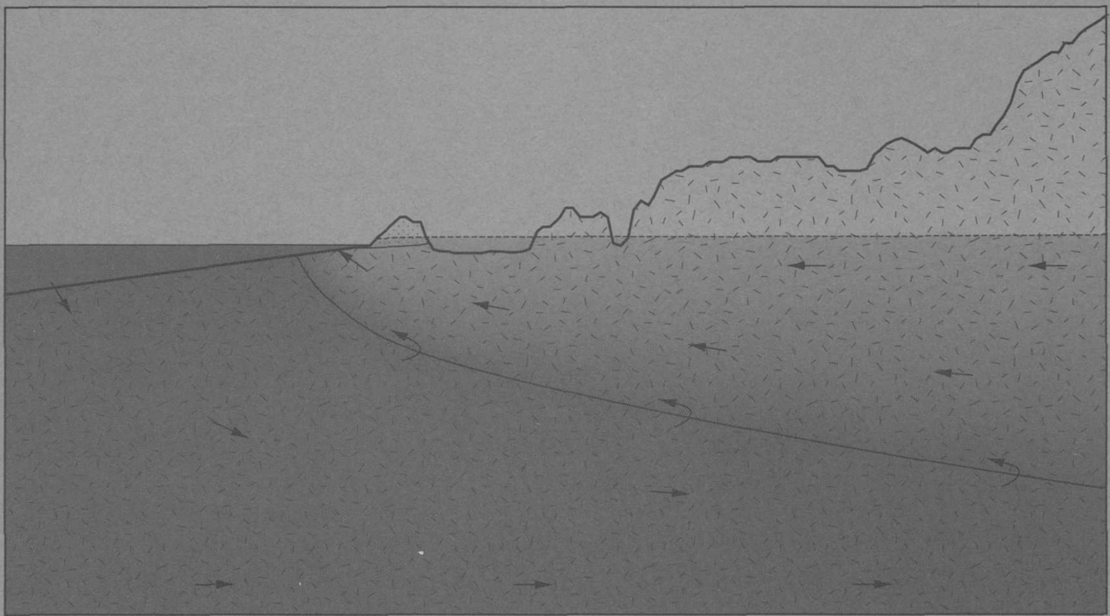
U.S. Department of the Interior

Ground-Water Resources in Kaloko-Honokohau National Historical Park, Island of Hawaii, and Numerical Simulation of the Effects of Ground-Water Withdrawals

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 99-4070



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By Delwyn S. Oki, Gordon W. Tribble, William R. Souza, and Edward L. Bolke

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Honolulu, Hawaii

1999

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
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Conversion Factors

Multiply	By	To obtain
acre	4,047	square meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
inch (in.)	25.4	millimeter
inch per year (in/yr)	2.54	centimeter per year
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per day per foot [(ft/d)/ft]	1	meter per day per meter
foot per mile (ft/mi)	0.1894	meter per kilometer
gallon per minute (gal/min)	0.003785	cubic meter per minute
million gallons per day (Mgal/d)	0.04381	cubic meter per second

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

$$°F = 1.8 \times °C + 32.$$

Abbreviations used in water-quality descriptions: mg/L, milligrams per liter
µg/L, micrograms per liter
µg/kg, micrograms per kilogram

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Abstract

Within the Kaloko-Honokohau National Historical Park, which was established in 1978, the ground-water flow system is composed of brackish water overlying saltwater. Ground-water levels measured in the Park range from about 1 to 2 feet above mean sea level, and fluctuate daily by about 0.5 to 1.5 feet in response to ocean tides. The brackish water is formed by mixing of seaward flowing fresh ground water with underlying saltwater from the ocean. The major source of fresh ground water is from subsurface flow originating from inland areas to the east of the Park. Ground-water recharge from the direct infiltration of precipitation within the Park area, which has land-surface altitudes less than 100 feet, is small because of low rainfall and high rates of evaporation. Brackish water flowing through the Park ultimately discharges to the fishponds in the Park or to the ocean. The ground water, fishponds, and anchialine ponds in the Park are hydrologically connected; thus, the water levels in the ponds mark the local position of the water table.

Within the Park, ground water near the water table is brackish; measured chloride concentrations of water samples from three exploratory wells in the Park range from 2,610 to 5,910 milligrams per liter. Chromium and copper were detected in water samples from the three wells in the Park and one well upgradient of the Park at concentrations of 1 to 5 micrograms per liter. One semi-volatile organic compound, phenol, was detected in water samples from the three wells in the Park at concentrations between 4 and 10 micrograms per liter.

A regional, two-dimensional (areal), freshwater-saltwater, sharp-interface ground-water flow model was used to simulate the effects of regional withdrawals on ground-water flow within the Park. For average 1978 withdrawal rates, the estimated rate of fresh ground-water discharge to the ocean within the Park is about 6.48 million gallons per day, or about 3 million gallons per day per mile of coastline. Although the coastal discharge within the Park is actually brackish water, the model assumes that freshwater and saltwater do not mix and therefore the model-calculated coastal discharge within the Park is in the form of freshwater discharge.

Model results indicate that ground-water withdrawals in excess of average 1978 withdrawal rates will reduce the rate of freshwater coastal discharge within the Park. Withdrawals from wells directly upgradient of the Park had the greatest effect on the model-calculated freshwater coastal discharge within the Park, whereas withdrawals from wells south of Papa Bay had little effect on the freshwater discharge within the Park. For an increased ground-water withdrawal rate of 56.8 million gallons per day, relative to average 1978 withdrawal rates in the Kona area, model-calculated freshwater coastal discharge within the Park was reduced by about 47 percent.

INTRODUCTION

The Kaloko-Honokohau National Historical Park (referred to as the Park in this report) is located on the western flank of Hualalai Volcano along the coast about 3 mi north of the town of Kailua on the island of Hawaii (fig. 1). The Park was established in 1978 by Public Law 95-625 "to provide a center for the preservation, interpretation, and perpetuation of traditional native Hawaiian activities and culture, and to demonstrate historic land-use patterns as well as to provide a needed resource for the education, enjoyment, and appreciation of such traditional native Hawaiian activities and culture by local residents and visitors..." The Park has extensive natural and cultural resources and nearly all of the land has been designated a national historical landmark. Along with archeological sites, the Park contains wetlands and fishponds (fig. 2) that are nesting and feeding habitat for two species of waterbirds, the Hawaiian coot (*Fulica americana alai*) and the Hawaiian stilt (*Himantopus mexicanus knedseni*), which are on the federal list of endangered species. Anchialine ponds in the Park provide a habitat for native species. An anchialine pond is a saltwater or brackish-water pond that lacks a surface connection to the ocean, but which is hydrologically connected to the ground water and the ocean through a permeable aquifer (Holthuis, 1973; Brock and Kam, 1997). The freshwater component of ground-water flow in the Park may be important to sustain wetland and pond ecosystems.

Before 1994, ground-water withdrawals for domestic use in western Hawaii were limited to wells within about 3 mi of the coast. These wells tapped a coastal freshwater/brackish-water body with water levels generally less than 5 ft above sea level. In 1991–93, about 14.0 million gallons per day (Mgal/d) of ground water was withdrawn from wells in the Kona area of western Hawaii (fig. 1). (For the purposes of this report, the Kona area is considered as the area bounded on the north by the northwest rift zone of Hualalai Volcano, on the east by the south-southeast rift zone of Hualalai Volcano and the southwest rift zone of Mauna Loa Volcano, and on the west and south by the coast.) The high salinity of pumped water limited further development.

In 1990, exploratory drilling in the uplands east of the existing coastal wells revealed the presence of ground water with substantially higher water levels (greater than 40 ft above sea level) between Kalaoa and Honaunau. The discovery of high water levels indicated that a significant source of freshwater was available at land-surface altitudes greater than about 1,600 ft. It has been estimated that this source may have a sustainable yield of at least 47 Mgal/d (State of Hawaii, 1995). There is concern, however, that increased pumping may affect ground-water flow, water levels, and salinity of the ponds and wetlands in the Park and possibly adversely affect the Park's ecosystems.

The U.S. Geological Survey (USGS), in cooperation with the National Park Service, undertook an investigation of the ground-water flow system in the vicinity of Kaloko-Honokohau National Historical Park. An existing numerical ground-water flow model (Oki, 1999) was used to estimate potential changes in the quantity of ground-water flow through Kaloko-Honokohau National Historical Park caused by ground-water development.

Purpose and Scope

The purpose of this report is to describe (1) the occurrence of ground water in the Park, (2) a reconnaissance of salinity levels of water from three wells in the Park, and in the Park's fishponds, anchialine ponds, and the ocean, (3) concentrations of trace metals and organic contaminants from three wells in the Park and one well upgradient of the Park, and (4) estimates of changes in the amount of ground-water flow through the Park caused by withdrawing water at rates in excess of those that existed in 1978, when the Park was established.

Steady-state ground-water levels and discharge were simulated using average ground-water withdrawals for 1978. The model-calculated, steady-state coastal-discharge distribution was then used as the base to compute simulated change in freshwater coastal discharge for a series of ground-water withdrawal scenarios. The first withdrawal scenario involved simulating withdrawals at full-capacity pumping rates from wells used during 1978, and this was followed by 38 additional scenarios in which withdrawals from wells were added to the system according to (1) dates that water-use declarations were made to the Hawaii State Commission on Water Resource Management (CWRM), (2) dates when pump-installation permits were issued by CWRM, and (3) dates when well-construction permits were issued by CWRM. Existing wells associated with water-use declarations made during 1989–90 were

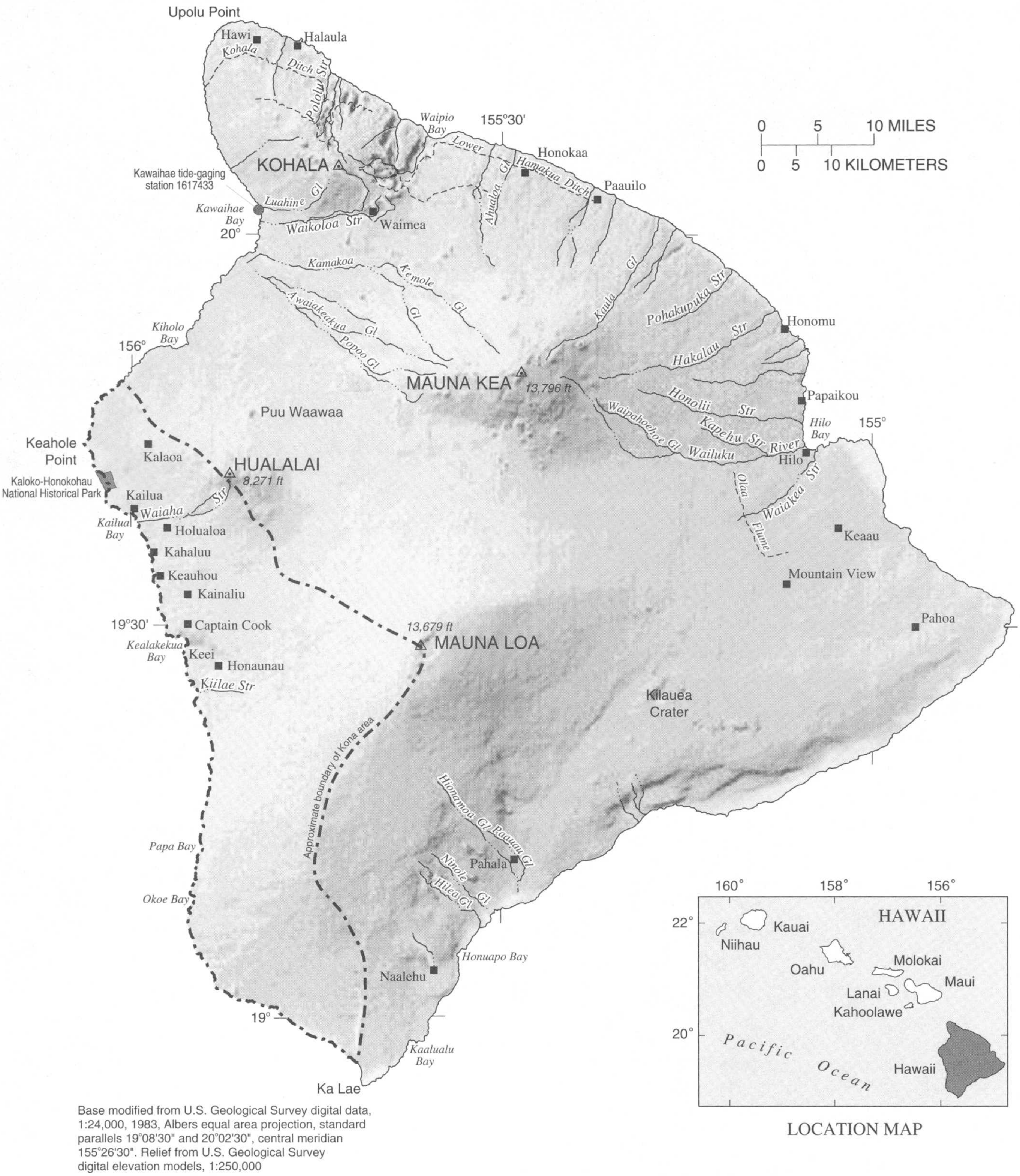


Figure 1. Geographic features, island of Hawaii, and location of Kaloko-Honokohau National Historical Park.

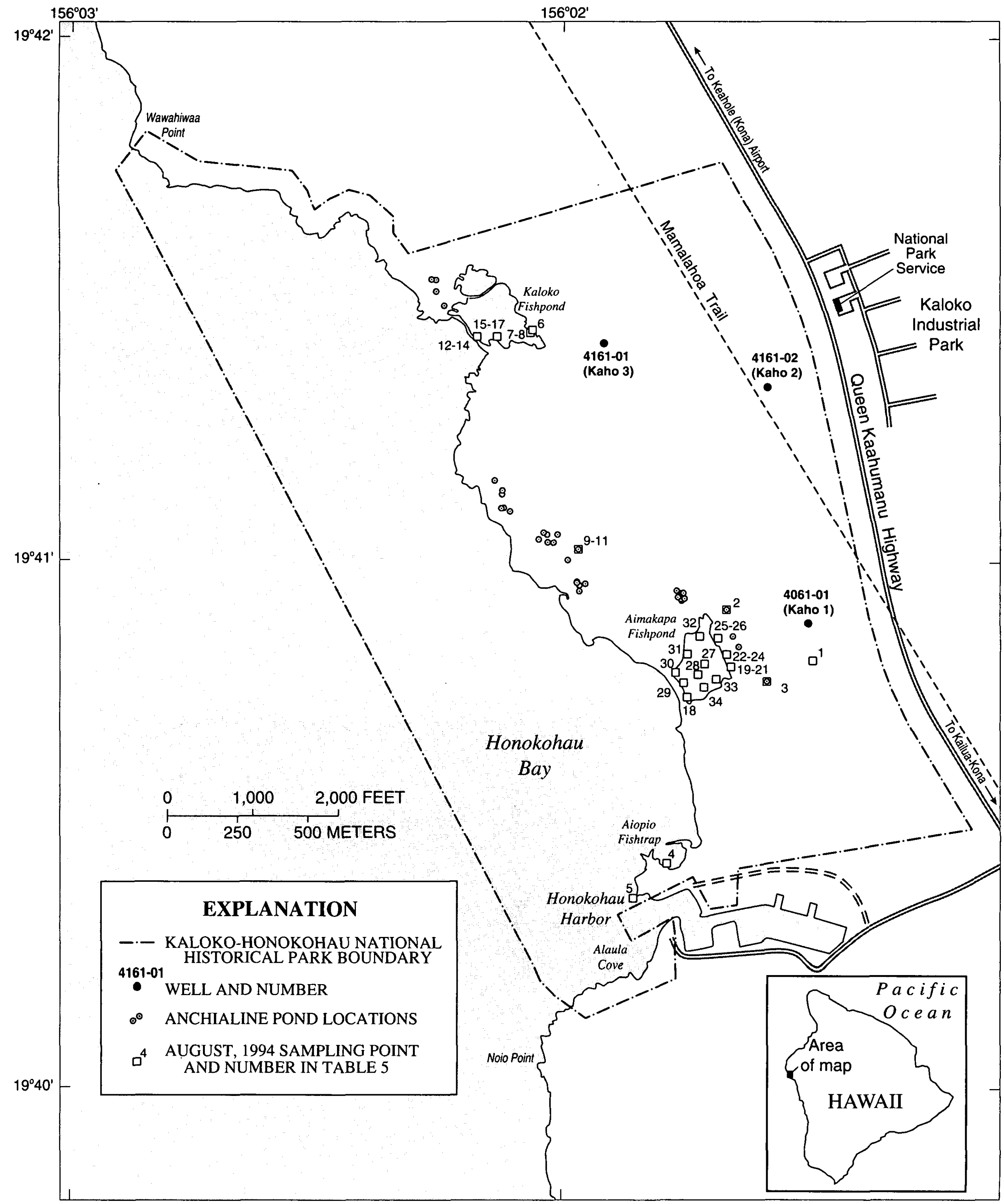


Figure 2. Koloko-Honokahau National Historical Park, island of Hawaii (modified from National Park Service, 1994). Anchialine pond locations from National Park Service.

added to the system first, followed by existing wells with pump-installation permits issued during 1990–97. Other existing and proposed wells were added to the system last, according to the issue date of the well-construction permit. All withdrawals from wells, with the exception of the 1978 average withdrawals simulated in the base case, were assumed to be pumping at full capacity, unless these rates caused the model-calculated water table to be lowered below the bottom of any well. In these cases, the simulated pumping rate at the most recently added well was reduced, to either 50, 25, or 0 percent of the full-capacity pumping rate, until the model-calculated water table remained above the bottoms of all wells.

Description of Study Site

Physical Setting

The island of Hawaii, which has an area of about 4,030 mi^2, is the largest of the Hawaiian islands and lies between longitude 154°48′W and 156°04′W and between latitude 18°54′N and 20°17′N (fig. 1). The island is composed of five shield volcanoes: Kohala, Mauna Kea, Hualalai, Mauna Loa, and Kilauea (Langenheim and Clague, 1987).

Climate

Using the Koeppen classification, which is based primarily on temperature, climate at Kaloko-Honokohau National Historical Park was classified as hot semidesert (Juvik and others, 1978). Mean annual rainfall at the Park is between 20 and 30 in. (Giambelluca and others, 1986). Upslope of the Park, rainfall increases to a maximum of about 60 in/yr between altitudes of 1,000 and 2,000 ft on Hualalai. Above 2,000 ft rainfall decreases to less than 20 in/yr near the summit of Hualalai (fig. 3). Mean annual pan evaporation at the Park is about 70 in. (Ekern and Chang, 1985). Using the Thornthwaite climatic classification, which considers the relationship between precipitation and potential evapotranspiration, climate near the Park was classified as subhumid to semiarid (Giambelluca and Sanderson, 1993).

Land Use and Potential Sources of Ground-Water Contamination

Activities and types of land use inland of the Park were visually surveyed in January 1996 to identify potential sources of contaminants to ground water near the Park. Most of the area near the Park was undeveloped, and covered by sparse vegetation. In some areas, volcanic rocks with no soil cover were exposed at the land surface. Where soil does exist in the vicinity of the Park, it is generally only a few feet deep, and more commonly less than a foot deep (Sato and others, 1973).

Low- to medium-density residential areas at altitudes above 600 ft, mostly in a band adjacent to Palani Road (fig. 4), were surveyed. Flowers and vegetables were grown at many of the small farms and rural houses in the area. Horses and other outdoor domestic animals were also common. Wastewater flowed to cesspools and septic tanks, although developments built after 1996 will be connected to a municipal sanitary-sewer system.

Three industrial areas directly inland of the Park were surveyed (fig. 4). The northernmost industrial area was the Kaloko Industrial Park. The industrial park contained about 50 lots, many of which had several businesses in warehouses and variously configured service buildings. Businesses in the industrial park included metal fabrication shops, automobile repair, and pest-control operations (table 1). South of the industrial park was a quarry and baseyard for heavy equipment. Inland of the southeastern border of the Park was a third industrial area that included an automobile service station, heavy equipment sales and repair facilities, baseyards for shipping and construction contractors, parking areas for boats and trucks, and offices. Wastewater flowed to cesspools in volcanic rocks. Stormwater runoff from these industrial areas inland of the Park flows either to adjacent undeveloped areas or is channeled to dry wells.

The Kealakehe Landfill (fig. 4), closed in 1989, was about 1 mi southeast of the southeast corner of the Park. The landfill was unlined and covered about 50 acres. During the 1996 survey, a cap was in place over the landfill, and the adjacent area included a refuse-transfer station, with metal recycling as well as scrap-metal and yard-waste collection. Nearby were buildings for heavy-equipment repair and sale of industrial supplies, plus a police station and animal shelter.

The Kealakehe Wastewater Treatment Plant (WWTP) was located on 50 acres of land about 4,000 ft south of the southern Park boundary. The plant was designed to treat as much as 5.3 Mgal/d of raw sewage to a standard acceptable for golf-course irrigation. As of mid-1998, the plant treated about 1.5 Mgal/d, and

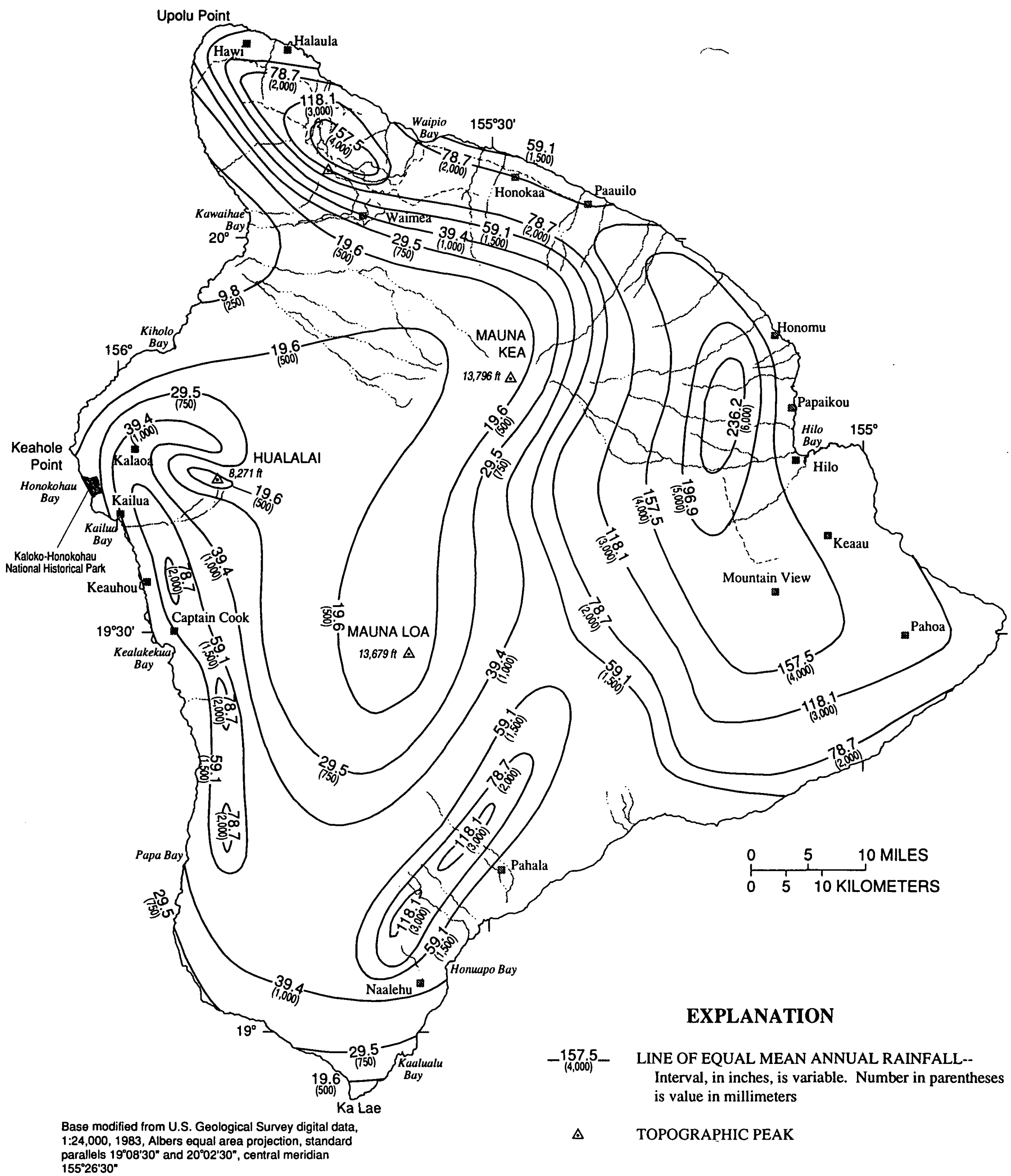


Figure 3. Mean annual rainfall, island of Hawaii (modified from Giambelluca and others, 1986).

