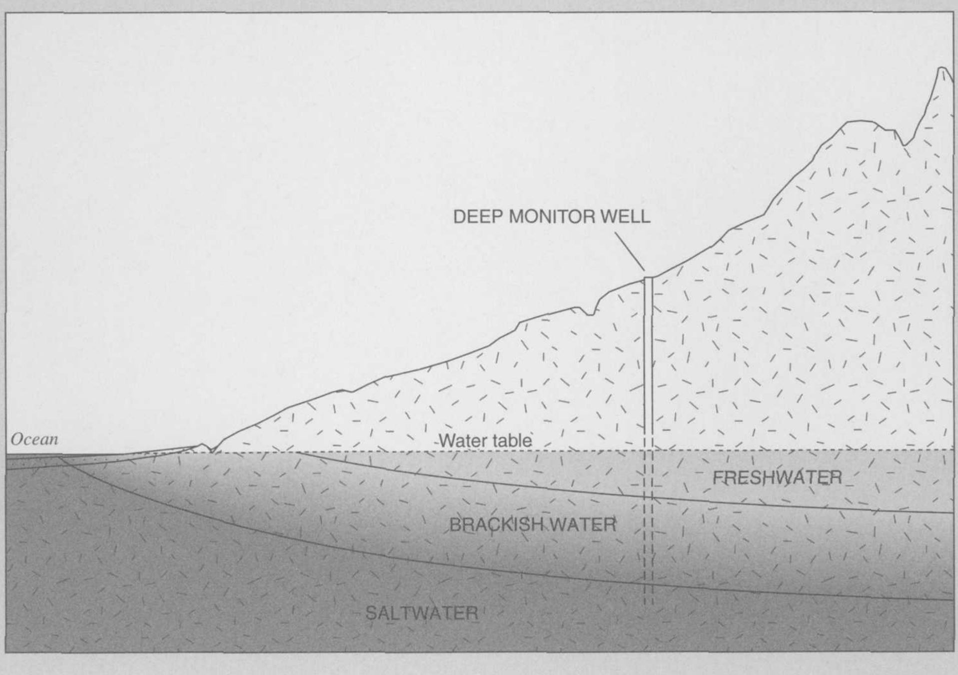
U.S. Department of the Interior

Site Selection for a Deep Monitor Well, Kualapuu, Molokai, Hawaii

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 99-4291



Prepared in cooperation with the
DEPARTMENT OF HAWAIIAN HOME LANDS

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By Delwyn S. Oki

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Honolulu, Hawaii

2000

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

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Conversion Factors

Multiply	By	To obtain
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
inch (in.)	2.54	centimeter
inch per year (in/yr)	2.54	centimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
gallons per minute (gal/min)	3.785	liters per minute
million gallons per day (Mgal/d)	0.04381	cubic meters per second

Abbreviations

mg/L   Milligrams per liter

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Abstract

Management of the ground-water resources near Kualapuu on the island of Molokai, Hawaii, is hindered by the uncertainty in the vertical salinity structure in the aquifer. In the State of Hawaii, vertical profiles of ground-water salinity are commonly obtained from deep monitor wells, and these profiles are used to estimate the thicknesses of the freshwater part of the ground-water flow system and the freshwater-saltwater transition zone. Information from a deep monitor well would improve the understanding of the ground-water flow system and the ability to effectively manage the ground-water resources near Kualapuu; however, as of mid-1999 no deep monitor wells had been drilled on the island of Molokai.

Selection of an appropriate site for drilling a deep monitor well in the Kualapuu area depends partly on where future ground-water development may occur. Simulations using an areally two-dimensional, steady-state, sharp-interface ground-water flow model previously developed for the island of Molokai, Hawaii, indicate that the southeastern part of the Kualapuu area is a possible area of future ground-water development because (1) withdrawals from this area have a small effect on water levels at existing wells in the Kualapuu area (relative to effects from withdrawals in other parts of the Kualapuu area that are outside of the dike complex), and (2) model-calculated water levels in this part of the Kualapuu area are high relative to water levels in other parts of the Kualapuu area that are outside of the dike complex.

Additional site-selection criteria include (1) ground-water level, (2) ground-surface altitude, (3) land classification, ownership, and accessibility, (4) geology, (5) locations of existing production wells, and (6) historical ground-water quality information. A deep monitor well in the Kualapuu area will likely be most useful for management purposes if it is located (1) in the vicinity of future ground-water development, (2) in an area where water levels are between about 8 and 12 feet above sea level, (3) at a ground-surface altitude that is between about 1,000 and 1,100 feet, (4) on government-owned land, (5) outside of the dike complex and as far from known volcanic vents as possible, (6) at least about 1,000 feet from, but within the same hydrogeologic setting as, existing or proposed production wells, and (7) east of well 0902-01. A viable area for drilling a deep monitor well is about a half mile southeast of existing wells 0801-01 to -03 and a half mile north of a known volcanic vent, Puu Luahine.

INTRODUCTION

Management of the ground-water resources of the island of Molokai, Hawaii is hindered by the uncertainty in the vertical salinity structure in the aquifer near the town of Kualapuu (fig. 1), where projected demand for water is high. The Kualapuu study area corresponds to the Kualapuu aquifer system (fig. 2) as defined by the State of Hawaii Commission on Water Resource Management (CWRM) (State of Hawaii, 1990). The Kualapuu study area extends about 7 mi in an east-west direction and about 4 mi in a north-south direction, and has an area of about 18 mi^2. In the Kualapuu area, the ground-water flow system consists of a body of

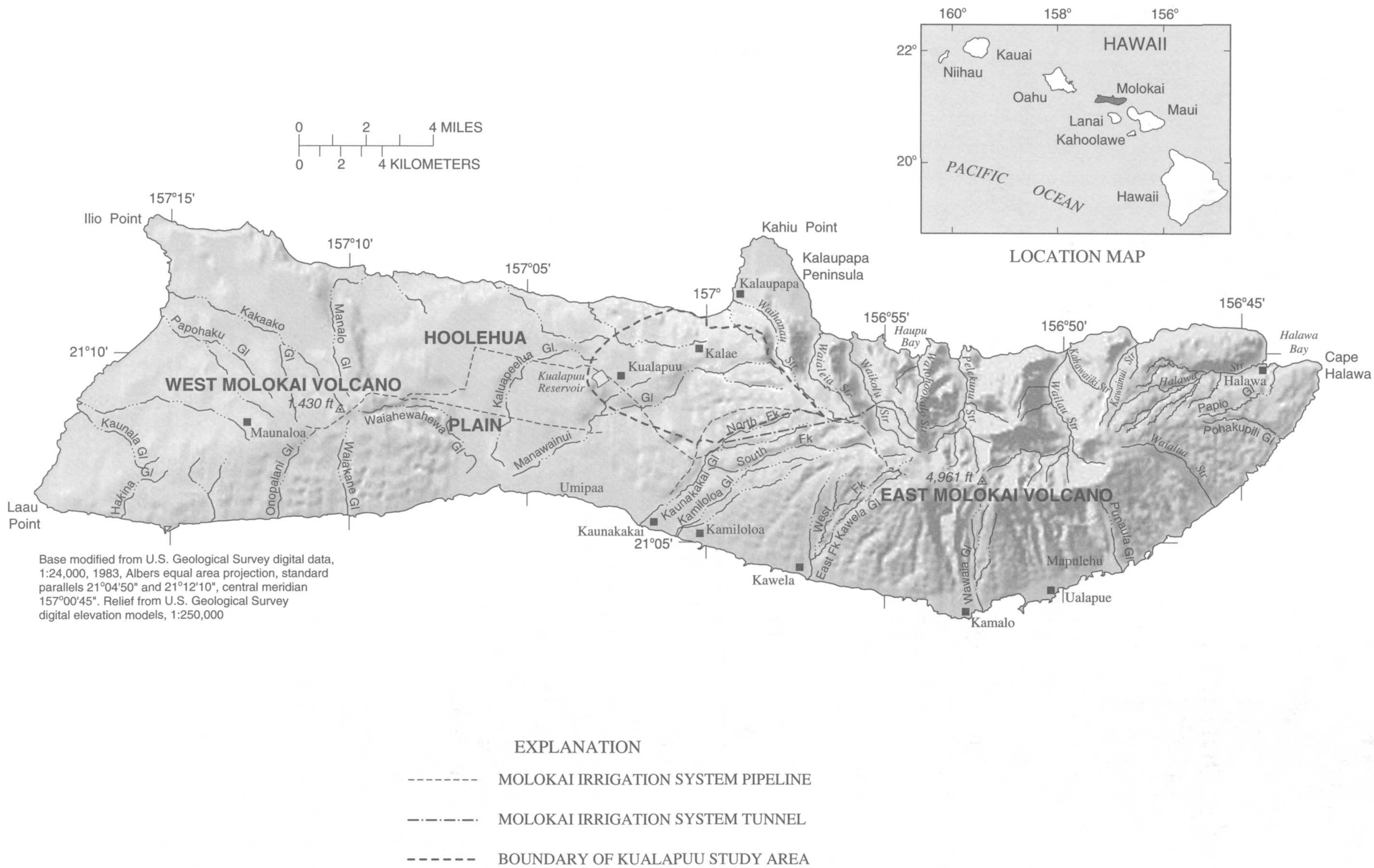


Figure 1. Geographic features, island of Molokai, Hawaii, and location of Kualapuu study area.

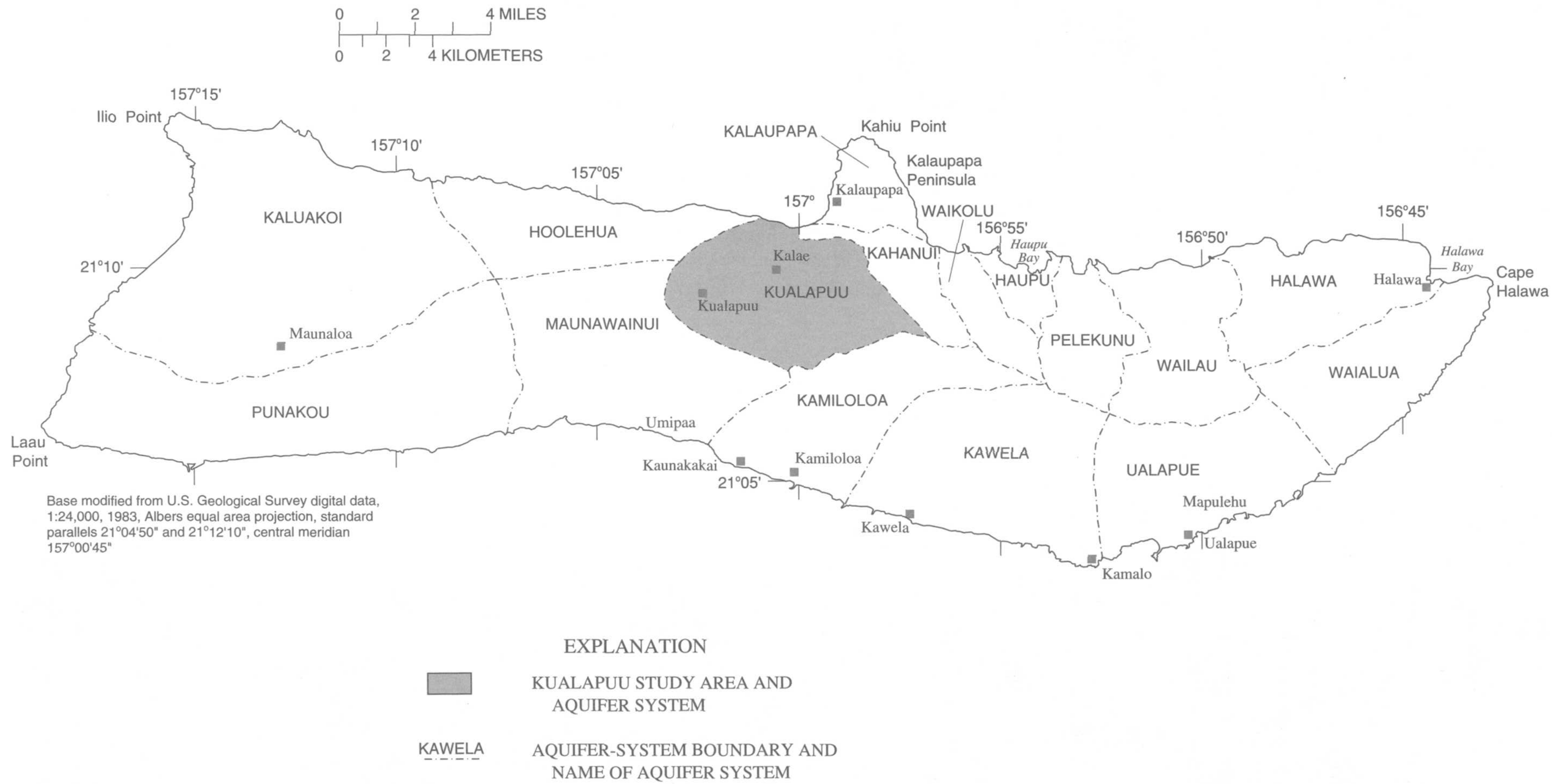


Figure 2. Hawaii Commission on Water Resource Management aquifer-system boundaries, Molokai, Hawaii (modified from State of Hawaii, 1990).

freshwater floating on denser saltwater. A brackish-water transition zone of unknown thickness exists between the freshwater and underlying saltwater (fig. 3).

In response to projected water demand on the island of Molokai, CWRM designated the entire island as a Ground Water Management Area in 1992. This action authorized the State to manage ground-water withdrawals on Molokai through a permitting process to protect the water resources of the island. Ground-water withdrawals on Molokai are currently limited by sustainable-yield estimates for 16 areas denoted as aquifer systems (fig. 2), primarily delineated on the basis of geologic conditions and topographic divides (Mink and Lau, 1992). As of March 1999, CWRM had issued water-use permits authorizing a total of 6.6432 million gallons per day (Mgal/d) of ground-water withdrawals from wells and tunnels on Molokai (table 1, fig. 4). In addition, the State of Hawaii Department of Hawaiian Home Lands (DHHL) has a reservation for 2.905 Mgal/d of ground water from the Kualapuu area, and Kukui (Molokai), Inc. is currently attempting to increase its authorized water use for well 0901-01 (table 1, fig. 4) in the Kualapuu area from 0.871 Mgal/d to 1.259 Mgal/d.

A numerical ground-water flow model of the entire island of Molokai was previously developed to estimate the regional effects of ground-water withdrawals on water levels and coastal discharge (Oki, 1997). Current knowledge of the effects of ground-water withdrawals on water quality, however, is limited partly because of the current lack of knowledge of the salinity structure of the ground-water flow system. The bottoms of production wells are usually located above the top of the brackish-water transition zone to reduce the risk of pumping high-salinity water. A deep monitor well drilled through the freshwater and into the brackish-water transition zone would improve the understanding of the salinity structure in the aquifer, thickness of the freshwater, and estimates of freshwater availability in the vicinity of the well.

The U.S. Geological Survey (USGS) undertook this investigation to locate a hydrologically suitable area for a deep monitor well in the Kualapuu area on the island of Molokai. Factors considered in selecting a suitable area include (1) possible sites of future ground-water development, (2) ground-water level, (3) ground-surface altitude, (4) land classification, ownership, and accessibility, (5) geology, (6) locations of existing production wells, and (7) historical ground-water quality information. The existing numerical ground-water flow model (Oki, 1997) for Molokai was used to estimate water-level declines caused by possible ground-water development near Kualapuu.

Purpose and Scope

The purpose of this report is to describe (1) results of model simulations that assess the hydrologic effects of withdrawals at rates in excess of the March 1999 permitted rates, and (2) the area where a deep monitor well could be located to provide information needed to effectively manage the ground-water resources in the Kualapuu area.

No new data were collected as part of this study. The existing USGS numerical ground-water flow model (Oki, 1997) of Molokai was used to estimate the effects of different withdrawal scenarios on regional ground-water levels.

Well-Numbering System

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

a-bbcc-dd,

where:

a is the island code;

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

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

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

An island code of "4" is used for all wells on Molokai and is omitted in this report.

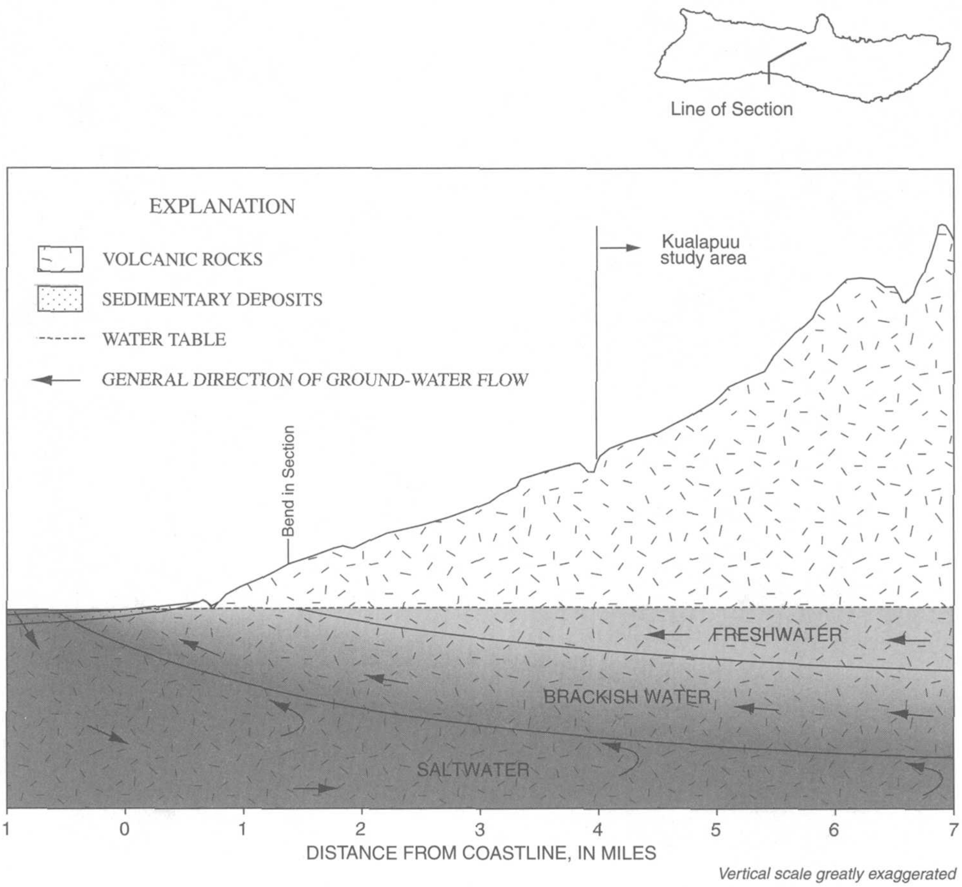


Figure 3. *Schematic cross section of the regional ground-water flow system in the Kualapuu area, Molokai, Hawaii.*

Table 1. State of Hawaii Commission on Water Resource Management March 1999 water-use permits, Molokai, Hawaii
[Mgal/d, million gallons per day]

