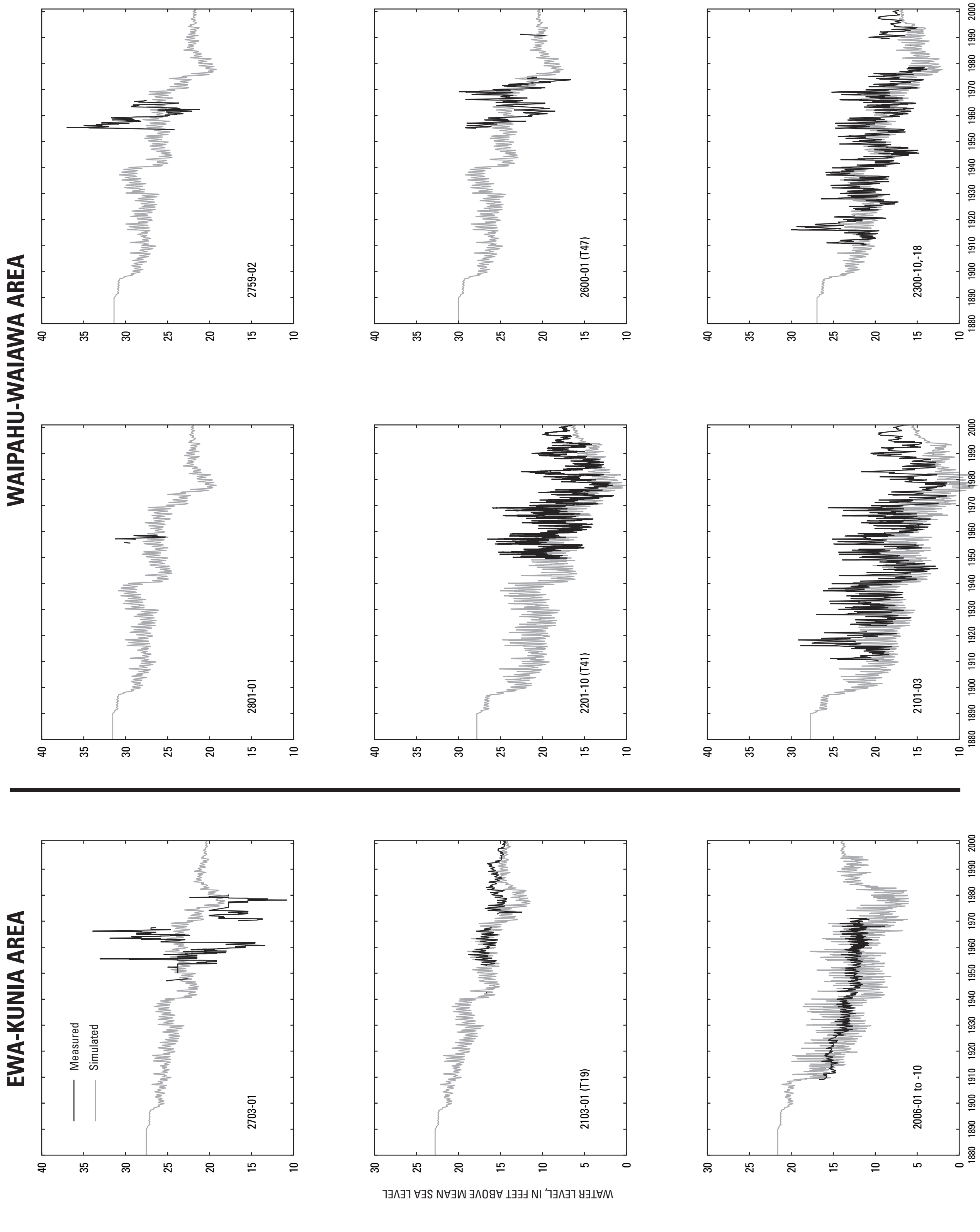


Figure 24. Measured and simulated (using base-case valley-fill barriers) water levels in selected wells in the Pearl Harbor area, Oahu, Hawaii.

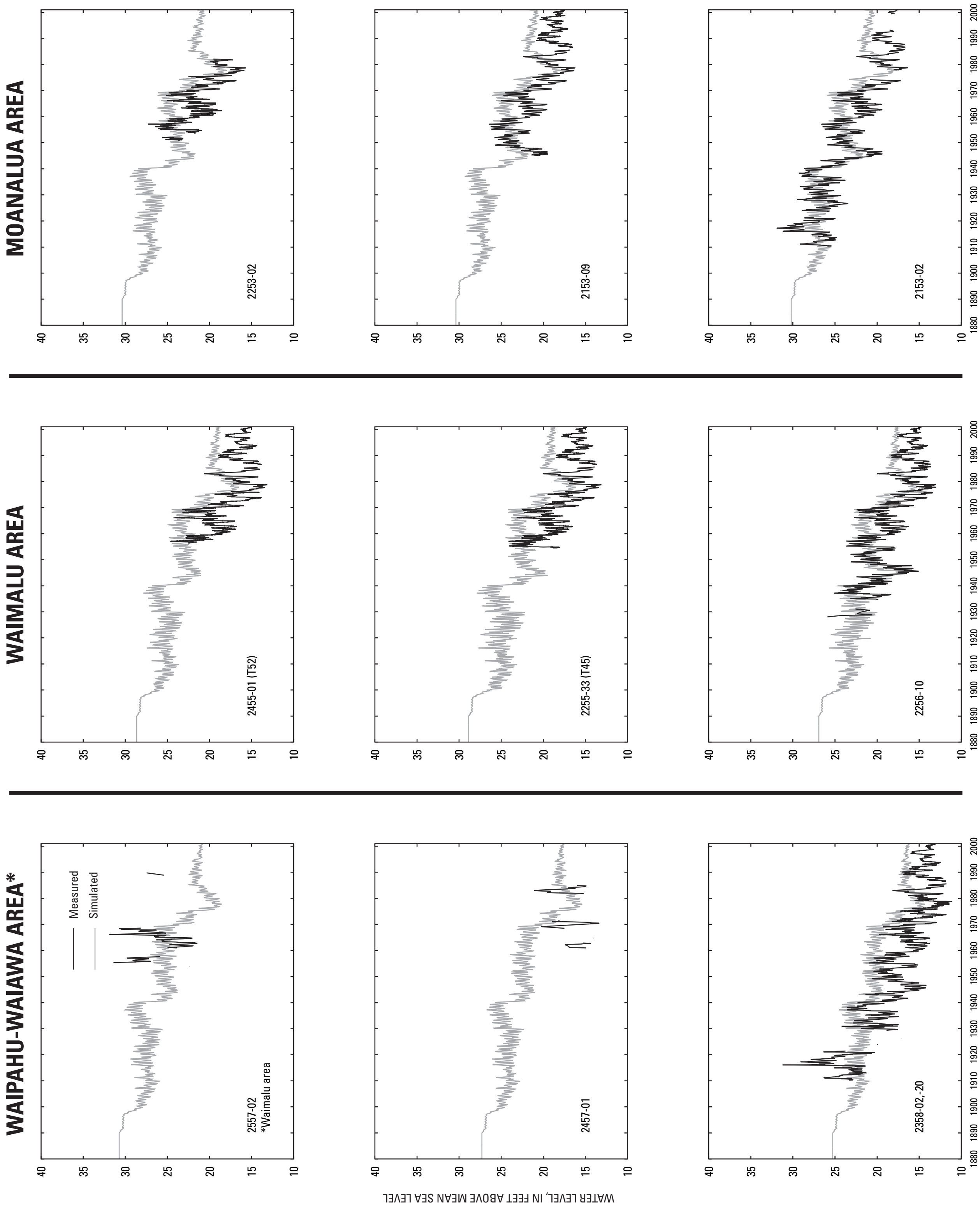


Figure 24. Measured and simulated (using base-case valley-fill barriers) water levels in selected wells in the Pearl Harbor area, Oahu, Hawaii—*Continued.*

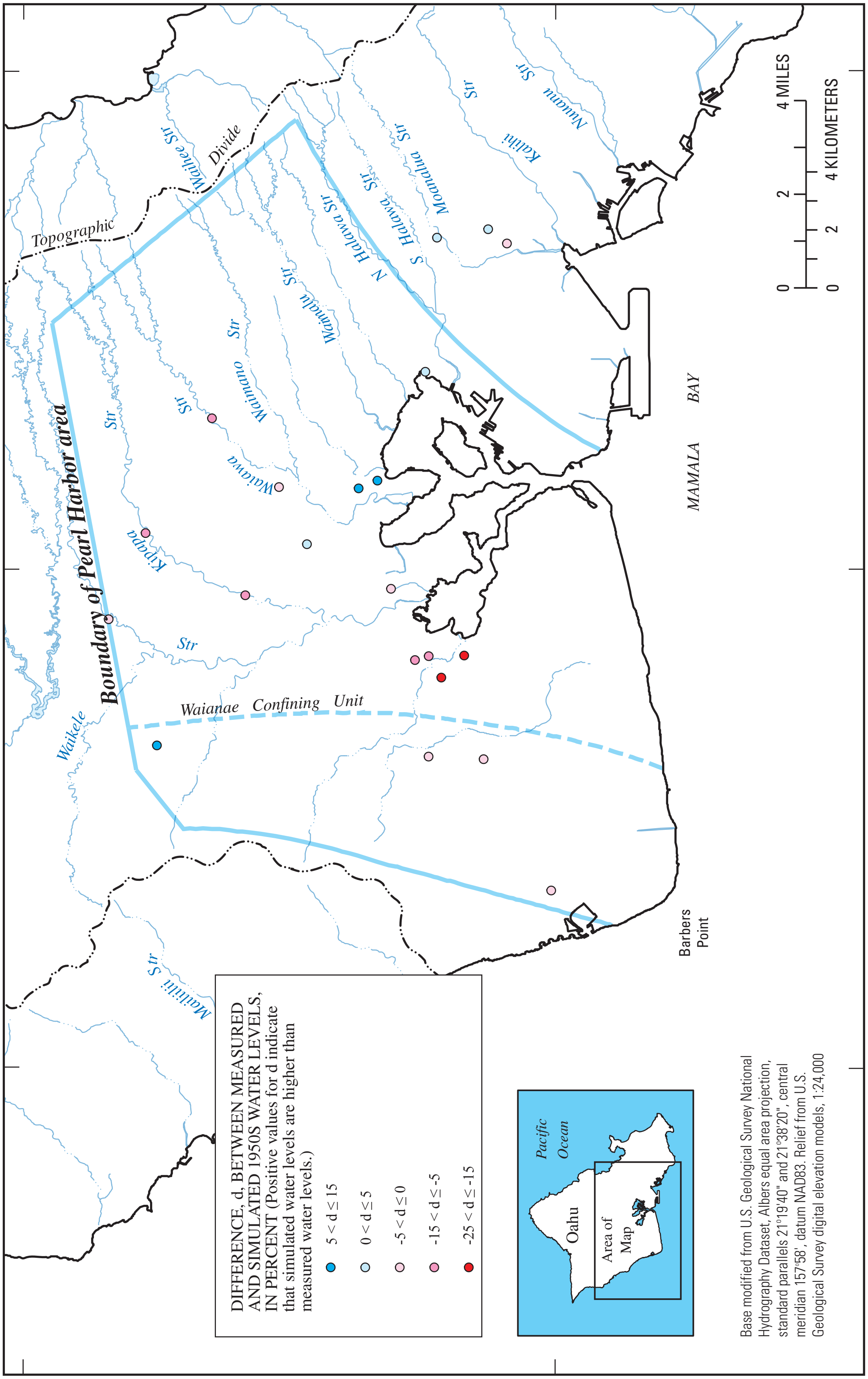


Figure 25. Difference between measured and simulated (using base-case valley-fill barriers) 1950s water levels at selected wells, Pearl Harbor area, Oahu, Hawaii.

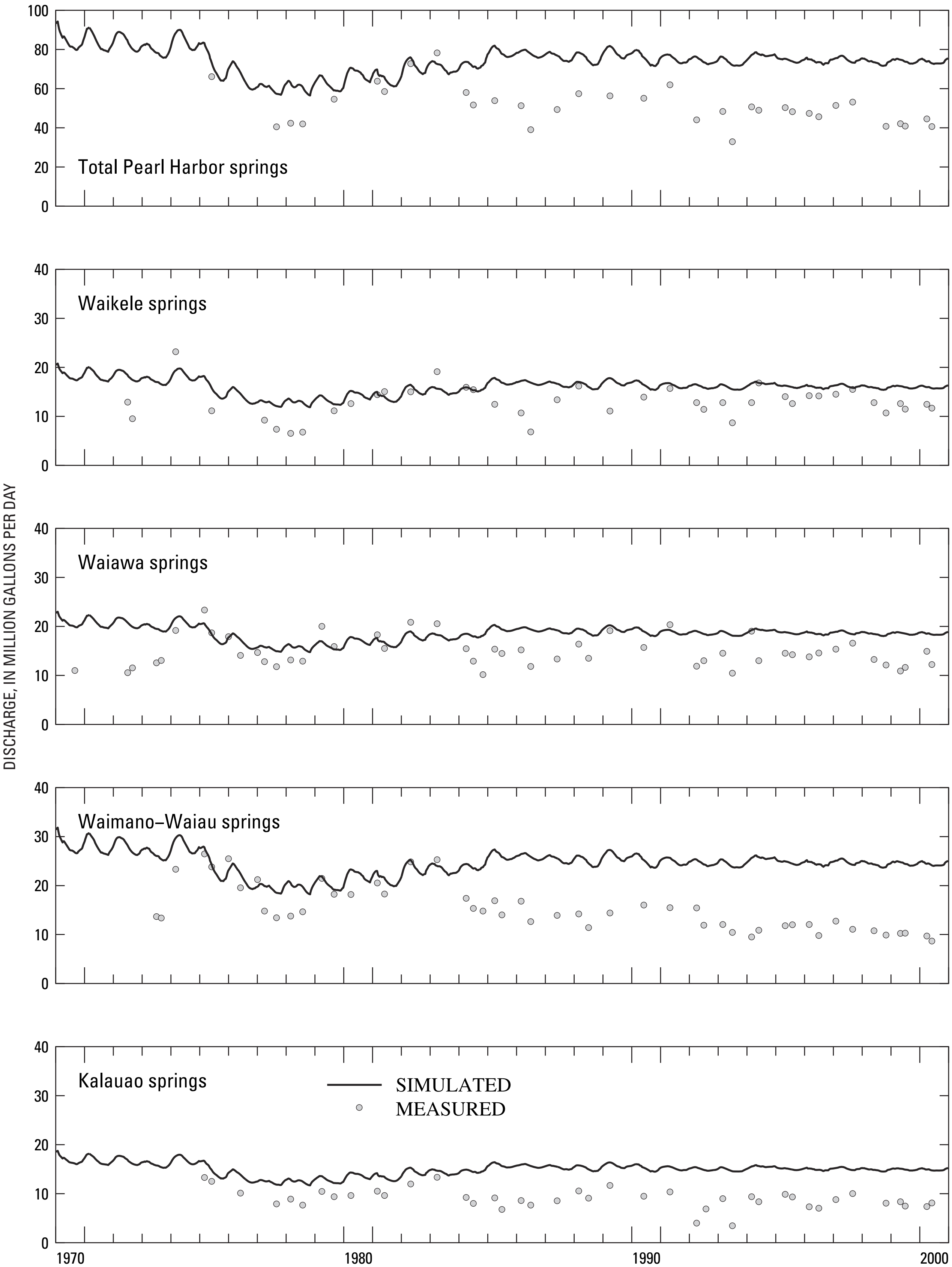


Figure 26. Measured and simulated (using base-case valley-fill barriers) discharge from the Pearl Harbor springs, Oahu, Hawaii.

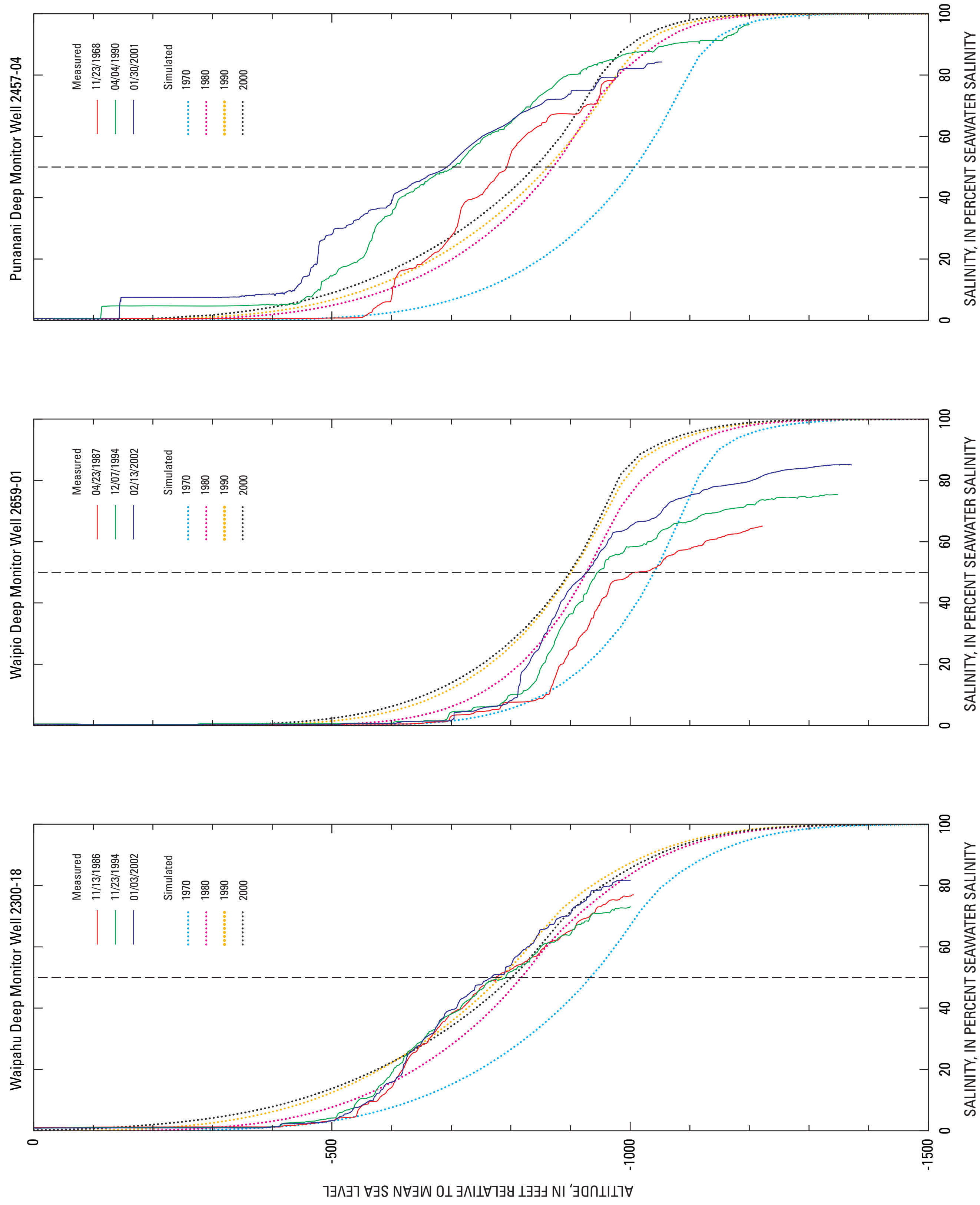


Figure 27. Measured and simulated (using base-case valley-fill barriers) salinity profiles in selected wells in the Pearl Harbor area, Oahu, Hawaii.

and extended seaward with a zero percent slope to where the caprock and valley-fill barriers are at common depths; (3) Waiawa valley-fill barrier deepened to a constant depth of 660 ft below mean sea level, extended inland to where the channel altitude is 800 ft, and extended seaward to where the caprock is at a depth of 660 ft below mean sea level; and (4) Waimalu valley-fill barrier deepened to a constant depth of 660 ft below mean sea level, extended inland to where the channel altitude is 800 ft, and extended seaward to where the caprock is at a depth of 660 ft below mean sea level (fig. 28). In the absence of definitive information on the valley-fill barriers, the hypothetical valley-fill barrier configurations represent a range of configurations that may exist. All aspects of the model other than the configuration of the valley-fill barriers were unchanged for the analysis.

Simulated water levels in the absence of valley-fill barriers generally were lower, by a few tenths of a foot or less, than simulated water levels using the base-case valley-fill barriers (figs. 24 and 29) because overall system permeability is higher in the absence of valley-fill barriers. With the valley-fill barriers deepened by 200 ft, simulated water levels generally were higher, by a few tenths of a foot, than simulated water levels in the base case, although simulated water levels were lower in some places near the eastern part of the Pearl Harbor area (see for example wells 2256-10, 2355-33, and 2455-01) with the deepened valley-fill barriers (figs. 24 and 30).

Deepening the Waiawa valley-fill barrier to 660 ft below mean sea level resulted in an increase in simulated water levels west of the Waiawa valley-fill barrier by as much as a foot relative to the base case (see wells 2101-03 and 2201-10 in the western part of the Pearl Harbor area in figs. 24 and 31), which represents an improvement in simulated water levels relative to the base case. Simulated water levels just east of the Waiawa valley-fill barrier were lower by a few tenths of a foot relative to the base case (see wells 2358-02, -20 in the central part of the Pearl Harbor area in figs. 24 and 31), which also represents an improvement in simulated water levels relative to the base case for most periods. The increase in simulated water levels west of the deepened Waiawa valley-fill barrier and the decrease in simulated water levels east of the barrier result from a redistribution of ground-water flow relative to the base case.

Deepening the Waimalu valley-fill barrier to 660 ft below mean sea level resulted in an increase in simulated water levels west of the Waimalu valley-fill barrier by as much as a foot relative to the base case (see wells 2101-03 and 2201-10 in the western part of the Pearl Harbor area in figs. 24 and 32), which represents an improvement in simulated water levels relative to the base case. Simulated water levels in the central part of the Pearl Harbor area also increased by about a foot relative to the base case (see wells 2358-02, -20 in figs. 24 and 32), and this represents a decrease in accuracy in simulated water levels relative to the base case. Simulated water levels just east of the Waimalu valley-fill barrier were lower by a few tenths of a foot relative to the base case (see wells 2256-10 and 2255-33 in figs. 24 and 32), which represents a slight improvement in simulated water levels relative to the base case. The increase in simulated water levels west of the deepened Waimalu valley-fill barrier and the decrease in simulated water levels east of the barrier result from a redistribution of ground-water flow relative to the base case.

Simulated salinity profiles generally were consistent with the simulated water levels. For example, in the absence of valley-fill barriers, simulated salinity profiles were shallower, by about 10 ft, than simulated salinity profiles at common sites and times with the base-case valley-fill barriers. This result is consistent with the lower water levels simulated in the absence of valley-fill barriers relative to the base case.

Deepening the Waiawa valley-fill barrier to 660 ft below mean sea level generally resulted in a deeper simulated transition zone west of the Waiawa valley-fill barrier by as much as a few tens of feet in some places relative to the base case for common sites and times (figs. 27 and 33). At the Punanani deep monitor well (2457-04) east of the Waiawa valley-fill barrier, the transition zone was widened because of enhanced dispersion in the area (figs. 27 and 33).

Simulation of Redistributed Withdrawals 2001-2025

The model constructed for this study was used to simulate the hydrologic effects of redistributing ground-water withdrawals by reducing withdrawals in the eastern part of the Waimalu area and increasing withdrawals farther to the west by an equal amount. The simulated initial conditions for redistributed withdrawal scenarios were the final conditions from the appropriate (depending on the valley-fill barriers simulated) 1880-2000 transient simulation. The effects of redistributing withdrawals were simulated with 25-year transient simulations from 2001-2025 using average recharge from the period 1995-2000 for the top of the model and predevelopment recharge for the inland vertical boundaries. Assigned total recharge over the model domain for the period 2001-2025 (274 Mgal/d) is lower than the long-term average and also is lower than estimated predevelopment recharge (307 Mgal/d). A simulation with withdrawals equal to the 2003 permitted rates at all wells (table 6) was used as the basis for comparison with various redistributed withdrawal scenarios.

Seven redistributed withdrawal scenarios were tested (table 7) using the base-case valley-fill barriers. (For one of the redistributed withdrawal scenarios, scenario 1, two additional valley-fill barrier configurations were tested.) In these scenarios, withdrawals from Halawa Shaft (2354-01) or the Kalauao Wells (2355-09 to -14) were reduced and withdrawals from Pearl City III (2557-03) or Kunia III (2401-04) were increased. The Halawa Shaft and Kalauao Wells are located in the eastern part of the Waimalu management system, Pearl City III is located just west of the Waimalu management system within the Waipahu-Waiawa management system,

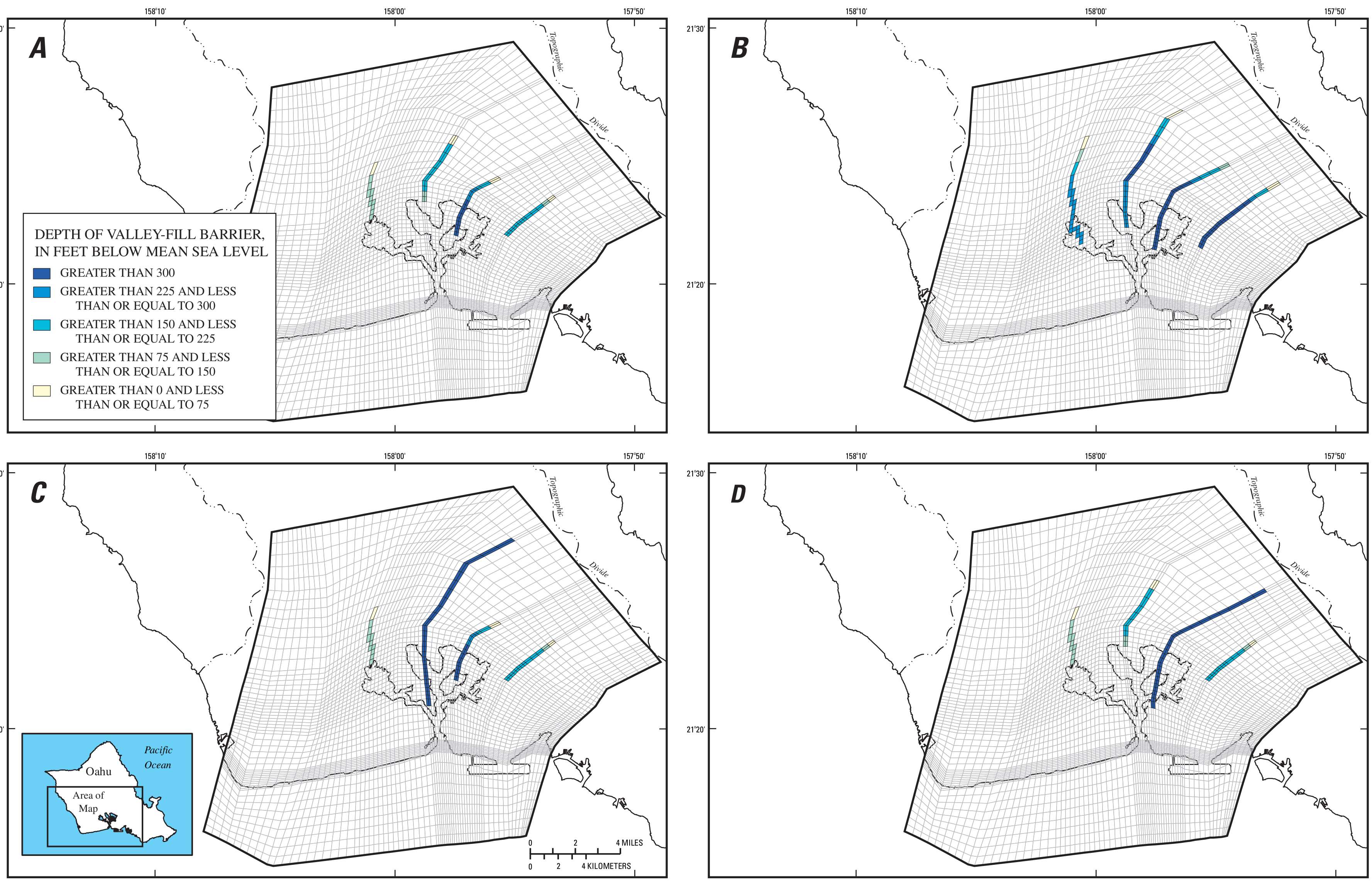


Figure 28. Valley-fill barrier depths and configurations used in sensitivity tests of the numerical ground-water model, Pearl Harbor area, Oahu, Hawaii. Valley-fill-barrier configurations shown are for the following cases: (A) the base case; (B) base-case valley-fill barriers deepened by 200 feet, extended inland using a 3-percent slope, and extended seaward using a zero-percent slope; (C) Waiawa valley-fill barrier deepened to a constant depth of 660 feet below mean sea level, extended inland to where the channel altitude is 800 feet, and extended seaward to where the caprock is at a depth of 660 feet below mean sea level; and (D) Waimalu valley-fill barrier deepened to a constant depth of 660 feet below mean sea level, extended inland to where the channel altitude is 800 feet, and extended seaward to where the caprock is at a depth of 660 feet below mean sea level.

