The Response of the Iao Aquifer to Ground-Water Development, Rainfall, and Land-Use Practices Between 1940 and 1998, Island of Maui, Hawaii

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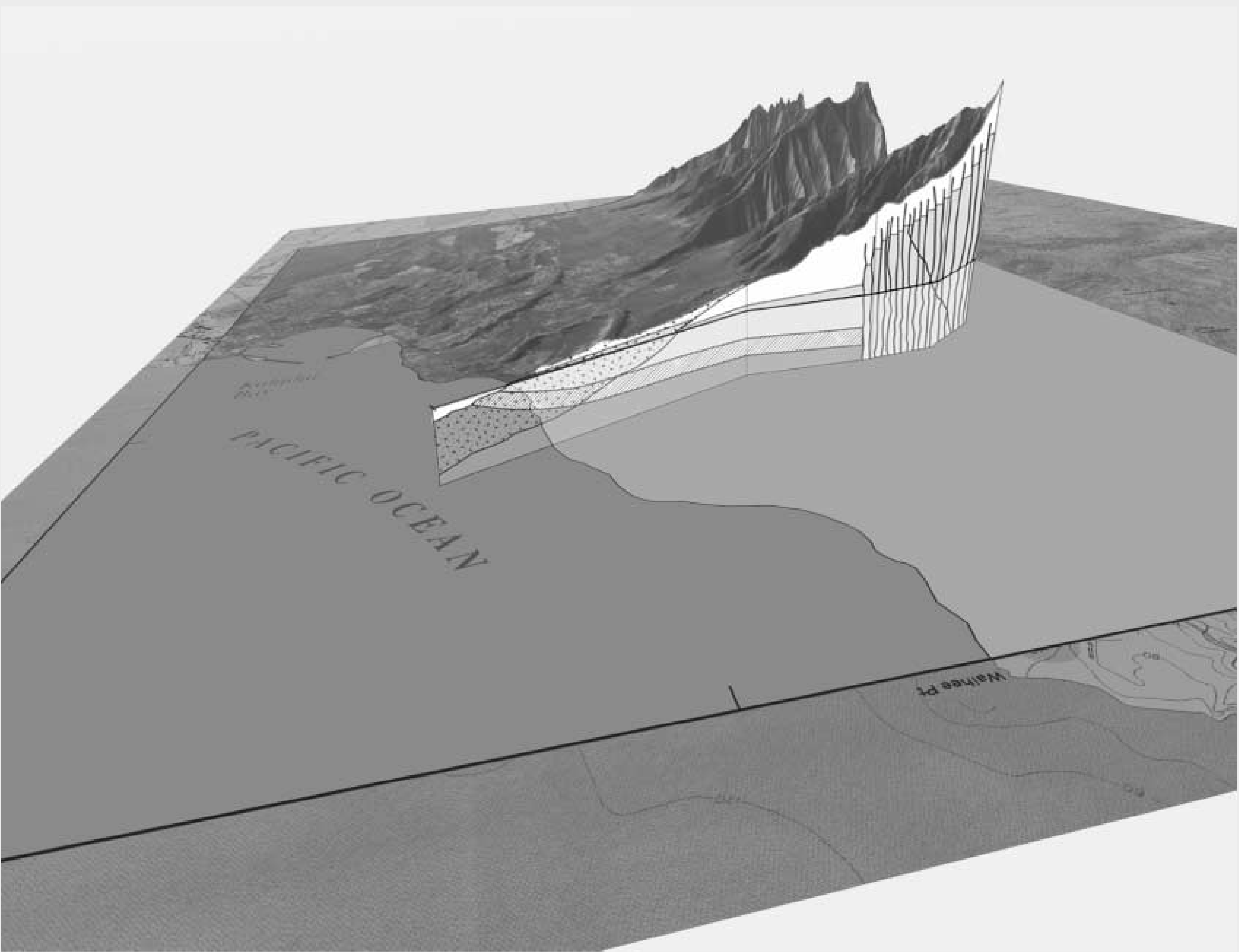

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U.S. GEOLOGICAL SURVEY

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

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information write to:

District Chief
U.S. Geological Survey
677 Ala Moana Blvd., Suite 415
Honolulu, HI 96813

Copies of this report can be purchased from:

U.S. Geological Survey
Branch of Information Services
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CONTENTS

FIGURES

TABLES

Conversion Factors

Multiply	By	To obtain
foot (ft)	0.3048	meter
million gallons per day (Mgal/d)	0.04381	cubic meter per second
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
inch (in.)	25.4	millimeter
inch per year (in/yr)	2.54	centimeter per year

Abbreviations used in water-quality descriptions:

mg/L, milligrams per liter

µS/cm, microsiemen per centimeter at 25° Celsius

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Abstract

Ground water pumped from the Iao aquifer has been used for agricultural purposes since 1948, and domestic purposes since 1955. In 1990, the Hawaii State Commission on Water Resource Management established a value of 20 million gallons per day for the sustainable yield of the aquifer. Water-level data from observation wells throughout the aquifer and information on the depth to and thickness of the transition zone between freshwater and saltwater at the Waiehu deep monitor well indicate that pumping rates near the sustainable yield value of 20 million gallons per day could result in saltwater intrusion in some pumped wells.

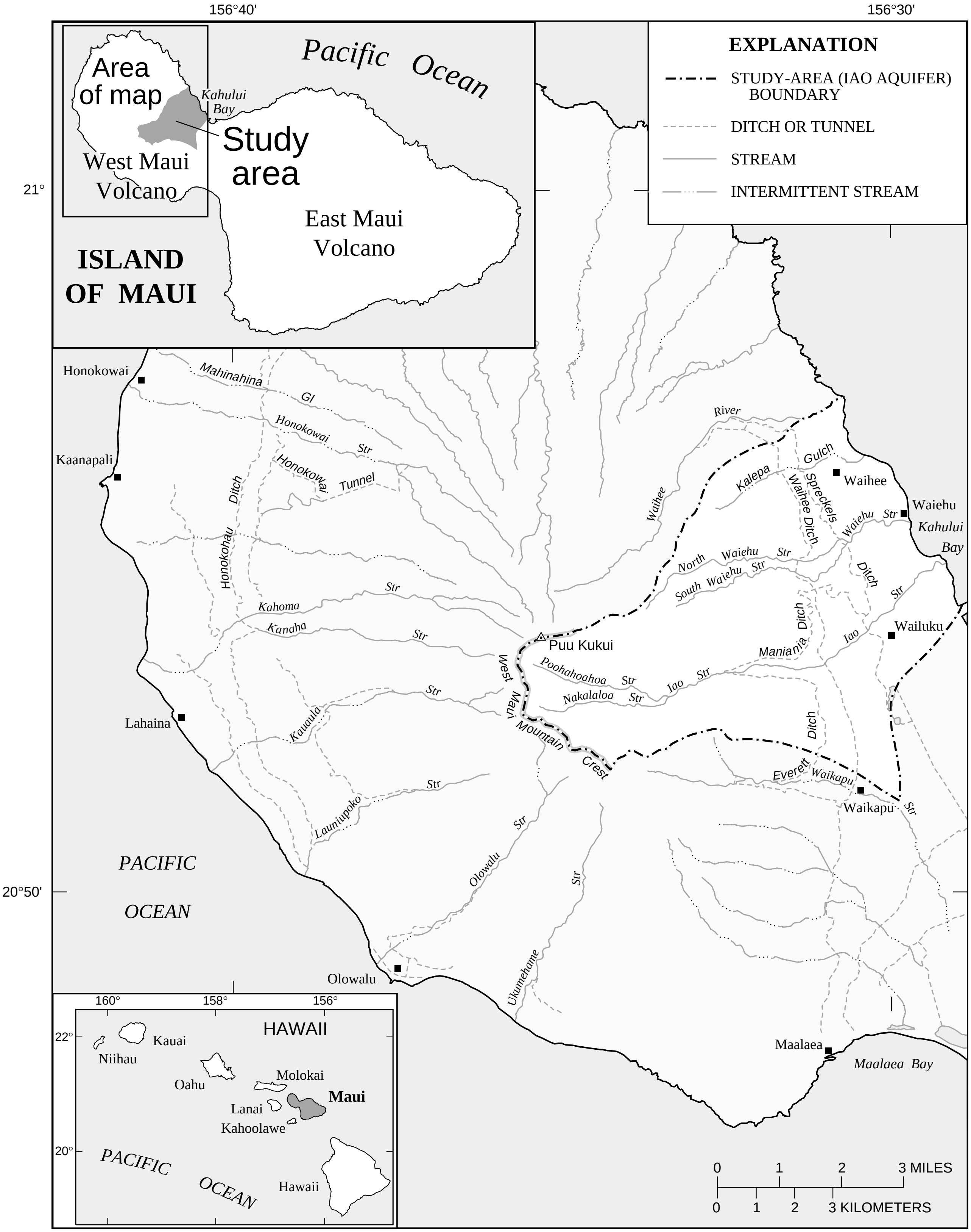
Since the introduction of pumpage in 1948 and the reduction of recharge in 1980, water levels have declined, chloride concentrations of the pumped water have increased, and the transition zone between freshwater and saltwater has risen. Water levels declined by about 18 feet between 1940 and 1998 in the area near Iao Stream, and by as much as 6 feet between 1977 and 1997 in the vicinity of the major well fields near Waiehu Stream. Chloride concentrations of pumped water have risen at all the well fields, but are presently below the U.S. Environmental Protection Agency recommended standard of 250 milligrams per liter. The chloride concentration of water pumped from Mokuhau 2, however, was 460 milligrams per liter in late 1996 when pumping was halted at this well. The midpoint of the transition zone, as measured at the Waiehu deep monitor well, rose by about 108 feet between 1985 and 1998.

INTRODUCTION

The Iao aquifer, on the eastern side of West Maui Mountain (fig. 1), is the principal source of domestic water supply for the island of Maui. Ground-water withdrawal from the aquifer provides water to the Wailuku area (fig. 1) and the populated central isthmus of the island. In 1998, about 76 percent of the ground water supplied by the County of Maui Department of Water Supply (DWS) to the island was from the Iao aquifer (unpub. data from Maui Department of Water Supply).

Plantation agriculture has been the dominant land use overlying the coastal part of the Iao aquifer since the formation of the Wailuku Sugar Company (Shade, 1997), which was first organized in 1862 (Wilcox, 1996). Large-scale furrow irrigation of sugarcane began after the completion of the Waihee Ditch in 1907. The ditch derives its water from the Waihee River and from higher elevation springs and tunnels along the river. Irrigation increased ground-water recharge above the natural rate, although changes in irrigation practices and land use over time have resulted in changes in the rate of recharge.

Significant ground-water withdrawal from the aquifer for irrigation began in 1948 to supplement the water diverted by the ditch systems. Withdrawal for domestic use began in 1955. Since 1985, water has been pumped only for domestic use, and is withdrawn from five locations (shaft 33, Kepaniwai well, Mokuhau well field, Waiehu Heights well field, and Waihee well field) (figs. 2 and 3, table 1). The annual average rate of ground-water withdrawal from the aquifer has ranged widely, with maximum pumpage in 1995 and 1996 (fig. 4, see table 4).



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 20°35' and 21°00', central meridian 156°20'

Figure 1. The Hawaiian islands, island of Maui, West Maui Mountain, and the Iao aquifer study area, Hawaii.

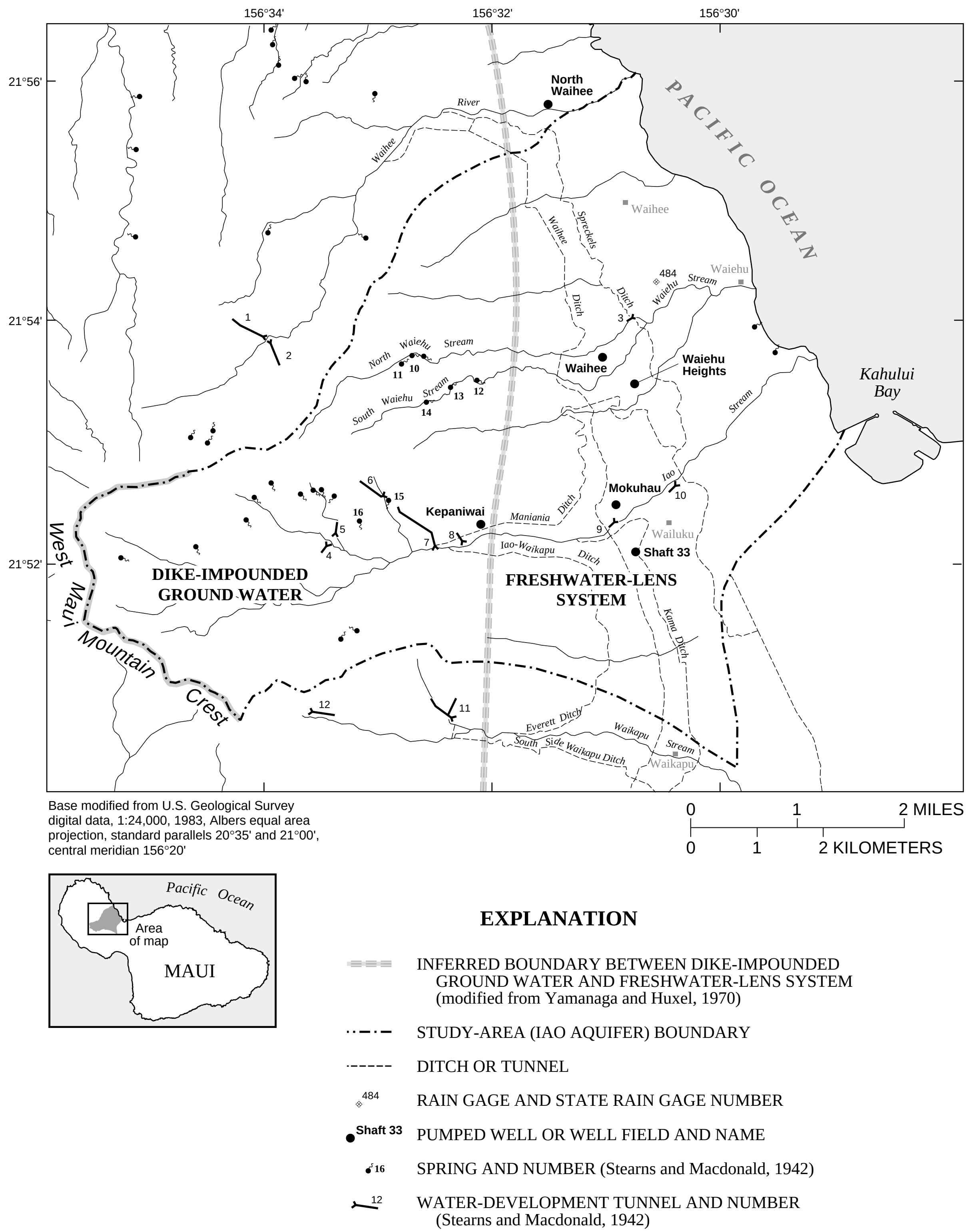
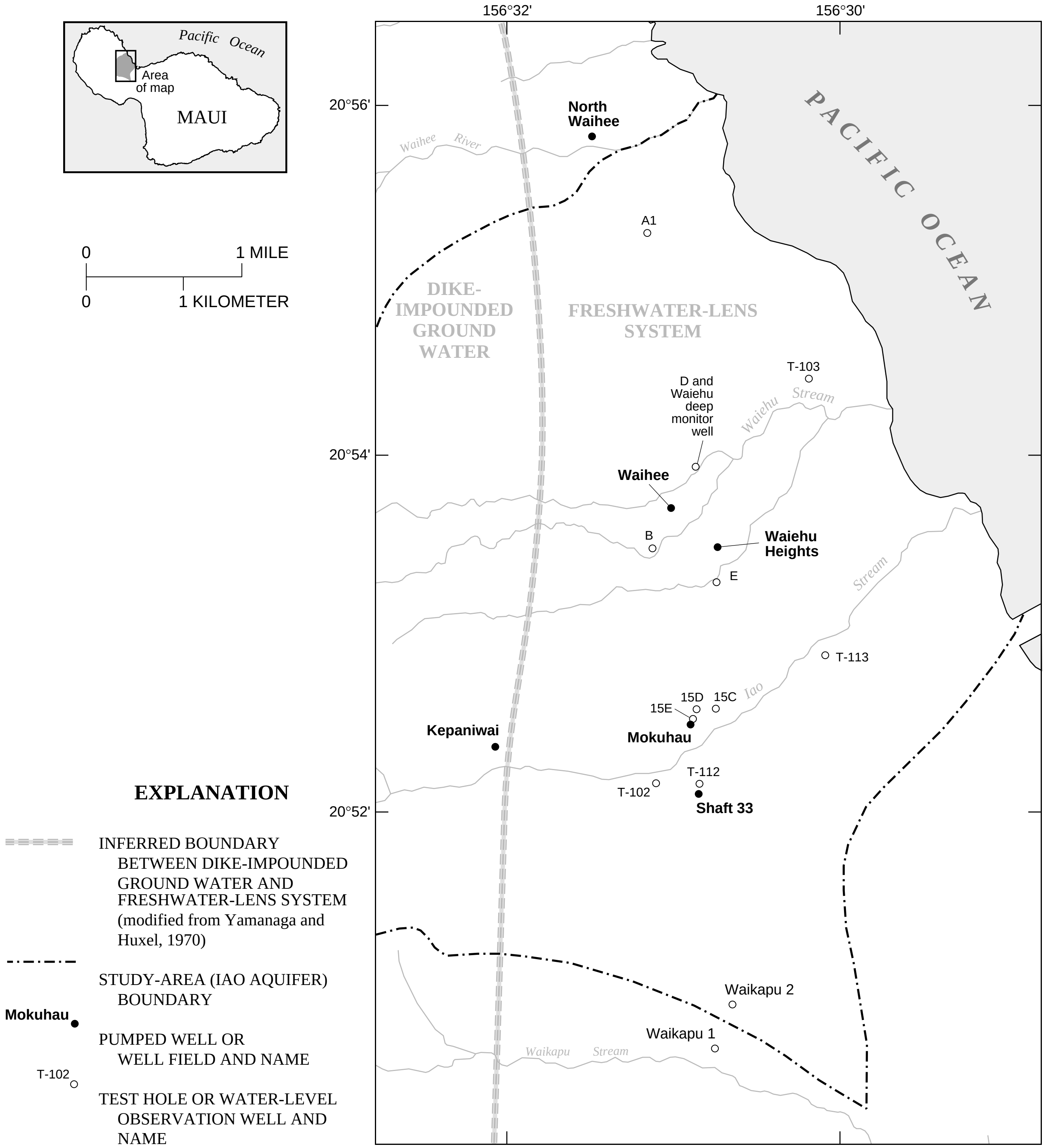


Figure 2. Springs, dike-impounded water-development tunnels, and pumped wells in the Iao aquifer and surrounding area, Maui, Hawaii. (Spring and tunnel locations from Stearns and Macdonald, 1942; rain gage locations from State of Hawaii, 1973.)



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 20°35' and 21°00', central meridian 156°20'

Figure 3. Selected wells in the Iao aquifer, Maui, Hawaii.

Table 1. Wells described in this report, Iao aquifer area, Maui, Hawaii
[--, none]

State well number	Well name	Alternate well name	Use	Altitude of top of well, in feet	Altitude of bottom of well, in feet	Year drilled
5130-01	Waikapu 1	--	Water-level observation	551	-206	1961
5130-02	Waikapu 2	--	Water-level observation	518	-502	1974
5330-03	Test hole T-112	Field 63	Water-level observation	457	-20	1945
5330-04	Test hole T-113	Wailuku mill TH	Test hole	180	-524	1945
5330-05	Shaft 33	Wailuku shaft	Production, water-level observation	[a]32	-280	1946
5330-06	Mokuhau test hole 15C	EX1	Test hole	310	-121	1950
5330-07	Mokuhau test hole 15D	EX2	Test hole, water-level observation	484	-101	1951
5330-08	Mokuhau test hole 15E	EX3	Test hole	364	-102	1953
5330-09	Mokuhau pump 2	15A	Production, water-level observation	353	-247	1953
5330-10	Mokuhau pump 1	15B	Production	353	-247	1953
5330-11	Mokuhau pump 3	15F	Production	354	-251	1967
5330-12	Test hole C	--	Test hole	398	-212	1975
5331-01	Test hole T-102	--	Water-level observation	454	-21	1940
5332-04	Kepaniwai observation well	Kepaniwai test hole	Water-level observation	713	459	1973
5332-05	Kepaniwai well	--	Production	713	413	1974
5430-01	Waiehu Heights 1	--	Production	337	-338	1975
5430-02	Waiehu Heights 2	--	Production	337	-206	1975
5430-03	Test hole E	--	Water-level observation	415	-165	1976
5430-04	Test hole D	--	Water-level observation	382	-108	1975
5430-05	Waiehu deep monitor well	--	Water-level observation, transition-zone monitoring	380	-1,020	1982
5431-01	Test hole B	--	Water-level observation	494	-61	1974
5431-02	Waihee 1	--	Production	498	-182	1976
5431-03	Waihee 2	--	Production	493	-150	1976
5431-04	Waihee 3	--	Production	493	-157	1981
5530-02	Test hole T-103	--	Test hole	80	-97	1933
5631-01	Test hole A1	--	Water-level observation	248	-52	1974
5631-02	North Waihee 1	--	Production, water-level observation	281	-106	1981
5631-03	North Waihee 2	--	Production	281	-106	1981

[a] Portal to shaft has an altitude of 401 ft.

Since the introduction of pumping, ground-water levels have declined significantly and the chloride concentration of pumped water has risen above predevelopment levels at all of the well fields. In addition, the transition zone between freshwater and saltwater, which has been monitored at the Waiehu deep monitor well (fig. 3) since 1985, has been moving upward during the period of record.

In 1990, the Hawaii State Commission on Water Resource Management (CWRM) established a value of 20.0 Mgal/d for the sustainable yield of the Iao aquifer (Commission on Water Resource Management, 1990). This pumpage value was surpassed by 0.50 and 0.35 Mgal/d in 1995 and 1996, respectively.

The combination of high pumpage, decline in water levels, and the rise in the transition zone has caused concern by CWRM regarding the long-term availability of ground water from existing well fields. In 1996, CWRM required that annual mean pumpage be reduced below 20 Mgal/d. In response to this requirement, the DWS reduced pumpage by about 1 Mgal/d in 1997 and 1998.

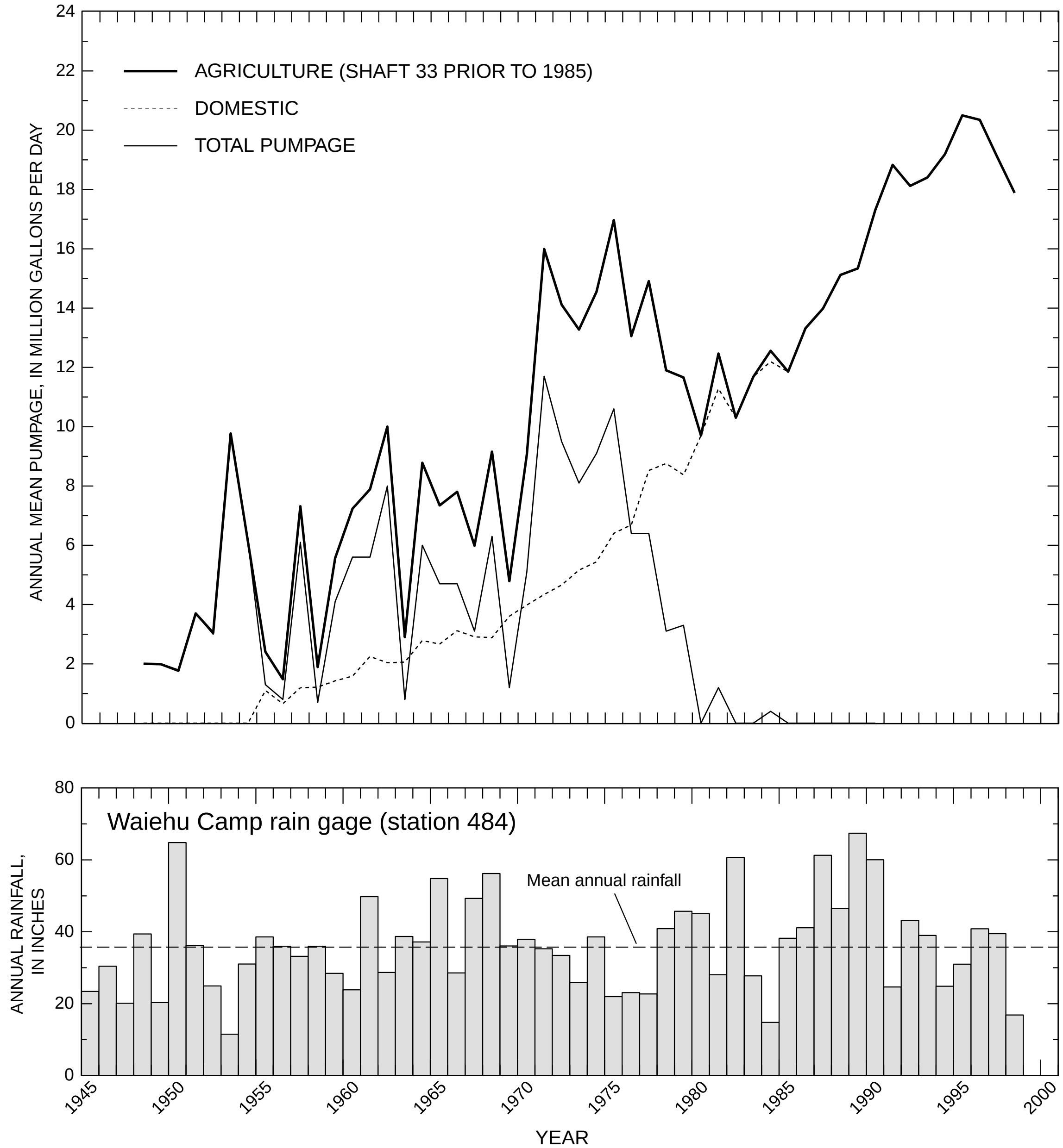


Figure 4. Annual mean pumpage in the Iao aquifer, and annual rainfall for Waiehu Camp rain gage, Maui, Hawaii. (Pumpage data from Maui Department of Water Supply and unpublished data from Wailuku Sugar Company in U.S. Geological Survey well files, Honolulu; unpublished rainfall data from Commission on Water Resource Management and the University of Hawaii Meteorology Department.)

Purpose and Scope

The purpose of this report is to (1) describe the hydrogeologic framework of the Iao aquifer, (2) discuss the response of the freshwater lens in the Iao aquifer to changes in pumpage, rainfall, and land-use practices in terms of water-level and chloride changes, and (3) discuss the sustainability of withdrawals from the aquifer on the basis of historical data.

This report uses water-level, chloride-concentration, rainfall, and pumpage data collected by the USGS, the National Oceanic and Atmospheric Administration (NOAA), and the Maui Department of Water Supply (DWS), and unpublished data available in USGS well files. Ground-water data are available from 14 pumping wells and at least 14 observation wells in the Iao aquifer area. Nearly 30 years of pumpage, rainfall, and water-level data have been collected since the last study of the Iao aquifer (Yamanaga and Huxel, 1970).

Well-Numbering System

Wells mentioned in this report are referred to by the local names used by the DWS and noted in USGS well folders (on file at U.S. Geological Survey, Honolulu). Wells also are numbered according to the State of Hawaii numbering system. Well numbers contain seven digits and are based on a latitude-longitude one-minute grid system. Well numbers are of the form:

a-bbcc-dd,

where:

a is the island code;

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

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

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

An island code of "6" is used for all wells on Maui, however, this number is omitted in this report. The location of all the wells mentioned in this report are shown in figure 3, and the corresponding local well names, numbers, and well information are listed in table 1.

Previous Geohydrologic Studies

The first comprehensive description of the geology and hydrology of the island of Maui was written by Stearns and Macdonald (1942). This description chronicled the initial development of the ground-water and surface-water resources on Maui, and includes early hydrologic data.

Yamanaga and Huxel (1970) described the general geohydrologic setting of the Wailuku area, including the Iao aquifer area, and included descriptions of rainfall, runoff characteristics of streams, ground-water occurrence, and the location and construction history of wells. Yamanaga and Huxel (1970) also provided a limited account of the effect of ground-water development on the aquifer in terms of changes in water levels, and chloride concentration of pumped water.

The State of Hawaii Water Resources Protection Plan (Commission on Water Resource Management, 1990) contains descriptions of the aquifer areas of the State of Hawaii and estimates of sustainable yields for the aquifer areas.

Description of the Study Area

Physical Setting

The island of Maui is formed by the East Maui Volcano and the West Maui Volcano (fig. 1). The Iao aquifer lies on the flank of the West Maui Volcano and covers about 24.7 mi^2. The boundaries of the Iao aquifer, as defined by the Commission on Water Resource Management (1990) and Mink and Lau (1990), are: the ridge south of Waihee River and north of Kalepa Gulch extending from the coast to the summit of West Maui Mountain; the crest of the West Maui Mountain; the ridge north of Waikapu Stream extending from the crest to the isthmus; and the southern divide of Iao Stream to Kahului Bay (figs. 1 and 2). The area is characterized by a steep and mountainous region to the west, an area of sloping alluvial and colluvial plains extending east from the mountains, and an area of lithified sand dunes and coastal plains near the ocean.