Well no.	Well name	Applicant name	Permit no.	Date approved	Permitted use (Mgal/d)	Model node no.[1]
Kahanui aquifer system						
1058-01	Waihanau #239	National Park Service	201	8/4/93	0.094	3664
Kamiloloa aquifer system						
0501-04	Kupa shaft	Hawaiian Research, Limited	273	9/15/93	0.056	3202
0501-06	Home Pumehana	Hale Mahaolu	312	11/17/93	0.005	3203
0501-07	Kaunakakai Park	Maui County Dept. of Parks and Recreation	195	8/4/93	0.075	3155
0601-01	Oloolo Kaunakakai	Hawaiian Research, Limited	274	9/15/93	0.075	3153
0759-01	Waiola no. 1	Waiola Molokai, Incorporated	429	12/28/98	0.656	3483
Kawela aquifer system						
0352-10	Kamalo-Curtis	Curtis, David	177	3/14/95	0.012	4602
0352-11	Shige's Farm	Inouye, Shigenobu	184	8/4/93	0.004	4555
0354-01	Meyer Incorporated, #1	T.T. Meyer, Incorporated	308	4/14/94	0.029	4266
0354-02	Meyer Incorporated, #2	T.T. Meyer, Incorporated	299	4/14/94	0.040	4265
0354-03	Well #3	Kanukuawa Ranch	338	4/14/94	0.017	4266
0354-04	Meyer Incorporated, #4	T.T. Meyer, Incorporated	300	4/14/94	0.005	4218
0354-07	Bostwick well no. 1	Bostwick, Charles	442	9/24/96	0.045	4266
0456-04	Breadfruit well	Kawela Plantation Homeowners Assoc.	207	3/14/95	0.285	3880
0456-06	DW3	Kawela Plantation Homeowners Assoc.	208	3/14/95	included with well 0456-04	3879
0456-08	DW2	Kawela Plantation Homeowners Assoc.	208	3/14/95	included with well 0456-04	3927
0456-09	DW1	Kawela Plantation Homeowners Assoc.	208	3/14/95	included with well 0456-04	3975
0456-16	Kawela-Iaea #3	Iaea, John Wm., Sr.	266	3/14/95	0.017	3880
0456-17	Johnson	Granger, R.M.	268	3/14/95	0.016	3928
0457-01	Kawela shaft	Maui County Dept. of Water Supply	223	3/14/95	0.330	3831
0457-04	Ag #1	Kawela Plantation Homeowners Assoc.	209	3/14/95	included with well 0456-04	3734
Kualapuu aquifer system						
0801-01	DHHL 1	Hawaii State Dept. of Hawaiian Home Lands	267	9/15/93	0.367	3142
0801-02	DHHL 2	Hawaii State Dept. of Hawaiian Home Lands	267	9/15/93	included with well 0801-01	3142
0801-03	Kualapuu Mauka	Maui County Dept. of Water Supply	359	10/20/95	0.516	3142
0901-01	Well #17	Kukui (Molokai), Incorporated	341	3/14/95	0.871[2]	3094
1059-01	Waikalae tunnel	Maui County Dept. of Water Supply	269	9/15/93	0.036	element 3260
Manawainui aquifer system						
0602-03	Kalaiakamanu Hou	Kalaiakamanu Hou Church	200	8/4/93	0.005	2961
0603-01	Umipaa	Hawaiian Research, Limited	216	11/17/93	0.046	2767
0603-07	Naiwa dug	Maui Electric Company	293	11/17/93	0.0001	2719
0604-03	Naiwa MECO open pit	Maui Electric Company	294	11/17/93	0.0001	2671

Table 1. State of Hawaii Commission on Water Resource Management March 1999 water-use permits, Molokai, Hawaii--Continued

[Mgal/d, million gallons per day]

Well no.	Well name	Applicant name	Permit no.	Date approved	Permitted use (Mgal/d)	Model node no.[1]
Manawainui aquifer system--Continued						
0605-01	Orca shaft #1	Molokai Ranch, Limited	276	9/15/93	0.600	2526
0605-02	Orca #2	Molokai Ranch, Limited	276	9/15/93	included with well 0605-01	2431
0605-03	Orca #3	Molokai Ranch, Limited	277	9/15/93	0.040	2526
0705-05	Naiwa	Cargill, Incorporated	339	4/14/94	0.012	2474
0706-02	South Hoolehua	Palaau Prawn and Shrimp	278	11/17/93	0.864	2285
Ualapue aquifer system						
0350-05	Wescoatt	Wescoatt, Wren	354	3/14/95	0.004	4985
0350-07	Manawai #1	Hawaiian Research, Limited	462	6/17/98	0.015	4938
0352-09	Kamalo	Mahealani Ranch	206	8/4/93	0.010	4554
0352-12	Urauchi #1	Urauchi, John N.	291	11/17/93	0.001	4556
0448-01	Mapulehu shaft #1	HSPA	214	11/16/93	0.003	5271
0448-03	Mapulehu shaft	Kerner, Greg	461	4/16/97	0.007	5271
0449-01	Ualapue shaft	Maui County Dept. of Water Supply	221	9/15/93	0.185	5032
0549-01	Mapulehu tunnel	Petro, Pearl Friel	310	11/17/93	0.010	5123
Waialua aquifer system						
0546-02	Puelelu well	Kainalu Ranch	222	6/2/94	0.202	5601
0844-01	Puu O Hoku no. 1	Puu O Hoku Ranch	490	11/6/98	0.235	5879
Waikolu aquifer system						
0855-01	Waikolu #22	Hawaii State Dept. of Agriculture	220	1/12/94	0.853	4104
0855-02	Waikolu #23	Hawaii State Dept. of Agriculture	220	1/12/94	included with well 0855-01	4103
0855-03	Waikolu #24	Hawaii State Dept. of Agriculture	220	1/12/94	included with well 0855-01	4151

[1] Finite element node number and element number can be determined from the row and column number of the cell:

Node number (upper left or northwest corner of the cell) = row + 48 × (column -1)
Node number (lower left or southwest corner of the cell) = row + 48 × (column -1) + 1
Node number (upper right or northeast corner of the cell) = row + 48 × (column)
Node number (lower right or southeast corner of the cell) = row + 48 × (column) + 1
Element number = row + 47 × (column - 1)

[2] Applicant has requested a permit for 1.259 Mgal/d

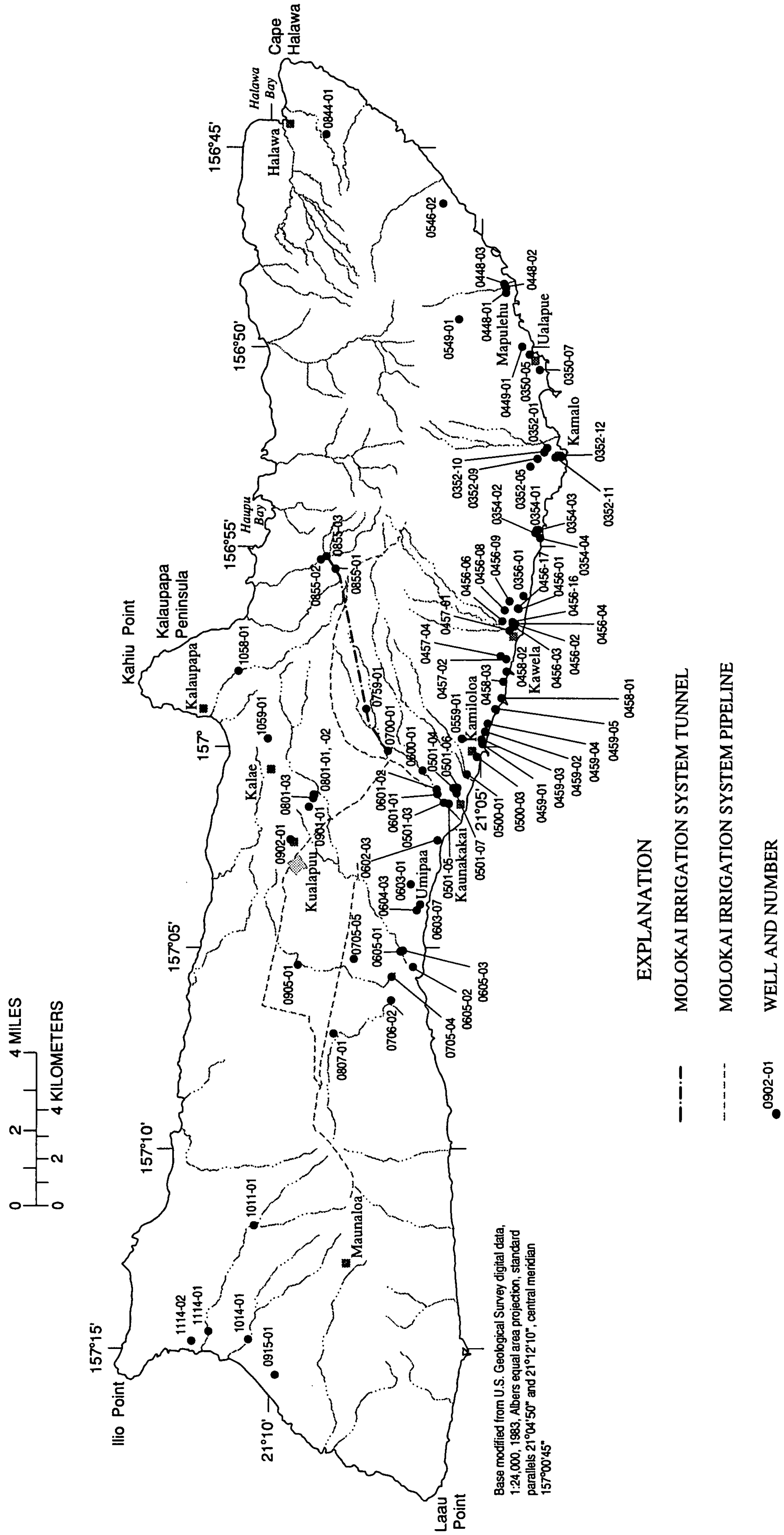


Figure 4. Locations of selected wells, Molokai, Hawaii.

Description of Study Site

Physical Setting

The island of Molokai, which has an area of 261 mi^2, is the fifth largest of the Hawaiian islands and is located between longitude 157°20'W and 156°40'W and between latitude 21°00'N and 21°15'N (fig. 1). It is composed mainly of two shield volcanoes (Stearns and Macdonald, 1947): the older West Molokai Volcano, which rises to an altitude of 1,430 ft, and the younger East Molokai Volcano, which rises to an altitude of 4,961 ft. The town of Kualapuu lies on the Hoolehua Plain in the central saddle area of the island.

Land Use

Land use on Molokai is classified by the Hawaii State Land Use Commission into conservation, urban, rural, and agricultural zones (fig. 5). The conservation districts cover 77.8 mi^2 (Oliver, 1995) mainly in the wet, northeastern part of the island. Urban and rural districts cover 6.8 mi^2 (Oliver, 1995) mainly near the towns of Maunaloa, Kualapuu, Kalae, and Kalaupapa and along the southern, eastern, and western coasts. The remainder of the island is classified as agricultural land used for, among other things, field crops, nurseries, and livestock grazing. In the Kualapuu study area, land use is classified as 72 percent (12.8 mi^2) agriculture, 26 percent (4.7 mi^2) conservation, and 2 percent (0.4 mi^2) urban.

Molokai Ranch, Limited controls about a third of the land on Molokai. Their land is used mainly for grazing and recreation. In central and eastern Molokai, the land is controlled mainly by DHHL, other State of Hawaii agencies, and private land owners. DHHL controls 39.7 mi^2, or about 15 percent of the land on Molokai. Within the Kualapuu area, land is owned primarily by Molokai Ranch, Limited and the State of Hawaii (including DHHL) (fig. 6).

Climate

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

Rainfall

Rainfall on Molokai is characterized by maxima at high altitudes and steep spatial gradients (fig. 7). Highest mean annual rainfall occurs in northeastern Molokai. The maximum mean annual rainfall is near the summit of the East Molokai Volcano and exceeds 150 in. Over West Molokai Volcano, the maximum mean annual rainfall is about 25 in. Along the coastal areas of southern and western Molokai, mean annual rainfall is less than 16 in. Annual rainfall at Kualapuu (rain gage 534, fig. 7) varied from about 13 to 59 in. during 1900–93 (fig. 8). Farther south at Kaunakakai (rain gage 536, fig. 7) annual rainfall is less and has varied from about 3 to 35 in. during 1933–94 (fig. 8). For comparison, mean annual rainfall over the open ocean is estimated to be between 22 in. and 28 in. (Elliot and Reed, 1984; Dorman and Bourke, 1979).

Evaporation

Published pan-evaporation records for Molokai are available for only three sites; two are located in the Hoolehua Plain and one is near the town of Maunaloa in west Molokai. Mean annual pan evaporation at the three sites ranges from 81 in. at Maunaloa to 118 in. in the Hoolehua Plain (Ekern and Chang, 1985). The high pan-evaporation rate on the dry, windy uplands of central Molokai is attributed to the extreme positive advection of heat from the dry surrounding areas (Ekern and Chang, 1985). Over the open ocean, the computed evaporation rate is about 65 in/yr (Seckel, 1962).

GEOLOGY

The evolution of Hawaiian volcanoes generally progresses through four stages: preshield, shield, postshield, and rejuvenated. However, not all Hawaiian volcanoes have a postshield stage or a rejuvenated stage. The preshield stage is the earliest, submarine phase of

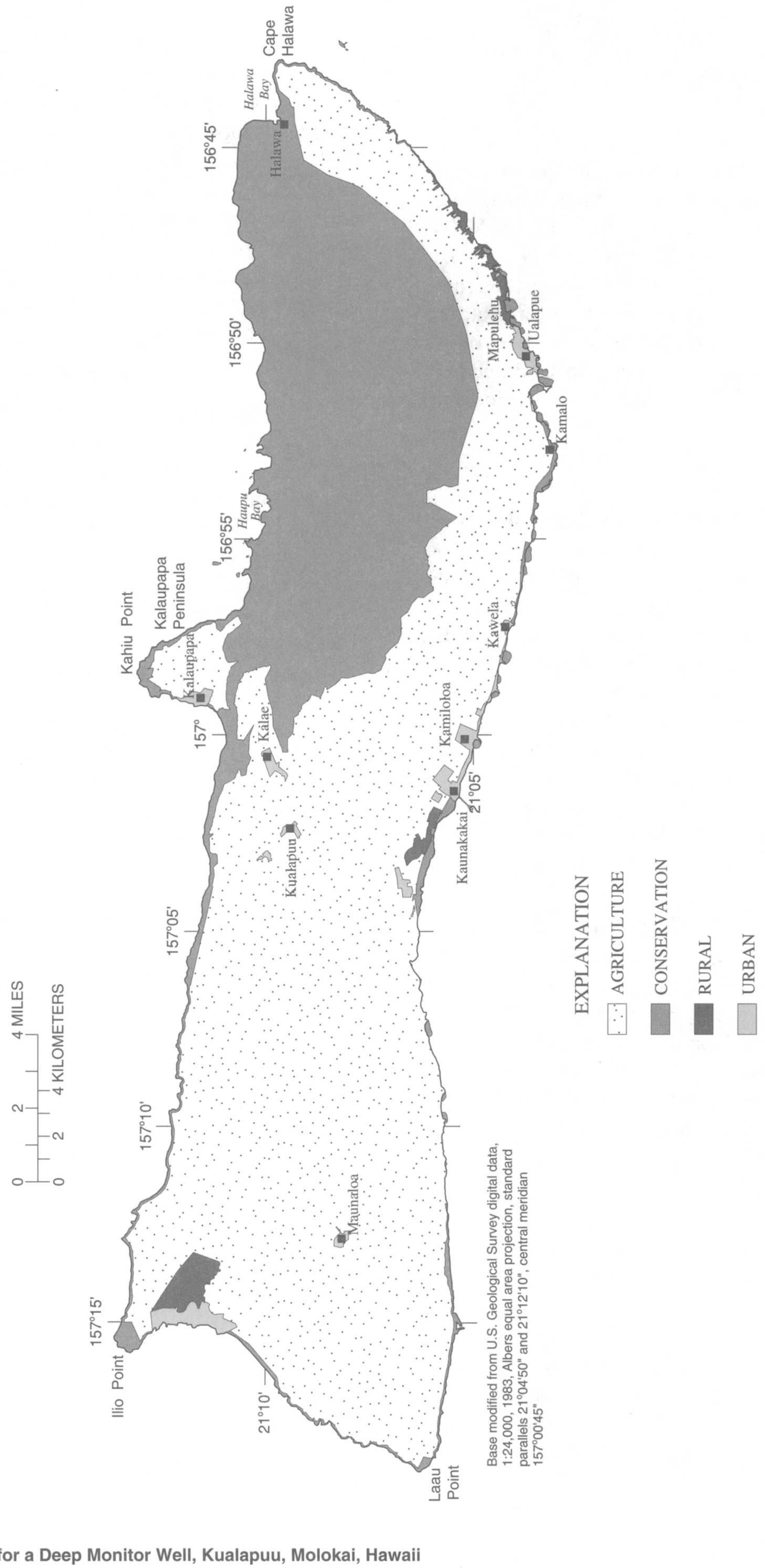


Figure 5. State land-use districts for 1995, Molokai, Hawaii (modified from State of Hawaii, 1999).