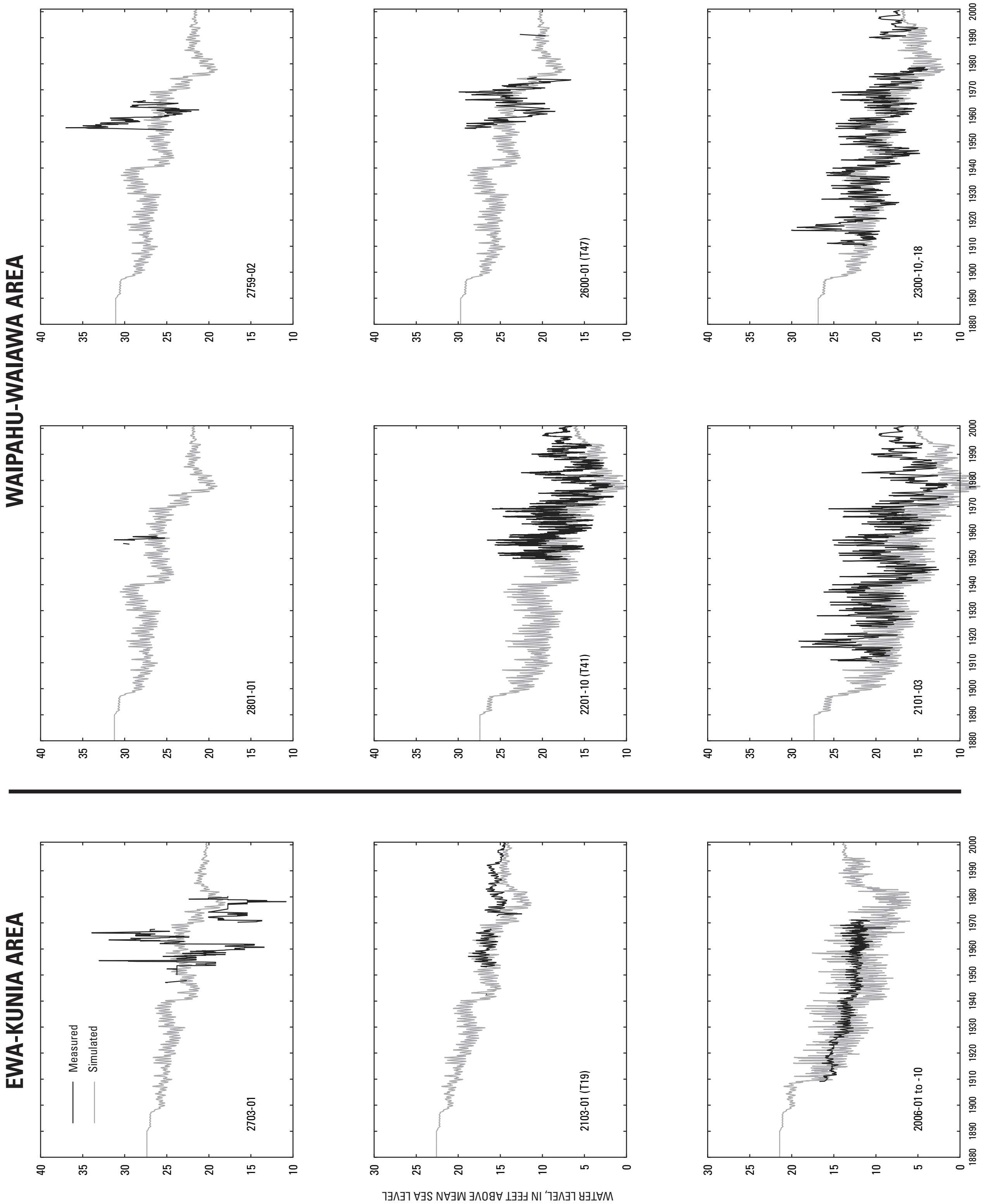


Figure 29. Measured and simulated (with no valley-fill barriers) water levels in selected wells in the Pearl Harbor area, Oahu, Hawaii.

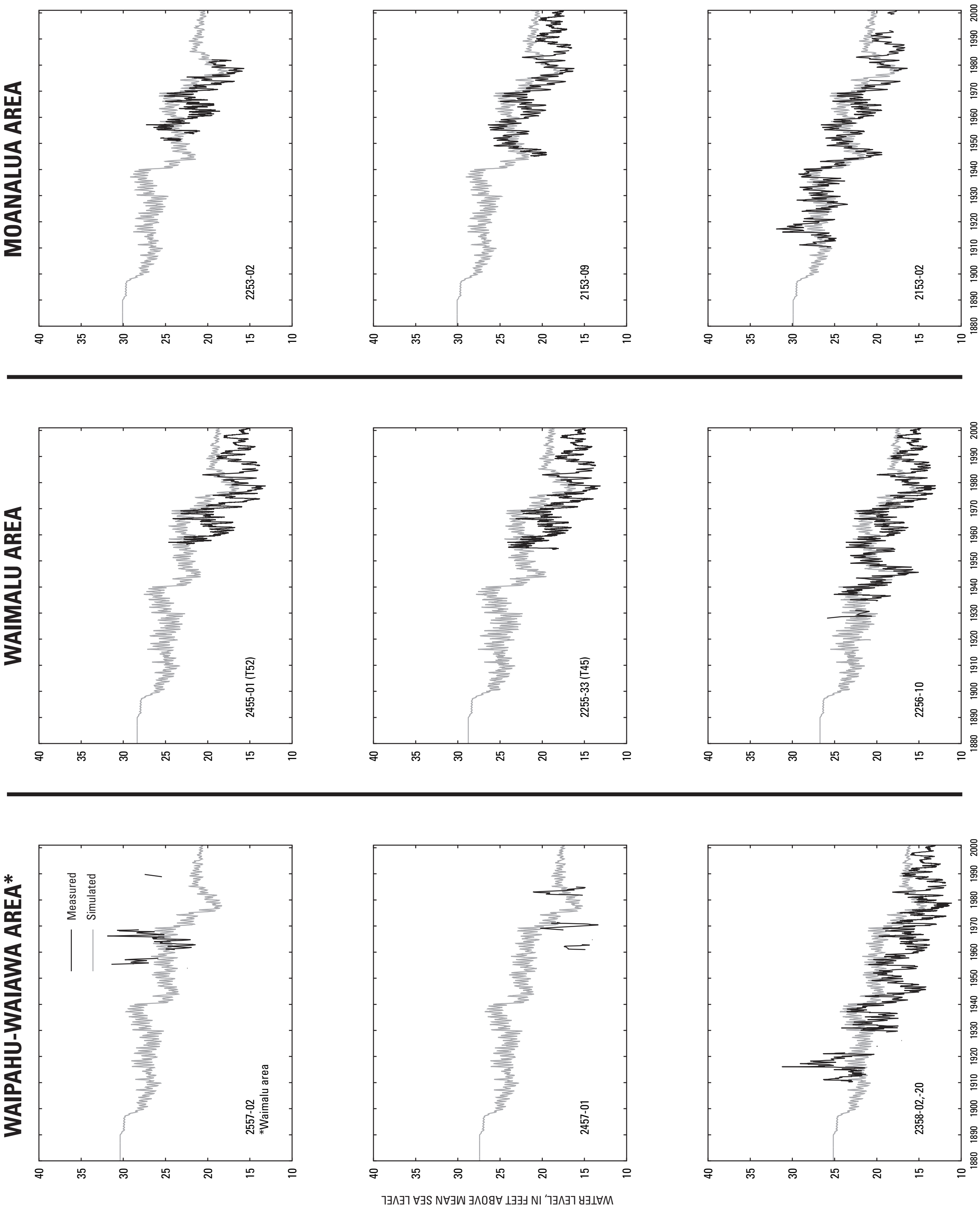


Figure 29. Measured and simulated (with no valley-fill barriers) water levels in selected wells in the Pearl Harbor area, Oahu, Hawaii—*Continued.*

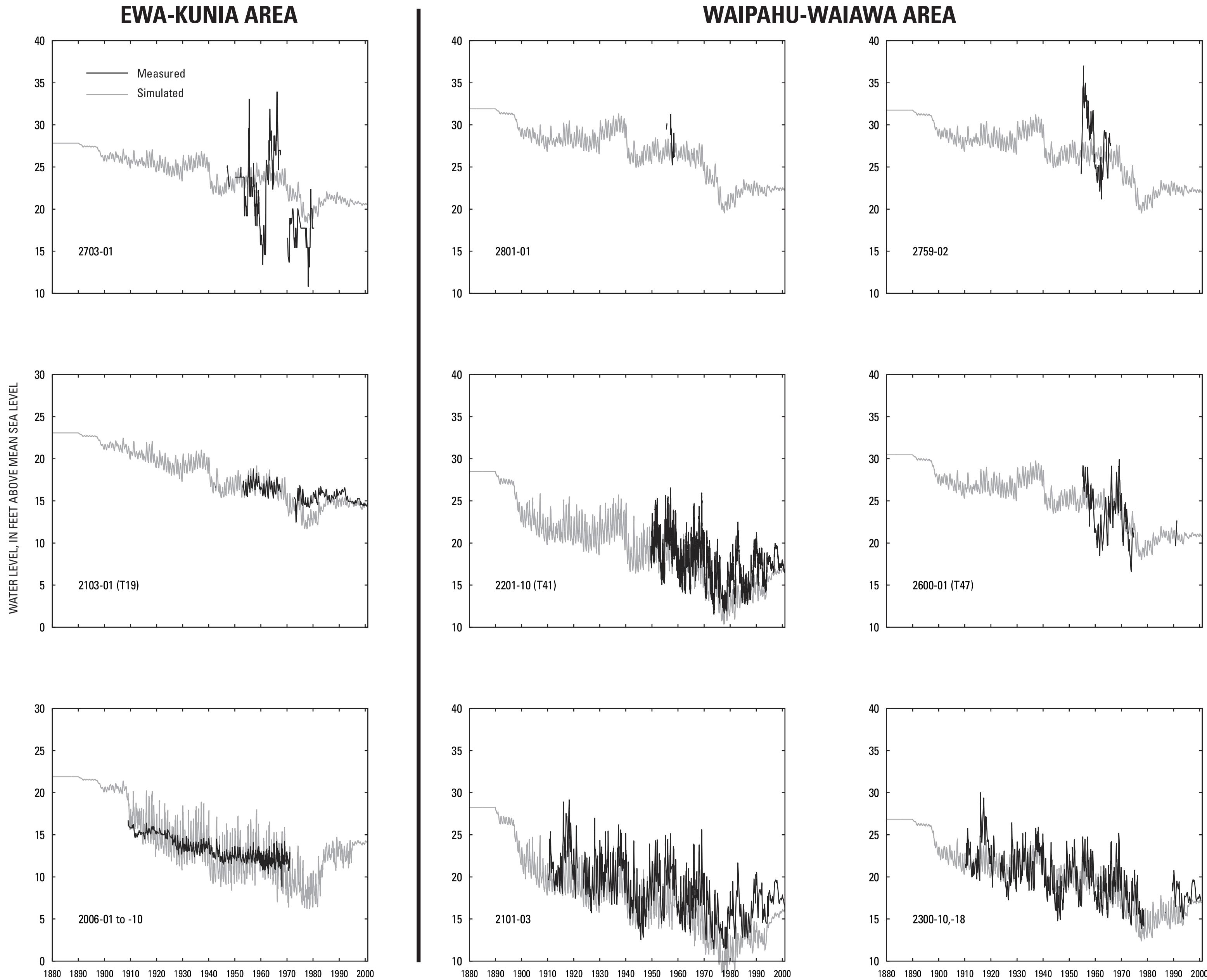


Figure 30. Measured and simulated (with base-case valley-fill barriers deepened by 200 ft) water levels in selected wells in the Pearl Harbor area, Oahu, Hawaii.

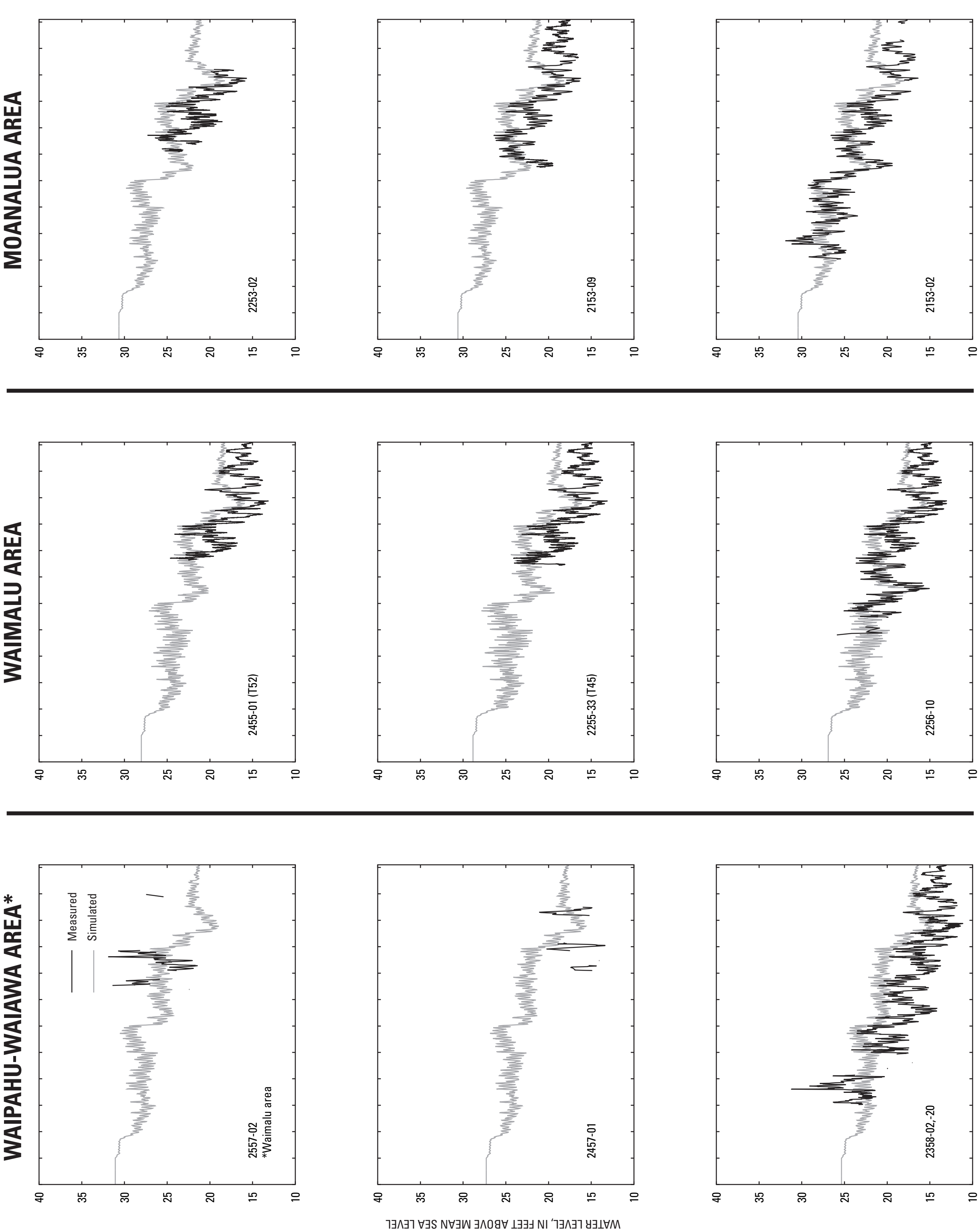


Figure 30. Measured and simulated (with base-case valley-fill barriers deepened by 200 ft) water levels in selected wells in the Pearl Harbor area, Oahu, Hawaii—*Continued.*

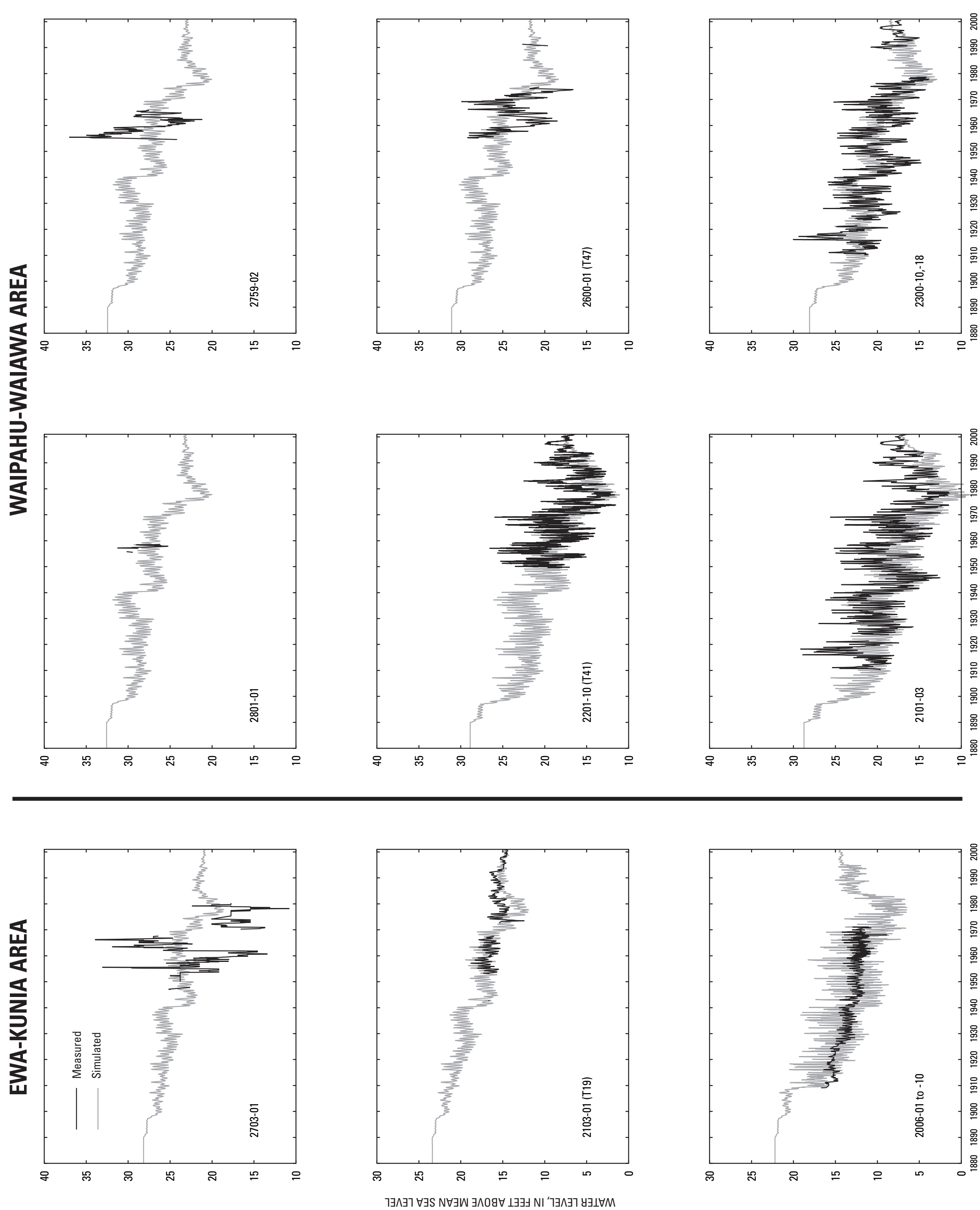


Figure 31. Measured and simulated (with Waiawa valley-fill barrier deepened to 660 ft below mean sea level) water levels in selected wells in the Pearl Harbor area, Oahu, Hawaii.

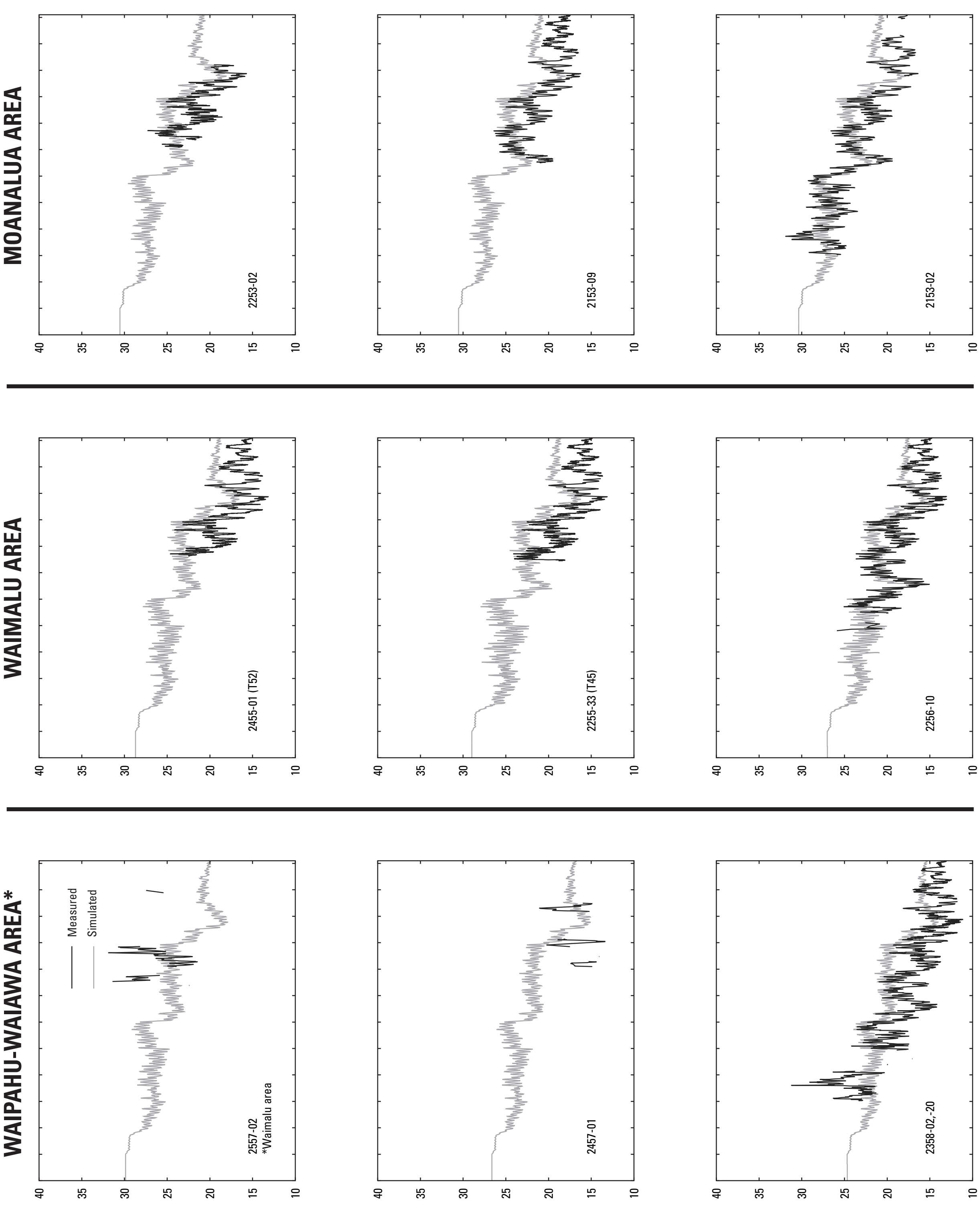


Figure 31. Measured and simulated (with Waiawa valley-fill barrier deepened to 660 ft below mean sea level) water levels in selected wells in the Pearl Harbor area, Oahu, Hawaii—*Continued.*

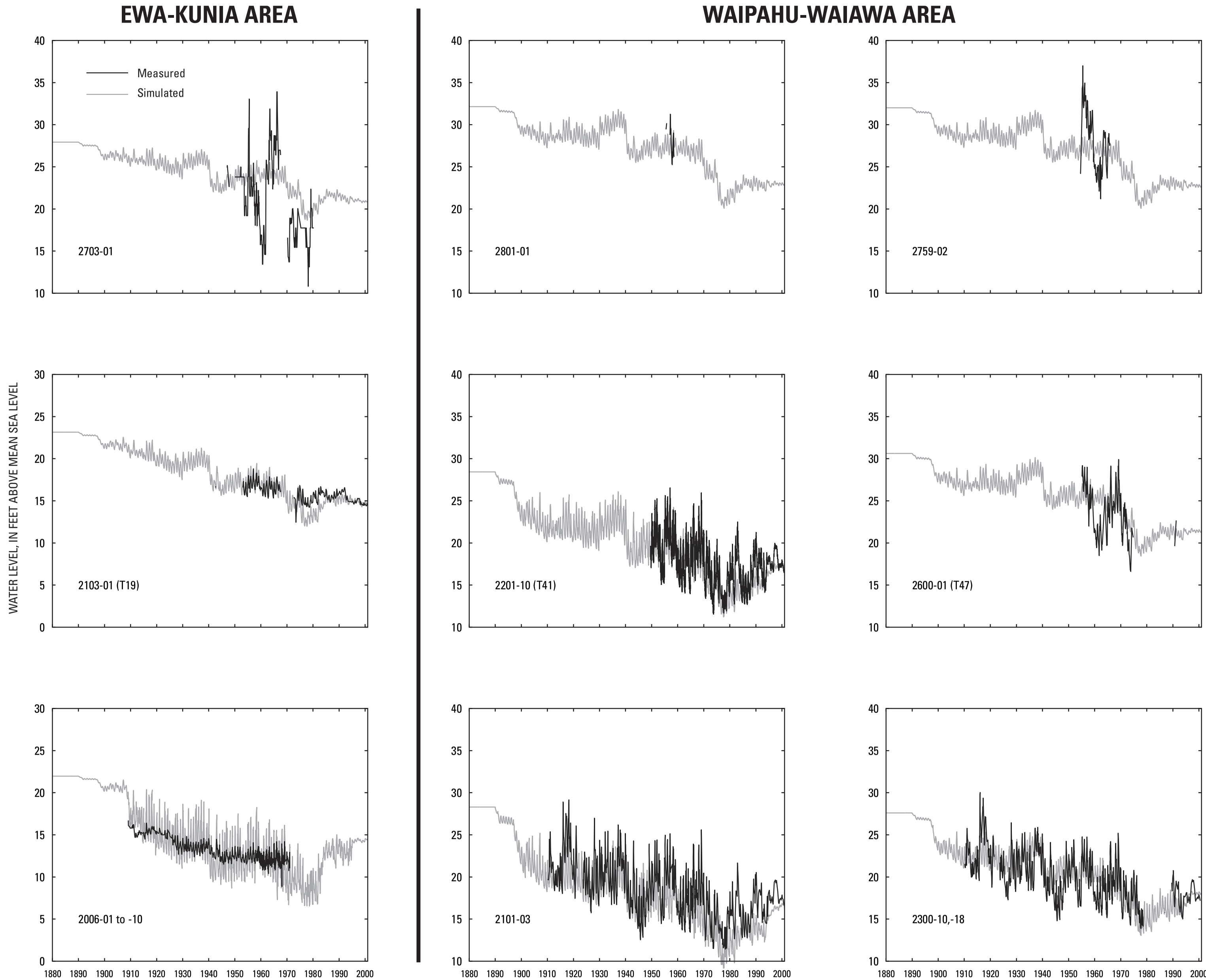


Figure 32. Measured and simulated (with Waimalu valley-fill barrier deepened to 660 ft below mean sea level) water levels in selected wells in the Pearl Harbor area, Oahu, Hawaii.