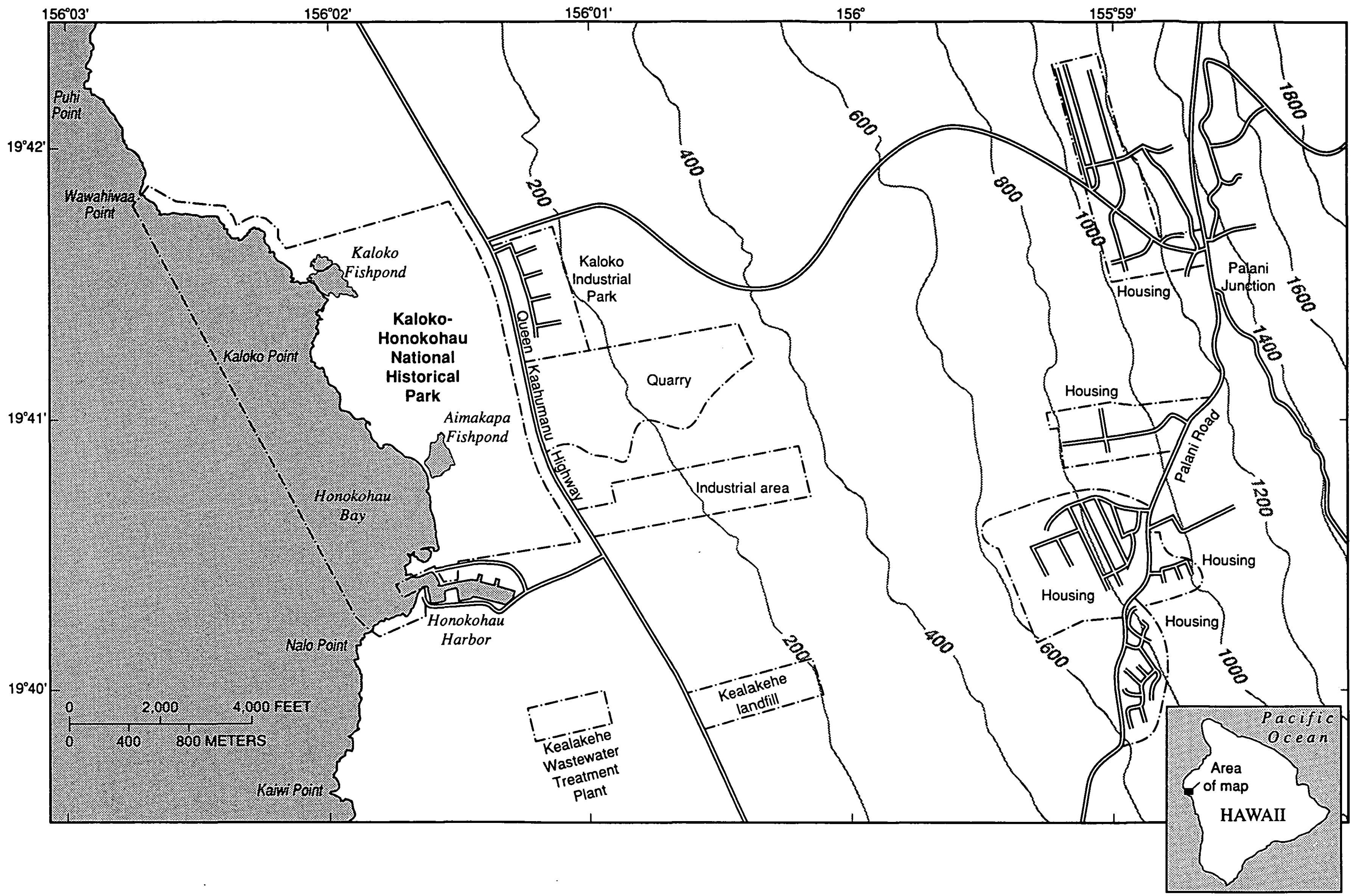


Figure 4. Land use near Kaloko-Honokohau National Historical Park, island of Hawaii, 1996. (Topographic contour interval is 200 feet.)

Table 1. Types of businesses found in 1996 in Kaloko Industrial Park, island of Hawaii

Sales	
	air conditioners and refrigerators
	construction materials
	foods and beverages
	furniture
	irrigation, landscape, fencing supplies
	marine supplies
	nursery plants
	office, kitchen, and interior supplies and equipment
	paints
	pipes
	solar heaters
Services	
	automobile repair
	building, electrical, plumbing, and metal contracting
	bus and van tours
	electrostatic coating and sandblasting
	metal working
	pest control
	printing
	dumpster-refuse collection and disposal
	service station
	shipping and packing
	trucking
	upholstering
	woodworking
Other	
	bar, dance club, gym, restaurant
	general offices
	general retailing (clothing, candles, frames, guitars, billiard supplies, coffee, tools, lamps)
	self-storage facilities
	shooting gallery

disposed of the effluent in a drainage pit inland of the plant near the Queen Kaahumanu Highway. A reuse plan is currently (1998) being developed that calls for injection wells to dispose of wastewater not used for irrigation.

Because wastewater and stormwater from homes and businesses near the Park are discharged to cesspools and dry wells, contaminants that may be dissolved in either stormwater runoff or wastewater have a higher potential to reach the water table than in areas with a municipal sewer and stormwater collection system. The specific types of contaminants were not determined, but because of the diverse types of industrial, agricultural, and domestic activities in the vicinity of the Park, a wide range of contaminants is possible. Of greatest concern are contaminants from areas inland of the Park.

GEOLOGY

The evolution of Hawaiian volcanoes generally progresses through four stages--preshield, shield, postshield, and rejuvenated. However, not all Hawaiian volcanoes have a postshield stage or a rejuvenated stage. The preshield stage is the earliest, submarine phase of activity. Lava from the preshield stage consists predominantly of alkalic basalt (basalt that is low in silica and high in sodium and potassium). Lava from the principal stage of volcano building, called the shield stage, consists of fluid tholeiitic basalts (silica-saturated basalt) that characteristically form thin flows. This basalt forms during submarine, as well as subaerial, eruptions. A large central caldera can form during the preshield or shield stages and might later be partly or completely filled during subsequent eruptions. Thousands of lava flows erupt from the central caldera and from two or three rift zones that radiate out from the central part of the volcano. Intrusive dikes fed by rising magma extend down the rift zones and may erupt if they reach the surface. The shield stage is the most voluminous phase of eruptive activity during which more than 95 percent of the volcano is formed. The postshield stage is marked by a change in lava chemistry and character. Postshield-stage lava includes alkalic basalt, and more viscous hawaiite, ankaramite, mugearite, and trachyte. Lava from the postshield stage may erupt from locations outside of the rift zones formed during the shield stage and forms a veneer atop the shield-stage basalt. After a period of quiescence, lava might issue from isolated vents on the volcano during the rejuvenated stage.

Volcanic rocks in Hawaii can be divided into three main groups on the basis of modes of emplacement: lava flows, dikes, and pyroclastic deposits. In general, lava flows that erupt from rift zones are less than 10 ft thick and are either pahoehoe, which is characterized by smooth, ropy surfaces, or aa, which contains a massive central core typically sandwiched between rubbly clinker layers. Aa flows are typically more abundant at greater distances from eruptive sources (Lockwood and Lipman, 1987).

Dikes are thin, near-vertical sheets of massive rock that intrude existing rocks, commonly lava flows. Dikes are commonly exposed by erosion within the rift zones of older volcanoes (see for example Takasaki and Mink, 1985), including Kohala on the island of Hawaii. Because Hualalai has not been significantly dissected, dikes are not exposed on this volcano. Evidence from volcanoes on other Hawaiian islands suggests that dikes associated with the rift zones of Hualalai are probably most abundant within the central part of the rift zones.

The dikes and the rocks they intrude are collectively referred to as dike complexes. In the central part of a rift zone, the number of dikes can be as many as 1,000 per mile of horizontal distance across the zone (Takasaki and Mink, 1985). The number of dikes decreases toward the outer edges of a rift zone. Within the central part of a dike complex, the dike rocks typically compose 10 percent or more of the total rock volume. At the outer part of the dike complex, within the marginal dike zone, dikes usually constitute less than 5 percent of the total rock volume (Takasaki and Mink, 1985). Wentworth and Macdonald (1953) estimate that 200 dikes are needed to build 1,000 ft of a shield volcano.

Pyroclastic rocks are rocks that form by explosive volcanic activity and that 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 but probably form less than 1 percent of the mass of a Hawaiian volcano (Wentworth and Macdonald, 1953).

The general geology of the island of Hawaii has been described by numerous investigators (see for example Stearns and Macdonald, 1946; Macdonald and others, 1983, Stearns, 1985). Langenheim and Clague (1987) described the stratigraphic framework of volcanic rocks on the island of Hawaii. Wolfe and Morris (1996) compiled a geologic map of Hawaii. Moore and others (1987) summarized geologic, petrologic, and geophysical data related to Hualalai Volcano.

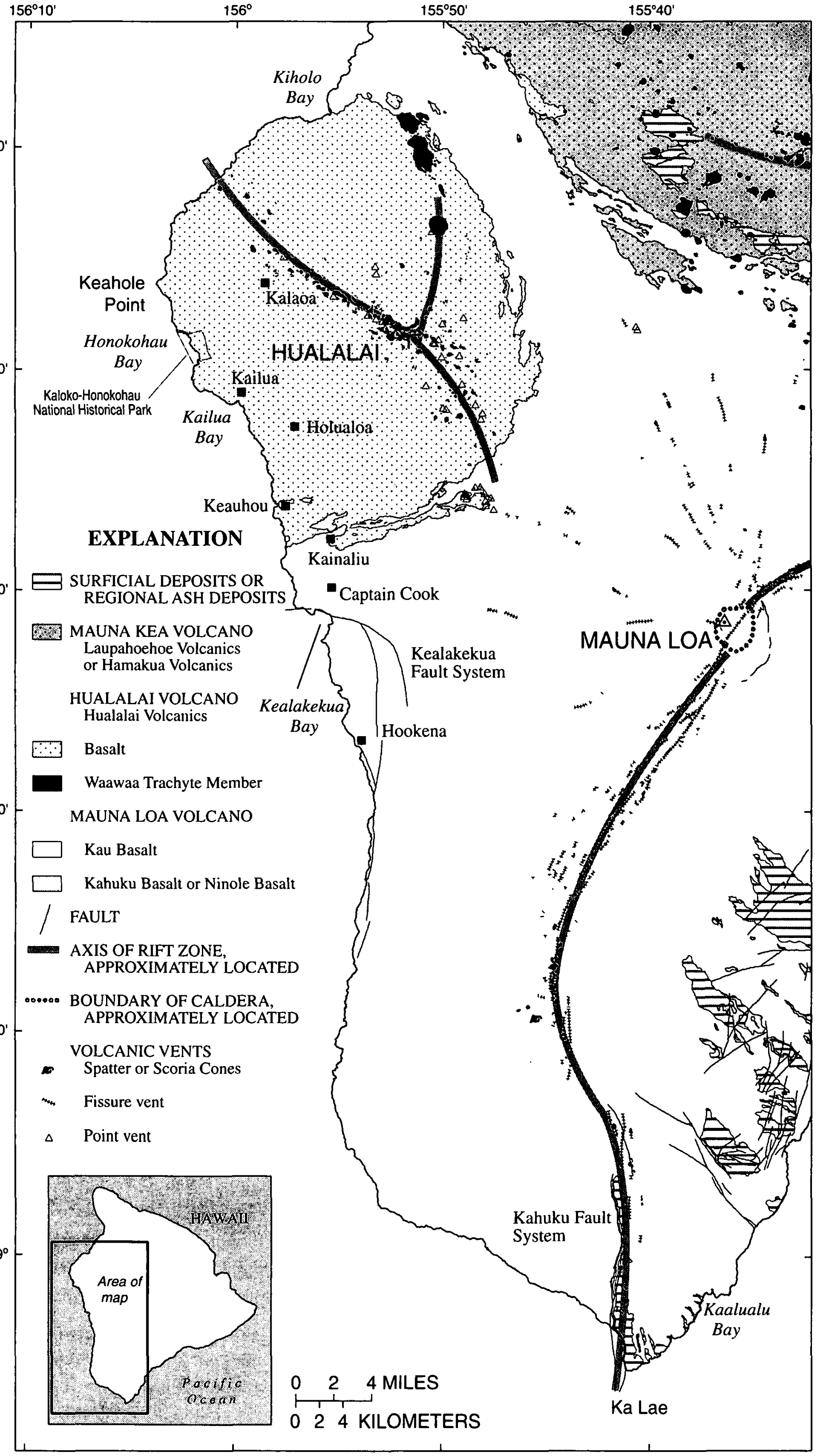
The island of Hawaii is formed primarily by the shield-stage volcanic rocks of Mauna Loa and Kilauea and the shield- and postshield-stage volcanic rocks of Kohala, Hualalai, and Mauna Kea (Langenheim and Clague, 1987). The surface and subsurface rocks in and near the Park consist of highly permeable rocks from Hualalai. Sedimentary deposits are of limited extent offshore.

Hualalai Volcano

Kaloko-Honokohau National Historical Park lies along the coastline on the western flank of Hualalai Volcano. Hualalai is the third youngest of the five volcanoes that form the island of Hawaii. The summit of Hualalai, at an altitude of 8,271 ft, lies 10 mi east of the Park.

The primary rift zones of Hualalai trend northwest and south-southeast, emanate from near the summit of the volcano, and are marked by numerous cinder and spatter cones (fig. 5). A third, less well-defined rift zone extends north from the summit of Hualalai (Macdonald and others, 1983; Moore and others, 1987). The subaerial part of the northwest rift zone is 1.2 to 2.5 mi wide and 15 mi long. The submarine part of the northwest rift zone may extend about 43 mi offshore. The south-southeast rift zone is 1.9 to 3.1 mi wide and about 8 mi long (Moore and others, 1987). There is no direct evidence that a caldera ever existed on Hualalai (Macdonald and others, 1983). Magnetic lows, which are probably related to rocks that have been chemically altered by hydrothermal fluids, exist near the three rift zones (Hildenbrand and others, 1993). A positive gravity anomaly exists near, but is somewhat west of, the south-southeast rift zone of the volcano (Kinoshita and others, 1963; Kinoshita, 1965). Zucca and others (1982) analyzed gravity and seismic refraction data, and indicated that a dense structure with high seismic velocity lies parallel to the Kona coast in the vicinity of the positive gravity anomaly and probably represents a buried rift zone.

The entire subaerial surface of Hualalai consists of postshield-stage alkalic basalt, with minor hawaiite and trachyte, collectively named the Hualalai Volcanics (Wolfe and Morris, 1996; Langenheim and Clague, 1987). Although the shield-stage tholeiitic basalt of Hualalai is not exposed on the land surface, submarine samples from dredges (Clague, 1982) and samples from drilled wells (Moore and others, 1987; Clague, 1987) have contained tholeiitic rocks. Clague (1987) reported that trachyte overlying tholeiitic basalt was found beneath about 1,000 ft of alkalic basalt flows (presumably at Huehue Ranch well 4559-01; fig. 6). In addition, tholeiitic basalt possibly originating from Hualalai was found about 250 ft below the ground surface at Kahaluu shaft (well 3557-05) (Clague, 1987). The Waawaa Trachyte Member of the Hualalai Volcanics consists of a trachyte cone (Puu Waawaa, fig. 1) and trachyte flow. Mapped dips of the Hualalai Volcanics are typically about 2° to 15° (Stearns and Macdonald, 1946).



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 19°08'30" and 20°02'30", central meridian 155°26'30"

Figure 5. Generalized surficial geology of the western part of the island of Hawaii (modified from Wolfe and Morris, 1996).

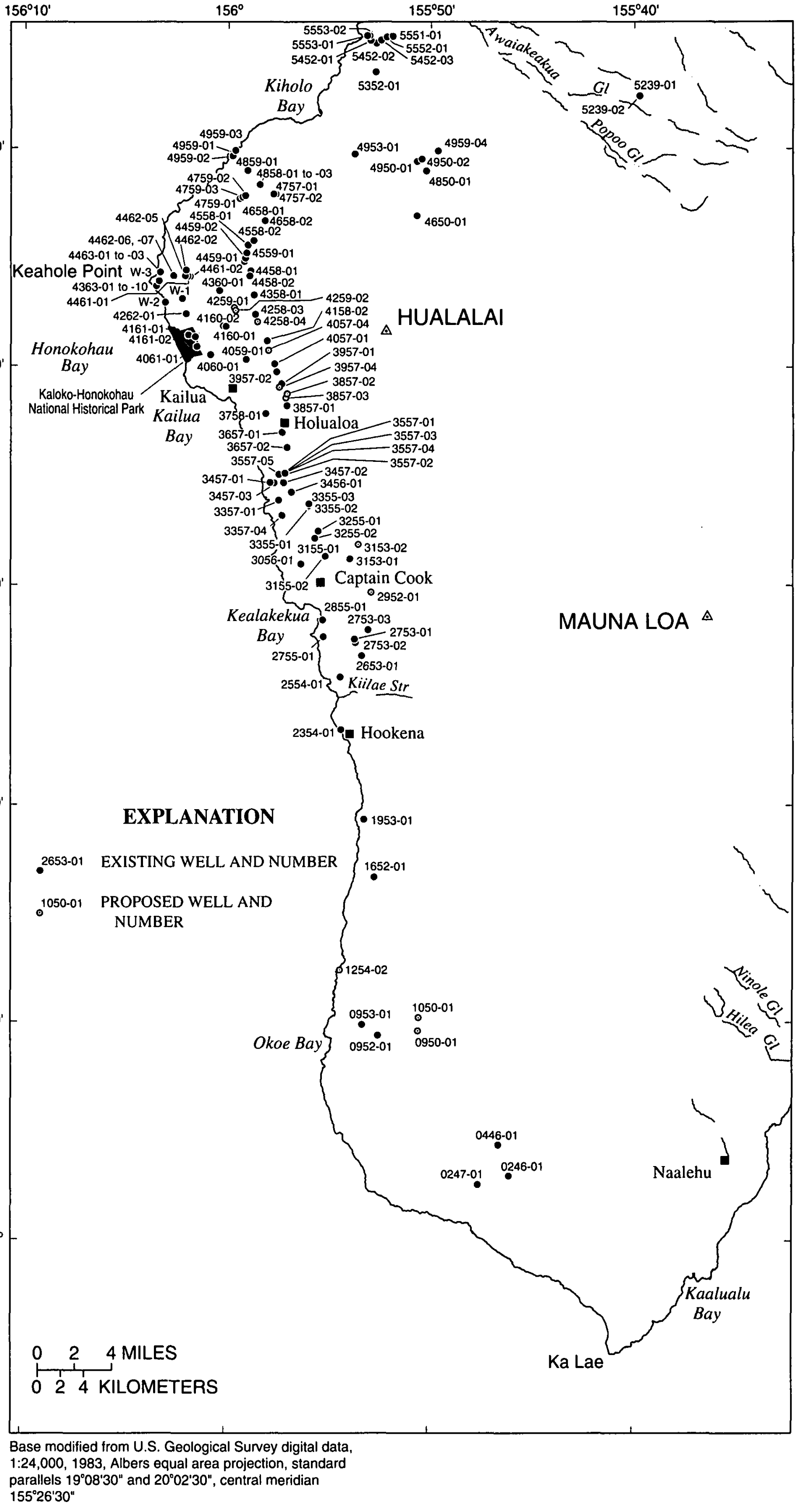


Figure 6. Selected wells in the western part of the island of Hawaii.

The Hualalai Volcanics ranges in age from Pleistocene to Holocene. The oldest exposed basalt flow of the Hualalai Volcanics is at least 13,000 years old (Wolfe and Morris, 1996). The youngest rocks from Hualalai are from an 1801 flow originating from the northwest rift zone. Funkhouser and others (1968) published a potassium-argon age of 0.4±0.3 Ma (million years) for the Waawaa Trachyte Member, and Langenheim and Clague (1987) report an age of about 0.105 Ma.

The surface and subsurface rocks in and near the Park consist entirely of Hualalai Volcanics that are from 1,500 to 10,000 years old (Wolfe and Morris, 1996). Because of the young age of the rocks and low rainfall, the development of soil is minimal within the Park.

Coastal Deposits

In general, coastal deposits in western Hawaii are limited. Near the Park, the shoreline is predominantly rocky and irregular, although a sand beach fronts Honokohau Bay (fig. 2). Terrestrial sediments are generally not present along the shoreline near the Park.

Several drowned carbonate reefs exist off the west coast of Hawaii (Moore and Szabo, 1986; Clague, 1987). The youngest carbonate reef drowned 13,000 years ago and exists 500 ft below sea level (Moore and Fornari, 1984; Moore and Clague, 1987). The reef is covered in places by younger lava flows from both Hualalai and Mauna Loa. The next deeper reef is about 1,300 ft below sea level and has an age of about 120,000 years (Szabo and Moore, 1986).

Faults

Mass-wasting deposits related to prodigious submarine landslides have been identified off the Kona coast using sonar images (Lipman and others, 1988; Moore and others, 1989). Debris avalanches in the Kona area moved about 60 mi from their source near the present shoreline to depths of about 16,000 ft (Moore and others, 1989). The subaerially exposed fault system near Kealakekua Bay (fig. 5) is associated with a large-scale submarine landslide. There may be additional onshore faults in western Hawaii that have been buried by younger lava flows.

HYDRAULIC CONDUCTIVITY OF THE ROCKS

Hydraulic conductivity is a quantitative measure of the capacity of a rock to transmit water (see for example Domenico and Schwartz, 1990). Few published estimates exist for the hydraulic conductivity of Hualalai Volcanics near the Park. In qualitative terms, permeability describes the ease with which fluid can move through a porous rock (see for example Domenico and Schwartz, 1990). The permeability of volcanic rocks is variable and depends mainly on the mode of emplacement of the rocks.

Lava Flows

In a layered sequence of subaerial, shield-stage lava flows of a volcano, where dike intrusions are not present, the overall permeability is high (Stearns and Macdonald, 1946). The main features of lava flows contributing to the high 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. In volcanic-rock aquifers composed of mainly flat-lying lava flows, the hydraulic conductivity is greatest parallel to the direction of the flows, and is least perpendicular to the layered sequence of flows. On the island of Oahu, the horizontal hydraulic conductivity of the volcanic-rock aquifer has been estimated to be 200 times greater than the vertical hydraulic conductivity (Souza and Voss, 1987). In general, trachyte flows on Hualalai are poorly permeable (Stearns and Macdonald, 1946) and form confining units in some areas.