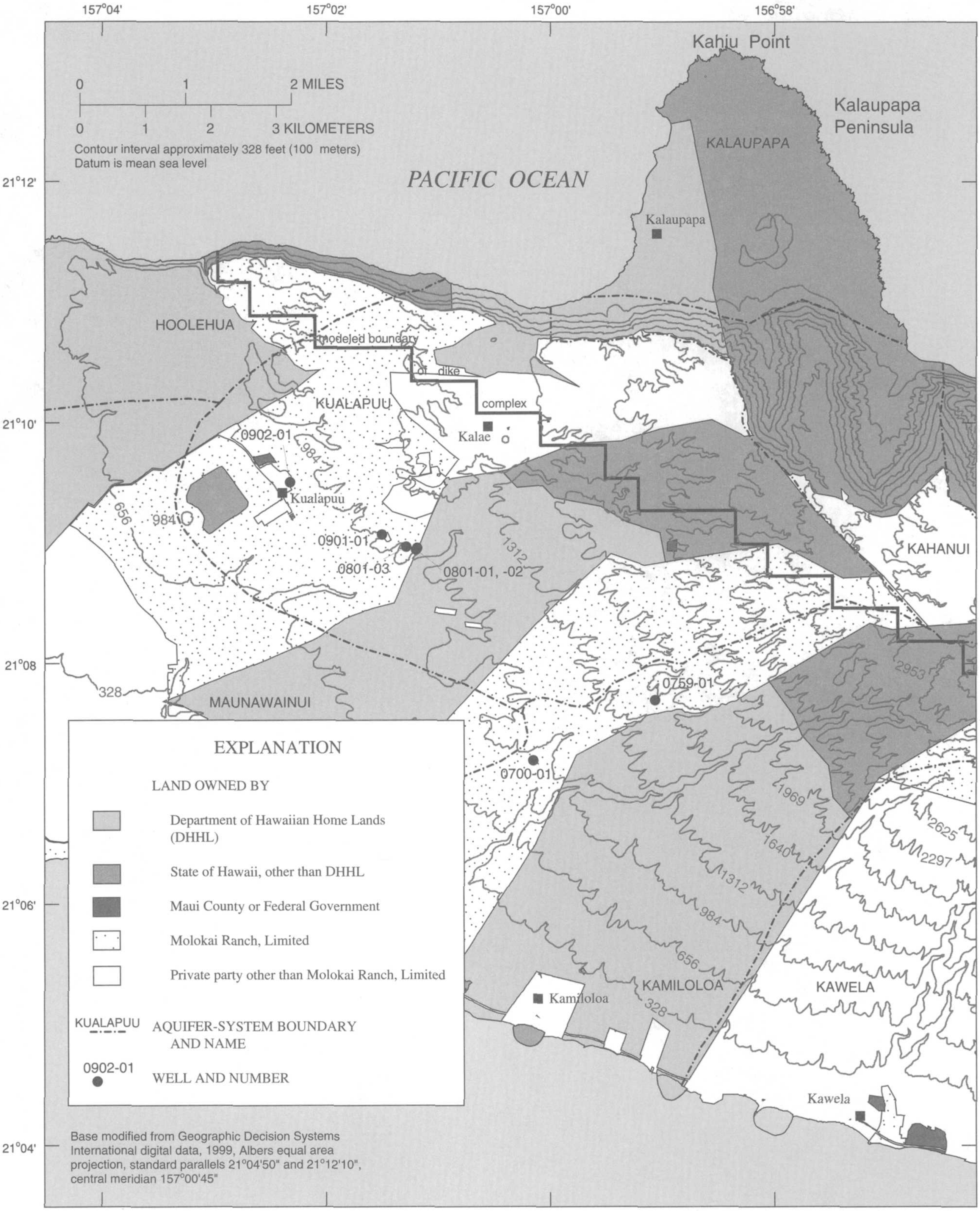
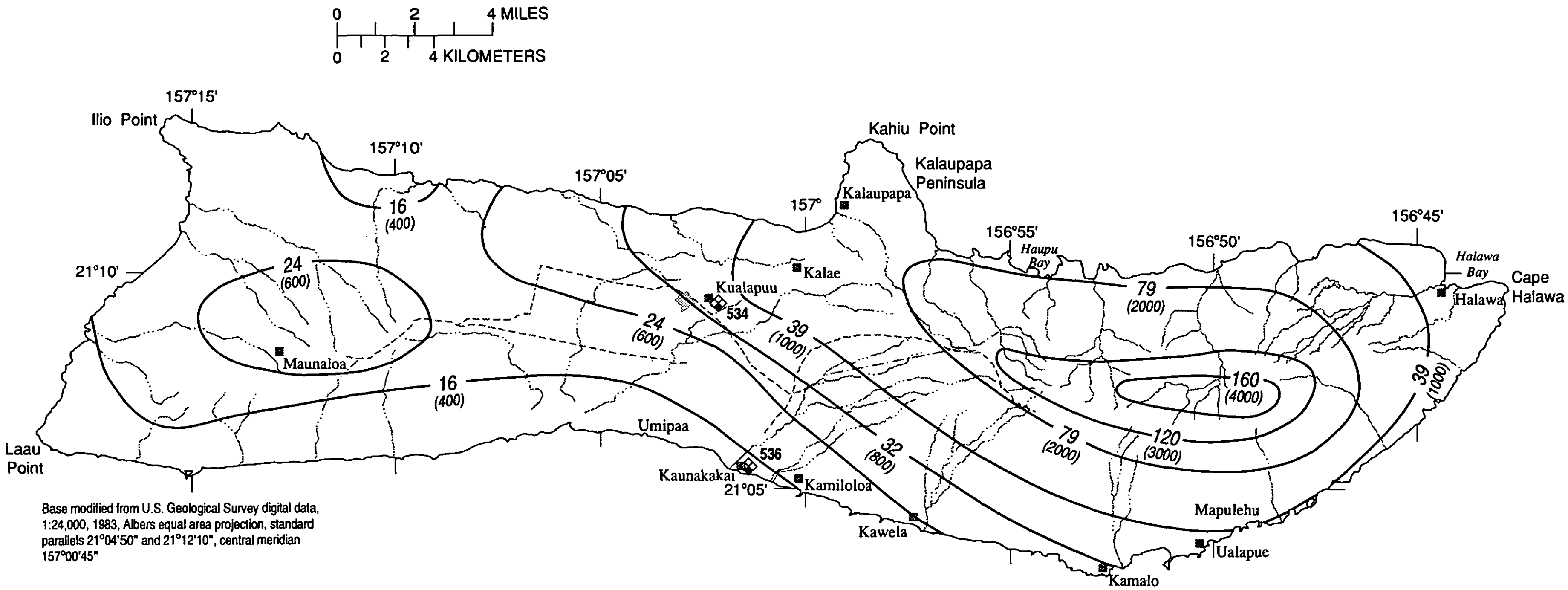


Figure 6. Land ownership in the Kualapuu area, Molokai, Hawaii (modified from digital data, Geographic Decision Systems International, 1999).



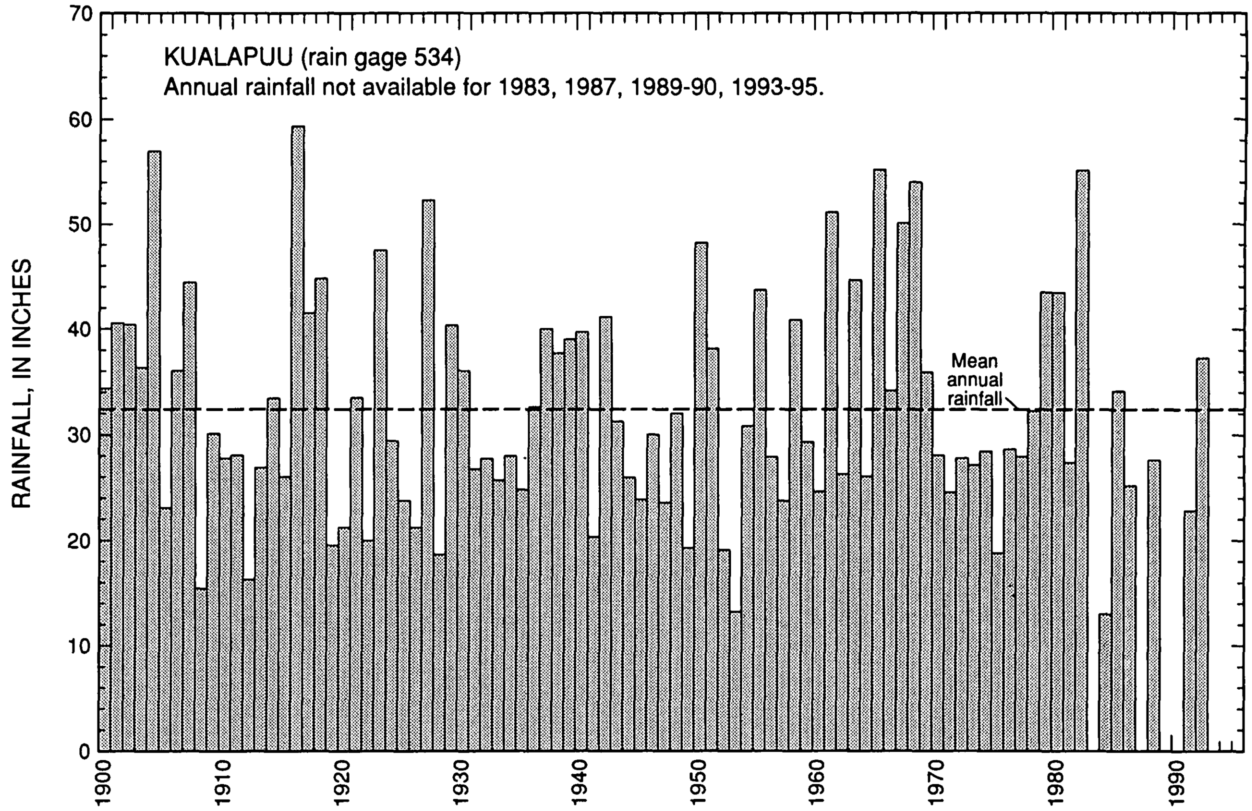
EXPLANATION

— 16 — (400) LINE OF EQUAL MEAN ANNUAL RAINFALL--Interval, in inches, is variable. Number in parentheses is value in millimeters

-------- MOLOKAI IRRIGATION SYSTEM PIPELINE

536 RAIN GAGE AND STATE KEY NUMBER

Figure 7. Mean annual rainfall, Molokai, Hawaii (modified from Giambelluca and others, 1986).



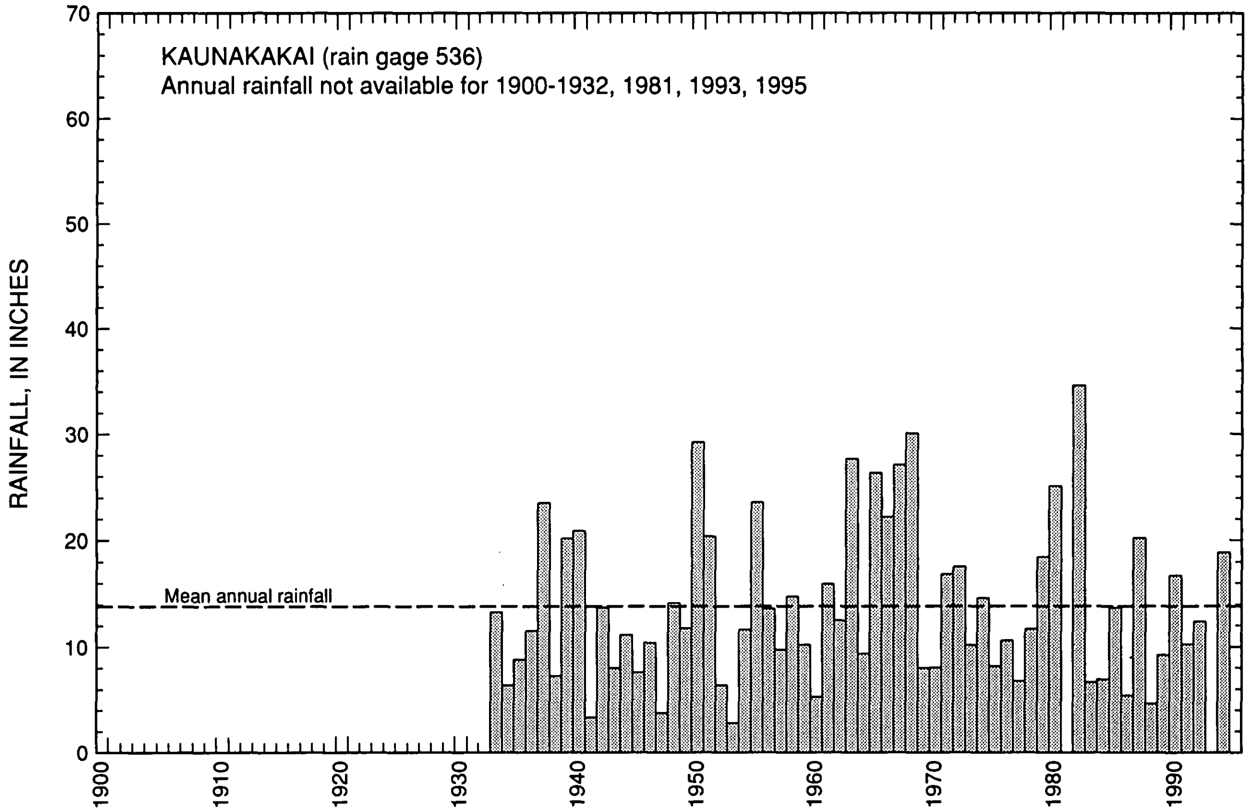


Figure 8. Annual rainfall at Kualapuu and Kaunakaki rain gages, Molokai, Hawaii (Data from National Climatic Data Center, 1984-94, and Commission on Water Resource Management, 1996, unpub.).

activity. Lava from the preshield stage consists predominantly of alkalic basalt (basalt that is low in silica and high in sodium and potassium). Lava from the principal stage of volcano building, called the shield stage, consists of fluid tholeiitic basalt (silica-saturated basalt) that characteristically forms thin flows. This basalt forms during submarine, as well as subaerial, eruptions. A large central caldera can form during the preshield or shield stages and might later be partly or completely filled during subsequent eruptions. Thousands of lava flows originate from the central caldera and from two or three rift zones that radiate out from the central part of the volcano. Intrusive dikes formed by rising magma exist within the rift zones and caldera area. The shield stage is the most voluminous phase of eruptive activity during which more than 95 percent of the volcano is formed. The postshield stage is marked by a change in lava chemistry and character. Postshield-stage lava includes alkalic basalt, and more viscous hawaiite, ankaramite, mugearite, and trachyte. Lava from the postshield stage may erupt from locations outside of the rift zones formed during the shield stage and forms a veneer atop the shield-stage basalt. After a period of quiescence, lava might issue from isolated vents on the volcano during the rejuvenated stage.

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

Dikes are thin, near-vertical sheets of massive rock that intrude existing rocks, such as lava flows. Dikes are commonly exposed by erosion within the rift zones of older volcanoes (see for example Takasaki and Mink, 1985), including West and East Molokai Volcanoes.

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

Takasaki and Mink (1985, p. 5) define a dike complex as the "aggregates of dikes and the rocks they intrude..." By this definition, the marginal dike zone should be considered part of the dike complex. However, in their earlier description of a dike complex, Stearns and Vaksvik (1935, p. 97) recognized that dikes do occur outside of the dike complex. Thus, for the purposes of this report, the dike complex is considered as the central part of the rift zone, where dikes compose 10 percent or more of the total rock volume, and the marginal dike zone is adjacent to the dike complex.

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

The overall geology of Molokai has been described by numerous investigators (see for example Lindgren, 1903; Stearns and Macdonald, 1947; Macdonald and others, 1983; Stearns, 1985). Langenheim and Clague (1987) described the stratigraphic framework of volcanic rocks on Molokai.

The island of Molokai is formed primarily by the shield- and postshield-stage volcanic rocks of West Molokai Volcano and East Molokai Volcano, and secondarily by rejuvenated-stage volcanic rocks at Kalaupapa Peninsula (Langenheim and Clague, 1987). Intrusive volcanic rocks in the form of dikes associated with rift zones and volcanic vents exist on both West and East Molokai. Coastal deposits consisting of sediments and limestone reefs are found along the southern coast.

West Molokai Volcano

The primary rift zones of the West Molokai Volcano trend roughly northwest and southwest (fig. 9) in the direction of broad ridges that extend from near the summit of the volcano. A few southeast-trending dikes exposed near the southern coast may be evidence of a third rift zone associated with West Molokai Volcano. There is no surface evidence of a summit caldera on

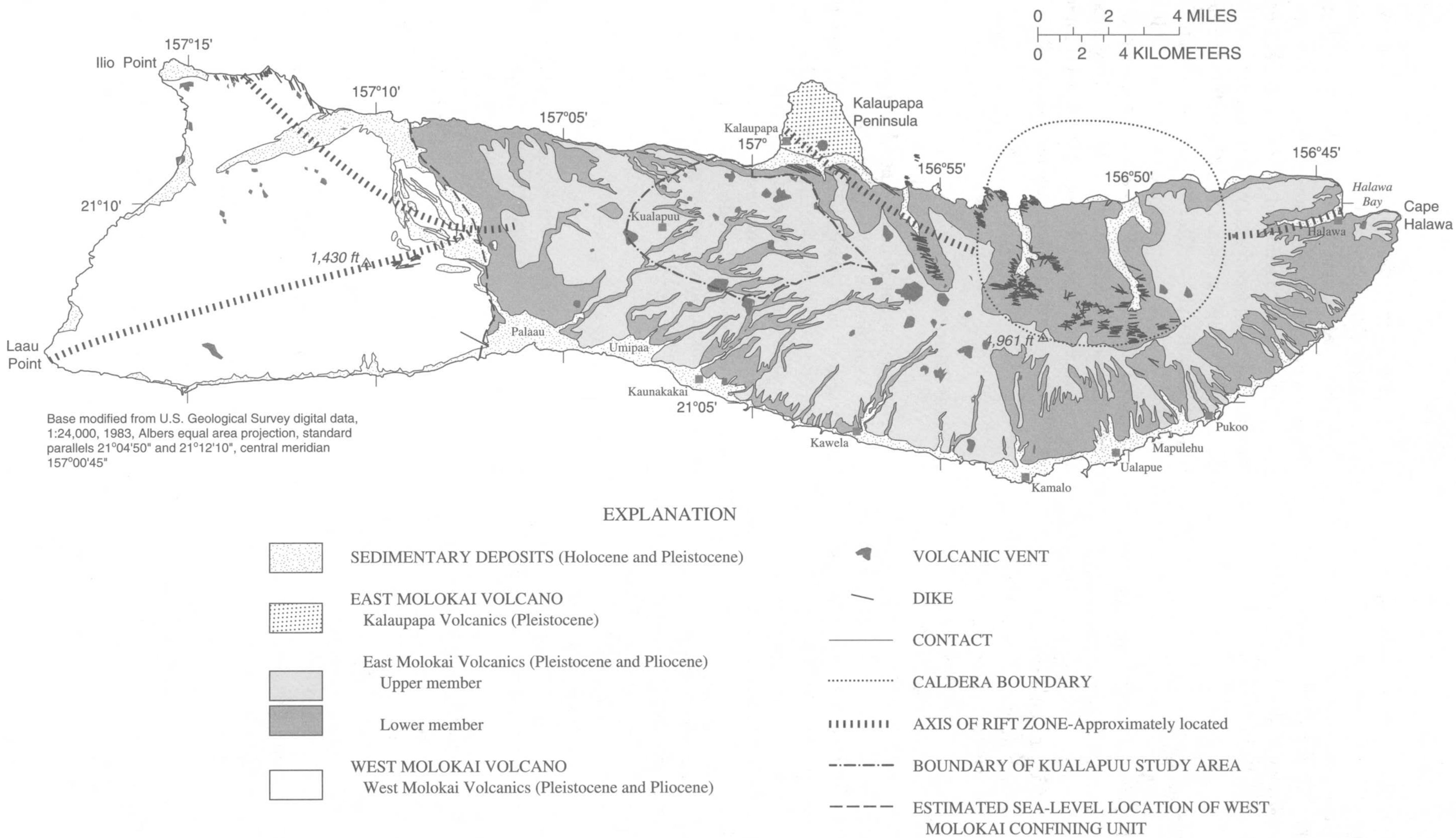


Figure 9. Generalized surficial geology of Molokai, Hawaii (from Stearns and Macdonald, 1947; and Langenheim and Clague, 1987).

West Molokai Volcano (Langenheim and Clague, 1987). The exposed rocks of West Molokai are shield-stage tholeiitic basalt and postshield-stage hawaiite and alkalic basalt. Collectively, the volcanic rocks of West Molokai Volcano are known as the West Molokai Volcanics (Langenheim and Clague, 1987).

East Molokai Volcano

The primary rift zones of the East Molokai Volcano trend northwest and east from a central caldera complex (fig. 9). Macdonald (1956) suggests that there also may be a southern rift zone emanating from the caldera. Furthermore, Malahoff and Woollard (1966) interpreted results from a magnetic survey and indicated that there may be a southwest rift zone emanating from the caldera complex. The northwest and east rift zones are marked by numerous vertical to nearly vertical intrusive dikes (Stearns and Macdonald, 1947). The caldera complex of East Molokai Volcano is exposed in Pelekunu and Wailau Stream valleys (fig. 1), and is composed of stocks, plugs, crater fills, ponded lavas, and talus and fault breccias cut by dike swarms (Stearns and Macdonald, 1947).

Stearns and Macdonald (1947) mapped numerous vent features, including cinder and spatter cones, along the western and southern flanks of the East Molokai Volcano (fig. 9). Many of these features do not appear to lie along the trends of the two primary rift zones of the volcano, which may indicate that (1) a marginal dike zone exists or (2) more than two primary rift zones exist.