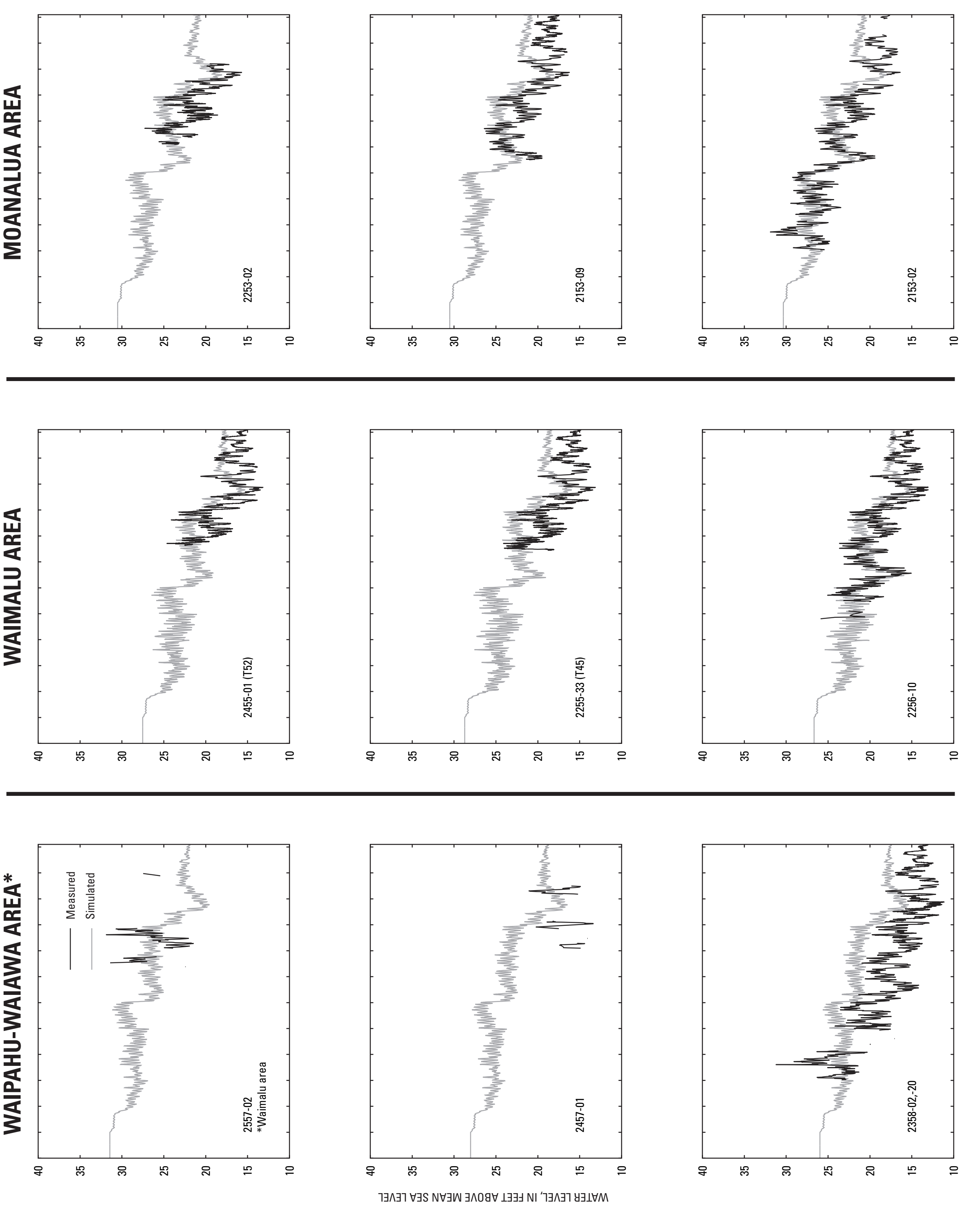


Figure 32. Measured and simulated (with Waimalu valley-fill barrier deepened to 660 ft below mean sea level) water levels in selected wells in the Pearl Harbor area, Oahu, Hawaii—*Continued.*

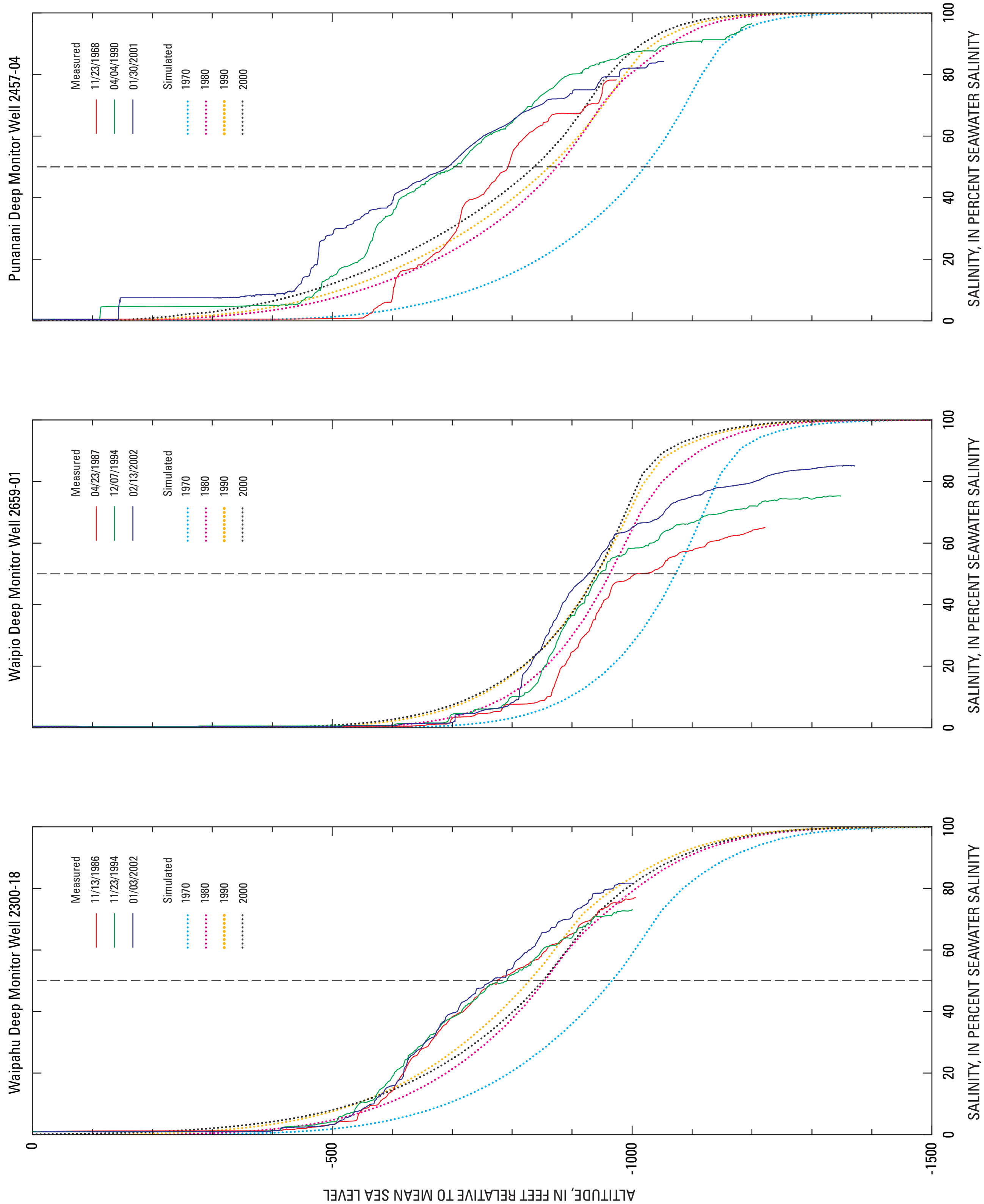


Figure 33. Measured and simulated (with Waiawa valley-fill barrier deepened to 660 feet below mean sea level) salinity profiles in selected wells in the Pearl Harbor area, Oahu, Hawaii.

Table 6. 2003 permitted withdrawal rates from the Pearl Harbor and Moanalua areas, Oahu, Hawaii.

[Mgal/d, million gallons per day; well nos. indicated in bold represent Maui-type shafts with infiltration tunnels]

Well no.	2003 permitted withdrawal, in Mgal/d	Well no.	2003 permitted withdrawal, in Mgal/d
1805-04	3.168	2300-11	0.68
1806-09	2.26	2300-20	0.4
1900-02	1.201	2301-01 to -10	0.95
1900-21	0.1	2301-34 to -39	6.61
1900-22	0.6	2301-44	1
1900-23	0.023	2302-01 to -04	4.357
1901-05	0.056	2303-01,-02	2.24
1901-06	3.3	2303-03 to -06	4.48
1902-03	0.5	**2354-01**	**11.32**
1905-04	1	2355-03 to -05	0.98
1905-05	0.5	2355-06,-07	1.3
1905-08	0.302	2355-09 to -14	11.75
2001-01	5.89	2356-49,-50	0.08
2001-02	0.08	2356-54	0.33
2001-03	0.03	2356-55,-56	1.35
2001-04	0.04	2356-58,-59	1.2
2001-05	0.066	2356-70	0.1
2001-06	0.08	2357-23,-24	1.11
2001-07	0.063	2358-36	0.004
2001-08	0.048	2358-44	0.04
2001-09	0.023	2358-49	0.003
2001-10	0.022	2359-10	0.005
2001-12	0.249	2359-19	0.18
2001-13	0.8	2400-01 to -04	6
2001-14	0.892	2400-05,-06,-08,-14	2.1
2002-12	0.04	2400-09	3.029
2002-17	0.498	2401-04	1.5
2003-01	1	2401-07	0.6
2003-04	0.494	2402-01 to -03, -05	2.71
2003-08	0.237	2455-02	0.158
2004-04	1.5	2456-01 to -03	1.5
2006-01 to -11	0.957	2457-01 to -03	1.8
2006-13	0.7	2457-05 to -12	11.97
2006-14	1	2457-13 to -15	1.89
2052-08	**9.5**	2458-01	1.22
2053-11	1.035	2458-03,-04	0.7
2101-01	0.11	2458-05	0.1
2101-14	0.216	2459-19,-20	0.63
2102-02,-04 to -22	7.969	2459-21	0.006
2103-03	**2.337**	2459-23,-24	0.68
2104-01	0.168	2500-01,-02	1
2153-02	0.021	2557-01,-02	0.136
2153-07,-08	0.609	2557-03	0.5
2153-10 to -12	3.79	**2558-10**	**14.977**
2154-01	0.346	2600-02	0.1
2201-02	0.021	2600-03,-04	1.55
2201-14	0.003	2603-01	0.4
2202-01	0.003	2659-02,-03	0.85
2202-02	0.009	2703-01	1.075
2202-21	**12.154**	2800-01 to -04	2.98
2254-01	**4.659**	2858-01 to -03	1.722
2255-32	**0.697**	2859-01,-02	1.9
2255-37 to -39	1.08	STATE DHHL [01]	1.358
		Total	188.056

Table 7. Summary of simulated withdrawals for redistributed withdrawal scenarios in the Pearl Harbor area, Oahu, Hawaii[1].

[Mgal/d, million gallons per day]

Scenario	Simulated withdrawal, in Mgal/d				
	Halawa Shaft (2354-01)	Kalauao Wells (2355-09 to -14)	Pearl City III (2557-03)	Kunia III (2401-04)	Total
Base case	11.32	11.75	0.50	1.50	25.07
1	5.66	11.75	6.16	1.50	25.07
2	8.49	11.75	3.33	1.50	25.07
3	5.66	11.75	0.50	7.16	25.07
4	11.32	5.88	6.38	1.50	25.08
5	11.32	8.81	3.44	1.50	25.07
6	11.32	5.88	0.50	7.38	25.08
7	8.49	8.81	0.50	7.27	25.07

[1]Simluated withdrawals from all wells in the modeled area that are not listed in the table were equal to the 2003 permitted rates.

and Kunia III is located in the western part of the Waipahu-Waiawa management system (fig. 1).

For each of the seven scenarios tested, model-simulation results are shown in terms of the change in the depth of the bottom of the freshwater (2-percent salinity) part of the ground-water system. In general, a reduction of withdrawal from a site causes a deepening of the 2-percent salinity depth (increase in freshwater thickness) near that site, and an increase of withdrawal from a site causes a shallowing of the 2-percent salinity depth (decrease in freshwater thickness) near that site.

Scenario 1

In scenario 1, withdrawal from Halawa Shaft (2354-01) was reduced by 5.66 Mgal/d and withdrawal from Pearl City III (2557-03) was increased by 5.66 Mgal/d relative to the 2003 permitted rates. Model results indicate that the 2-percent salinity depth does not change (0-ft line of equal change in 2-percent salinity depth) along a line that runs from Pearl Harbor to the inland extent of the model, about midway between Halawa Shaft and Pearl City III (fig. 34). East of the 0-ft line of equal change, toward Halawa Shaft, the 2-percent salinity depth deepens in response to decreased withdrawal from Halawa Shaft. West of the 0-ft line of equal change, toward Pearl City III, the 2-percent salinity depth shallows in response to increased withdrawal from Pearl City III. Near Halawa Shaft the 2-percent salinity depth deepens by about 30 ft, and near Pearl City III the 2-percent salinity depth shallows by about 20 ft.

Simulated changes in the 2-percent salinity depth are greatest downgradient from the wells with redistributed withdrawals, not directly beneath the wells as might be expected if local upconing were the only process by which underlying brackish water moved in response to increased withdrawal. Because brackish water moves both landward and upward into areas previously occupied by freshwater in response to increased withdrawal, the location where the simulated shallowing of the 2-percent salinity depth is greatest is downgradient of Pearl City III, where withdrawal was increased in the model. Similarly, because freshwater water moves both seaward and downward into areas previously occupied by brackish water in response to decreased withdrawal, the location where the simulated deepening of the 2-percent salinity depth is greatest is downgradient of Halawa Shaft, where withdrawal was decreased in the model. In scenario 1, the change in 50-percent salinity depth caused by the redistributed withdrawal is less than 15 ft.

For scenario 1 only, the effects of two additional valley-fill barrier configurations were tested: (1) no valley-fill barriers, (2) Waiawa valley-fill barrier deepened to a constant depth of 660 ft below mean sea level, extended inland to where the channel altitude is 800 ft, and extended seaward to where the caprock is at a depth of 660 ft below mean sea level. Initial conditions for simulations with the additional valley-fill barrier configurations were the final conditions from 1880-2000 transient simulations using these additional valley-fill barrier configurations. In the absence of valley-fill barriers, the simulated deepening of the 2-percent salinity depth east of Halawa Shaft is increased relative to the simulated deepening using the

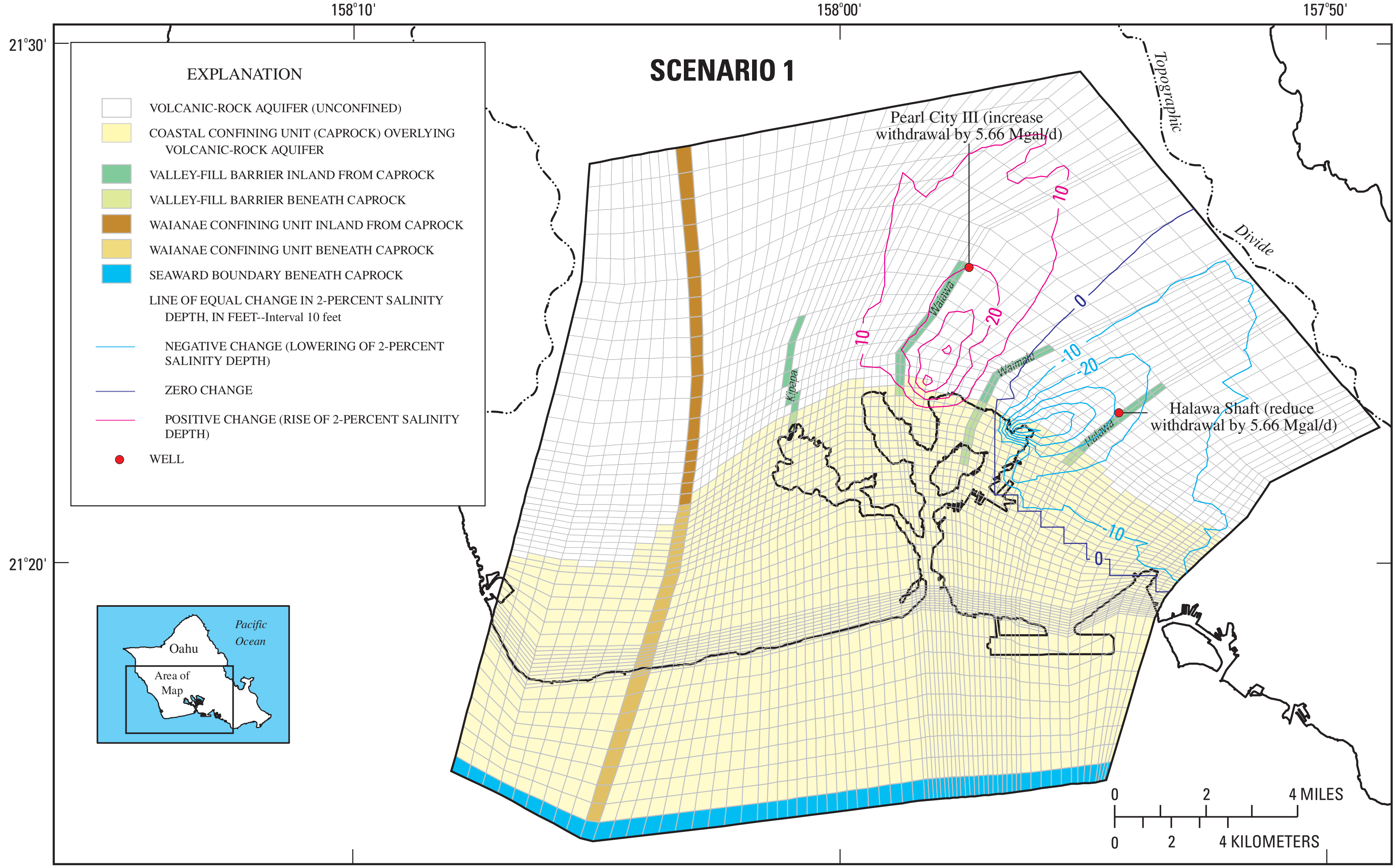


Figure 34. Simulated change in 2-percent salinity depth caused by reducing withdrawal from the Halawa Shaft (2354-01) by 5.66 million gallons per day and increasing withdrawal from Pearl City III (2557-03) by the same amount relative to the 2003 permitted rates. Salinity changes were determined by comparing two simulations that differ only in the rates of withdrawal from the Halawa Shaft and Pearl City III; the first simulation includes withdrawals equal to the 2003 permitted rates from all wells in the modeled area, and the second simulation includes reduced withdrawal from Halawa Shaft (11.32 to 5.66 million gallons per day), increased withdrawal from Pearl City III (0.5 to 6.16 million gallons per day), and withdrawals equal to the 2003 permitted rates from all other wells in the modeled area. Salinity changes shown are after 25 years of simulation using the ending results from the 1880-2000 transient simulation as initial conditions.

base case valley-fill barriers (figs. 34 and 35). With Waiawa valley-fill barrier deepened to 660 ft below mean sea level, the simulated deepening of the 2-percent salinity depth east of Halawa Shaft is slightly decreased relative to the simulated deepening using the base case valley-fill barriers (figs. 34 and 36). In all cases, the simulated deepening of the 2-percent salinity depth downgradient of Halawa Shaft exceeds 50 ft. With Waiawa valley-fill barrier deepened to 660 ft below mean sea level, the simulated shallowing of the 2-percent salinity depth near Pearl City III is truncated west of the Waiawa valley-fill barrier relative to the base-case valley-fill barriers and no valley-fill barrier case. The 0-ft line of equal change in 2-percent salinity depth does not vary much with the different valley-fill barrier configurations tested.

The locations where change in 2-percent salinity depth are greatest are controlled by factors including, (1) proximity of the pumped wells to brackish ground water, (2) hydraulic characteristics of the rocks (horizontal and vertical permeability), and (3) presence of low-permeability barriers. Saltwater intrusion can be enhanced if (1) pumping rates are high, (2) wells are drilled close to a source of brackish ground water, (3) aquifer permeability, particularly in the vertical direction, is high, and (4) pumped wells are located close to low-permeability valley-fill barriers.

Scenario 2

In scenario 2, withdrawal from Halawa Shaft (2354-01) was reduced by 2.83 Mgal/d and withdrawal from Pearl City III (2557-03) was increased by 2.83 Mgal/d relative to the 2003 permitted rates. The location of the 0-ft line of equal change in 2-percent salinity depth simulated in scenario 2 is nearly the same as that simulated in scenario 1 (figs. 34 and 37). Near Halawa Shaft, the 2-percent salinity depth deepens by about 15 ft, and near Pearl City III the 2-percent salinity depth shallows by about 10 ft. In scenario 2, the reduction in withdrawal from Halawa Shaft is half that simulated in scenario 1. At common locations, the simulated change in 2-percent salinity depth in scenario 2 also is about half the magnitude of the simulated change in scenario 1. In scenario 2, the change in 50-percent salinity depth caused by the redistributed withdrawal is less than 10 ft.

Scenario 3

In scenario 3, withdrawal from Halawa Shaft (2354-01) was reduced by 5.66 Mgal/d and withdrawal from Kunia III (2401-04) was increased by 5.66 Mgal/d relative to the 2003 permitted rates. Model results indicate that the 2-percent salinity depth does not change (0-ft line of equal change in 2-percent salinity depth) along a line that runs from Pearl Harbor to the inland extent of the model, about midway between Halawa Shaft and Kunia III (fig. 38). Relative to scenario 1, the 0-ft line of equal change in 2-percent salinity depth simulated in scenario 3 extends farther westward, indicating a larger zone where freshwater thickness increases in scenario 3 relative to scenario 1. Thus, by redistributing 5.66 Mgal/d from Pearl City III (scenario 1) to Kunia III (scenario 3), located farther to the west, the zone where freshwater thickness increases expands westward. Near Halawa Shaft the 2-percent salinity depth deepens by about 30 ft, and near Kunia III the 2-percent salinity depth shallows by about 35 ft.

In scenario 3, shallowing of the 50-percent salinity depth is greatest to the southwest of Kunia III, and is as much as 40 ft (fig. 39). Shallowing of the 50-percent salinity depth is enhanced by the presence of the low-permeability Waianae confining unit, which is represented in the model as a vertical barrier.

Scenario 4

In scenario 4, withdrawal from the Kalauao Wells (2355-09 to -14) was reduced by 5.88 Mgal/d and withdrawal from Pearl City III (2557-03) was increased by 5.88 Mgal/d relative to the 2003 permitted rates. Model results indicate that the 2-percent salinity depth does not change (0-ft line of equal change in 2-percent salinity depth) along a line that runs from Pearl Harbor to the inland extent of the model, about a third of the way from the Kalauao Wells to Pearl City III (fig. 40). East of the 0-ft line of equal change, toward the Kalauao Wells, the 2-percent salinity depth deepens in response to decreased withdrawal from the Kalauao Wells. West of the 0-ft line of equal change, toward Pearl City III, the 2-percent salinity depth shallows in response to increased withdrawal from Pearl City III. Near the Kalauao Wells the 2-percent salinity depth deepens by about 20 ft, and near Pearl City III the 2-percent salinity depth shallows by about 20 ft. In scenario 4, the change in 50-percent salinity depth caused by the redistributed withdrawal is less than 15 ft.

Scenarios 1 and 4 are similar in the amount of redistributed withdrawal to Pearl City III (5.66 Mgal/d in scenario 1 and 5.88 Mgal/d in scenario 4). The size and shape of the zones in which freshwater thickness increases also are similar in scenarios 1 and 4. In general, however, the deepening of the 2-percent salinity depth is greater in scenario 1 relative to scenario 4. Within the simulated zones in which freshwater thickness decreases, shallowing of the 2-percent salinity depth is slightly greater in scenario 4 relative to scenario 1 because simulated withdrawal from Pearl City III is slightly higher in scenario 4.

Scenario 5

In scenario 5, withdrawal from the Kalauao Wells (2355-09 to -14) was reduced by 2.94 Mgal/d and withdrawal from Pearl City III (2557-03) was increased by 2.94 Mgal/d relative to the 2003 permitted rates. The 0-ft line of equal change in 2-percent salinity depth simulated in scenario 5 is nearly the same as that simulated in scenario 4 (figs. 40 and 41). Near the Kalauao Wells the 2-percent salinity depth deepens by about

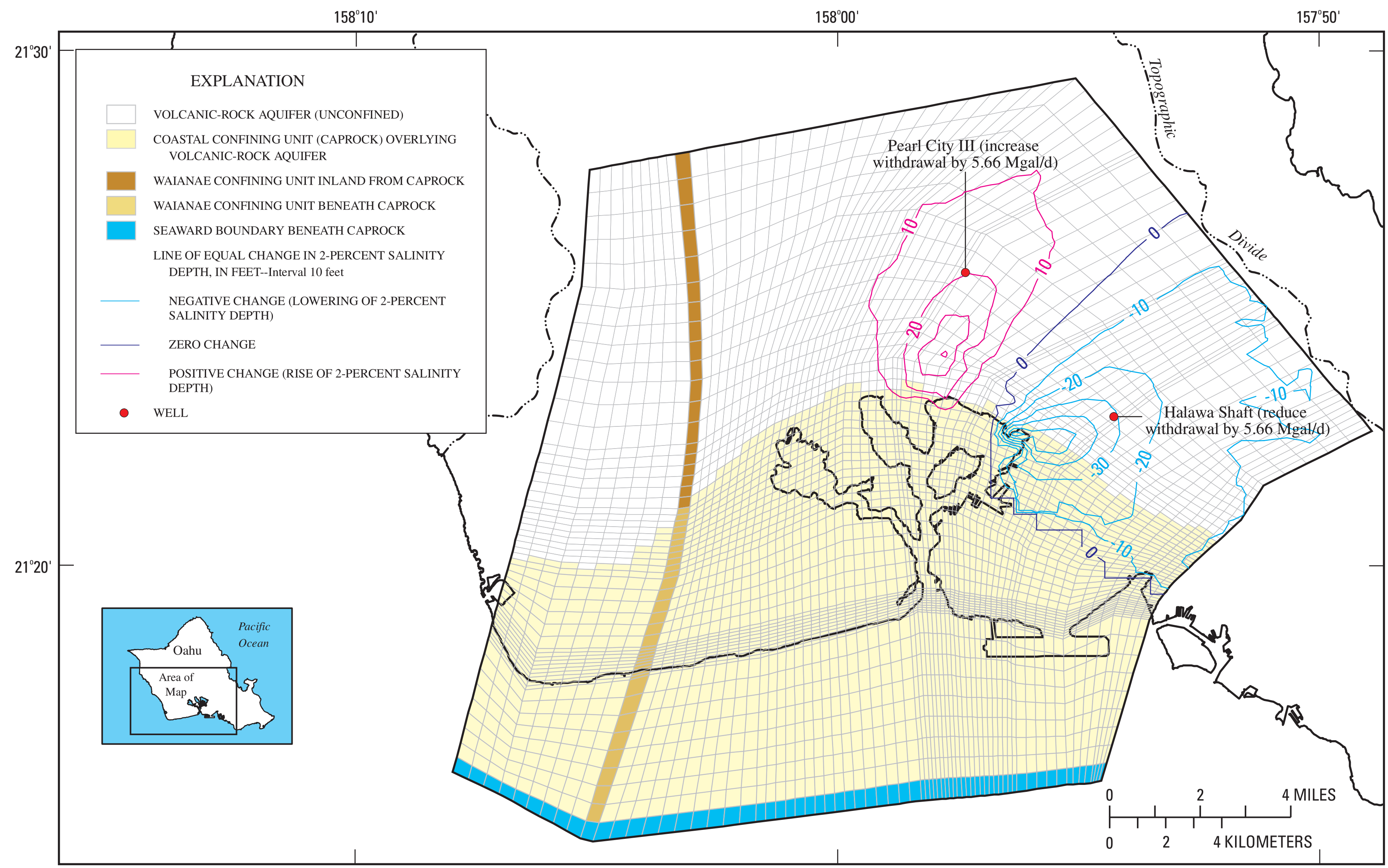


Figure 35. Simulated (with no valley-fill barriers) change in 2-percent salinity depth caused by reducing withdrawal from the Halawa Shaft (2354-01) by 5.66 million gallons per day and increasing withdrawal from Pearl City III (2557-03) by the same amount relative to the 2003 permitted rates. Salinity changes were determined by comparing two simulations that differ only in the rates of withdrawal from the Halawa Shaft and Pearl City III; the first simulation includes withdrawals equal to the 2003 permitted rates from all wells in the modeled area, and the second simulation includes reduced withdrawal from Halawa Shaft (11.32 to 5.66 million gallons per day), increased withdrawal from Pearl City III (0.5 to 6.16 million gallons per day), and withdrawals equal to the 2003 permitted rates from all other wells in the modeled area. Salinity changes shown are after 25 years of simulation using the ending results from the 1880-2000 transient simulation as initial conditions.