The mountainous areas have steep ridges and deep valleys, and range in altitude from about 300 ft at the base to 5,788 ft at the summit (Puu Kukui). The mountainous areas are typically rain forests and are designated as Hawaii State conservation lands. The alluvial and colluvial plains range in altitude from about 100 ft near the coast to more than 600 ft near Waikapu Stream. In the past, sugarcane was grown on the alluvial plains, but presently the land is used for macadamia nuts, pineapple, papaya, or left fallow. The urban areas of Waihee, Wailuku, and Waikapu also are on the alluvial plains. Lithified sand dunes are found on the flat coastal plains and extend from the outlet of Iao Stream to Waikapu. The sand dunes are generally less than 100 ft high.

Two major streams (Iao and Waiehu) drain the Iao aquifer area. Waikapu Stream is situated immediately south of the aquifer. Waihee River flows immediately north of the aquifer and forms the northern boundary of the aquifer near the shoreline (fig. 2). The streams and the river emanate radially from the center summit region of the volcano, forming deep valleys that expose thousands of feet of lava flows.

Climate, Rainfall, and Fog Drip

The climate of Hawaii is characterized by mild and fairly uniform temperatures, seasonal variation in rainfall, and great geographic variation in rainfall (Blumenstock and Price, 1967). The cooler rainy season lasts from October through April, and the hotter dry season is between May and September. Average temperature in Wailuku, near the coast, is 75 degrees, and tradewinds blow 50 to 80 percent of the time in the winter and 80 to 95 percent of the time in the summer (Blumenstock and Price, 1967).

The Iao aquifer area has large range in rainfall between Puu Kukui, and the shoreline (fig. 5) (Giambelluca and others, 1986). The mean annual rainfall at Puu Kukui (greater than 355 in.) is the second highest recorded in the State. Mean annual rainfall declines rapidly toward the ocean and is 30 in. or less at the shoreline. Precipitation in the area is actually a combination of rainfall over all elevations and fog drip at higher elevations where the montane forest canopy intercepts cloud water. Fog drip has not been measured on West Maui Mountain, but studies of other high mountains in Hawaii have shown that fog drip can significantly augment rainfall at elevations above 2,000 ft (Juvik and Ekern, 1978; Juvik and Nullet, 1995).

Irrigation Ditches

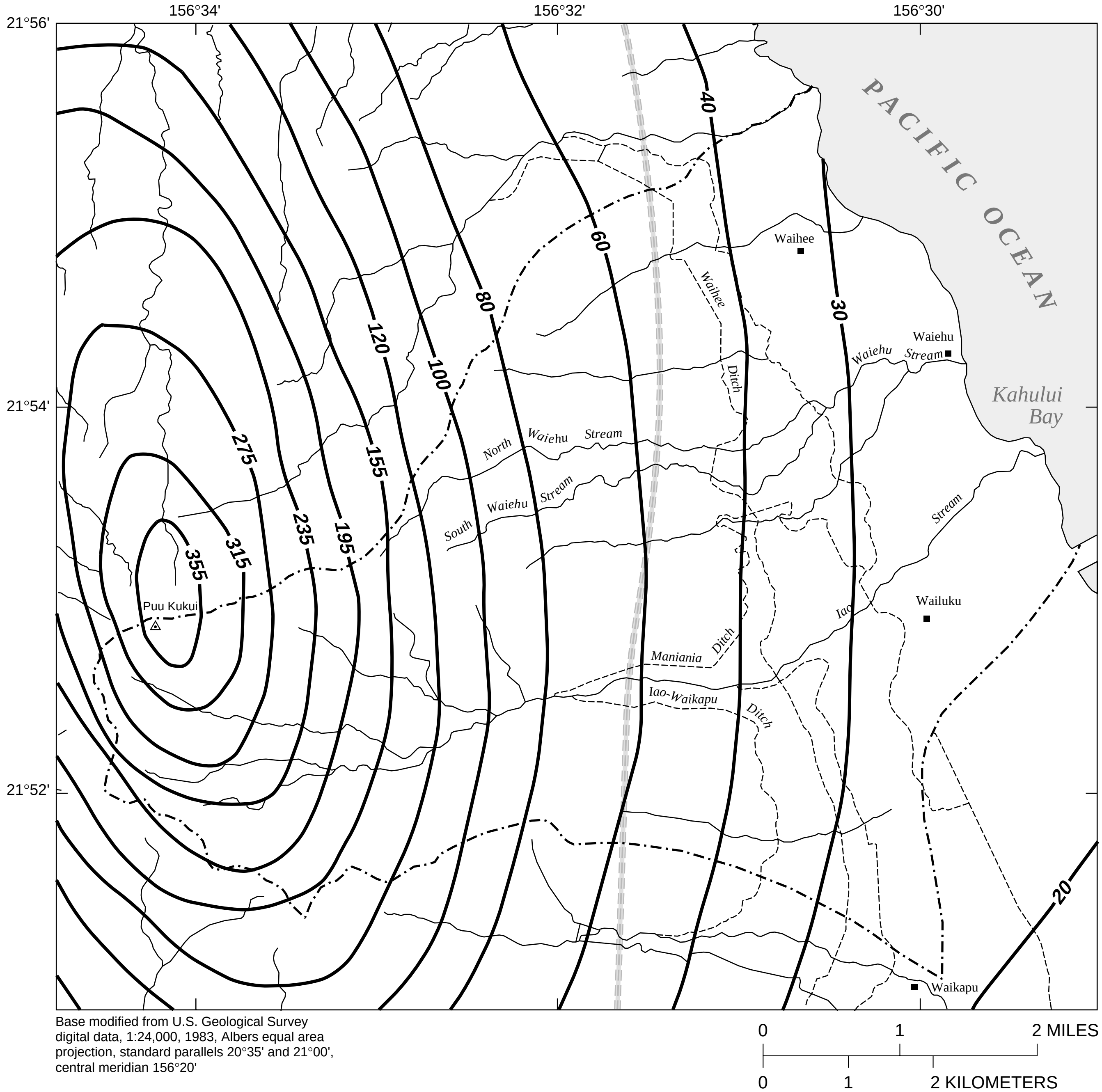
Two major ditches and nine smaller ditches were built in the early 1900’s in the Iao aquifer area (Wilcox, 1996); however, only six of the ditches are still in use (figs. 1 and 2). The ditches divert springs, tunnel water, and streams. The Spreckels Ditch and the Waihee Ditch, the two major ditches in the area, divert and capture an average of about 40 Mgal/d from Waihee River and from tunnels driven into the valley walls above the stream, and about 6 Mgal/d from diversions on the two forks of Waiehu Stream (Yamanaga and Huxel, 1970). Two smaller ditches, the Maniania Ditch and the Iao-Waikapu Ditch, carry about 18 Mgal/d from diversions in the Iao Stream and from tunnels driven in Iao Stream valley. A third small ditch, the Kama Ditch, diverts water from Iao Stream at a lower elevation than the shared diversion of the Maniania and Iao-Waikapu Ditches. In Waikapu Stream valley, the South Side Waikapu Ditch carries about 3 Mgal/d from a diversion in the Waikapu Stream and from tunnels. A second ditch in Waikapu Valley, the Everett Ditch, is no longer in use because of blockage from rock slides.

GEOLOGY

West Maui Volcano is a deeply eroded volcanic dome (fig. 6). The volcano is composed of three volcanic units: the shield-stage Wailuku Basalt; the post-shield-stage Honolua Volcanics, and the rejuvenated-stage Lahaina Volcanics (Stearns and Macdonald, 1942; and Langenheim and Clague, 1987).

The structure of the West Maui Volcano consists of a central caldera, two main rift zones (trending northwest and southeast), and the flanks (Stearns and Macdonald, 1942). The assemblage of rock within the caldera, known as the caldera complex, is composed of dikes, vent breccias, talus, crater-filling flows, pyroclastic material, and faulted rock.

Emanating from the caldera are thousands of dikes composed of Wailuku Basalt and Honolua Volcanics. The number of dikes generally decreases with distance from the caldera, and increases with depth. Most of the dikes intruded along the main rift zones (fig. 6). Other dikes intruded outside of the general trends of the rift zones, creating a radial pattern of dike emplacement emanating from the caldera (Macdonald and others,



EXPLANATION

—*355*—	MEAN ANNUAL RAINFALL--Interval, in inches, is variable
═ ═ ═ ═	INFERRED BOUNDARY BETWEEN DIKE-IMPOUNDED GROUND WATER AND FRESHWATER-LENS SYSTEM (modified from Yamanaga and Huxel, 1970)
·—·—·—	STUDY-AREA (IAO AQUIFER) BOUNDARY
----------	DITCH

Figure 5. Mean annual rainfall in the Iao aquifer area, Maui, Hawaii (modified from Giambelluca and others, 1986).

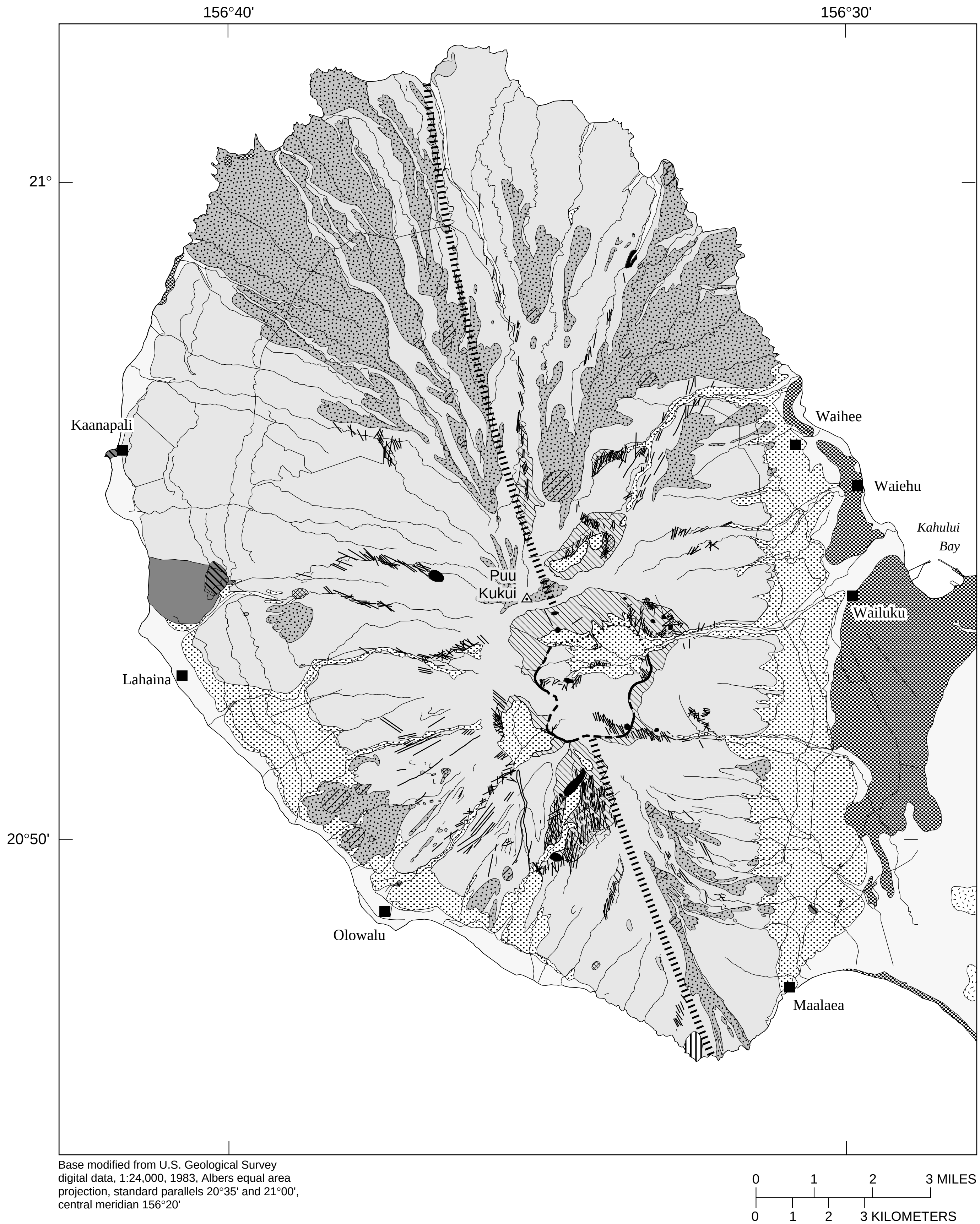


Figure 6. Geology of West Maui Volcano, Hawaii (modified from Stearns and Macdonald, 1942, and Langenheim and Clague, 1987).

EXPLANATION

SEDIMENTARY DEPOSITS

- Unconsolidated deposits, chiefly younger alluvium
- Calcareous sand dunes
- Consolidated earthy deposits, chiefly older alluvium

VOLCANIC ROCKS

- Lahaina Volcanics
- Honolua Volcanics
- Kula Volcanics
- Wailuku Basalt

CONES, VENTS, DOMES, CRATERS, BOSSES, AND DIKES

- Cone or vent of Lahaina Volcanics
- Cones or domes of Honolua Volcanics
- Cones or vents of Wailuku Basalt
- Pit craters
- Bosses of Wailuku Basalt
- Dikes of either Wailuku Basalt or Honolua Volcanics
- Dikes, where too numerous to show individually
- Axis of main rift zones (from Macdonald and others, 1983)
- Caldera boundary, dotted where concealed, dashed where inferred

1983). The aggregate of dikes and the rocks they intrude is known as a dike complex (Stearns and Vaksvik, 1935). The dike complex is exposed in the upper parts of the valleys of West Maui, such as Ukumehame, Waikapu, and Iao Stream valleys, and Waihee River valley.

The flanks of the volcano are predominantly composed of Wailuku Basalt, which is exposed over most of the volcano's surface (Stearns and Macdonald, 1942). Thousands of flows of the tholeiitic Wailuku Basalt emanated from vents in the caldera and along the rift zones. The thin-bedded flows of Wailuku Basalt consist of both aa and pahoehoe (Stearns and Macdonald, 1942). Thin, localized ash deposits and pyroclastic layers lie within the upper part of the sequence of flows.

In a relatively small part of the study area, north of Waiehu Stream valley and south of Waihee River, the Wailuku Basalt is overlain by lava flows of the Honolua Volcanics (fig. 7 and fig. 8, section A-A′). The Honolua Volcanics forms only a thin veneer of dense, massive flows of lighter colored rock. The Honolua Volcanics is not considered important to the hydrology of the Iao aquifer mainly because of its geographic distribution.

Sedimentary deposits overlie the volcanic rocks on the southeastern and southwestern sides of West Maui Volcano, and the entire coast of the Iao aquifer area (fig. 7). Stearns and Macdonald (1942) divided the sedimentary deposits into consolidated earthy deposits, calcareous sand dunes, and unconsolidated deposits. The consolidated earthy deposits are primarily older alluvium which forms the bulk of the alluvial plains stretching from the mountains to the coast (fig. 8). The consolidated earthy deposits are composed primarily of poorly sorted conglomerates. Within these deposits, a thin layer of Lahaina Volcanics was found while drilling one of the test holes in the area (test hole E), but this lava flow is not exposed on the surface. The older alluvium has since been eroded by Waikapu, Iao, and Waiehu Streams, and Waihee River. Calcareous sand dunes are found seaward of the exposed consolidated earthy deposits. Unconsolidated deposits are found in streambeds and in the coastal areas, and are primarily composed of younger, poorly sorted alluvium.

In the Iao aquifer area, sedimentary deposits generally increase in thickness and width in a north-to-south direction, creating an increasingly wider coastal plain (fig. 8, sections A-A′, B-B′, and C-C′). To the north, the coastal plain does not extend past Waihee River valley.

Within the valleys in the Iao aquifer area, zones of weathered basalt probably extend downward beneath the stream floor alluvium. On Oahu, wells drilled in the valley floors indicate that zones of weathered basalt, tens to hundreds of feet thick, lie beneath stream valleys below the contact between the basalt and the alluvium (R.M. Towill Corporation, 1978; and Hunt, 1996).

Lavas from East Maui Volcano are not exposed in the Iao aquifer, but have been found in wells drilled closer to the coast and East Maui Volcano. Data from drilling logs (unpub. data from well files at U.S. Geological Survey, Honolulu) were used to locate the upper contact of the lavas of East Maui Volcano and the sedimentary deposits (fig. 8, section C-C′). These lavas likely interfinger with sedimentary deposits derived from West Maui Volcano.

Geologic setting of wells and test holes.--The geologic logs (unpub. data from well files at U.S. Geological Survey, Honolulu) for most of the wells in the Iao aquifer area are summarized in figure 9. Because the location of the contact between the sedimentary deposits and the underlying basalt was of primary importance for the construction of pumping wells, the general stratigraphy of most of the test holes and pumping wells was logged as the holes were constructed. The first occurrence of ground water during drilling was also documented for some of the wells.

The geologic logs of the wells drilled in the Iao aquifer area show that the thickness of the sedimentary deposits, and the depth of the contact between the sedimentary deposits and the volcanic rocks, is variable throughout. The greater depths and thicknesses are assumed to be relative to where stream valleys are buried. For wells north of Iao Stream and south of Waihee River (fig. 3), the thicknesses of the sedimentary deposits range from 31 ft at test hole B to 491 ft at test hole E, and the altitude of the contact between the sedimentary deposits and the basalt ranges from 463 ft at test hole B to -76 ft at test hole E, which is about 0.5 mi away. Test hole E and the wells and test holes 15D and 15E of the Mokuhau well field, are the only wells in the Iao aquifer that penetrate the Wailuku Basalt near or below sea level.

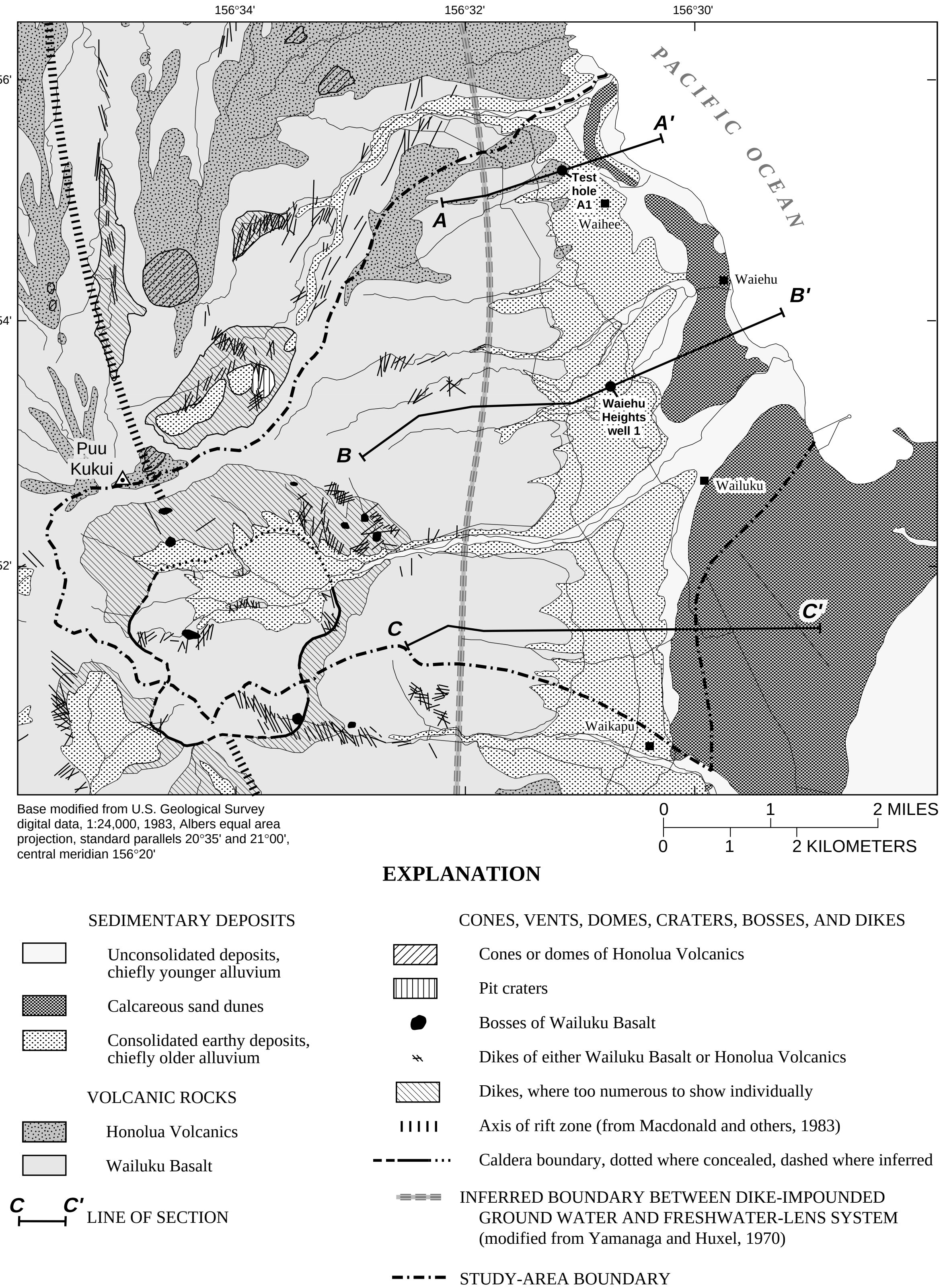


Figure 7. Geology of the Iao aquifer area, Maui, Hawaii (modified from Stearns and Macdonald, 1942, and Langenheim and Clague, 1987).

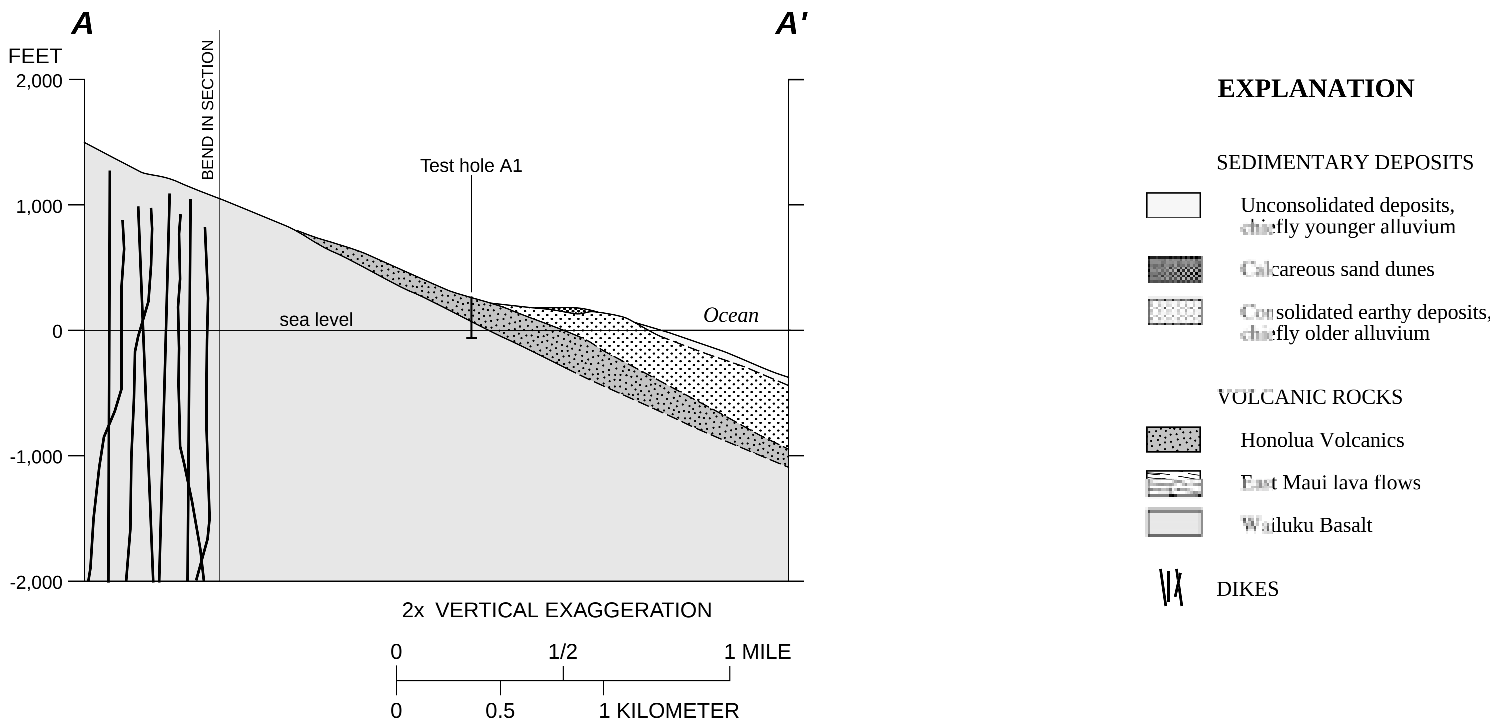


Figure 8. Geologic cross sections of the Iao aquifer area, Maui, Hawaii (geology modified from Stearns and Macdonald, 1942, and Langenheim and Clague, 1987).