Oki (1999) estimated the horizontal hydraulic conductivity of the volcanic rocks in the vicinity of the Park to be 7,500 ft/d. Using measured ground-water level variations caused by ocean tides, Nance (1991) estimated the hydraulic conductivity of the volcanic rocks near Keahole Point just north of the Park to range from 500 to 33,900 ft/d.

Dikes

Although most dikes are typically less than 10 ft thick, dikes are hydrologically important because they have low permeability and can extend vertically and laterally for thousands of feet. Within a dike complex, dikes intersect at various angles and compartmentalize the more permeable intruded rock in which ground water can be impounded to high altitudes. Because dikes lower overall rock porosity and permeability, the average hydraulic conductivity of a dike complex decreases as the number of dike intrusions 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.

Meyer and Souza (1995) used a numerical model to estimate that the average effective horizontal 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). Williams and Soroos (1973) published analyses of aquifer tests conducted in areas with dikes on the islands of Oahu, Molokai, and Maui, but no estimates were made of the effective hydraulic conductivity of the dike complexes.

Pyroclastic Deposits

Pyroclastic deposits are commonly granular and the permeability of the deposits depends on grain size and degree of sorting. Coarse deposits, such as cinder, are generally more permeable than fine ash. Takasaki and Mink (1982) estimated that the hydraulic conductivity of pyroclastic deposits of southeast Oahu generally ranges from 1 to 500 ft/d. No estimates are available for the hydraulic conductivity of pyroclastic deposits of western Hawaii.

REGIONAL GROUND-WATER FLOW SYSTEM

The ground-water flow system in the Kona area is bounded on the north by the northwest rift zone of Hualalai Volcano, and on the east by the south-southeast rift zone of Hualalai Volcano and the southwest rift zone of Mauna Loa Volcano. Ground water is recharged by infiltration of rainfall over most of the Kona study area. Near the coastal and summit areas, however, ground-water recharge rates are low because of the low rainfall and high evaporation rates. The area of greatest recharge lies between altitudes of 2,000 and 6,000 ft, where rainfall and fog drip are greatest. Water that recharges the ground-water system flows from zones of higher to lower hydraulic head, as measured by water levels. Water-level data and geophysical information indicate that ground water generally flows in westward and southward directions, from the mountainous interior areas to coastal discharge areas. Most of the fresh ground water that is not withdrawn from wells eventually discharges naturally from the aquifer at subaerial and submarine coastal springs and seeps. A small amount of ground water may be lost to evaporation and transpiration near the coast. Streams in the Kona area are ephemeral and generally do not discharge ground water (see for example Davis and Yamanaga, 1968) and are therefore not considered in this report.

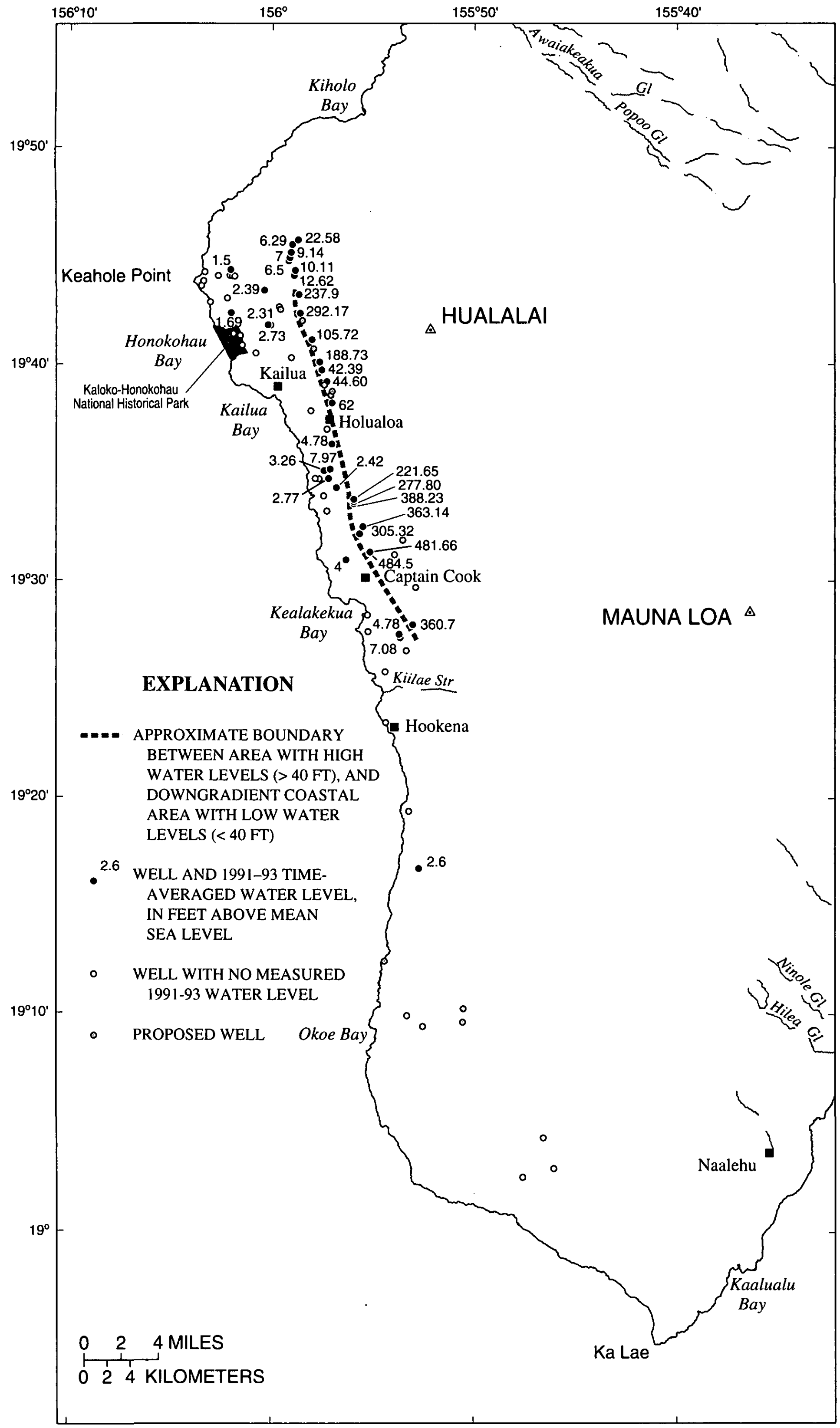
Ground water in the Kona area is generally unconfined in the inland areas. In some inland areas, however, low-permeability rocks may form local confining units.

Seismic refraction studies (Zucca and others, 1982; Hill and Zucca, 1987) indicated that seismic velocity and density increase at a depth of about 6,000 ft below the ground surface in the Kona area. The increases in seismic velocity and density were attributed to a reduction of porosity at depth. Although the base of the aquifer in the Kona area is unknown, it may extend down to the depth where seismic velocity and density increase.

Fresh ground water in the Kona area is found in two main forms: (1) as a lens-shaped body of freshwater, called a freshwater lens, floating on denser, underlying saltwater within permeable dike-free lava flows near the coast, and (2) as water impounded to high levels within the inland part of the aquifer with lower overall permeability. For the purposes of this report, high water levels are defined as water levels greater than 40 ft above sea level. (The area with high water levels is referred to as the high water-level area). Fresh ground water flows from the high water-level area to the downgradient freshwater lens, where water levels are generally less than 10 ft above sea level (figs. 7 and 8).

Freshwater Lens

The source of freshwater in the freshwater lens of western Hawaii is ground-water recharge from (1) the upgradient high water-level area, (2) infiltration of rainfall and fog drip, and (3) irrigation water.



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 19°08'30" and 20°02'30", central meridian 155°26'30"

Figure 7. Time-averaged measured water levels for 1991–93 in the western part of the island of Hawaii.

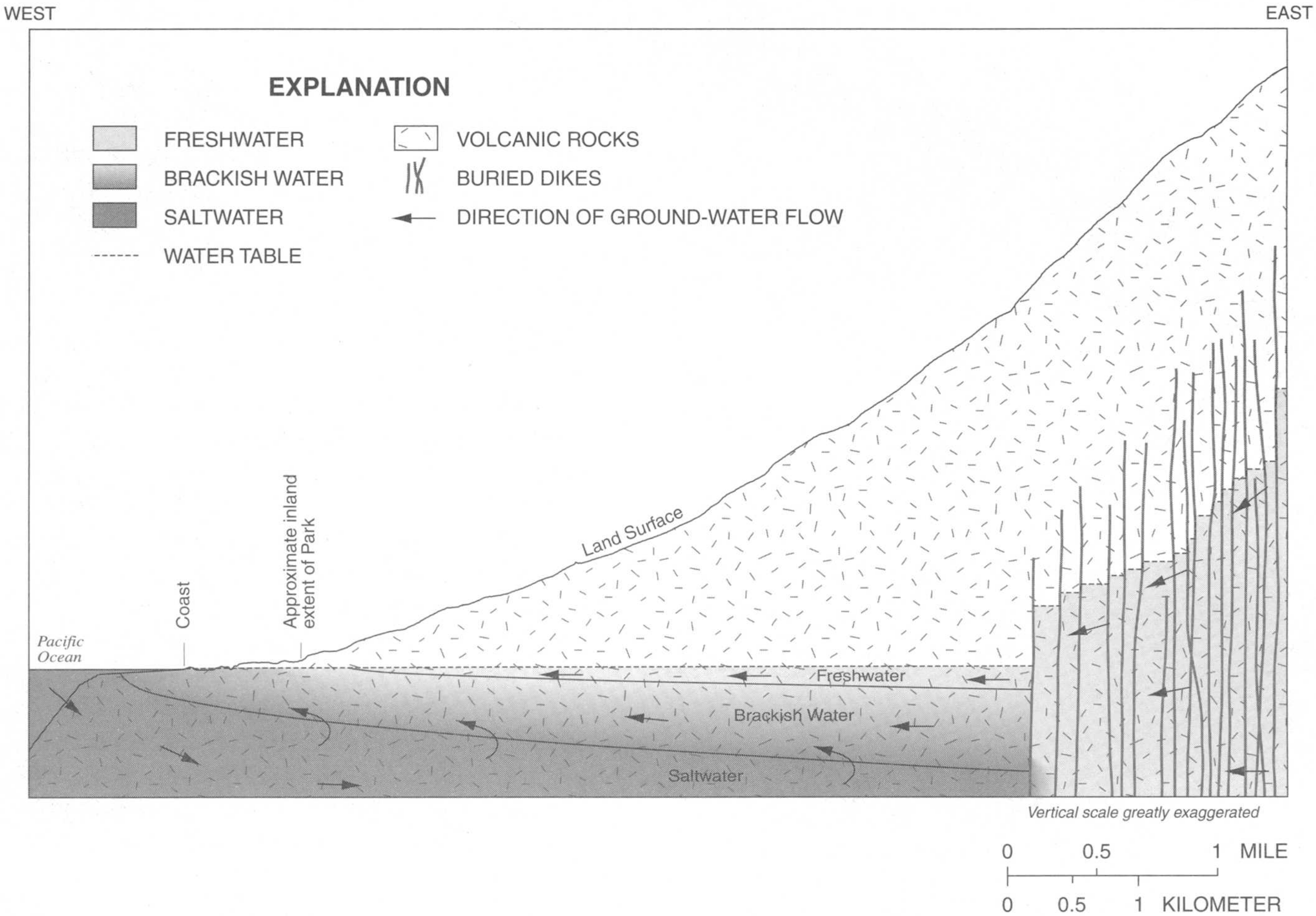


Figure 8. Schematic cross section of the regional ground-water flow system near Kaloko-Honokohau National Historical Park, island of Hawaii.

Freshwater in the highly permeable lava flows near the coast exists in only the upper part of the aquifer, and in only a small fraction of the total thickness of the aquifer. Fresh ground water flows from inland areas to coastal discharge areas. Ground-water discharge from the aquifer is primarily by diffuse submarine discharge to the ocean and by discharge to ponds and wetlands near the coast, and secondarily by discharge from pumped wells. Because the volcanic rocks are highly permeable and crop out offshore, freshwater can readily discharge to the ocean, ground-water levels are relatively low (generally less than 10 ft above sea level and commonly less than 5 ft above sea level), and the magnitude of the horizontal head gradient is small (on the order of a foot per mile). In addition, because of the highly permeable offshore volcanic-rock outcrops, saltwater can readily enter the aquifer. A saltwater-circulation system exists beneath the freshwater lens (Cooper and others, 1964; Souza and Voss, 1987). Saltwater flows landward in the deeper parts of the aquifer, rises, and then mixes with seaward-flowing freshwater (fig. 8). This mixing creates a brackish-water transition zone. In areas near the coast where saltwater mixes thoroughly with seaward-flowing freshwater, a freshwater lens may not form and brackish water may exist immediately below the water table.

Several shallow monitoring wells (less than 50 ft into the aquifer) were drilled near Keahole Point (fig. 6) to determine the salinity of ground water in the aquifer as a function of depth (Nance, 1991). Salinity profiles from these wells indicate that brackish water exists immediately below the water table and salinity increases with depth (fig. 9). At any given depth below the water table, the salinity in well W-1, located about

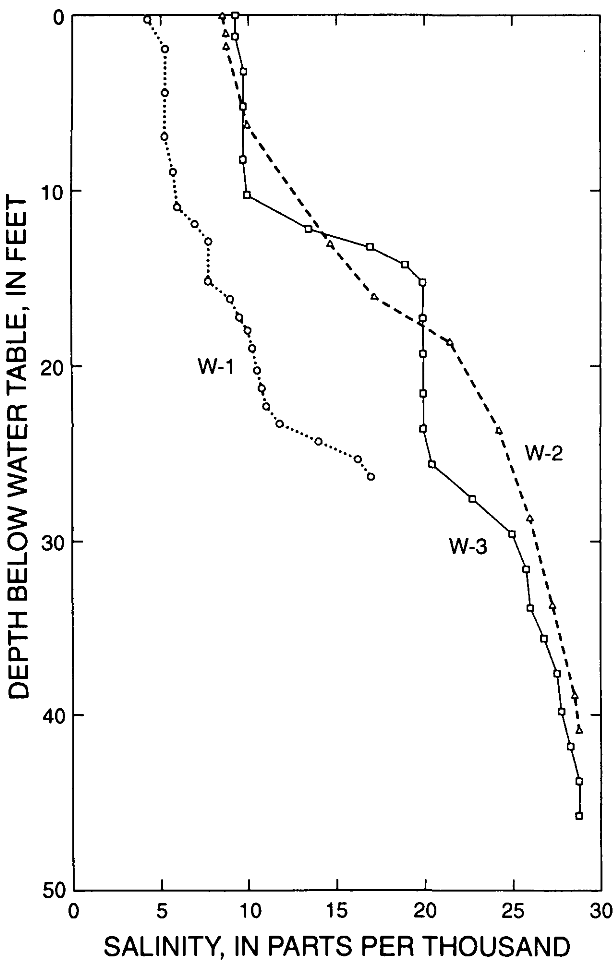


Figure 9. Salinity profiles, measured on June 15 and 21, 1991, in selected monitoring wells near Keahole Point, island of Hawaii (modified from Nance, 1991).

5,200 ft inland, is less than the salinity in well W-2, which is closer to the coast (fig. 9).

Chloride concentrations of water samples from wells in western Hawaii drilled in the highly permeable, dike-free lava flows near the coast range from less than 10 mg/L to more than 1,000 mg/L. Long-term records of chloride concentrations are available for eight pumped wells in western Hawaii (fig. 10). At six of the eight wells, chloride concentrations of pumped water have remained less than 250 mg/L. Chloride concentrations of pumped water from wells 2753-02 and 3557-05 have exceeded 250 mg/L in recent years. Chloride concentrations of pumped water have increased as pumping rates have increased (see "Ground-Water Withdrawals" section of this report).

High Water-Level Area

The source of freshwater in the high water-level area is ground-water recharge from (1) infiltration of rainfall and fog drip and (2) irrigation water. Fresh ground water in the high water-level area that is not withdrawn from wells flows to downgradient areas where water levels are lower and where a freshwater lens may exist.

Wells with measured water levels greater than 40 ft above sea level have been drilled between Kalaoa and Honaunau, at distances ranging from 2 to 4.5 mi inland. In this area, measured water levels are generally between 40 and 500 ft above sea level, but a water level of 1,280 ft above sea level has also been measured. Ground-water levels are substantially higher in this area than in the downgradient, coastal freshwater lens. The abrupt rise in water levels indicates that a major hydrogeologic feature, trending approximately north-south, exists inland of the freshwater lens and impedes the flow of ground water. The geologic nature of the structure or structures associated with the high water levels in the Kona area is unknown. The high water levels may be associated with buried, low-permeability rocks in the form of dikes (fig. 8), lava-draped fault scarps, or massive lava flows.

Although the geologic nature of the structure associated with the high water levels in the Kona area is unknown, aquifer tests have provided some insight into the hydrogeologic characteristics of the structure. One test was done from May 24 to 31, 1993 (unpub. data, USGS Hawaii District well files), when the State Halekii well 3155-02 (fig. 6) was pumped at a rate of about 1,225 gal/min and USGS Halekii well 3155-01, located about 34 ft from the pumped well, was used as an observation well. A semilogarithmic plot of drawdown as a function of time (fig. 11) at the observation well, with time plotted on the logarithmic scale, shows changes in slope that are typically associated with ground-water barriers (see for example Ferris and others, 1962). This aquifer test, and other similar tests done in the Kona area, indicate that the aquifer has a compartmental nature that could be related to the presence of dikes. Because of this compartmentalization of the aquifer, water levels can change by hundreds of feet over horizontal distances of less than a mile.

Results from the aquifer test alone do not rule out the possibility that the structure may be related to

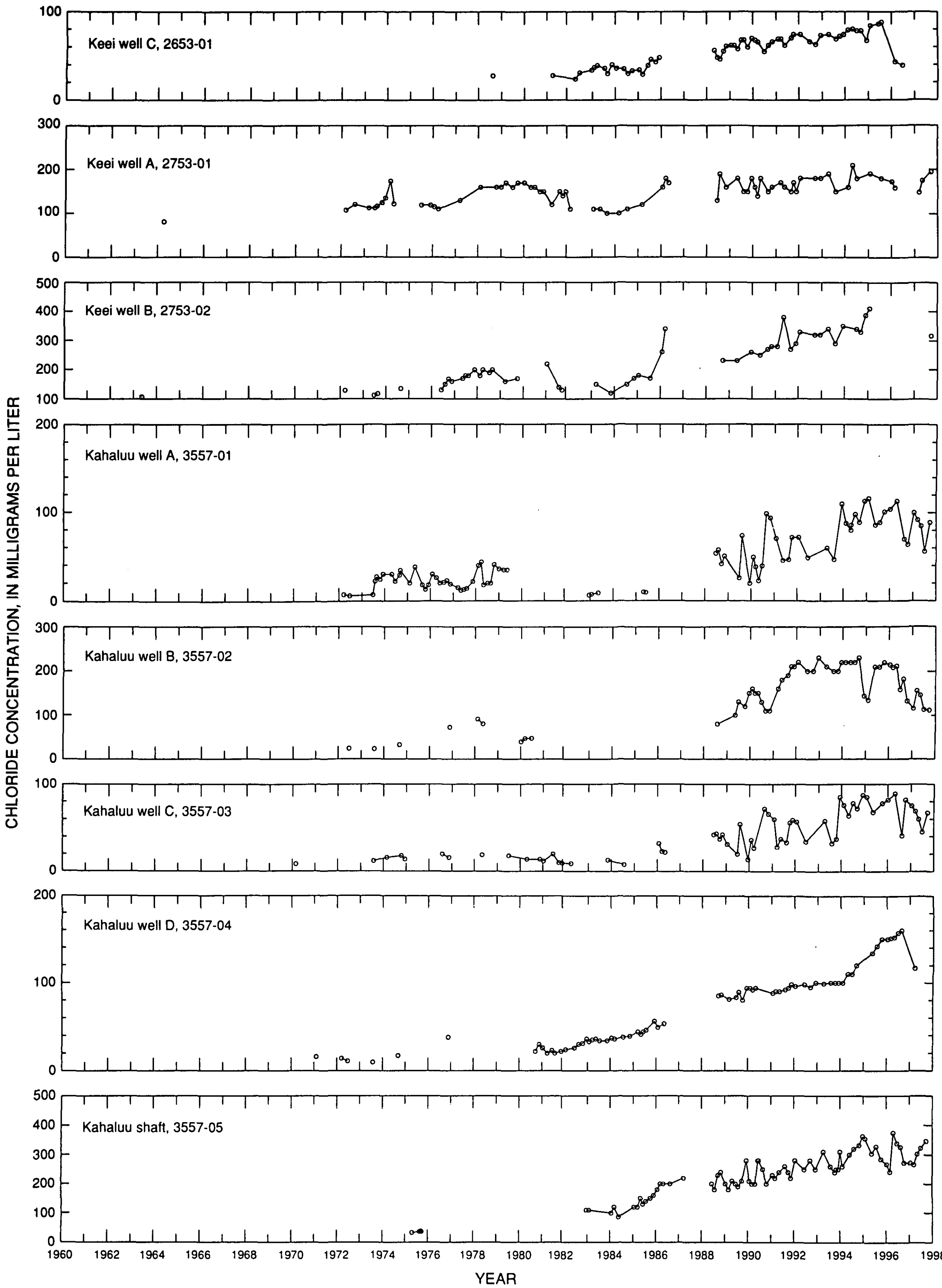


Figure 10. Chloride concentration of water samples from selected wells, Kona, island of Hawaii (data points not connected for data gaps exceeding one year).

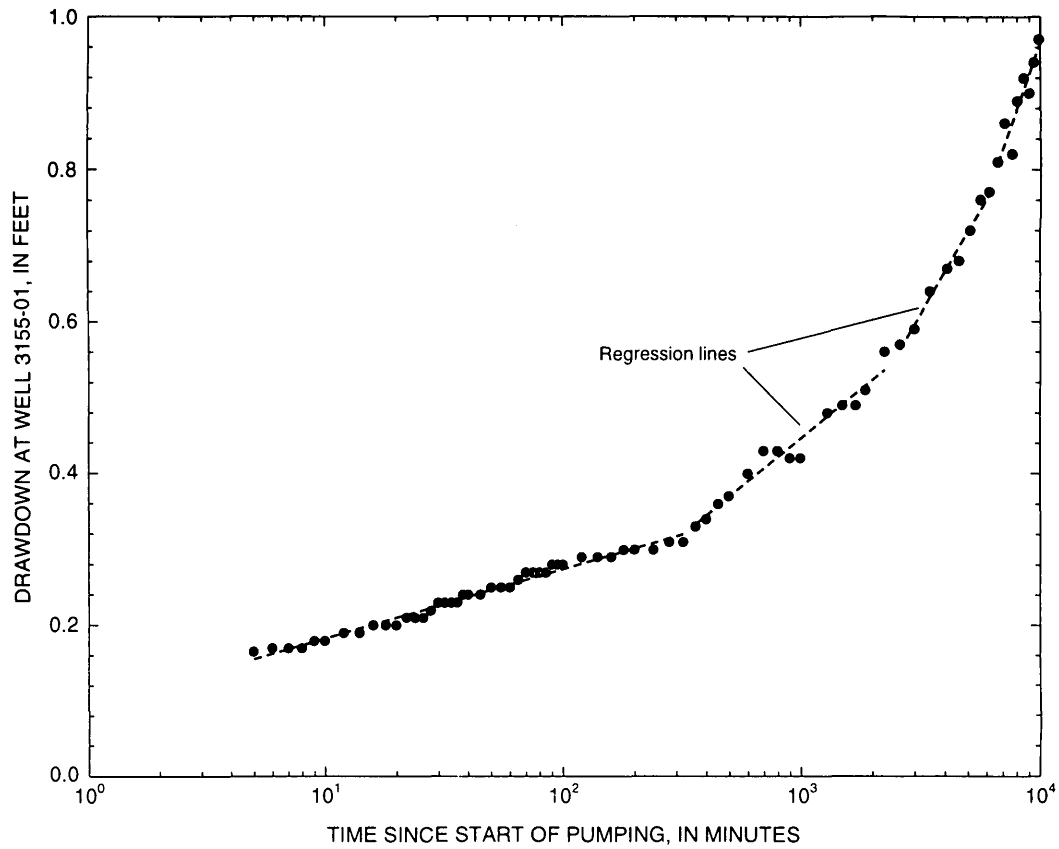


Figure 11. Drawdown as a function of time at well 3155-01 during an aquifer test starting May 24, 1993, Kona, island of Hawaii. Well 3155-02, located about 34 feet from observation well 3155-01, was pumped at a sustained rate of about 1,230 gallons per minute.

faulting. However, gravity and seismic-refraction data (Zucca and others, 1982) indicate that a dense structure with high seismic velocity, such as a buried dike complex, may exist where high water levels have been measured. Thus, a buried dike complex is most consistent with all the available hydrologic and geophysical evidence. Faults and low-permeability lava flows, however, may exist in combination with a buried dike complex.