The exposed rocks of East Molokai Volcano are named the East Molokai Volcanics and Kalaupapa Volcanics (Langenheim and Clague, 1987). The East Molokai Volcanics are divided into two informal members. The lower member consists of shield-stage tholeiitic, olivine-tholeiitic, and picritic-tholeiitic basalts, and postshield-stage alkalic basalt. The upper member consists of postshield-stage mugearite, with lesser amounts of hawaiite and trachyte. The upper member of the East Molokai Volcanics forms a relatively thin veneer, about 50 to 500 ft thick, over the lower member (Stearns and Macdonald, 1947). The Kalaupapa Volcanics include the rejuvenated-stage alkalic basalt and basanite that form Kalaupapa Peninsula (Langenheim and Clague, 1987).

Estimated ages of rocks from West and East Molokai Volcanoes (Naughton and others, 1980; McDougall, 1964; Langenheim and Clague, 1987) indicate that the volcanoes may have formed almost contemporaneously. Stearns and Macdonald (1947) noted, however, that an erosional unconformity, which dips about 10° to the east, is exposed at an altitude of 250 ft in the east bank of Waiahewahewa Gulch (fig. 1). At this site, East and West Molokai Volcanics are separated by 3 ft of soil and 6 ft of spheroidally weathered basalt, with the West Molokai Volcanics at the bottom of the sequence. The sequence indicates that West Molokai Volcanics are older than East Molokai Volcanics at the site of the exposed unconformity.

Coastal Deposits

Along southern Molokai, a coral reef extends from the coast to about 1 mi offshore, and limestone has also been described in a geologic log from a well near the southern coast of the island (Lindgren, 1903). In addition, along the southern shore of East Molokai Volcano and the Hoolehua Plain, an apron of alluvium has formed by deposition of eroded soil. Off the northern coast of Molokai, only a thin veneer of recent sediments exists (Mathewson, 1970).

Kualapuu Area

The surface rocks in the Kualapuu study area consist of the shield- and postshield-stage volcanic rocks of East Molokai Volcano (fig. 9). Numerous volcanic vents associated with East Molokai Volcano exist in the Kualapuu area. Available geological, hydrological, and geophysical information indicate that the northeastern part of the Kualapuu area is probably within the dike complex of the northwest-trending rift zone of East Molokai Volcano, and the southwestern part of the Kualapuu area may be within a marginal dike zone.

HYDRAULIC CONDUCTIVITY OF THE ROCKS

Hydraulic conductivity is a quantitative measure of the capacity of a rock to transmit water. The hydraulic conductivity of a rock can be qualitatively described by permeability. Permeability describes the ease with which fluid can move through a porous rock (see for example Domenico and Schwartz, 1990). The permeability of volcanic rocks is variable and depends on the mode of emplacement of the rocks.

Lava Flows

In a layered sequence of subaerial, shield-stage lava flows of a volcano, where dike intrusions are not present, the overall permeability is high (Stearns and Macdonald, 1947). The main features of lava flows contributing to the high permeability are (1) clinker zones associated with aa flows, (2) voids along the contacts between flows, (3) cooling joints normal to flow surfaces, and (4) lava tubes associated with pahoehoe flows. Oki (1997) estimated the horizontal hydraulic conductivity of the dike-free, shield-stage lava flows of Molokai to be 1,000 feet per day (ft/d).

Dikes

Although most dikes are less than 10 ft thick, dikes are hydrologically important because they have low permeability and can extend vertically and laterally for thousands of feet. Within a dike complex, dikes intersect at various angles and compartmentalize the more permeable intruded rock so that ground water can be impounded to high altitudes. Because dikes lower overall rock porosity and permeability, the average hydraulic conductivity of a dike complex decreases as the number of dike intrusions increases. Although the geometry and the local-scale hydrologic effects of the dikes that fed the scattered vents of East Molokai Volcano near Kualapuu are not known, these dikes intrude the aquifer and probably lower the overall permeability of the aquifer.

From a ground-water flow model, Oki (1997) estimated the overall hydraulic conductivity of the dike complexes of West and East Molokai to be 2 and 0.02 ft/d, respectively. The horizontal hydraulic conductivity of the marginal dike zone near Kualapuu was estimated to be 100 ft/d (Oki, 1997).

Weathering

Weathering tends to reduce the permeability of the volcanic rocks. The zone of weathered West Molokai Volcanics and soil beneath the contact of the West and East Molokai Volcanics likely impedes ground-water flow between East and West Molokai. This weathered zone is referred to as the West Molokai confining unit in this report. No data are available to determine whether this unit is truly an effective barrier to ground-water flow. However, on the basis of information from Oahu on weathered volcanic rocks and a similar geohydrologic barrier (Oki, 1998), the hydraulic conductivity of the West Molokai confining unit is probably on the order of 1 ft/d.

Coastal Deposits

Coastal deposits and underlying weathered volcanic rocks impede the seaward discharge of freshwater on southern Molokai. The permeability of the interbedded coastal deposits may vary widely, from low-permeability compacted alluvium to cavernous limestone deposits. In southern Molokai, Oki (1997) estimated the overall vertical hydraulic conductivity of the coastal deposits to range from 0.5 to 5 ft/d.

REGIONAL GROUND-WATER FLOW SYSTEM

Precipitation is the source of all freshwater on Molokai. The precipitation either (1) runs off, (2) evaporates or is transpired by vegetation, or (3) recharges the ground-water system. Water that recharges the ground-water system flows from zones of higher to lower hydraulic head, as measured by water levels. Water levels are highest in the mountainous interior parts of the island, particularly in the northeastern part of the island, and lowest near the coast and, thus, ground water flows from the mountainous interior areas to coastal discharge areas. Ground water originating from eastern and western Molokai also flows toward the central Hoolehua Plain, from where it flows to either the northern or southern coast.

Ground water that is not withdrawn from wells and tunnels discharges naturally from the aquifer at onshore springs and seeps in deeply incised valleys and at subaerial and submarine coastal springs and seeps. In northeastern Molokai, springs form where stream erosion has cut through dike compartments below the level of the water table. Ground-water discharge at these springs contributes to the base flow of streams. Along the southern coast, native Hawaiians built fishponds in shallow coastal waters by constructing rock-wall enclosures extending from the shoreline. References to fishpond construction on Molokai date back to the sixteenth century, and the most recently constructed fishpond on Molokai was built around 1829 (Farber, 1997). Because freshwater discharge to the ponds is necessary for growth of plants on which fish feed, the ponds may be evidence of the existence of springs (Stearns and Macdonald, 1947).

Ground water on Molokai is unconfined in the inland areas. Along the southern coast, ground water may be confined by sedimentary deposits that impede the seaward discharge of fresh ground water. A measured seismic-velocity discontinuity at an altitude of about -6,000 ft measured in southwestern Oahu may coincide with a reduction in permeability of the volcanic rocks (Furumoto and others, 1970). Kauahikaua (1993) also suggests that a reduction in porosity on the island of Hawaii may occur near an altitude of -6,000 ft. The base of the aquifer on Molokai is unknown, but may extend down to an altitude near -6,000 ft. However, freshwater probably occurs in only the upper part of the aquifer, and perhaps in only a small fraction of the total thickness of the aquifer.

Fresh ground water on Molokai is found in two main forms: (1) as a lens-shaped body of freshwater, called a freshwater lens, floating on denser, underlying saltwater within permeable dike-free lava flows, and (2) as dike-impounded water with higher water levels (ten to hundreds of feet above sea level) where overall permeability is reduced because of the presence of dikes. Stearns and Macdonald (1947) also suggest that perched water exists on Molokai.

Ground-Water Recharge

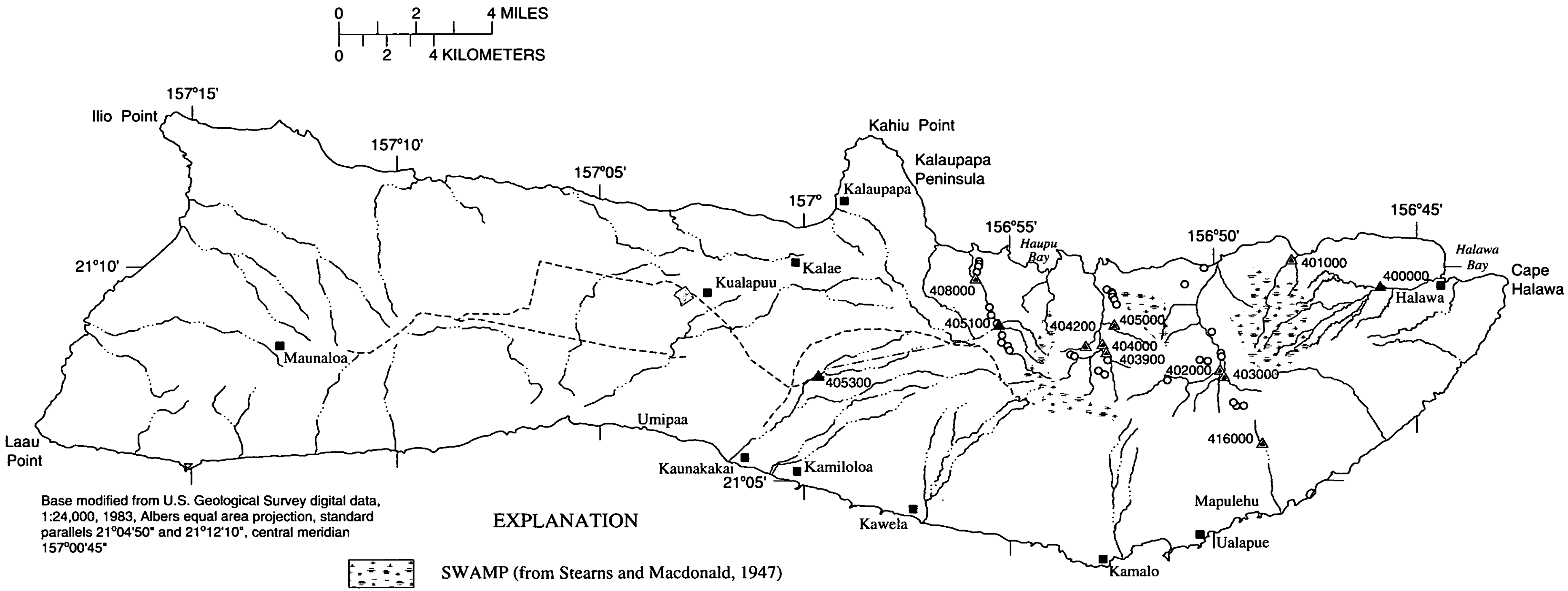
Ground water is recharged by direct infiltration of rainfall over much of Molokai. Over West Molokai Volcano and the Hoolehua Plain, however, ground-water recharge rates are low because of the low rainfall and high evaporation rates. The area of greatest recharge lies near the topographic peak of East Molokai Volcano, where rainfall is greatest.

Ground-water recharge on Molokai was estimated to be 144 Mgal/d with an annual water budget (State of Hawaii, 1990). More recently, Shade (1997) estimated that ground-water recharge was 188.6 Mgal/d for natural vegetation conditions. This represents an average of about 15 in/yr over the island. However, recharge varies greatly areally from a minimum of near zero in/yr in western Molokai to a maximum of about 100 in/yr in northeastern Molokai.

Ground-Water Discharge to Streams

Streams on Molokai have steep gradients in the mountainous, high-rainfall regions and flatter gradients near the coast. No perennial streams exist in western Molokai or the central Hoolehua Plain. In contrast, streams in the windward, northeastern valleys of Molokai are perennial throughout most of their lengths. Most streams that drain to the southern coast of East Molokai Volcano are perennial only in the upper reaches where rainfall is persistent or where water is drained from marsh areas or springs. These streams are generally perennial only where they flow over lavas of the upper member of the East Molokai Volcanics. Where streams flow over the more permeable lavas of the lower member, surface water is more readily lost to infiltration (Stearns and Macdonald, 1947, p. 47).

Daily streamflow records are available at nine stream-gaging stations on streams in the windward, northeastern valleys of Molokai (fig. 10). Streamflow consists of direct runoff of rainfall and base flow. Base flow represents ground-water discharge. Oki (1997) used a computerized base-flow separation method (Wahl and Wahl, 1995) to estimate the base-flow component of streamflow at the gaging stations. The sum of the estimated average annual base flow in the gaged streams of northeastern Molokai is 38.8 Mgal/d (table 2). Base flow at gaging station 16403900 was not included in the total base-flow estimate because flow measured at this gaging station is included in the base-flow estimate at downstream station 16404000. At station 16408000, Waikolu Stream, only data prior to 1961 were used because of diversions after November 1960. The total base flow on Molokai is unknown because not all streams are gaged at their mouths. Base flow estimates were used to estimate the leakance (see "Boundary Conditions" subsection of the "Model Description" section) for streams in northeastern Molokai.



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 21°04'50" and 21°12'10", central meridian 157°00'45"

EXPLANATION

SWAMP (from Stearns and Macdonald, 1947)

—·—·— MOLOKAI IRRIGATION SYSTEM TUNNEL

------ MOLOKAI IRRIGATION SYSTEM PIPELINE

GAGING STATION AND ABBREVIATED NUMBER--Complete number is preceded by 16

400000 ▲ Continuous-record, active station

402000 ▲ Continuous-record, inactive station

o SPRING (from Stearns and Macdonald, 1947)

Figure 10. Surface-water gaging stations, Molokai, Hawaii.

Table 2. Estimated base flow for northeastern Molokai streams, Hawaii
[BFI, base flow index program (Wahl and Wahl, 1995); Mgal/d, million gallons per day]

Station	Station name	Complete years of record used in BFI program	Average streamflow[1] (Mgal/d)	Average base flow, (Mgal/d)
16400000	Halawa Stream near Halawa	1918, 1921-31, 1938-95	19.5	5.2
16401000	Papalaua Stream near Pukoo	1921-28	13.8	4.1
16402000	Pulena Stream near Wailau	1920-27, 1938-56	22.2	8.9
16403000	Waiakeakua Stream near Wailau	1920-28, 1938-56	7.5	3.8
16403900	Kawainui Stream near Pelekunu	1969-79, 1995	5.1	2.2
16404000	Pelekunu Stream near Pelekunu	1920-28, 1938-46, 1949-56, 1972-81	10.6	4.6
16404200	Pilipililau Stream near Pelekunu	1969-95	1.0	0.7
16405000	Lanipuni Stream near Pelekunu	1920-28, 1938-56	9.1	4.3
16408000	Waikolu Stream below pipeline crossing near Kalaupapa	1921-29, 1938-47, 1949-60	12.3	7.2

[1] Data available at URL http://wwwdhihnl.wr.usgs.gov.

Ground-Water Levels

Measured water levels are available primarily at wells along the southern coast and in the central plain area (figs. 4 and 11, table 3). In the vicinity of Kualapuu, water levels are about 8 to 12 ft above sea level. Along the south shore, water levels are 1 to 3 ft above sea level between Umipaa and Kawela, and 4 to 5 ft above sea level between Kamalo and Mapulehu.

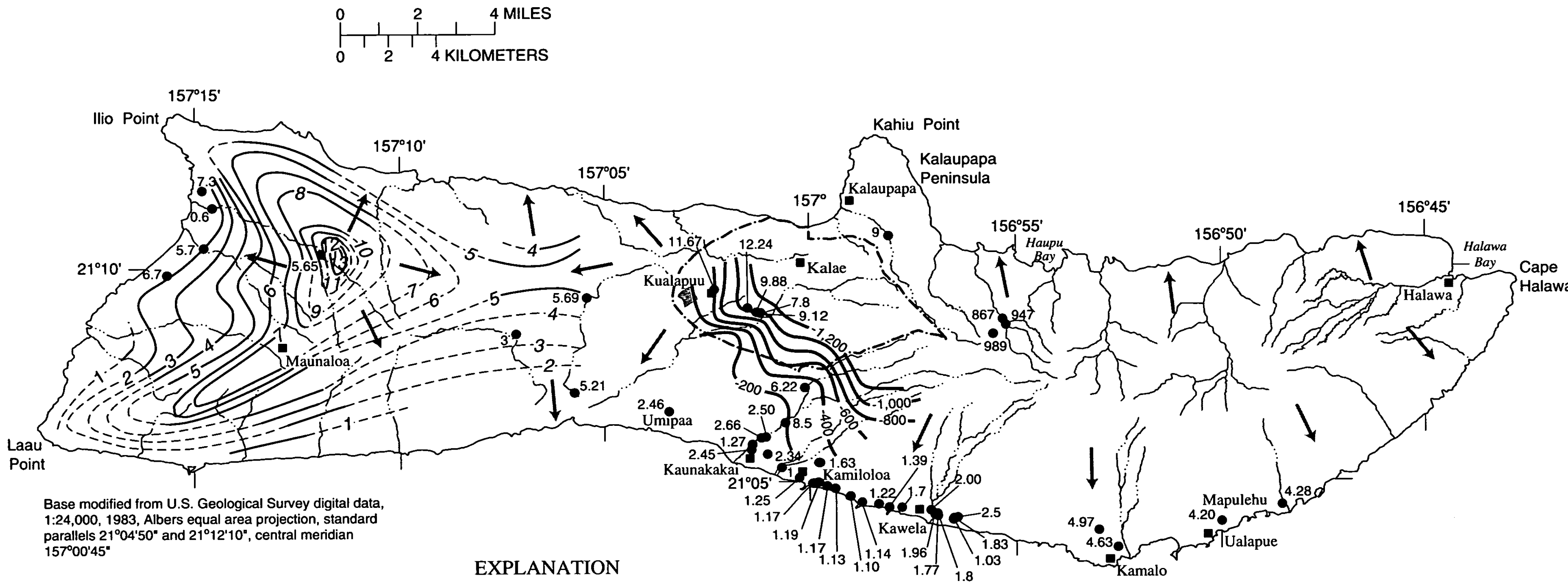
Within the northwest rift zone of the East Molokai Volcano near Waikolu Stream valley, water levels at wells 0855-01 to -03 were about 900 ft above sea level in 1961. At the northern margin of the dike complex, near Kalaupapa Peninsula, the water level at well 1058-01 was reported to be 9 ft above sea level. The 9-ft water level at well 1058-01 probably represents an upper limit for the water-table altitude in the dike-free Kalaupapa Volcanics. Results from an electrical resistivity survey indicated that the lens in the Kalaupapa Volcanics was thin (Takasaki, 1986).

In the West Molokai Volcanics, the water level at well 1011-01 was reported by Stearns and Macdonald (1947, p. 61) to be 5.6 ft above sea level in 1946.

The distribution of water levels on Molokai, averaged from measurements taken over a period of about 60 years, is shown in figure 11. A detailed contour map of water levels for the entire island cannot be drawn using existing well data. MacCarthy (1941) used electrical-resistivity measurements to determine the depth to saltwater, then applied the Ghyben-Herzberg principle (see following discussion in the section "Freshwater Lens") to estimate the altitude of the water table in western Molokai (fig. 11). MacCarthy (1941) estimated that the water-table altitude in western Molokai ranges from about 1 to 14 ft above sea level. The water-level estimates made from the resistivity measurements are only approximate because use of the Ghyben-Herzberg principle to predict water levels from estimated depths to saltwater (1) ignores the freshwater-saltwater transition zone separating freshwater from saltwater and (2) does not account for dynamic conditions in the system where vertical flow is present. It is also likely that unquantified errors are associated with the resistivity measurements and the geophysical models used to represent the actual subsurface conditions.