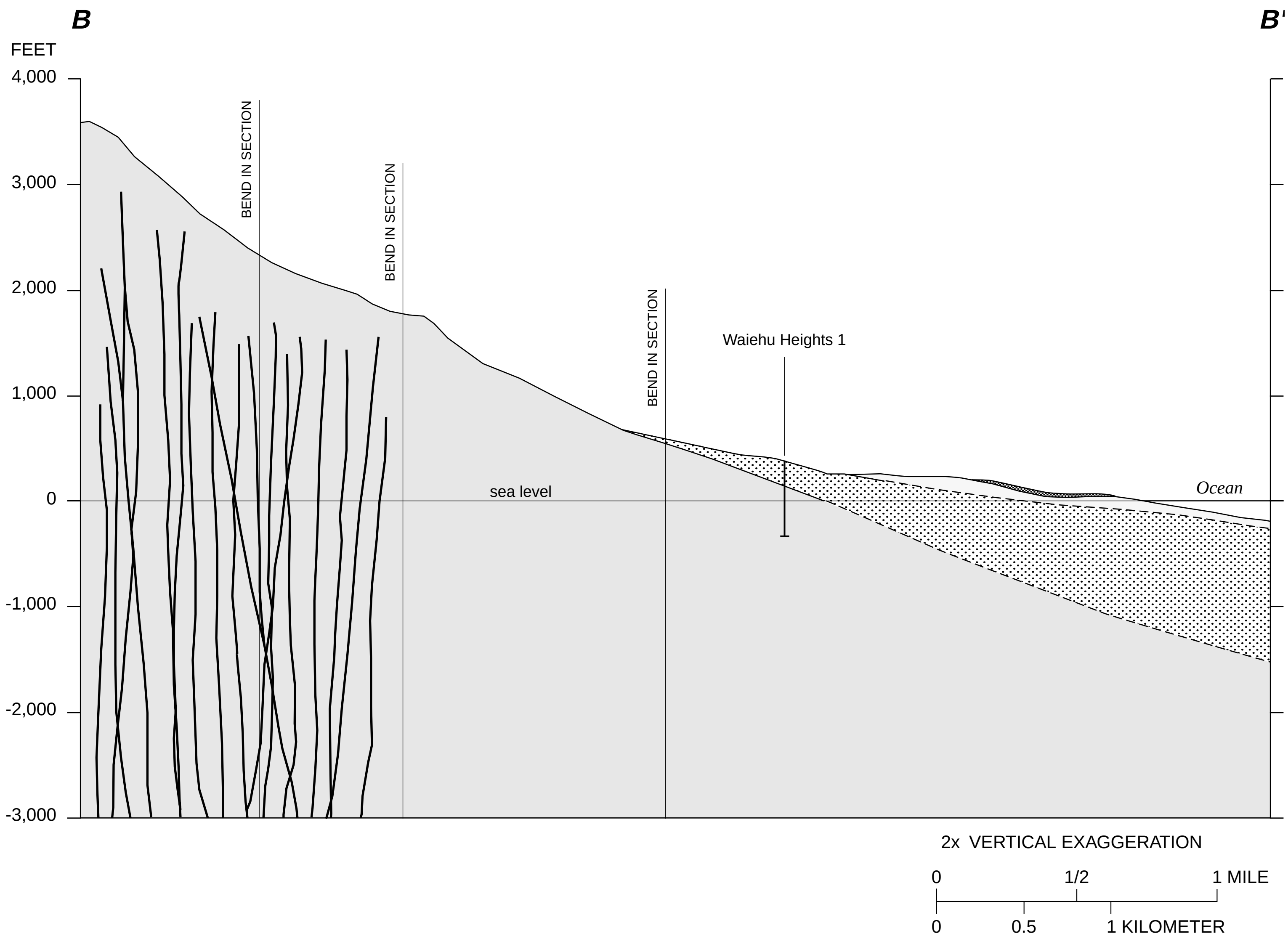
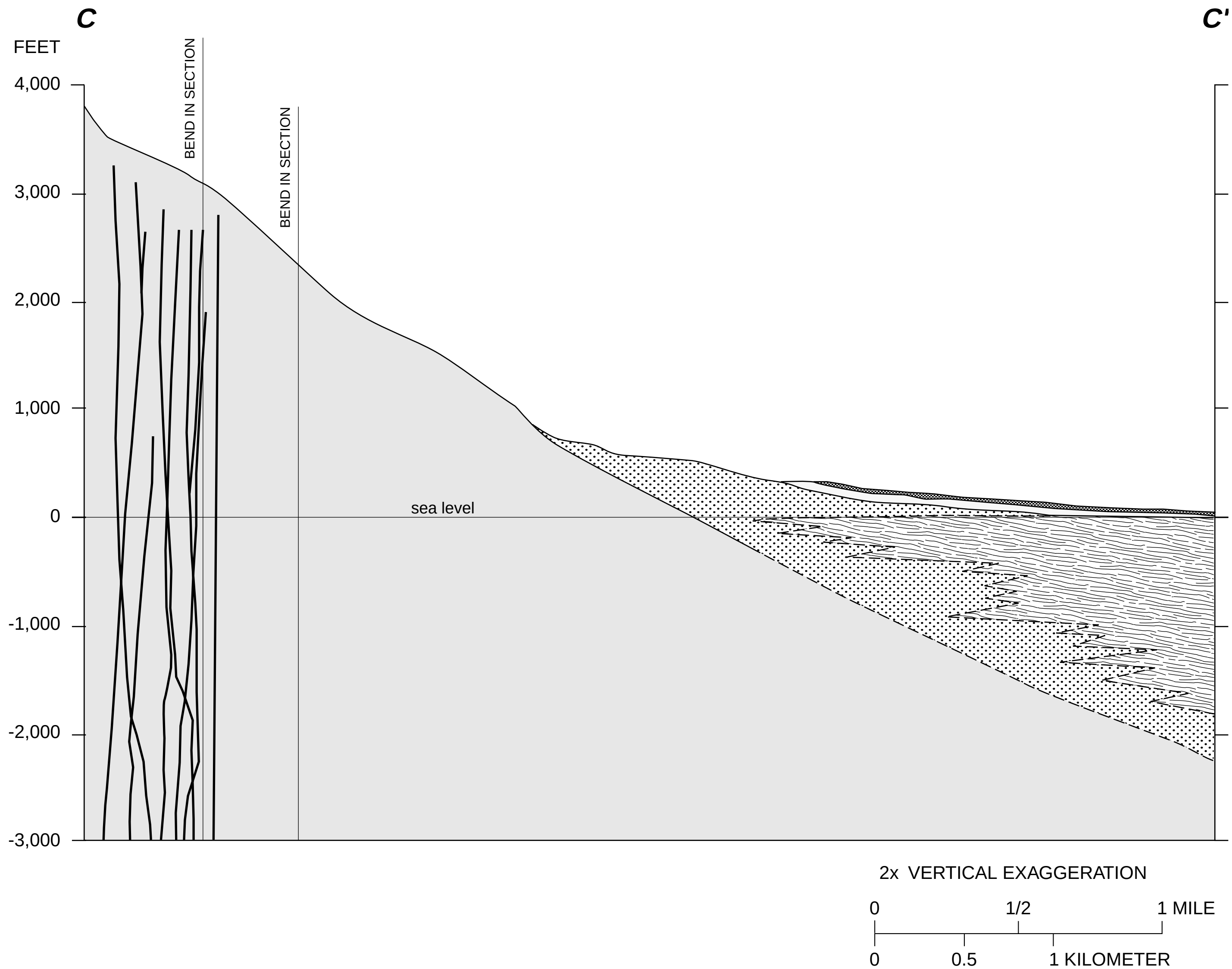


Figure 8. Geologic cross sections of the Iao aquifer area, Maui, Hawaii (geology modified from Stearns and Macdonald, 1942, and Langenheim and Clague, 1987)--Continued.



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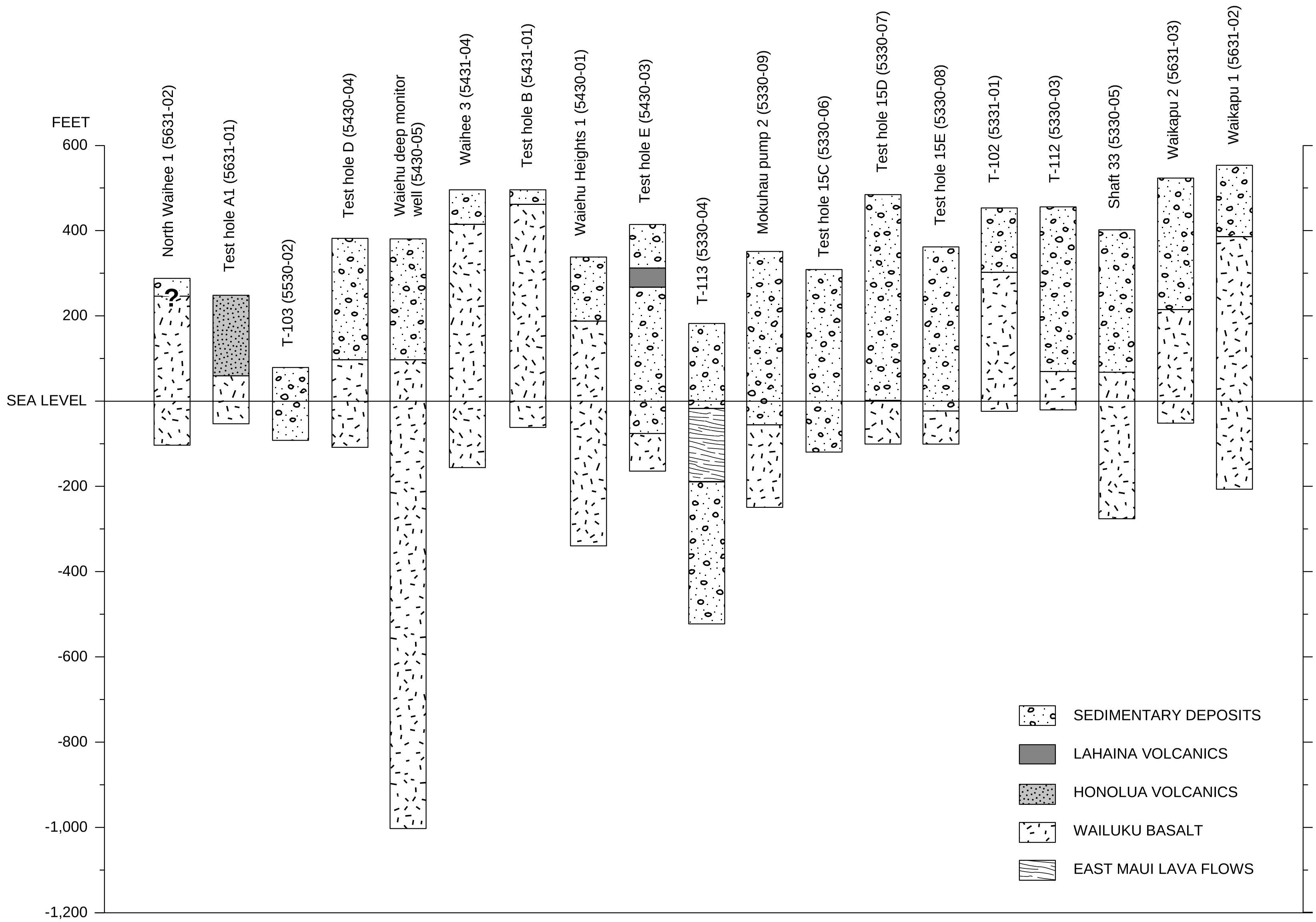


Figure 9. Geologic logs of wells and test holes in the Iao aquifer area, Maui, Hawaii. (Unpublished data from U.S. Geological Survey well files, Honolulu.)

South of Iao Stream, wells penetrate basalt above sea level. These wells have thicknesses of the sedimentary deposits of 150 ft at test hole T-102 to 332 ft at shaft 33, and penetrate the basalt at altitudes ranging from 68 ft at shaft 33 to 383 ft at Waikapu 1.

Three test holes, T-103, T-113, and 15C, never penetrate into the Wailuku Basalt. Test hole T-103, located about 0.5 mi from the coast at an altitude of 80 ft, penetrated 177 ft of sediment to an altitude of -97 ft. Test hole T-113, located about 1.3 mi from the coast at an altitude of 181 ft, penetrated sediment to -16 ft, lava flows between the altitudes of about -16 and -191 ft, and more sedimentary deposits beneath the flows from -191 to -524 ft (unpub. data from well files at U.S. Geological Survey, Honolulu). It is assumed that the lava flows penetrated by this well are from East Maui Volcano, but this cannot be verified. Test hole 15C, located about 2.1 mi from the coast at an altitude of 310 ft, penetrated 431 ft of sediment to an altitude of -121 ft. Drilling was aborted at this site prior to reaching the basalt. However, two other test holes (15D and 15E) were drilled a few hundred feet farther inland, and reached basalt near sea level (fig. 9).

HYDROLOGY

Ground-Water Occurrence and Movement

The fresh ground-water system in the Iao aquifer contains: (1) dike-impounded water, (2) a freshwater lens floating on saltwater, and (3) perched water (fig. 10). The dike-impounded water body is found in the mountainous interior part of the aquifer. A freshwater-lens system is found within the dike-free volcanic rocks and also in the coastal sedimentary deposits. Perched water in the sedimentary deposits overlying volcanic rocks is vertically separated from the freshwater lens by a zone of unsaturated rock. Within the sedimentary deposits, however, perched water may be continuous with and upgradient from the part of the freshwater-lens system in the sedimentary deposits. The general movement of fresh ground water in the Iao aquifer area is from the dike-impounded water body into the freshwater-lens system and then to the ocean.

Dike-Impounded System

A dike-impounded system is found in the dike complex of the West Maui Volcano where low-permeability dikes have intruded other rocks. The inferred eastern boundary of the dike-impounded water body (figs. 10 and 11), as drawn by Yamanaga and Huxel (1970), is located at the seaward extent of dikes mapped by Stearns and Macdonald (1942). Near-vertical dikes tend to compartmentalize areas of permeable volcanic rocks. The dike-impounded flow system includes a freshwater body, and where it exists, underlying brackish water and saltwater. In the Iao aquifer area, dikes impound freshwater to heights ranging from hundreds of feet to over 2,000 ft. Water levels, as indicated by tunnels and springs, range in altitude from 787 to 2,050 ft (see tables 2 and 3). Information is unavailable to determine whether, or at what depth, saltwater exists beneath the freshwater body in the dike complex of West Maui Volcano.

Water enters the dike-impounded system mainly by direct infiltration of some part of rainfall and fog drip and from seepage from streams where they overlie the water table. Water discharges from the system as springs, seepage to streams where they intersect the water table, withdrawal from wells and tunnels, and ground-water flow to the downgradient freshwater-lens system. Where erosion has exposed dike compartments in stream valleys and where the ground-water level is higher than the stream, ground water can discharge directly to the streams. Discharge from the dike-impounded water body maintains perennial flow in Waihee River and Iao, Waikapu, and North and South Waiehu Streams.

Freshwater-Lens System

The freshwater-lens system includes a lens-shaped freshwater body, an intermediate transition zone of brackish water, and underlying saltwater. The freshwater lens floats on denser saltwater. The brackish-water transition zone is formed by mixing of seaward-flowing freshwater with landward-flowing saltwater.

Meinzer (1930) defined water below the lowest water table as basal ground water to distinguish it from perched water. According to this broad definition, ground water in freshwater-lens and dike-impounded systems both can be considered basal ground water. Descriptions of ground water in Hawaii have generally limited the use of the term “basal” to freshwater-lens systems with a water table near sea level in high-permeability rocks, although Meinzer's definition of basal ground water was not so restrictive. In the Iao aquifer,

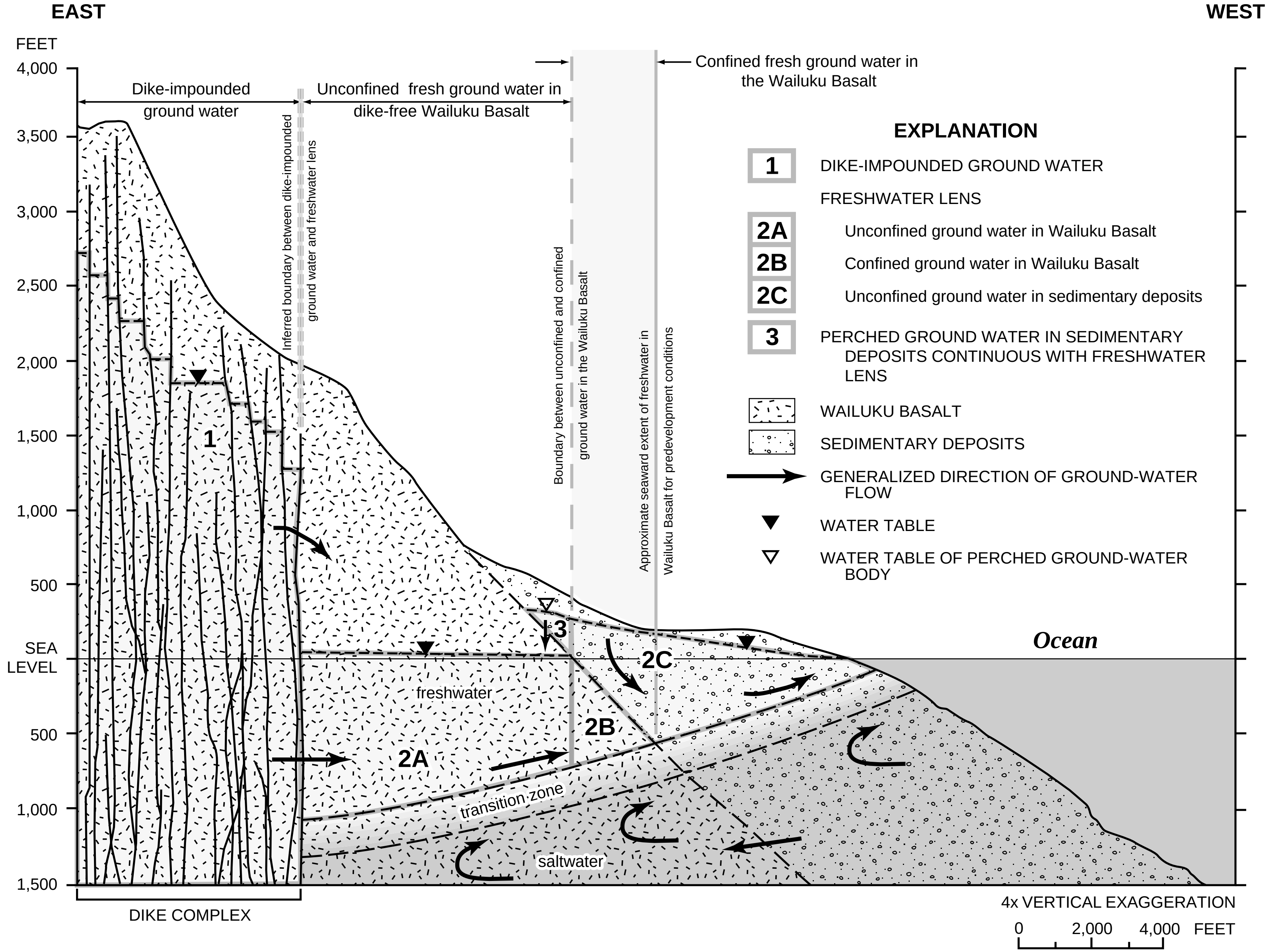


Figure 10. Geologic cross section of the Iao aquifer area showing ground-water occurrence and movement, Maui, Hawaii.

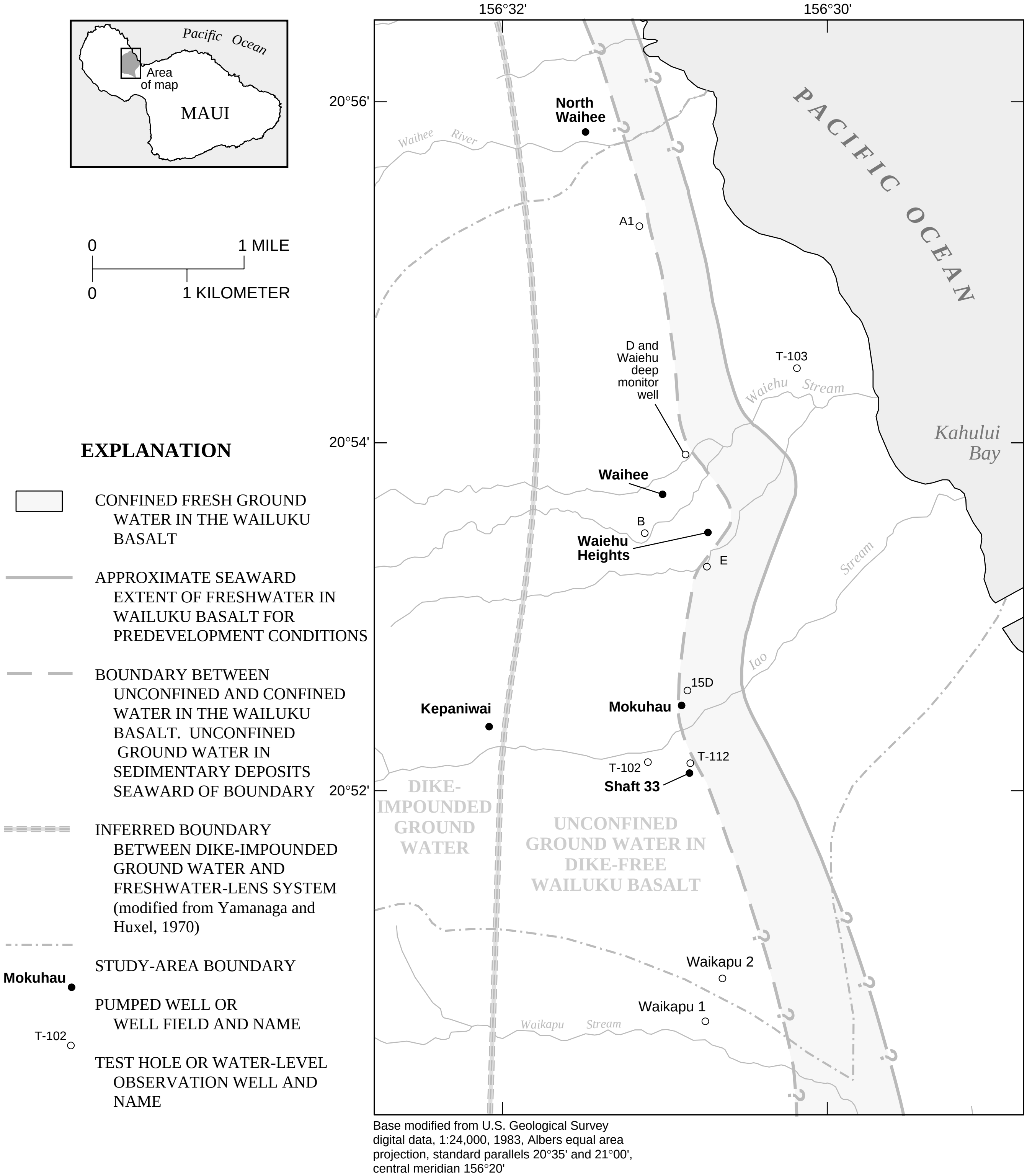


Figure 11. Areal distribution of ground-water occurrence in the Iao aquifer area based on predevelopment conditions, Maui, Hawaii.

the freshwater-lens system is vertically extensive and forms a continuous ground-water system within both the dike-free volcanic rocks and the coastal sedimentary deposits and, according to Meinzer's definition, may be considered basal ground water.

The permeability of the dike-free volcanic rocks, which extend to depths far below sea level, generally is high. Although the permeability of the sedimentary deposits that overlie the dike-free volcanic rocks may be high in places, the overall permeability of the sedimentary deposits is low relative to that of the dike-free volcanic rocks. Thus, the sedimentary deposits form a confining unit above the dike-free volcanic rocks within the coastal plain.

Where sedimentary deposits do not overlie the dike-free volcanic rocks, and where sedimentary deposits overlie the dike-free volcanic rocks but are above the water table in the volcanic rocks, ground water in the volcanic rocks is unconfined (fig. 10). Seaward of where the base of the sedimentary deposits intersects the water table in the dike-free volcanic rocks, ground water in the volcanic rocks is confined by the low-permeability sedimentary deposits. Water levels in wells completed in the dike-free volcanic rocks generally are less than a few tens of feet above sea level. Prior to the end of 1998, water-level altitudes measured in wells in the Iao aquifer area have ranged from a high of 37 ft at test hole T-102 in the early 1940's to a low of 9.21 ft at shaft 33 in 1996. In the dike-free volcanic rocks, the freshwater lens is truncated by the base of the sedimentary deposits before reaching the coast (figs. 10 and 11).

Within the sedimentary deposits, ground water in the freshwater-lens system is unconfined from where the sediments overlie the confined ground water in the volcanic rocks to the coast (2C in fig. 10), and may be saturated to altitudes as high as a few hundred feet. Ground water in the sedimentary deposits was documented in driller's logs from test holes 15C, 15D, and 15E (5330-06 to -08), test hole E (5430-03), and T-103 (5530-02). In test holes 15E and T-103, water levels ranged from 332 ft to 65 ft, respectively, where the holes were entirely in the sedimentary deposits and the bottoms of the holes were below sea level (unpub. well logs on file at the U.S. Geological Survey, Honolulu).

Water-level measurements were made in the small diameter test holes 15C, 15D, and 15E as they were being drilled. In wells 15D and 15E, water levels dropped below 30 ft (fig. 12) once the holes penetrated into the volcanic rocks, and the confined ground water was reached. Since construction of the wells, water-level altitudes in the volcanic rocks in the area of these test holes have ranged from 25.5 ft in 1954 to 9.25 ft in 1998.

Sedimentary deposits are generally heterogeneous, and ground-water occurrence in the sedimentary deposits may be more complex than indicated. The presence of water in the test holes, and the measurements of the water levels as the wells were being drilled (fig. 12), do not rule out the possibility that perched water may exist above the freshwater-lens system in the sedimentary deposits. Data from the small-diameter test holes may not accurately reflect water-level changes in the aquifer with depth.

Water enters the freshwater-lens system by direct infiltration of precipitation and irrigation water, seepage from irrigation ditches and streams where the water table is below the streambed, and inflow from upgradient ground-water bodies. Ground-water flow from the dike-impounded water body recharges the downgradient freshwater lens in the dike-free volcanic rocks. Downward moving water from perched-water bodies also recharges the freshwater-lens system. Discharge of freshwater from and inflow of saltwater to the dike-free volcanic rocks is impeded by the overlying, low-permeability sedimentary deposits. Discharge from the dike-free volcanic rocks to the sedimentary deposits may occur by flow parallel to the coast to areas where the sedimentary deposits are either more permeable or less extensive. Discharge from the freshwater lens in the sedimentary deposits is by seepage to streams where the ground-water level is higher than the stream, by subaerial and submarine coastal springs, and by diffuse seepage near the coast.

Perched System

Perched water may occur where saturated, low-permeability sedimentary deposits or low-permeability volcanic rocks overlie unsaturated rocks. Perched water in the sedimentary deposits was found in Waikapu 1 (5130-01), T-102 (5331-01), and shaft 33 (5330-05) at altitudes of 386, 246, and 135 ft, respectively. Although perched water bodies in the sedimentary deposits are separated from the freshwater lens in the volcanic rocks by a zone of unsaturated volcanic rocks, they may be

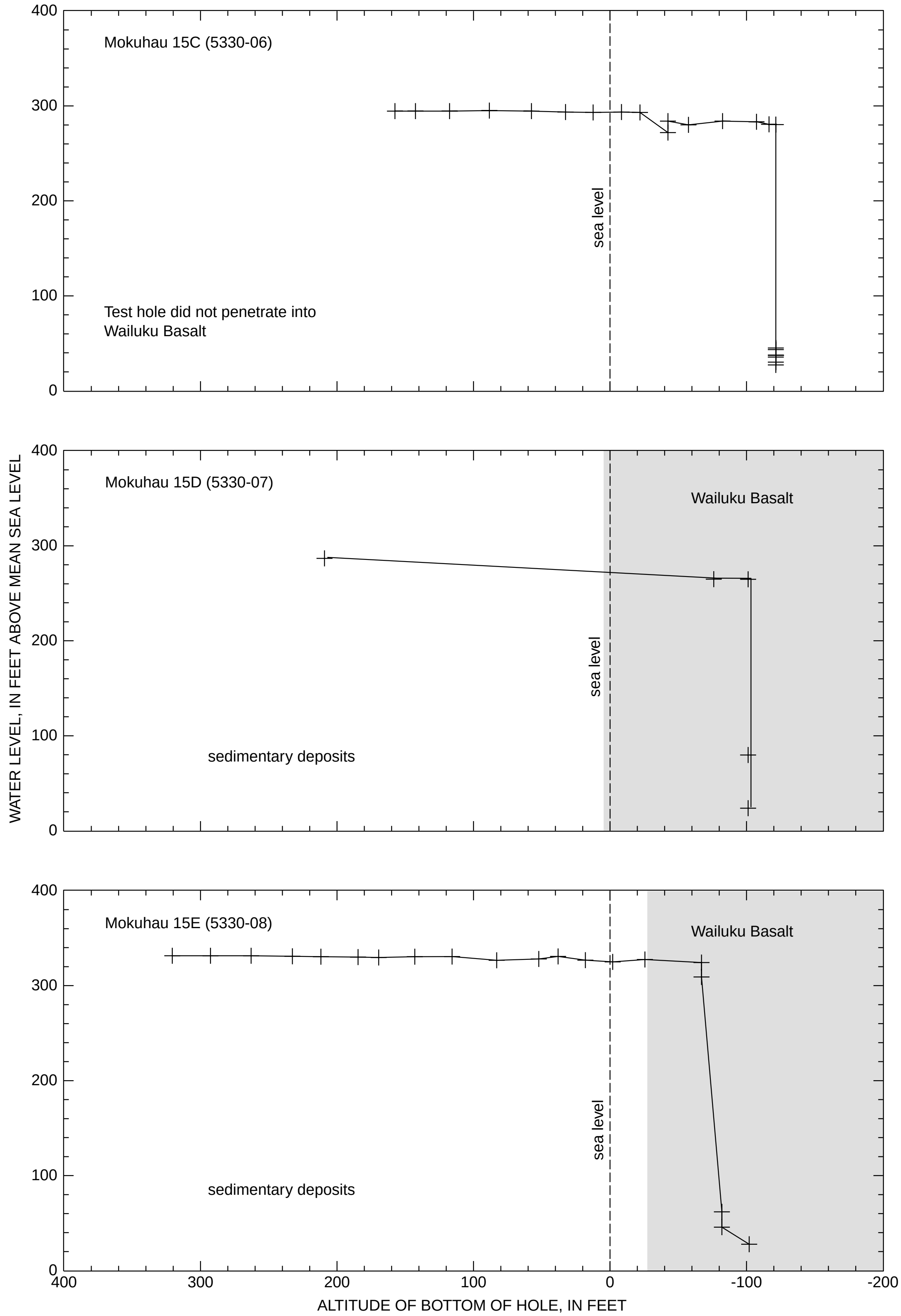


Figure 12. Water level above sea level as a function of altitude of bottom of hole during drilling for test holes 15C, 15D, and 15E (wells 5330-06, 5330-07, and 5330-08), Maui, Hawaii. (Unpublished data in U.S. Geological Survey well files, Honolulu.)

adjacent to and hydrologically continuous with the freshwater lens in the sedimentary deposits (fig. 10).

Recharge to the perched water body is from direct infiltration of precipitation and irrigation water. Discharge from the perched system is downward to a lower water table in the volcanic rocks, downgradient to the freshwater lens in the sedimentary deposits, or to streams that intersect perched-water tables.

Effect of Land-Use Change on Ground-Water Recharge

Shade (1997) estimated that under natural (or predevelopment) conditions, recharge within the dike complex and to the ground-water system seaward of the dike complex was about 24 Mgal/d and 10 Mgal/d, respectively, for a total of 34 Mgal/d. The water-budget accounting method used by Shade (1997) probably maximizes values for ground-water recharge, and as a result, actual recharge rates may be less by some unknown amount.

The introduction of sugarcane agriculture in 1856 increased rates of ground-water recharge in areas under cultivation (fig. 13). For these areas, Shade (1997) estimated changes in the rate of recharge for three time periods: 1926–79, when sugarcane was the only crop and the furrow irrigation method was used; 1980–85, when sugarcane acreage was reduced and replaced by macadamia nut tree acreage, and when the furrow irrigation method was largely replaced by drip irrigation; and 1986–95, when sugarcane acreage was reduced further to only about 5 percent of the original sugarcane acreage and some of the remaining acreage was used for pineapple. These time periods represent relatively constant but different periods of land use (fig. 13) and irrigation practices. Land use did not change for the dike-impounded ground-water area during these times. Total recharge rates estimated by Shade (1997) for the area underlain by the freshwater lens are 27, 16, and 12 Mgal/d for 1926–79, 1980–85, and 1986–95, respectively. Given a natural recharge rate to the dike-impounded ground-water area of 24 Mgal/d, the total recharge to the Iao aquifer ranged from a natural rate of 34 Mgal/d, to 51 Mgal/d for 1926–79, 40 Mgal/d for 1980–85, and 36 Mgal/d for 1986–95.