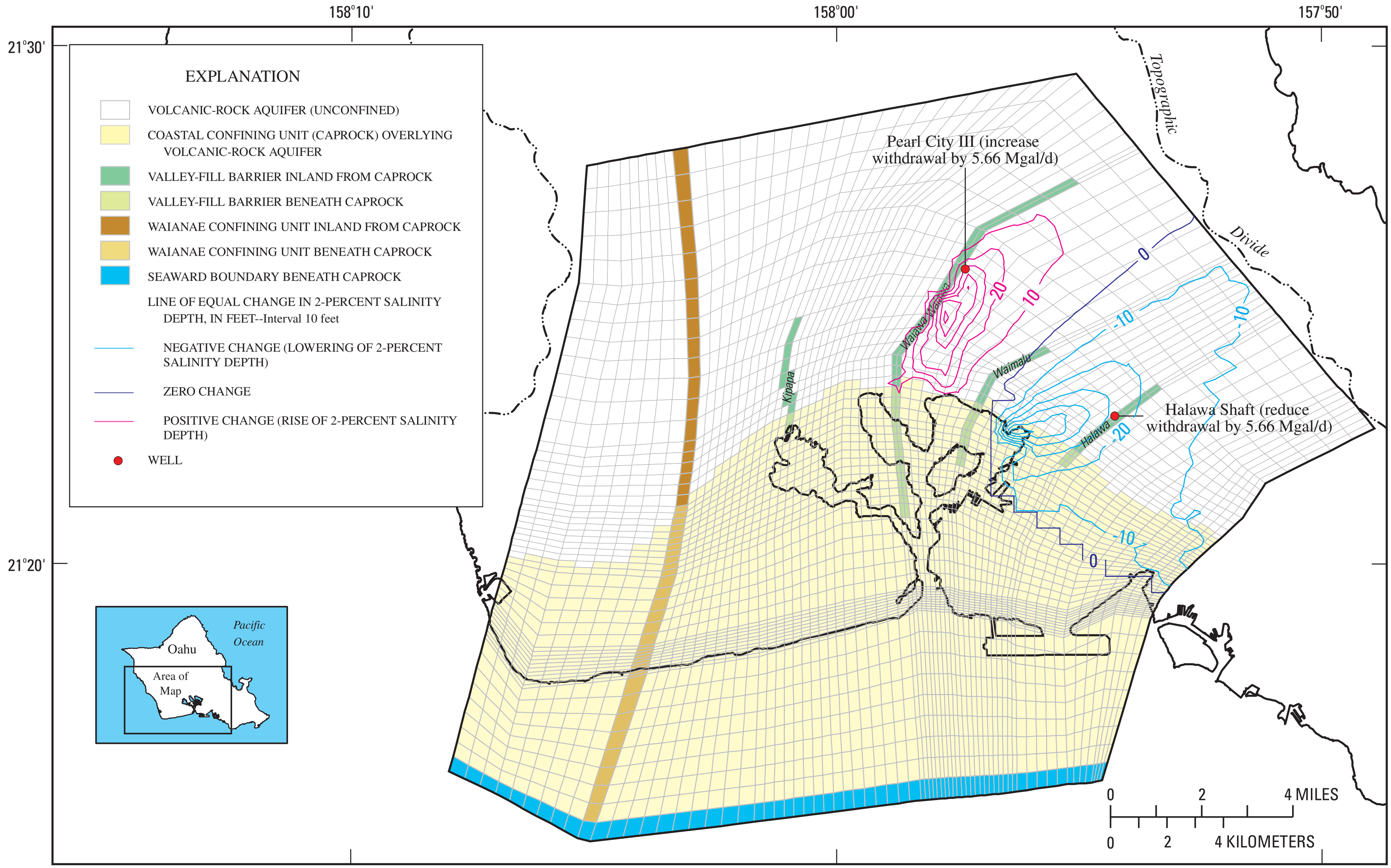


Figure 36. Simulated (with Waiawa valley-fill barrier deepened to 660 feet below mean sea level) change in 2-percent salinity depth caused by reducing withdrawal from the Halawa Shaft (2354-01) by 5.66 million gallons per day and increasing withdrawal from Pearl City III (2557-03) by the same amount relative to the 2003 permitted rates. Salinity changes were determined by comparing two simulations that differ only in the rates of withdrawal from the Halawa Shaft and Pearl City III; the first simulation includes withdrawals equal to the 2003 permitted rates from all wells in the modeled area, and the second simulation includes reduced withdrawal from Halawa Shaft (11.32 to 5.66 million gallons per day), increased withdrawal from Pearl City III (0.5 to 6.16 million gallons per day), and withdrawals equal to the 2003 permitted rates from all other wells in the modeled area. Salinity changes shown are after 25 years of simulation using the ending results from the 1880-2000 transient simulation as initial conditions.

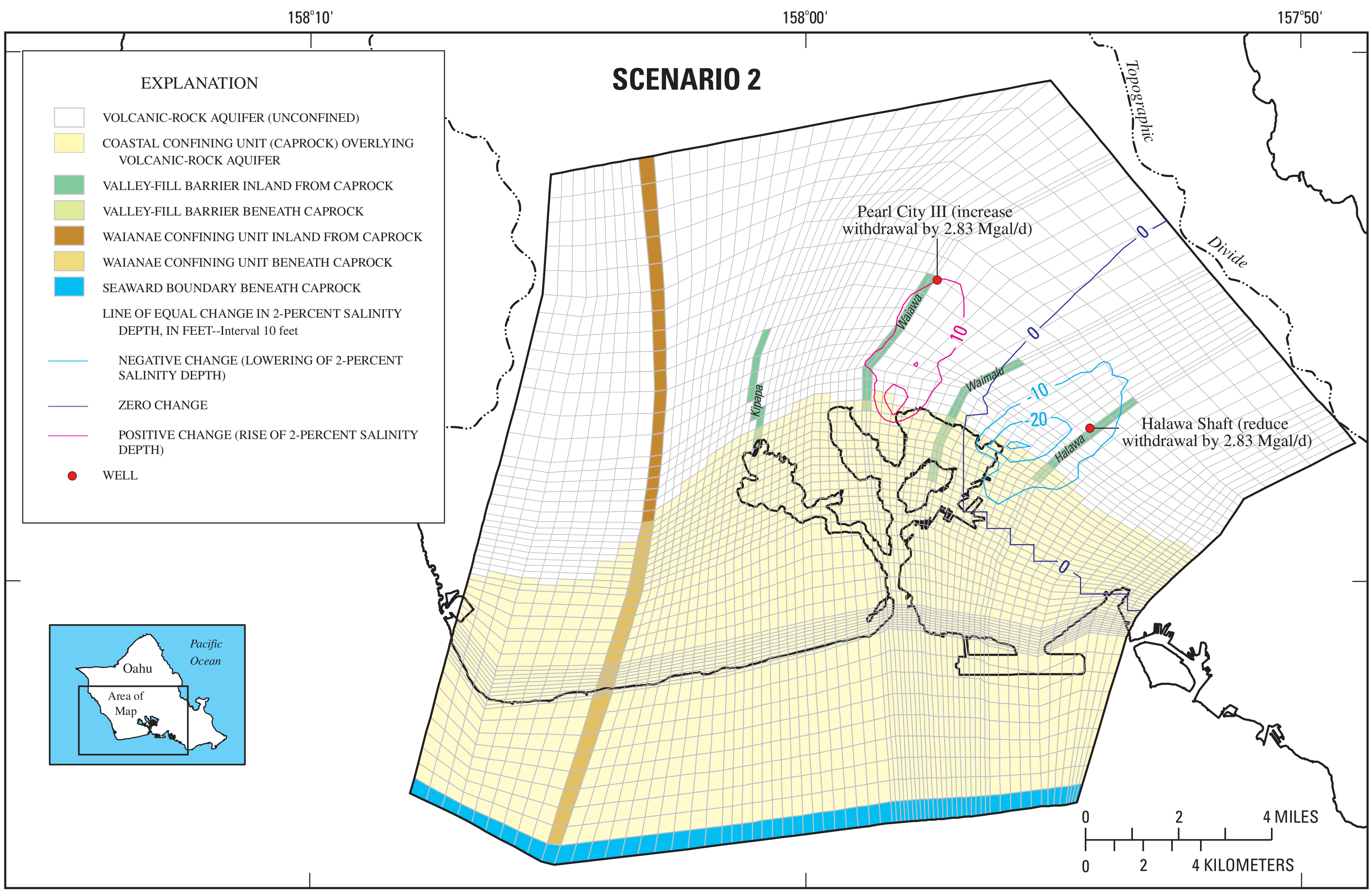


Figure 37. Simulated change in 2-percent salinity depth caused by reducing withdrawal from the Halawa Shaft (2354-01) by 2.83 million gallons per day and increasing withdrawal from Pearl City III (2557-03) by the same amount relative to the 2003 permitted rates. Salinity changes were determined by comparing two simulations that differ only in the rates of withdrawal from the Halawa Shaft and Pearl City III; the first simulation includes withdrawals equal to the 2003 permitted rates from all wells in the modeled area, and the second simulation includes reduced withdrawal from Halawa Shaft (11.32 to 8.49 million gallons per day), increased withdrawal from Pearl City III (0.5 to 3.33 million gallons per day), and withdrawals equal to the 2003 permitted rates from all other wells in the modeled area. Salinity changes shown are after 25 years of simulation using the ending results from the 1880-2000 transient simulation as initial conditions.

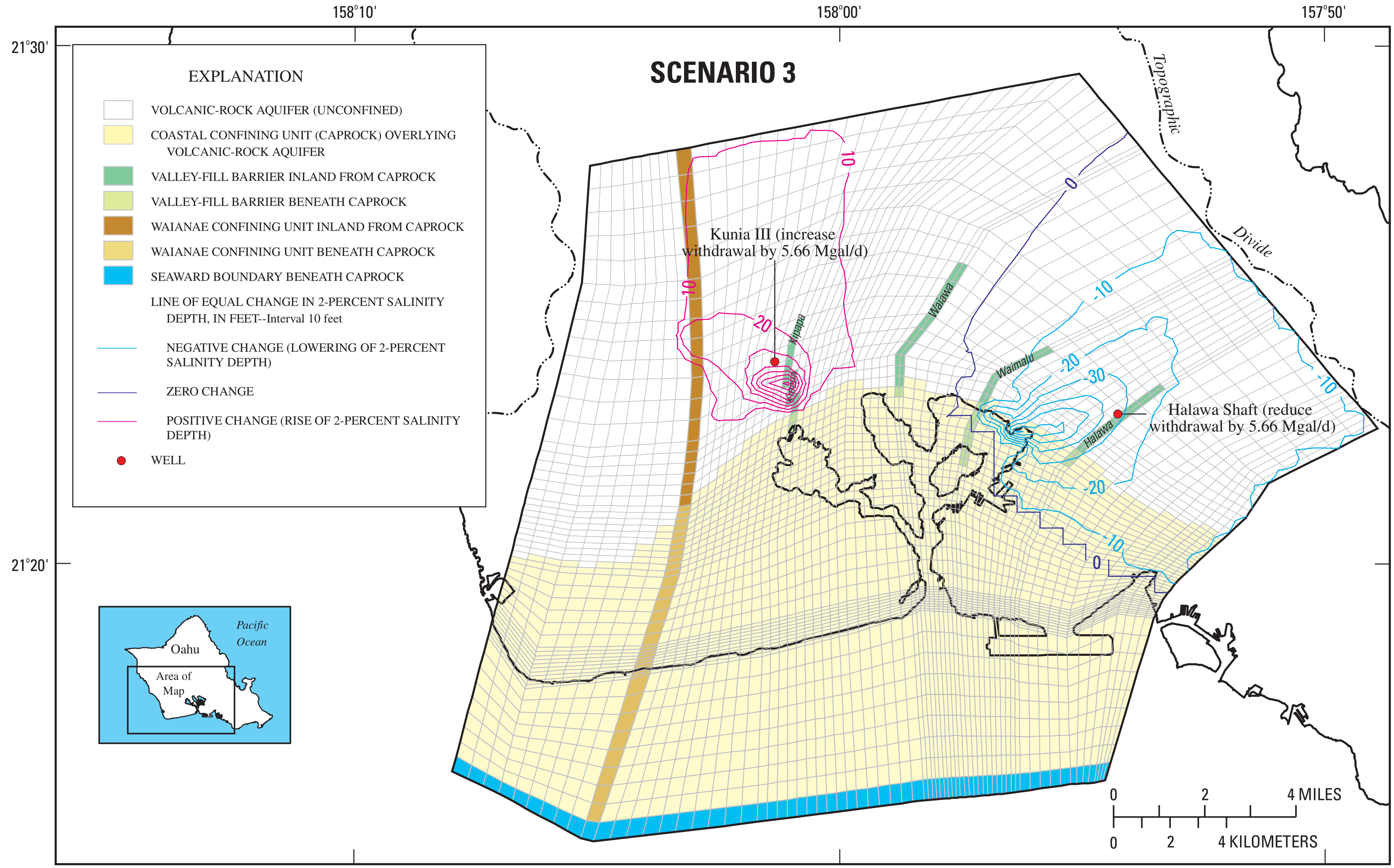


Figure 38. Simulated change in 2-percent salinity depth caused by reducing withdrawal from the Halawa Shaft (2354-01) by 5.66 million gallons per day and increasing withdrawal from Kunia III (2401-04) by the same amount relative to the 2003 permitted rates. Salinity changes were determined by comparing two simulations that differ only in the rates of withdrawal from the Halawa Shaft and Kunia III; the first simulation includes withdrawals equal to the 2003 permitted rates from all wells in the modeled area, and the second simulation includes reduced withdrawal from Halawa Shaft (11.32 to 5.66 million gallons per day), increased withdrawal from Kunia III (1.5 to 7.16 million gallons per day), and withdrawals equal to the 2003 permitted rates from all other wells in the modeled area. Salinity changes shown are after 25 years of simulation using the ending results from the 1880-2000 transient simulation as initial conditions.

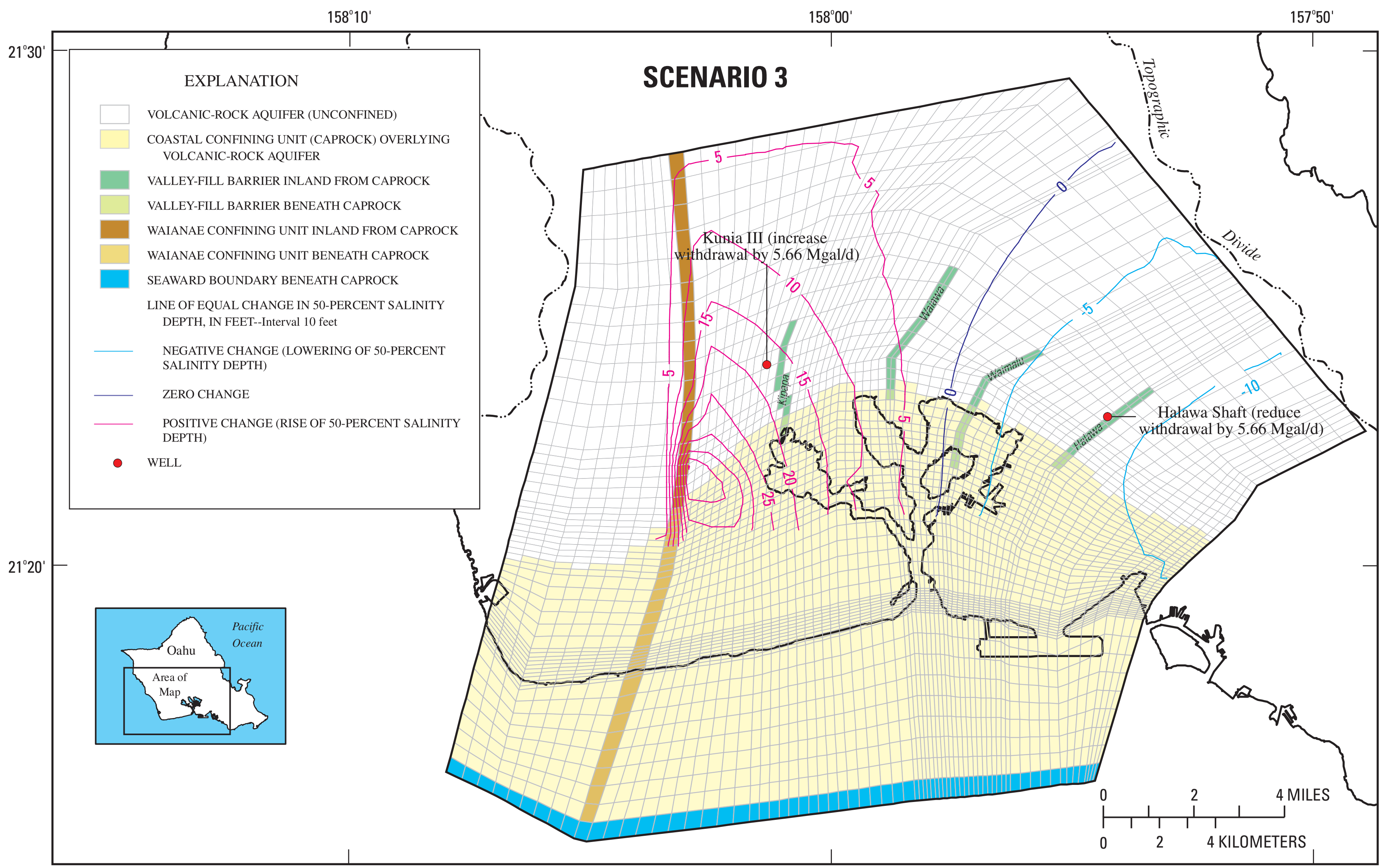


Figure 39. Simulated change in 50-percent salinity depth caused by reducing withdrawal from the Halawa Shaft (2354-01) by 5.66 million gallons per day and increasing withdrawal from Kunia III (2401-04) by the same amount relative to the 2003 permitted rates. Salinity changes were determined by comparing two simulations that differ only in the rates of withdrawal from the Halawa Shaft and Kunia III; the first simulation includes withdrawals equal to the 2003 permitted rates from all wells in the modeled area, and the second simulation includes reduced withdrawal from Halawa Shaft (11.32 to 5.66 million gallons per day), increased withdrawal from Kunia III (1.5 to 7.16 million gallons per day), and withdrawals equal to the 2003 permitted rates from all other wells in the modeled area. Salinity changes shown are after 25 years of simulation using the ending results from the 1880-2000 transient simulation as initial conditions.

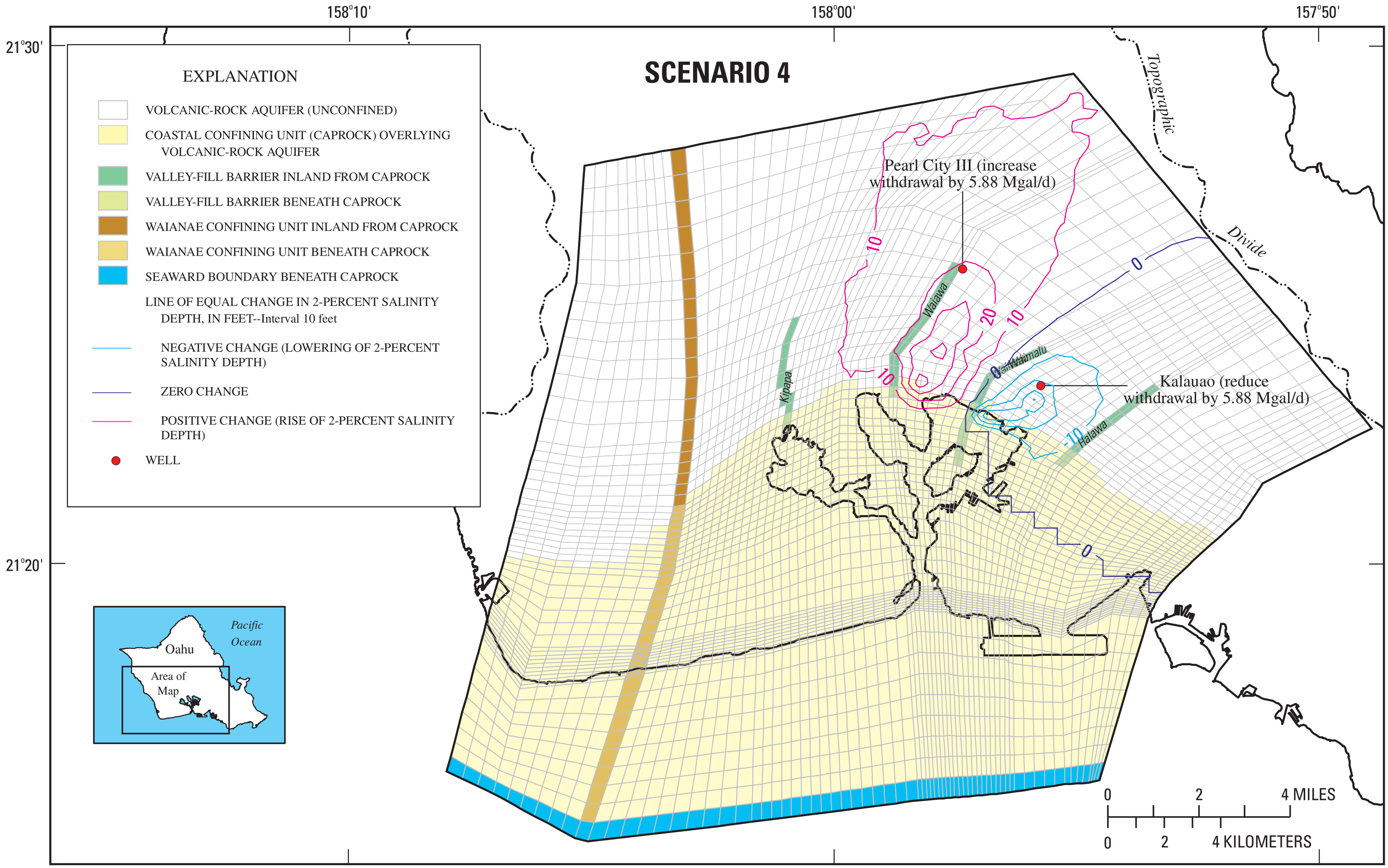


Figure 40. Simulated change in 2-percent salinity depth caused by reducing withdrawal from the Kalauao Wells (2355-09 to -14) by 5.88 million gallons per day and increasing withdrawal from Pearl City III (2557-03) by the same amount relative to the 2003 permitted rates. Salinity changes were determined by comparing two simulations that differ only in the rates of withdrawal from the Kalauao Wells and Pearl City III; the first simulation includes withdrawals equal to the 2003 permitted rates from all wells in the modeled area, and the second simulation includes reduced withdrawal from Kalauao (11.75 to 5.88 million gallons per day), increased withdrawal from Pearl City III (0.5 to 6.38 million gallons per day), and withdrawals equal to the 2003 permitted rates from all other wells in the modeled area. Salinity changes shown are after 25 years of simulation using the ending results from the 1880-2000 transient simulation as initial conditions.

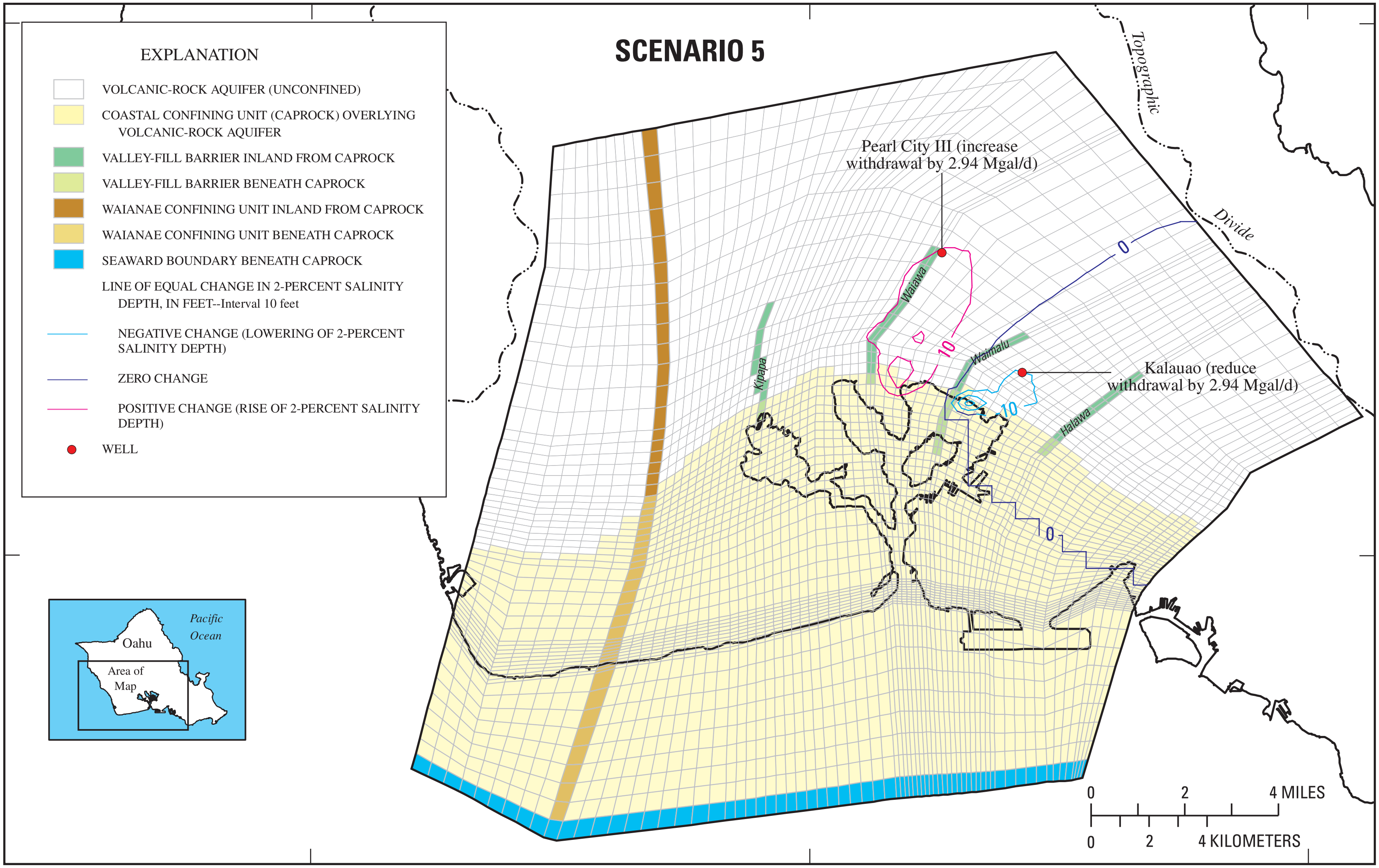


Figure 41. Simulated change in 2-percent salinity depth caused by reducing withdrawal from the Kalauao Wells (2355-09 to -14) by 2.94 million gallons per day and increasing withdrawal from Pearl City III (2557-03) by the same amount relative to the 2003 permitted rates. Salinity changes were determined by comparing two simulations that differ only in the rates of withdrawal from the Kalauao Wells and Pearl City III; the first simulation includes withdrawals equal to the 2003 permitted rates from all wells in the modeled area, and the second simulation includes reduced withdrawal from Kalauao (11.75 to 8.81 million gallons per day), increased withdrawal from Pearl City III (0.5 to 3.44 million gallons per day), and withdrawals equal to the 2003 permitted rates from all other wells in the modeled area. Salinity changes shown are after 25 years of simulation using the ending results from the 1880-2000 transient simulation as initial conditions.

10 ft, and near Pearl City III the 2-percent salinity depth shallows by about 10 ft. In scenario 5, the change in 50-percent salinity depth caused by the redistributed withdrawal is less than 10 ft. In scenario 5, the reduction in withdrawal from the Kalauao Wells is half that simulated in scenario 4. At common locations, the simulated change in 2-percent salinity depth in scenario 5 also is about half the magnitude of the simulated change in scenario 4.

Scenario 6

In scenario 6, withdrawal from the Kalauao Wells (2355-09 to -14) was reduced by 5.88 Mgal/d and withdrawal from Kunia III (2401-04) was increased by 5.88 Mgal/d relative to the 2003 permitted rates. Model results indicate that the 2-percent salinity depth does not change (0-ft line of equal change in 2-percent salinity depth) along a line that runs from Pearl Harbor to the inland extent of the model, a third of the way from the Kalauao Wells to Kunia III (fig. 42). Relative to scenario 4, the 0-ft line of equal change in 2-percent salinity depth simulated in scenario 6 extends farther westward, indicating a larger zone where freshwater thickness increases in scenario 6 relative to scenario 4. Thus, by redistributing 5.88 Mgal/d from Pearl City III (scenario 4) to Kunia III (scenario 6), located farther to the west, the zone where freshwater thickness increases expands westward. Near the Kalauao Wells the 2-percent salinity depth deepens by about 30 ft, and near Kunia III the 2-percent salinity depth shallows by about 35 ft.

In scenario 6, shallowing of the 50-percent salinity depth is greatest to the southwest of Kunia III, and is as much as 45 ft (fig. 43). Shallowing of the 50-percent salinity depth is enhanced by the presence of the low-permeability Waianae confining unit, which is represented in the model as a vertical barrier.

Scenarios 3 and 6 are similar in the amount of redistributed withdrawal to Kunia III (5.66 Mgal/d in scenario 3 and 5.88 Mgal/d in scenario 6). The size and shape of the zones in which freshwater thickness increases also are similar in scenarios 3 and 6. In general, however, the deepening of the 2-percent salinity depth is greater in scenario 3 relative to scenario 6. Within the simulated zones in which freshwater thickness decreases, shallowing of the 2-percent salinity depth is slightly greater in scenario 6 relative to scenario 3 because simulated withdrawal from Kunia III is slightly higher in scenario 6.

Scenario 7

In scenario 7, withdrawal from Halawa Shaft (2354-01) was reduced by 2.83 Mgal/d, withdrawal from the Kalauao Wells (2355-09 to -14) was reduced by 2.94 Mgal/d, and withdrawal from Kunia III (2401-04) was increased by 5.77 Mgal/d relative to the 2003 permitted rates. Model results indicate that the 2-percent salinity depth does not change (0-ft line of equal change in 2-percent salinity depth) along a line that runs from Pearl Harbor to the inland extent of the model, about midway between Halawa Shaft and Kunia III (fig. 44). The 0-ft line of equal change in 2-percent salinity depth simulated in scenario 7 is similar to that of scenario 3. In scenario 7, shallowing of the 50-percent salinity depth is greatest to the southwest of Kunia III, and is as much as 45 ft (fig. 45).