Freshwater Lens

Water levels measured in wells drilled into the permeable dike-free lava flows of the island are less than 15 ft above sea level. Within the dike-free lava flows, a lens of freshwater floats on denser, underlying saltwater. The source of freshwater in the lens is ground-water recharge from (1) the upgradient dike complex where water levels are high, (2) infiltration of rainfall, and (3) irrigation water. Fresh ground water flows from inland recharge areas to coastal discharge areas. A saltwater-circulation system exists beneath the lens (fig. 3) (Cooper and others, 1964; Souza and Voss, 1987). Saltwater flows landward in the deeper parts of the aquifer, rises, and then mixes with seaward-flowing freshwater. This mixing creates a freshwater-saltwater transition zone.



EXPLANATION

—4—	LINE OF EQUAL WATER-TABLE ALTITUDE, DETERMINED BY RESISTIVITY MEASUREMENTS (MacCARTHY, 1941) Interval 1 foot. Datum is mean sea level. Dashed where inferred
—-200—	LINE OF EQUAL DEPTH TO SALINE WATER BODY DETERMINED FROM TIME-DOMAIN ELECTROMAGNETIC SURVEY (STATE OF HAWAII, 1997) Interval 200 feet. Datum is mean sea level.
-·-·-·-	BOUNDARY OF KUALAPUU STUDY AREA
→	APPROXIMATE DIRECTION OF GROUND-WATER FLOW
• 2.46	WELL AND AVERAGE MEASURED WATER LEVEL, IN FEET ABOVE MEAN SEA LEVEL

Figure 11. Arithmetic mean of measured water levels for the period 1938-97, water-table altitude from resistivity measurements, and depth to saline water body determined from a time-domain electromagnetic survey, Molokai, Hawaii.

Table 3. Summary of measured, nonpumping water levels at selected wells, Molokai, Hawaii
[Data from: Stearns and Macdonald, 1947; Anthony, 1995; Takasaki, 1986; USGS Hawaii District well files; --, none or not applicable]

Well no.	Period	Water level, in feet			Standard deviation (feet)	No. of daily measurements
		Arithmetic mean[a]	Maximum	Minimum		
0352-01	08/47-06/61	4.63	4.10	5.40	0.26	80
0352-05	11/27/61	4.97	--	--	--	1
0448-02	09/70-07/97	4.28	3.67	5.45	0.31	191
0449-01	06/47-07/97	4.20	2.09	6.05	0.91	283
0456-01	05/48	1.03	1.36	0.56	0.27	10
0456-02	no date	1.77	--	--	--	1
0456-03	no date	1.96	--	--	--	1
0456-04	no date	1.8	--	--	--	1
0456-98[b]	no dates	1.83	1.83	1.83	0.52	3
0456-99[c]	no date	2.5	--	--	--	1
0457-01	06/47-08/97	2.00	1.47	2.78	0.20	201
0457-02	no date	1.7	--	--	--	1
0458-01	no date	1.14	--	--	--	1
0458-02	no date	1.39	--	--	--	1
0458-03	no date	1.22	--	--	--	1
0459-01	no date	1.17	--	--	--	1
0459-02	no date	1.17	--	--	--	1
0459-03	no date	1.19	--	--	--	1
0459-04	no date	1.13	--	--	--	1
0459-05	no date	1.10	--	--	--	1
0500-01	no date	1	--	--	--	1
0500-03	no date	1.25	--	--	--	1
0501-03	06/38-08/45	1.27	0.75	2.00	0.35	87
0501-04	no date	2.34	--	--	--	1
0501-05	06/47-01/54	2.45	2.03	3.27	0.19	52
0559-01	no date	1.63	--	--	--	1
0600-01	08/39-09/39	8.5	8.9	7.7	0.67	3
0601-01	05/54-07/97	2.66	1.60	3.30	0.23	290
0601-02	no date	2.50	--	--	--	1
0603-01	12/67-09/77	2.46	2.10	3.52	0.24	69
0700-01	07/76-01/97	6.22	5.72	6.70	0.26	81
0705-04	11/22/72	5.21	--	--	--	1
0801-01	03/48-06/95	9.12	10.74	8.4	0.74	12
0801-02	no date	7.8	--	--	--	1
0801-03	07/87-09/97	9.88	11.7	8.06	2.57	2
0807-01	11/03/75	3	--	--	--	1
0855-01	06/29/61	989.15	--	--	--	1
0855-02	04/03/61	866.52	--	--	--	1
0855-03	07/10/61	947.04	--	--	--	1
0901-01	05/52-06/76	12.24	8.65	17.90	1.24	274
0902-01	06/53-06/63	11.67	7.53	14.46	1.69	118
0905-01	06/38-05/46	5.69	4.47	6.52	0.56	92
0915-01	no date	6.7	--	--	--	1
1011-01	01/18/46	5.65	--	--	--	1
1014-01	no date	5.7	--	--	--	1
1058-01	no date	9	--	--	--	--
1114-01	no date	0.6	--	--	--	1
1114-02	no date	7.3	--	--	--	1

[a] The arithmetic mean is an average obtained by dividing the sum of the water-level measurements by the number of water-level measurements. For some wells, only a single water-level measurement was available.

[b] No state number assigned to this well, old well 13 (Stearns and Macdonald, 1947).

[c] No state number assigned to this well, old well 14 (Stearns and Macdonald, 1947).

For hydrostatic conditions, the thickness of a freshwater lens can be estimated by the Ghyben-Herzberg principle. If the specific gravities of freshwater and saltwater are assumed to be 1.000 and 1.025, respectively, and if the freshwater and saltwater are assumed to be separated by a sharp interface, then the Ghyben-Herzberg principle predicts that every foot of freshwater above sea level must be balanced by 40 ft of freshwater below sea level. For dynamic conditions, the Ghyben-Herzberg principle tends to underestimate freshwater-lens thickness near the discharge zone and overestimate lens thickness near the recharge zone.

Dike-Impounded Ground Water

Within the dike complex of the East Molokai Volcano, fresh ground water is impounded to high levels in the volcanic rocks between low-permeability dikes. In the valleys of northeast Molokai, the presence of springs indicates that ground water in the dike complex is probably impounded to altitudes greater than 2,000 ft above sea level (Stearns and Macdonald, 1947, p. 75). Because of low recharge rates in west Molokai, water levels in the dike complex of West Molokai Volcano are probably less than about 15 ft above sea level (MacCarthy, 1941).

The abundance of dikes in a rift zone increases with depth, which reduces the overall permeability of the dike complex with depth. No data exist that indicate the depth to which rocks are saturated with freshwater in the dike complex. In the marginal dike zone where dike intrusions are few, freshwater floats on saltwater.

GROUND-WATER FLOW SYSTEM IN THE KUALAPUU AREA

The northeastern part of the Kualapuu area is within the dike complex of the northwest rift zone of East Molokai Volcano. No wells have been drilled in the northeastern part of the Kualapuu area, but ground water there is probably impounded to high levels (tens to hundreds of feet above sea level) in the volcanic rocks between low-permeability dikes. Within the Kualapuu area, ground water generally flows to the southwest, where water levels are about 8 to 12 ft above sea level. The southwest part of the Kualapuu area lies within a marginal dike zone of East Molokai Volcano. In the southwest part of the Kualapuu area, a freshwater body of unknown thickness overlies a brackish-water transition zone of unknown thickness, which in turn overlies saltwater. Ground water in the Kualapuu area that is not withdrawn from wells flows either to the west or south, where ground-water levels are lower, or directly to the ocean in the north.

Ground-Water Levels

As of 1999, only five wells (0801-01 to -03, 0901-01, and 0902-01) (fig. 4) had been drilled in the Kualapuu area, and four of them are within about 2,000 ft of each other. The earliest reported water level in the Kualapuu area is from well 0902-01, and measured 10.5 ft above sea level in 1946 (unpub. data in U.S. Geological Survey, Honolulu, well files). Hydrographs for wells 0902-01 and 0901-01 show relatively large variations in water levels from one measurement to the next (Oki, 1997). Water levels in well 0902-01 ranged from 7.53 to 14.46 ft above sea level during the period 1953–63, and water levels in well 0901-01 ranged from 8.65 to 17.90 ft above sea level during the period 1952–76. The large variations could be caused by pumping or changes in recharge, but are more likely associated with the inaccuracy of the pressure measurements made with the air-line device used to monitor water levels in these wells.

The water level in DHHL well 1 (0801-01) measured 10.48 to 10.69 ft above sea level on March 31, 1948, when the well was 1,011 ft deep, and 10.74 ft above sea level on May 11, 1949, when the well was 1,055 ft deep (unpub. data in U.S. Geological Survey, Honolulu, well files). The final completed depth of well 0801-01 was 1,095 ft in 1949. During 1995 after the pump in well 0801-01 was removed, water levels in this well were measured by the USGS and ranged from 8.4 to 9.2 ft above sea level during May and June 1995. The water levels measured in the late 1940's are higher than those measured during 1995, which may be the result of increased withdrawals or decreased recharge in the Kualapuu area since the late 1940's.

The only reported water-level measurement from DHHL well 2 (0801-02), which was drilled in 1979, was 7.8 ft above sea level in July 1979 (unpub. data in Commission on Water Resource Management well files). Maui County Department of Water Supply (DWS) well 0801-03 was drilled in 1987, and the initial water-level measurement at this well was 11.70 ft above sea level on July 27, 1987 (unpub. data in Commission on Water Resource Management well files). The USGS measured a water level of 6.91 ft above sea level on April 5, 1995 in well 0801-03 with the pump in operation, and Tom Nance Water Resource Engineering (State of Hawaii, 1998) measured a water level of 8.06 ft above sea level on September 18, 1997 after the pump had been turned off for an unspecified period of time.

Depth to Saline Water

A time-domain electromagnetic survey was made in the vicinity of the Kualapuu area by Blackhawk Geosciences, Inc. (State of Hawaii, 1997) to estimate the depth to saline (unspecified salinity) water. Results of the survey indicate that the altitude of the saline-water zone in the aquifer rises to the southwest (fig. 11). The estimated altitude of the saline-water zone near wells 0801-01 to -03 is about 1,000 ft below sea level. Near the western part of the Kualapuu area, the altitude of the saline water is about 400 ft below sea level. The results of the time-domain electromagnetic survey are consistent with the expected decrease in water levels in a southwesterly direction.

In the Kualapuu area, the estimated depths to saline water from the time-domain electromagnetic survey cannot be used to accurately predict water levels using the Ghyben-Herzberg principle. For example, the estimated depth to saline water of 1,000 ft below sea level near wells 0801-01 to -03 would correspond to a water level of 25 ft if the Ghyben-Herzberg principle were assumed to be applicable. However, measured water levels near wells 0801-01 to -03 are less than 12 ft above sea level.

Chloride Concentration

Chloride concentration is commonly used as an indicator of salinity, which may increase as a result of saltwater intrusion into the ground-water system. The chloride concentration of water from wells in the Kualapuu area has generally been below 200 mg/L except at well 0902-01. During the period from 1950 through 1961, the chloride concentration of water withdrawn from well 0902-01 ranged from 252 to 430 mg/L. For comparison, the chloride concentration of rainfall is typically less than 10 to 20 mg/L (Swain, 1973), and the chloride concentration of seawater is about 19,500 mg/L (Wentworth, 1939).

During the 1990's, chloride concentrations of pumped water from wells 0801-01, 0801-02, 0801-03, and 0901-01 in the Kualapuu area have been less than 200 mg/L. DWS began pumping well 0801-03 in mid-1991. Chloride concentrations of water pumped from DHHL wells 0801-01 and 0801-02 rose by about 20 mg/L and 10 mg/L, respectively, following the start of pumping from the DWS well (0801-03).

Vertical Profiles of Chloride Concentration in Well 0801-01

During 1994–95, the pump in DHHL well 1 (0801-01) was removed, making it possible to measure chloride concentration with depth on four separate dates. The well is at a ground-surface altitude of about 1,006 ft in the Kualapuu area, and has a solid casing from the top of the well to an altitude of about -3 ft, a perforated casing between -3 ft and -71 ft, and is open from -71 ft to the bottom of the hole at -89 ft (fig. 12). The well is about 130 ft from DHHL well 2 (0801-02) and 560 ft from the DWS well (0801-03). DHHL well 2 has perforated casing between an altitude of -27 ft and the bottom of the hole at -87 ft. The DWS well has perforated casing between altitudes of 13 ft and -37 ft, and is open from -37 ft to the bottom of the hole at -96 ft (fig. 12).

In the days prior to May 15, 1995, both DHHL well 2 and the DWS well were pumped intermittently (fig. 13). The pump capacities for DHHL well 2 and the DWS well are about 700 and 750 gallons per minute (gal/min), respectively. During May 15–22, 1995, DHHL well 2 was pumped continuously at a rate of about 700 gal/min, and the DWS well was not pumped. Pumped water samples were collected from DHHL well 2 during the period May 15–22, 1995 (fig. 14). Chloride-concentration profiles in DHHL well 1 were obtained on two separate dates prior to May 15, 1995 (November 3, 1994 and May 12, 1995), and on two separate dates during the period when DHHL well 2 was being pumped continuously (May 18, 1995 and May 22, 1995) (Fontaine and others, 1997).

Profile of November 3, 1994.--The chloride-concentration profile in DHHL well 1 from November 3, 1994 indicates a chloride concentration of about 35 mg/L within the part of the borehole with solid casing (fig. 12). Beneath the solid casing, chloride

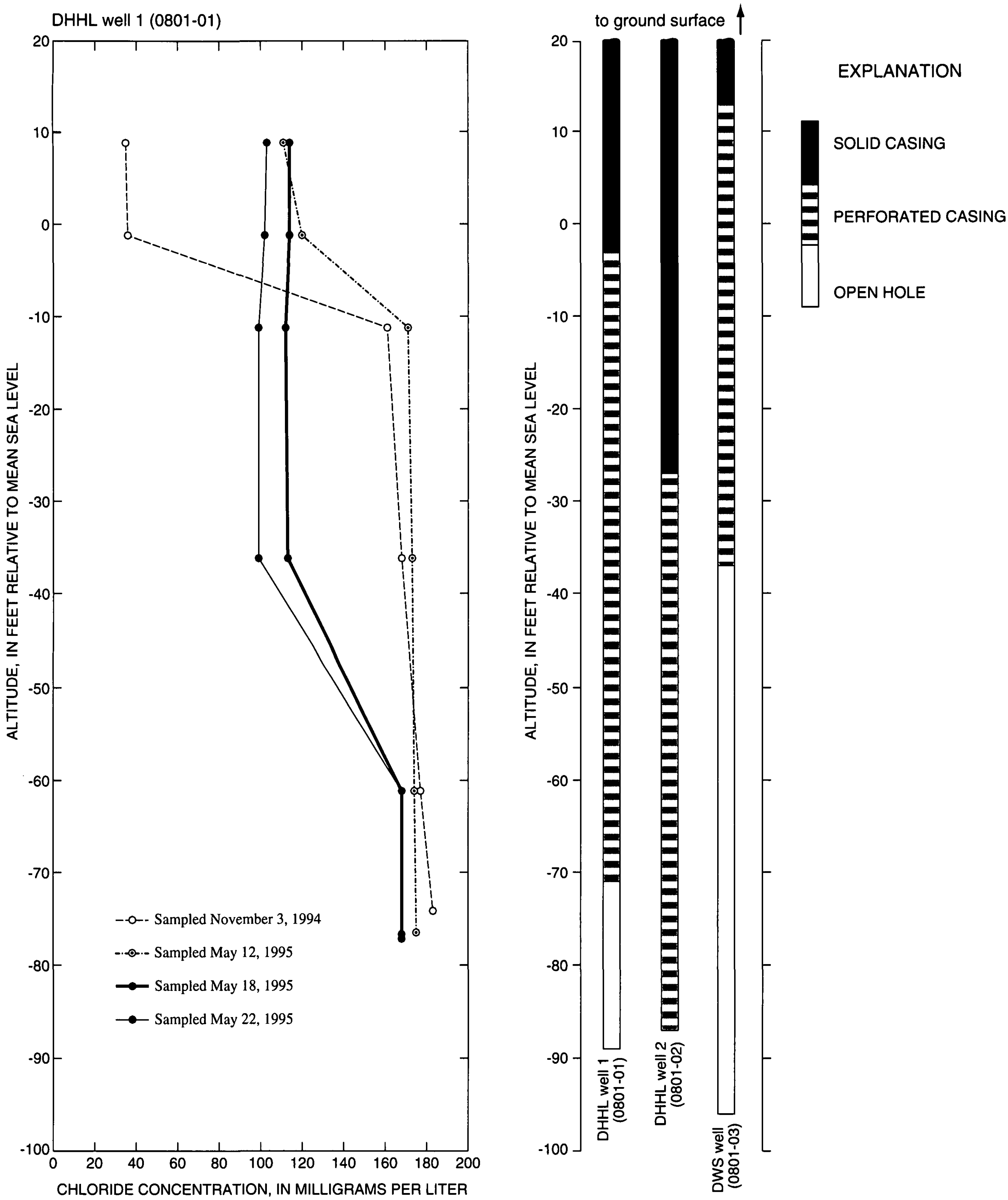


Figure 12. Chloride concentration of water samples from different depths in Department of Hawaiian Home Lands well 1 (0801-01), and diagram of well-casing depth and type for wells 0801-01 to -03, Molokai, Hawaii. There were no reported withdrawals from well 0801-01 from October 1993 to December 1995. During the period October 1993 to May 15, 1995, Department of Hawaiian Home Lands well 2 (0801-02) and Maui County Department of Water Supply well 0801-03 were pumped on an intermittent basis. During the period May 15-22, 1995, well 0801-02 was pumped at a continuous rate of about 700 gallons per minute and well 0801-03 was not pumped.