GROUND-WATER DEVELOPMENT

Development of ground water from the Iao aquifer began with the construction of tunnels to divert dike-impounded water and with the improvement of springs (fig. 2, table 2). Twelve tunnels in the Iao aquifer area were excavated between 1900 and 1926 (table 3), but most of the history and records of their construction has been lost (Stearns and Macdonald, 1942). Eight of the tunnels penetrate into the dike complex and tap dike-impounded water. The other four tunnels penetrate alluvium beneath Iao and Waiehu Streams and collect water from beneath the streams in the valley-floor alluvium (Stearns and Macdonald, 1942).

The total amount of ground water developed by the tunnels in the Iao aquifer area and the adjacent Waikapu Stream and Waihee River valleys that penetrate into the dike compartments was about 9.0 Mgal/d as of 1970 (Yamanaga and Huxel, 1970). Stearns and Macdonald (1942) and Yamanaga and Huxel (1970) suggested that most of the tunnel water (about 7.5 Mgal/d) would have discharged naturally into the streams had it not been intercepted by the tunnels. The remaining water (about 1.5 Mgal/d) would have recharged the freshwater-lens system beyond the dike complex had it not been captured by the tunnels. Tunnels 1 and 2, in Waihee River valley, discharge dike-impounded water at an altitude of about 1,650 ft into Waihee River. A diversion on Waihee River farther downstream feeds ditches used for irrigation in the study area. Other tunnels, such as tunnel 7 in Iao Stream valley and tunnel 11 in Waikapu Stream valley, tap dike-impounded water at altitudes of 787 ft and 1,800 ft, respectively. The descriptions of the other four tunnels (4, 5, 6, and 12) indicate that they were not as successful as tunnels 1, 2, 7, and 11 (Stearns and Macdonald, 1942). Tunnels 3, 8, 9, and 10 were dug in the alluvium and captured about 0.75 Mgal/d (Stearns and Macdonald, 1942).

At the present time (1998), ground water is pumped from five major wells or well fields (shaft 33, Mokuhau, Waiehu Heights, Waihee, and Kepaniwai). Most ground water is pumped from the freshwater lens in the dike-free volcanic rocks, except for the Kepaniwai well, which pumps ground water from the dike-impounded system.

Large-scale withdrawal of ground water from the freshwater lens of the Iao aquifer began in 1948 with

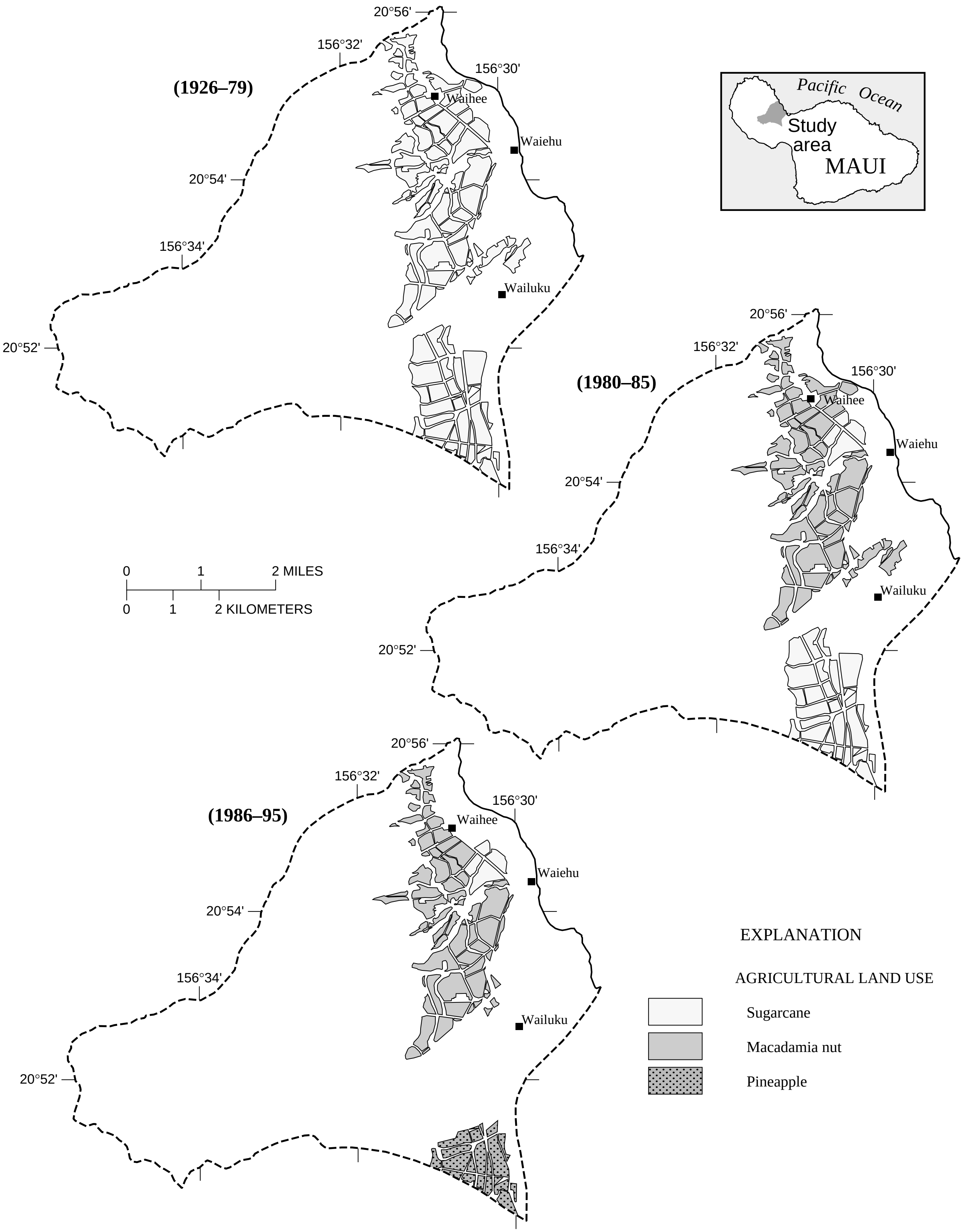


Figure 13. Agricultural land use for three different periods, Iao aquifer area, Maui, Hawaii (modified from Shade, 1997).

Table 2. Springs in the dike complex of the Iao aquifer area, Maui, Hawaii

[Data from Stearns and Macdonald, 1942]

Spring number	Name	Location (stream valley)	Altitude (feet)	Average daily discharge (gallons)
10	Lower	North Waiehu	1,500	150,000
11	Upper	North Waiehu	2,050	1,500,000
12	Lower	South Waiehu	1,000	200,000
13	Middle	South Waiehu	1,325	500,000
14	Upper	South Waiehu	1,500	1,000,000
15	Black Gorge	Iao	1,200	600,000
16	Needle	Iao	1,100	250,000

Table 3. Ground-water development tunnels in the Iao aquifer area, Maui, Hawaii

[Mgal/d, million gallons per day; --, no data]

Tunnel number	Location (stream or river valley)	Altitude (feet)	Yield from Stearns and Macdonald, 1942 (Mgal/d)	Yield from Yamanaga and Huxel, 1970 (Mgal/d)	Length (feet)	Geology
1	Waihee	1,625	4.6	4.6	2,200	Older alluvium and dike complex
2	Waihee	1,650	1.0	1.0	2,500	Older alluvium, dike complex in the Wailuku Basalt, and pit crater breccia
3	Waiehu	300	0.25	0.25	500	Alluvium
4	Iao	1,425	0.075	--	2,500	Dike complex, Wailuku Basalt
5	Iao	1,475	0.075	--	caved	Caldera complex, Wailuku Basalt
6	Iao	1,305	0.6	--	1,413	Dike complex, Wailuku Basalt
7	Iao	787	2.05	2.30	2,630	Dike complex, Wailuku Basalt
8	Iao	700	0.1	--	caved	Alluvium and Wailuku Basalt
9	Iao	440	0.15	0.15	1,000	Alluvium
10	Iao	240	0.25	0.25	2,000	Alluvium
11	Waikapu	1,800	1.0	1.0	2,943	Dikes in Wailuku Basalt
12	Waikapu	1,770	0.0007	--	1,500	Vent breccia of the caldera complex

the completion of shaft 33 (figs. 2 and 3). A 647-ft tunnel inclined at 30 degrees was excavated, terminating in a large vault at an altitude of 30 ft. Three wells were drilled about 10 ft apart and about 310 ft deep in the vault. The bottoms of the wells are about -280 ft in altitude.

Shaft 33 was used for agricultural supply during 1948–84, with an annual mean withdrawal ranging from 0.00 to 11.65 Mgal/d (fig. 14). The monthly mean pumpage depended largely on rainfall and varied significantly, ranging from 0.00 to 20.90 Mgal/d (probably the maximum pump capacity). Shaft 33 was not used between 1985 and early 1991. In mid-1991, the Maui DWS started using the shaft for domestic supply. The DWS uses only one of the pumps in the shaft, which was pumped continuously at a rate of about 5.16 Mgal/d between July 1991 and June 1994, about 5.31 Mgal/d between January 1995 and December 1996, and at a reduced rate of about 4.72 Mgal/d from August 1997 through the end of 1998. Pumping was interrupted during the last 6 months of 1994 and the first 7 months of 1997.

The Mokuhau well field was the second major ground-water withdrawal site added to the Iao aquifer with the construction of two wells in 1953. A third well was added to the well field in 1967. Water from the Mokuhau well field was the sole source of domestic water from the Iao aquifer until 1977. The well field was placed at an altitude of about 353 ft, and the three wells were drilled to a bottom altitude of about -250 ft each. Annual mean pumpage from the well field increased steadily from about 1.10 Mgal/d in 1955 to more than 8 Mgal/d in 1977 and 1978 (fig. 14). These 2 years represent the peak annual pumpage from the well field. Since 1978, the mean annual pumpage has been about 5.53 Mgal/d, ranging from 3.05 to 7.66 Mgal/d. In 1997, the annual mean pumpage from Mokuhau well field was about 6.29 Mgal/d.

Waiehu Heights and Waihee well fields were added in 1977 and 1979, respectively, in order to meet increasing domestic demand. Pumpage from the Waiehu Heights well field has been lower relative to the Mokuhau well field. The mean annual pumpage at Waiehu Heights well field was 0.43 Mgal/d from 1977 to 1990, with annual mean pumpage ranging between 0.18 and 0.92 Mgal/d (fig. 15). From 1991 to the end of 1997, annual mean pumpage from the Waiehu Heights well field ranged between 1.08 and 1.96 Mgal/d. Pumpage in 1998 dropped to 0.23 Mgal/d. Pumpage from Waihee well field, which initially consisted of two wells (Waihee 1 and 2), was about 1.37 Mgal/d in 1979; annual mean pumpage increased to 6.15 Mgal/d in 1980. Annual mean pumpage ranged from about 4.87 to 6.63 Mgal/d between 1981 and 1986 (fig. 15), and increased to about 8.53 Mgal/d in 1987, after a third well (Waihee 3) was constructed at this well field in late 1981. Annual mean pumpage has been between 7.24 Mgal/d and 9.11 Mgal/d since 1987.

The next well added to the DWS distribution system in the Iao aquifer was the Kepaniwai well in 1991. Before being added to the distribution system, the well was used locally during 1977–86. The well is just north of Iao Stream at an altitude of about 713 ft and taps dike-impounded water. Annual mean pumpage reached a maximum in 1991 at 1.03 Mgal/d (fig. 15). After 1991, the mean annual pumpage has been about 0.55 Mgal/d.

In 1997, two wells immediately north of Waihee River were added to the distribution system. The North Waihee well field (fig. 3) is considered outside of the Iao aquifer area for management purposes, thus the pumpage from this well field is not added to the total pumpage for the aquifer. The well field is at an altitude of about 285 ft. The bottoms of both wells are at altitudes of about -106 ft. The two wells have submersible pumps installed that can deliver about 1.6 Mgal/d each. The maximum monthly pumpage from this well field has been about 2.38 Mgal/d.

The annual mean rate of ground-water withdrawal from the Iao aquifer has ranged widely, but generally has increased with time (fig. 4 and table 4). The record of total pumpage can be divided into four periods where pumpage trends are distinguishable. The trends are a result of differences in rainfall, irrigation, and pumpage for domestic needs.

Between 1948 and 1970, the annual mean total pumpage ranged from 1.49 to 10.01 Mgal/d and the average was about 5.57 Mgal/d. From 1971 through 1977, annual mean total pumpage ranged from a low of 13.06 Mgal/d in 1973 to a high of 16.96 Mgal/d in 1975, and the average was 14.69 Mgal/d. Years with high pumpage within these two periods were years with low rainfall and high water demand for irrigation. Annual mean total pumpage between 1978 and 1985 (fig. 4) was less than during the 1970’s primarily because of changes in agricultural practices. The maximum annual mean total pumpage for this time was 12.57 Mgal/d, the

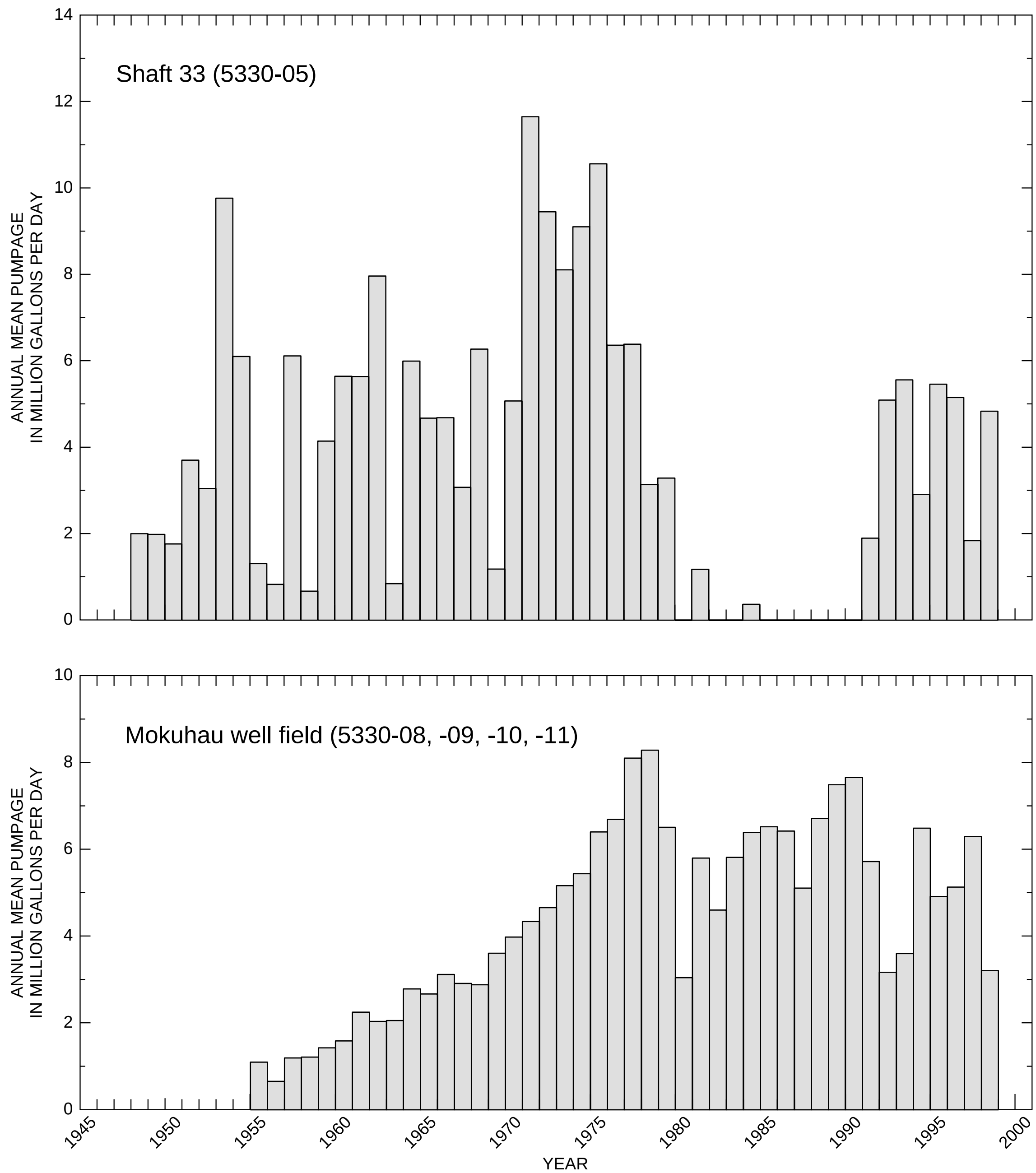


Figure 14. Annual mean pumpage for shaft 33 and Mokuhau well field, Maui, Hawaii. (Data from Maui Department of Water Supply and unpublished data from Wailuku Sugar Company in U.S. Geological Survey well files, Honolulu.)

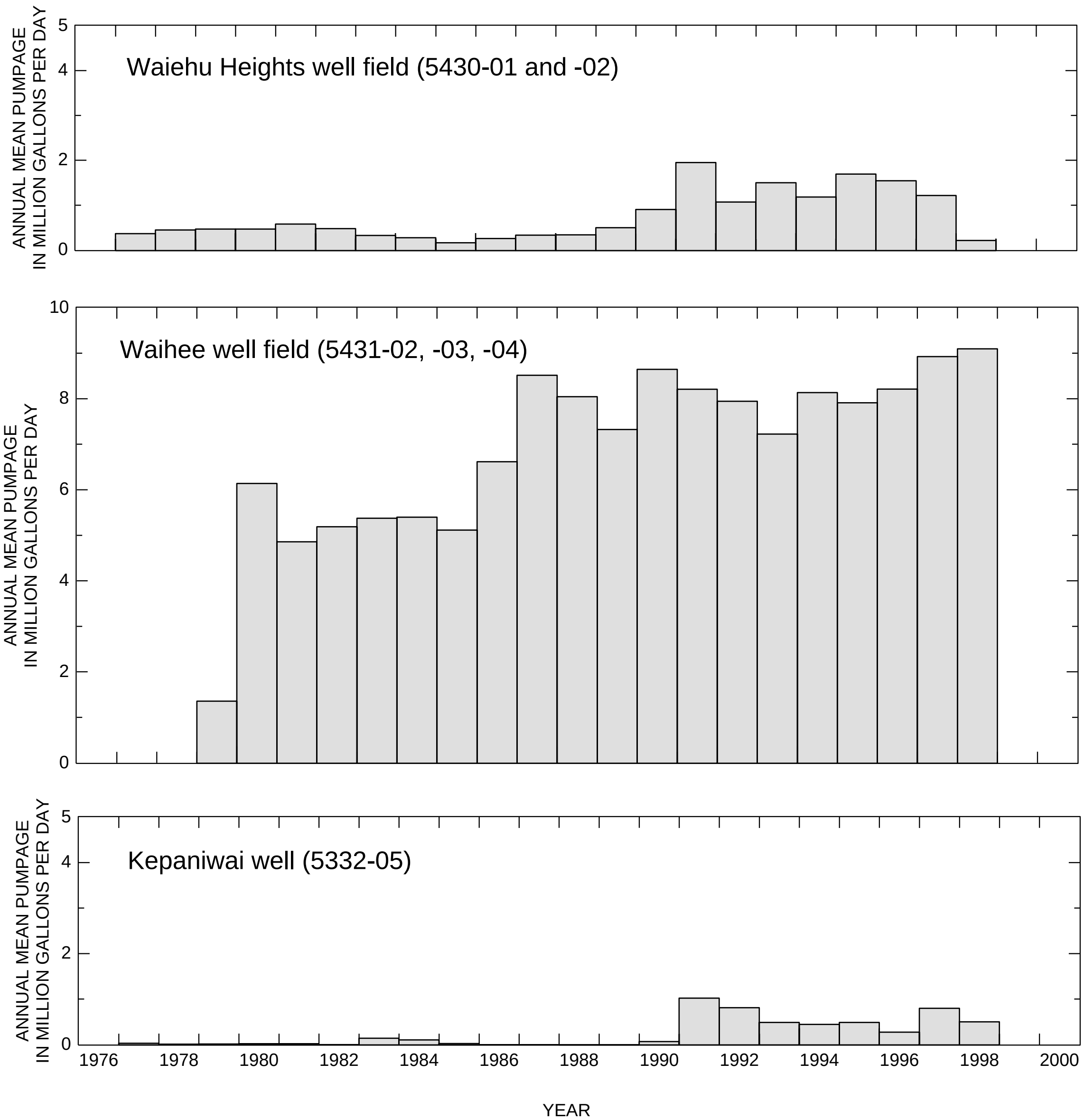


Figure 15. Annual mean pumpage for Waiehu Heights well field, Waihee well field, and Kepaniwai well, Maui, Hawaii. (Data from Maui Department of Water Supply.)

Table 4. Annual ground-water withdrawal from the Iao aquifer, Maui, Hawaii

[Values in million gallons per day, or percentage where noted; --, not applicable; data from Maui Department of Water Supply and unpublished data from Wailuku Sugar Co. in U.S. Geological Survey well files, Honolulu]

Year	Well field					Total	Domestic	Domestic (percentage of total)
	Waiehu Heights	Waihee	Kepaniwai	Mokuhau	Shaft 33			
1948	--	--	--	--	2.00	2.00	0.00	0.0
1949	--	--	--	--	1.99	1.99	0.00	0.0
1950	--	--	--	--	1.77	1.77	0.00	0.0
1951	--	--	--	--	3.70	3.70	0.00	0.0
1952	--	--	--	--	3.05	3.05	0.00	0.0
1953	--	--	--	--	9.77	9.77	0.00	0.0
1954	--	--	--	--	6.11	6.11	0.00	0.0
1955	--	--	--	1.10	1.31	2.41	1.10	45.6
1956	--	--	--	0.66	0.83	1.49	0.66	44.3
1957	--	--	--	1.19	6.12	7.31	1.19	16.3
1958	--	--	--	1.22	0.67	1.89	1.22	64.6
1959	--	--	--	1.43	4.15	5.58	1.43	25.6
1960	--	--	--	1.59	5.65	7.24	1.59	22.0
1961	--	--	--	2.25	5.64	7.89	2.25	28.5
1962	--	--	--	2.04	7.97	10.01	2.04	20.4
1963	--	--	--	2.06	0.85	2.91	2.06	70.8
1964	--	--	--	2.79	6.00	8.79	2.79	31.7
1965	--	--	--	2.67	4.68	7.35	2.67	36.3
1966	--	--	--	3.12	4.69	7.81	3.12	39.9
1967	--	--	--	2.91	3.08	5.99	2.91	48.6
1968	--	--	--	2.88	6.28	9.16	2.88	31.4
1969	--	--	--	3.61	1.18	4.79	3.61	75.4
1970	--	--	--	3.98	5.08	9.06	3.98	43.9
1971	--	--	--	4.34	11.65	15.99	4.34	27.1
1972	--	--	--	4.66	9.45	14.11	4.66	33.0
1973	--	--	--	5.16	8.11	13.27	5.16	38.9
1974	--	--	--	5.44	9.11	14.55	5.44	37.4
1975	--	--	--	6.40	10.56	16.96	6.40	37.7
1976	--	--	--	6.69	6.37	13.06	6.69	51.2
1977	0.38	--	0.04	8.10	6.39	14.91	8.52	57.1
1978	0.46	--	0.01	8.29	3.14	11.90	8.76	73.6
1979	0.48	1.37	0.02	6.51	3.29	11.67	8.38	71.8
1980	0.48	6.15	0.02	3.05	0.00	9.70	9.70	100.0
1981	0.59	4.87	0.03	5.80	1.18	12.47	11.29	90.5
1982	0.49	5.20	0.007	4.60	0.00	10.30	10.30	100.0
1983	0.34	5.39	0.14	5.82	0.00	11.69	11.69	100.0
1984	0.29	5.41	0.11	6.39	0.37	12.57	12.20	97.1
1985	0.18	5.12	0.03	6.52	0.00	11.85	11.85	100.0
1986	0.27	6.63	0.003	6.42	0.00	13.32	13.32	100.0
1987	0.34	8.53	0.003	5.11	0.00	13.98	13.98	100.0
1988	0.35	8.06	0.00	6.71	0.00	15.12	15.12	100.0
1989	0.51	7.34	0.00	7.49	0.00	15.34	15.34	100.0
1990	0.92	8.66	0.07	7.66	0.00	17.31	17.31	100.0
1991	1.96	8.22	1.03	5.72	1.90	18.83	18.83	100.0
1992	1.08	7.96	0.82	3.17	5.10	18.13	18.13	100.0
1993	1.51	7.24	0.49	3.60	5.56	18.40	18.40	100.0
1994	1.20	8.15	0.45	6.49	2.91	19.20	19.20	100.0
1995	1.71	7.92	0.49	4.92	5.46	20.50	20.50	100.0
1996	1.56	8.22	0.28	5.13	5.16	20.35	20.35	100.0
1997	1.23	8.94	0.80	6.29	1.84	19.10	19.10	100.0
1998	0.23	9.11	0.51	3.21	4.84	17.90	17.90	100.0

minimum was about 9.70 Mgal/d, and the average was about 11.52 Mgal/d.

Since 1984, all of the water pumped from the Iao aquifer has been for domestic use. Between 1985 and 1995, annual mean total pumpage increased by about 0.86 Mgal/d each year as domestic needs increased. In 1995, annual mean total pumpage peaked at a value of 20.50 Mgal/d.

In 1996, the annual mean total pumpage was 20.35 Mgal/d, nearly equal to the peak pumpage of the previous year. Annual mean total pumpage was reduced in the Iao aquifer area by about 1 Mgal/d per year in 1997 and 1998, primarily as a result of the additional pumpage from the North Waihee well field. Annual mean total pumpage decreased to 19.10 Mgal/d in 1997, and further decreased to 17.90 Mgal/d in 1998.

AQUIFER RESPONSE TO PUMPAGE, RAINFALL, AND LAND-USE CHANGES

Water-Level Changes Since the Introduction of Pumping

Pumping from the Iao aquifer has caused an overall decline in water levels that has resulted in a corresponding rise of the freshwater/saltwater transition zone. Pumping from each well field generates a cone of depression that overlaps with the cones of depression from one or more of the other well fields.

Water levels in the Iao aquifer have been monitored for various periods of time since 1940, beginning with measurements from test hole T-102 (fig. 3). However, the temporal-spatial distribution of observation wells has been insufficient to permit documentation of the change in water levels throughout the aquifer since the start of pumping. Also, sufficient data do not exist to fully document the temporal changes in water levels since the inception of pumping at any particular location.

Available data indicate that water levels not only respond to pumping, but also correspond closely to the departure of the mean of the preceding 12 months of rainfall from the mean rainfall of the entire record. Yamanaga and Huxel (1970) were the first to recognize that water levels in the Iao aquifer respond to changes in rainfall, and the findings of the present study reinforce this conclusion. In addition, water levels fluctuate seasonally, with annual highs occurring during the winter and lows occurring during the late summer or early fall.

Ground-water levels near shaft 33.--Initial efforts to monitor water levels in the Iao aquifer were at wells T-102 and T-112 (fig. 3). Water-level measurements were made at the two wells for various periods between 1940 and 1970, beginning at well T-102 in 1940, 8 years before pumping started at shaft 33. T-102 is about 1,800 ft upgradient of shaft 33 and about 2,300 ft from the Mokuhau well field (figs. 2 and 3). Test hole T-112, which was destroyed in 1996, was about 260 ft from the location of the wells in shaft 33. Water levels from T-112 are assumed for this report to be representative of water levels at shaft 33.

Water levels were measured monthly at T-102 during 1940–55 and continuously during 1968–70 (fig. 16). Water levels were measured monthly in T-112 during 1948–55 and continuously during 1968–70. Some breaks in the record exist for both wells. Pre-development water-level altitudes measured during 1940–47 at T-102 ranged from a low of about 26.9 ft to a high of 36.6 ft and averaged 31.4 ft. Water-level altitudes measured at T-112 ranged from 26.1 to 31.3 ft between 1946 and 1947 and averaged about 28.5 ft.

The hydrographs for T-102 and T-112 indicate that water levels near shaft 33 declined more than 5 ft within the first year of pumping at the shaft (1948), but thereafter, no definitive change was observed in the two wells until 1953. Water levels at the two wells fell an additional 5 to 10 ft during 1953, a year for which pumpage was high compared with preceding and following years and rainfall was low (fig. 16). Water levels recovered to within a few feet of pre-1953 levels between 1954 and 1955 when increased rainfall resulted in pumpage below that of 1953. Water levels at T-102 and T-112 during 1968–70 fell within the general range observed at these wells in 1954–55.