Scenarios 3 and 7 are similar in the amount of redistributed withdrawal to Kunia III (5.66 Mgal/d in scenario 3 and 5.77 Mgal/d in scenario 7). The size and shape of the zones in which freshwater thickness increases also are similar in scenarios 3 and 7. In general, however, the deepening of the 2-percent salinity depth is greater in scenario 3 relative to scenario 7. Within the simulated zones in which freshwater thickness decreases, shallowing of the 2-percent salinity depth is slightly greater in scenario 7 relative to scenario 3 because simulated withdrawal from Kunia III is slightly higher in scenario 7.

Summary of Effects of Redistributing Withdrawals

Results of the simulation of seven scenarios of redistributed withdrawal indicate the following: (1) redistributing withdrawal from Halawa Shaft (2354-01) or the Kalauao Wells (2355-09 to -14), near the eastern part of the Waimalu management system, to Pearl City III (2557-03), near the western part of the Waimalu management system, results in a thickening of the freshwater zone east of Waimalu Stream and a thinning of the freshwater zone west of Waimalu Stream; (2) in general, redistributing withdrawal from Halawa Shaft to Pearl City III results in greater thickening of the freshwater in the eastern part of the Waimalu management system relative to redistributing an equal amount of withdrawal from the Kalauao Wells to Pearl City III; (3) redistributing withdrawal from Halawa Shaft or the Kalauao Wells, near the eastern part of the Waimalu management system, to Kunia III (2557-03), near the western part of the Waipahu-Waiawa management system, results in a thickening of the freshwater zone throughout most of the Waimalu management system and a thinning of the freshwater zone in the Waipahu-Waiawa management system; (4) in general, redistributing withdrawal from Halawa Shaft to Kunia III results in greater thickening of the freshwater in the eastern part of the Waimalu management system relative to redistributing an equal amount of withdrawal from the Kalauao Wells to Kunia III; (5) the extent of freshwater thickening in the eastern part of the Waimalu management system caused by reducing withdrawal from the area is directly related to the amount of the reduction; (6) the zone where freshwater thickens in response to reducing withdrawal from a well is greatest downgradient from the well, between the well and the shore; and (7) valley-fill barriers can potentially reduce the zone where freshwater thickness increases in response to a reduction of withdrawal.

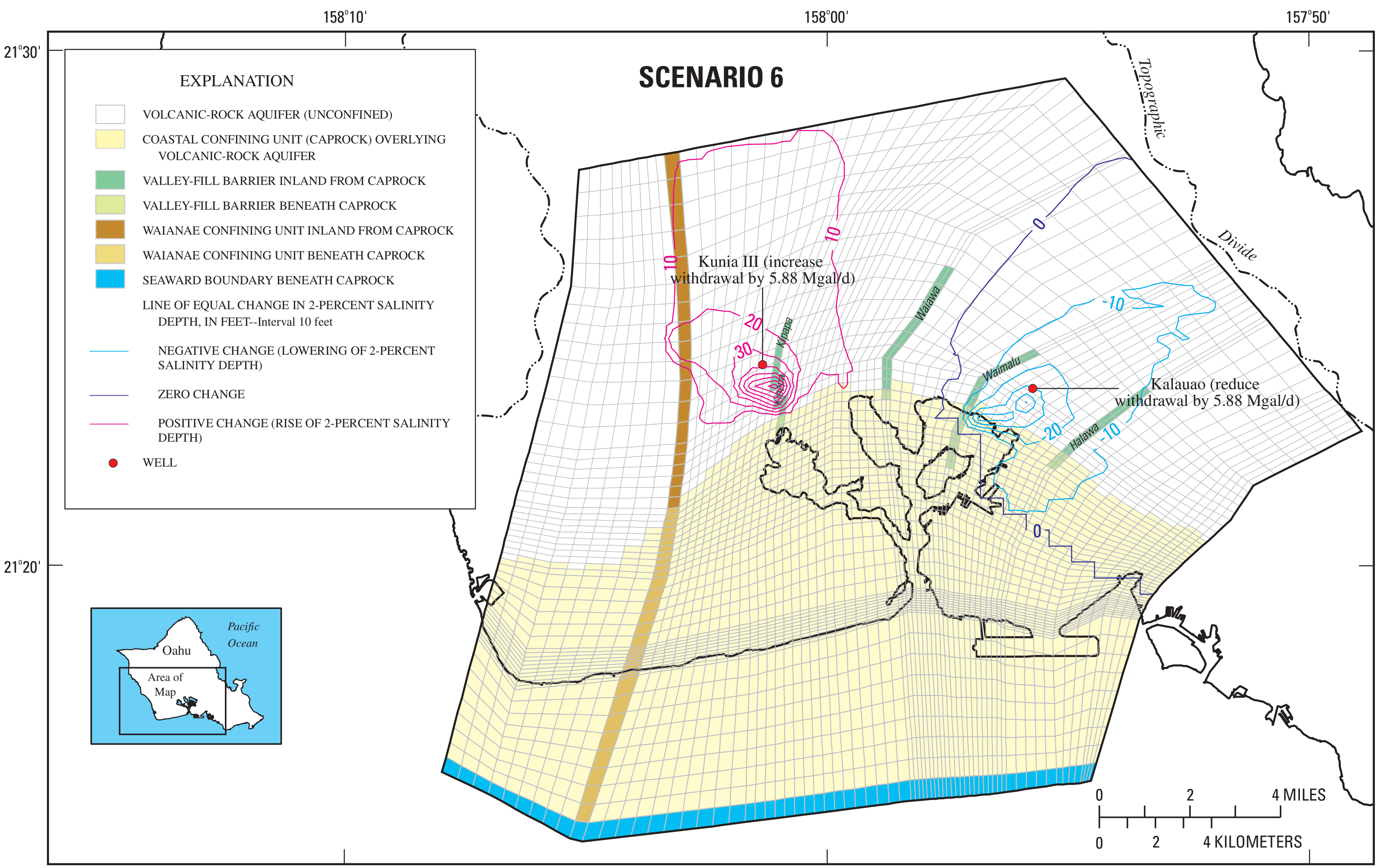


Figure 42. Simulated change in 2-percent salinity depth caused by reducing withdrawal from the Kalauao Wells (2355-09 to -14) by 5.88 million gallons per day and increasing withdrawal from Kunia III (2401-04) by the same amount relative to the 2003 permitted rates. Salinity changes were determined by comparing two simulations that differ only in the rates of withdrawal from the Kalauao Wells and Kunia III; the first simulation includes withdrawals equal to the 2003 permitted rates from all wells in the modeled area, and the second simulation includes reduced withdrawal from Kalauao (11.75 to 5.88 million gallons per day), increased withdrawal from Kunia III (1.5 to 7.38 million gallons per day), and withdrawals equal to the 2003 permitted rates from all other wells in the modeled area. Salinity changes shown are after 25 years of simulation using the ending results from the 1880-2000 transient simulation as initial conditions.

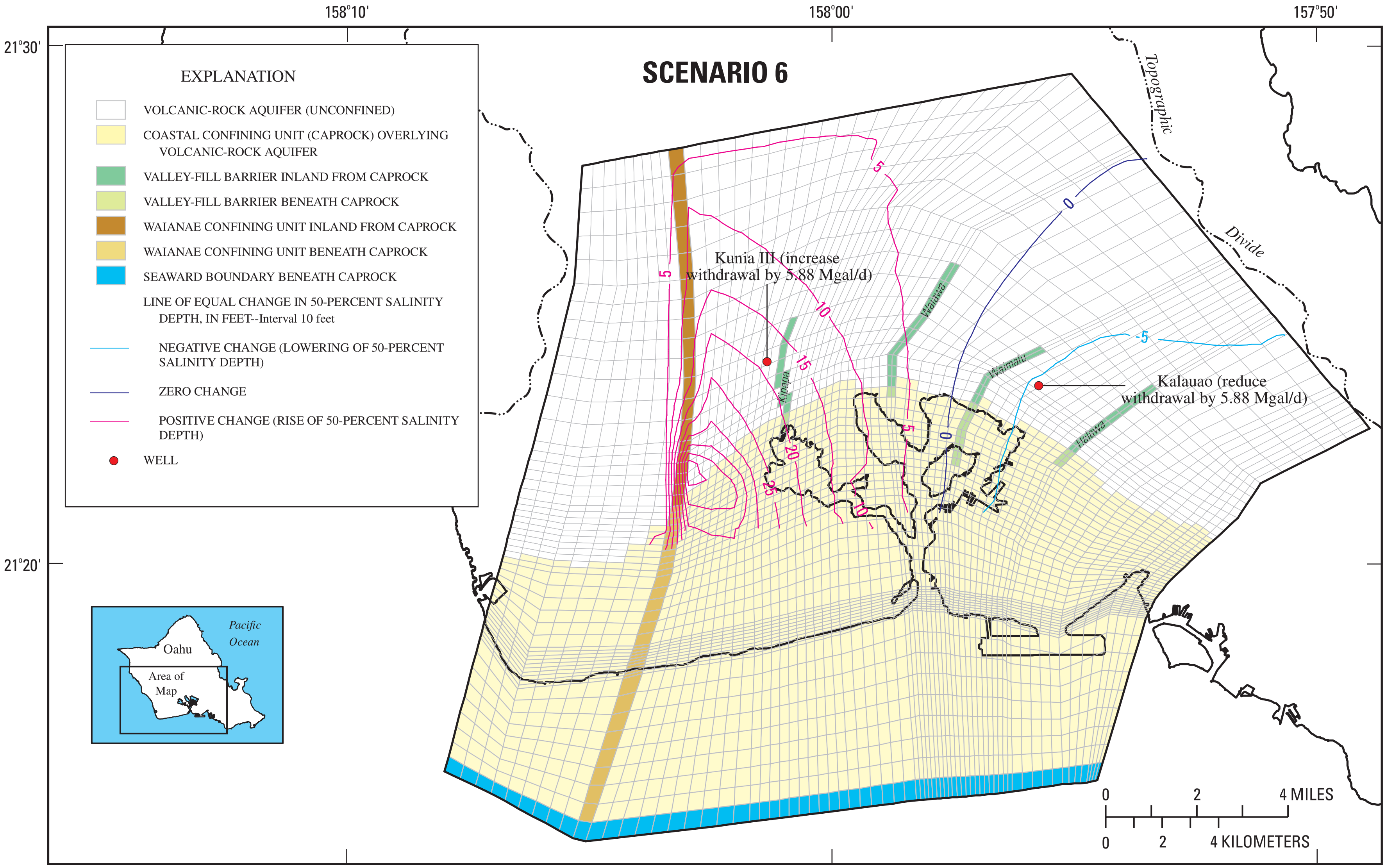


Figure 43. Simulated change in 50-percent salinity depth caused by reducing withdrawal from the Kalauao Wells (2355-09 to -14) by 5.88 million gallons per day and increasing withdrawal from Kunia III (2401-04) by the same amount relative to the 2003 permitted rates. Salinity changes were determined by comparing two simulations that differ only in the rates of withdrawal from the Kalauao Wells and Kunia III; the first simulation includes withdrawals equal to the 2003 permitted rates from all wells in the modeled area, and the second simulation includes reduced withdrawal from Kalauao (11.75 to 5.88 million gallons per day), increased withdrawal from Kunia III (1.5 to 7.38 million gallons per day), and withdrawals equal to the 2003 permitted rates from all other wells in the modeled area. Salinity changes shown are after 25 years of simulation using the ending results from the 1880-2000 transient simulation as initial conditions.

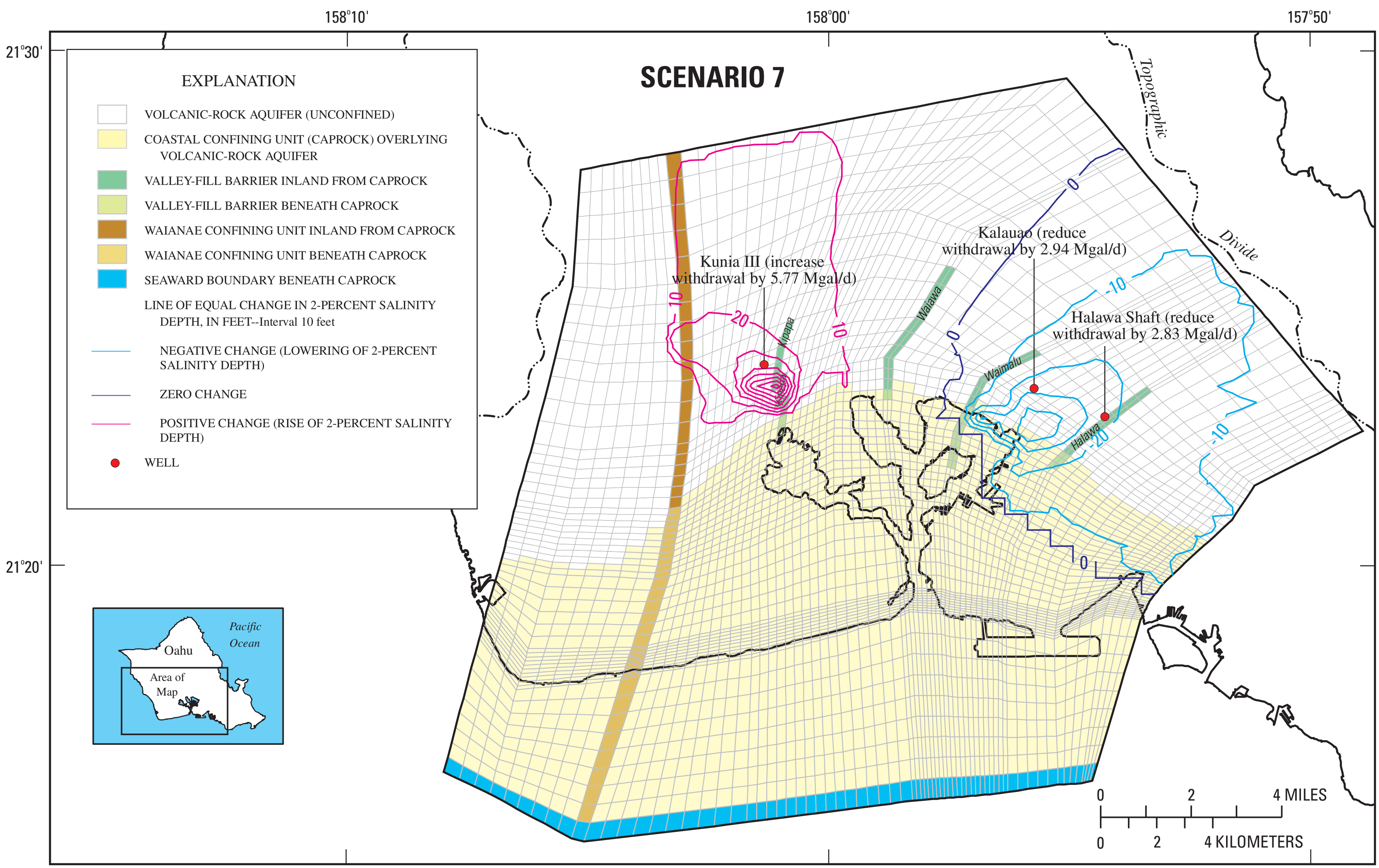


Figure 44. Simulated change in 2-percent salinity depth caused by reducing withdrawals from the Halawa Shaft (2354-01) by 2.83 million gallons per day and the Kalauao Wells (2355-09 to -14) by 2.94 million gallons per day and increasing withdrawal from Kunia III (2401-04) by 5.77 million gallons per day relative to the 2003 permitted rates. Salinity changes were determined by comparing two simulations that differ only in the rates of withdrawal from the Halawa Shaft, Kalauao Wells, and Kunia III; the first simulation includes withdrawals equal to the 2003 permitted rates from all wells in the modeled area, and the second simulation includes reduced withdrawal from Halawa Shaft (11.32 to 8.49 million gallons per day), reduced withdrawal from Kalauao (11.75 to 8.81 million gallons per day), increased withdrawal from Kunia III (1.5 to 7.27 million gallons per day), and withdrawals equal to the 2003 permitted rates from all other wells in the modeled area. Salinity changes shown are after 25 years of simulation using the ending results from the 1880-2000 transient simulation as initial conditions.

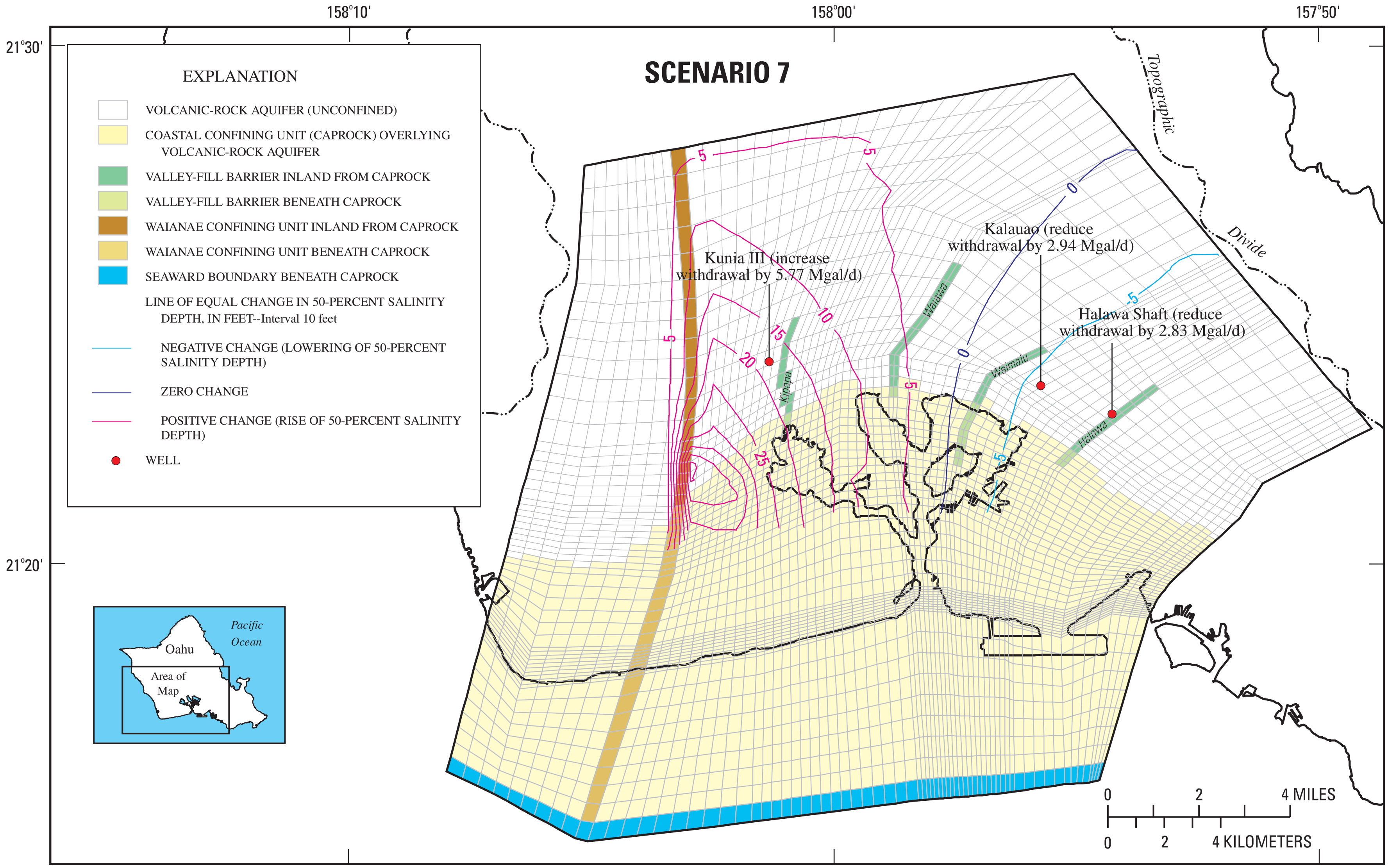


Figure 45. Simulated change in 50-percent salinity depth caused by reducing withdrawals from the Halawa Shaft (2354-01) by 2.83 million gallons per day and the Kalauao Wells (2355-09 to -14) by 2.94 million gallons per day and increasing withdrawal from Kunia III (2401-04) by 5.77 million gallons per day relative to the 2003 permitted rates. Salinity changes were determined by comparing two simulations that differ only in the rates of withdrawal from the Halawa Shaft, Kalauao Wells, and Kunia III; the first simulation includes withdrawals equal to the 2003 permitted rates from all wells in the modeled area, and the second simulation includes reduced withdrawal from Halawa Shaft (11.32 to 8.49 million gallons per day), reduced withdrawal from Kalauao (11.75 to 8.81 million gallons per day), increased withdrawal from Kunia III (1.5 to 7.27 million gallons per day), and withdrawals equal to the 2003 permitted rates from all other wells in the modeled area. Salinity changes shown are after 25 years of simulation using the ending results from the 1880-2000 transient simulation as initial conditions.

Model Limitations

The numerical model developed for this study simulates water levels and salinity on a regional scale and may not accurately predict either the pumping water level at an individual well or the salinity of water pumped from that well. Salinity of water pumped from a well may be controlled by local heterogeneities in the aquifer that are not represented in the model, and the level of model discretization affects the numerical accuracy with which transport mechanisms are simulated. The model has several other limitations for predictive purposes because of the various assumptions used and possible uncertainties in input data. These limitations are discussed below.

Differences between measured and simulated water levels and salinity profiles are greater in some areas than others, which may reflect uncertainties in the recharge or withdrawal estimates, boundary conditions, assigned parameter values in the model, or representations of the different hydrogeological features in the model. Recharge estimates in Hawaii generally are based on water-budget computations that could be improved with a better understanding of the spatial distributions of rainfall, evapotranspiration, runoff, and land-cover characteristics. Additional studies that could reduce uncertainties include: (1) directly measuring recharge using field lysimeters, (2) measuring changes in soil moisture below the plant root zone, (3) quantifying increases in the chloride concentration of infiltrating water caused by evapotranspiration, (4) measuring ground-water discharge with offshore seepage meters, and (5) developing an integrated surface-water/ground-water model. Improved recharge estimates in the study area will lead to improved estimates for parameter values in the numerical ground-water model and greater confidence in model results. Withdrawals represented in the model were based on available information. Unreported withdrawals and uncertainties in reported withdrawals that cannot be quantified also affect the accuracy of model results.

For this study, no-flow boundaries were assigned in the east and west, which precludes movement of ground water across these boundaries. Although some flow likely takes place across these boundaries, the amount cannot be quantified without expanding the modeled area.

The distributions of parameter values assigned in the model were kept simple to avoid creating an overly complex model that could not be justified on the basis of existing information. Heterogeneity in the ground-water system likely exists but is currently poorly understood. Values assigned to model parameters generally were based on existing estimates. However, some of these parameter values may be poorly known. Improved estimates of the distribution of hydraulic characteristics in the study area can be obtained using controlled aquifer tests as well as by careful monitoring of pumping and water-level conditions throughout the aquifer. Accurate pumping data in conjunction with water-level drawdown and recovery data can be used for calibration of a numerical ground-water flow model, particularly during periods when recharge does not vary.

The geometrical representation of the valley-fill barriers, caprock, and Waianae confining unit also were kept simple for the model. Because of uncertainty in the configuration of the valley-fill barriers, different configurations were tested in a sensitivity analysis. The sensitivity analysis indicated that model results could be improved in some places by adjusting valley-fill configurations. Our understanding of the geometry of the valley-fill barriers can be improved using surface geophysical techniques in conjunction with drilling additional monitor wells within the valleys (see for example R.M. Towill Corporation, 1978). In addition, careful monitoring of water levels on opposite sides of valley-fill barriers can provide insight as to the hydrologic effectiveness of the barriers.

For this study, the coastal caprock was represented as a homogeneous zone of low permeability except near the top of the caprock, where a high-permeability limestone unit was modeled. Other high-permeability zones likely exist in the caprock but they are poorly understood and were not represented in the model for this study. The Waianae confining unit was represented in the model as a vertical unit located near the sea-level contact between Waianae Volcanics and Koolau Basalt. Although the Waianae confining unit may dip about 10º away from the Waianae Volcano toward the east, it was represented in the model as a vertical unit because of uncertainty in the location of the confining unit eastward of the sea-level contact between Waianae Volcanics and Koolau Basalt.

Flow of water at the vertical seaward boundary of the model, below the caprock, was controlled by the hydraulic conductivity of the row of elements at the boundary. The ease with which saltwater enters the model at this boundary has an effect on the transient response of the system to changes in recharge and withdrawals. Extension of the model farther offshore may reduce the sensitivity of the model to the assigned hydraulic conductivity at the seaward boundary.

Two modeling artifices were incorporated to improve numerical stability in the model: (1) shallow zones (top two elements at most) of high dispersivity were created near zones of discharge, and (2) withdrawal from selected Maui-type shafts with infiltration tunnels was represented at more than one model node. These modeling artifices could be relaxed in future models that have finer discretization, although neither of these artifices likely affect the overall conclusions of this study.

Confidence in model results can be improved by addressing the limitations described in this section. In particular, improved estimates of recharge and the distribution of model parameters likely will lead to better model reliability.

Summary

The aquifer in the Pearl Harbor area of southern Oahu is the most heavily used aquifer in the State of Hawaii. For management purposes, the State Commission on Water Resource Management has divided the Pearl Harbor area into three hydrologically connected aquifer-management systems. From west to east, these management systems are the Ewa-Kunia system, the Waipahu-Waiawa system, and the Waimalu system. During 2001, reported withdrawals from the Waimalu management system averaged 46.5 Mgal/d. Ground-water withdrawal from the Waimalu management system is slightly higher than the State's sustainable-yield estimate of 45 Mgal/d for the area. This has led to concern regarding saltwater intrusion associated with long-term withdrawals from the Waimalu management system.

In the Waimalu management system, ground-water flow may be influenced by valley-fill barriers associated with existing stream valleys. Valley-fill barriers are formed by low-permeability valley-fill deposits and weathered volcanic rocks beneath those deposits that impede ground-water movement. The State's sustainable-yield estimate for the Waimalu management system does not account for the hydrologic effects of these possible barriers.

In cooperation with the City and County of Honolulu Board of Water Supply (BWS), the U.S. Geological Survey (USGS) undertook an investigation to evaluate the possible hydrologic effects of valley-fill barriers in the Pearl Harbor area. The objectives of this study were to (1) obtain a better understanding of the hydrologic effects of valley-fill barriers in the Pearl Harbor area, (2) determine the possible effects of valley-fill barriers on water levels and salinity in the Pearl Harbor area, and (3) estimate the effects of redistributing existing withdrawals on the freshwater resource.

To date, only limited information has been published on valley-fill barriers in the Pearl Harbor area. As part of this study, water levels from wells on opposite sides of Waiawa Stream valley were measured to determine if water-level recovery associated with shutting off a large-capacity production well could be measured. The Waiawa Shaft (well 2558-10), which is located on the west side of Waiawa Stream valley, was shut off for a period of about 2 days. During the week prior to the shut-off, withdrawal from Waiawa Shaft was steady at about 10 Mgal/d. During the 2-day period when Waiawa Shaft was shut off, water levels on each side of Waiawa Stream valley appeared to recover, indicating that Waiawa Stream valley is not a totally effective hydrologic barrier in the vicinity of Waiawa Shaft.

A three-dimensional numerical ground-water model capable of simulating density-dependent solute transport was developed as part of this study. The model used published estimates for most of the permeability, storage, and dispersivity values. Simulated water levels and salinity profiles generally were in agreement with measured water levels and salinity profiles from representative wells in the modeled area.

Simulated water levels during some periods were a few feet too high in the eastern part of the Koolau Basalt aquifer and a few feet too low in the western part. Furthermore, the model underestimates, by about 4 ft, the reported predevelopment head of 32 ft above mean sea level near the southwestern part of the Koolau Basalt aquifer. Some of the discrepancy between measured and simulated water levels can be attributed to uncertainties in the estimated distribution of hydraulic properties in the model. In addition, some of the discrepancy may be related to factors including: (1) the reported predevelopment head may be from a period with climatic conditions that are not representative of long-term conditions, (2) the estimated distributions of recharge for different time periods are uncertain, (3) the reported ground-water withdrawal information may be inaccurate, (4) the hydraulic characteristics of the caprock may have changed over time because of the drilling of numerous artesian wells, which flowed freely at the surface and may have leaked in the subsurface.

Model sensitivity tests of valley-fill barrier configuration indicated that simulated water levels and salinity can be affected by the depth and length of the simulated valley-fill barriers. Deepening the Waiawa valley-fill barrier to 660 ft below mean sea level and extending it inland and seaward resulted in a redistribution of ground-water flow and simulated water-level changes of as much as a foot relative to the base-case valley-fill barriers. Deepening the Waiawa valley-fill barrier to 660 ft below mean sea level generally resulted in deeper simulated salinity profiles west of the Waiawa valley-fill barrier by as much as a few tens of feet in some places relative to the base case for common sites and times.