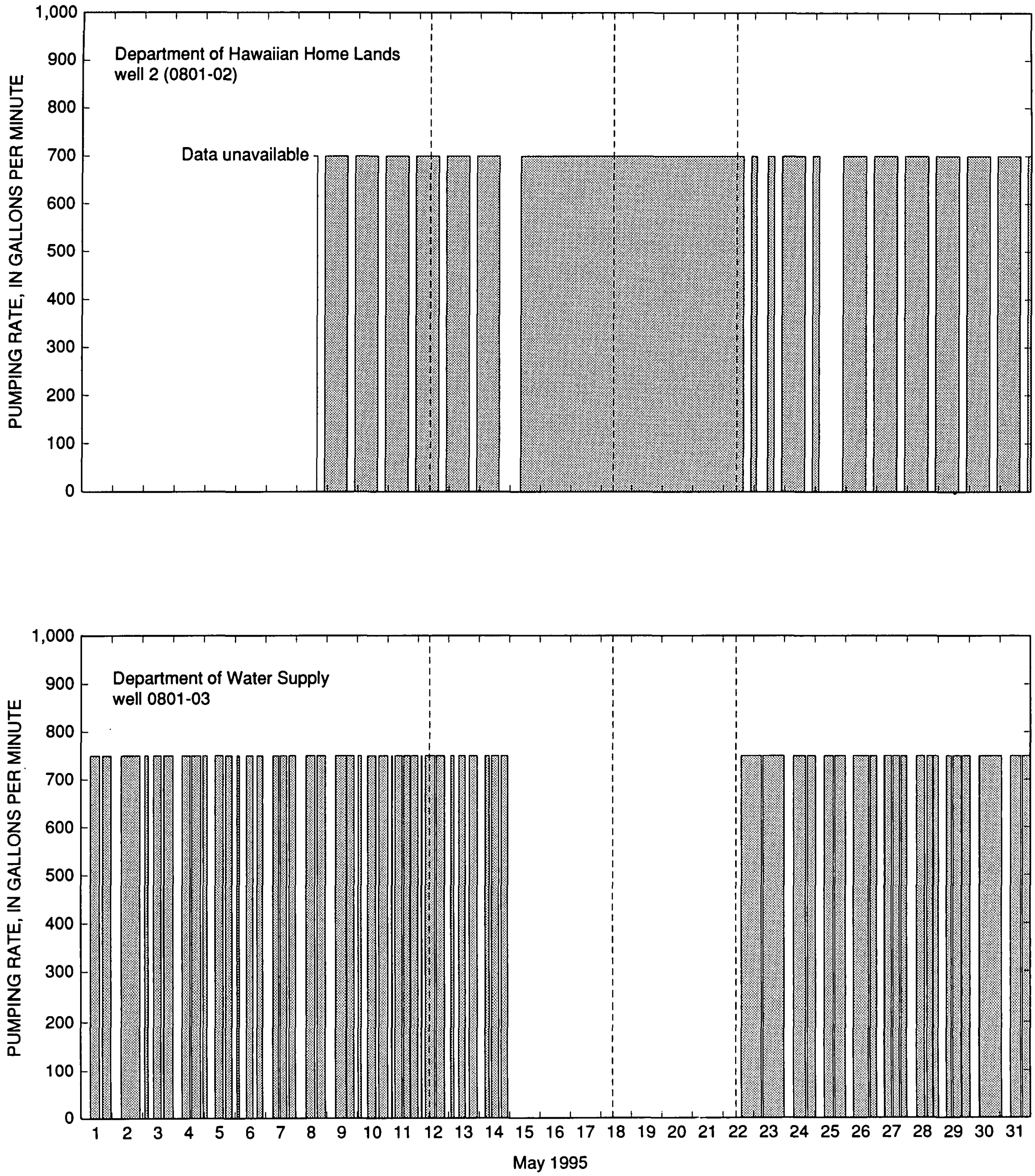


Figure 13. Estimated pumping rates at Department of Hawaiian Home Lands well 2 (0801-02) and Department of Water Supply well 0801-03 during May 1995, Molokai, Hawaii. Vertical dashed lines represent times of water sampling for chloride concentration profiles in Department of Hawaiian Home Lands well 1 (0801-01).

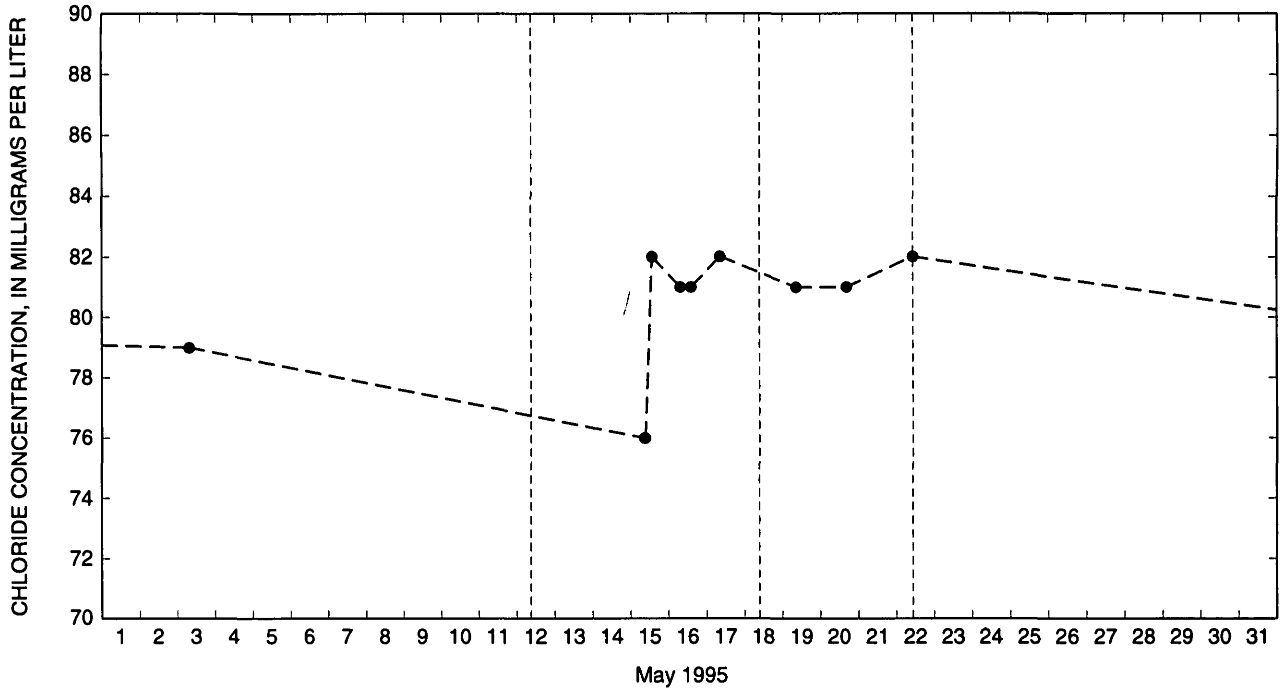


Figure 14. Chloride concentration of water samples from Department of Hawaiian Home Lands well 2 (0801-02) during May 1995, Molokai, Hawaii. Vertical dashed lines represent times of water sampling for chloride concentration profiles in Department of Hawaiian Home Lands well 1 (0801-01).

concentrations ranged from 161 to 183 mg/L. Reported pumpage from DHHL well 2 during October 1994 averaged 0.58 Mgal/d (400 gal/min), and reported pumpage from the DWS well during October 1994 averaged 0.68 Mgal/d (470 gal/min).

Profile of May 12, 1995.--The chloride-concentration profile in DHHL well 1 from May 12, 1995 indicates a chloride concentration of about 111 to 120 mg/L within the part of the borehole with solid casing (fig. 12). Beneath the solid casing, chloride concentrations ranged from 171 to 175 mg/L. Thus, beneath the solid casing, chloride concentrations in the borehole were approximately uniform with depth. At the time the water samples were being collected on May 12, 1995, both DHHL well 2 and the DWS well were being pumped (fig. 13).

Profile of May 18, 1995.--The chloride-concentration profile in DHHL well 1 from May 18, 1995 indicates a chloride concentration of about 113 mg/L from the top of the sampled water column within the solid casing to an altitude of -36 ft (fig. 12). Between altitudes of -61 and -74 ft, the chloride concentration was 168 mg/L.

Profile of May 22, 1995.--The chloride-concentration profile in DHHL well 1 from May 22, 1995 indicates about a 10 mg/L decrease in chloride concentration, relative to the profile obtained on May 18, 1995, from the top of the sampled water column to an altitude of -36 ft (fig. 12). The chloride concentration near the bottom of the borehole, between altitudes of -61 to -74 ft, remained at about 168 mg/L.

From November 3, 1994 to May 12, 1995, the chloride concentration in the part of DHHL well 1 with solid casing increased from about 35 mg/L to 111 to 120 mg/L. The two profiles obtained before May 15, 1995 indicate that the chloride concentration within the part of the DHHL well 1 borehole with solid casing is lower than in the screened part of the borehole. Furthermore, the chloride concentrations beneath the solid casing were almost constant with depth. These data indicate that upward flow within the borehole may cause mixing within the screened part of the borehole. Pumping at the DWS well and DHHL well 2 could cause a reduction in head near the top of the aquifer, which could create a vertical head gradient. This vertical gradient could cause saltier water from near the bottom of the DHHL well 1 borehole to flow upward in the borehole, mix within the borehole, and flow out of the borehole into a permeable zone near the top of the aquifer.

The profile obtained on May 12, 1995 indicates a chloride concentration of 111 to 120 mg/L within the part of DHHL well 1 with solid casing, and a chloride concentration of 171 to 175 mg/L beneath the solid casing. The chloride-concentration profile obtained on May 18, 1995 indicates an approximately uniform chloride concentration of about 113 mg/L within the part of the borehole with solid casing and down to an altitude of -36 ft. Thus, over a period of 3 days (May 15–18, 1995), continuous pumping at DHHL well 2 and no pumping from the DWS well apparently caused a greater amount of fresher water near the top of the aquifer to enter the screened part of the borehole of DHHL well 1. There is no evidence, however, that the chloride concentration of pumped water from DHHL well 2 decreased between May 15 and May 18, 1995. (fig. 14).

On May 22, 1995, the chloride concentrations in DHHL well 1 above an altitude of -36 ft decreased by about 10 mg/L relative to the chloride concentrations from May 18, 1995. Thus, continuous pumping from May 18 to May 22, 1995 at DHHL well 2 (and no pumping from the DWS well) caused a further freshening of the water in the DHHL well 1 borehole above an altitude of -36 ft. At the bottom of the DHHL well 1 borehole, however, the chloride concentration was relatively constant (168 mg/L) from May 18 to May 22, 1995.

The chloride concentration of water in the DHHL well 1 borehole is apparently affected by nearby pumping from DHHL well 2 and the DWS well. The magnitude and duration of pumping, the locations of pumped wells, and the structure of the aquifer are some of the factors that can control the vertical distribution of chloride concentration in a nonpumped, open monitor well.

Salinity profiles from open boreholes are used in Hawaii to estimate the location of the transition zone. However, the estimated location of the transition may be unreliable if significant vertical flow causes mixing of water within the borehole. A flow meter can be used to estimate the rate of vertical flow at different depths in an open borehole. Alternatively, the mixing effects caused by vertical flow can be eliminated by using a series of piezometers, each open at a different depth in the aquifer, rather than a single open borehole.

GROUND-WATER WITHDRAWALS

Most of the ground water withdrawn on Molokai is from the Kualapuu area, the south shore of eastern Molokai, and the dike complex in northeastern Molokai. The reported annual mean pumpage for Molokai during 1996 was 4.336 Mgal/d (computed from data supplied by Neal Fujii, CWRM, written commun., 1997).

Five production wells (0801-01 to -03, 0901-01, and 0902-01) have been drilled in the Kualapuu area for either irrigation or domestic use. Wells 0902-01 and 0901-01 (fig. 4), drilled in 1946 and 1950, respectively, were originally used to irrigate pineapple fields in the Hoolehua Plain area. Well 0902-01 was abandoned in 1964 when surface water from the Molokai Irrigation System (MIS) tunnel (fig. 4) became available. Since 1976, water from well 0901-01 has been used for domestic and irrigation purposes in western Molokai. Prior to the completion of the MIS tunnel, combined withdrawals from wells 0901-01 and 0902-01 varied seasonally from near zero to about 1 Mgal/d (fig. 15). DHHL wells 0801-01 and 0801-02 (fig. 4) were completed in 1949 and 1979, respectively, and DWS well 0801-03 was drilled in 1987. Monthly mean withdrawal rates from each of wells 0801-01 to -03 have remained below 1 Mgal/d (fig. 15). During 1996, annual mean combined withdrawal from the four active wells in the Kualapuu area was 2.029 Mgal/d.

Along the south shore of eastern Molokai, ground-water withdrawals are mainly from two Maui-type wells (consisting of a shaft excavated to or below the water table, and one or more infiltration tunnels extending outward from the shaft); one near Kawela (0457-01) completed in 1921, and the other near Ualapue (0449-01) completed in 1936 (fig. 4). During 1996, annual mean withdrawals from wells 0457-01 and 0449-01 were 0.398 and 0.204 Mgal/d, respectively. Total unreported withdrawals from several other drilled wells and numerous shallow dug wells along the southern coast of Molokai are probably small.

Three production wells (0855-01 to -03) (fig. 4) drilled in 1961 withdraw water from the dike complex in northeastern Molokai. Water from these wells enters the Molokai Irrigation System. Monthly mean combined withdrawal from these three wells averages about

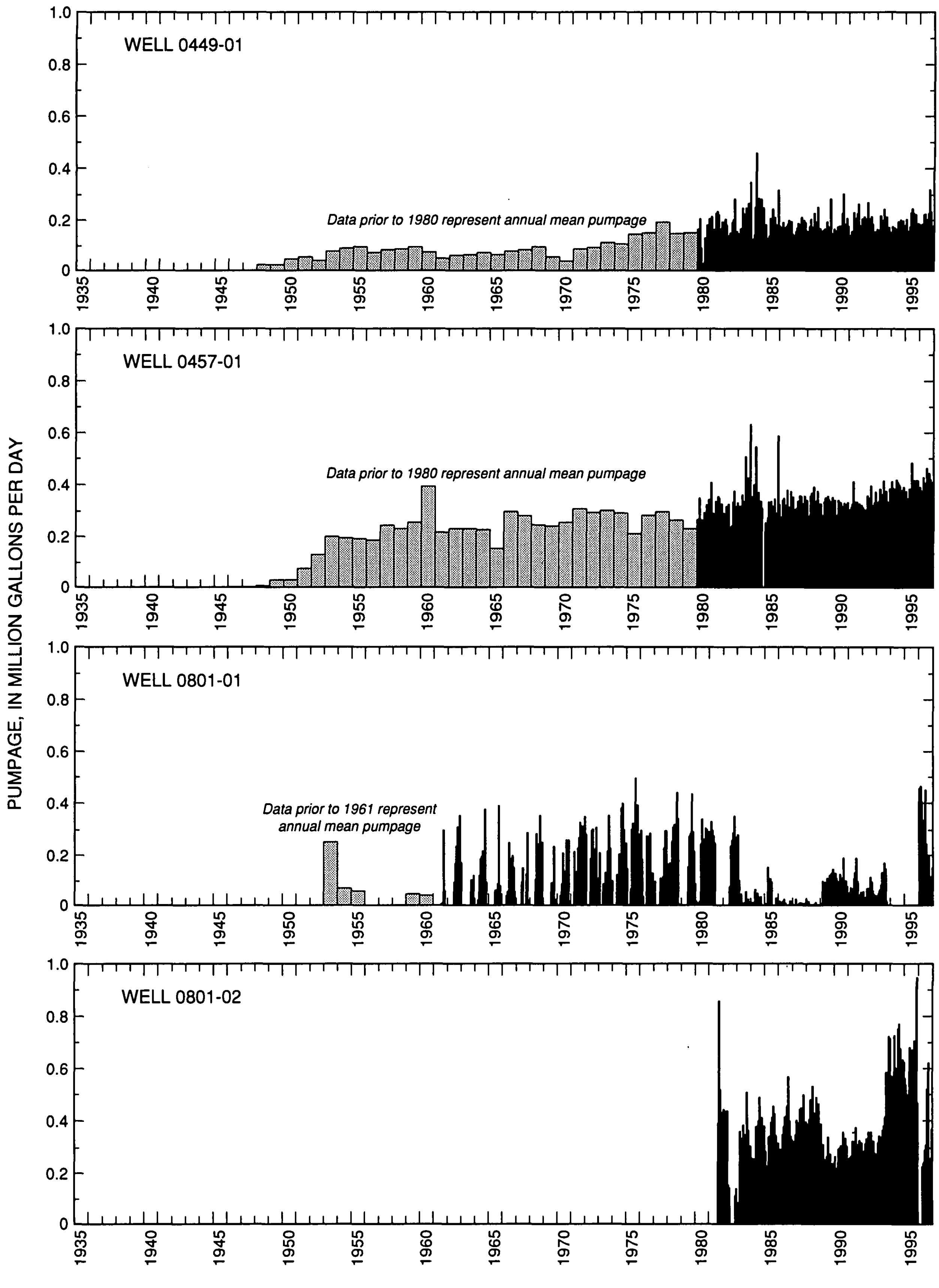


Figure 15. Monthly or annual mean pumpage from selected wells, Molokai, Hawaii.

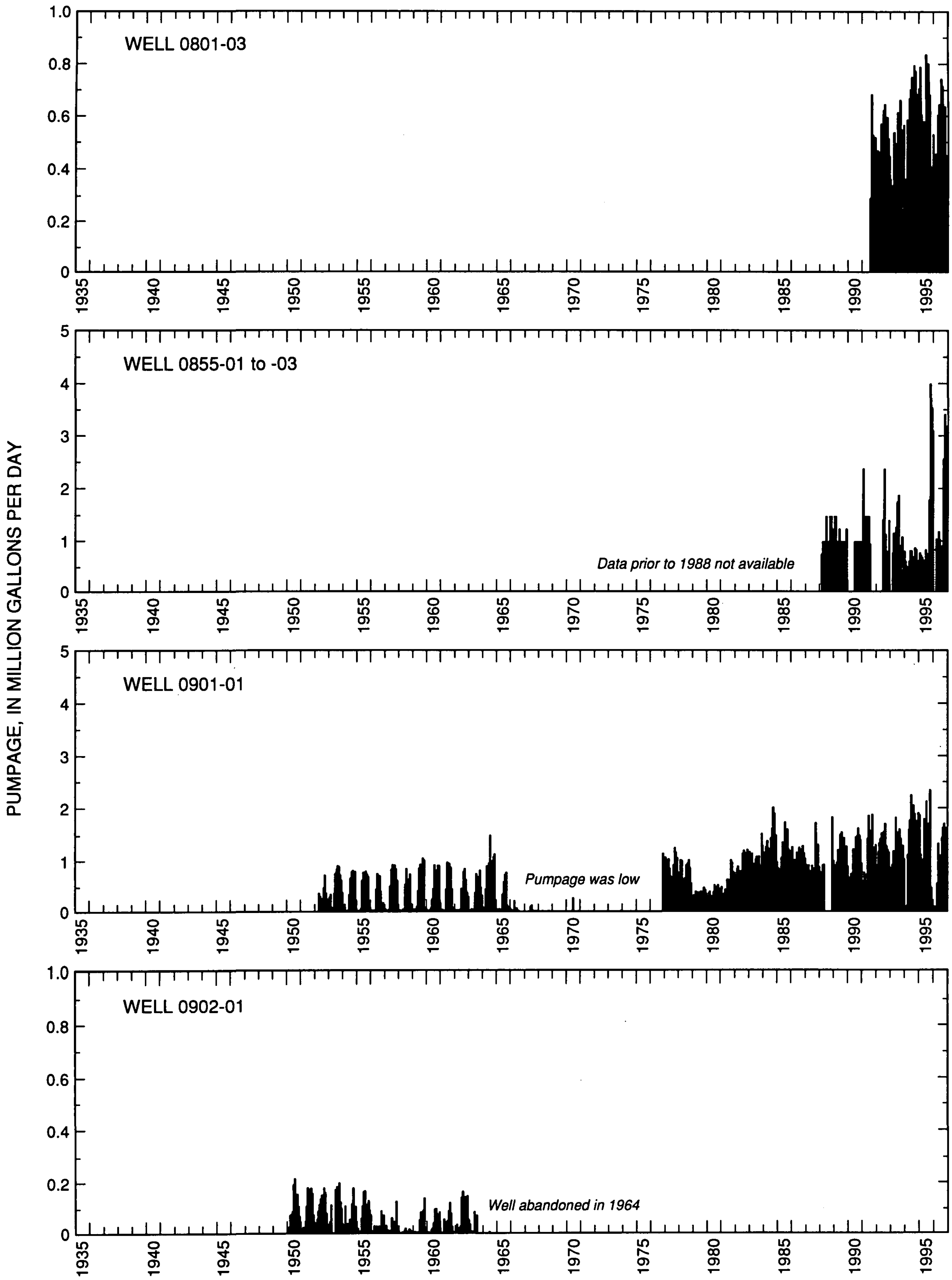


Figure 15. Monthly or annual mean pumpage from selected wells, Molokai, Hawaii--*Continued.*

1 Mgal/d (fig. 15). During 1996, annual mean combined withdrawal was 1.438 Mgal/d.

Because parts of the MIS tunnel are below the water table, ground water discharges directly into the tunnel by gravity. During periods in which wells 0855-01 to -03 were not in use, direct discharge of ground water to the tunnel was estimated from the difference between the discharges at stations 16405300 and 16405100, and averaged 1.822 Mgal/d.