Water-level measurements were made in shaft 33 during 1973–75, and ranged from 23.5 to 19.3 ft. Water-level measurements resumed in the shaft in 1996 and have continued to the present time (1998) in one of the unused pumping wells located about 10 ft from the pumped well. The annual mean pumpage from the shaft between 1991 and 1996 ranged from 1.90 Mgal/d to 5.56 Mgal/d and averaged 4.35 Mgal/d. Water levels during 1996 dropped to a low of 9.2 ft above sea level after 22 months of continuous pumping (fig. 17). The shaft was not pumped during the first 7 months of 1997, and water levels rose to 16.4 ft. Pumping resumed in August 1997, and the water level in the shaft has since

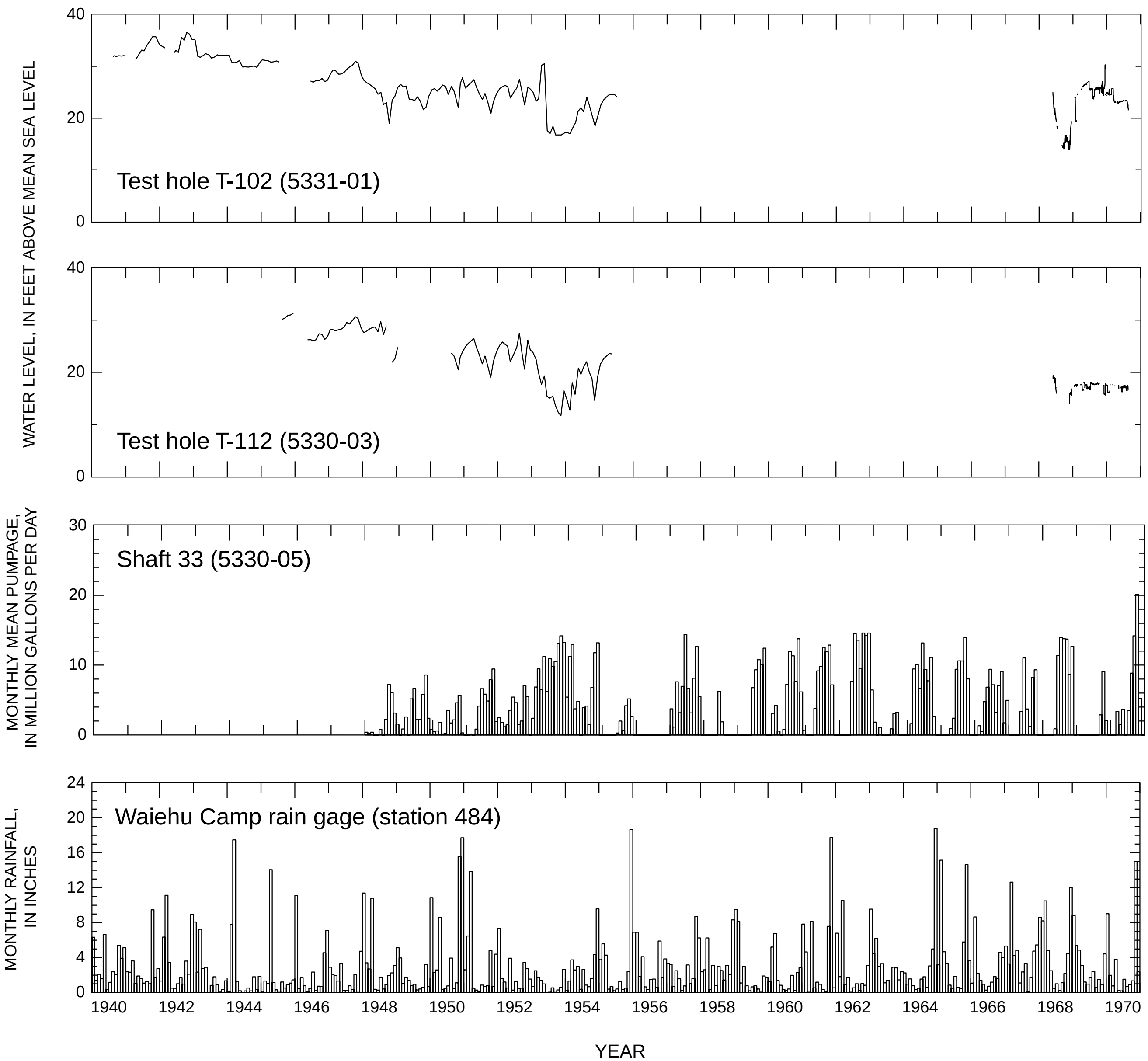


Figure 16. Water levels for test holes T-102 and T-112, monthly mean pumpage for shaft 33 and monthly rainfall for Waiehu Camp rain gage, for 1940–70, Maui, Hawaii. (Hydrographs from unpublished data in U.S. Geological Survey well files, Honolulu; unpublished pumpage data from Wailuku Sugar Company in U.S. Geological Survey well files, Honolulu; unpublished rainfall data from Commission on Water Resource Management and the University of Hawaii Meteorology Department.)

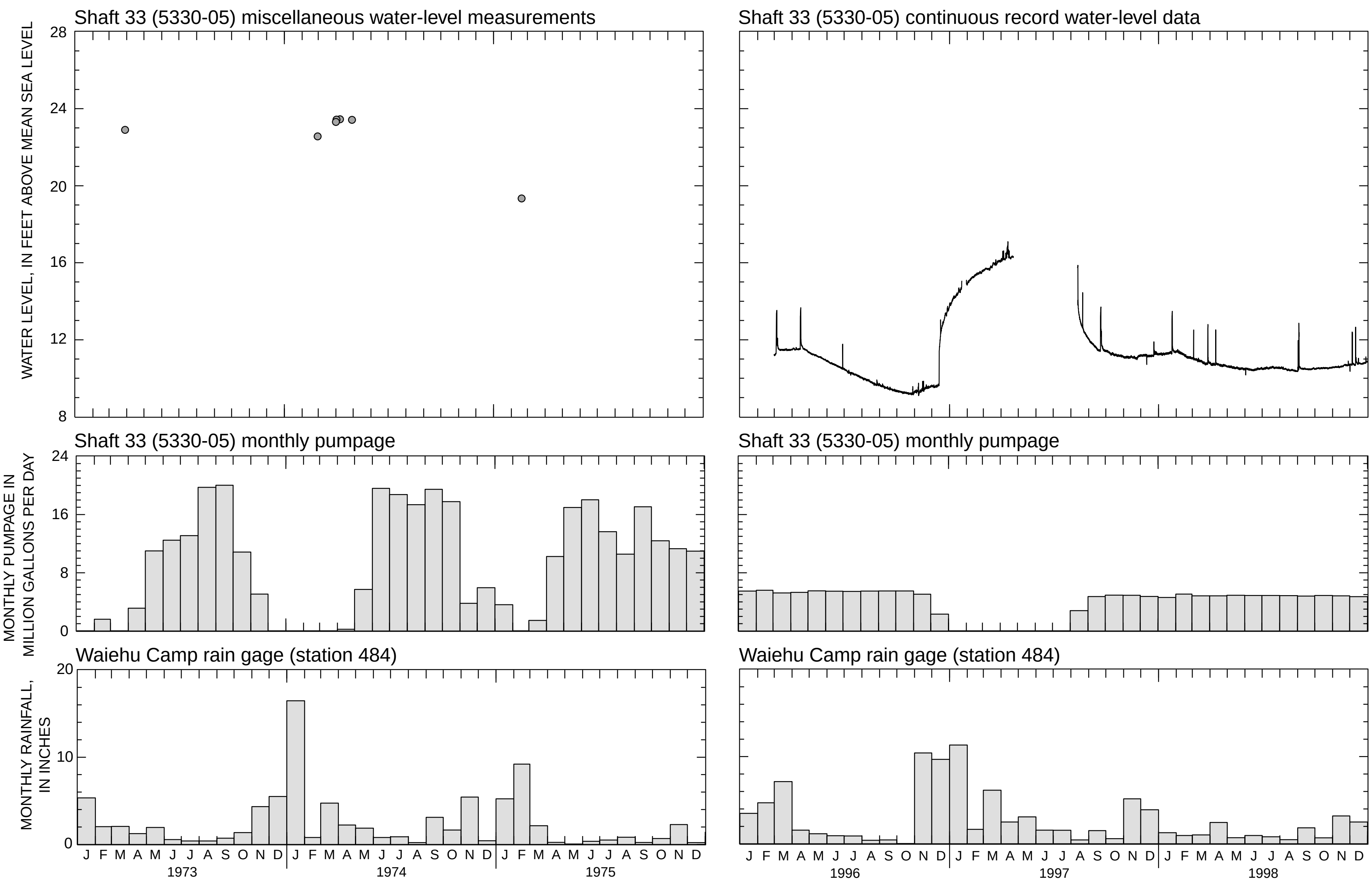


Figure 17. Water levels and monthly pumpage for shaft 33, and monthly rainfall for Waiehu Camp rain gage, for 1973–75 and 1996–98, Maui, Hawaii. (Pumpage data from Maui Department of Water Supply; unpublished rainfall data from Commission on Water Resource Management and the University of Hawaii Meteorology Department.)

declined by about 5 ft. The altitudes of the water levels remained between 10 and 11 ft for the last 9 months of 1998.

Water-level changes at Mokuhau well field.-- The initial water-level measurements in the vicinity of Mokuhau well field were measured in test hole 15D (fig. 3) in 1951. This well is located about 250 ft northwest of the well field. Water levels for test hole 15D are available for May 15, 1951 and for March 17, August 4, September 14, and October 5, 1952, as well as April 16, 1968 (fig. 18). Water levels in 1952 ranged from an altitude of 24.5 ft on March 17 to 23.2 ft on September 14 (fig. 18).

Water levels for the Mokuhau well field (Mokuhau pump 1, also known as well 15B; and Mokuhau pump 2, also known as well 15A, in figure 18) were recorded between 1954 and 1979. Pumpage from Mokuhau well field increased from about 1.10 Mgal/d in 1955 when pumping started, to about 2.91 Mgal/d in 1967 (fig. 18), but the effect of this pumping is not discernible from the hydrograph. Water levels may have dropped 2 or 3 ft over the first year of pumping, but this is not verifiable with the available data.

From 1951 to 1970, water levels generally ranged from seasonal lows around 16 to 17 ft to seasonal highs around 21 to 23 ft. Water levels at the well field began a steady decline between 1969 and 1975 with the seasonal low falling from over 20 ft in 1969 to about 8 ft in 1975–76. Water levels remained between 8 and 10.5 ft through 1976, 1977, and most of 1978. This decline occurred during a period when rainfall, for the most part, was below normal and pumping was significantly above previous rates (fig. 18 and table 4). Water levels rose to about 16 ft in early 1979 in apparent response to reduced pumpage and higher rainfall. However, after late 1979, water levels were not recorded again until 1998. During 1998, the water level in Mokuhau pump 2 ranged from a seasonal low of 9.1 ft in September to a high of 12.0 ft in December.

Ground-water levels in the northern part of the Iao aquifer.--Ground-water levels between Iao Stream and the Waihee River were first measured in January 1977 when five test holes were drilled (A1, B, C, D, and E) (fig. 3). Test hole C caved before it could be properly cased, but the other four test holes were successfully completed and have since been used as water-level observation wells. All the holes were drilled to obtain stratigraphic and hydrologic information as part of an exploratory program for a new well field in the vicinity of Waiehu Stream. Additionally, the Waiehu deep monitor well was drilled in 1982 to characterize and monitor the movement of the transition zone of the aquifer at this location. The deep monitor well is about 15.5 ft away from test hole D and is also in the vicinity of Waihee and Waiehu Heights well fields (fig. 3). The Waiehu deep monitor well was drilled to an altitude of -1,020 ft below sea level, and is uncased and open to the aquifer from an altitude of -20 ft to -1,020 ft.

Except for a period of about a year (1981–82), water-level measurements have continued in test hole E to the present (1998) (fig. 19). Measurements in the other test holes were interrupted between May 1977 to 1979, 1982, or 1983 depending on the location (fig. 19). The hydrograph for test hole D and the Waiehu deep monitor well is a composite of the measurements at both wells through time. Thirteen measurements, made in both wells within a few minutes of each other between 1983 and 1989, indicate that the altitude of water levels in the two wells are identical, allowing the data from the two wells to be combined into one hydrograph. In 1986, a water-level recorder was installed on the Waiehu deep monitor well.

The configuration of water-level contours in the flank flows of the Wailuku Basalt north of Iao Stream in April 1977 is consistent with the concept of a general movement of water from the dike complex to the ocean between Waiehu Stream and Waihee River, and water levels decreasing in an seaward direction (fig. 20). Water-level contours are based on the average water levels in the test holes for the month (table 5). On the basis of the contours, the average water level in the vicinity of Waihee well field (which had yet to be constructed) was about 15 ft at this time, and the average water level at Waiehu Heights well field was about 15.6 ft. The average water level at Mokuhau well field was 10.3 ft.

Contours bend inland near Waiehu Heights and Waihee well fields, and there is an inferred bending of contours inland at Mokuhau well field. The upstream bending of the contours in the Mokuhau area is expected given ground-water withdrawal at the well field. The cause of the bending of contours near Waiehu Heights and Waihee well fields is not clear. Pumping from Waiehu Heights well field began in 1977, but the exact date pumping started cannot be determined from

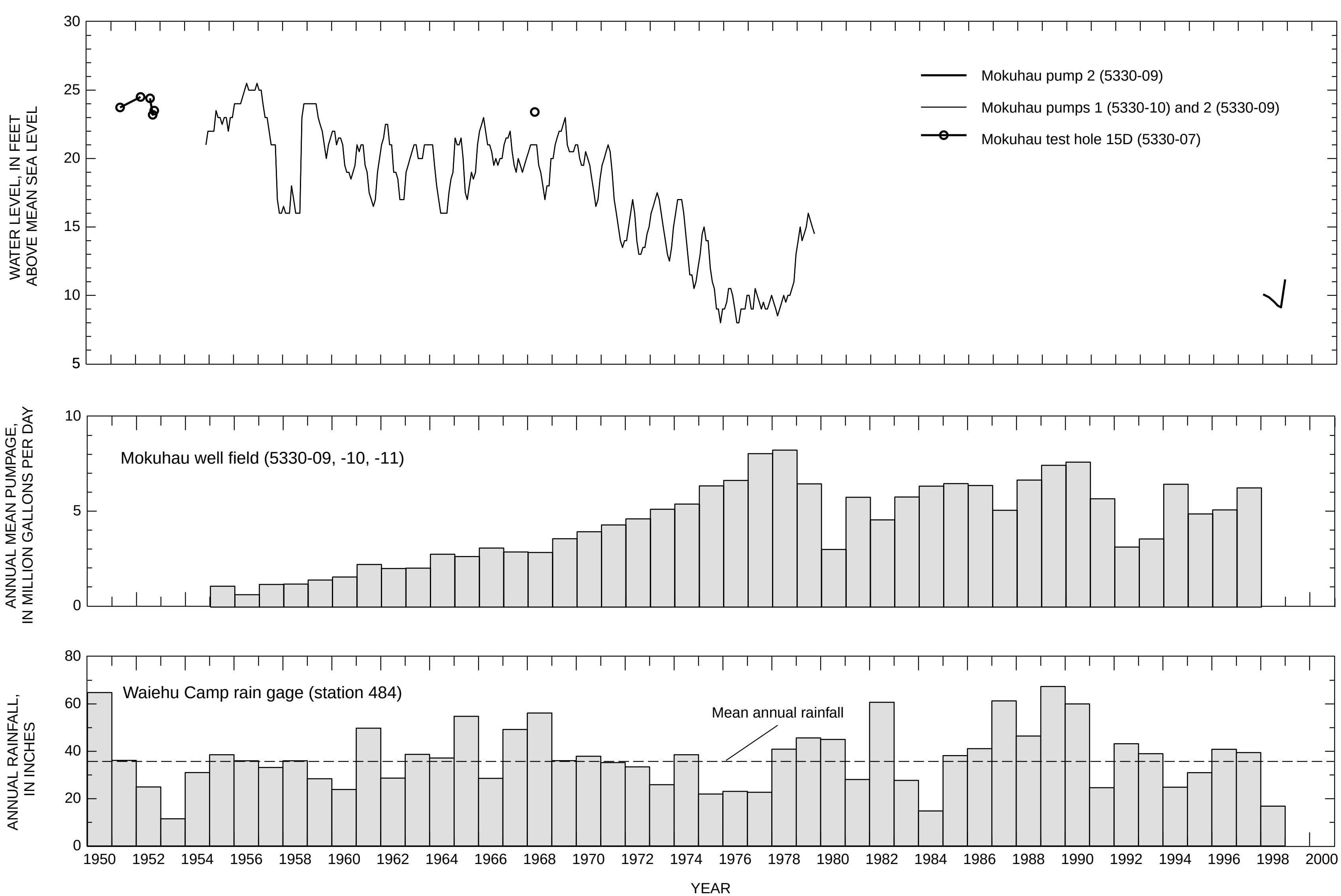


Figure 18. Water levels and annual mean pumpage for the Mokuhau well field, and annual rainfall for Waiehu Camp rain gage, Maui, Hawaii. (Water-level data prior to 1998 from unpublished data in U.S. Geological Survey well files, Honolulu; 1998 water-level data from U.S. Geological Survey data base; unpublished rainfall data from Commission on Water Resource Management; pumpage data from Maui Department of Water Supply.)

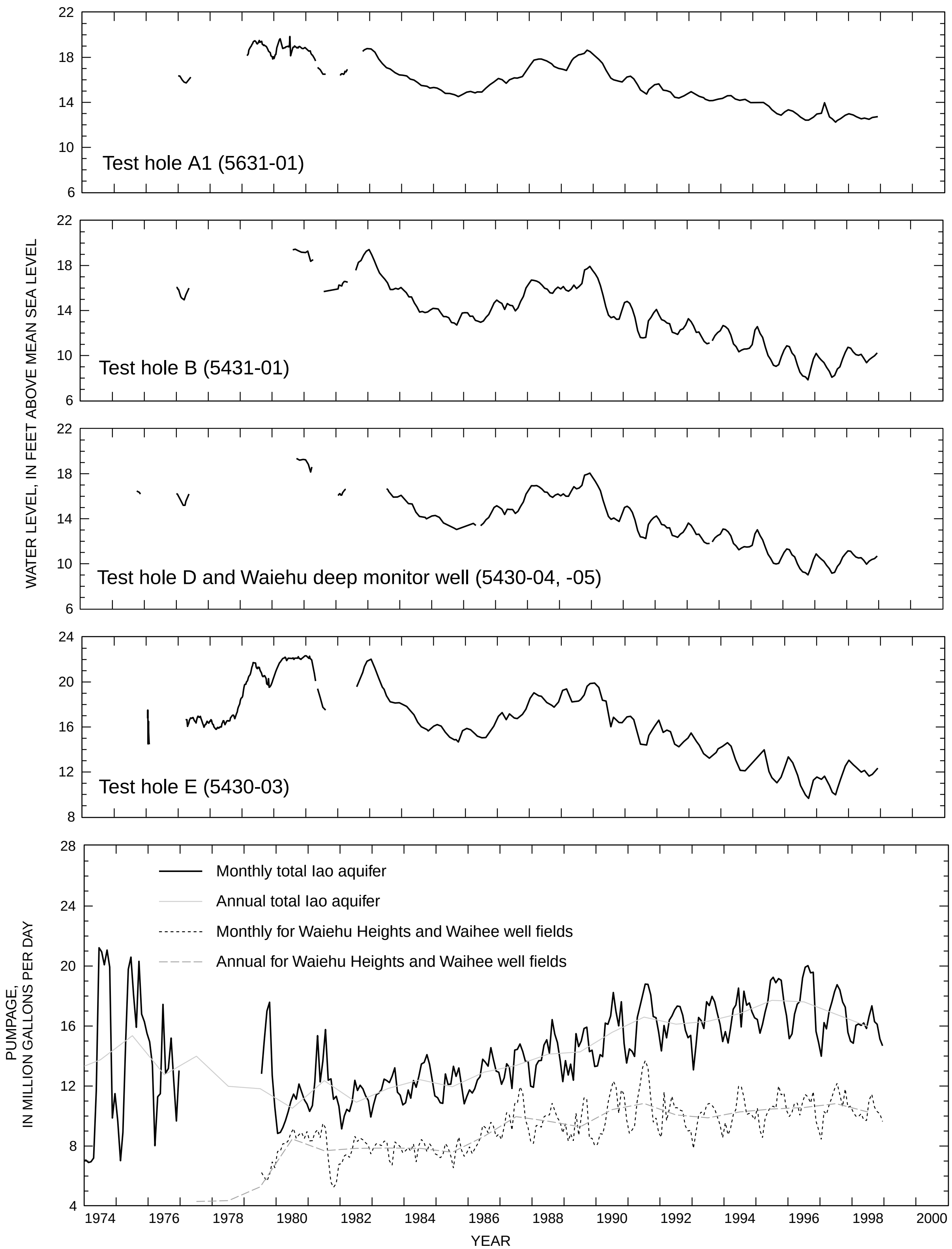


Figure 19. Water levels for test holes in the northern part of the Iao aquifer, and pumpage for Iao aquifer and for Waiehu Heights and Waihee well fields, Maui, Hawaii. (Water levels from unpublished data in U.S. Geological Survey well files and data base; pumpage data from Maui Department of Water Supply; monthly pumpage not available for Waiehu Heights and Waihee well fields for years 1977 and 1978, thus total monthly pumpage not shown for these 2 years.)

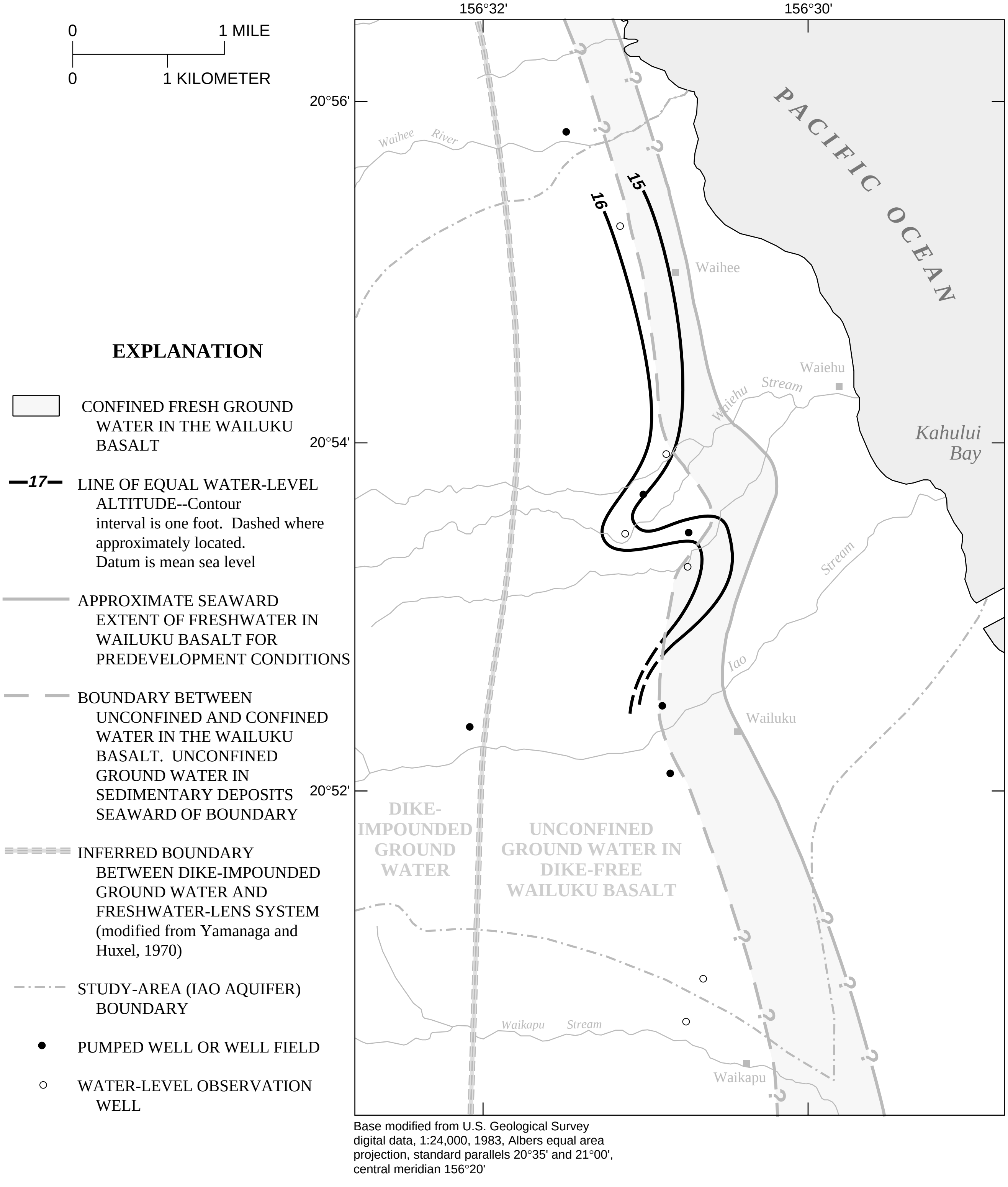


Figure 20. Mean water levels in the flank flows of Wailuku Basalt, April 1977, for the northern part of the Iao aquifer, Maui, Hawaii (see table 3).

Table 5. Mean water levels for April 1977, April 1997, and the year 1998; and seasonal low water levels for 1996 and 1998 for wells in the Iao aquifer area, Maui, Hawaii

[All values in feet; --, no data; datum is mean sea level; negative values are declines]

Well name	Mean water level of April 1977 (figure 20)	Mean water level of April 1997	Difference between mean water level of April 1977 and mean water level of April 1997 (figure 21)	Seasonal water-level low of 1996 (October) (figure 22)	Seasonal water-level low of 1998 (August) (figure 22)	Difference between seasonal water-level low of 1996 (October) and seasonal low of 1998 (August) (figure 22)	Mean water level of 1998 (figure 25)
Test hole A1	15.9	13.6	-2.3	12.4	12.5	0.07	12.7
Test hole B	15.3	9.4	-5.9	7.8	9.4	1.5	10.1
Waiehu deep monitor well and test hole D	15.5	10.2	-5.3	9.0	10.0	1.0	10.6
Test hole E	16.4	11.4	-5.0	9.7	11.6	2.0	12.3
Waikapu 1	--	15.9	--	12.0	12.0	--	12.3
Waikapu 2	--	13.0	--	11.9	12.1	-0.2	12.2
North Waihee well field	--	--	--	--	--	--	6.8
Waihee well field	--	--	--	--	--	--	--
Waiehu Heights well field	15.6	--	--	--	--	--	--
Mokuhau well field	10.3	--	--	--	9.3	--	10.0
Shaft 33	--	--	--	9.2	10.5	1.3	10.8

existing data. Pumping from Waihee well field began in 1979.

The hydrograph from test hole E (fig. 19) indicates that, despite the introduction of pumping from Waiehu Heights and Waihee well fields in 1977 and 1979, respectively (table 4), and despite a general increase in total pumpage from the aquifer between 1980 and 1996 (fig. 19), water levels actually began to rise in mid-1978 and in late 1982 to early 1983. Water levels were as much as 5 ft higher in the test holes than those measured in 1977. This peak was followed by a general decline in water levels in all the test holes (fig. 19) that lasted until late 1985 to early 1986 when water levels were as much as 3 ft below those recorded in 1977. Beginning in early 1986, water levels generally increased through late 1989 to early 1990, rising to several feet or more above those recorded for April 1977. The possible reason for water-level increases during 1977–83 and during 1985–90 is discussed in the following section on water-level changes relative to rainfall.

From mid-1990 or mid-1991 (depending on the test well) to the present (1998), water levels dropped below 1977 recorded values. A declining water-level trend continued until 1996–97, after which water levels started to increase. The water-level increase corresponds to the decrease in the annual rate of ground-water withdrawal that began in 1997 (table 4, fig. 4). The contoured areal decline in water levels from April 1977 to April 1997 for the northern half of the aquifer is shown in figure 21. Maximum water-level decline is greater than 6 ft and centered around Waihee and Waiehu Heights well fields. The decline decreases in an outward direction from the well fields.