The model constructed for this study was used to simulate the hydrologic effects of redistributing withdrawals in the Pearl Harbor area by reducing withdrawals in the eastern part of the Waimalu area and increasing withdrawals farther to the west by an equal amount. Simulation results from seven scenarios of redistributed withdrawal indicate the following: (1) redistributing withdrawal from Halawa Shaft (2354-01) or the Kalauao Wells (2355-09 to -14), near the eastern part of the Waimalu management system, to Pearl City III (2557-03), near the western part of the Waimalu management system, results in a thickening of the freshwater zone east of Waimalu Stream and a thinning of the freshwater zone west of Waimalu Stream; (2) in general, redistributing withdrawal from Halawa Shaft to Pearl City III results in greater thickening of the freshwater in the eastern part of the Waimalu management system relative to redistributing an equal amount of withdrawal from the Kalauao Wells to Pearl City III; (3) redistributing withdrawal from Halawa Shaft or the Kalauao Wells, near the eastern part of the Waimalu management system, to Kunia III (2557-03), near the western part of the Waipahu-Waiawa management system, results in a thickening of the freshwater zone throughout most of the Waimalu management system and a thinning of the freshwater zone in the Waipahu-Waiawa management system; (4) in general, redistributing withdrawal from Halawa Shaft to Kunia III results in greater thickening of the freshwater in the eastern part of the Waimalu management system relative to redistributing an equal amount of withdrawal from the Kalauao Wells to Kunia III; (5) the extent of freshwater thickening in the eastern part of the Waimalu management system caused by reducing withdrawal from the area is directly related to the amount of the reduction; (6)

the zone where freshwater thickens in response to reducing withdrawal from a well is greatest downgradient from the well, between the well and the shore; and (7) valley-fill barriers can potentially reduce the zone where freshwater thickness changes in response to a reduction of withdrawal.

The numerical model developed for this study simulates water levels and salinity on a regional scale and may not accurately predict either the pumping water level at an individual well or the salinity of water pumped from that well. Salinity of water pumped from a well may be controlled by local heterogeneities in the aquifer that are not represented in the model. The model has several other limitations for predictive purposes because of the various assumptions used and possible uncertainties in input data. Model reliability can be improved as understanding of ground-water recharge, the distribution of model parameter values, and the geometry of the valley-fill barriers improves.

Recharge estimates in Hawaii generally are based on water-budget computations that could be improved with a better understanding of the spatial distributions of rainfall, evapotranspiration, runoff, and land-cover characteristics. Additional studies that could lead to improved recharge estimates include, (1) directly measuring recharge using field lysimeters, (2) measuring changes in soil moisture below the plant root zone, (3) quantifying increases in the chloride concentration of infiltrating water caused by evapotranspiration, (4) measuring ground-water discharge with offshore seepage meters, and (5) developing an integrated surface-water/ground-water model.

Improved estimates of the distribution of hydraulic characteristics in the study area can be obtained using controlled aquifer tests as well as by careful monitoring of pumping and water-level conditions throughout the aquifer. Accurate pumping data in conjunction with water-level drawdown and recovery data can be used for calibration of a numerical ground-water flow model, particularly during periods when recharge does not vary.

Our understanding of the geometry of the valley-fill barriers could be improved using surface geophysical techniques in conjunction with drilling additional monitor wells within the valleys. In addition, careful monitoring of water levels on opposite sides of a valley could provide insight as to the effectiveness of the valley-fill barrier.

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Appendix A. Monthly ground-water withdrawals during 1890 to 2000 from wells in the Pearl Harbor and Moanalua areas, Oahu, Hawaii

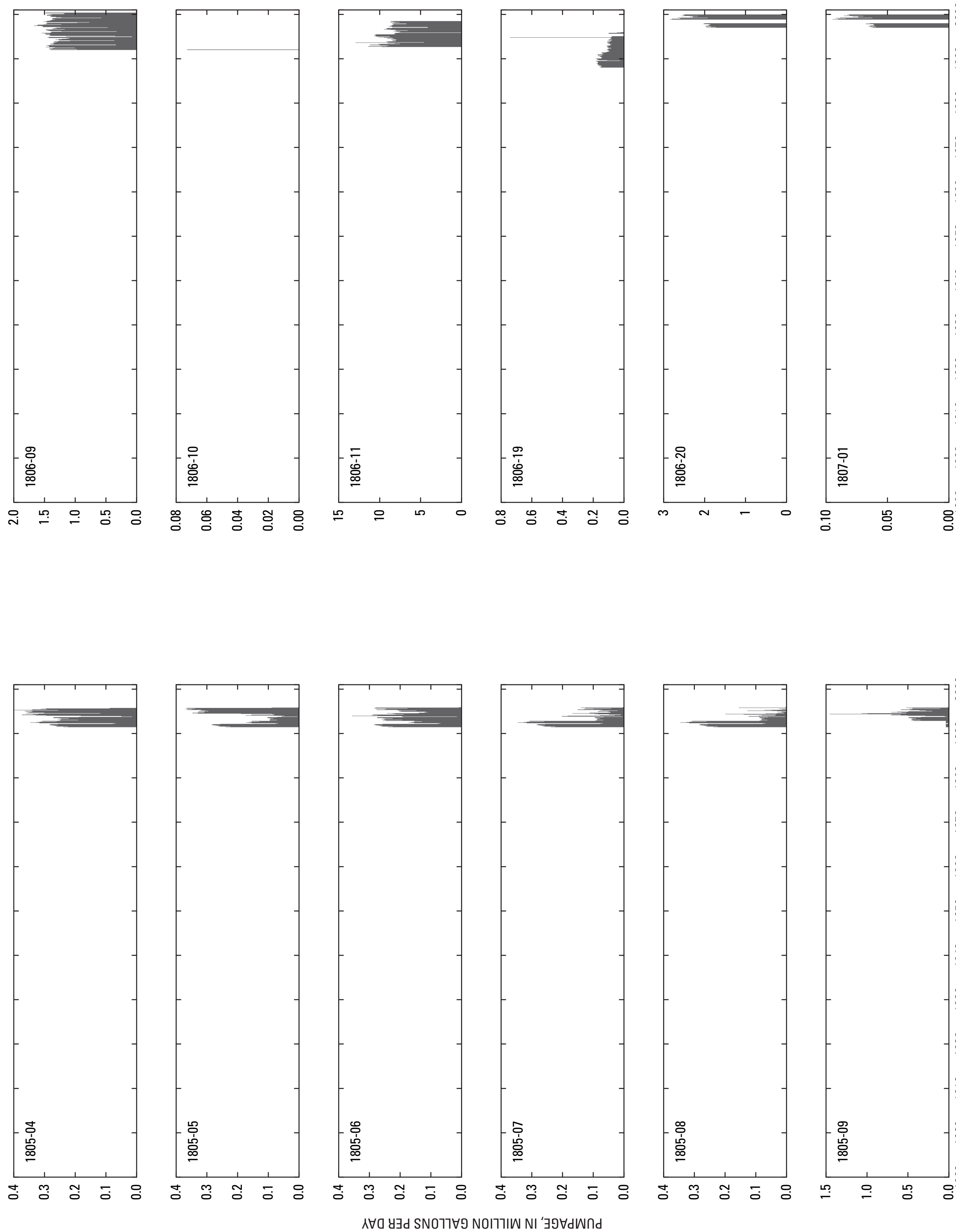


Figure A1. Monthly ground-water withdrawals during 1890 to 2000 from wells in the Pearl Harbor and Moanalua areas, Oahu, Hawaii.

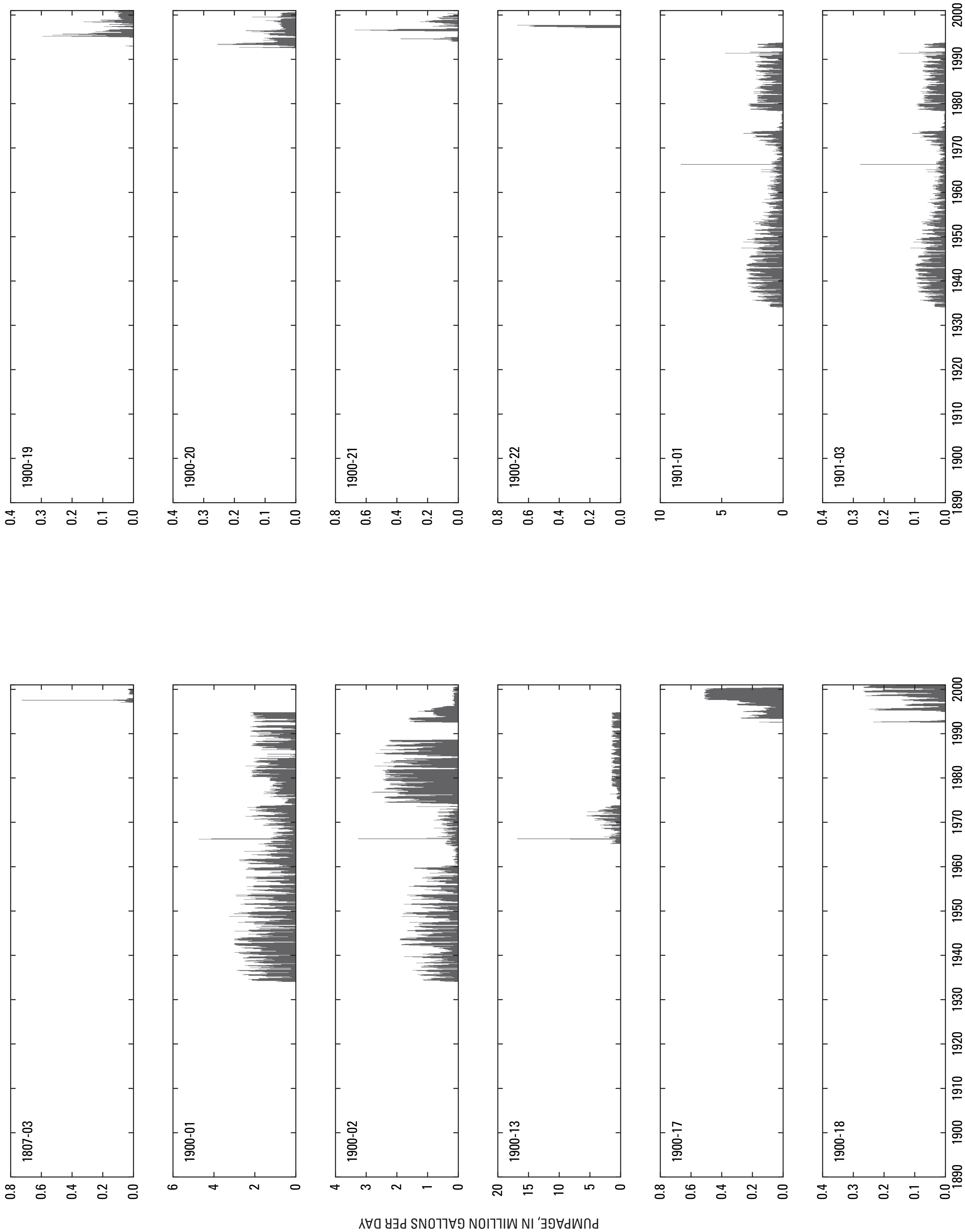
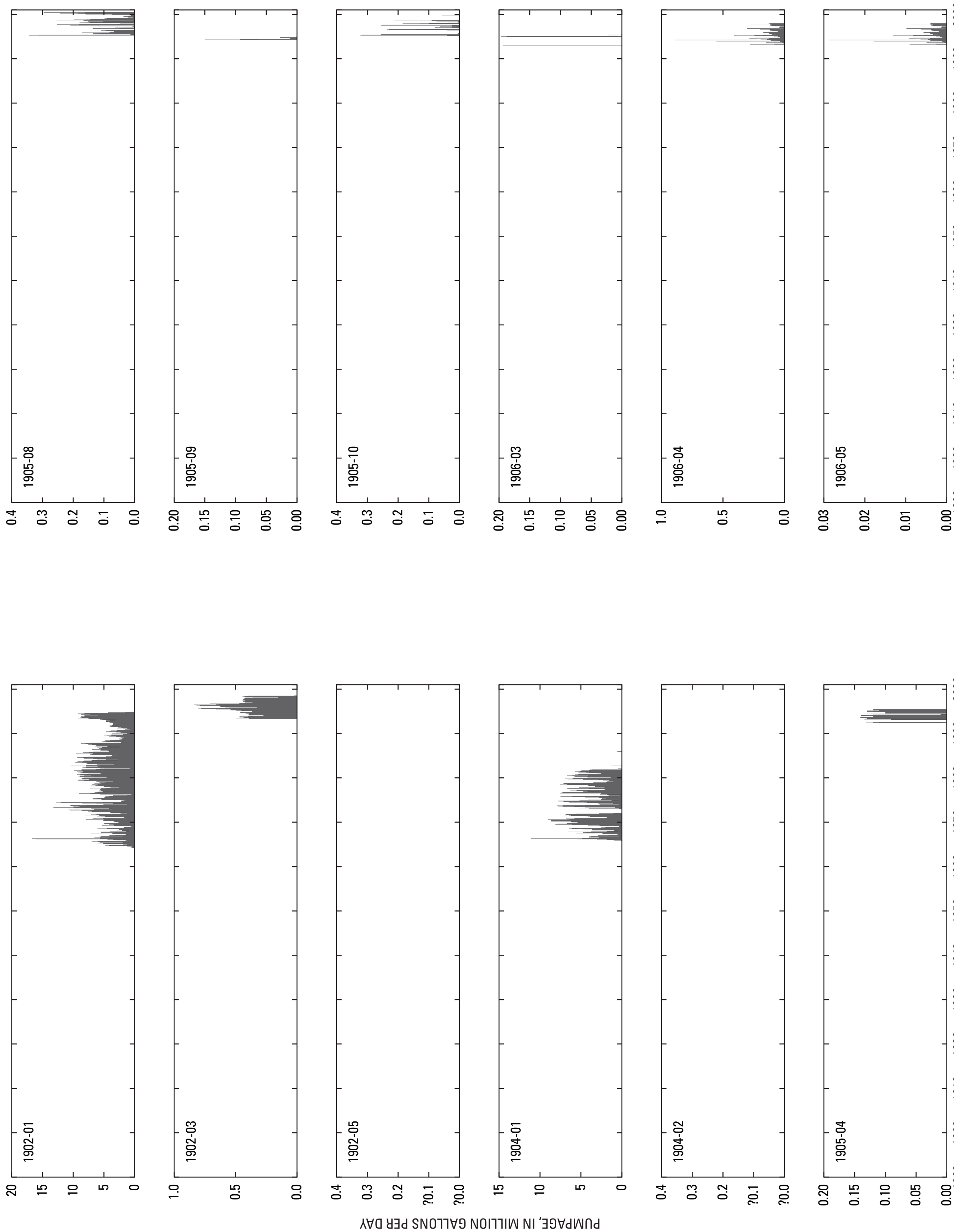


Figure A1. Monthly ground-water withdrawals during 1890 to 2000 from wells in the Pearl Harbor and Moanalua areas, Oahu, Hawaii—*Continued.*



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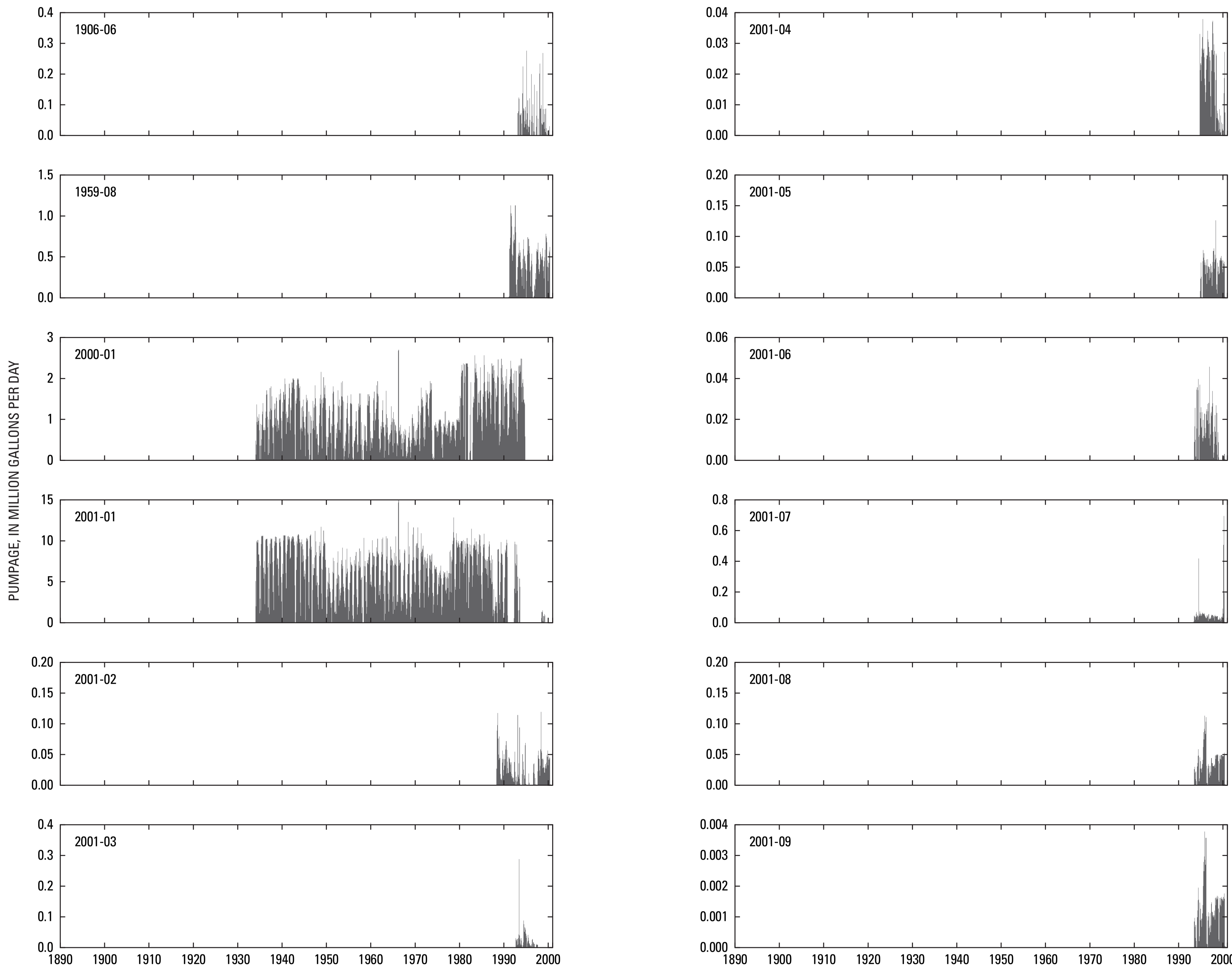

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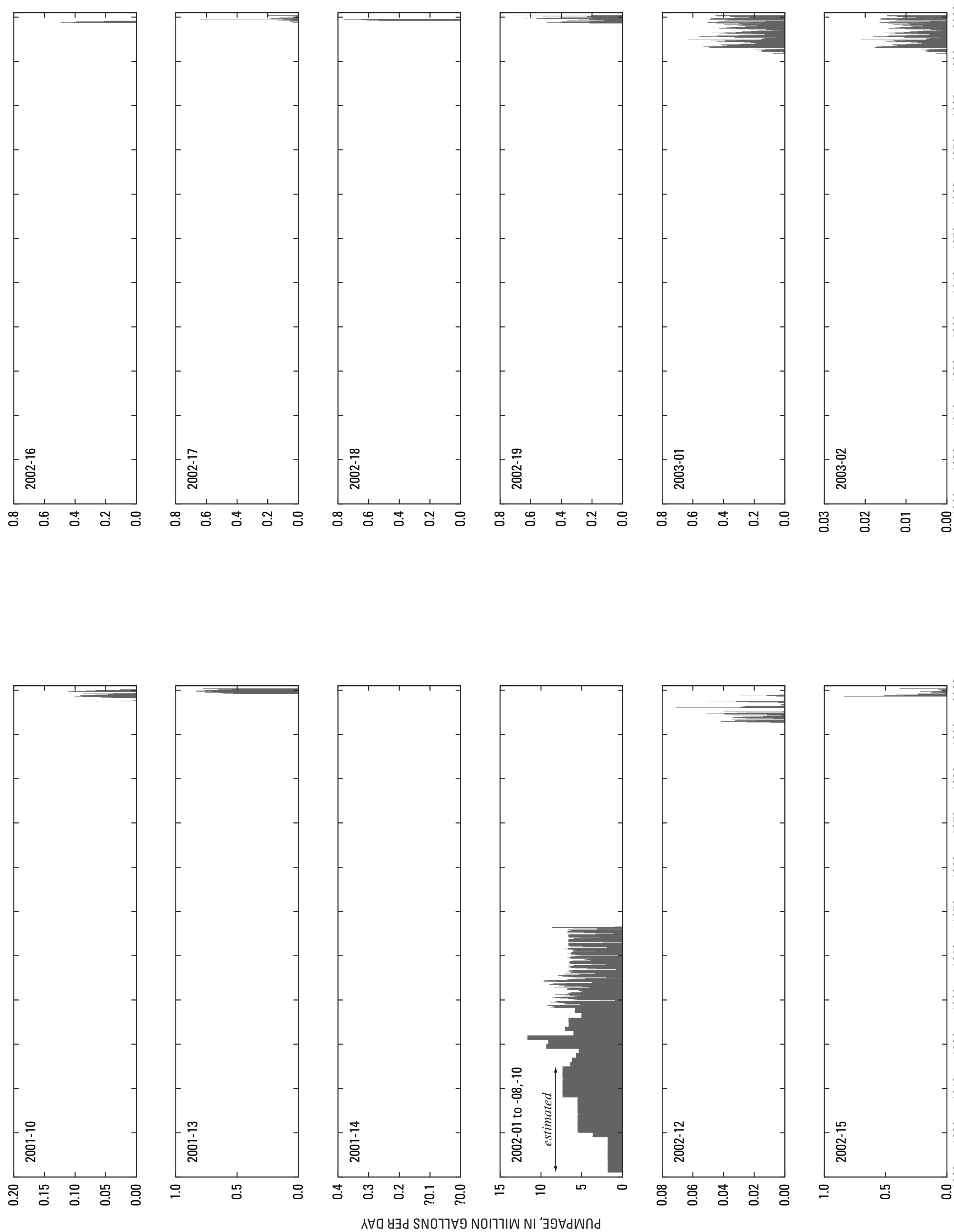

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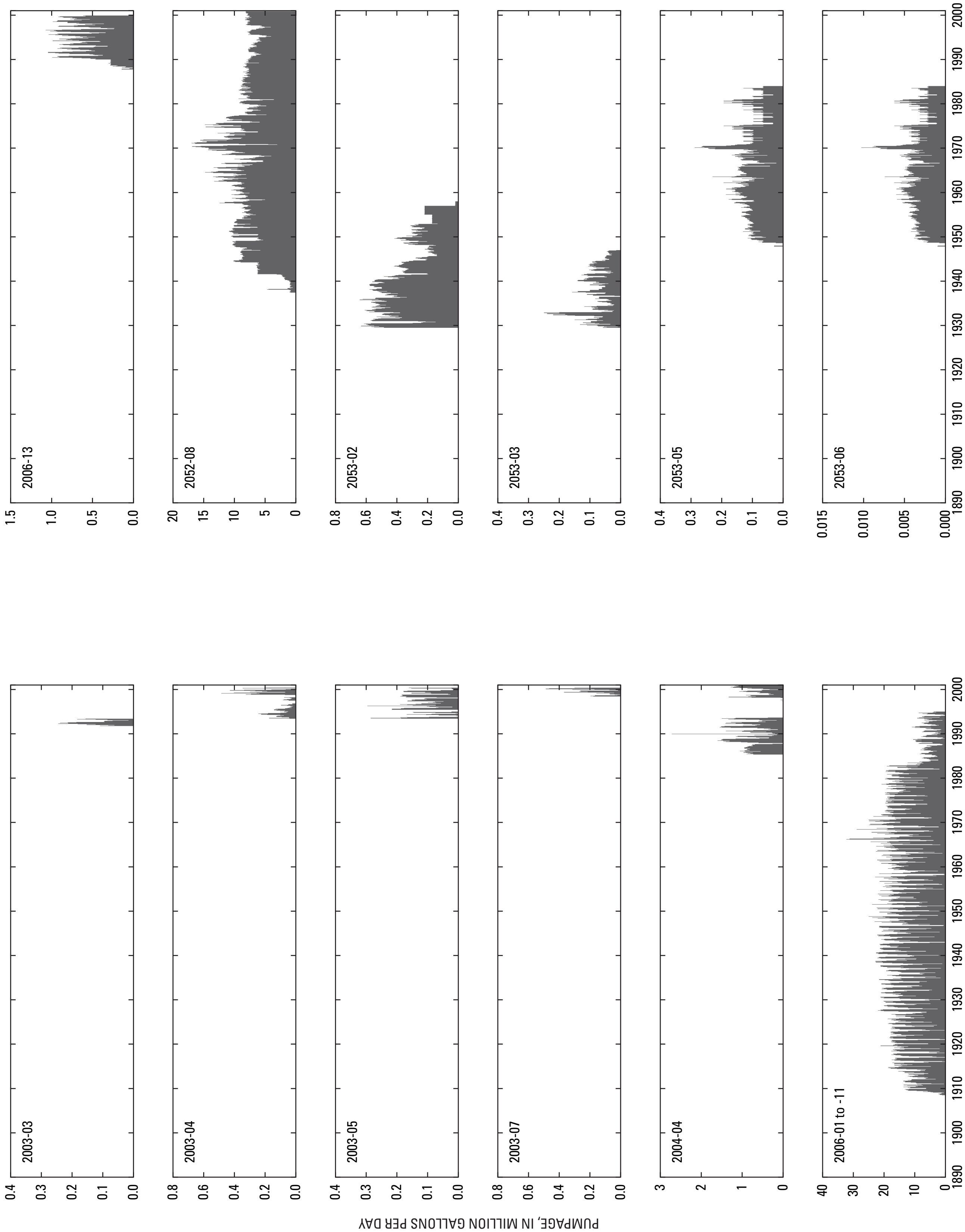

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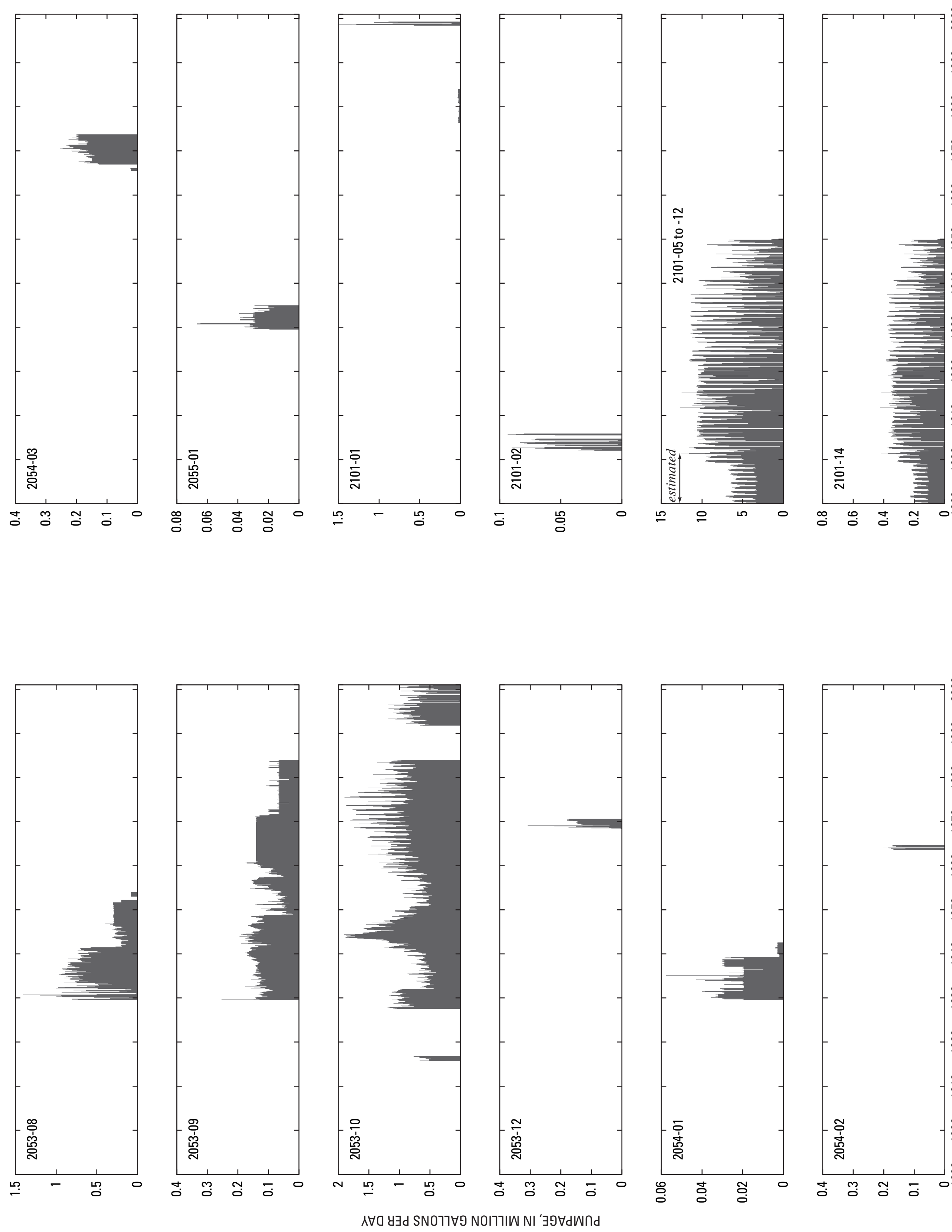