NUMERICAL SIMULATION TO DETERMINE AREAS OF POSSIBLE FUTURE GROUND-WATER DEVELOPMENT

One of the factors to be considered in selecting a site for a deep monitor well in the Kualapuu area is where future ground-water development may occur. A deep monitor well located near an area of possible future ground-water development would provide useful information related to the availability of freshwater in the area. Salinity profiles obtained from a deep monitor well located near an area where production wells are likely to be drilled could establish (1) whether the production wells can be successfully developed, or (2) suitable construction details for the production wells. Furthermore, if the production wells are eventually drilled, a deep monitor well located in the vicinity of the production wells could provide relevant, long-term water-quality information.

A numerical ground-water flow model was previously developed to simulate steady-state regional ground-water flow on Molokai (Oki, 1997). The numerical model was used in this study to estimate water-level declines caused by possible future ground-water development in the Kualapuu area of Molokai.

Model Description

The regional model used the two-dimensional (areal), finite-element code AQUIFEM-SALT (Voss, 1984). This code was designed to simulate flow of confined or unconfined fresh ground water in systems that may have a freshwater body floating on denser underlying saltwater. AQUIFEM-SALT treats freshwater and saltwater as immiscible fluids separated by a sharp interface. The depth of the interface is determined by the Ghyben-Herzberg relation. In reality, a diffuse transition zone exists between the core of freshwater and the underlying saltwater. In this study, it was assumed that the position of the surface of 50-percent seawater salinity is approximated by the sharp-interface position. AQUIFEM-SALT simulates the vertically averaged freshwater head in the aquifer and assumes that flow is entirely horizontal and all wells fully penetrate the freshwater body.

The model mesh, boundary conditions, hydraulic characteristics, and recharge used in this study are the same as those used in the regional model (Oki, 1997). For a complete description of these features and other information regarding the construction details of the model, refer to Oki (1997). A brief summary of the model is provided below.

Model Mesh

The finite-element mesh used in this study consists of 6,432 nodes and 6,251 square elements, 1,640 ft on a side, arranged in a rectangular array with 47 rows and 133 columns. The mesh covers the entire island of Molokai and extends at least a mile offshore to include the entire zone where fresh ground water discharges to the ocean.

Boundary Conditions

AQUIFEM-SALT supports three types of boundary conditions: (1) specified head, (2) specified flow (which includes no flow), and (3) head-dependent discharge. Specified-head boundary conditions were not used for this study. The perimeter of the mesh is a no-flow boundary. The aquifer bottom was treated as a no-flow boundary at an altitude of 6,000 ft below sea level.

All elements representing offshore areas and subaerial springs near the coast and in northeastern Molokai valleys were modeled using a head-dependent discharge boundary condition. All elements not simulated as a head-dependent discharge boundary were unconfined, water-table elements. Head-dependent discharge elements associated with streams in northeastern Molokai valleys were simulated as confined elements if the model-calculated head was above the base of the stream, and as water-table elements otherwise. The base of the stream within an element was estimated from the average stream-channel altitude (U.S. Geological Survey, 1952) within that element.

Flow out of the model at head-dependent discharge elements was assumed to be linearly related to the difference between the head in the aquifer and the head overlying the confining unit at the discharge site according to the equation:

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

where:

Q is the rate of discharge within a model element $[L^3/T]$,

K' is the vertical hydraulic conductivity of the confining unit overlying the aquifer [L/T],

B' is the thickness of the confining unit overlying the aquifer [L],

A is the area of the model element $[L^2]$,

h is the head in the aquifer [L], and

h_0 is the head above the confining unit [L].

Six discharge zones were defined (fig. 16): (1) southeastern Molokai coast (K'= 0.5 ft/d), (2) southwestern Molokai coast (K'= 5 ft/d), (3) northern Molokai coast exclusive of Kalaupapa Peninsula (K'/B'= 0.1 per day), (4) Kalaupapa Peninsula (K'/B'= 0.1 per day), (5) northeastern Molokai streams in the dike complex within the caldera area ($K'/B' = 6.1 \times 10^{-5}$ per day), and (6) northeastern Molokai streams in the dike complex outside the caldera area ($K'/B' = 1.2 \times 10^{-3}$ per day). The confining-unit vertical hydraulic conductivity (K') divided by the confining-unit thickness (B') forms a lumped parameter known as the leakance. No attempt was made to estimate separate values for confining-unit thickness and vertical hydraulic conductivity for the northern Molokai coast (including Kalaupapa Peninsula) and the northeastern Molokai streams.

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

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

where Z is the altitude of the ocean floor.

For elements representing the springs in northeastern Molokai valleys, h_0 was assigned a value corresponding to the average altitude (U.S. Geological Survey, 1952) of the stream channel within the model element.

Hydraulic-Conductivity Zones

The island of Molokai was divided into seven zones (fig. 17) with separate horizontal hydraulic-conductivity values: (1) 1,000 ft/d for the dike-free West Molokai Volcanics, (2) 1,000 ft/d for the dike-free East Molokai Volcanics, (3) 500 ft/d for the Kalaupapa Volcanics, (4) 1 ft/d for the West Molokai Volcanics confining unit, (5) 2 ft/d for the West Molokai Volcanics dike complex, (6) 0.02 ft/d for the East Molokai Volcanics dike complex, and (7) 100 ft/d for the East Molokai Volcanics marginal dike zone. The West Molokai confining-unit zone represents the zone formed by weathered volcanic rocks and soil between West and East Molokai Volcanics. Although the confining unit dips at an angle of only 10° it extends throughout the freshwater thickness and impedes ground-water flow between the West and East Molokai Volcanics. In this study, the West Molokai confining unit was represented in the two-dimensional model as a zone of reduced hydraulic conductivity. The West and East Molokai dike-complex zones were modeled as zones of lower overall hydraulic conductivity relative to the dike-free volcanic-aquifer zones. A model zone was created for the assumed East Molokai marginal dike zone, where numerous volcanic-vent features exist. The hydraulic conductivity of the East Molokai marginal dike zone was presumed to be between the values for the dike-free volcanic rocks and the East Molokai dike complex.

Recharge

Ground-water recharge to the model was distributed over the modeled area according to the mean annual recharge rates estimated by Shade (1997). The areal distribution of recharge used in the model is shown in figure 18. Total island-wide recharge estimated by Shade (1997) was 188.6 Mgal/d. Total recharge used in the model was 187.3 Mgal/d because discretization at the coastline resulted in land area that receives 1.3 Mgal/d recharge being assigned to offshore elements. This loss in recharge is less than 1 percent of the total value, and is well within the range of uncertainty associated with the recharge estimates.

Model Results

The numerical model was used to estimate ground-water levels that result from pumping at rates equal to

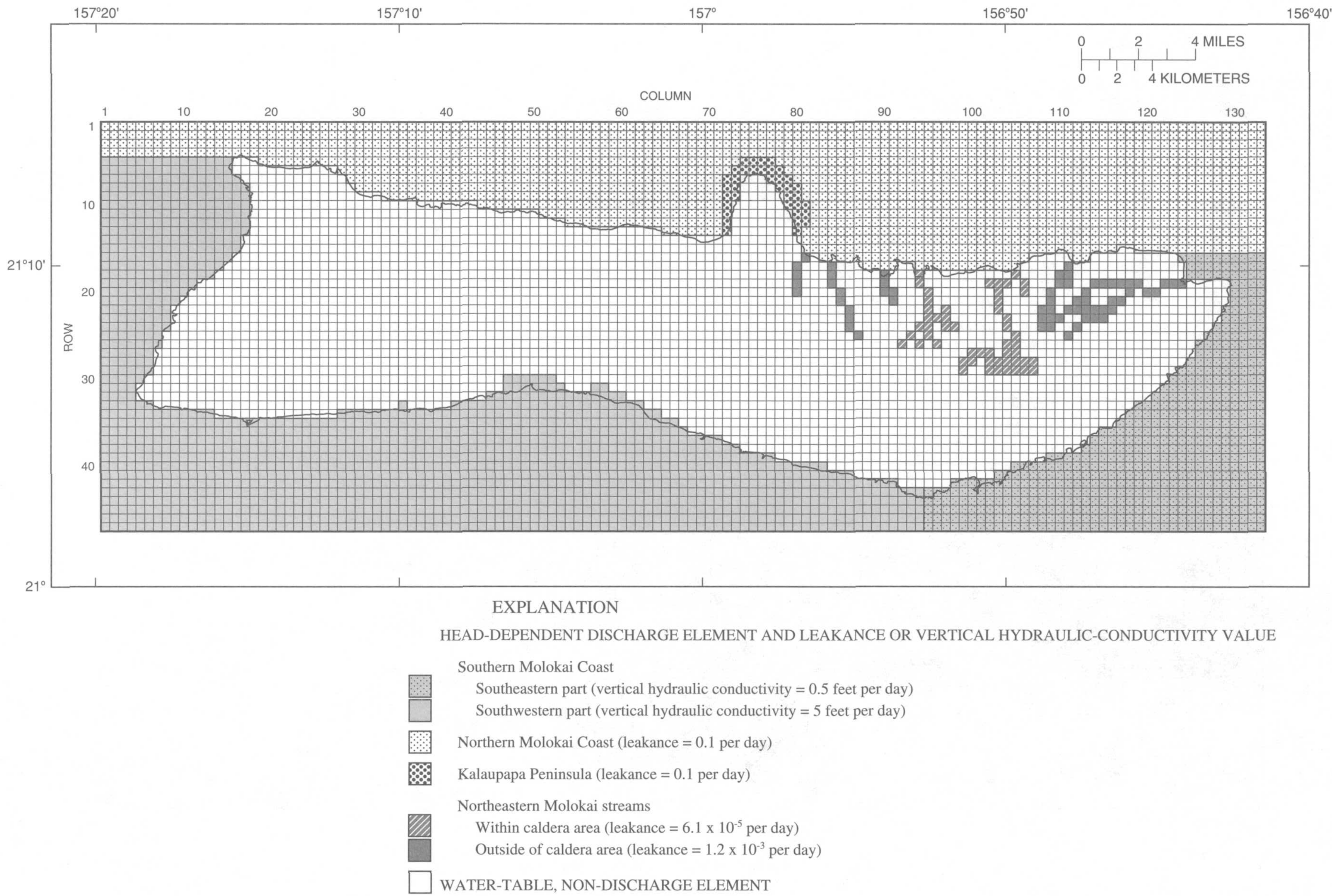
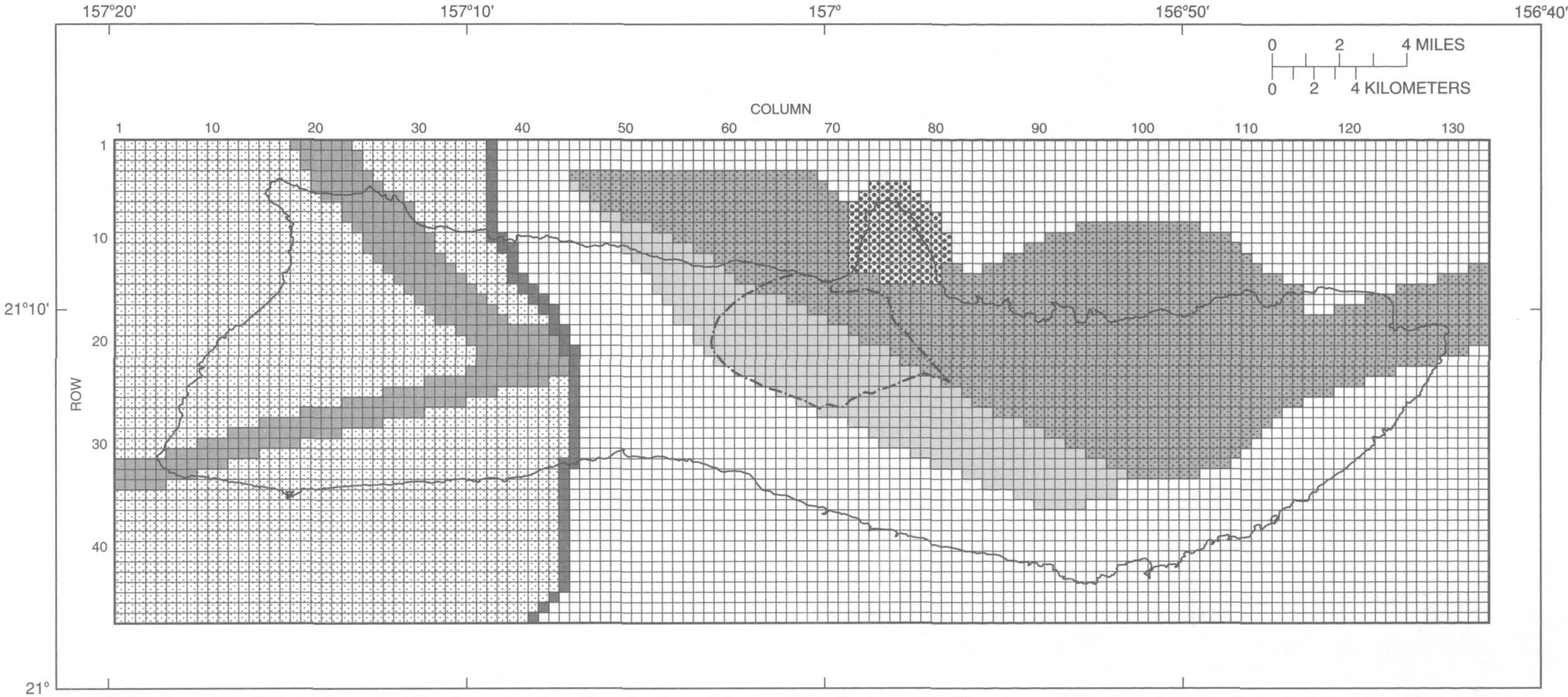


Figure 16. Ground-water discharge zones used in the ground-water flow model, Molokai, Hawaii.



NOTE: In the model grid, hydraulic-conductivity values are assigned to nodes. If a node is associated with elements in different zones in the figure, the hydraulic conductivity assigned to that node is the lowest among the values for these zones.

EXPLANATION

HYDRAULIC-CONDUCTIVITY ZONE AND HYDRAULIC-CONDUCTIVITY VALUE ASSIGNED IN THE GROUND-WATER FLOW MODEL

West Molokai Volcanics

- Dike free (1,000 feet per day)
- Dike complex (2 feet per day)
- Confining unit (1 foot per day)

East Molokai Volcanics

- Dike free (1,000 feet per day)
- Dike complex (0.02 feet per day)
- Marginal dike zone (100 feet per day)
- Kalaupapa Volcanics (500 feet per day)

BOUNDARY OF KUALAPUU STUDY AREA

Figure 17. Horizontal hydraulic-conductivity zones used in the ground-water flow model, Molokai, Hawaii.

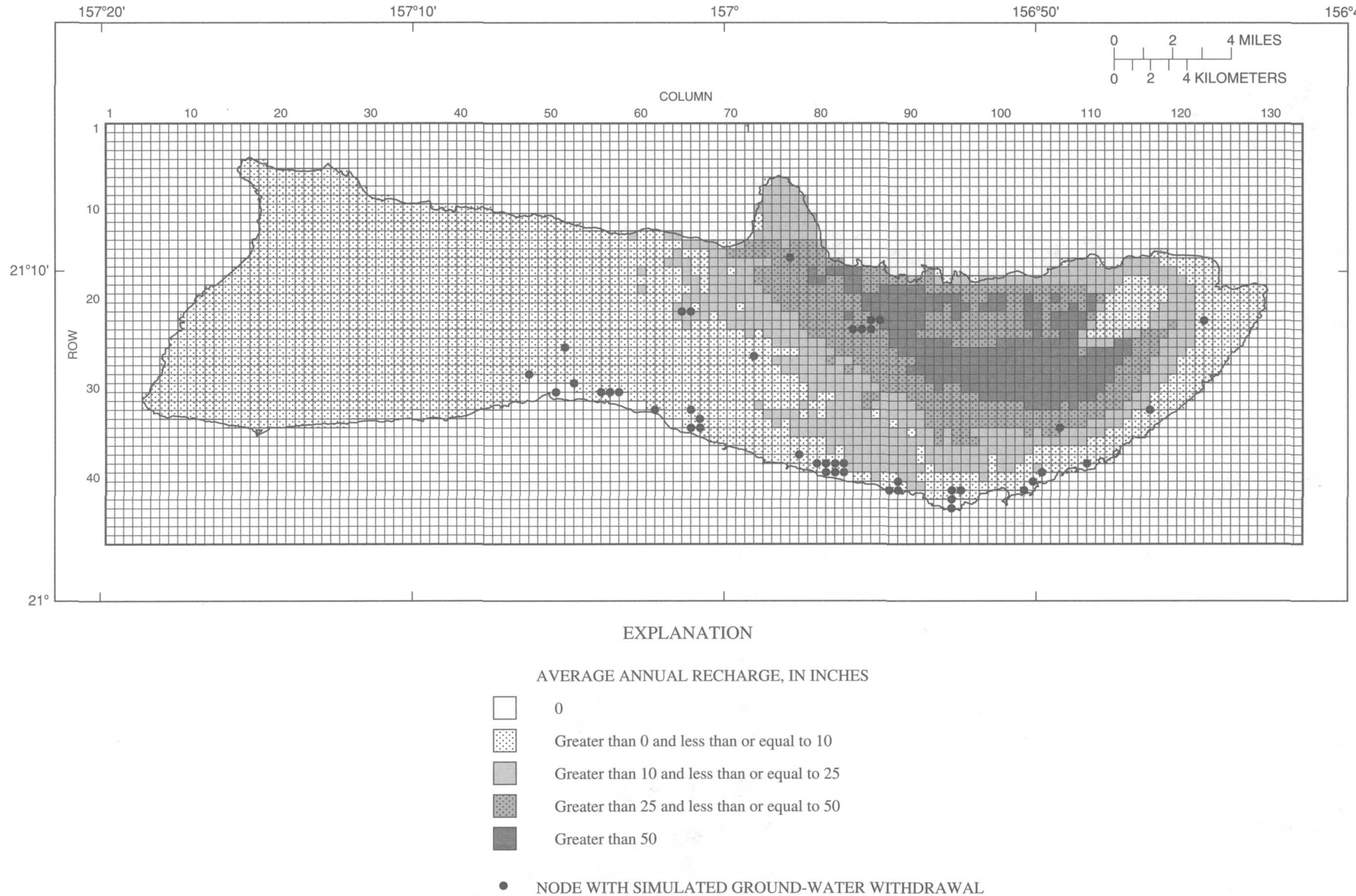


Figure 18. Average annual recharge used in the ground-water flow model and nodes with simulated 1999-allocated ground-water withdrawal, Molokai, Hawaii.

and in excess of the March 1999 allocated rates from existing and hypothetical wells in the Kualapuu area. Withdrawal rates of 0.5 and 1.0 Mgal/d in excess of the March 1999 total allocation rate were simulated at selected individual sites in the Kualapuu area, outside of the modeled dike complex. The simulations are consistent with the original assumptions upon which the numerical model was based, and the additional simulated withdrawals did not stress the modeled system beyond the original design limits of the model.