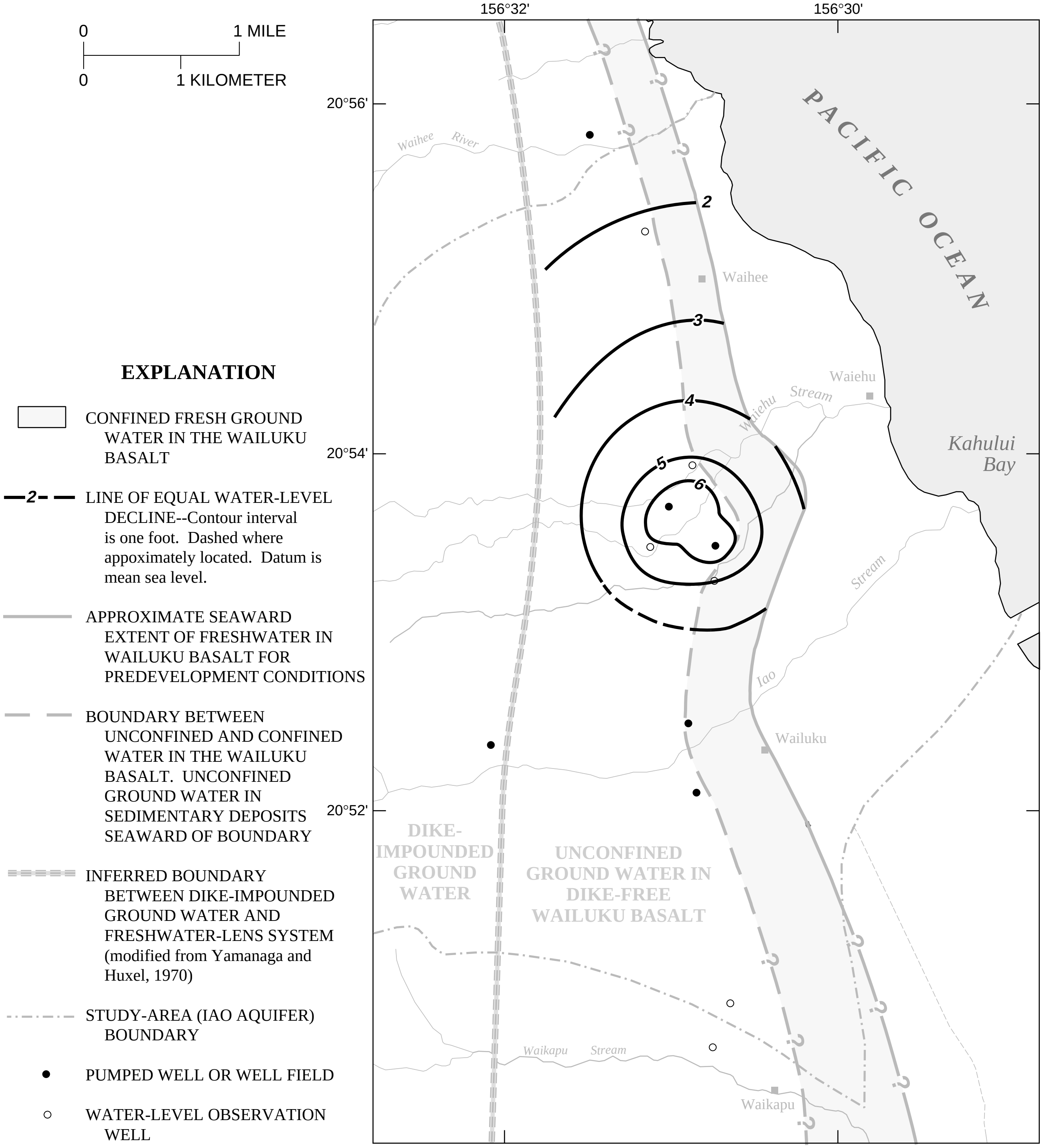
The lowest water levels measured during 1990–97, when water levels generally were declining, occurred in August 1996. These water levels were also the seasonal-low water levels for 1996. Following the reduction in pumping in 1997 and 1998, water levels increased such that the seasonal-low water levels in 1997 were greater than the seasonal-low water levels in 1996, and the seasonal-low water levels in 1998 were greater than the seasonal-low water levels of 1997. The contoured areal rise in the seasonal low between 1996 and 1998 is shown in figure 22. The greatest rise (2.0 ft) in water levels is centered around Waiehu Heights well field, where annual average pumpage decreased from 1.56 Mgal/d in 1996 to 0.23 Mgal/d in 1998. The water levels also rose by about 1.3 ft at shaft 33, where the monthly pumping rate was reduced from about 5.16 Mgal/d to 4.84 Mgal/d during 1996–98. No water-level data are available during 1996 for the Mokuhau well field, but pumpage was reduced at the well field from an annual average of 5.13 Mgal/d to 3.21 Mgal/d during 1996–98.

Other water-level measurements.--Water levels have been consistently measured near Waikapu Stream at Waikapu wells 1 and 2 since 1989 and 1983, respectively (fig. 23). Water levels were measured in Waikapu 1 for a few months in 1967 and in Waikapu 2 for a few months during 1974–75. Water levels were measured at North Waihee 1 between 1988 and 1996 (fig. 23). Water-level measurements continued at this well following the start of pumping in 1997. Since 1991, water levels have been measured in the Kepaniwai observation well near the Kepaniwai well (fig. 24).

The water-level trends for the two Waikapu wells follow the trends of the other wells in the Iao aquifer, with a general decline in water levels from 1990–96. The water-level record for Waikapu 1 shows greater seasonal fluctuation than other wells in the Iao aquifer and a greater overall decline between 1990 and 1996 than Waikapu 2. Seasonal water-level trends at Waikapu 2 more closely parallel those at observation wells farther north in the aquifer. Water levels increased in 1997–98 in both of the Waikapu wells, which may have been a response to the decrease in pumpage over these 2 years.

The water-level trend at North Waihee 1 during 1988–96 is similar to the trends of the other monitor wells in the Iao aquifer (fig. 19), although the water levels were 4 to 5 ft lower than the closest monitor well south of the Waihee River (test hole A1). Although water-level measurements continued since the start of pumping at this well in 1997, the measurements are of limited value for monitoring aquifer trends and are not discussed in this report.

Water levels have been measured at Kepaniwai observation well (fig. 3) since 1991. The well head is at an elevation of about 713 ft above sea level, and penetrates into the dike-impounded water body. The observation well is about 10 ft from the Kepaniwai well. The initial water level for the pumped well was about 675 ft above sea level in 1973. Water levels in the observation well have ranged from 630.3 to 673.6 ft above sea level



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 20°35' and 21°00', central meridian 156°20'

Figure 21. Water-level declines in the flank flows of Wailuku Basalt between April 1977 and April 1997 for the northern part of the Iao aquifer, Maui, Hawaii (see table 3).

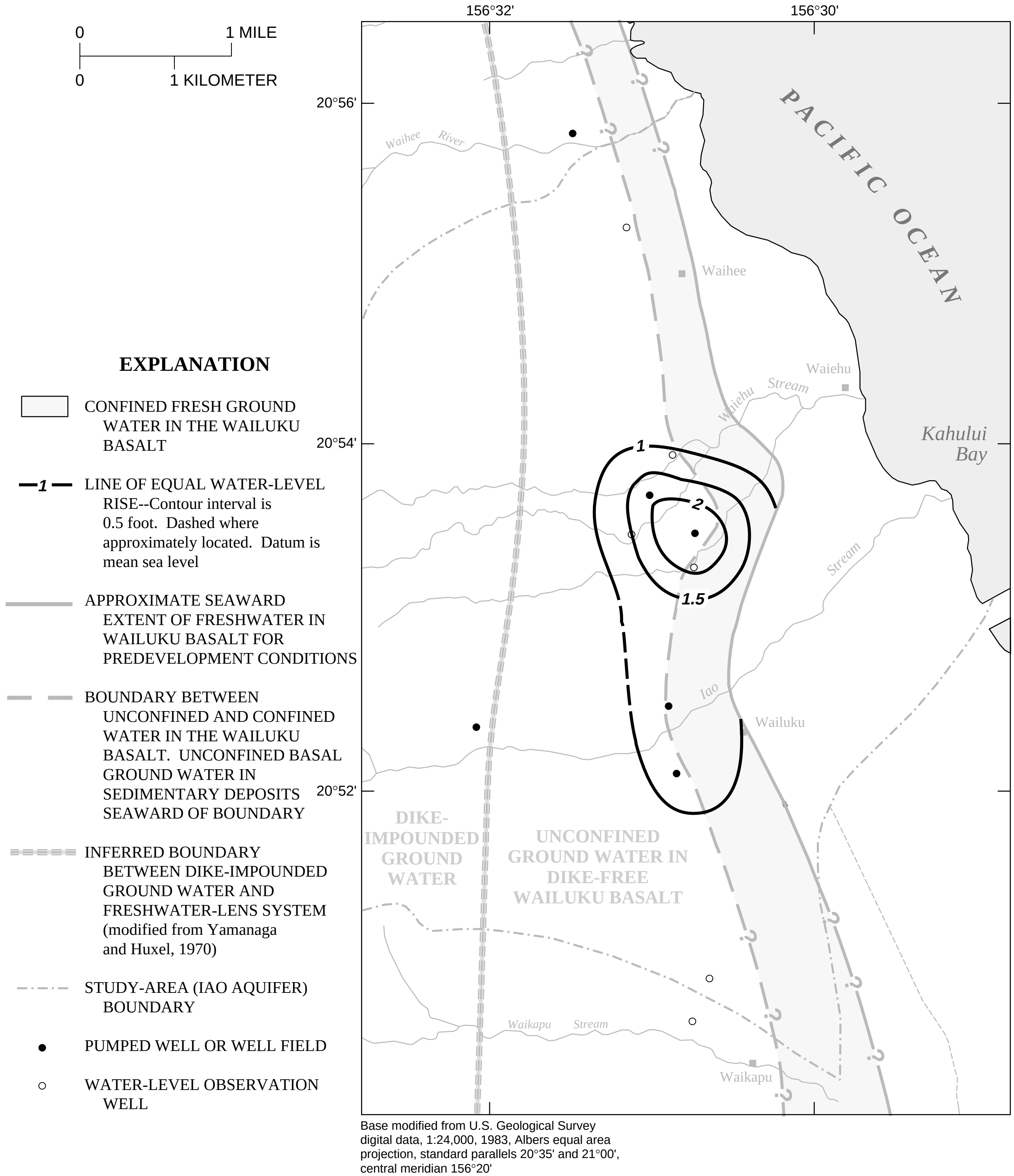


Figure 22. Water-level rise in the flank flows of Wailuku Basalt between the seasonal low of 1996 and the seasonal low of 1998 for the Iao aquifer, Maui, Hawaii (see table 5).

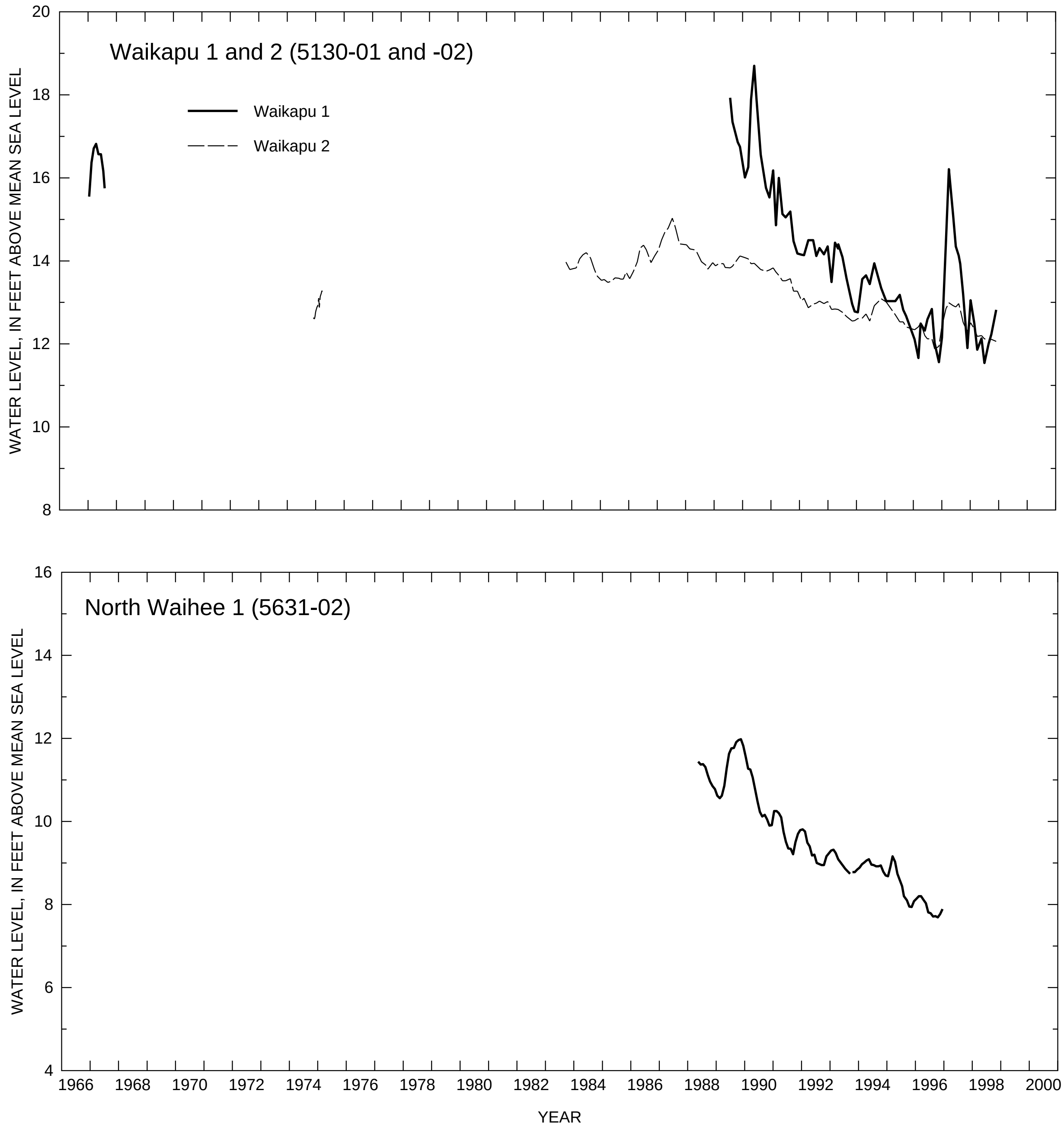


Figure 23. Water levels for Waikapu 1 and 2, and North Waihee 1, Maui, Hawaii (from U.S. Geological Survey data base and unpublished data in U.S. Geological Survey well files, Honolulu).

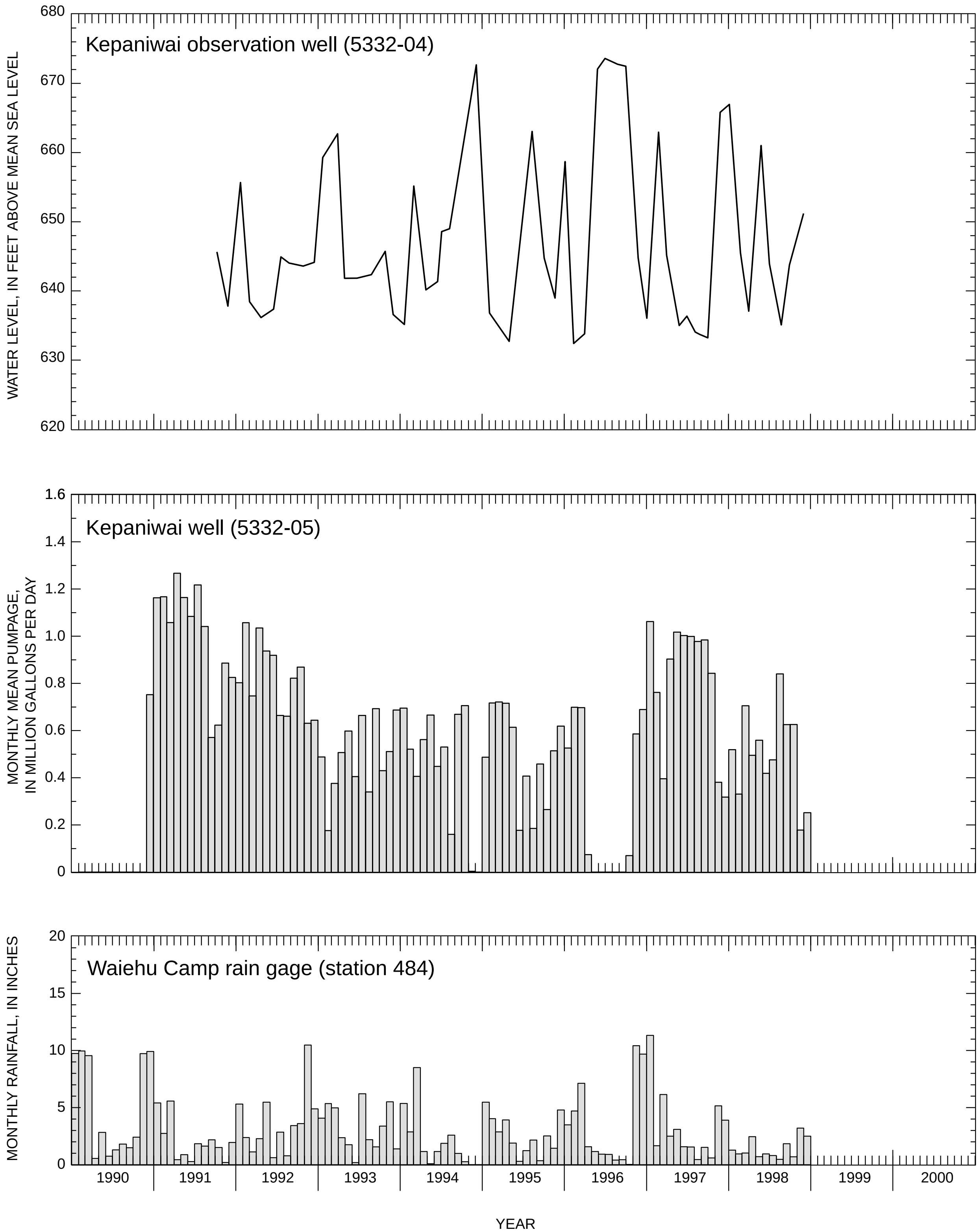


Figure 24. Water levels and monthly mean pumpage for the Kepaniwai wells, and rainfall for Waiehu Camp rain gage, for 1980–98, Maui, Hawaii. (Pumpage data from Maui Department of Water Supply; unpublished rainfall data from Commission on Water Resource Management and the University of Hawaii Meteorology Department.)

over the period of record with no discernible declining or rising trend (fig. 24). Water-level fluctuations in the Kepaniwai observation well correspond to pumping fluctuations in the pumped well.

Water levels in the Iao aquifer, 1998.--The water-level measurements at Mokuhau well field in 1998, combined with the measurements at Waikapu 1 and 2, shaft 33, the Waiehu deep monitor well, and test holes A1, B, and E, make it possible to construct a map of mean water-level contours between Waikapu Stream and Waihee River for 1998 (fig. 25 and table 5). The contours indicate a general movement of water toward the ocean, as would be expected. They also bend upgradient near Mokuhau well field, and near Waihee and Waiehu Heights well fields, similar to the water-level contours for 1977 (fig. 20).

The average water level near the major well fields was about 10 ft in 1998. Water levels were about 18 ft below the predevelopment water level at shaft 33, as measured in T-112 in 1940, and about 14 ft below the average water level measured at Mokuhau well field in 1952. The average 1998 water level at Waihee and Waiehu Heights well fields is more than 5 ft below average water levels at these locations during April 1977 (fig. 20).

Water-Level Changes Relative to Rainfall

From 1948 to 1980, large fluctuations in total pumpage were primarily due to increased agricultural irrigation pumping during dry periods. Low rainfall during 1952–54, 1962, 1964, and 1975–78, corresponds to periods of increased pumpage from shaft 33, which was used only for agriculture during this time. Water levels in the Iao aquifer declined during these periods indicating that these declines may be a combined result of increased pumping and low rainfall (figs. 4, 16, and 18).

The best data available for examining the relation among water levels, rainfall, and pumpage are the hydrographs for test holes A, B, and E, and the combined hydrograph for test hole D and the Waiehu deep monitor well (fig. 19). Assuming no other influence, water levels in the general area encompassed by the test holes would be expected to decline after the start of pumping from Waiehu Heights and Waihee well fields, at least on an annual basis. However, several times during the 1980's, water levels rose above 1977 water levels (the year that pumping started at Waiehu Heights) and above 1979 water levels (the year that pumping started at Waihee well field). The increase in water levels indicates that another factor such as rainfall, or a combination of factors, influence ground-water levels, and that these factors are sufficient, at least temporarily, to offset declines induced by the combined pumping at the two well fields.

One factor, other than rainfall, that would probably cause a temporary increase in water levels above 1977 values in the area of the Waiehu Heights and Waihee well fields, is that during 1975–80, annual rates of pumping from Mokuhau well field and shaft 33 were reduced from about 17 Mgal/d to below 10 Mgal/d. Most of the reduction was at shaft 33. Ground-water pumpage from the aquifer did not reach or exceed that of 1975 until 1990 (fig. 4). However, offsetting the reduction of pumpage was the loss of recharge to the aquifer in the late 1970's and early 1980's as a result of changes in irrigation practices (furrow to drip), changes in crops grown, and a reduction of agricultural acreage. The reduction of recharge from 51 Mgal/d during 1926–79 to 40 Mgal/d during 1980–85, together with the introduction of pumping at the Waiehu Heights and Waihee well fields, would collectively have caused water levels to decline below 1977 values if rainfall and pumpage from Mokuhau well field and shaft 33 had remained constant.

Yamanaga and Huxel (1970) concluded that water levels in the aquifer seemed to respond to annual or seasonal changes in rainfall rather than monthly fluctuations, and this apparent relation was investigated further for this study. Daily and monthly rainfall data were used to compare trends in rainfall and water levels. Plots of the percent departure of 6-, 12-, 18-, and 24-month average from the long-term mean rainfall for station 484 (fig. 2) were also compared to the hydrographs of the test holes. The plot using the departure of the 12-month average best matched the long-term trend of the hydrographs (fig. 26). Prior to 1991, the match is apparent. The match of the trends indicates that the time required for the infiltrating rainfall to affect the altitude of the water tables is similar to the 6-month time lag resulting from the averaging process of the rainfall record. Although not shown, this relation is similar for the other wells.

Long-term trends in water levels during 1977–91 in the area of Waiehu Heights and Waihee well fields

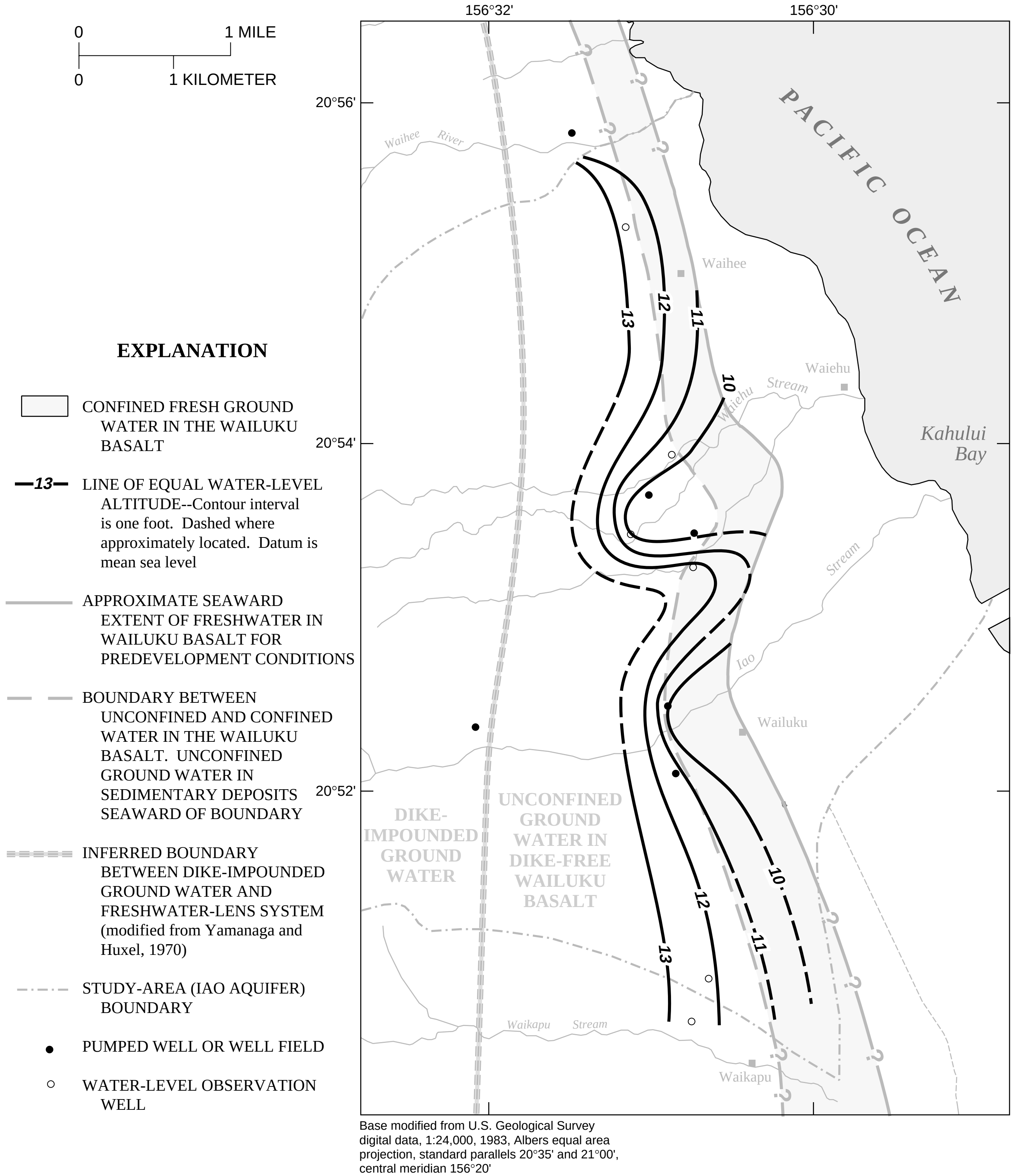


Figure 25. Mean water levels in the flank flows of Wailuku Basalt in 1998 for the Iao aquifer, Maui, Hawaii.

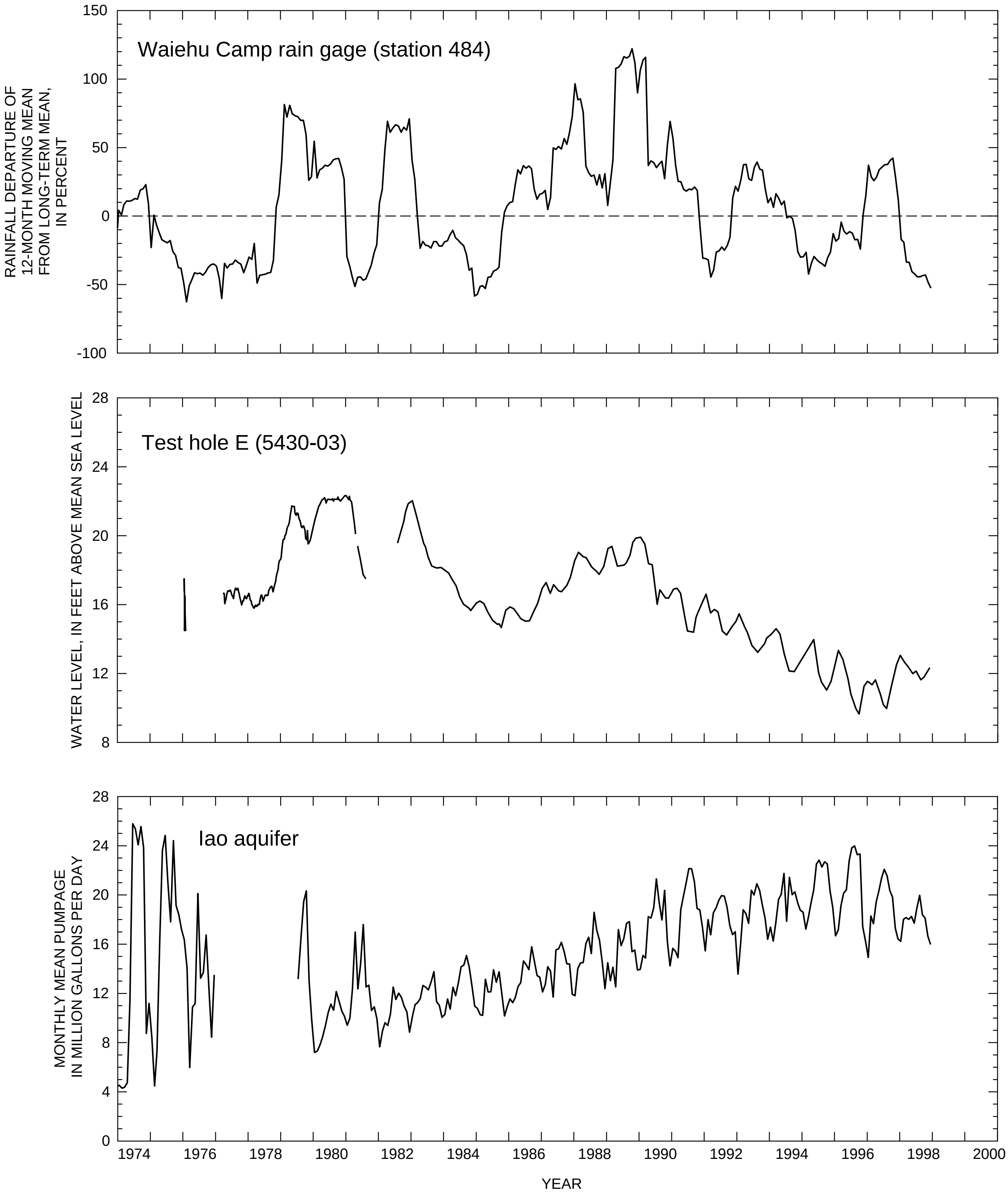


Figure 26. Rainfall departure of backward-looking 12-month moving mean from long-term mean for Waiehu Camp rain gage, water levels for test hole E, and monthly mean total pumpage for the Iao aquifer, Maui, Hawaii. (Water-level data prior to 1982 from unpublished data in U.S. Geological Survey well files, Honolulu; water-level data including and after 1982 from U.S. Geological Survey data base; unpublished rainfall data from Commission on Water Resource Management and the University of Hawaii Meteorology Department; pumpage data from Maui Department of Water Supply; monthly pumpage is not available for Waiehu Heights and Waihee well fields for 1977 and 1978, thus total monthly pumpage is not shown for these 2 years.)

correspond to the departure of rainfall for the preceding 12 months from mean rainfall, and not pumpage (fig. 26). Water levels failed to mimic the higher rainfall in 1993 and other changes in rainfall thereafter, indicating that pumpage from 1993 onward had reached a magnitude (18.40 Mgal/d) such that the effect of pumpage on water levels exceeded the effect of rainfall variation on water levels.