Although the freshwater body is known to be more than 300 ft thick in some places, no data exist to evaluate the depth to which rocks are saturated with freshwater in this high water-level area. In addition, no data from wells are available to determine the depth at which saltwater may exist beneath the freshwater body in the high water-level area.

GROUND WATER IN THE KALOKO-HONOKOHAU NATIONAL HISTORICAL PARK

The ground-water flow system in the vicinity of the Park is part of the regional brackish-water transition zone. Recharge from direct infiltration of precipitation within the Park is small because of low rainfall and high rates of evaporation. Therefore, it is assumed that the main freshwater component of brackish water flowing through the Park is from subsurface flow originating from inland areas east of the Park. Brackish ground water forms by seaward flowing freshwater mixing with saltwater. The area of extensive mixing with saltwater extends upgradient from the Park. The brackish groundwater body overlies saltwater and extends to an estimated depth of about 50 to 100 ft at the inland boundary of the Park where the ground water is freshest.

The Park contains two large fishponds: Kaloko fishpond, which has an area of about 11 acres, is formed by a constructed rock seawall that encloses a natural embayment, and Aimakapa fishpond, which has an area of about 15 acres, is formed behind a barrier beach (National Park Service, 1994). Wetland areas exist adjacent to the fishponds. The following brief descriptions of Kaloko and Aimakapa fishponds are from Kikuchi and Belshe (1971).

The original rock seawall used to enclose Kaloko fishpond was about 750 ft long, and 35 ft wide at the top. The ocean and pond faces of the wall were constructed at angles of about 25 and 18 degrees, respectively. Seawater entered Kaloko fishpond through the seawall and also through two sluice gates. The seawall has been damaged by waves, and one of the sluice gates has been destroyed and the other is filled with rocks. (As of May 1999, the rock seawall was being rebuilt and one of the sluice gates had been restored.) Although most of Kaloko fishpond is 3 ft deep or less, the maximum depth to volcanic rocks is about 12 ft.

Aimakapa fishpond is presently separated from the ocean by a barrier beach. An archaeological excavation is needed to determine whether a man-made rock seawall once enclosed the pond. A channel cut through the barrier beach near the northern part of the fishpond is now filled with sand but once formed a sluice gate. Another sluice gate may have existed farther south. Partition walls subdivide the inland part of the fishpond. Typical depths of Aimakapa fishpond are 2 to 6 ft. About 15 acres of wetland areas exist adjacent to the fishpond.

Within the Park, collapse features in the lava flows near the shore contain small inland bodies of water known as anchialine ponds. Although the western coast of the island of Hawaii has the largest number of known anchialine ponds in the State, the islands of Maui, Oahu, and Kahoolawe also have anchialine ponds (Bailey-Brock and Brock, 1993; Brock and Kam, 1997). Because of the high permeability of the volcanic rocks and close proximity of the anchialine ponds to the ocean, the water levels in anchialine ponds in the Park fluctuate with ocean tides. Anchialine ponds in the Park generally have irregular basins, and are small (surface areas less than about 100 ft^2) and shallow (less than 1.5 ft deep) (Brock and Kam, 1997). About a third of the anchialine ponds in the Park contain the native shrimp opaeula (*Halocaridina rubra*), but introduction of exotic fish into the ponds has had a negative effect on the abundance of native anchialine species (Brock and Kam, 1997).

The freshwater component of ground water in the Park originates from upgradient areas, flows toward the coast, and mixes with underlying saltwater, and the mixed water ultimately discharges as submarine springs along the coast and into the ponds and wetland areas in the Park (fig. 12). Fischer and others (1966) used infrared images to identify the locations of coastal springs in the vicinity of the Park, where ground water colder than the ambient ocean was discharging. Ground water that discharges to the anchialine ponds may evaporate, but the evaporation losses are probably small compared with other discharges from the aquifer. The water levels in the ponds mark the position of the local ground-water table.

During January 1996, three exploratory wells were drilled in the Park (wells 4061-01, 4161-01, and 4161-02; fig. 2) for this study. Water levels were monitored in each of the three wells for periods of about 2 to 4 weeks. Water levels were monitored from April 3, 1996 to May 3, 1996 in wells 4061-01 and 4161-02, and from May 3, 1996 to May 17, 1996 in well 4161-01. The resulting hydrographs (fig. 13), show water-level fluctuations of as much as 1.5 ft in response to ocean tides. The maximum range in ocean tides during this period was about 2 ft. Average ground-water levels for this period were 1.3, 1.4, and 1.5 ft above mean sea level in wells 4161-01, 4061-01, and 4161-02, respectively. The average water levels indicate that the water table slopes about 0.7 ft/mi toward the coastline to the west. Brackish ground water flows in the general direction of decreasing water levels, but during high tides, ground water flows inland near the coast and causes significant mixing. The extent of inland flow and mixing is unknown, however.

Ground-Water Quality

An initial field survey on January 19, 1996 of electrical conductivity of water in the three exploratory wells in the Park indicates that ground water near the water table is brackish, and that salinity increases, and temperature decreases with depth in the aquifer (table 2). Water samples for laboratory analysis of chloride were subsequently obtained on May 3, 1996, May 17, 1996, and September 3, 1997 from the three wells, and

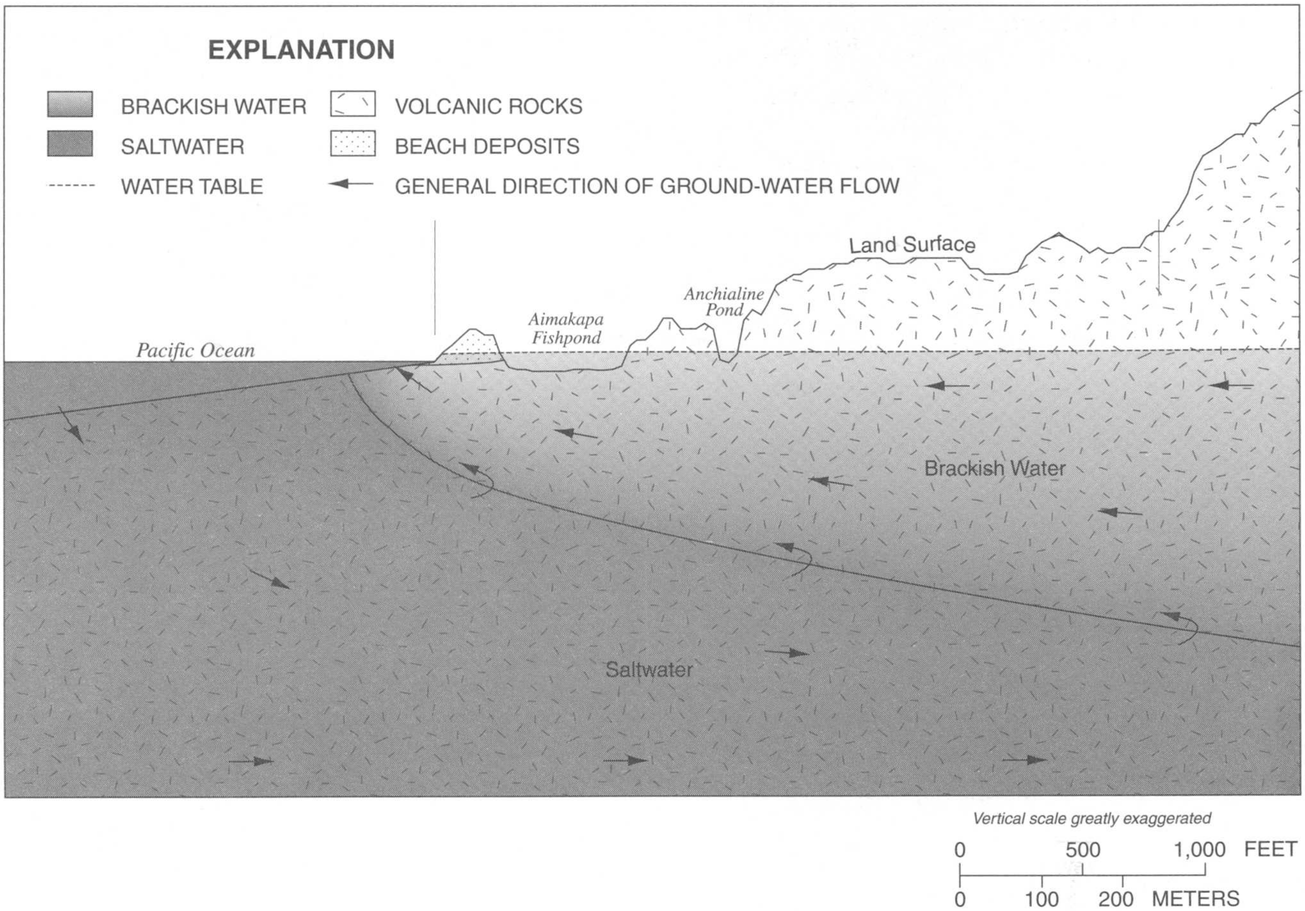


Figure 12. Schematic cross section of the ground-water flow system in Kaloko-Honokohau National Historical Park, island of Hawaii.

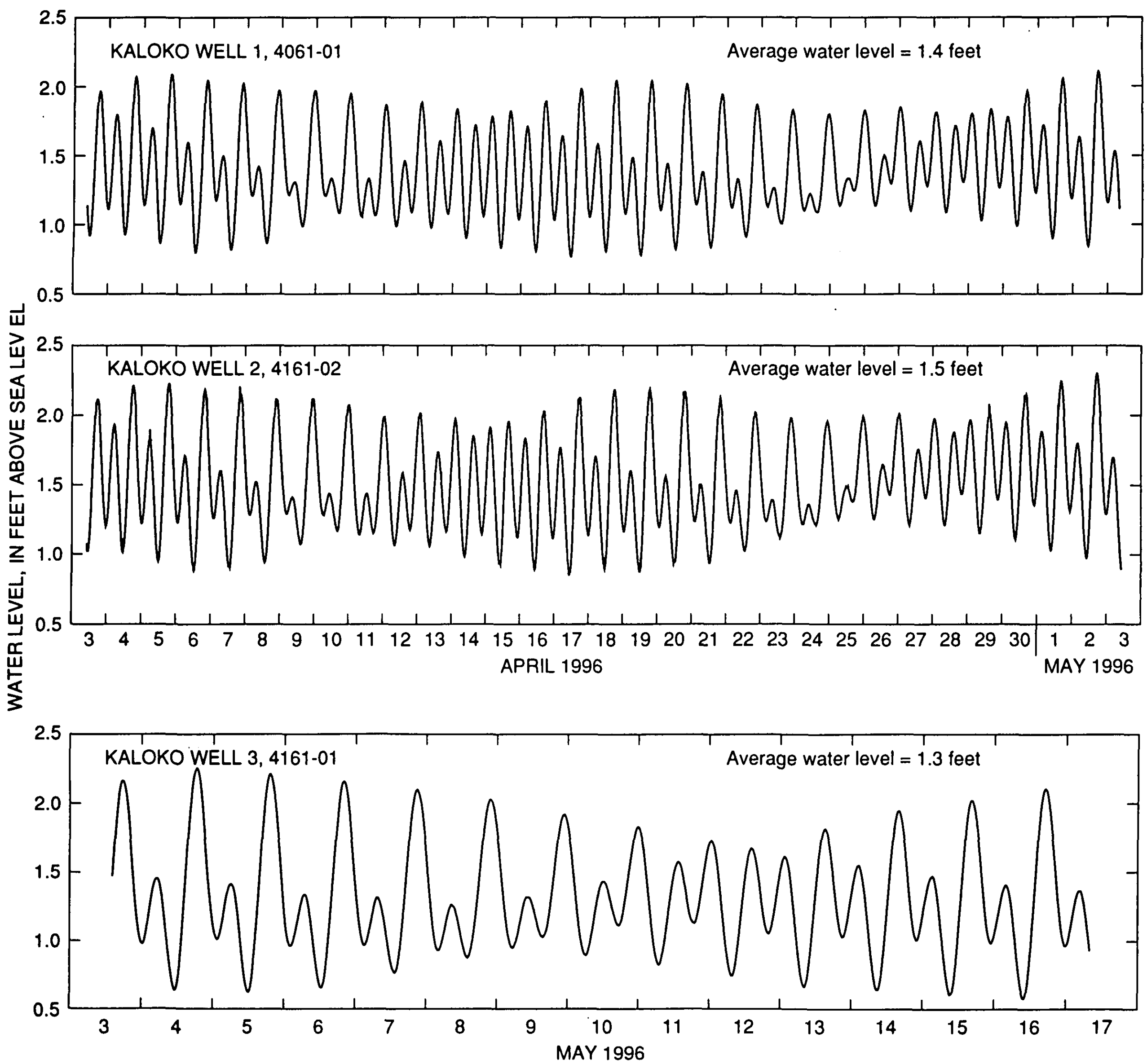


Figure 13. Water level at wells 4061-01, 4161-02, and 4161-01 during 1996, Kaloko-Honokohau National Historical Park, island of Hawaii.

Table 2. Initial specific-conductance survey of wells at Kaloko-Honokohau National Historical Park, island of Hawaii, January 19, 1996

[Percentage of seawater salinity calculated using specific conductance equals 52.8 mS/cm for 100 percent seawater; mS/cm, millisiemens per centimeter at 25°C; °C, degrees Celsius]

Well	Time	Depth to water from top of casing (feet)	Depth below water table (feet)	Specific conductance (mS/cm)	Salinity, as percentage of seawater salinity	Temperature (°C)	Notes
4061-01	0910	36.5	0.5	13.64	26	20.7	Well bottom about 44 ft below top of casing
			3.5	15.94	30	20.4	
			6.5	17.73	34	20.6	
4161-01	0840	22.5	0.5	9.10	17	20.3	Well bottom about 32 ft below top of casing
			3.5	9.11	17	19.9	
			6.5	9.22	17	19.3	
			9.5	9.87	19	19.1	
4161-02	0817	54.2	1	6.98	13	19.2	Well bottom about 32 ft below top of casing
			6	7.46	14	19.1	
			11	8.00	15	18.9	
	1045	54.7					
	1223	54.6					
	1530	54.2					

Table 3. Chloride concentrations of ground-water samples from wells 4061-01, 4161-01, and 4161-02, Kaloko-Honokohau National Historical Park, island of Hawaii

Date	Chloride concentration (mg/L) 4061-01 (Kaho 1)	4161-02 (Kaho 2)	4161-01 (Kaho 3)
May 3, 1996	5,910	2,820	3,300
May 17, 1996	5,480	2,700	3,310
September 3, 1997	5,560	2,610	3,190
March 4, 1998	no sample	2,710	no sample

an additional sample from well 4161-02 was collected on March 4, 1998. At each well, a disposable bailer was used to transfer water directly into sample bottles after purging three well-volumes of water. Chloride concentrations of water samples from the wells ranged from 2,610 to 5,910 mg/L (table 3). The water samples from well 4161-02, the most inland well, were the freshest obtained from any source within the Park.

Ground-water samples from the three exploratory wells in the Park also were analyzed for metal and organic contaminants. The three wells were initially sampled on September 3, 1997. Well 4161-02 was resampled for organochlorine pesticides on March 4, 1998 because the original sample was mishandled during preparation.

Water from a fourth well (4358-01), in the high water-level area inland of the industrial areas, was collected to provide a sample upgradient of most human activity and therefore assumed free of human-related contaminants. (Although the capture zone of well 4358-01 was not delineated, it is possible that the capture zone may contain limited areas affected by human activity.) The well was sampled on September 4, 1997 by collecting water from a pump outlet at the well head. Prior to sample collection, the well had been pumped for about 10 hours.

The metals chromium and copper were found in trace amounts (1 to 5 μg/L) in unfiltered water samples from all four wells (table 4, at end of report). Three other metals were detected in trace amounts in individual wells at the lowest concentration analytically reportable: nickel (1 μg/L) in well 4161-01, zinc (10 μg/L) in well 4161-02, and selenium (1 μg/L) in well 4358-01 (table 4, at end of report). The low concentrations of metals measured in ground-water samples do not provide conclusive evidence of contamination at the time of sampling. The chemical weathering of basalt that forms the aquifer (see for example Halbig and others, 1986) may be the source of the metals in the ground water.

No volatile organic compounds, organochlorine pesticides, or organophosphate pesticides were detected in water samples from any of the four wells (table 4). One semi-volatile organic compound, phenol, was detected in the three wells within the Park at low concentrations (4 to 10 μg/L). Phenol was not detected in water from well 4358-01, located upgradient of the Park and industrial areas. Phenol is a widespread compound used in many industrial and domestic products. If confirmed by additional sampling, the presence of phenol in ground water in the Park would indicate that domestic, agricultural, or industrial activities have released organic contaminants to ground water upgradient of the Park, and that water resources in the Park are vulnerable to contamination.

Ponds and Wetlands

In the Park, the fishponds and anchialine ponds are hydrologically connected with the ground water. Numerous springs around the fishponds supply the adjacent wetlands with brackish ground water. Previous studies of the water quality in the ponds and wetlands include those of Kikuchi and Belshe (1971), Maciolek and Brock (1974), Chai (1991), Bhambare (1996), Brock and Kam (1997), and Brasher (1998).

Kikuchi and Belshe (1971) identified two main water layers within Kaloko fishpond: (1) a lower-density surface layer, 5 to 18 in. thick, with salinity in the range of 18 to 24 parts per thousand (ppt) and temperature in the range of 20° to 24°C, and (2) a deeper layer containing the main body of brackish water, with salinity in the range of 25 to 29 ppt and temperature in the range of 28° to 31°C. A third layer, in which decomposition of accumulated deposits depleted the oxygen and released hydrogen sulfide, could sometimes be distinguished near the bottom of the fishpond. Near inland springs that supplied water to Kaloko fishpond, the salinity of pond water was 4 to 8 ppt and temperature was 18° to 20°C (Kikuchi and Belshe, 1971). The central waters of Aimakapa fishpond were described by Kikuchi and Belshe (1971) as having a salinity of 7.9 ppt and a temperature of 27.8°C.

Maciolek and Brock (1974) surveyed 318 ponds, including Kaloko and Aimakapa fishponds, along the western coast of Hawaii. The reported range of measured salinities in Kaloko fishpond was 7 to 18 ppt, and the range of salinities in Aimakapa fishpond was 7 to 8 ppt (Maciolek and Brock, 1974).

In 1988, Chai (1991) measured salinity and temperature of water in Kaloko fishpond and the adjacent wetland areas. In Kaloko fishpond, surface salinity averaged 25.4 ppt near peripheral areas (except near the seawall during an afternoon high tide), and 35.2 ppt near the center of the pond. The salinity of water near the bottom of the pond averaged 33.1 ppt (Chai, 1991). In the adjacent wetland areas, salinity ranged from 9.5 to 26.0 ppt. In general, water temperatures in Kaloko fishpond were positively correlated with salinities, except in the central pond areas that had relatively low surface temperatures (averaging 24.6°C) and high salinities (averaging 35.7 ppt) (Chai, 1991). In the adjacent wetland areas, temperature ranged from 19.0° to 28.8°C. Chai (1991) indicated that at the time of the 1971 study of Kikuchi and Belshe, there may have been a larger freshwater component of ground-water discharge entering Kaloko fishpond than in 1988. Salinity in 10 anchialine ponds near Kaloko fishpond ranged from 8.5 to 20.5 ppt, and temperature ranged from 18.5° to 23.5°C (Chai, 1991).

In 1995, Bhambare (1996) measured salinity, temperature, dissolved oxygen, pH, and oxidation-reduction potential in Kaloko fishpond using a remotely controlled data-acquisition system. Salinity in the pond ranged from 11.5 to 31.5 ppt, and varied with location, depth, and tidal stage. Salinity generally increased with depth, but at depths greater than 20 in. salinity rarely varied by more than 1 part per thousand over the pond during calm periods. Bhambare (1996) found that temperature of water in Kaloko fishpond was dependent on solar radiation and generally increased with depth.

During 1994–96, Brock and Kam (1997) sampled water from Kaloko and Aimakapa fishponds, anchialine ponds, and three wells in the Park and noted that concentrations of nitrate, total nitrogen, orthophosphorus, total phosphorus, and silica increased in an inland direction. The decreasing concentrations with proximity to the coast were attributed to mixing and dilution with saltwater from the ocean.

In 1997, Brasher (1998) measured salinity, temperature, pH, and dissolved oxygen at two depths (surface and 12 in. from the bottom) and along two transects in Kaloko fishpond. Results from Brasher (1998) are generally consistent with earlier results from Chai (1991), Bhambare (1996), and Brock and Kam (1997).

Brock and Kam (1997) analyzed sediments and fish tissues from Aimakapa fishpond. The sediment and tissue samples were analyzed for 159 compounds (26 chlorinated pesticides, 21 organophosphate pesticides, 53 volatile-organic compounds, and 59 acid-base-neutral extractables) and none of the compounds were detected. However, sediment samples collected in 1997 for this study from Aimakapa fishpond contained polychlorinated biphenyls (0.10 to 5.12 μg/kg), chlorinated benzenes (0.09 to 2.57 μg/kg), heptachlor (0.56 to 3.00 μg/kg) and other chlordane-related compounds (0.05 to 0.65 μg/kg), dieldrin (0.12 μg/kg), and mirex (0.76 to 1.27 μg/kg), and fish-tissue samples contained polychlorinated biphenyls (0.02 to 12.66 μg/kg), chlorinated-benzene compounds (0.37 to 2.00 μg/kg), chlordane-related compounds (0.14 to 2.82 μg/kg), gamma hexachlorocyclohexane (2.02 μg/kg), dieldrin (0.44 μg/kg), endrin (1.10 μg/kg), pentachloroanisole (0.49 μg/kg), chlorpyrifos (1.10 μg/kg), 2,4′-DDE (2.68 to 3.02 μg/kg), 4,4′-DDE (0.89 μg/kg), 4,4′-DDD/PCB 114 (0.42 μg/kg), 2,4′-DDT (1.34 μg/kg), and 4,4′-DDT (0.18 μg/kg) (unpub. data, National Park Service, written commun., 1999). (Note that only quantified results are listed, and some of the specified concentrations are below the analytical-method detection limits.) In addition, the sediment samples collected in 1997 were analyzed for 44 polynuclear aromatic hydrocarbon (PAH) compounds and were found to contain PAHs and alkyl PAHs at concentrations of 0.1 to 25.2 μg/kg. The concentrations of PAHs and alkyl PAHs in the sediment samples were low, probably more reflective of background conditions and presumably normal atmospheric fallout than any particular spill source. (Roy Irwin, National Park Service, written commun., 1999).