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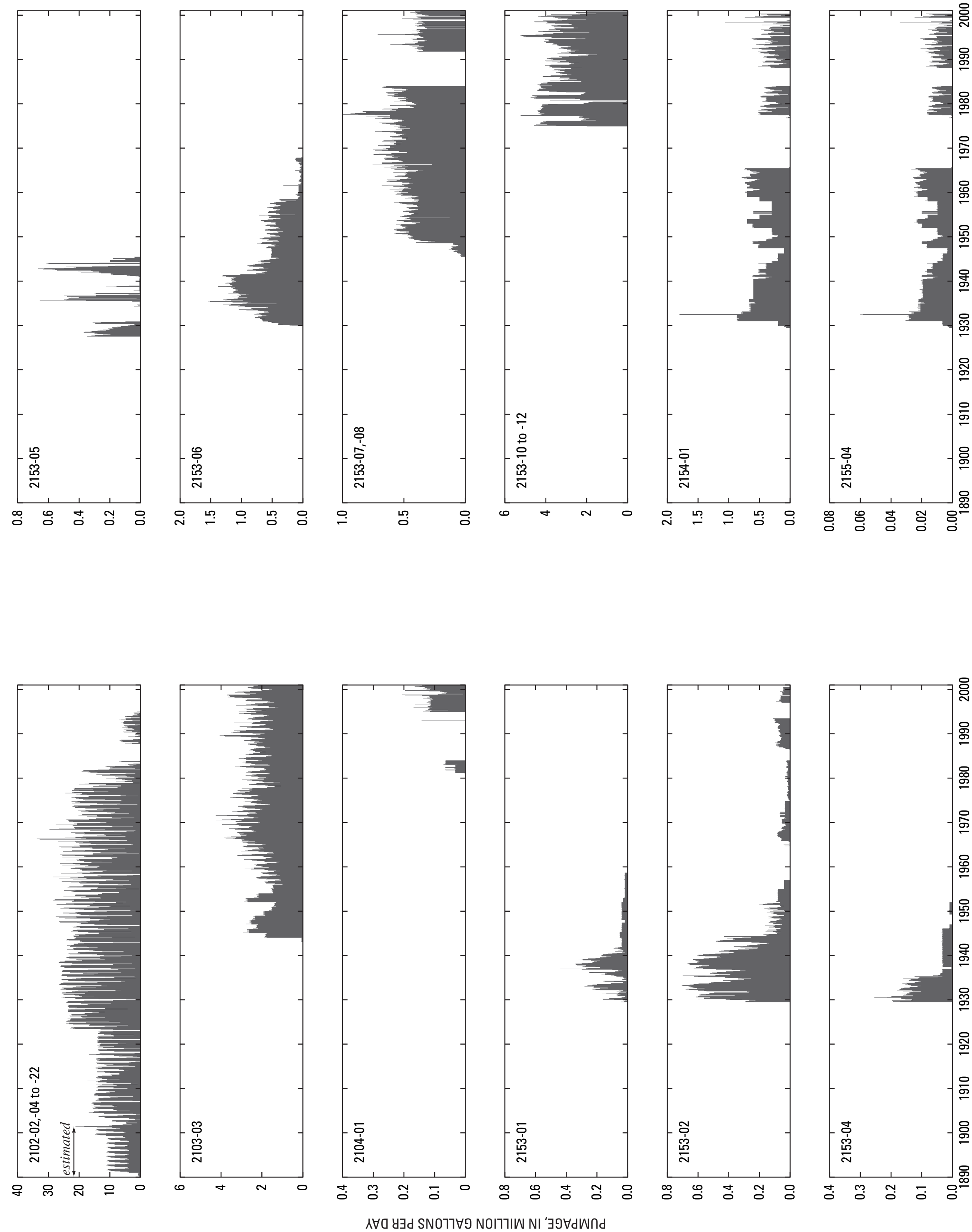
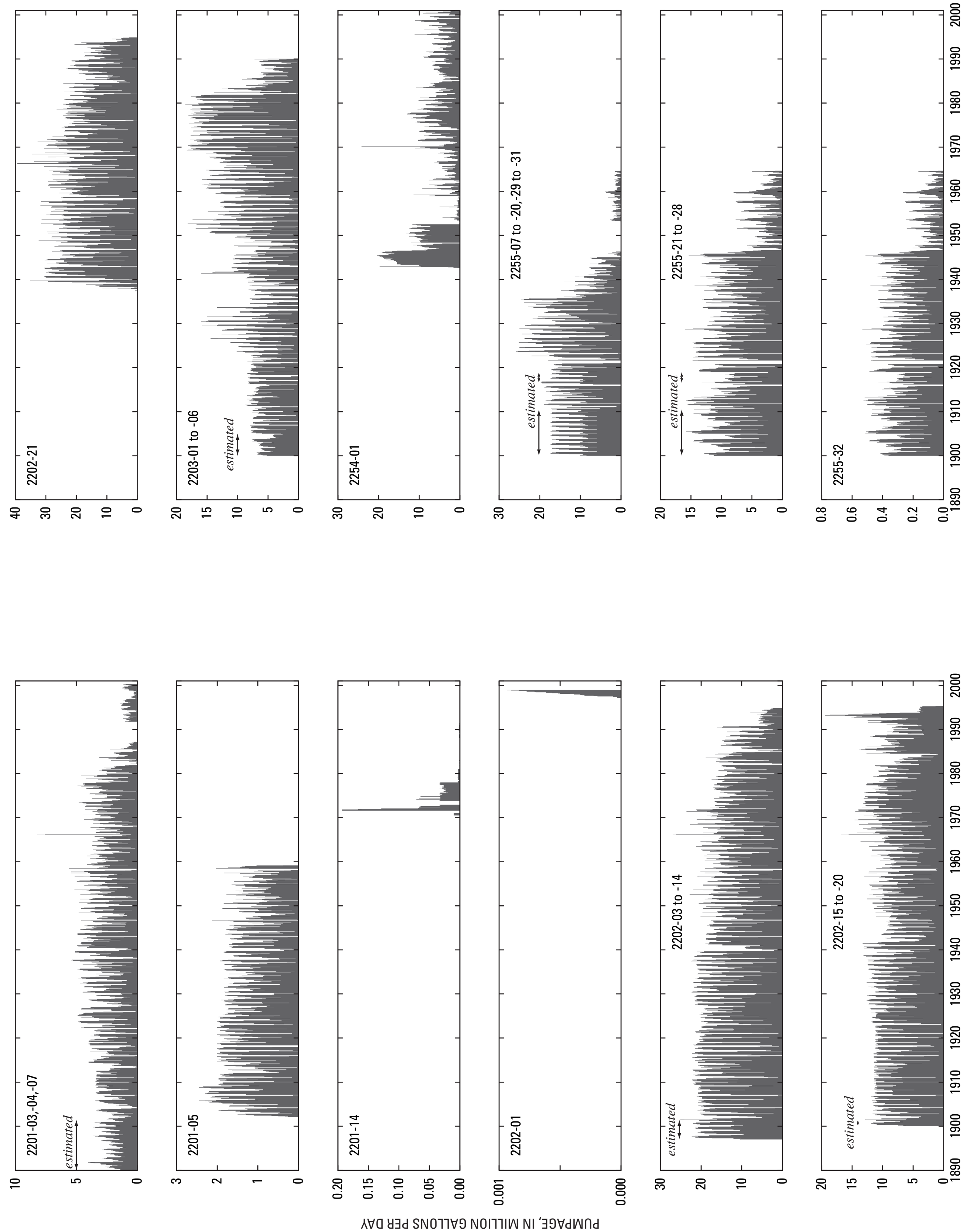


Figure A1. Monthly ground-water withdrawals during 1890 to 2000 from wells in the Pearl Harbor and Moanalua areas, Oahu, Hawaii—*Continued.*



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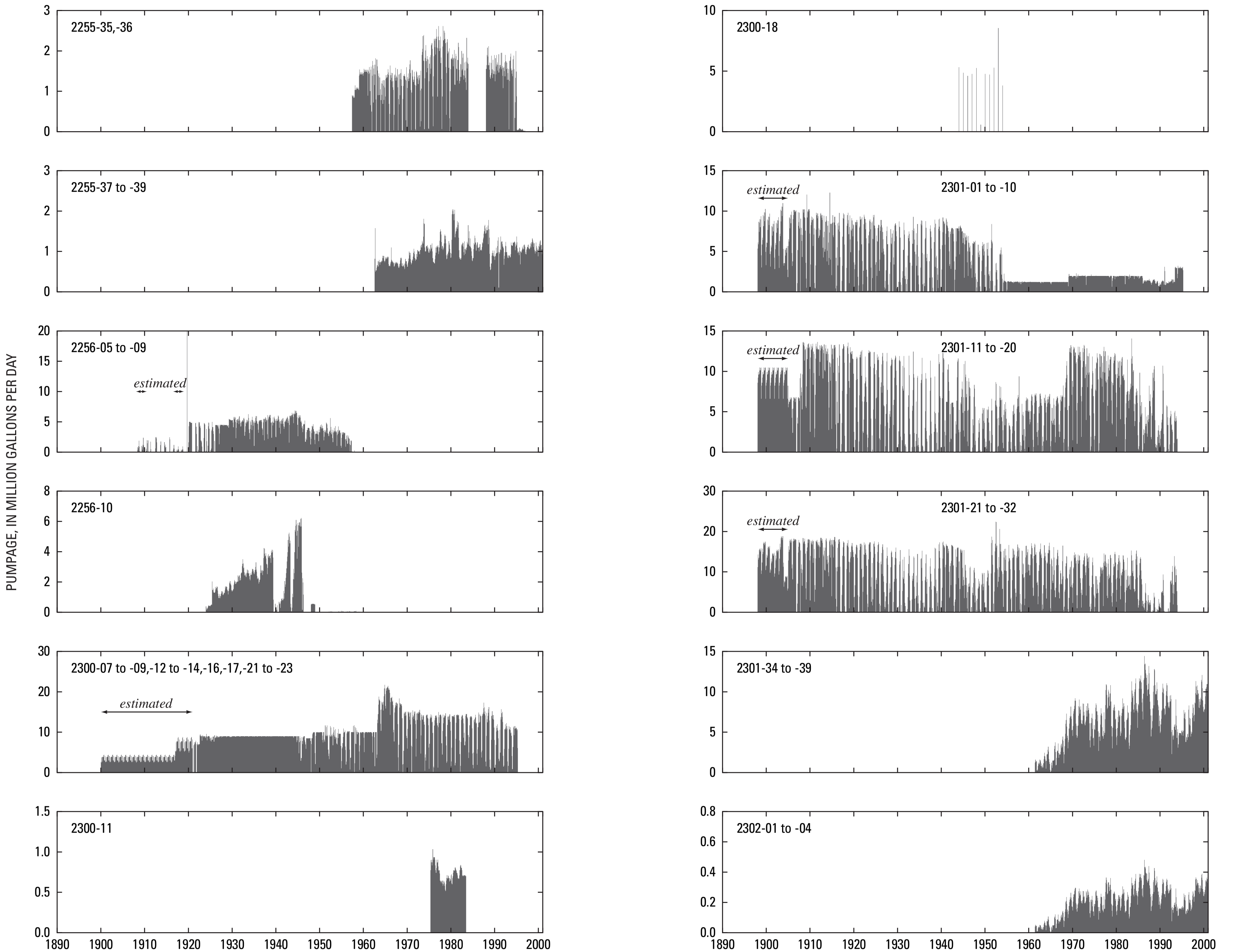

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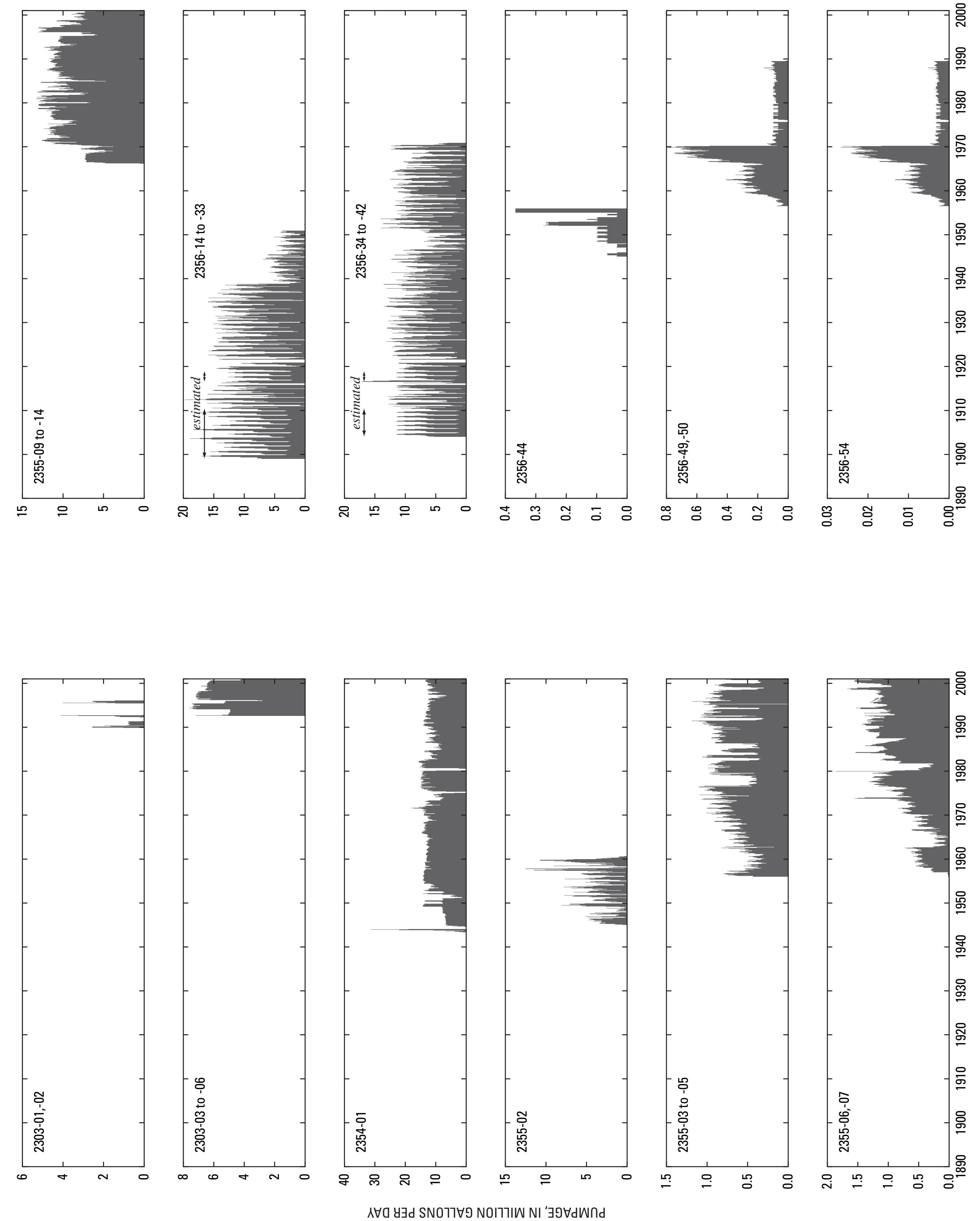

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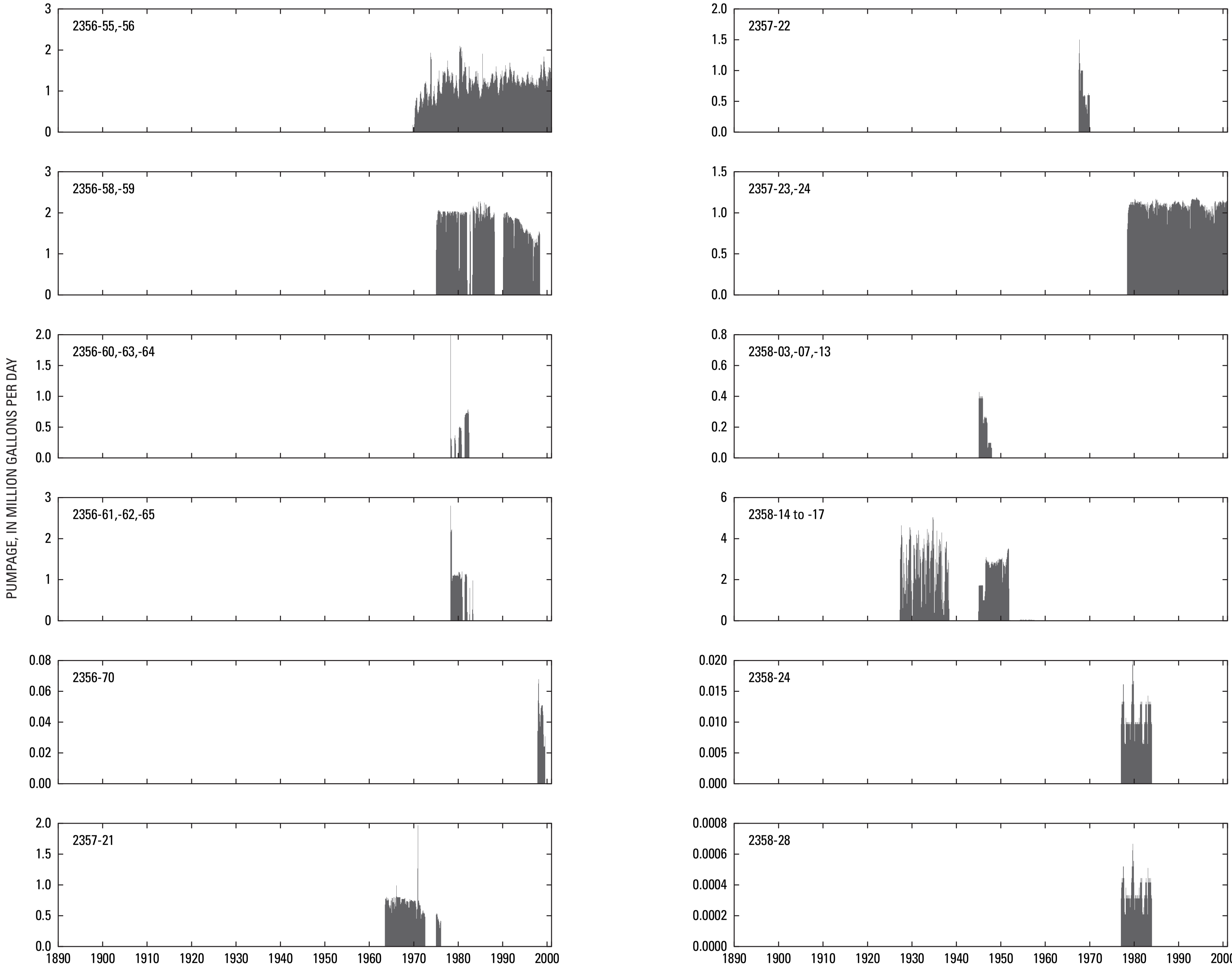

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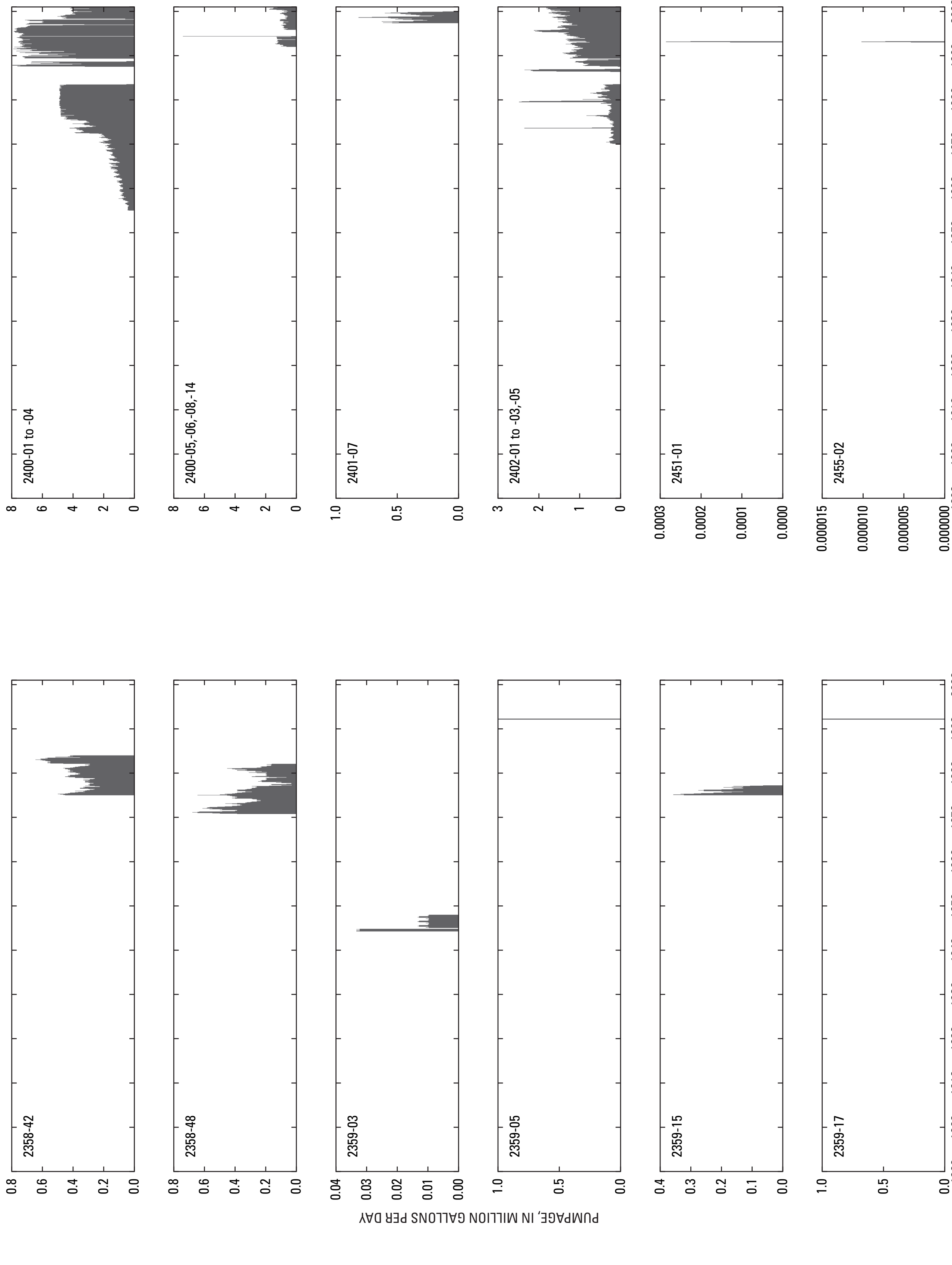

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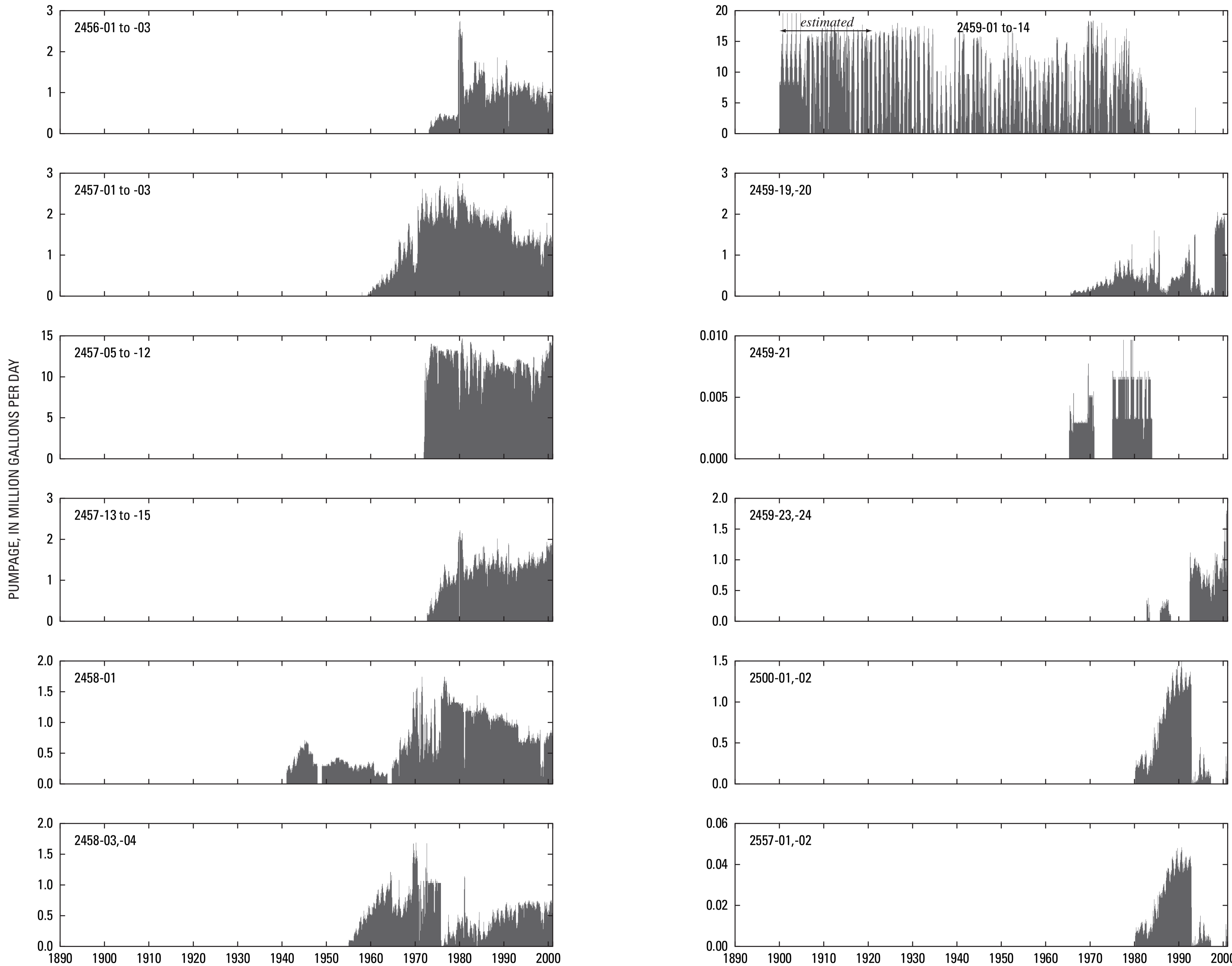

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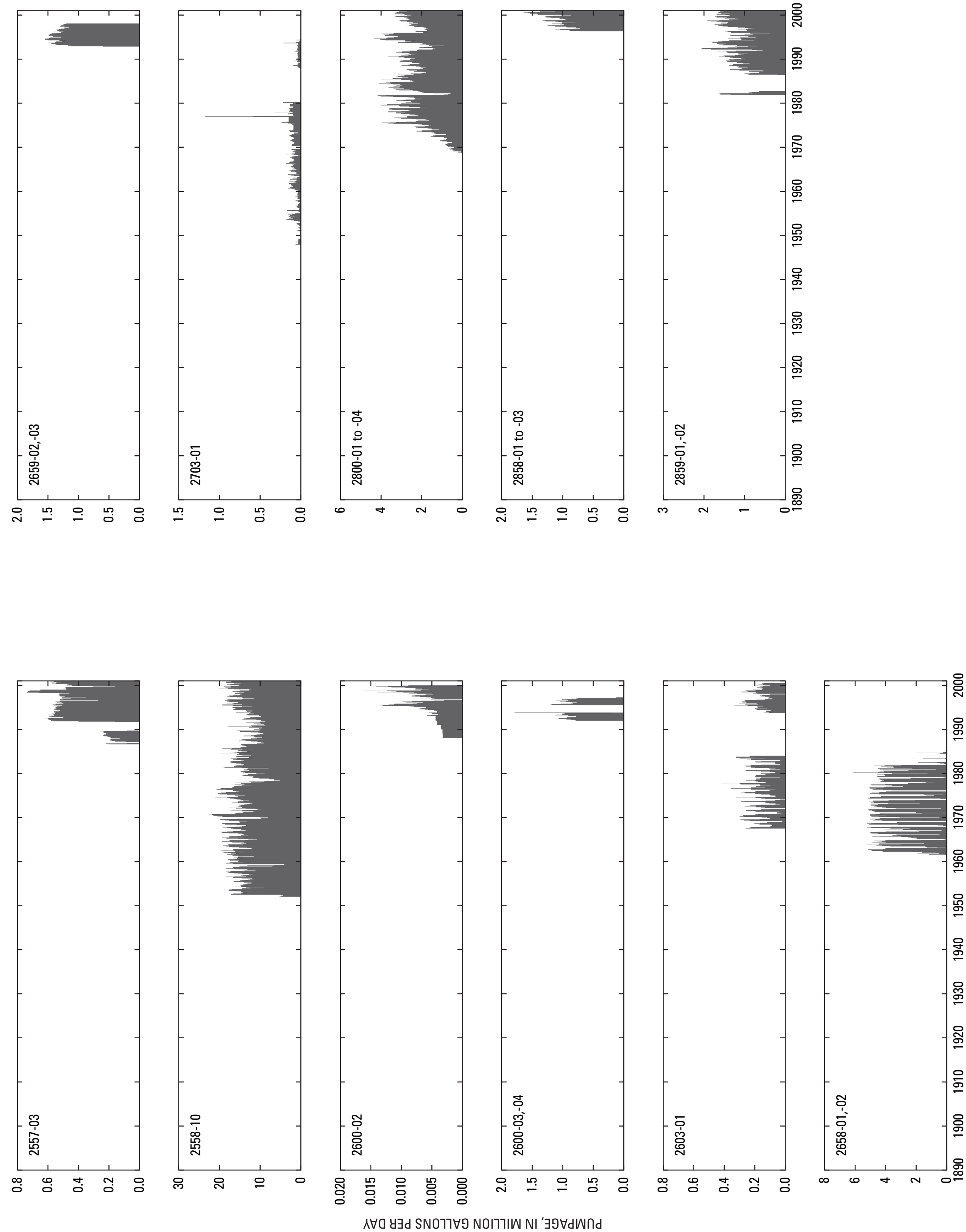

Figure A1. Monthly ground-water withdrawals during 1890 to 2000 from wells in the Pearl Harbor and Moanalua areas, Oahu, Hawaii—*Continued.*

Appendix B. Properties of pumped wells in the Pearl Harbor area

Table B1. Properties of pumped wells in the Pearl Harbor area, Oahu, Hawaii (modified from unpub. digital database, 2002, Hawaii Commission on Water Resource Management).