Seasonal Variation.--In addition to the long-term trend, water levels in test holes A1, B, D, and E also fluctuated seasonally as much as 2 ft (fig. 19) during 1991–98. The highest water levels were in either January or February of the year, and the lowest water levels were in August, September, or October. Seasonal changes in water levels are probably induced by seasonal changes in rainfall and pumpage. The highest rainfall months in the Wailuku area are in December through March, and the lowest rainfall months are in June through September (Blumenstock and Price, 1967). Pumpage is generally highest in August through October, and lowest during the winter months.

An indication that seasonal change in water levels is most influenced by pumpage is shown by the comparison of hydrographs prior to pumping (1941–48) for test holes T-102 and T-112 (fig. 27), to the hydrograph of test hole E during the more recent period of pumping (1991–98) (fig. 26). The hydrographs for test holes T-102 and T-112 show little seasonal variation and no apparent correlation with seasonal fluctuations of rainfall, whereas the hydrographs of test holes A1, B, D, and E (fig. 19) show seasonal fluctuation of water levels corresponding to the seasonal fluctuation in pumpage.

Movement of the Freshwater/Saltwater Transition Zone

The decline in water levels from increased pumpage and reduced recharge has resulted in an upward movement of the saltwater that underlies the freshwater body. Ultimately, the amount of fresh ground water that can be developed is limited by the upward and landward movement of saltwater.

For the purposes of this report, freshwater is defined as having a chloride concentration of less than 250 mg/L, on the basis of the USEPA secondary maximum contaminant levels for chloride concentration of domestic water (U.S. Environmental Protection Agency, 1996). The chloride concentration of seawater around the Hawaiian islands is about 19,600 mg/L (Wentworth, 1939). The change from freshwater to saltwater at depth in an aquifer is not abrupt; rather, freshwater and saltwater mix and the change is gradual through the transition zone. The transition zone includes water with chloride concentrations between 250 mg/L and 19,600 mg/L.

On the basis of the density difference between freshwater and saltwater, freshwater is sometimes assumed to extend below sea level to a depth equal to 40 times the water level above sea level, assuming that hydrostatic conditions prevail. This relation is referred to as the Ghyben-Herzberg relation (see, for example, Bear, 1979, p. 560). In practice, the depth defined by the Ghyben-Herzberg relation approximates the point in the transition zone where the salinity of the ground water is equivalent to a mixture of 50 percent freshwater and 50 percent saltwater, and therefore is commonly referred to as the midpoint (Lau, 1962). This midpoint, however, may not represent the half-way point of the total thickness of the transition zone. As used in this report, the term midpoint represents the altitude in a well at which the chloride concentration is 9,800 mg/L.

Because the amount of water that can be developed from a freshwater lens for potable use is constrained by the salinity of the water, the altitude of the top of the transition zone and the thickness of the transition zone are of great practical interest. Additionally, since the approximate altitude of the midpoint of the transition zone can be estimated from static water levels in wells, the thickness of the upper part of the transition zone between the freshwater limit and the midpoint is also of interest.

Waiehu deep monitor well.--The deep monitor well, drilled to an altitude of about -1,020 ft, penetrates most of the transition zone. Since 1985, water samples for chloride-concentration analysis have been collected quarterly from discrete depths (fig. 28). Chloride-concentration data from the Waiehu deep monitor well would be expected to most reflect changes in the aquifer as a result of pumping from the Waihee and Waiehu Heights well fields because the deep monitor well is located closest to these well fields. Because the well is uncased, it is possible that the value of chloride concentration of the water collected at any depth in the well is influenced by borehole flow. Thus, chloride concentration for a given depth may not reflect the actual chloride concentration of water in the aquifer at that depth.

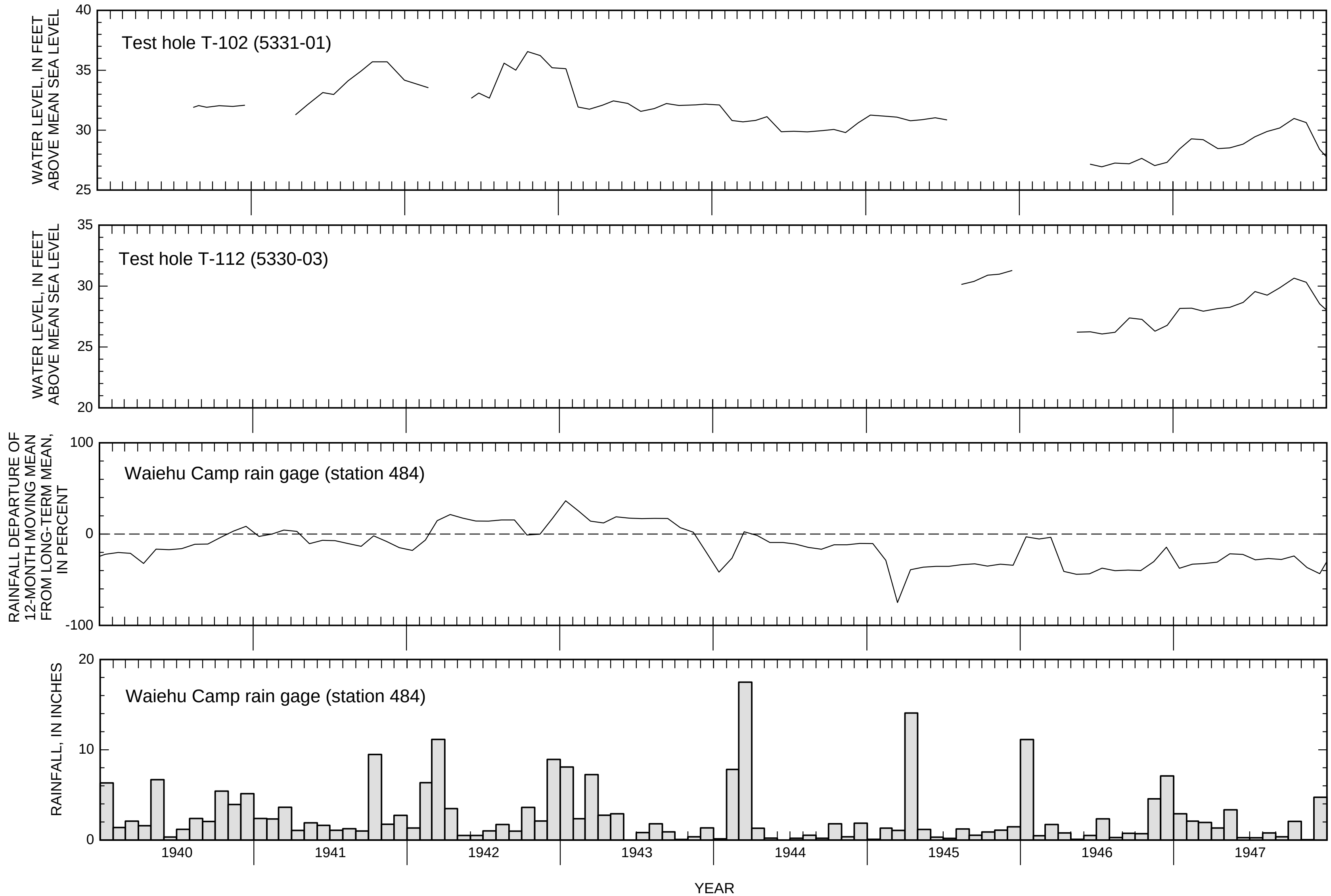


Figure 27. Water levels and rainfall before the start of ground-water withdrawal in the Iao aquifer, Maui, Hawaii. (Unpublished water-level data in U.S. Geological Survey well files, Honolulu; unpublished rainfall data from Commission on Water Resource Management and the University of Hawaii Meteorology Department.)

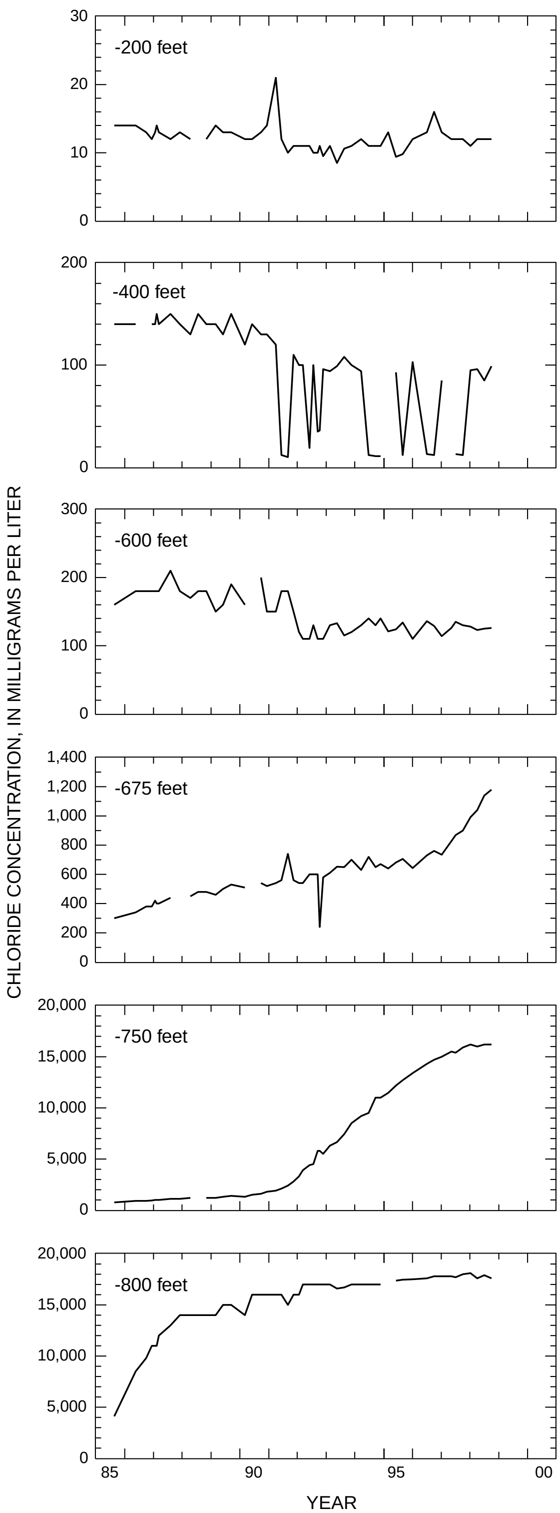


Figure 28. Chloride concentration with time for selected altitudes at the Waiehu deep monitor well (5430-05), Maui, Hawaii, 1985–98.

Nevertheless, discrete sampling with depth over time provides a general pattern of transition-zone thickness and movement.

Chloride concentrations have gradually decreased since 1985 for altitudes down to -600 ft. Chloride concentrations have risen and continue to increase with time at -675 and -750 ft. At -800 ft, chloride concentration initially rose, but has essentially stabilized at 17,000 mg/L.

Chloride concentrations at selected altitudes for 1985, 1990, 1995, and 1998 are shown in figure 29. By linearly interpolating between the chloride concentrations of the sampling points, the midpoint of the transition zone in August 1985 was about -823 ft. By September 1990 and August 1995 the midpoint rose to about -777 ft and -727 ft, respectively. By July 1998, the midpoint of the transition zone rose to about -715 ft. The total change in the position of the midpoint from 1985 to 1998 was about 108 ft, corresponding to an average rate of 8.4 ft/yr.

The top of the transition zone, on the basis of the interpolation of the sampling points in the well, was at about -648 ft in 1985 and about -613 ft in 1998. Thus, the top of the transition zone moved upward about 35 ft between 1985 and 1998 compared with 108 ft for the midpoint over the same time period. The thickness of the upper part of the transition zone, which is the water between the midpoint and top of the transition zone, thinned from about 173 ft in 1985 to about 102 ft in 1998. This apparent thinning of the upper part of the transition zone may be actual, or it may be an artifact resulting from the interpolation between data points to determine the depth where water with a chloride concentration of 250 mg/L occurs. Significant borehole flow, if present, could also influence the conclusion concerning the thinning of the upper part of the transition zone. Using the chloride-concentration data, it is probably more appropriate to conclude that the thickness of the upper part of the transition zone is somewhere between 100 to 175 ft, rather than to assume an actual thickness for the transition zone at a given time or that it has thinned over time.

Assuming a 40-to-1 Ghyben-Herzberg relation between the altitude of the midpoint below sea level and the altitude of the water table, the midpoint altitudes estimated for 1985, 1990, 1995, and 1998 correspond to water levels of 20.6, 19.4, 18.2, and 17.9 ft, respectively. The actual water level in the well was lower for each

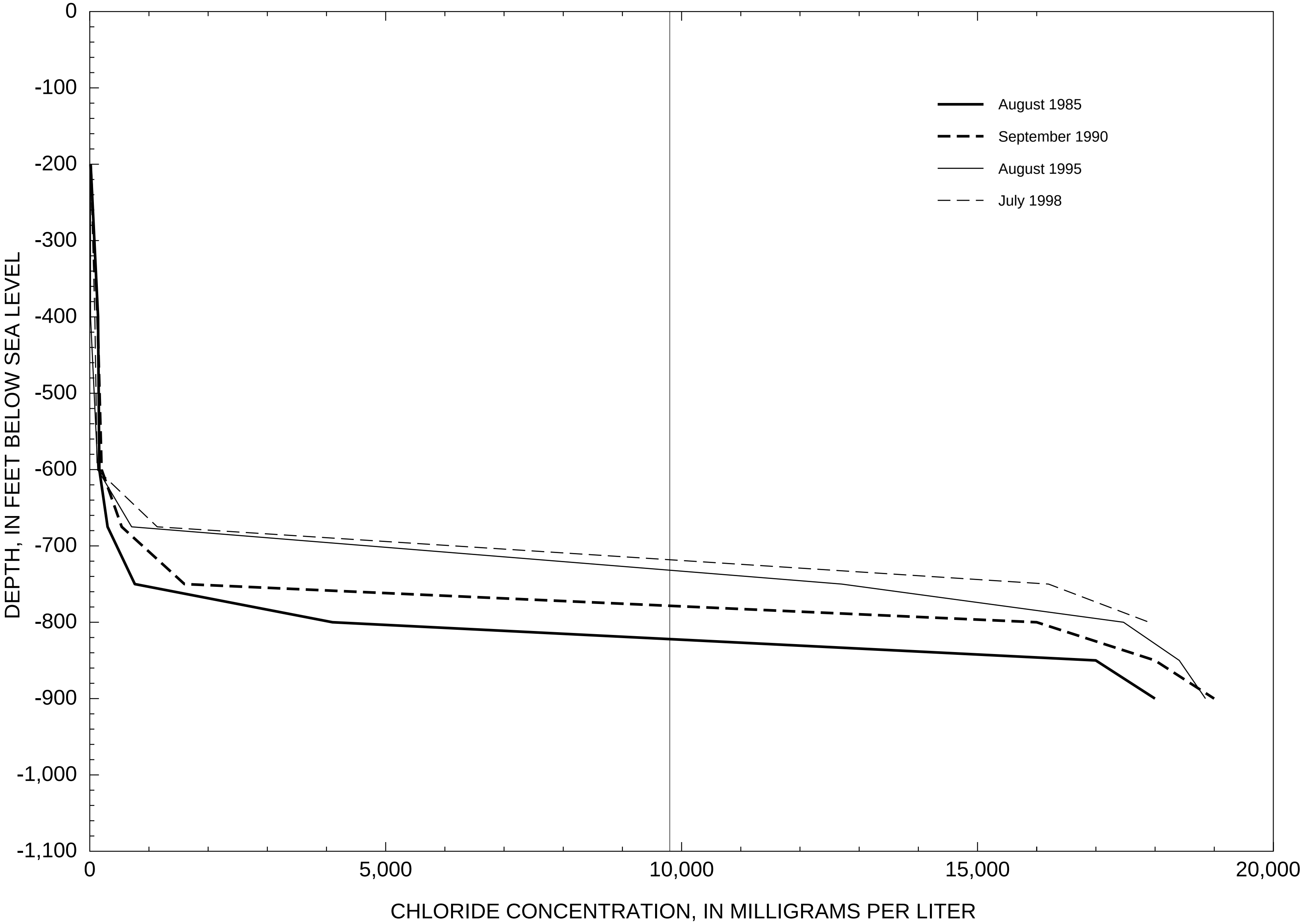


Figure 29. Chloride concentration with depth for selected depths and dates at the Waiehu deep monitor well (5430-05), Maui, Hawaii, 1985–98.

of these years, however. The water level was between 13 and 14 ft in 1985, 13 to 18 ft in 1990, between 10 to 13 ft in 1995, and between 10 and 11 ft in 1998. The discrepancy between the heads calculated from the Ghyben-Herzberg relation for the position of the midpoint of the transition zone in 1985, 1990, 1995, and 1998 and the actual water levels for these times is not surprising. Movement of the transition zone in response to a change in the position of the water table lags considerably behind the change in the water table (Essaid, 1986). This delay may be on the order of years to tens of years. The present position of the water table at the well is 10 to 11 ft above sea level, which corresponds to an altitude of the midpoint of about -400 to -440 ft. This indicates that the upward movement of the transition zone may continue if water levels remain near their present altitude.

The Ghyben-Herzberg relation assumes, however, that the head in the well does not change vertically through the thickness of the freshwater lens. (Hydraulic head at a given point is commonly measured by water levels in wells that are open to the aquifer only at that point.) If a vertical head gradient exists at the location of the Waiehu deep monitor well, such that there is greater head with depth in the well, then the depth to the midpoint in equilibrium conditions would actually be deeper than that calculated using the Ghyben-Herzberg relation (Izuka and Gingerich, 1998). If so, the upward movement of the transition zone could possibly halt at a depth greater than what would be expected if the water levels in the aquifer are maintained at present levels. Conversely, if the well is located within the area of the aquifer with less head with depth in the well, the upward movement of the midpoint would rise above the level predicted by the Ghyben-Herzberg relation. However, as discussed previously, water-level measurements made in test hole D (open to the aquifer between -68 to -108 ft) and the Waiehu deep monitor well (open to the aquifer between -20 and -1,020 ft) indicate that water levels in the two wells are the same. Thus, in the vicinity of the deep monitor well, the Ghyben-Herzberg assumption of no vertical head loss is met.

Changes in the Chloride Concentration of Pumped Water

Values of chloride concentration of the pumped water from the well fields are available from 1972 to the present. Comparison of these values with chloride-concentration values obtained at the well fields prior to pumping indicates that chloride concentrations of the water from pumped wells have increased above predevelopment levels.

Causes for changes in chloride concentration of the pumped water over time can be a function of pumping rate of the particular well, pumping at nearby wells, depth of the well, and overall aquifer trends. Therefore, the evaluation of aquifer conditions based on chloride-concentration trends from the pumping wells has limitations. If pumpage is held constant, however, changes in chloride concentration of water from a production well can be valuable for interpreting chloride-concentration trends at that location.

Despite the increase in chloride concentration at all of the wells, the chloride concentration of the pumped water since pumping began has been below the USEPA maximum contaminant level of 250 mg/L for all pumped wells in the aquifer, except for the water from Mokuhau pump 2. Chloride concentration at this well has been as high as 450 mg/L. Chloride concentrations in pumps 1 and 3 at the Mokuhau well field have occasionally exceeded 200 mg/L.

Predevelopment chloride concentrations in shaft 33 were between 18 and 22 mg/L (unpub. data in well files at U.S. Geological Survey, Honolulu). During 1991–98, shaft 33 produced water with chloride concentrations generally ranging between 30 and 65 mg/L (fig. 30). In 1998, the chloride concentration was about 40 mg/L.

Predevelopment chloride concentrations at the Mokuhau well field in 1953 were about 15 mg/L. During an aquifer test in 1964, chloride concentration of the pumped water was about 30 to 35 mg/L (unpub. data in well files at U.S. Geological Survey, Honolulu). Between 1972 and 1977, the chloride concentration of the pumped water ranged from about 20 to 80 mg/L in Mokuhau pump 1, from 20 to 90 mg/L in Mokuhau pump 2, and from 20 to 30 mg/L in Mokuhau pump 3 (fig. 31). During 1977–98, chloride concentration of the pumped water at Mokuhau well field fluctuated greatly and generally rose; the pumped water from Mokuhau pump 1 and pump 3 ranged from 20 to 240 mg/L. In Mokuhau pump 2, the chloride concentration of the pumped water ranged from 100 to 360 mg/L during 1977–89 with most of the measurements falling below 220 mg/L, and during 1989–96, the chloride concentration ranged between 100 to 460 mg/L. Mokuhau pump

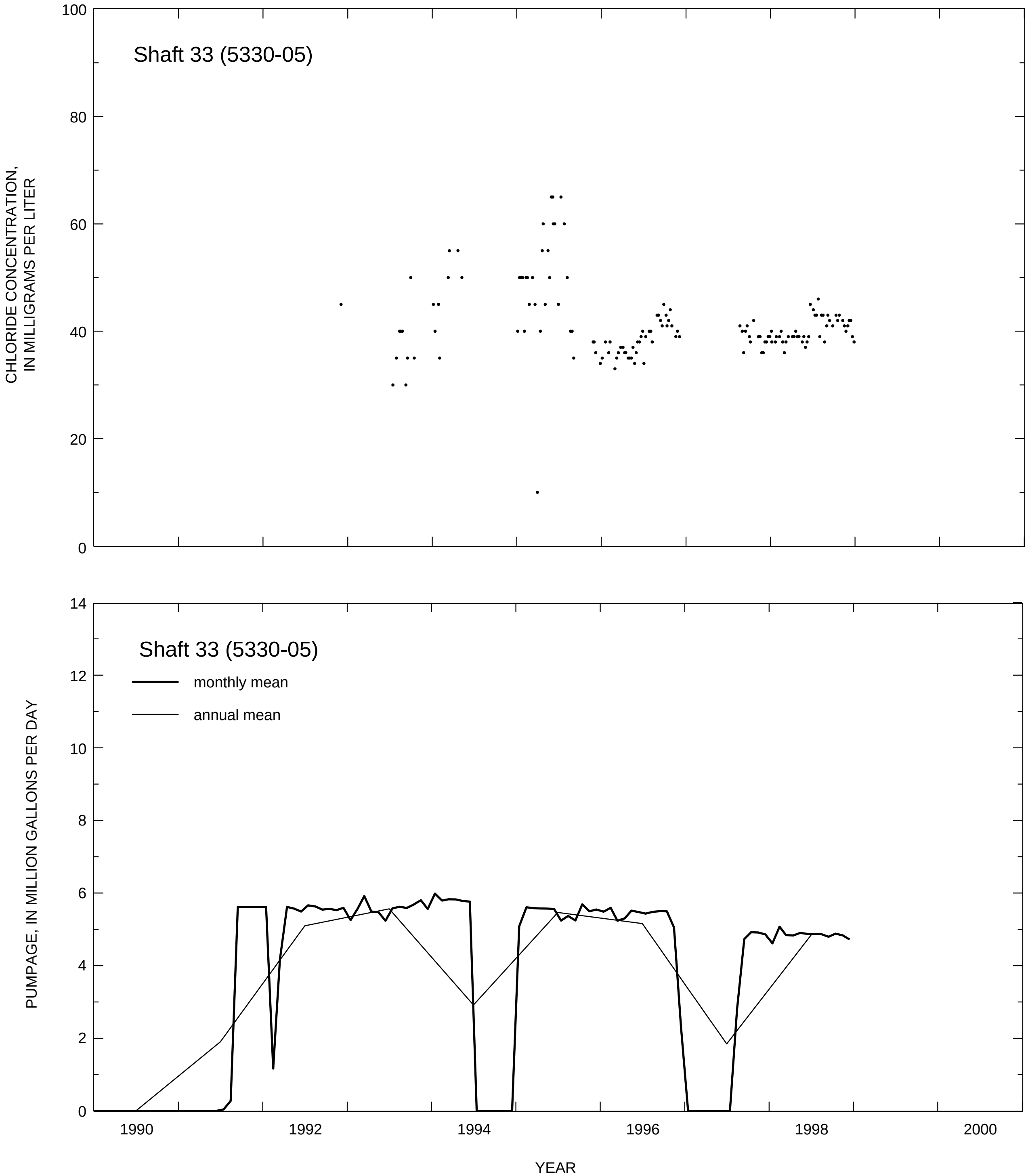


Figure 30. Chloride concentration, monthly mean pumpage, and annual mean pumpage for shaft 33, Maui, Hawaii. (Data from Maui Department of Water Supply.)

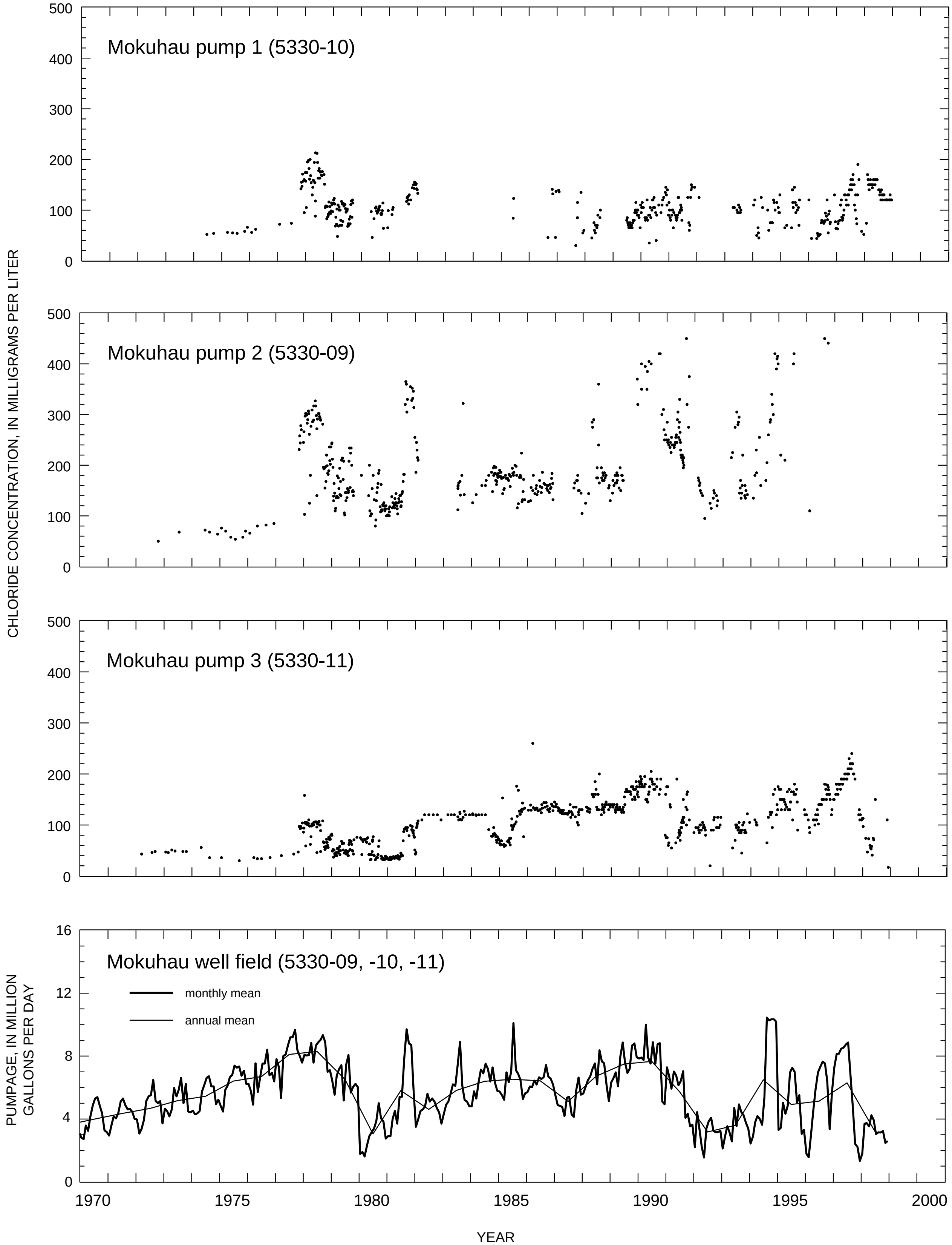


Figure 31. Chloride concentration, monthly mean pumpage, and annual mean pumpage for the Mokuhau well field, Maui, Hawaii. (Data from Maui Department of Water Supply.)