A reconnaissance survey of water quality of wetlands in the Park was made in August 1994 for this study. Using a field conductivity meter, salinity was measured in ground water emerging from springs into Kaloko and Aimakapa fishponds and other available surface-water sites (fig. 2, table 5). The data indicate that water in the ponds and wetlands is brackish, ranging in salinity from 10 to 34 ppt. Results of the survey indicate that the salinity of water in Kaloko fishpond is about 2 to 3 times greater than the salinity of water in Aimakapa fishpond, which is consistent with data from Brock and Kam (1997). The higher salinity of the water at Kaloko fishpond may be caused by mixing with seawater that enters the pond through the rock seawall or by greater flow of high salinity ground water into the pond.

Water levels were recorded at the inland part of Aimakapa fishpond (fig. 14) for about 30 hours during October 28–29, 1996. The water level in the pond fluctuated about 0.8 ft in response to ocean tides. Water in Aimakapa fishpond is only slightly more saline than the surrounding ground water. Water levels and tidal

Table 5. Specific-conductance sampling sites at Kaloko-Honokohau National Historical Park, island of Hawaii, August 1994

[ns, no stratification was noted as probe was lowered through water column; mS/cm, millisiemens per centimeter; conductivity values automatically corrected to temperature equals 25°C; °C, degrees Celsius; salinity calculated using specific conductance = 52.8 mS/cm for salinity = 35 ppt and assuming a linear relation; ppt, parts per thousand; --, no data]

Site	Sample no.	Pond depth[1] (inches)	Sample depth[1] (inches)	Date	Time (±30 minutes)	Specific conductance (mS/cm)	Temperature (°C)	Calculated salinity (ppt)
Pit near maintenance trailer	1	--	--	Aug. 9	1100	14.2	22.5	9
Queens bath (Kahinahinaula, Kaho#PO16)	9	36	2	Aug. 9	1440	15.4	25.0	10
" "	10	36	12	Aug. 9	1440	15.6	23.3	10
" "	11	36	30–36	Aug. 9	1440	16.3	21.6	11
Aiopio fishtrap	4	--	--	Aug. 9	1215	37.2	28.1	25
Harbor, North Point	5	--	--	Aug. 9	1230	50.7	28.3	34
Aimakapa-southeast anchialine pond	3	--	--	Aug. 9	1130	16.9	23.3	11
Aimakapa-northeast spring	2	--	--	Aug. 9	1120	20.0	28.5	13
Aimakapa-back pond #1, south side	19	9	2	Aug. 10	1030	20.1	28.2	13
" "	20	9	6–8	Aug. 10	1030	19.8	27.7	13
" "	21	9	9	Aug. 10	1030	18.1	28.0	12
Aimakapa-1/3 from east edge, south side	33	18	ns	Aug. 10	1030	20.7	29.1	14
Aimakapa-1/3 from west edge, south side	34	12	ns	Aug. 10	1030	20.7	29.0	14
Aimakapa-west edge, south side	18	4	2	Aug. 10	1030	20.9	29.1	14
Aimakapa-back pond #2, middle	22	10	2	Aug. 10	1030	19.8	27.8	13
" "	23	10	4–8	Aug. 10	1030	19.8	27.8	13
" "	24	10	10	Aug. 10	1030	17.9	27.9	12
Aimakapa-1/3 from east edge, middle transect	27	24	ns	Aug. 10	1030	20.2	27.9	13
Aimakapa-1/3 from west edge, middle transect	28	24	ns	Aug. 10	1030	20.8	28.3	14
Aimakapa-east edge, middle transect	29	12	ns	Aug. 10	1030	20.8	28.6	14
Aimakapa-back pond #3, north side	25	18	2	Aug. 10	1030	20.3	28.2	13
" "	26	18	18	Aug. 10	1030	20.3	28.2	13
Aimakapa-1/3 from east edge, north side	32	12	ns	Aug. 10	1030	20.2	28.7	13
Aimakapa-1/3 from west edge, north side	31	10	ns	Aug. 10	1030	20.5	29.0	14
Aimakapa-west edge, north side	30	10	ns	Aug. 10	1030	20.8	29.3	14
Kaloko-spring near caretaker house site	6	--	--	Aug. 9	1400	26.9	26.9	18
Kaloko-in pond west of spring	7	10	2	Aug. 9	1400	44.2	33.1	29
" "	8	10	8	Aug. 9	1400	48.1	33.6	32
Kaloko-in front of parking lot	15	36	2	Aug. 9	1515	50.6	32.5	34
" "	16	36	12	Aug. 9	1515	50.6	30.8	34
" "	17	36	36	Aug. 9	1515	38.9	31.2	26
Kaloko-west edge	12	12	2	Aug. 9	1500	51.8	31.8	34
" "	13	12	6	Aug. 9	1500	51.8	31.7	34
" "	14	12	12	Aug. 9	1500	51.7	31.7	34

[1] Depths are estimates only

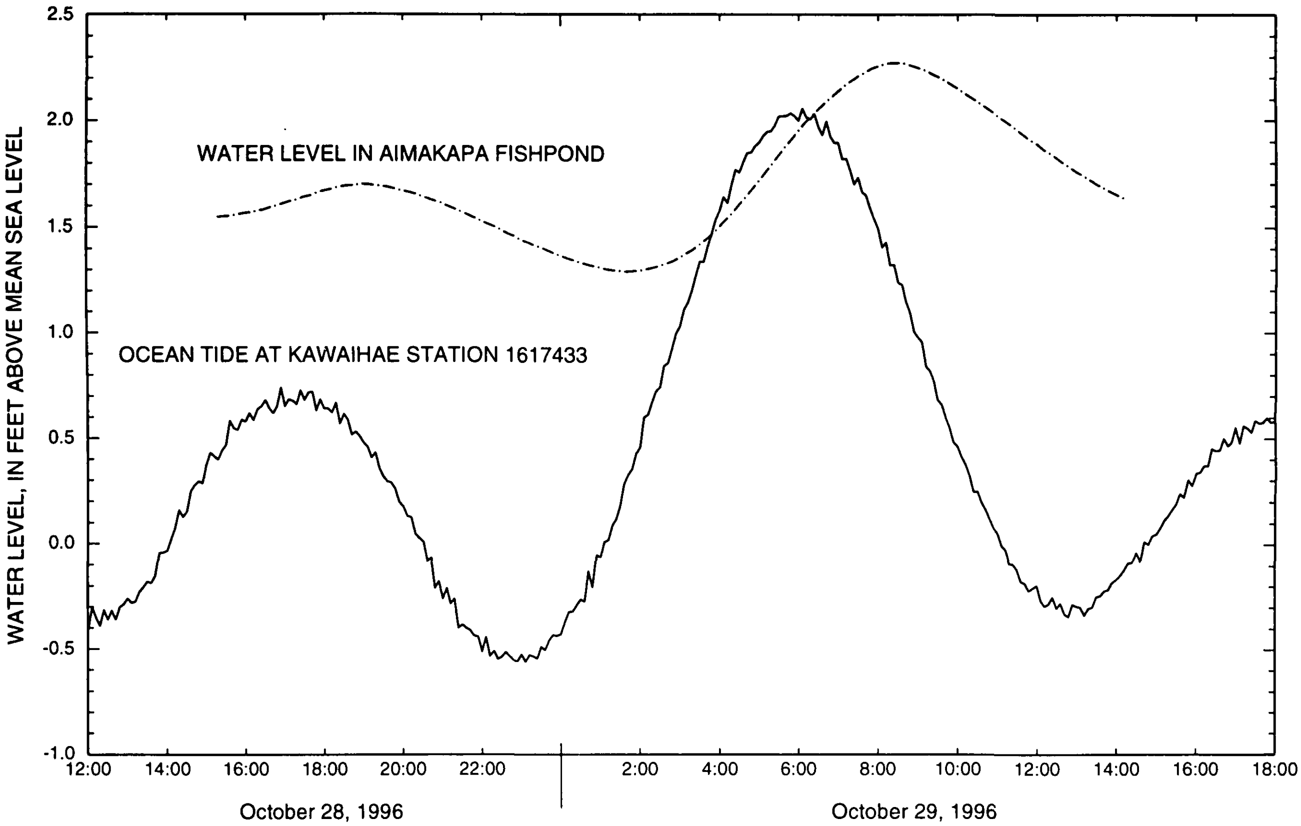


Figure 14. Water level in Aimakapa fishpond and ocean tide at Kawaihae station 1617433 during October 28–29, 1996, island of Hawaii. Data for Kawaihae station 1617433 obtained from National Oceanic and Atmospheric Administration.

influence were not recorded in Kaloko fishpond, but because seawater can readily enter the pond through and over the rock seawall, the average water level is expected to be near mean sea level.

GROUND-WATER WITHDRAWALS

Most of the ground water withdrawn from the Kona area is from a coastal body of freshwater or brackish water floating on denser saltwater, and a smaller amount is withdrawn from the inland area where high water levels exist. The total reported annual mean pumpage for the Kona area during 1997 was 11.1 Mgal/d (computed from unpub. data from Hawaii Commission on Water Resource Management). An additional estimated 2.9 Mgal/d of saline water also was withdrawn from the Kona area. Of the reported 11.1 Mgal/d withdrawn in 1997, 9.8 Mgal/d was withdrawn by the County of Hawaii Department of Water Supply (DWS).

The DWS maintains five wells near Kahaluu (3557-01 to -05), three wells near Keei (2653-01, 2753-01 to -02), and one well near Holualoa (3657-01) (figs. 1 and 6) that are used to withdraw water from the coastal part of the ground-water system, seaward of the area where high water levels exist. Combined withdrawals from these nine DWS wells have increased with time (fig. 15) and averaged 7.7 Mgal/d in 1997. The Kahaluu wells (3557-01 to -05) were drilled between 1959 and 1976, the Keei wells (2653-01, 2753-01 to -02) were drilled between 1958 and 1978, and the Holualoa well (3657-01) was drilled in 1983 (table 6, at end of report).

Beginning in 1994, the DWS began withdrawing ground water from the area with high water levels from Kalaoa well 4358-01. By 1997, the DWS was using three additional wells (Keei well D, 2753-03; Queen Liliuokalani Trust well, 4057-01; and Halekii well, 3155-02) to withdraw ground water from the high water-level area. During 1997, the average combined withdrawal from the four DWS wells in the high water-level area was 2.1 Mgal/d. During December 1997, combined withdrawal from these four DWS wells reached 2.5 Mgal/d (fig. 16).

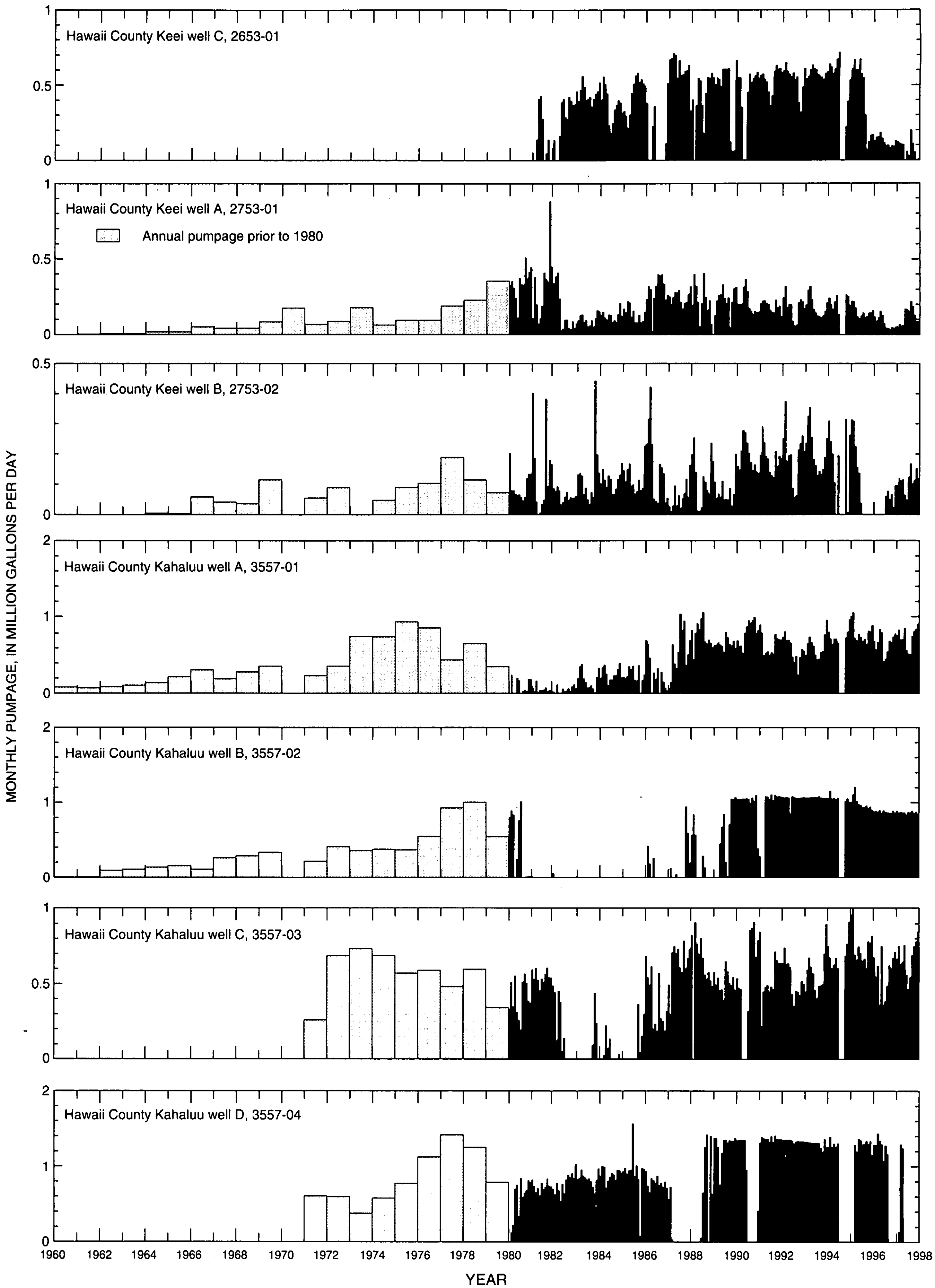


Figure 15. Monthly pumpage from selected wells located seaward of the high water-level area, Kona, island of Hawaii (data after 1980 from Commission on Water Resource Management, 1998, unpub.). Data missing from July 1994 to September 1994 for Hawaii County wells.

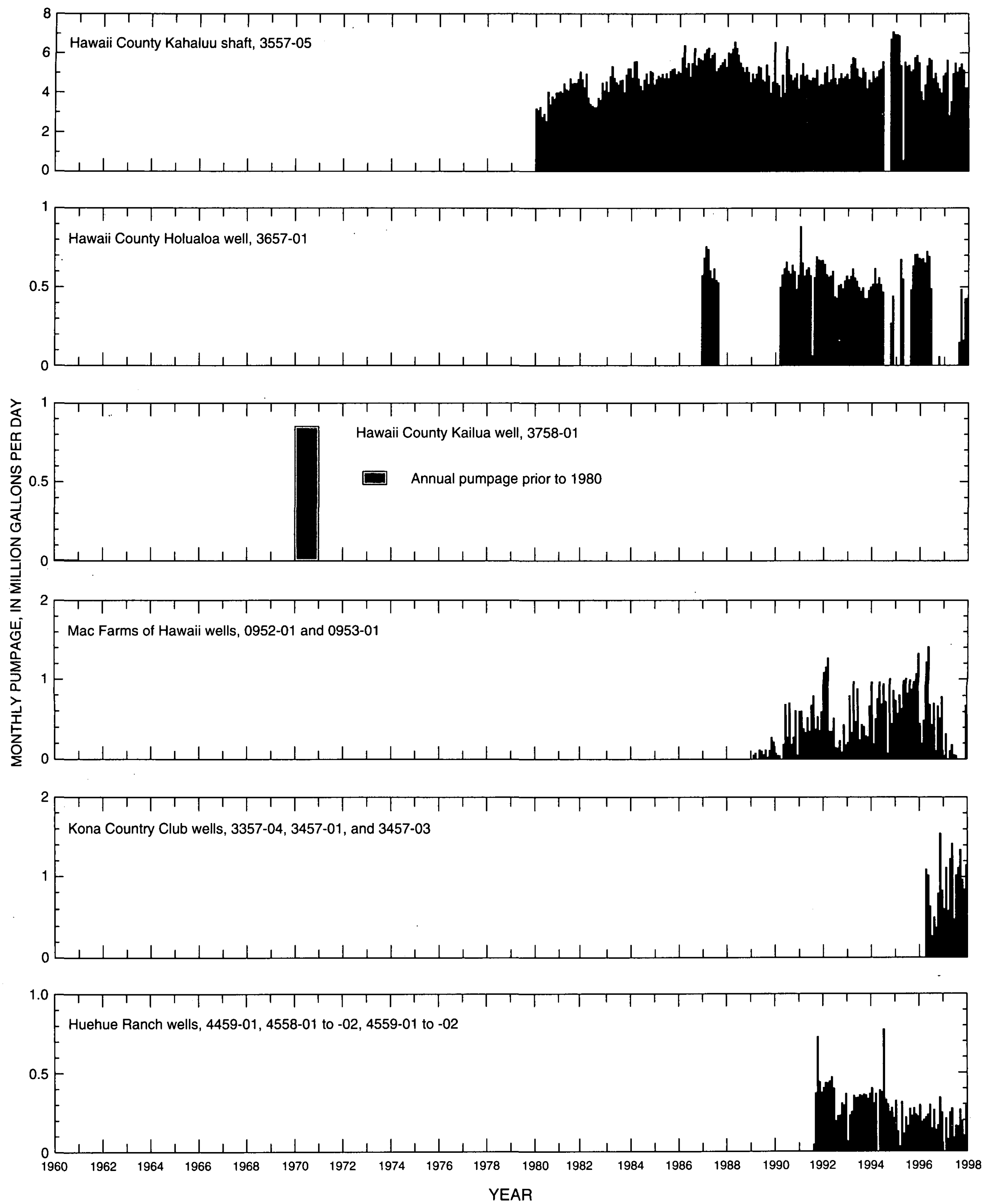


Figure 15. Monthly pumpage from selected wells located seaward of the high water-level area, Kona, island of Hawaii (data after 1980 from Commission on Water Resource Management, 1998, unpub.). Data missing from July 1994 to September 1994 for Hawaii County wells--Continued.

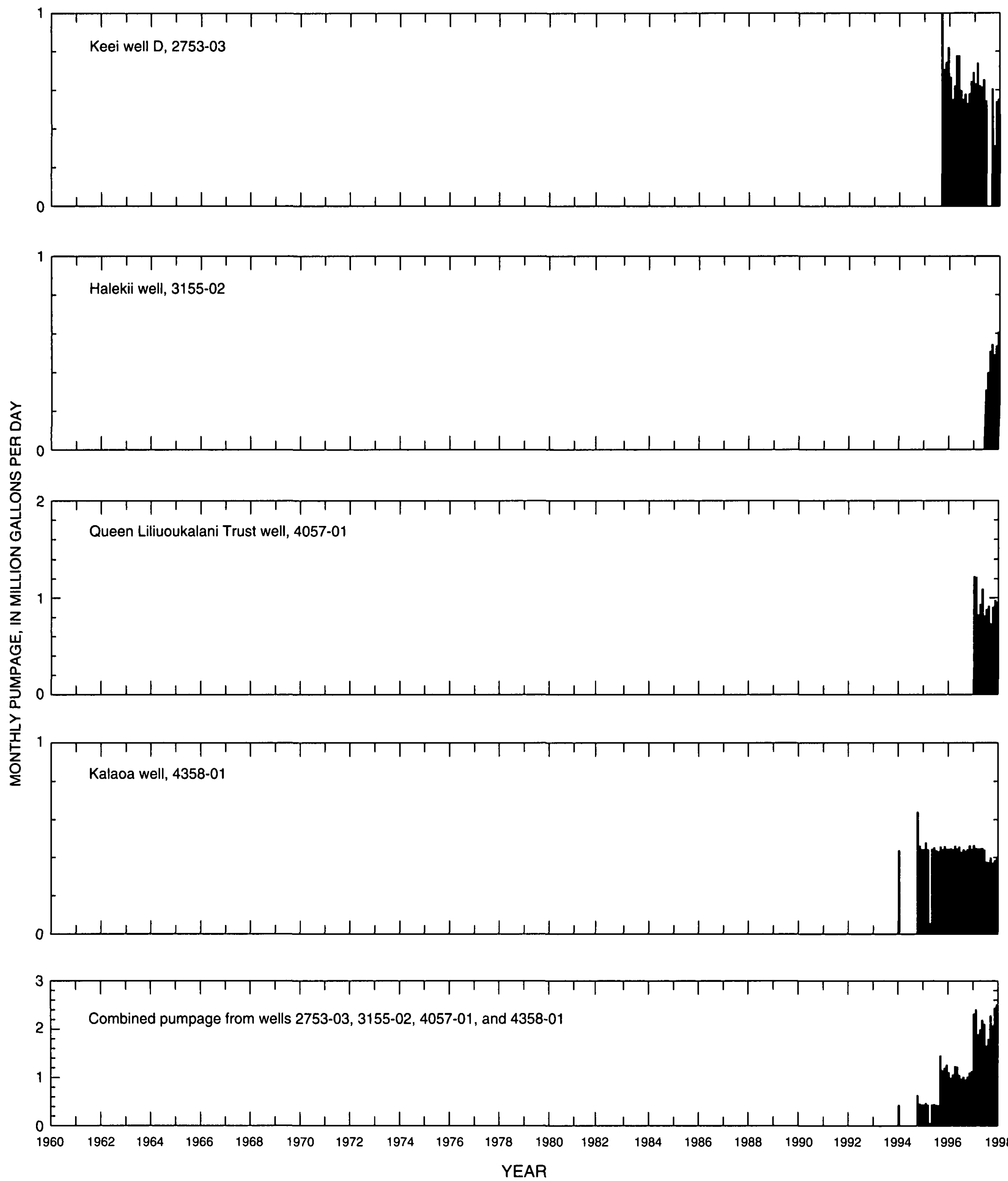


Figure 16. Monthly pumpage from selected Hawaii County wells, high water-level area, Kona, island of Hawaii (data from Commission on Water Resource Management, 1998, unpub.).

A number of privately owned wells are used to withdraw water from the coastal part of the ground-water system in the Kona area, where water levels are generally less than 10 ft above sea level. Reported combined withdrawal from two agricultural irrigation wells (0952-01 and 0953-01) near Okoe Bay (fig. 6) has averaged about 0.5 Mgal/d during 1989–97 (fig. 15). Reported combined withdrawal from three privately owned golf-course irrigation wells (3357-04, 3457-01, and 3457-03) near Keauhou has usually been between 0.5 and 1.5 Mgal/d since 1996. Five privately owned wells (Huehue Ranch wells 4459-01 to -02, 4558-01 to -02, and 4559-01) near Kalaoa are used for both domestic and irrigation purposes. Combined withdrawals from the Huehue Ranch wells have usually been between 0.2 and 0.5 Mgal/d since 1991. During the 1990's, the estimated withdrawal of saline water for aquaculture from Keahole wells 4363-01 to -10 has been about 2.9 Mgal/d (Neal Fujii, Commission on Water Resource Management, personal commun., 1998). Total unreported withdrawals from other privately owned wells that are used to withdraw ground water from the Kona area are probably small.