[--, data not available]

Well no.	Well name	Year drilled	Ground altitude, in feet	Well depth, in feet	Depth of solid casing, in feet
1805-04	Kalaeloa PW-1	1990	13	25	17
1805-05	Kalaeloa PW-2	1990	14	25	17
1805-06	Kalaeloa PW-3	1990	13	25	17
1805-07	Kalaeloa PW-4	1990	14	25	17
1805-08	Kalaeloa PW-5	1990	14	25	17
1805-09	Kalaeloa PW-6	1990	14	40	17
1806-09	Facility Maint 1	1986	12	103	50
1806-10	Facility Maint 2	1986	12	105	50
1806-11	AES Prod 1	1989	12	115	60
1806-19	Ewa Island Comm	--	--	25	--
1806-20	Acid Plant	1959	5	--	--
1807-01	Lpg Storage Area	1959	3	--	--
1807-03	Mauka-Makai St	1959	4	--	--
1900-01	Ep 20	1930	25	30	--
1900-02	Ep 22	1930	23	29	--
1900-13	EP 30	1965	5	8	--
1900-17	Haw Prince Irr 2	1990	20	26	18
1900-18	Haw Prince Irr 3	1990	20	25	17
1900-19	Haw Prince Irr 4	1990	20	25	17
1900-20	Haw Prince Irr 5	1990	20	25	17
1900-21	New Ewa Intl G C	1991	18	30	15
1900-22	Dug C	1988	--	12	--
1900-23	Pac Tsunami Cntr	1999	--	9	9
1901-01	Ep 24	1932	24	29	--
1901-03	Haw Prince Irr 1	1990	21	26	18
1901-05	Gentry Area 13	1999	33	43	31
1901-06	--	--	--	--	--
1902-01	Ep 27A&B, 28&29	1964	5	8	--
1902-03	Honouliuli STP 1	1991	36	51	31
1902-05	Coral Creek 5	1998	36	68	40
1904-01	Ep 31&32	1965	5	8	--
1904-02	Makakilo G C 1	1991	--	77	57
1905-04	Ewa Desalt Basal	1988	--	380	275
1905-05	Caprock 1	1988	--	80	52
1905-08	Kapolei Irr 1	1991	65	84	64
1905-09	Caprock 3	1992	54	80	60
1905-10	Kapolei Irr 2	1993	65	94	54
1906-03	Grace Pac C-3	1988	--	120	40
1906-04	Grace Pac C-2	1988	--	120	40
1906-05	Grace Pac B-1	1988	--	250	120
1906-06	Grace Pac C-1	1987	--	118	45
1959-08	Dug D	1988	--	12	--
2000-01	Ep 21	1930	25	30	--
2001-01	Ep 23	1931	43	47	--
2001-02	Gentry Entry Irr	1987	28	38	29
2001-03	Geiger Park	1989	38	56	36
2001-04	Sunrise	1994	38	61	36
2001-05	Sun Terra	1994	36	65	35
2001-06	Palm Villa I	1990	41	60	40
2001-07	Arbors GV 1	1991	33	50	28
2001-08	Palm Villa 2	1991	36	61	41
2001-09	Ft Weaver Apt.	1994	35	56	31
2001-10	Gentry Area 24	1996	34	52	30
2001-12	Keaunui Area 30	1999	31	39	29
2001-13	Coral Creek 4	1998	34	48	35
2001-14	Lake 10	1998	--	5	--
2002-01	Ewa	1891	47	507	419
2002-02	Ewa	1891	46	523	450

Table B1. Properties of pumped wells in the Pearl Harbor area, Oahu, Hawaii (modified from unpub. digital database, 2002, Hawaii Commission on Water Resource Management)—Continued.

[--, data not available]

Well no.	Well name	Year drilled	Ground altitude, in feet	Well depth, in feet	Depth of solid casing, in feet
2002-03	Ewa	1899	46	551	438
2002-04	Ewa	1899	46	550	450
2002-05	Ewa	1900	46	522	450
2002-06	Ewa	1900	46	518	445
2002-07	Ewa	1908	46	498	--
2002-08	Ewa	1908	46	497	464
2002-10	Ewa	1944	40	213	--
2002-12	Palm Court 3	1989	40	60	40
2002-15	Coral Creek 1	1997	40	55	38
2002-17	Coral Creek 2	1998	30	48	37
2002-18	Coral Creek 3	1998	34	47	37
2002-19	Lake A	1998	--	5	--
2003-01	Kapolei Irr A	1991	60	85	65
2003-02	Kapolei Irr B	1991	60	82	62
2003-03	Kapolei Irr C	1991	--	77	52
2003-04	Kapolei Irr D	1991	59	73	53
2003-05	Kapolei Irr E	1991	60	100	62
2003-07	Kapolei Irr C-1	1994	62	81	60
2003-08	East Kapolei	1999	51	70	51
2004-04	Makakilo	1981	141	268	188
2006-01	Ep 10 A	1908	41	--	--
2006-02	Ep 10 C	1908	41	282	62
2006-03	Ep 10 D	1908	41	--	--
2006-04	Ep 10 E	1908	41	155	--
2006-05	Ep 10 F	1908	41	165	--
2006-06	Ep 10 G	1908	41	165	--
2006-07	Ep 10 H	1908	41	--	--
2006-08	Ep 10 J	1913	41	--	--
2006-09	Ep 10 K	1913	41	--	--
2006-10	Ep 10 B	1923	41	160	60
2006-11	Ep 10 I	1923	41	160	57
2006-13	W Beach Estates	1986	58	120	58
2006-14	BP Non-Potable 1	1988	179	285	228
2052-08	Kalihi Shaft	1937	160	154	--
2053-02	Ft Shafter	1885	10	427	238
2053-03	Kalihi	1886	27	645	520
2053-05	Kalihi	1894	20	471	347
2053-06	Ft Shafter	1895	8	330	236
2053-08	Kalihi	1903	7	670	507
2053-09	Kalihi	1905	22	607	449
2053-10	Ft Shafter Mon.	1914	20	279	168
2053-11	Ft Shafter	1960	21	330	175
2053-12	Kalihi	1967	6	789	588
2054-01	Puuloa Rd	1898	19	824	692
2054-02	Puuloa Rd	1959	6	677	616
2054-03	Puuloa Rd.	1965	6	668	597
2055-01	Nimitz Hwy	--	20	795	517
2101-01	Honouliuli	--	20	325	208
2101-02	Honouliuli	--	25	--	--
2101-05	Honouliuli B	1890	30	456	320
2101-06	Honouliuli C	1890	30	451	310
2101-07	Honouliuli D	1890	30	468	302
2101-08	Honouliuli E	1890	30	462	310
2101-09	Honouliuli F	1890	31	448	432
2101-10	Honouliuli G	1899	30	462	304
2101-11	Honouliuli	1899	30	450	316
2101-12	Honouliuli A	1901	30	452	298
2101-14	Honouliuli	1978	6	12	4

Table B1. Properties of pumped wells in the Pearl Harbor area, Oahu, Hawaii (modified from unpub. digital database, 2002, Hawaii Commission on Water Resource Management)—Continued.

[--, data not available]

Well no.	Well name	Year drilled	Ground altitude, in feet	Well depth, in feet	Depth of solid casing, in feet
2102-02	Ep 18 Battery	1890	44	332	--
2102-04	Ep 18 Battery	1891	44	326	--
2102-05	Ep 18 Battery	1891	44	369	--
2102-06	Ep 18 Battery	1891	44	405	208
2102-07	Ep 18 Battery	1891	44	410	214
2102-08	Ep 18 Battery	1891	44	410	--
2102-09	Ep 18 Battery	1891	44	410	--
2102-10	Ep 18 Battery	1891	44	413	--
2102-11	Ep 18 Battery	1891	44	433	--
2102-12	Ep 18 Battery	1891	44	432	--
2102-13	Ep 18 Battery	1891	44	436	--
2102-14	Ep 18 Battery	1891	44	430	--
2102-15	Ep 18 Battery	1899	44	441	218
2102-16	Ep 18 Battery	1899	44	435	223
2102-17	Ep 18 Battery	1899	44	442	212
2102-18	Ep 18 Battery	1899	44	444	223
2102-19	Ep 18 Battery	1921	44	416	212
2102-20	Ep 18 Battery	1921	44	419	222
2102-21	Ep 18 Battery	1921	44	425	217
2102-22	Ep 18 Battery	1921	44	420	240
2103-03	Barbers Pt Shaft	1943	200	204	--
2104-01	Makakilo Quarry	1976	125	176	140
2153-01	Moanalua	1888	25	492	447
2153-02	Moanalua	1889	20	289	79
2153-04	Moanalua	1909	24	280	48
2153-05	Moanalua Deep	1980	35	--	65
2153-06	Moanalua	1929	18	282	143
2153-07	Moanalua	1945	30	302	52
2153-08	Moanalua	1945	29	306	57
2153-10	Moanalua 1	1973	36	300	150
2153-11	Moanalua 2	1973	35	300	150
2153-12	Moanalua 3	1974	35	335	185
2154-01	HICC	1909	14	294	103
2155-04	Makalapa	1941	91	288	148
2201-02	Honouliuli	--	17	356	77
2201-03	Ep 2	1891	40	230	50
2201-04	Ep 2	1891	40	226	50
2201-05	Pearl Harbor	1892	11	170	98
2201-07	Ep 2	1921	40	282	62
2201-14	Pearl Harbor	1969	18	185	114
2202-01	Honouliuli	--	23	500	--
2202-02	Honouliuli	--	16	395	96
2202-03	Ep 18 Battery	1896	50	304	70
2202-04	Ep 18 Battery	1896	50	305	70
2202-05	Ep 18 Battery	1896	50	310	70
2202-06	Ep 18 Battery	1896	50	304	70
2202-07	Ep 18 Battery	1896	50	306	70
2202-08	Ep 18 Battery	1896	50	303	70
2202-09	Ep 18 Battery	1896	50	312	70
2202-10	Ep 18 Battery	1897	50	307	70
2202-11	Ep 18 Battery	1897	50	306	70
2202-12	Ep 18 Battery	1897	50	308	70
2202-13	Ep 18 Battery	1897	50	308	70
2202-14	Ep 18 Battery	1897	50	308	70
2202-15	Ep 18 Battery	1899	46	468	107
2202-16	Ep 18 Battery	1900	46	476	116
2202-17	Ep 18 Battery	1900	46	475	116
2202-18	Ep 18 Battery	1900	46	475	116

Table B1. Properties of pumped wells in the Pearl Harbor area, Oahu, Hawaii (modified from unpub. digital database, 2002, Hawaii Commission on Water Resource Management)—Continued.

[--, data not available]

Well no.	Well name	Year drilled	Ground altitude, in feet	Well depth, in feet	Depth of solid casing, in feet
2202-19	Ep 18 Battery	1900	46	481	107
2202-20	Ep 18 Battery	1900	46	475	108
2202-21	Ep 15,16	1939	150	156	--
2203-01	Waipahu Wp5	1900	19	213	88
2203-02	Waipahu Wp5	1900	19	158	88
2203-03	Waipahu Wp5	1900	19	263	88
2203-04	Waipahu Wp5	1900	19	233	88
2203-05	Waipahu Wp5	1900	19	246	88
2203-06	Waipahu Wp5	1900	19	197	88
2254-01	Halawa Red Hill	1943	200	210	--
2255-07	Halawa	1900	21	391	150
2255-08	Halawa	1900	19	173	127
2255-09	Halawa	1900	23	399	160
2255-10	Halawa	1900	25	500	--
2255-11	Halawa	1900	25	500	--
2255-12	Halawa	1900	19	205	155
2255-13	Halawa	1900	22	288	150
2255-14	Halawa	1900	20	236	134
2255-15	Halawa	1900	23	431	135
2255-16	Halawa	1900	22	422	132
2255-17	Halawa	1900	25	450	152
2255-18	Halawa	1900	26	457	157
2255-19	Halawa	1900	22	426	130
2255-20	Halawa	1900	21	421	120
2255-21	Halawa	1900	31	394	225
2255-22	Halawa	1900	32	403	400
2255-23	Halawa	1900	23	404	118
2255-24	Halawa	1900	26	220	150
2255-25	Halawa	1900	23	388	96
2255-26	Halawa	1900	33	365	350
2255-27	Halawa	1900	20	303	300
2255-28	Halawa	1900	22	128	103
2255-29	Halawa	1930	26	440	149
2255-30	Halawa	1930	20	427	195
2255-31	Halawa	1930	20	423	190
2255-32	Aiea Halawa Shft	1937	95	99	--
2255-35	Aiea Refinery 1	1956	119	196	151
2255-36	Aiea Refinery 2	1956	119	240	151
2255-37	Halawa 2	1961	256	345	285
2255-38	Halawa 3	1961	270	359	314
2255-39	Halawa 1	1961	258	399	276
2256-05	Aiea	1908	38	344	87
2256-06	Aiea	1908	38	338	93
2256-07	Aiea	1908	38	345	71
2256-08	Aiea	1908	38	359	98
2256-09	Aiea	1908	45	--	80
2256-10	Aiea	1922	11	173	143
2300-07	Waipahu P7A	1900	60	--	--
2300-08	Waipahu P7B	1900	60	--	--
2300-09	Waipahu P7C	1900	60	--	--
2300-11	Waipahu	1913	18	202	56
2300-12	Waipahu P7D	1917	60	400	92
2300-13	Waipahu P7E	1917	60	400	102
2300-14	Waipahu P7F	1917	60	402	128
2300-16	Waipahu P7G	1924	60	412	98
2300-17	Waipahu P7H	1924	60	430	92
2300-18	Waipahu Deep	1980	26	--	38
2300-20	Waipahu	1959	13	204	56

Table B1. Properties of pumped wells in the Pearl Harbor area, Oahu, Hawaii (modified from unpub. digital database, 2002, Hawaii Commission on Water Resource Management)—Continued.

[--, data not available]

Well no.	Well name	Year drilled	Ground altitude, in feet	Well depth, in feet	Depth of solid casing, in feet
2300-21	Waipahu P7A	1962	64	320	101
2300-22	Waipahu P7B	1962	64	364	101
2300-23	Waipahu P7C	1962	64	378	102
2301-01	Waipahu WP1	--	21	425	--
2301-02	Waipahu WP1	--	30	--	--
2301-03	Waipahu WP1	--	30	400	--
2301-04	Waipahu WP1	--	30	400	--
2301-05	Waipahu WP1	--	43	410	--
2301-06	Waipahu WP1	--	30	400	--
2301-07	Waipahu WP1	--	29	400	--
2301-08	Waipahu WP1	--	30	412	--
2301-09	Waipahu WP1	--	31	490	--
2301-10	Waipahu WP1	--	31	498	--
2301-11	Waipahu WP4B	1898	19	500	--
2301-12	Waipahu WP4B	1898	19	500	--
2301-13	Waipahu WP4B	1898	19	500	--
2301-14	Waipahu WP4B	1898	19	500	--
2301-15	Waipahu WP4B	1898	19	500	--
2301-16	Waipahu WP4B	1898	19	500	--
2301-17	Waipahu WP4B	1898	19	500	--
2301-18	Waipahu WP4A	1898	19	500	--
2301-19	Waipahu WP4A	1898	19	500	--
2301-20	Waipahu WP4A	1898	19	500	--
2301-21	Waipahu WP2A2B	1898	20	425	--
2301-22	Waipahu WP2A2B	1898	20	425	--
2301-23	Waipahu WP2A2B	1898	20	400	--
2301-24	Waipahu WP2A2B	1898	20	410	--
2301-25	Waipahu WP2A2B	1898	20	414	--
2301-26	Waipahu WP2A2B	1898	20	410	--
2301-27	Waipahu WP2C2D	1898	20	400	--
2301-28	Waipahu WP2C2D	1898	20	400	--
2301-29	Waipahu WP2C2D	1898	20	410	--
2301-30	Waipahu WP2C2D	1898	20	420	--
2301-31	Waipahu WP2C2D	1898	20	429	--
2301-32	Waipahu WP2C2D	1898	20	439	--
2301-34	Hoaeae P1	1959	131	194	107
2301-35	Hoaeae P2	1959	133	197	113
2301-36	Hoaeae P3	1959	131	198	107
2301-37	Hoaeae P4	1959	130	195	108
2301-38	Hoaeae P5	1974	126	276	176
2301-39	Hoaeae P6	1974	123	273	173
2301-44	Waipahu IV-2	1998	133	273	173
2301-45	Waipahu IV-3	1998	136	276	176
2301-46	Waipahu IV-1	1998	131	271	171
2301-47	Waipahu IV-4	1999	134	273	173
2302-01	Kunia I P1	1957	201	350	221
2302-02	Kunia I P2	1957	201	338	221
2302-03	Kunia I P3	1972	206	427	246
2302-04	Kunia I P4	1972	201	420	241
2303-01	Honouliuli I-1	1987	412	625	550
2303-02	Honouliuli I-2	1987	411	563	550
2303-03	Honouliuli II-3	1987	419	534	450
2303-04	Honouliuli II-4	1988	421	555	455
2303-05	Honouliuli II-5	1989	432	545	465
2303-06	Honouliuli II-6	1989	432	535	455
2354-01	Halawa Shaft	1944	165	183	--
2355-02	Aiea	1945	195	200	--
2355-03	Aiea Gulch 1	1947	304	342	288

Table B1. Properties of pumped wells in the Pearl Harbor area, Oahu, Hawaii (modified from unpub. digital database, 2002, Hawaii Commission on Water Resource Management)—Continued.

[--, data not available]

Well no.	Well name	Year drilled	Ground altitude, in feet	Well depth, in feet	Depth of solid casing, in feet
2355-04	Aiea Gulch B	1947	304	289	--
2355-05	Aiea Gulch 2	1947	304	344	286
2355-06	Aiea 1	1955	258	360	290
2355-07	Aiea 2	1955	258	358	288
2355-09	Kalauao 1	1965	159	413	221
2355-10	Kalauao 2	1965	159	413	222
2355-11	Kalauao 3	1965	159	413	219
2355-12	Kalauao 4	1965	159	413	221
2355-13	Kalauao 5	1969	159	413	227
2355-14	Kalauao 6	1969	159	413	230
2356-14	Aiea	1899	46	550	--
2356-15	Aiea	1899	46	550	--
2356-16	Aiea	1899	46	550	--
2356-17	Aiea	1899	46	550	--
2356-18	Aiea	1899	46	550	--
2356-19	Aiea	1899	46	550	--
2356-20	Aiea	1899	46	985	--
2356-21	Aiea	1899	46	464	--
2356-22	Aiea	1899	46	470	--
2356-23	Aiea	1899	46	550	--
2356-24	Aiea	1899	46	550	--
2356-25	Aiea	1899	46	550	--
2356-26	Aiea	1899	46	550	--
2356-27	Aiea	1899	46	620	--
2356-28	Aiea	1899	46	550	--
2356-29	Aiea	1899	46	550	--
2356-30	Aiea	1899	46	550	--
2356-31	Aiea	1899	46	550	--
2356-32	Aiea	1899	46	550	--
2356-33	Aiea	1899	46	550	--
2356-34	Aiea	1904	56	955	200
2356-35	Aiea	1904	56	--	--
2356-36	Aiea	1904	56	--	--
2356-37	Aiea	1904	56	707	206
2356-38	Aiea	1904	56	405	58
2356-39	Aiea	1904	56	503	88
2356-40	Aiea	1904	56	510	130
2356-41	Aiea	1904	56	504	76
2356-42	Aiea	1904	56	484	40
2356-44	Aiea	1941	81	100	34
2356-49	Waimalu I-1	1954	102	327	129
2356-50	Waimalu I-2	1955	102	327	127
2356-54	Pearl C C Golf	1966	374	552	395
2356-55	Kaonohi I-1	1966	252	542	289
2356-56	Kaonohi I-2	1966	252	549	296
2356-58	Kaamilo 1	1973	147	340	190
2356-59	Kaamilo 2	1973	148	340	190
2356-60	Waimalu II-1	1975	23	240	100
2356-61	Kaonohi II-1	1975	112	330	190
2356-62	Kaonohi II-2	1975	117	340	200
2356-63	Waimalu II-2	1975	26	240	100
2356-64	Waimalu II-3	1975	20	240	163
2356-65	Kaonohi II-3	1975	112	335	195
2356-70	Kalauao	1987	--	261	170
2357-21	Waiau	1963	11	167	67
2357-22	Kalauao	1965	7	200	137
2357-23	Kaahumanu I-1	1975	49	230	90
2357-24	Kaahumanu I-2	1975	45	265	125

Table B1. Properties of pumped wells in the Pearl Harbor area, Oahu, Hawaii (modified from unpub. digital database, 2002, Hawaii Commission on Water Resource Management)—Continued.

[--, data not available]

Well no.	Well name	Year drilled	Ground altitude, in feet	Well depth, in feet	Depth of solid casing, in feet
2358-03	Pearl City	--	28	165	--
2358-07	Pearl City Pen	1905	28	197	--
2358-13	Pearl City	1926	30	140	54
2358-14	Pearl City	1926	15	175	--
2358-15	Pearl City	1926	15	180	100
2358-16	Pearl City	1926	15	176	53
2358-17	Pearl City	1926	15	176	63
2358-24	Pearl City	1949	23	120	67
2358-28	Pearl City	1953	15	118	37
2358-36	Pearl City	1954	13	102	52
2358-42	Pearl City	1958	10	110	62
2358-44	Pearl City	1962	14	165	37
2358-48	Pearl City	1969	5	195	123
2358-49	Pearl City	1976	21	125	76
2359-03	Waipahu	1943	97	177	100
2359-05	Waipahu	1953	9	150	57
2359-10	Waipahu	1954	23	100	43
2359-15	Waipahu	1958	9	191	38
2359-17	Waipahu	1958	11	175	60
2359-19	PHNWR NO. 1	--	--	--	--
2400-01	Waipahu I P2	1954	200	355	231
2400-02	Waipahu I P1	1954	200	355	231
2400-03	Waipahu I P3	1969	203	386	254
2400-04	Waipahu I P4	1969	203	386	254
2400-05	Waipahu II-2	1983	207	342	239
2400-06	Waipahu II-1	1983	211	344	241
2400-08	Waipahu II-3	1993	206	340	240
2400-09	Waipahu III-1	1994	318	458	358
2400-10	Waipahu III-2	1994	317	457	357
2400-11	Waipahu III-3	1994	312	455	355
2400-12	Waipahu III-5	1994	314	456	356
2400-13	Waipahu III-4	1995	314	453	353
2400-14	Waipahu II-4	1999	208	360	240
2401-04	Kunia III-1	1995	317	452	352
2401-05	Kunia III-2	1995	316	454	357
2401-06	Kunia III-3	1995	315	460	356
2401-07	Royal Kunia C C	1996	463	570	483
2402-01	Kunia II P1	1969	430	575	460
2402-02	Kunia II P2	1969	430	575	465
2402-03	Kunia II P3	1990	417	610	460
2402-05	Kunia II P4	1996	420	559	459
2451-01	N. Halawa-DOT	1991	1,036	918	835
2455-02	Waimalu	1958	128	206	140
2456-01	Newtown 1	1972	263	500	300
2456-02	Newtown 2	1972	263	500	300
2456-03	Newtown 3	1972	263	500	300
2457-01	Pearl City II-1	1957	267	398	281
2457-02	Pearl City II-2	1957	267	415	281
2457-03	Pearl City II-3	1968	272	423	283
2457-05	Punanani 6	1970	145	444	289
2457-06	Punanani 1	1970	151	458	312
2457-07	Punanani	1970	--	455	--
2457-08	Punanani	1970	--	338	--
2457-09	Punanani 2	1970	153	461	312
2457-10	Punanani 4	1970	146	368	217
2457-11	Punanani 3B	1970	141	363	211
2457-12	Punanani 5B	1970	140	367	210
2457-13	Waiau 2	1971	263	504	300

Table B1. Properties of pumped wells in the Pearl Harbor area, Oahu, Hawaii (modified from unpub. digital database, 2002, Hawaii Commission on Water Resource Management)—Continued.

[--, data not available]

Well no.	Well name	Year drilled	Ground altitude, in feet	Well depth, in feet	Depth of solid casing, in feet
2457-14	Waiau 1	1971	263	503	300
2457-15	Waiau 3	1971	263	503	300
2458-01	Pearl City Shaft	1940	111	151	27
2458-03	Pearl City I-1	1953	120	150	56
2458-04	Pearl City I-2	1953	120	140	58
2458-05	Manana 1	1998	137	277	177
2459-01	Waipahu WP6A,6B	--	40	704	--
2459-02	Waipahu WP6A,6B	--	40	582	--
2459-03	Waipahu WP6A,6B	--	40	739	--
2459-04	Waipahu WP6A,6B	--	40	706	--
2459-05	Waipahu WP6A,6B	--	40	600	--
2459-06	Waipahu WP6A,6B	--	40	700	--
2459-07	Waipahu WP6A,6B	--	40	590	--
2459-08	Waipahu WP6A,6B	--	40	577	--
2459-09	Waipahu WP6A,6B	--	40	707	--
2459-10	Waipahu WP6A,6B	--	40	700	--
2459-11	Waipahu WP6A,6B	--	40	--	--
2459-12	Waipahu WP6A,6B	--	40	--	--
2459-13	Waipahu WP6A,6B	--	40	700	--
2459-14	Waipahu WP6A,6B	--	40	700	--
2459-19	Waipio Hts 2	1964	202	337	234
2459-20	Waipio Hts 1	1964	202	337	234
2459-21	Waipahu	1965	32	456	260
2459-23	Waipio Hts. I-3	1977	200	325	235
2459-24	Waipio Hts. I-4	1977	200	315	235
2500-01	Waipio Hts II-1	1978	416	546	446
2500-02	Waipio Hts II-2	1978	419	560	450
2557-01	Waimano Trng Sch	1941	495	512	472
2557-02	Waimano Trng Sch	1950	495	592	479
2557-03	Pearl City III	1977	620	750	650
2558-10	Waiawa Shaft	1951	150	170	--
2600-02	Kipapa Gulch	1957	297	401	299
2600-03	Mililani III-1	1980	664	814	704
2600-04	Mililani III-2	1979	665	815	705
2603-01	Waikele	1961	745	991	726
2658-01	Waipahu Wp17A	1961	703	805	693
2658-02	Waipahu Wp17B	1961	702	835	716
2659-02	Waipio Hts III-1	1987	571	710	604
2659-03	Waipio Hts III-2	1988	572	700	601
2703-01	Kunia Camp 1	1946	847	976	626
2800-01	Mililani I P1	1968	762	1,012	802
2800-02	Mililani I P2	1968	758	1,008	798
2800-03	Mililani I P3	1972	760	1,022	802
2800-04	Mililani I P4	1975	757	1,008	797
2858-01	Mililani IV	1984	960	1,160	1,030
2858-02	Mililani IV	1985	960	1,160	1,000
2858-03	Mililani IV	1985	960	1,160	1,000
2859-01	Mililani II P1	1978	835	995	875
2859-02	Mililani II P2	1979	835	985	875

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