2 has produced the saltiest water from the aquifer and 23 percent of the samples collected between 1972 and 1996 have exceeded the USEPA standard. Mokuhau pump 2 has not been used since late 1996.

Predevelopment chloride concentration of water collected during initial tests of the production wells at the Waiehu Heights well field in 1975 ranged between 20 and 52 mg/L (unpub. data in well files at U.S. Geological Survey, Honolulu). Since then, the well field has shown a pattern of increasing chloride concentration of the pumped water (fig. 32), similar to that at the Mokuhau well field. Waiehu Heights 1, which is the deepest production well in the aquifer at 338 ft below sea level, had a general increase in chloride concentrations of the pumped water from the start of pumping in 1977 to 1989 with values that ranged between about 15 and 100 mg/L. During 1989–98, chloride concentration of the pumped water increased, ranging from about 80 to 160 mg/L. In the Waiehu Heights 2, chloride concentration ranged from about 15 to 60 mg/L during 1977–86, and ranged from about 25 to 100 mg/L during 1986–98.

Predevelopment chloride concentration of water at Waihee well field was about 15 mg /L as measured in Waihee 1 and 2 in late 1976 (unpub. data in well files at U.S. Geological Survey, Honolulu). Water from Waihee 1 and 2 remained at nearly the same chloride concentration during 1980–87, with values that ranged between 10 and 20 mg/L (fig. 33). During 1987–98, chloride concentrations ranged between about 10 and 60 mg/L. Chloride concentration in the water pumped from Waihee 3 was initially recorded in 1985. The initial value, 16.5 mg/L, is similar to that recorded in the other two wells at this time. Chloride concentration of water pumped from this well remained similar to those measured in Waihee 1 and 2 during 1985–95. During 1995–98, concentrations ranged from 15 to 30 mg/L.

Predevelopment chloride concentration of water at Kepaniwai well, which was drilled in 1974, was 24 mg/L (unpub. data in well files at U.S. Geological Survey, Honolulu). During 1977–86, chloride concentrations of the pumped water ranged from about 16 to 24 mg/L (fig. 34). Since the connection of the well to the municipal distribution system in 1991, chloride concentrations have ranged from about 10 mg/L to more than 50 mg/L. Chloride concentration of the pumped water has remained at about 20 mg/L since late 1995.

SUSTAINABLE YIELD

The sustainable yield of the Iao aquifer was set at 20.0 Mgal/d by CWRM (Commission on Water Resource Management, 1990). As defined by the State of Hawaii, sustainable yield refers to the amount of water that can be withdrawn from an aquifer indefinitely, without affecting either the quality of pumped water or the rate of pumping (Commission on Water Resource Management, 1990). Hydrologically, in a setting such as the Iao aquifer, the upward movement of the transition zone caused by pumping is the process that is generally expected to limit ground-water development. Although the value for sustainable yield of the Iao aquifer is presently set at 20 Mgal/d, the response of the aquifer to pumping (in terms of water-level declines and the rise in the freshwater/saltwater interface) has raised questions concerning this value, at least with regard to existing rates and distribution of pumping.

The ability to maintain a pumping rate of about 20 Mgal/d at existing well fields was examined by comparing the estimated top of the transition zone for average 1996 water levels to the depths of the production wells, assuming that water levels had stabilized. Water levels were still declining in 1996 with pumpage at 20.35 Mgal/d, however. Thus, if the calculations indicate intrusion of the transition zone into the wells for assumed stable water levels, sustained pumpage at 20.35 Mgal/d from existing infrastructure would not be feasible.

The first step in calculating the top of the transition zone involved use of the Ghyben-Herzberg relation to calculate the altitude of the midpoint of the transition zone. The altitude of the top of the transition zone was then estimated by adding the thickness of the upper part of the transition zone as indicated by field data at the Waiehu deep monitor well to the altitude of the midpoint. The altitude of the top of the transition zone was then compared to the altitude of the bottom of the wells in the major well fields to estimate the difference between the two (table 6). Two values (100 and 175 ft) for the thickness of the upper part of the transition zone were used in these calculations owing to the uncertainty in the actual value for the thickness.

The results of the above calculations indicate that the transition zone would ultimately intrude into Waiehu Heights 1 for a thickness of the upper part of the transition zone of 100 ft (fig. 35). The top of the

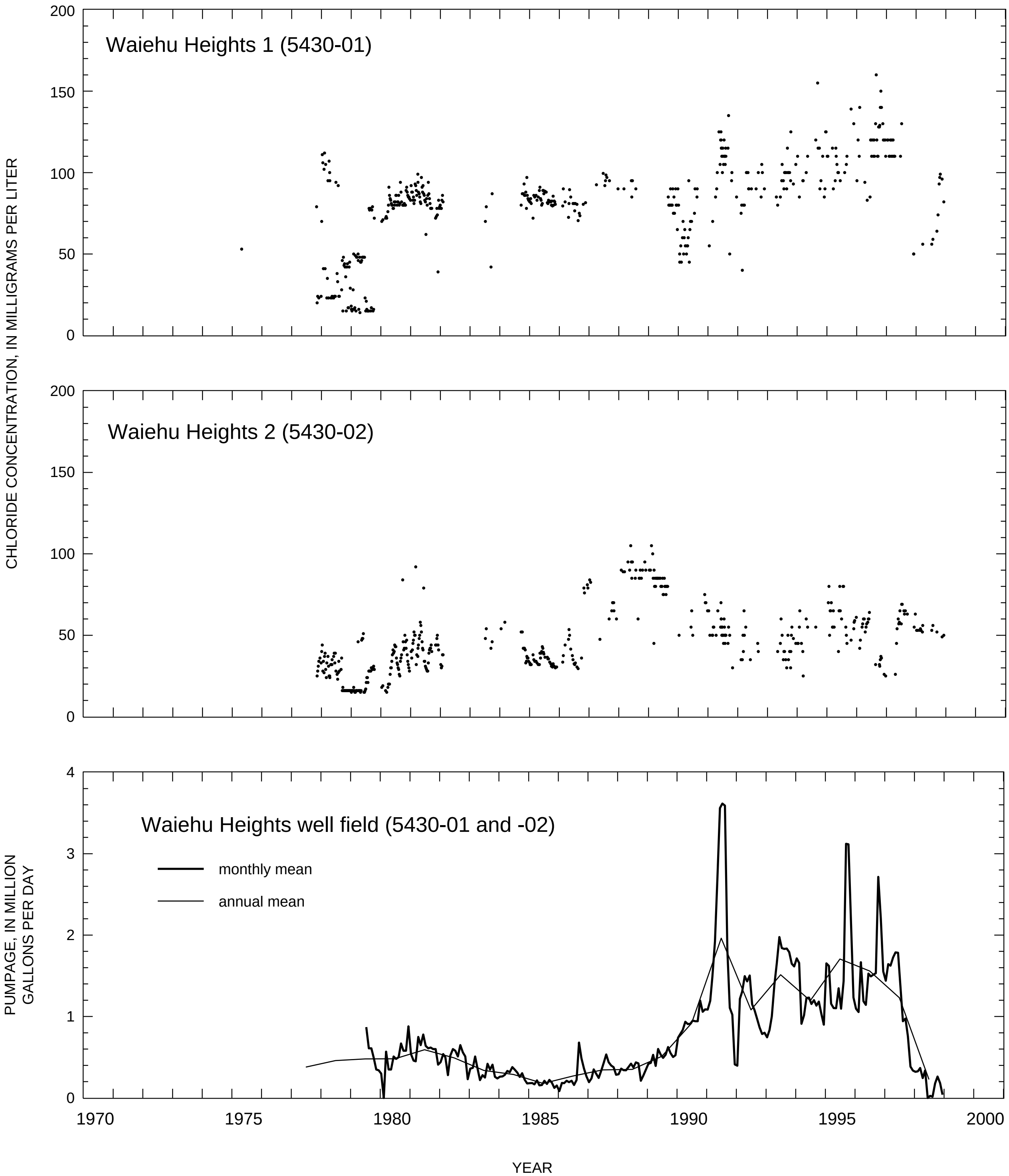


Figure 32. Chloride concentration, monthly mean pumpage, and annual mean pumpage for the Waiehu Heights well field, Maui, Hawaii. (Data from Maui Department of Water Supply.)

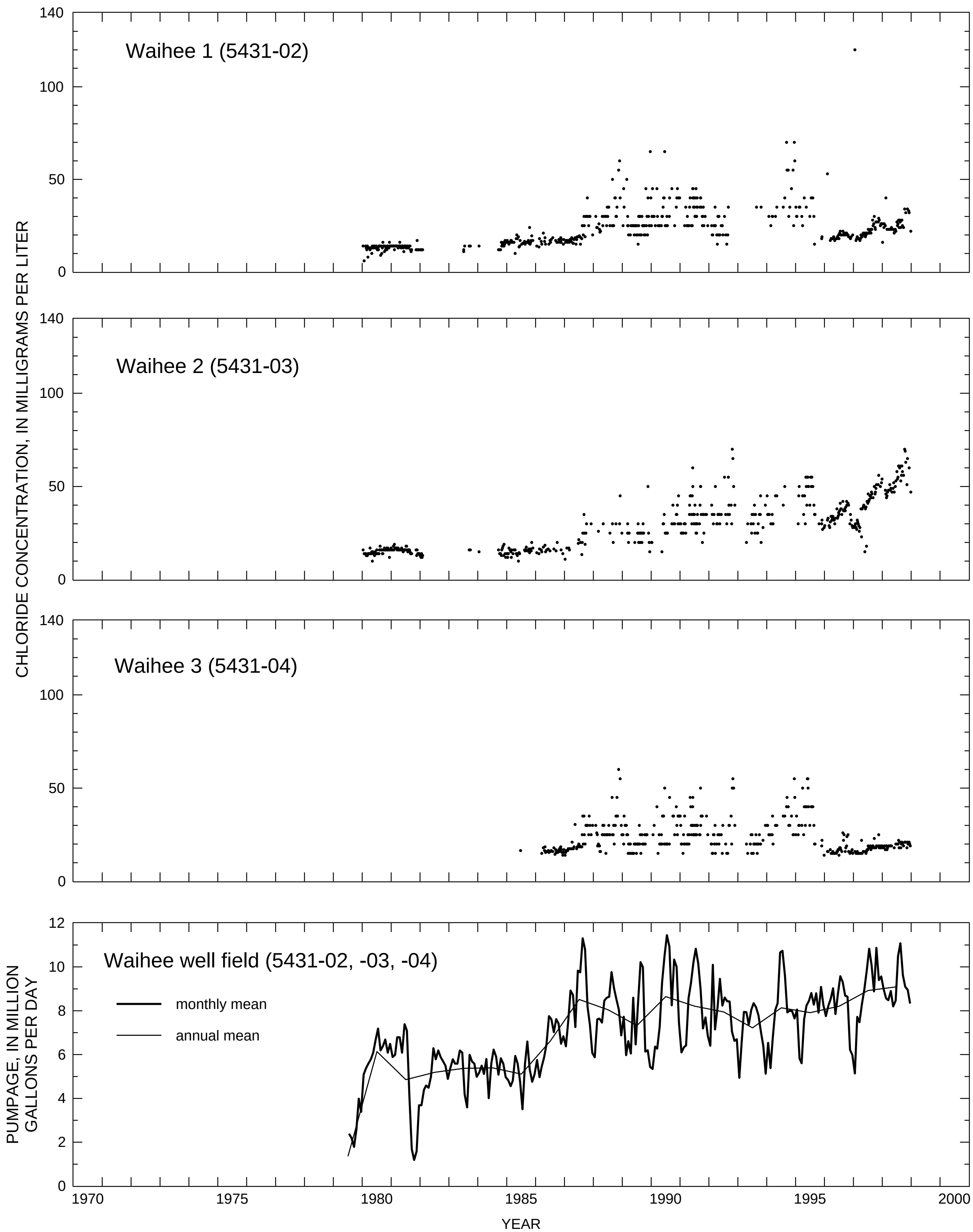


Figure 33. Chloride concentration, monthly mean pumpage, and annual mean pumpage for the Waihee well field, Maui, Hawaii. (Data from Maui Department of Water Supply.)

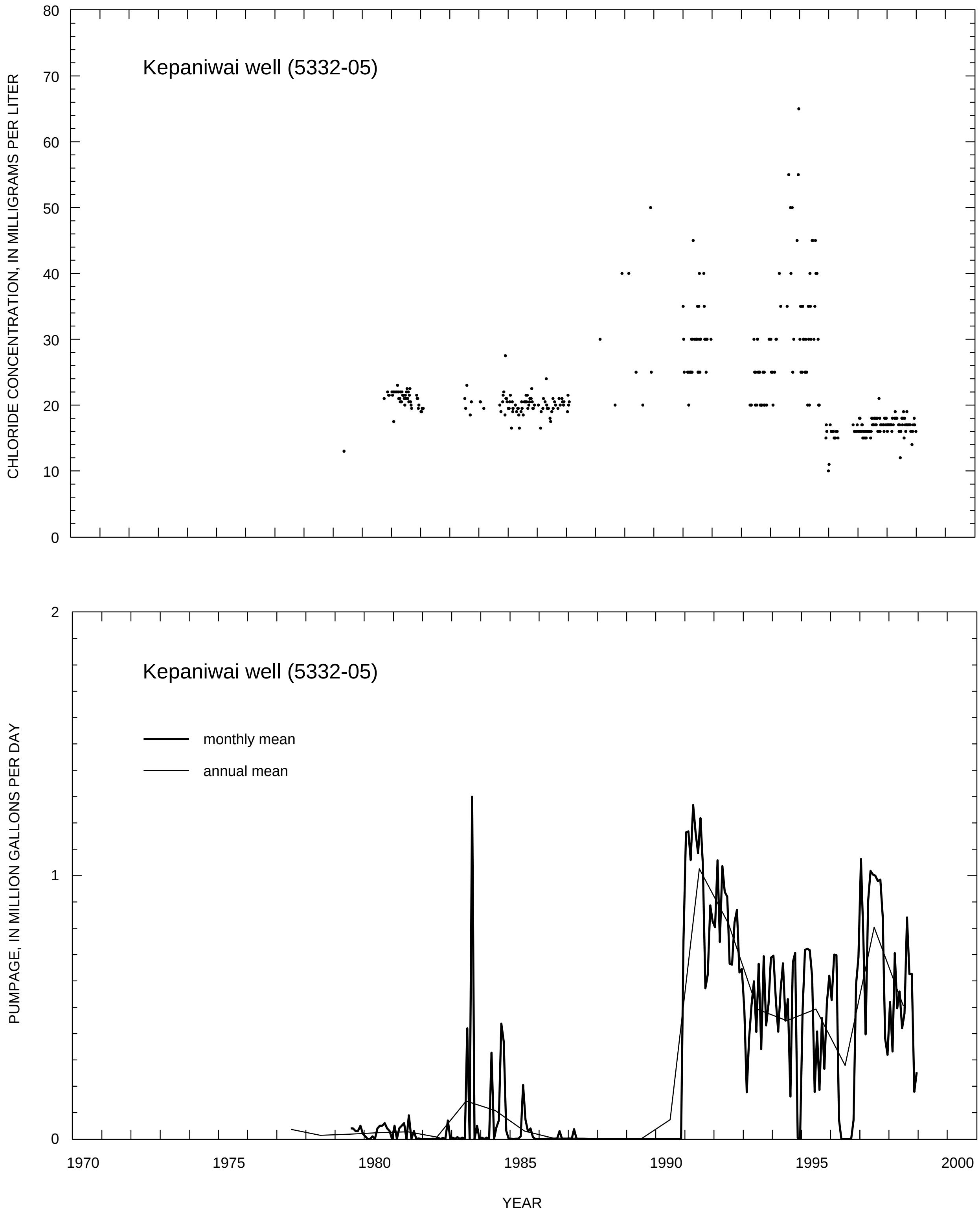


Figure 34. Chloride concentration, monthly mean pumpage, and annual mean pumpage for the Kepaniwai well, Maui, Hawaii. (Data from Maui Department of Water Supply.)

Table 6. Altitude of bottom of wells and estimated altitude of the top of the transition zone at pumped wells in the freshwater lens part of the Iao aquifer, Maui, Hawaii, for assumed stabilized 1996 and 1998 water levels, and for estimated thicknesses of the upper part of the transition zone of 100 ft (column a) and 175 ft (column b)

[All values in feet; --, no measurement; datum is mean sea level]

Well field	Well	Altitude of bottom of well	Average water level in 1996	Estimated altitude of top of transition zone using 1996 water levels		Estimated difference between bottom of well and top of transition zone for 1996		Average water level in 1998	Estimated altitude of top of transition zone using 1998 water levels		Estimated difference between bottom of well and top of transition zone for 1998	
				a	b	a	b		a	b	a	b
Shaft 33	unused pumping well	-280	10.2	-308	-233	28	-47	--	--	--	--	--
	pumping well	-280	--	--	--	--	--	--	--	--	--	--
Mokuhau	pump 1	-247	--	--	--	--	--	--	--	--	53	-22
	pump 2	-247	--	--	--	--	--	10.0	-300	-225	53	-22
	pump 3	-251	--	--	--	--	--	--	--	--	49	-26
Waiehu Heights	1	-338	[1]9.4	-276	-201	-62	-137	--	--	--	--	--
	2	-206	--	--	--	70	-5	--	--	--	--	--
Waihee	1	-182	[1]8.9	-256	-181	74	-1	--	--	--	--	--
	2	-150	--	--	--	106	31	--	--	--	--	--
	3	-157	--	--	--	99	24	--	--	--	--	--

[1] Estimated from average 1996 water levels in test holes B and E, and Waiehu deep monitor well

transition zone would be below other wells by values ranging from 28 to 106 ft for this thickness of the transition zone. For a thickness of the upper part of the transition zone equal to 175 ft, the transition zone intrudes into shaft 33, the two wells at Waiehu Heights, and just reaches Waihee 1. The top of the transition zone is still below Waihee 2 and 3 by 31 and 24 ft, respectively.

The 1996 water levels are not available for the Mokuhau well field so that the above calculations were made for this well field using average 1998 water levels. Available data indicate that 1998 water levels at Mokuhau well field were higher than those in 1996 and thus the use of 1998 water levels is somewhat more conservative than the use of 1996 water levels at the other well fields.

Calculations for the Mokuhau well field indicate that the top of the transition zone would be 49 to 53 ft below the bottom of the Mokuhau wells for a thickness of the upper part of the transition zone equal to 100 ft. The top of the transition zone would intrude into the wells, however, for a thickness of the upper part of the transition zone equal to 175 ft.

Given the above results and the continuing decline in water levels in 1996 for a pumping rate of 20.35 Mgal/d, it is unlikely that 20 Mgal/d can be obtained from existing infrastructure on a long-term basis. Pumping in the Iao aquifer area is concentrated in the middle one-third of the area which thus intensifies water-level declines. In freshwater lenses subject to saltwater intrusion, development of freshwater is best accomplished by minimizing drawdowns at pumping centers (McWhorter and Sunada, 1977, p. 162). Therefore, total yield from the aquifer could be enhanced, above that possible with the existing distribution of pumpage, if wells were distributed more evenly between Waikapu Stream and Waihee River, thereby reducing water-level decline at any given location in the aquifer for the same amount of pumpage.

Away from a well or well field, the decline in water levels induced by pumping is reduced, and as a

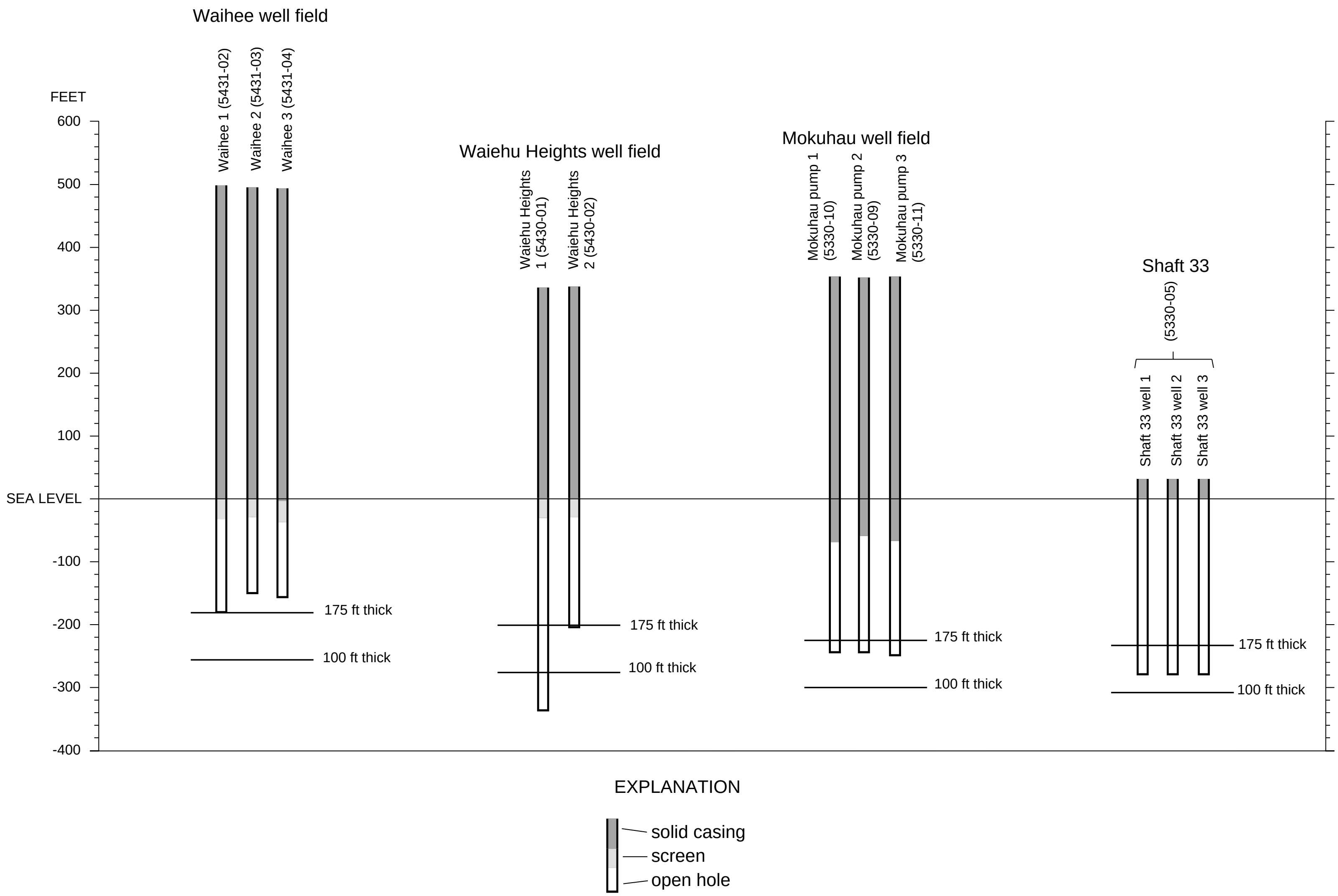


Figure 35. Altitude of the top of the transition zone for estimated thicknesses of the upper part of the transition zone of 100 and 175 feet, relative to the bottoms of pumping wells in the Iao aquifer area, Maui, Hawaii, using assumed stabilized 1996 or 1998 water levels (see table 5).

result, the area of greatest upward movement of the transition zone is at the well or well field. Depending on spacing between wells, pumpage from one well may cause water-level declines in the other wells. This results in a greater upward movement of the transition zone in excess of that caused by pumping at that particular well. Within the Iao aquifer, for example, pumping at Waihee well field is affecting water levels at Waiehu Heights and vice versa. Pumping from both well fields may also be causing water levels at the Mokuhau well field and shaft 33 to decline. However, sufficient data are not available to permit a complete analysis of the influence one well field in the Iao aquifer has on others.

Not only is the areal distribution of wells important with regard to the amount of water that can be developed, the depth of a given well in comparison to the altitude of the transition zone is also of major importance. The closer the well bottom is to the transition zone before pumping is started, the less water-level decline in the well is required for saltwater to intrude the well. As a result, yield from a well can potentially be increased simply by raising the altitude of the bottom of the well relative to the altitude of the top of the transition zone.

SUMMARY AND CONCLUSIONS

The Iao aquifer is located on the eastern side of the West Maui Mountain on the island of Maui. The mountain is primarily composed of volcanic rocks from West Maui Volcano, which are overlain by sedimentary deposits in stream valleys and near the coast. The volcano is mostly composed of Wailuku Basalt, and the Iao aquifer is primarily within this rock unit. The aquifer is actually part of a larger regional ground-water system because the Wailuku Basalt and sediments extend beyond the geographic boundaries of the Iao aquifer. Ground water in the Iao aquifer occurs as: (1) dike-impounded water in the dike complex, (2) a freshwater-lens system in the dike-free volcanic rocks and sedimentary deposits, and (3) as water perched in the sedimentary deposits.

Recharge to the aquifer is from the infiltration of rainfall and fog drip, from seepage through streambeds that overlie the water table, and from irrigation. The predevelopment rate of ground-water recharge to the aquifer was about 34 Mgal/d. With the introduction of sugarcane agriculture in 1856, recharge increased to as high as 51 Mgal/d owing to irrigation in some of the areas of the aquifer. The irrigation water has primarily been supplied by diverted streamflow and development tunnels in Waihee River valley and Waiehu, Waikapu, and Iao Stream valleys. Irrigation practices have changed through time, and this has resulted in a reduction of recharge to about 40 Mgal/d during 1980–85, and to about 36 Mgal/d during 1986–95.

Ground water from the Iao aquifer has been used for agricultural and domestic supply. Development of ground water from the Iao aquifer began with the construction of tunnels that penetrate into dike compartments to divert the dike-impounded water and with the improvement of springs. The total amount of ground water developed by the tunnels was about 9.0 Mgal/d in 1970. Large-scale withdrawal of ground water from the dike-free part of the Iao aquifer began in 1948 with the completion of shaft 33. Water from shaft 33 was used for agriculture during 1948–84, with annual average withdrawal ranging from zero to 11.65 Mgal/d. The Mokuhau well field was the second major area of ground-water withdrawal from Iao aquifer. Two wells were constructed in 1953 and a third well was added to the well field in 1967. The Waihee and Waiehu Heights well fields were added in 1977 and 1979, respectively, to supply the increasing domestic demand. Shaft 33 was refurbished to supply domestic water in 1991. The annual average rate of ground-water withdrawal from the aquifer has varied widely, but generally has increased with time, reaching more than 20 Mgal/d in 1995 and 1996. Pumpage has diminished by about 1 Mgal/d each in 1997 and 1998.

Ground-water data indicate that withdrawal from the freshwater lens from four well fields, and the reduction of recharge to the aquifer, have resulted in a decline of ground-water levels and a corresponding rise and upward movement of the transition zone. Water-level data, collected since 1940, have responded to seasonal variations in pumpage, the overall long-term increase in pumpage, and to changes in recharge resulting from variations in rainfall and changes in land use. Water levels generally decreased between 1990 and 1998. Water samples for chloride-concentration analysis from the Waiehu deep monitor well have been collected quarterly from discrete depths since 1985. The chloride-concentration data from the well indicate that the midpoint of the transition zone rose about 108 ft from 1985 to 1998, corresponding to an average rate of 8.4 feet per year.

In 1990, the Hawaii State Commission on Water Resource Management established a value of 20.0 Mgal/d for the sustainable yield of the Iao aquifer area. Water-level data and changes in the vertical extent of freshwater measured at the Waiehu deep monitor well, however, indicate that pumping rates near the sustainable yield of 20.0 Mgal/d could result in saltwater intrusion in some of the existing wells. The withdrawal from the Iao aquifer is concentrated in the middle one-third of the area. Also, some of the wells are deep relative to the altitude of the top of the transition zone. In aquifers susceptible to saltwater intrusion, the maximum development of ground water generally can be obtained by distributing pumpage to minimize water-level decline at any location for a given pumping rate, and by using shallower wells.

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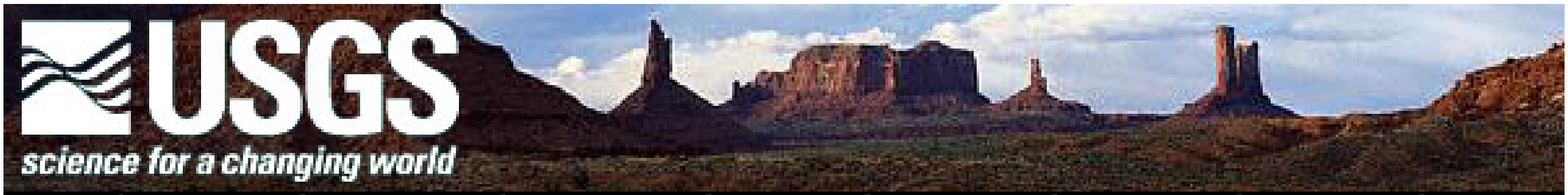

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