NUMERICAL SIMULATION OF THE GROUND-WATER FLOW SYSTEM

The movement of ground water into, through, and out of the Kaloko-Honokohau National Historical Park area was evaluated using a numerical ground-water flow model developed for the regional aquifer in western Hawaii (Oki, 1999). The regional model used the model code SHARP (Essaid, 1990), which uses a finite-difference approach to simulate flow in a ground-water system containing both freshwater and saltwater and treats freshwater and saltwater as immiscible fluids separated by a sharp interface. In reality, a diffuse transition zone exists between the core of freshwater and the underlying saltwater. In this study, it is assumed that the position of the surface defined by ground water with 50-percent seawater salinity (a mixture of half freshwater and half saltwater) is approximated by the sharp-interface position. The SHARP code simulates vertically averaged freshwater heads and vertically averaged saltwater heads in the aquifer and assumes that flow within a model layer is entirely horizontal.

The model grid, representation of the physical system, boundary conditions, and recharge used in this study are the same as those used in the regional model (Oki, 1999). For a complete description of these features and other information regarding the construction details of the model refer to Oki (1999). A brief summary of the model is provided below.

Model Grid

The finite-difference grid used in this study consists of 9,135 cells, arranged in a rectangular array with 145 rows and 63 columns (fig. 17). The model grid covers the Kona area below a land-surface altitude of 6,000 ft. Although recharge within the Kona area above a land-surface altitude of 6,000 ft was included in the model, ground-water flow in these areas was not modeled because ground-water conditions are uncertain. The active part of the grid extends at least a mile offshore to include the entire zone where fresh ground water discharges to the ocean. Within the active part of the grid, the grid spacing ranges from 500 to 8,000 ft. Grid spacing is finest near the coast where ground water discharges.

Boundary Conditions

SHARP supports three types of boundary conditions: (1) specified head, (2) specified flow (which includes no flow), and (3) head-dependent discharge. Specified-head boundary conditions were not used for this study. The outer rows and columns of the grid are no-flow boundaries in the SHARP code.

The aquifer bottom is treated as a no-flow boundary. Onshore, the aquifer bottom was assumed to exist at a depth of 6,000 ft below the land surface, and offshore, the aquifer bottom was assumed to exist 6,000 ft below the ocean floor. Interior areas above an altitude of 6,000 ft were not modeled.

The central parts of the northwest and south-southeast rift zones of Hualalai and the southwest rift zone of Mauna Loa were assumed to correspond to ground-water divides. In the model, the central parts of these rift zones were assumed to be no-flow boundaries, and areas inland of the central parts of the rift zones were not modeled. Thus, the inland boundary of the modeled area is formed by either a rift zone or the 6,000-ft land-surface contour.

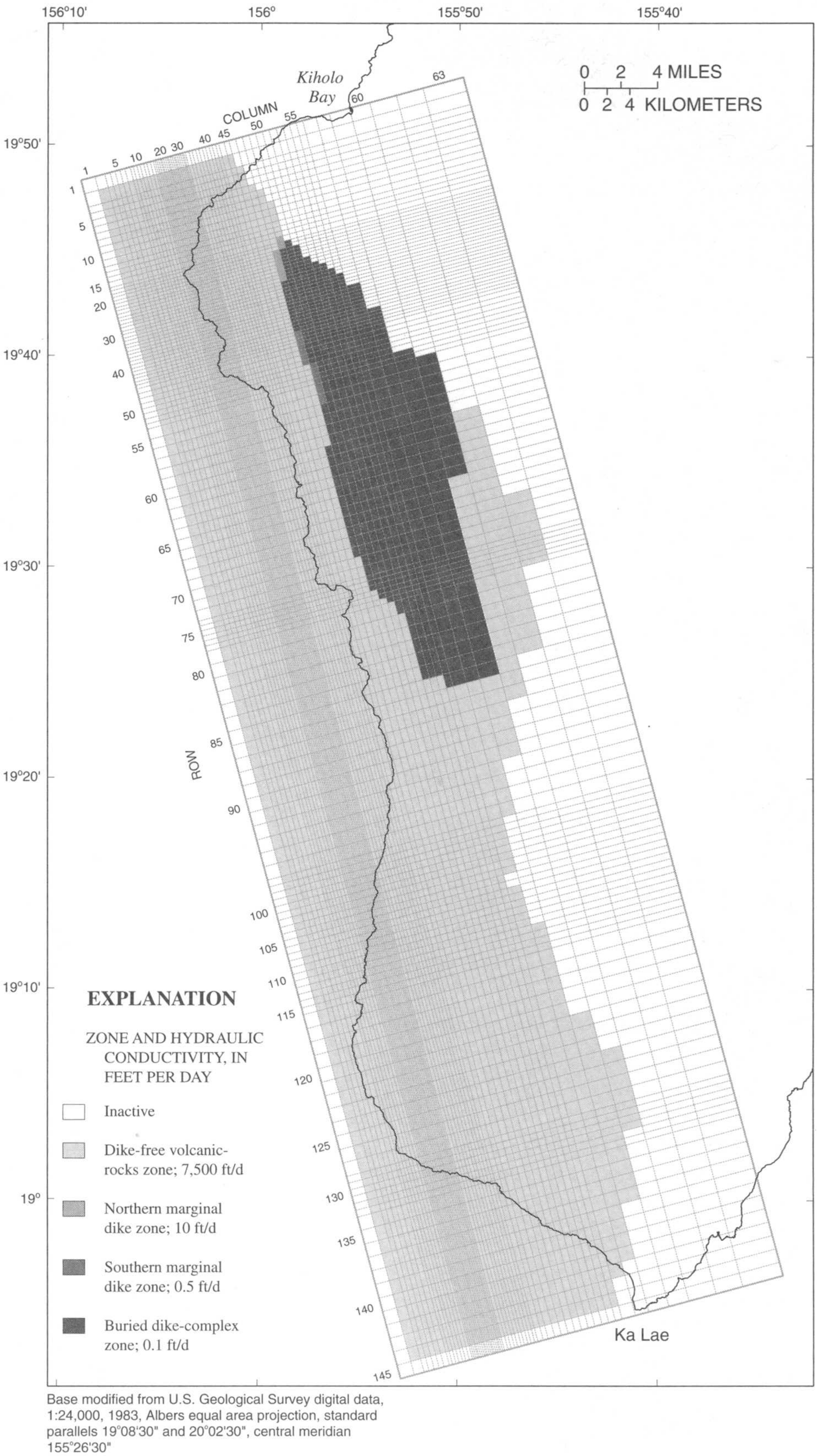


Figure 17. Finite-difference model grid and hydraulic-conductivity zones for western Hawaii, island of Hawaii.

All cells representing offshore areas and subaerial springs near the coast were modeled using a head-dependent discharge boundary condition. All cells not simulated as a head-dependent discharge boundary are unconfined cells (fig. 18).

Freshwater flow out of the model at head-dependent discharge cells is assumed to be linearly related to the difference between the head in the aquifer and the head overlying the aquifer at the discharge site according to the equation:

$$Q=(K'/B')A(h-h_0) \quad (1)$$

where:

Q is the rate of discharge from a model cell $[L^3/T]$,
K' is the vertical hydraulic conductivity of the confining unit overlying the aquifer [L/T],
B' is the thickness of the confining unit overlying the aquifer [L],
A is the area of the model cell $[L^2]$,
h is the head in the aquifer [L], and
h_0 is the head, measured relative to mean sea level, above the aquifer [L].

The vertical hydraulic conductivity of the confining unit divided by the confining-unit thickness is termed the coastal leakance in this report. Although a low-permeability coastal confining unit does not exist in the Kona area, the volcanic rocks do impede the discharge of ground water to the ocean. Thus, in the model, the vertical hydraulic conductivity of the confining unit is represented by the vertical hydraulic conductivity of the volcanic-rock aquifer, and the confining-unit thickness is represented by the aquifer thickness over which vertical discharge occurs. No attempt was made to estimate separate values for aquifer thickness over which vertical discharge occurs and vertical hydraulic conductivity for the Kona area; instead, the coastal leakance, which was assumed to be spatially constant, was estimated by trial and error to be 0.05 ft/d/ft.

The head, h_0, overlying the aquifer above onshore coastal-discharge cells is unknown but is probably near mean sea level, and is assumed to be zero. For offshore cells, h_0 was assigned a value corresponding to the freshwater-equivalent head of the saltwater column overlying the ocean floor within the cell. The freshwater-equivalent head, measured relative to a mean sea-level datum, was computed from the equation:

$$h_0=-Z/40, \quad (2)$$

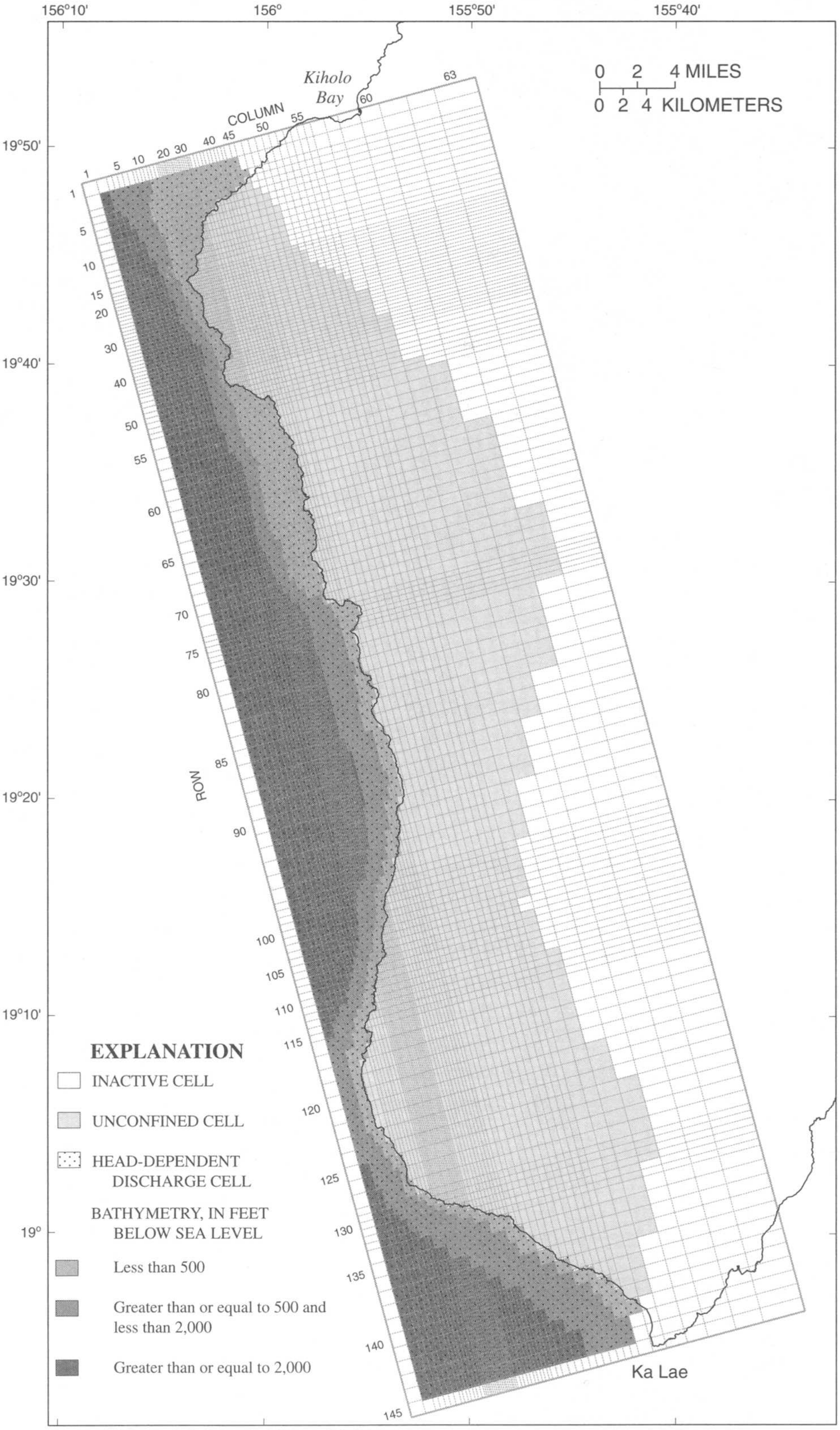
where Z is the altitude of the ocean floor (fig. 18).

Hydraulic-Conductivity Zones

The Kona study area was divided into four zones (fig. 17) with different horizontal hydraulic-conductivity values: (1) 7,500 ft/d for the dike-free volcanic rocks of Hualalai and Mauna Loa, (2) 0.1 ft/d for the buried Hualalai dike complex, (3) 10 ft/d for the northern marginal dike zone (north of Kalaoa) where measured water levels range from about 6 to 13 ft, and (4) 0.5 ft/d for the southern marginal dike zone inland of Kailua, between Palani Junction and Holualoa, where measured water levels range from about 40 to 200 ft. These four zones were created to adequately and efficiently represent the ground-water flow system. Available hydrologic and geologic information were considered insufficient to justify creation of additional zones. No hydraulic distinction was made between the dike-free volcanic rocks of Hualalai and Mauna Loa. The buried Hualalai dike-complex zone was located using hydrologic and geophysical information, and was modeled as a zone of lower overall hydraulic conductivity relative to the dike-free volcanic-rocks zone. On the basis of measured water levels, model zones were created for locations where marginal dike zones (the northern and southern marginal dike zones) are presumed to exist. The hydraulic conductivity of the marginal dike zones lies between the values for the dike-free volcanic rocks and the buried Hualalai dike complex.

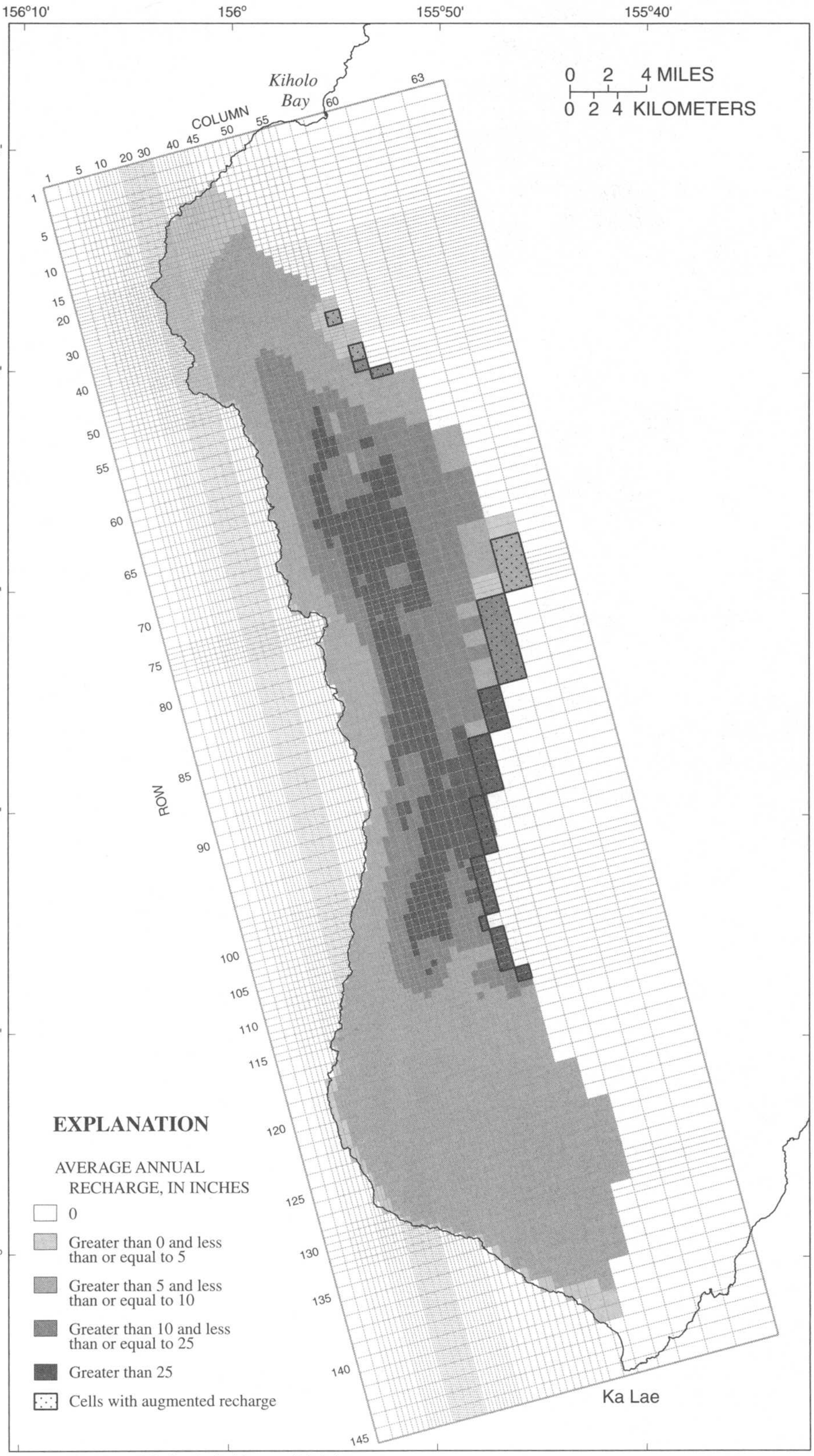
Recharge

Ground-water recharge to the model is distributed over the modeled area according to mean annual recharge rates estimated by Oki (1999) (fig. 19). The total recharge apportioned to the model was 357.5 Mgal/d. For cells lying along the 6,000-ft altitude boundary, recharge was added to account for recharge outside the model between the 6,000-ft level and the assumed inland ground-water divide defined by the central parts of the northwest and south-southeast rift zones of Hualalai and the southwest rift zone of Mauna Loa. Within a given row of the model grid, recharge in the Kona study area above an altitude of 6,000 ft was added to the easternmost active cell of the grid.



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 19°08'30" and 20°02'30", central meridian 155°26'30"

Figure 18. Finite-difference model grid and head-dependent discharge cells for western Hawaii, island of Hawaii.



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 19°08'30" and 20°02'30", central meridian 155°26'30"

Figure 19. Average annual recharge used in the ground-water flow model for western Hawaii, island of Hawaii.

Simulated Response of the Ground-Water Flow System to Withdrawals

All model simulations for this study were run to steady-state conditions. Ground-water withdrawals were added to the system in an order (table 7) determined on the basis of (1) whether the well was being used during 1978, the year the Park was established, (2) dates of water-use declarations to the CWRM, (3) dates when pump-installation permits were issued by CWRM, and (4) dates when well-construction permits were issued by CWRM. Changes in freshwater discharge through the Park were estimated relative to average 1978 conditions.

In the first simulation, average 1978 ground-water withdrawals of 3.853 Mgal/d from six wells (2753-01 to -02, 3557-01 to -04) (table 7) were used in the model to simulate ground-water levels and coastal discharge in the Park. For this 1978 base-case scenario, model-calculated water levels in the Park range from near sea level to about 2 ft above sea level (fig. 20), and total model-calculated freshwater coastal discharge within the Park is 6.48 Mgal/d, or about 3 Mgal/d per mile of coastline. For comparison, model-calculated freshwater coastal discharge within the Park for predevelopment (zero withdrawals) conditions is 6.55 Mgal/d. (Note that although the coastal discharge within the Park is actually brackish water, the model assumes that freshwater and saltwater do not mix and therefore the model-calculated coastal discharge within the Park is in the form of freshwater discharge.)

Model results indicate that, on a regional scale, water levels do not strictly increase in an inland direction and that a ground-water divide exists within the buried dike complex (fig. 20). Ground water to the west of this divide that is not withdrawn by wells flows toward coastal discharge areas. Ground water that originates from the buried dike complex to the east of this divide flows in an easterly, inland direction, then in a southerly direction around the southern extent of the low-permeability buried dike complex, and then in a southwesterly direction toward coastal discharge areas. Thus, model results indicate that the low-permeability buried dike complex may cause ground water to flow in directions that are not directly from inland areas to the coast. Data are not available, however, to verify model results in the area near and inland of the model-calculated ground-water divide.

In the second simulation, withdrawals from the six wells that were pumped during 1978 were increased to the capacity pumping rates (tables 6 and 7). The total capacity pumping rate from the six wells is 5.436 Mgal/d, which represents an increase of 1.583 Mgal/d relative to the average 1978 withdrawal rate. Because the model simulations were run to steady-state conditions, the 1.583 Mgal/d increase in ground-water withdrawals causes a corresponding decrease in coastal discharge of 1.583 Mgal/d. Of the total 1.583 Mgal/d reduction in coastal discharge, 0.02 Mgal/d reduction occurs within the Park, and this represents a 0.3 percent decrease relative to the 1978 base case (fig. 21).

For the remaining simulations, existing wells associated with water-use declarations made during 1989–90 were added to the system first, followed by existing wells with pump-installation permits issued during 1990–97. Other existing and proposed wells were added to the system last, according to the issue date of the well-construction permit. (Existing and proposed wells with well-construction permits issued prior to March 1998 were included.) All additional withdrawals from wells were assumed to be at the capacity pumping rates (tables 6 and 7), unless the model-calculated water table was lowered below the bottom of any well. In these cases, the simulated pumping rate at the most recently added well was reduced, to either 50, 25, or 0 percent of the capacity pumping rate, until the model-calculated water table remained above the bottoms of all wells.

Total ground-water withdrawals increased from one scenario to the next, and each increase in withdrawals caused a decrease in total coastal freshwater discharge. The decrease in coastal freshwater discharge was equal to the increase in freshwater withdrawals from one scenario to the next. The largest incremental increase in withdrawals was 9.108 Mgal/d resulting from the addition of wells 2653-01, 3457-02, 3557-05, 3657-01, and 3758-01, and the smallest incremental increase was 0.03 Mgal/d from well 0247-01.

Model-calculated freshwater coastal discharge within the Park also decreased from one scenario to the next in response to the increased withdrawals (fig. 21). The largest incremental decrease in model-calculated freshwater discharge within the Park was 0.44 Mgal/d caused by adding total withdrawals of 1.638 Mgal/d from wells 4160-01 and 4160-02. Wells 4160-01 and 4160-02 are about 1.5 mi directly upgradient from the Park. Withdrawals from wells south of Papa Bay had

Table 7. Order that pumped wells were added to the ground-water flow model, western Hawaii, island of Hawaii
[Mgal/d, million gallons per day]

Pumping order	Well no.	Well status	Model cell (row,column)	Pumping rate (Mgal/d)	Pumping rate notes
1	2753-01	existing well used in 1978	80,50	0.228	average 1978 pumping rate
1	2753-02	existing well used in 1978	80,50	0.115	average 1978 pumping rate
1	3557-01	existing well used in 1978	60,46	0.664	average 1978 pumping rate
1	3557-02	existing well used in 1978	61,46	1.004	average 1978 pumping rate
1	3557-03	existing well used in 1978	60,46	0.591	average 1978 pumping rate
1	3557-04	existing well used in 1978	61,46	1.251	average 1978 pumping rate
2	2753-01	existing well used in 1978	80,50	0.432	pump capacity
2	2753-02	existing well used in 1978	80,50	0.54	pump capacity
2	3557-01	existing well used in 1978	60,46	1.008	pump capacity
2	3557-02	existing well used in 1978	61,46	1.008	pump capacity
2	3557-03	existing well used in 1978	60,46	1.008	pump capacity
2	3557-04	existing well used in 1978	61,46	1.44	pump capacity
3	4160-01	existing well at time water-use declaration accepted on 2/28/89	35,42	0.999	pump capacity
3	4160-02	existing well at time water-use declaration accepted on 2/28/89	35,41	0.639	pump capacity
4	4559-01	existing well at time water-use declaration accepted on 5/18/89	17,49	0.504	pump capacity
5	3357-01	existing well at time water-use declaration accepted on 5/26/89	63,44	1.008	pump capacity
5	3457-01	existing well at time water-use declaration accepted on 5/26/89	61,43	1.008	pump capacity
5	3457-03	existing well at time water-use declaration accepted on 5/26/89	61,44	0.72	pump capacity
6	4461-01	existing well at time water-use declaration accepted on 5/30/89	19,35	0.144	estimated pump capacity
6	0953-01	existing well at time water-use declaration accepted on 5/30/89	116,25	1.14	pump capacity
6	0246-01	existing well at time water-use declaration accepted on 5/30/89	129,51	0.71	pump capacity
7	4363-01 to -10	existing well at time water-use declaration accepted on 5/21/90	19,18	3.6	estimated pump capacity
8	2653-01	existing well at time water-use declaration accepted on 11/5/90	81,50	0.72	pump capacity
8	3457-02	existing well at time water-use declaration accepted on 11/5/90	61,46	0.72	estimated pump capacity
8	3557-05	existing well at time water-use declaration accepted on 11/5/90	60,45	6.048	pump capacity
8	3657-01	existing well at time water-use declaration accepted on 11/5/90	57,47	0.72	pump capacity
8	3758-01	existing well at time water-use declaration accepted on 11/5/90	55,46	0.9	maximum annual withdrawal rate
9	4459-01	existing well at time pump-installation permit issued on 4/2/91	19,48	0.72	pump capacity
9	4459-02	existing well at time pump-installation permit issued on 4/2/91	18,48	0.72	pump capacity
9	4558-01	existing well at time pump-installation permit issued on 4/2/91	15,49	0.72	pump capacity
10	4462-02	existing well at time pump-installation permit issued on 9/8/92	17,35	0.144	pump capacity
11	2753-03	existing well at time pump-installation permit issued on 9/29/92	79,52	1.44	pump capacity
12	4158-02	existing well at time pump-installation permit issued on 1/29/93	42,48	2.016	pump capacity
12	4358-01	existing well at time pump-installation permit issued on 1/29/93	29,48	0.252	pump capacity
13	2354-01	existing well at time pump-installation permit issued on 11/3/93	85,44	0.288	pump capacity

Table 7. Order that pumped wells were added to the ground-water flow model, western Hawaii, island of Hawaii--Continued
[Mgal/d, million gallons per day]

Pumping order	Well no.	Well status	Model cell (row,column)	Pumping rate (Mgal/d)	Pumping rate notes
14	4057-01	existing well at time pump-installation permit issued on 7/7/94	48,49	1.512	pump capacity
15	3155-02	existing well at time pump-installation permit issued on 12/30/94	69,48	2.016	pump capacity
16	4060-01	existing well at time pump-installation permit issued on 5/19/95	41,36	0.036	pump capacity
17	3357-04	existing well at time pump-installation permit issued on 9/20/96	64,44	0.504	pump capacity
18	4258-03	existing well at time pump-installation permit issued on 1/7/97	34,48	1.44	pump capacity
19	4461-02	existing well at time pump-installation permit issued on 11/20/97	19,36	0.72	pump capacity
20	0247-01	well construction permit issued 1/12/87	129,47	0.03	pump capacity
21	0952-01	well construction permit issued 3/3/88	117,31	1.57	pump capacity
22	3456-01	well construction permit issued 10/31/88	62,46	0.999	pump capacity
23	3657-02	well construction permit issued 5/8/89	58,47	1.0	estimated pump capacity
24	4458-01	well construction permit issued 9/27/89	22,49	1.07	pump capacity
24	4458-02	well construction permit issued 9/27/89	23,48	1.07	pump capacity
25	3355-01	well construction permit issued 7/16/90	64,48	1.512	estimated pump capacity
26	4259-01	well construction permit issued 8/8/90	30,45	0.72	pump capacity
26	4259-02	well construction permit issued 8/8/90	31,45	0.72	pump capacity
27	3355-02	well construction permit issued 12/5/90	64,48	0.756	50 percent of pump capacity
27	3355-03	well construction permit issued 12/5/90	64,48	0.756	50 percent of pump capacity
27	3957-01	well construction permit issued 12/5/90	51,49	0.72	pump capacity
28	0446-01	well construction permit issued 8/20/91	126,51	0.032	pump capacity
29	3056-01	well construction permit issued 4/1/92	69,45	1.008	pump capacity
30	1652-01	well construction permit issued 4/27/92	96,43	1.0	estimated pump capacity
31	4057-04	well construction permit issued 1/29/93	44,48	1.44	pump capacity
32	3255-02	well construction permit issued 3/2/93	67,48	1.5	estimated pump capacity
33	0950-01	well construction permit issued 7/28/93	117,44	1.08	pump capacity
33	1050-01	well construction permit issued 7/28/93	116,44	1.08	pump capacity
34	4258-04	well construction permit issued 8/10/93	36,48	0.378	25 percent of pump capacity
35	3153-01	well construction permit issued 2/21/96	70,52	0.576	pump capacity
36	2952-01	well construction permit issued 7/17/96	74,53	1.296	pump capacity
37	1254-02	well construction permit issued 8/14/96	107,21	0.036	pump capacity
38	3957-04	well construction permit issued 3/27/97	52,48	0.432	pump capacity
39	3153-02	well construction permit issued 2/5/98	69,53	0.27	25 percent of pump capacity
40	3857-03	well construction application received 7/29/93	54,49	1.44	pump capacity
41	3857-02	well construction application received 2/2/98	53,49	0.00	0 percent of pump capacity

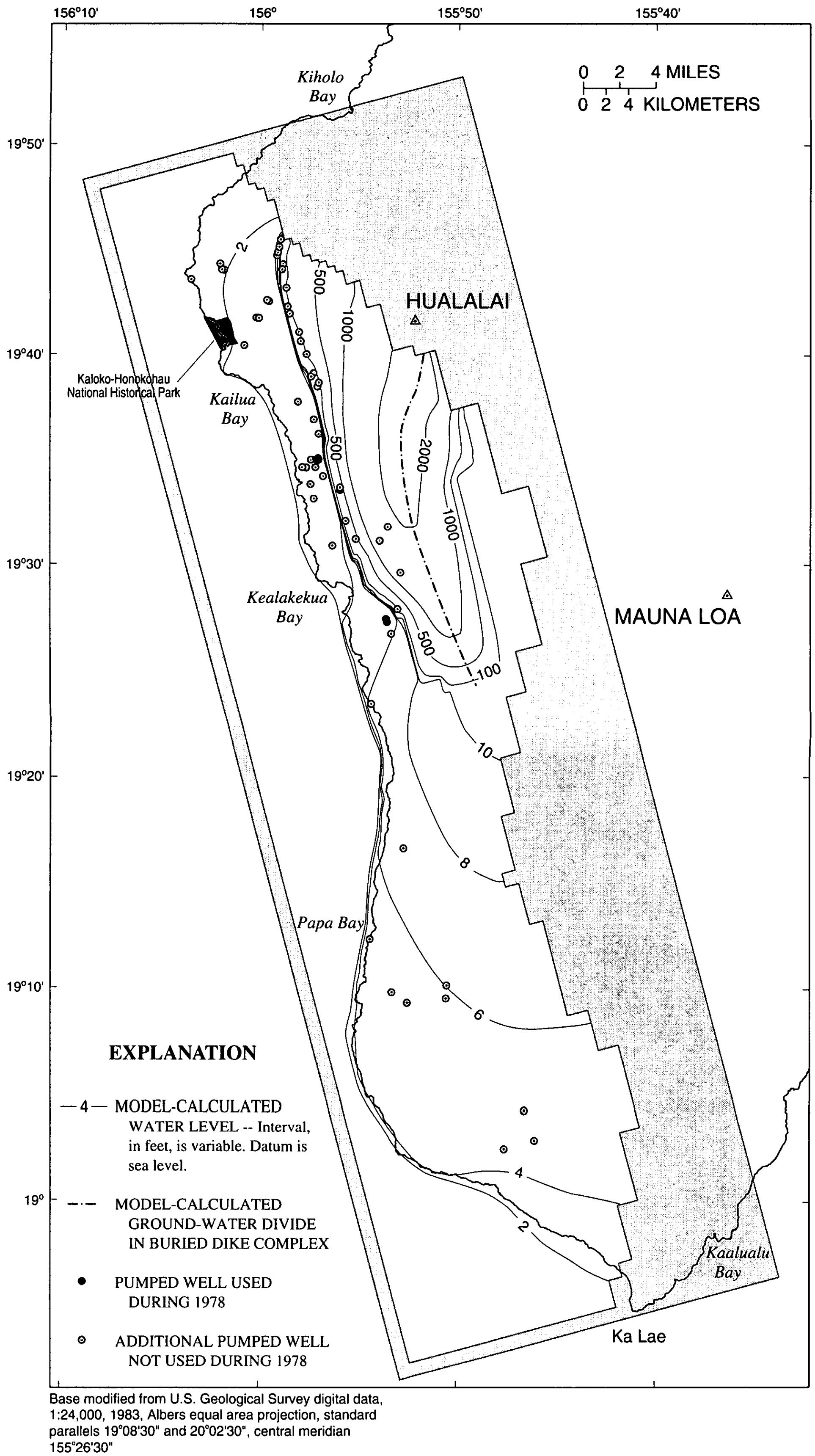


Figure 20. Model-calculated water levels for average 1978 ground-water withdrawal rates, western Hawaii, island of Hawaii.

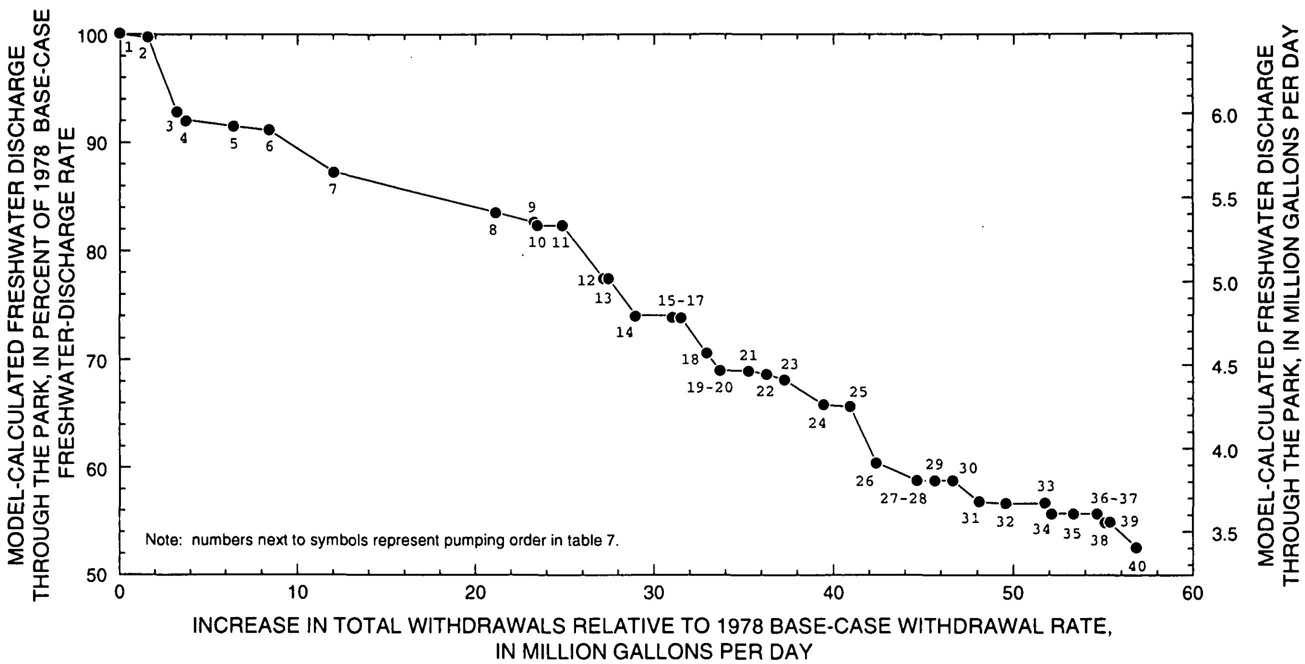


Figure 21. Reduction of model-calculated freshwater discharge through Koloko-Honokahau National Historical Park caused by ground-water withdrawals in excess of average 1978 withdrawal rates in western Hawaii, island of Hawaii.

little effect on the model-calculated freshwater discharge within the Park. A total increase in ground-water withdrawals, relative to the average 1978 withdrawal rates, of 56.8 Mgal/d caused a 47 percent reduction of model-calculated freshwater coastal discharge within the Park and water-level declines of about 0.6 ft within the Park (fig. 22). Although the model cannot predict salinity changes in response to a reduction in coastal discharge within the Park, salinity is expected to increase if the freshwater component of flow through the Park is reduced by 47 percent.

MODEL LIMITATIONS

The ground-water flow model of the Kona area used in this study has several limitations (Oki, 1999). Because available data are limited, the flow model is not considered to be calibrated. An insufficient number of monitor wells exist to define the spatial distribution of water levels in the southwestern part of the island and the inland parts of the Kona area above a land-surface altitude of 2,000 ft. Thus, the distribution of model-calculated water levels, although informative, is unverified in places.

The model developed for this study is not unique. That is, it is possible that different distributions of hydraulic conductivity, coastal leakance, and aquifer thickness can be used in a model to produce equally acceptable model-calculated water levels. Model zones were created to represent marginal dike zones. Although this zonation is plausible, other zonation geometries could probably produce similar results. The model developed for this study can be refined and a better representation of the flow system can be obtained as more data become available to constrain the model.

The model used in this study cannot predict the distribution of salinity within the aquifer and is not capable of predicting water quality changes in the Park. Because of mixing effects, a diffuse transition zone exists near the coastal parts of the Kona area. Furthermore, available data indicate that brackish water exists immediately below the water table in the Park. The regional model used in this study assumes that freshwater and saltwater do not mix. Thus, although coastal

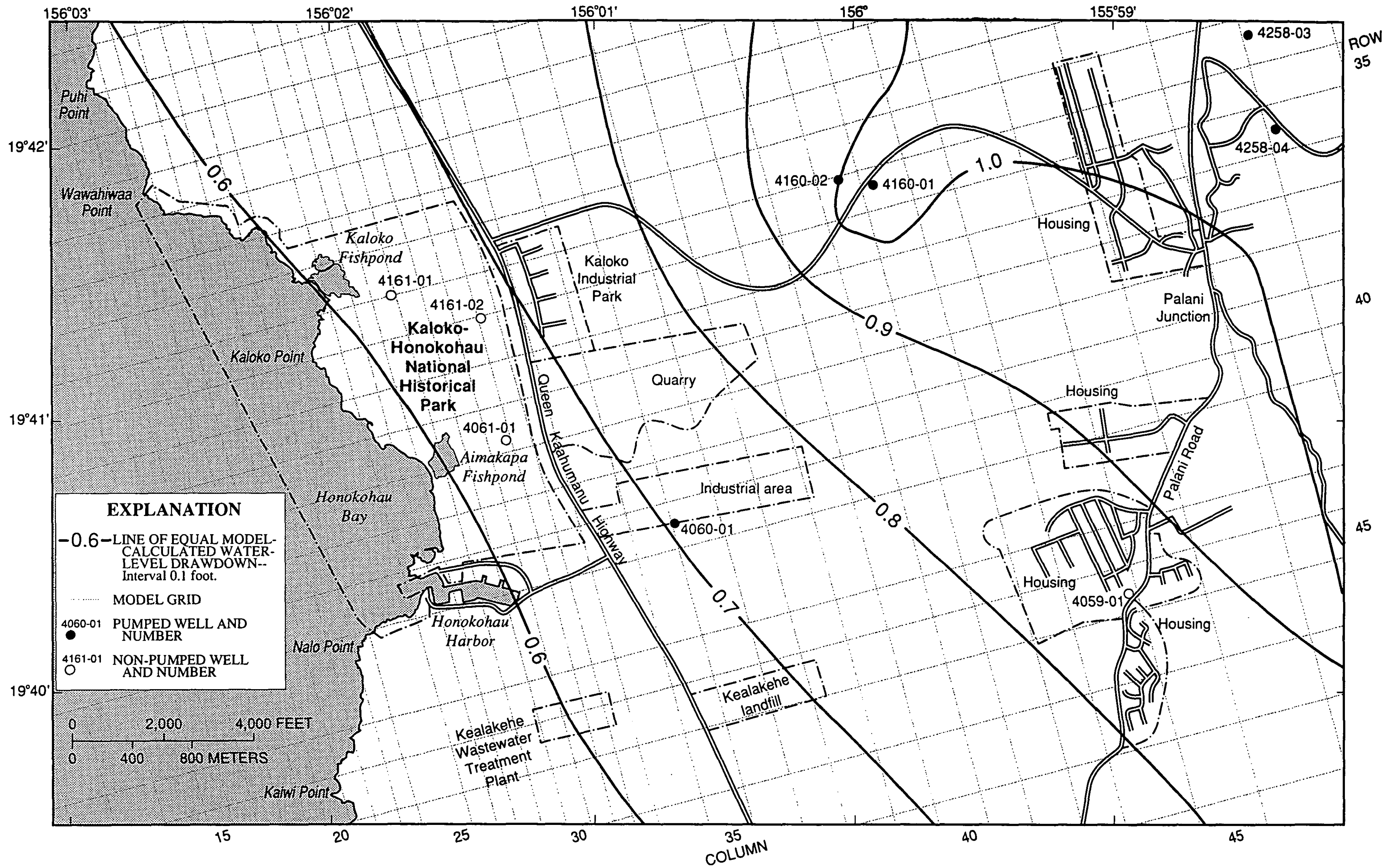


Figure 22. Model-calculated water-level drawdown near Kaloko-Honokohau National Historical Park (seaward of the high water-level area), relative to model-calculated water levels for average 1978 withdrawal rates, caused by withdrawing an additional 56.8 Mgal/d from the Kona area, island of Hawaii.

discharge within the Park is actually brackish water, the model-calculated coastal discharge within the Park is freshwater.

The model used in this study simulates regional water levels and ground-water flow, but the model should not be viewed as a highly accurate tool to predict local-scale changes because of the uncertainty in the hydraulic-conductivity distribution in the model. The model is, nevertheless, the best available tool for demonstrating the possible regional hydrologic effects of additional withdrawals in the vicinity of the Park for steady-state conditions.

SUMMARY AND CONCLUSIONS

In the Kona area, fresh ground water flows from inland areas to coastal discharge areas. Near the coast, seaward flowing freshwater mixes with underlying saltwater and a brackish-water transition zone is formed. Within Kaloko-Honokohau National Historical Park, brackish water exists immediately below the water table. Recharge from the direct infiltration of precipitation within the Park is small because of low rainfall and high rates of evaporation. The main freshwater component of brackish water flowing through the Park is from subsurface flow originating from inland areas east of the Park.

Brackish water flows through the Park and ultimately discharges to the fishponds, anchialine ponds, and wetland areas within the Park or directly to the ocean. The ground water, fishponds, and anchialine ponds in the Park are hydrologically connected with each other. The water levels in the ponds mark the local position of the water table. Ground-water levels in the Park range from about 1 to 2 ft above mean sea level, and fluctuate daily by about 0.5 to 1.5 ft in response to ocean tides.

Within the Park, water from three exploratory wells, 4060-01, 4161-02, and 4161-01, had chloride concentrations ranging from 2,610 to 5,910 mg/L. The water sample from well 4161-02, the most inland well, was the freshest sample obtained from any source within the Park. Chromium and copper were found in water samples from the three exploratory wells in the Park and one well upgradient of the Park at concentrations of 1 to 5 μg/L. One semi-volatile organic compound, phenol, was detected in water samples from the three wells in the Park at concentrations between 4 and 10 μg/L.

The movement of ground water into, through, and out of the Kaloko-Honokohau National Historical Park area was evaluated using a numerical ground-water flow model developed for the regional aquifer in western Hawaii. For average 1978 ground-water withdrawal conditions, the model-calculated rate of freshwater coastal discharge within the boundary of the Park is about 6.48 Mgal/d, or about 3 Mgal/d per mile of coastline. Model results indicate that ground-water withdrawals will reduce the rate of freshwater discharge within the Park. Withdrawals from wells directly upgradient of the Park had the greatest effect on the model-calculated freshwater discharge within the Park, whereas withdrawals from wells south of Papa Bay had little effect on the freshwater discharge within the Park. A total increase in ground-water withdrawals, relative to the average 1978 withdrawal rates, of 56.8 Mgal/d caused about a 47 percent reduction of model-calculated freshwater coastal discharge within the Park and water-level declines of about 0.6 ft within the Park. Although the model cannot predict salinity changes in response to a reduction in coastal discharge within the Park, salinity will increase by an unquantified amount if the freshwater component of flow through the Park is reduced by 47 percent.

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Table 4. Concentrations of trace metals and organic contaminants in water from three wells in Kaloko-Honokohau National Historical Park, island of Hawaii, and one well upgradient of industrial activity

[---, constituent was not detected by the analysis at the standard minimum reporting level; E, estimated concentration for detection below the minimum reporting level; µg/L, micrograms per liter]

	Well no. and name				Minimum reporting level	Units
	4061-01 (Kaho 1)	4161-02 (Kaho 2)	4161-01 (Kaho 3)	4358-01 (Kalaoa)		
Trace metals (USGS lab schedule 700)						
Antimony	---	---	---	---	1	µg/L
Arsenic	---	---	---	---	1	µg/L
Beryllium	---	---	---	---	10	µg/L
Cadmium	<5	---	---	---	1	µg/L
Chromium	3	1	2	3	1	µg/L
Copper	5	4	5	1	1	µg/L
Cyanide	---	---	---	---	0.010	mg/L
Lead	---	---	---	---	1	µg/L
Nickel	---	---	1	---	1	µg/L
Selenium	---	---	---	1	1	µg/L
Silver	---	---	---	---	1	µg/L
Zinc	---	10	---	---	10	µg/L
Volatile organic compounds (USGS lab schedule 1380)						
1,1,1,2-Tetrachloroethane	---	---	---	---	0.200	µg/L
1,1,1-Trichloroethane	---	---	---	---	0.200	µg/L
1,1,2,2-Tetrachloroethane	---	---	---	---	0.200	µg/L
1,1,2-Trichloroethane	---	---	---	---	0.200	µg/L
1,1,2-Trichlorotrifluoroethane	---	---	---	---	0.200	µg/L
1,1-Dichloroethane	---	---	---	---	0.200	µg/L
1,1-Dichloroethylene	---	---	---	---	0.200	µg/L
1,1-Dichloropropene	---	---	---	---	0.200	µg/L
1,2,3-Trichlorobenzene	---	---	---	---	0.200	µg/L
1,2,3-Trichloropropane	---	---	---	---	0.200	µg/L
1,2,4-Trichlorobenzene	---	---	---	---	0.200	µg/L
1,2,4-Trimethylbenzene	---	---	---	---	0.200	µg/L
1,2-Dibromo-3-chloropropane	---	---	---	---	1.00	µg/L
1,2-Dibromoethane	---	---	---	---	0.200	µg/L
1,2-Dichlorobenzene	---	---	---	---	0.200	µg/L
1,2-Dichloroethane	---	---	---	---	0.200	µg/L
1,2-Dichloropropane	---	---	---	---	0.200	µg/L
1,3,5-Trimethylbenzene	---	---	---	---	0.200	µg/L
1,3-Dichlorobenzene	---	---	---	---	0.200	µg/L
1,3-Dichloropropane	---	---	---	---	0.200	µg/L
1,4-Dichlorobenzene	---	---	---	---	0.200	µg/L
2,2-Dichloropropane	---	---	---	---	0.200	µg/L
2-Chlorotoluene	---	---	---	---	0.200	µg/L
4-Chlorotoluene	---	---	---	---	0.200	µg/L
4-Isopropyl-1-methylbenzene	---	---	---	---	0.200	µg/L
Benzene	---	---	---	---	0.200	µg/L
Bromobenzene	---	---	---	---	0.200	µg/L
Bromochloromethane	---	---	---	---	0.200	µg/L
Bromodichloromethane	---	---	---	---	0.200	µg/L
Bromoform	---	---	---	---	0.200	µg/L
Bromomethane	---	---	---	---	0.200	µg/L
Butylbenzene	---	---	---	---	0.200	µg/L
Chlorobenzene	---	---	---	---	0.200	µg/L
Chloroethane	---	---	---	---	0.200	µg/L
Chloroform	---	---	---	---	0.200	µg/L
Chloromethane	---	---	---	---	0.200	µg/L
cis-1,2-Dichloroethylene	---	---	---	---	0.200	µg/L
cis-1,3-Dichloropropene	---	---	---	---	0.200	µg/L
Dibromochloromethane	---	---	---	---	0.200	µg/L

Table 4. Concentrations of trace metals and organic contaminants in water from three wells in Kaloko-Honokohau National Historical Park, island of Hawaii, and one well upgradient of industrial activity--Continued

[---, constituent was not detected by the analysis at the standard minimum reporting level; E, estimated concentration for detection below the minimum reporting level; µg/L, micrograms per liter]

	Well no. and name				Minimum reporting level	Units
	4061-01 (Kaho 1)	4161-02 (Kaho 2)	4161-01 (Kaho 3)	4358-01 (Kalaoa)		
Volatile organic compounds (USGS lab schedule 1380)--Continued						
Dibromomethane	---	---	---	---	0.200	µg/L
Dichlorodifluoromethane	---	---	---	---	0.200	µg/L
Dichloromethane	---	---	---	---	0.200	µg/L
Ethylbenzene	---	---	---	---	0.200	µg/L
Hexachlorobutadiene	---	---	---	---	0.200	µg/L
Isopropylbenzene	---	---	---	---	0.200	µg/L
Naphthalene	---	---	---	---	0.200	µg/L
Propylbenzene	---	---	---	---	0.200	µg/L
sec-Butylbenzene	---	---	---	---	0.200	µg/L
Styrene	---	---	---	---	0.200	µg/L
tert-Butyl methyl ether	---	---	---	---	0.200	µg/L
tert-Butylbenzene	---	---	---	---	0.200	µg/L
Tetrachloroethylene	---	---	---	---	0.200	µg/L
Tetrachloromethane	---	---	---	---	0.200	µg/L
Toluene	---	---	---	---	0.200	µg/L
trans-1,2-Dichloroethylene	---	---	---	---	0.200	µg/L
trans-1,3-Dichloropropene	---	---	---	---	0.200	µg/L
Trichloroethylene	---	---	---	---	0.200	µg/L
Trichlorofluoromethane	---	---	---	---	0.200	µg/L
Vinyl chloride	---	---	---	---	0.200	µg/L
Xylene	---	---	---	---	0.200	µg/L
Semi-volatile organic compounds (USGS lab schedule 1383)						
1,2-Diphenylhydrazine	---	---	---	---	5.00	µg/L
2,4,6-Trichlorophenol	---	---	---	---	20.0	µg/L
2,4-Dichlorophenol	---	---	---	---	5.00	µg/L
2,4-Dimethylphenol or Dichlorprop	---	---	---	---	5.00	µg/L
2,4-Dinitrophenol	---	---	---	---	20.0	µg/L
2,4-Dinitrotoluene	---	---	---	---	5.00	µg/L
2,6-Dinitrotoluene	---	---	---	---	5.00	µg/L
2-Chloronaphthalene	---	---	---	---	5.00	µg/L
2-Chlorophenol	---	---	---	---	5.00	µg/L
2-Nitrophenol	---	---	---	---	5.00	µg/L
3,3′-Dichlorobenzidine	---	---	---	---	20.0	µg/L
4,6-Dinitro-2-methylphenol	---	---	---	---	30.0	µg/L
4-Bromophenylphenylether	---	---	---	---	5.00	µg/L
4-Chloro-3-methylphenol	---	---	---	---	30.0	µg/L
4-Chlorophenyl phenyl ether	---	---	---	---	5.00	µg/L
4-Nitrophenol	---	---	---	---	30.0	µg/L
Acenaphthene	---	---	---	---	5.00	µg/L
Acenaphthylene	---	---	---	---	5.00	µg/L
Anthacene	---	---	---	---	5.00	µg/L
Benz[*a*]anthracene	---	---	---	---	10.0	µg/L
Benzidine	---	---	---	---	40.0	µg/L
Benzo[*a*]pyrene	---	---	---	---	10.0	µg/L
Benzo[*b*]fluoranthene	---	---	---	---	10.0	µg/L
Benzo[*ghi*]perylene	---	---	---	---	10.0	µg/L
Benzo[*k*]fluoranthene	---	---	---	---	10.0	µg/L
bis(2-Chloroethoxy)methane	---	---	---	---	5.00	µg/L
bis(2-Chloroethyl)ether	---	---	---	---	5.00	µg/L
bis(2-chloroisopropyl) ether	---	---	---	---	5.00	µg/L
Bis(2-ethylhexyl) phthalate	---	---	---	---	5.00	µg/L
Butylbenzyl phthalate	---	---	---	---	5.00	µg/L

Table 4. Concentrations of trace metals and organic contaminants in water from three wells in Kaloko-Honokohau National Historical Park, island of Hawaii, and one well upgradient of industrial activity--Continued

[---, constituent was not detected by the analysis at the standard minimum reporting level; E, estimated concentration for detection below the minimum reporting level; µg/L, micrograms per liter]

	Well no. and name				Minimum reporting level	Units
	4061-01 (Kaho 1)	4161-02 (Kaho 2)	4161-01 (Kaho 3)	4358-01 (Kalaoa)		
Semi-volatile organic compounds (USGS lab schedule 1383)--Continued						
Chrysene	---	---	---	---	10.0	µg/L
Di-*n*-butyl phthalate	---	---	---	---	5.00	µg/L
Di-*n*-octyl phthalate	---	---	---	---	10.0	µg/L
Dibenz[*a,h*]anthracene	---	---	---	---	10.0	µg/L
Diethyl phthalate	---	---	---	---	5.00	µg/L
Dimethyl phthalate	---	---	---	---	5.00	µg/L
Fluoranthene	---	---	---	---	5.00	µg/L
Fluorene	---	---	---	---	5.00	µg/L
Hexachlorobenzene	---	---	---	---	5.00	µg/L
Hexachlorocyclopentadiene	---	---	---	---	20.0	µg/L
Hexachloroethane	---	---	---	---	5.00	µg/L
Indeno[1,2,3-*cd*]pyrene	---	---	---	---	10.0	µg/L
Isophorone	---	---	---	---	5.00	µg/L
N-Nitrosodi-*n*-propylamine	---	---	---	---	5.00	µg/L
N-Nitrosodimethylamine	---	---	---	---	5.00	µg/L
N-Nitrosodiphenylamine	---	---	---	---	5.00	µg/L
Nitrobenzene	---	---	---	---	5.00	µg/L
Pentachlorophenol	---	---	---	---	30.0	µg/L
Phenanthrene	---	---	---	---	5.00	µg/L
Phenol	7.14	9.17	E4.33	---	5.00	µg/L
Pyrene	---	---	---	---	5.00	µg/L
Organochlorine and organophosphate pesticides (USGS lab schedule 1334)						
Aldrin	---	---	---	---	0.010	µg/L
alpha-Endosulfan	---	---	---	---	0.010	µg/L
Carbophenothion	---	---	---	---	0.010	µg/L
Chlordane, technical mix	---	---	---	---	0.100	µg/L
Chlorpyrifos	---	---	---	---	0.010	µg/L
DEF	---	---	---	---	0.020	µg/L
Diazinon	---	---	---	---	0.010	µg/L
Dieldrin	---	---	---	---	0.010	µg/L
Disulfoton	---	---	---	---	0.030	µg/L
Endrin	---	---	---	---	0.010	µg/L
Ethion	---	---	---	---	0.010	µg/L
Fonofos	---	---	---	---	0.010	µg/L
Heptachlor	---	---	---	---	0.010	µg/L
Heptachlor epoxide	---	---	---	---	0.010	µg/L
Lindane	---	---	---	---	0.010	µg/L
Malathion	---	---	---	---	0.050	µg/L
Mirex	---	---	---	---	0.010	µg/L
p,p′-DDD	---	---	---	---	0.010	µg/L
p,p′-DDE	---	---	---	---	0.010	µg/L
p,p′-DDT	---	---	---	---	0.010	µg/L
p,p′-Methoxychlor	---	---	---	---	0.010	µg/L
Parathion	---	---	---	---	0.010	µg/L
Parathion-methyl	---	---	---	---	0.010	µg/L
Perthane	---	---	---	---	0.100	µg/L
Phorate	---	---	---	---	0.010	µg/L
Polychlorinated biphenyls	---	---	---	---	0.100	µg/L
Polychlorinated naphthalenes	---	---	---	---	0.10	µg/L
Toxaphene	---	---	---	---	1.00	µg/L

Table 6. Available information on existing and proposed wells, western Hawaii, island of Hawaii

[Data from CWRM State well index and USGS well files; --, data unavailable; (e), estimated; Mgal/d, million gallons per day; Mgal/d/ft, million gallons per day per foot of drawdown]

Well no.	Owner	Year drilled	Latitude	Longitude	Casing diameter (inches)	Altitude, in feet relative to mean sea level: Ground surface	Bottom of hole	Bottom of solid casing	Bottom of perforated casing	Specific capacity (Mgal/d/ft)	Pump capacity (Mgal/d)	Use	Year use checked
0246-01	Hawaii Kau Ranch	--	19°02′57″	155°46′02″	8	1,037	-58	-18	-58	--	0.71	unused	1998
0247-01	F.M. Thibedeau	--	19°02′33″	155°47′34″	4	600	-12	--	--	--	0.03	domestic	1998
0446-01	R. Scharfenberg	--	19°04′22″	155°46′34″	--	--	--	--	--	--	0.032	--	--
0950-01	Mac Farms Hawaii, Inc.	proposed	19°09′37″	155°50′32″	--	--	--	--	--	--	1.08	--	--
0952-01	Mac Farms Hawaii, Inc.	--	19°09′24″	155°52′30″	--	--	--	--	--	--	1.57	irrigation	1998
0953-01	Mac Farms Hawaii, Inc.	1980	19°09′54″	155°53′15″	12	848	-32	-2	-32	368	1.14	irrigation	1998
1050-01	Mac Farms Hawaii, Inc.	proposed	19°10′14″	155°50′30″	--	--	--	--	--	--	1.08	--	--
1254-02	Kuakalaelae Pt., Inc.	proposed	19°12′25″	155°54′23″	--	--	--	--	--	--	0.036	--	--
1652-01	SW Slopes, Inc.	1993	19°16′42″	155°52′41″	12	1,201	-21	3	-21	123	1.0(e)	unused	1993
1953-01	Magoon Estate	1965	19°19′21″	155°53′11″	8	206	-20	0	-20	--	0.216	unused	1998
2354-01	D. O'Shea	1994	19°23′27″	155°54′20″	--	9	-4	--	--	400	0.288	domestic	1998
2554-01	Bishop Estate	1956	19°25′47″	155°54′22″	10	178(e)	-15	1	-14	--	--	--	--
2653-01	Hawaii County DWS	1978	19°26′46″	155°53′20″	12	882	-31	-1	-31	592	0.72	municipal	1998
2753-01	Hawaii County DWS	1958	19°27′31″	155°53′41″	12	744	-36	-26	--	143	0.432	municipal	1998
2753-02	Hawaii County DWS	1963	19°27′22″	155°53′38″	12	737	-37	2	-37	900	0.54	municipal	1998
2753-03	Hawaii County DWS	1992	19°27′57″	155°53′01″	18	1,347	4	364	4	391	1.44	municipal	1998
2755-01	W. Thompson	1955	19°27′38″	155°55′13″	2	45	5	--	--	--	--	other	1974
2855-01	W. Thompson	1939	19°28′24″	155°55′15″	72	20	0	--	--	--	--	other	1974
2952-01	Kealakekua Dev. Corp.	proposed	19°29′41″	155°52′53″	--	--	--	--	--	--	1.296	--	--
3056-01	Oceanside 1250	1993	19°30′58″	155°56′19″	14	811	-38	2	-38	158	1.008	unused	1998
3153-01	Hokukano Ranch	1996	19°31′12″	155°53′56″	16	2,534	1,184	1,284	1,184	633	0.576	--	--
3153-02	Cardinal Investment	proposed	19°31′52″	155°53′32″	--	--	--	--	--	--	1.008	--	--
3155-01	USGS	1991	19°31′19″	155°55′08″	--	--	--	--	--	--	--	observation	1998
3155-02	Hawaii County DWS	1993	19°31′17″	155°55′08″	20	1,748	1	491	41	273	2.016	municipal	1997
3255-01	USGS	1991	19°32′29″	155°55′29″	--	--	--	--	--	--	--	observation	1998
3255-02	State of Hawaii, DLNR	1993	19°32′09″	155°55′39″	18	1,542	-58	314	-6	248	1.5(e)	unused	1993
3355-01	Kam Inv. Corp.	1991	19°33′40″	155°55′56″	18	1,618	33	258	98	178	1.512(e)	unused	1998
3355-02	Kam Inv. Corp.	1992	19°33′37″	155°55′56″	18	1,658	0	398	18	--	1.512	unused	1998
3355-03	Kam Inv. Corp.	1994	19°33′44″	155°55′56″	18	1,650	0	250	10	210	1.512	unused	1998
3357-01	Bishop Estate	1966	19°33′54″	155°57′26″	10	385	-45	15	-45	140	1.008	unused	1997
3357-04	Otaka Inc.	1990	19°33′12″	155°57′16″	12	397	-18	2	-18	2,150	0.504	irrigation	1990
3456-01	Kam Inv. Corp.	1989	19°34′17″	155°56′48″	14	1,018	-29	1	-29	127	0.999	unused	1998
3457-01	Bishop Estate	1956	19°34′42″	155°57′51″	10	169	-24	3	-17	45	1.008	irrigation	1998
3457-02	Hawaii County DWS	1985	19°34′42″	155°57′11″	16	740	-25	15	-25	305	0.72(e)	unused	1987
3457-03	Otaka Inc.	1985	19°34′41″	155°57′39″	12	366	-21	-1	-21	294	0.72	irrigation	--
3557-01	Hawaii County DWS	1959	19°35′10″	155°57′08″	12	833	-51	-31	-38	99	1.008	municipal	1998
3557-02	Hawaii County DWS	1959	19°35′05″	155°57′08″	12	839	-42	-30	--	56	1.008	municipal	1998
3557-03	Hawaii County DWS	1969	19°35′08″	155°57′07″	12	834	-34	15	-25	216	1.008	municipal	1998
3557-04	Hawaii County DWS	1970	19°35′05″	155°57′07″	14	855	-50	3	-45	485	1.44	municipal	1998
3557-05	Hawaii County DWS	1976	19°35′04″	155°57′25″	156	590	-5	--	--	--	6.048	municipal	1998
3657-01	Hawaii County DWS	1983	19°36′59″	155°57′17″	14	1,123	-45	-2	-42	172	0.72	municipal	1998

Table 6. Available information on existing and proposed wells, western Hawaii, island of Hawaii--Continued

[Data from CWRM State well index and USGS well files; --, data unavailable; (e), estimated; Mgal/d, million gallons per day; Mgal/d/ft, million gallons per day per foot of drawdown]

Well no.	Owner	Year drilled	Latitude	Longitude	Casing diameter (inches)	Altitude, in feet relative to mean sea level: Ground surface	Bottom of hole	Bottom of solid casing	Bottom of perforated casing	Specific capacity (Mgal/d/ft)	Pump capacity (Mgal/d)	Use	Year use checked
3657-02	Hawaii County DWS	1990	19°36′18″	155°57′02″	16	1,146	-34	960	--	333	1.0(e)	unused	1992
3758-01	Hawaii County DWS	1944	19°37′50″	155°58′05″	6	595	-20	55	--	17	0.9(e)	unused	1998
3857-01	Hawaii County DWS	--	19°38′12″	155°57′02″	20	1,542	-58	--	--	--	--	abandoned	1998
3857-02	Hawaii County DWS	proposed	19°38′44″	155°57′03″	--	--	--	--	--	--	1.08	--	--
3857-03	Bishop Estate	proposed	19°38′34″	155°57′06″	--	--	--	--	--	--	1.44	--	--
3957-01	Haseko-Hawaii	1993	19°39′12″	155°57′18″	14	1,674	-32	24	-26	114	0.72	unused	1993
3957-02	USGS	1991	19°39′47″	155°57′33″	--	1,600	-23	175	-23	--	--	observation	1998
3957-04	Douter Coffee Co.	proposed	19°39′01″	155°57′26″	--	--	--	--	--	--	0.432	--	--
4057-01	Hawaii County DWS	1994	19°40′06″	155°57′39″	16	1,762	-25	60	-25	387	1.512	municipal	1998
4057-04	Hawaii County DWS	proposed	19°40′43″	155°57′58″	--	--	--	--	--	--	1.44	--	--
4059-01	State of Hawaii, DLNR	1958	19°40′18″	155°59′03″	12	801	-52	14	-34	186	--	sealed	1972
4060-01	Honokohau Prop.	1995	19°40′31″	156°00′48″	6	121	-17	1	-17	175	0.036	dust control	1998
4061-01	National Park Service	1996	19°40′53″	156°01′30″	2	37	-15	4	-6	--	--	observation	1998
4158-02	Hawaii County DWS	1991	19°41′09″	155°58′02″	20	1,675	-60	-40	-60	142	2.016	municipal	1998
4160-01	Tokyo Green Hawaii	1985	19°41′49″	156°00′04″	12	565	-19	-6	-15	896	0.999	unused	1992
4160-02	Tokyo Green Hawaii	1985	19°41′50″	156°00′12″	12	543	-18	3	-18	4,600	0.639	unused	1992
4161-01	National Park Service	1996	19°41′25″	156°01′55″	2	23	-11	2	-8	--	--	observation	1998
4161-02	National Park Service	1996	19°41′20″	156°01′35″	2	54	-15	3	-7	--	--	observation	1998
4258-03	State of Hawaii, DLNR	1993	19°42′22″	155°58′37″	18	1,681	-142	176	-4	164	1.44	unused	1993
4258-04	Kahala Capital Corp.	proposed	19°42′01″	155°58′31″	--	--	--	--	--	--	1.512	--	--
4259-01	Nansay Hawaii	proposed	19°42′40″	155°59′40″	--	--	--	--	--	--	0.72	--	--
4259-02	Nansay Hawaii	proposed	19°42′33″	155°59′36″	--	--	--	--	--	--	0.72	--	--
4262-01	unknown	--	19°42′23″	156°02′02″	--	--	--	--	--	--	--	observation	1998
4358-01	Hawaii County DWS	1990	19°43′15″	155°58′41″	14	1,799	-51	69	-51	10	0.252	municipal	1998
4360-01	State of Hawaii, DLNR	1968	19°43′27″	156°00′23″	10	680	-22	-2	-22	250	--	unused	1972
4363-01	Uwajima Fish	1989	19°43′39″	156°03′30″	4	15	-17	-5	-15	--	0.36	aquaculture	1989
4363-02	Uwajima Fish	1989	19°43′39″	156°03′30″	4	15	-17	-5	-15	--	0.36	aquaculture	1989
4363-03	Uwajima Fish	1989	19°43′39″	156°03′30″	4	15	-17	-5	-15	--	0.36	aquaculture	1989
4363-04	Uwajima Fish	1989	19°43′39″	156°03′30″	4	15	-17	-5	-15	--	0.36	aquaculture	1990
4363-05	Uwajima Fish	1989	19°43′39″	156°03′30″	4	15	-17	-5	-15	--	0.36	aquaculture	1990
4363-06	Uwajima Fish	1989	19°43′39″	156°03′30″	4	15	-17	-5	-15	--	0.36	aquaculture	1990
4363-07	Uwajima Fish	1989	19°43′39″	156°03′30″	4	15	-17	-5	-15	--	--	unused	1989
4363-08	Uwajima Fish	1989	19°43′39″	156°03′30″	4	15	-17	-5	-15	--	0.36	aquaculture	1989
4363-09	Uwajima Fish	1989	19°43′39″	156°03′30″	4	15	-17	-5	-15	--	0.36	aquaculture	1989
4363-10	Uwajima Fish	1989	19°43′39″	156°03′30″	4	15	-17	-5	-15	--	0.36	aquaculture	1989
4363-11	Uwajima Fish	--	19°43′39″	156°03′30″	4	--	--	--	--	--	--	--	--
4363-12	Uwajima Fish	--	19°43′39″	156°03′30″	4	--	--	--	--	--	--	--	--
4363-13	Cyanotech Corp.	1987	19°43′41″	156°03′09″	36	--	--	--	--	--	0.115	net washing	1987
4458-01	Nansay Hawaii	1991	19°44′22″	155°58′51″	14	1,799	-153	7	-43	304	1.07	unused	1991
4458-02	Nansay Hawaii	1991	19°44′08″	155°58′54″	18	1,800	-80	-10	-50	400	1.07	unused	1991
4459-01	Huehue Ranch	1991	19°44′48″	155°59′10″	14	1,537	-84	0	-30	63	0.72	municipal	--
4459-02	Huehue Ranch	1992	19°44′57″	155°59′07″	14	1,532	-93	-3	-33	1,100	0.72	municipal	--

Table 6. Available information on existing and proposed wells, western Hawaii, island of Hawaii--Continued

[Data from CWRM State well index and USGS well files; --, data unavailable; (e), estimated; Mgal/d, million gallons per day; Mgal/d/ft, million gallons per day per foot of drawdown]

						Altitude, in feet relative to mean sea level							
Well no.	Owner	Year drilled	Latitude	Longitude	Casing diameter (inches)	Ground surface	Bottom of hole	Bottom of solid casing	Bottom of perforated casing	Specific capacity (Mgal/d/ft)	Pump capacity (Mgal/d)	Use	Year use checked
4461-01	M.B. Cooper	1985	19°44′07″	156°01′57″	4	161	-11	-9	3	--	0.144(e)	unused	1998
4461-02	HELCO	1993	19°44′06″	156°01′50″	12	210	-43	7	-33	1,667	0.72	unused	1998
4462-02	State of Hawaii, DOT	1992	19°44′24″	156°02′02″	8	134	-52	-4	-25	83	0.144	dust control	1998
4462-05	State of Hawaii, DOT	1996	19°44′04″	156°02′05″	2	140	-32	4	-32	--	--	observation	1998
4462-06	State of Hawaii, DOT	1996	19°44′02″	156°02′41″	2	55	-28	-13	-28	--	--	observation	1998
4462-07	State of Hawaii, DOT	1996	19°44′02″	156°02′41″	2	55	-9	6	-9	--	--	observation	1998
4463-01	State of Hawaii, DOT	1996	19°44′15″	156°03′20″	2	21	-29	-19	-29	--	--	observation	1998
4463-02	State of Hawaii, DOT	1996	19°44′15″	156°03′20″	2	21	-19	-9	-19	--	--	observation	1998
4463-03	State of Hawaii, DOT	1996	19°44′15″	156°03′20″	2	21	-9	1	-9	--	--	observation	1998
4463-04	Cyanotech Corp.	--	19°44′21″	156°03′10″	--	--	--	--	--	--	--	--	--
4558-01	Huehue Ranch	1991	19°45′33″	155°58′59″	14	1,519	-79	4	-26	114	0.72	municipal	1998
4558-02	Huehue Ranch	1992	19°45′45″	155°58′42″	14	1,529	-72	19	-21	1	0.72	municipal	1998
4559-01	Huehue Ranch	1985	19°45′11″	155°59′03″	10	1,579	-111	0	-30	121	0.504	municipal	1998

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