Withdrawal at the March 1999 Allocation Rate

The ground-water flow model was used to estimate the distribution of water levels in the Kualapuu area, outside of the modeled dike complex, for withdrawal rates corresponding to the March 1999 allocated rates. As of March 1999, CWRM had issued water-use permits authorizing a total of 6.6432 Mgal/d of ground-water withdrawals from wells and tunnels on Molokai (table 1), and these withdrawals were represented in the model. For the Kualapuu area, allocated withdrawals totaling 1.79 Mgal/d were represented in the model. The State of Hawaii Department of Hawaiian Home Lands reservation for 2.905 Mgal/d of ground water from the Kualapuu area was not represented in the model.

For withdrawal rates corresponding to the March 1999 allocated rates, model results indicate that the steady-state water level is about 8.64 ft above sea level near existing wells 0801-01 to 03 and about 7.59 ft above sea level near well 0901-01. Because the thicknesses of the freshwater body and the freshwater-saltwater transition zone are not known, it is uncertain whether a water level of 7.59 ft above sea level is sufficient to protect all existing wells. A deep monitor well in the Kualapuu area would help to address this issue.

Withdrawal of 0.5 Mgal/d from a Single Site

The ground-water flow model was used to simulate steady-state water levels that result from pumping from a single site in the Kualapuu area at a rate of 0.5 Mgal/d above the March 1999 total allocation rate. The 0.5 Mgal/d withdrawal was simulated at a total of 56 different sites in the Kualapuu area, outside of the modeled dike complex. Withdrawals in the dike complex were not simulated because there are no current plans to withdraw ground water from higher altitudes in the Kualapuu area, where costs associated with pumping and transmission would be high. For each of the 56 different scenarios (corresponding to the 56 different withdrawal sites), the hydrologic effects of the additional 0.5 Mgal/d withdrawal were quantified by considering model-calculated water levels at (1) well 0901-01, (2) wells 0801-01 to -03, and (3) the site of the additional 0.5 Mgal/d withdrawal.

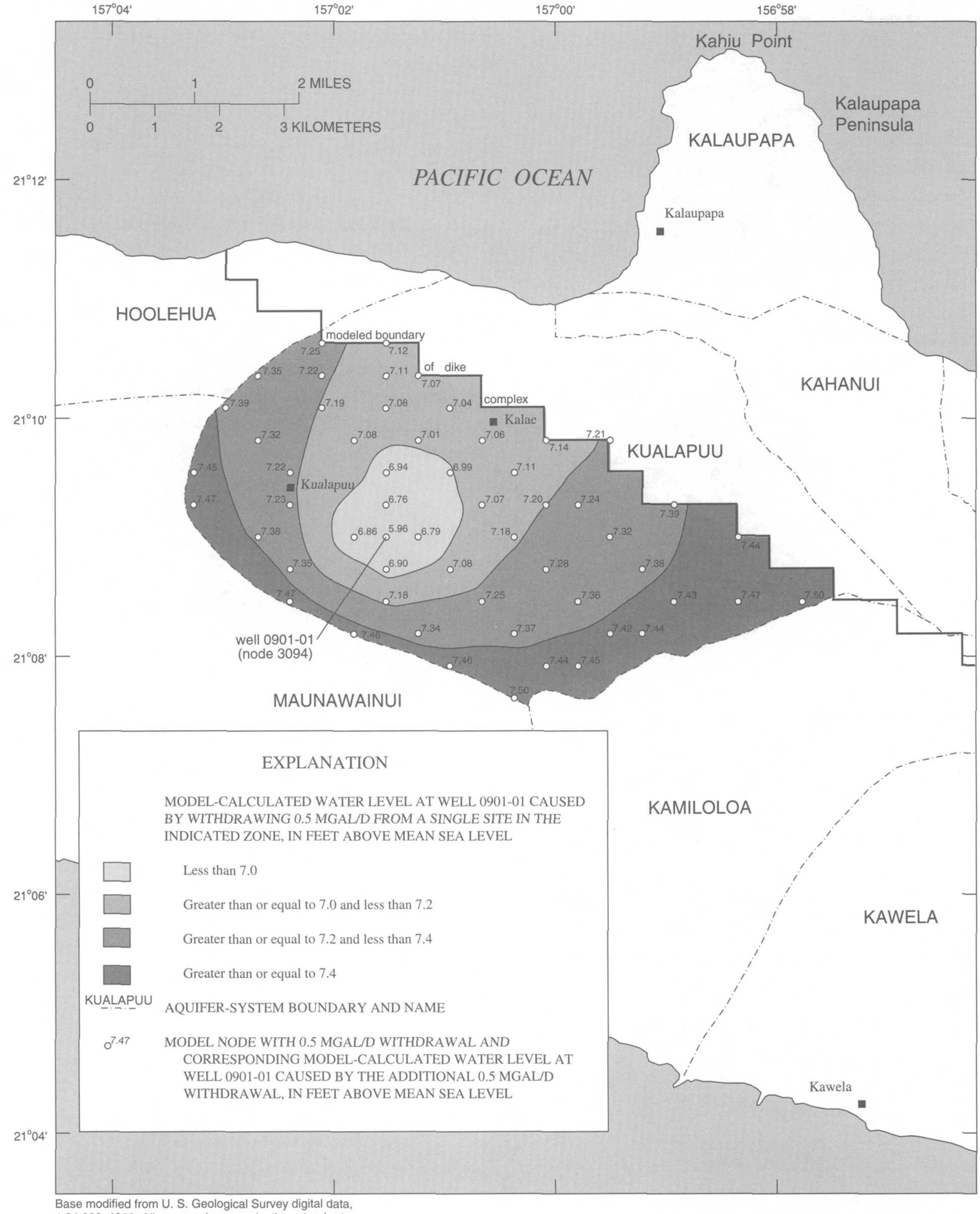
The model-calculated water level at existing well 0901-01 is lowest for cases in which the additional 0.5 Mgal/d withdrawal is placed at or near well 0901-01, and highest for cases in which the additional 0.5 Mgal/d withdrawal is placed near the southwestern and southeastern boundaries of the Kualapuu area (fig. 19). The model-calculated water level at well 0901-01 is 5.96 ft above sea level for the case of pumping an additional 0.5 Mgal/d from well 0901-01. Pumping the additional 0.5 Mgal/d from near the southern extent of the Kualapuu area results in a model-calculated water level at well 0901-01 of 7.50 ft above sea level.

Similarly, the model-calculated water level at wells 0801-01 to -03 is lowest for cases in which the additional 0.5 Mgal/d withdrawal is placed at or near existing wells 0801-01 to -03, and greatest for cases in which the additional 0.5 Mgal/d withdrawal is placed near the southwestern and southeastern boundaries of the Kualapuu area (fig. 20). The model-calculated water level at wells 0801-01 to -03 is 7.17 ft above sea level for the case of pumping an additional 0.5 Mgal/d from wells 0801-01 to -03. Pumping the additional 0.5 Mgal/d from near the southwestern boundary of the Kualapuu area results in a model-calculated water level at wells 0801-01 to -03 of 8.55 ft above sea level.

The model-calculated water level at the site of the additional 0.5 Mgal/d withdrawal is less than 5 ft above sea level for sites in the southwestern part of the Kualapuu area, and greater than 10 ft above sea level for sites in the central and southeastern parts of the Kualapuu area (fig. 21).

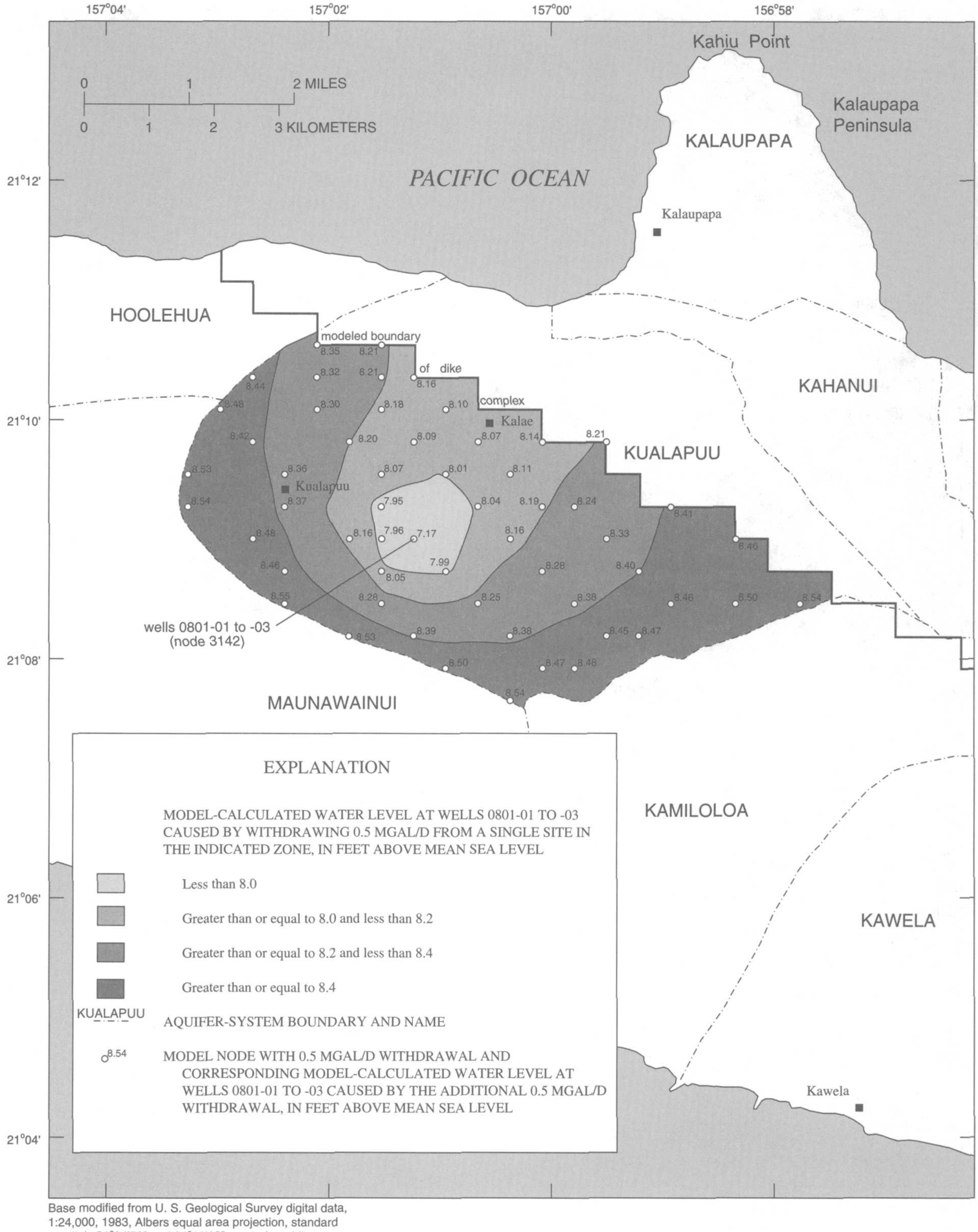
Withdrawal of 1.0 Mgal/d from a Single Site

The ground-water flow model was also used to simulate steady-state water levels that result from pumping from a single site in the Kualapuu area at a rate of 1.0 Mgal/d above the March 1999 total allocation rate. The 1.0 Mgal/d withdrawal was simulated at a total of 54 different sites in the Kualapuu area, outside of the modeled dike complex. For each of the 54 different scenarios (corresponding to the 54 different withdrawal sites), the hydrologic effects of the additional 1.0 Mgal/d withdrawal were quantified by considering



Base modified from U. S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 21°04'50" and 21°12'10", central meridian 157°00'45"

Figure 19. Model-calculated steady-state water levels at well 0901-01 (model node 3094) caused by withdrawing 0.5 million gallons per day, above the March 1999 total allocated withdrawal rate, from the Kualapuu area (outside of modeled dike complex), Molokai, Hawaii. The model-calculated water levels at well 0901-01 are shown adjacent to the selected sites where the additional 0.5 million gallons per day withdrawal was simulated. In all simulations, the 0.5 million gallons per day additional withdrawal was assumed to be from a single site.



Base modified from U. S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 21°04'50" and 21°12'10", central meridian 157°00'45"

Figure 20. Model-calculated steady-state water levels at wells 0801-01 to -03 (model node 3142) caused by withdrawing 0.5 million gallons per day, above the March 1999 total allocated withdrawal rate, from the Kualapuu area (outside of modeled dike complex), Molokai, Hawaii. The model-calculated water levels at wells 0801-01 to -03 are shown adjacent to the selected sites where the additional 0.5 million gallons per day withdrawal was simulated. In all simulations, the 0.5 million gallons per day additional withdrawal was assumed to be from a single site.

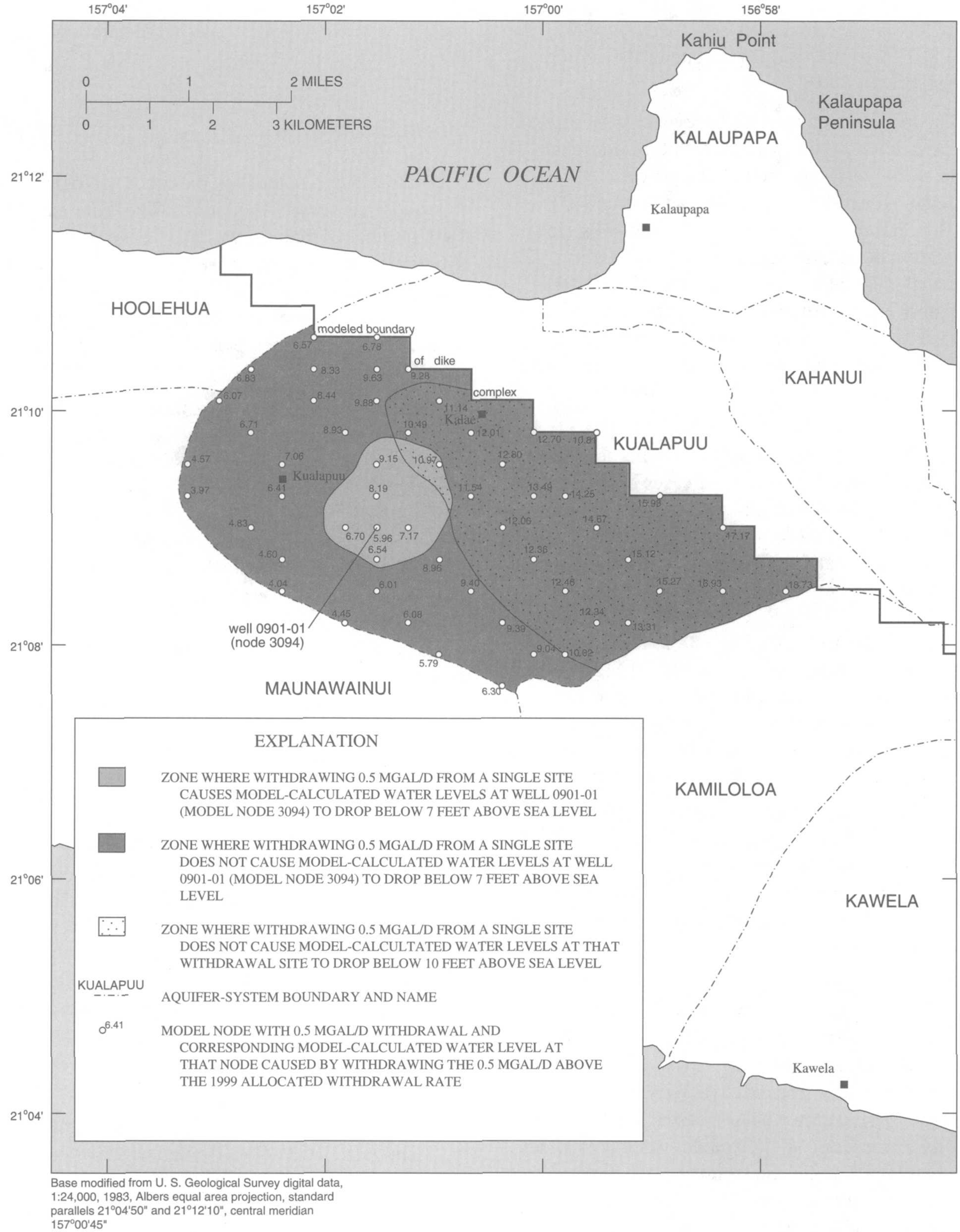


Figure 21. Model-calculated zone where withdrawing 0.5 million gallons per day from a single site does not cause the steady-state water level at the withdrawal site to drop below 10 feet above sea level, and model calculated zone where withdrawing 0.5 million gallons per day from a single site does not cause the water level at well 0901-01 (model node 3094) to drop below 7 feet above sea level, Kualapuu area (outside of modeled dike complex), Molokai, Hawaii.

model-calculated water levels at (1) well 0901-01, (2) wells 0801-01 to -03, and (3) the site of the additional 1.0 Mgal/d withdrawal.

The model-calculated water level at existing well 0901-01 is lowest for cases in which the additional 1.0 Mgal/d withdrawal is placed at or near well 0901-01, and greatest for cases in which the additional 1.0 Mgal/d withdrawal is placed near the southwestern and southeastern boundaries of the Kualapuu area (fig. 22). The model-calculated water level at well 0901-01 is 3.83 ft above sea level for the case of pumping an additional 1.0 Mgal/d from well 0901-01. Pumping the additional 1.0 Mgal/d from near the southern extent of the Kualapuu area results in a model-calculated water level at well 0901-01 of 7.41 ft above sea level.

Similarly, the model-calculated water level at wells 0801-01 to -03 is lowest for cases in which the additional 1.0 Mgal/d withdrawal is placed at or near existing wells 0801-01 to -03, and greatest for cases in which the additional 1.0 Mgal/d withdrawal is placed near the southwestern and southeastern boundaries of the Kualapuu area (fig. 23). The model-calculated water level at wells 0801-01 to -03 is 5.38 ft above sea level for the case of pumping an additional 1.0 Mgal/d from wells 0801-01 to -03. Pumping the additional 1.0 Mgal/d from near the southwestern boundary of the Kualapuu area results in a model-calculated water level at wells 0801-01 to -03 of 8.46 ft above sea level.

The model-calculated water level at the site of the additional 1.0 Mgal/d withdrawal is less than 5 ft above sea level for sites in the western and southwestern parts of the Kualapuu area, and greater than 10 ft above sea level for sites in the central and southeastern parts of the Kualapuu area (fig. 24).

Model results indicate that the southeastern part of the Kualapuu area is a possible area of future ground-water development because (1) withdrawals from this area have a small effect on water levels at existing wells in the Kualapuu area (relative to effects from withdrawals in other parts of the Kualapuu area that are outside of the dike complex), and (2) model-calculated water levels in this part of the Kualapuu area are high relative to water levels in other parts of the Kualapuu area that are outside of the dike complex. Although it may be possible to successfully withdraw additional ground water from other parts of the Kualapuu area, model results indicate that the effects on existing wells will be greater, water levels at the site of the additional pumping will be lower, or both.

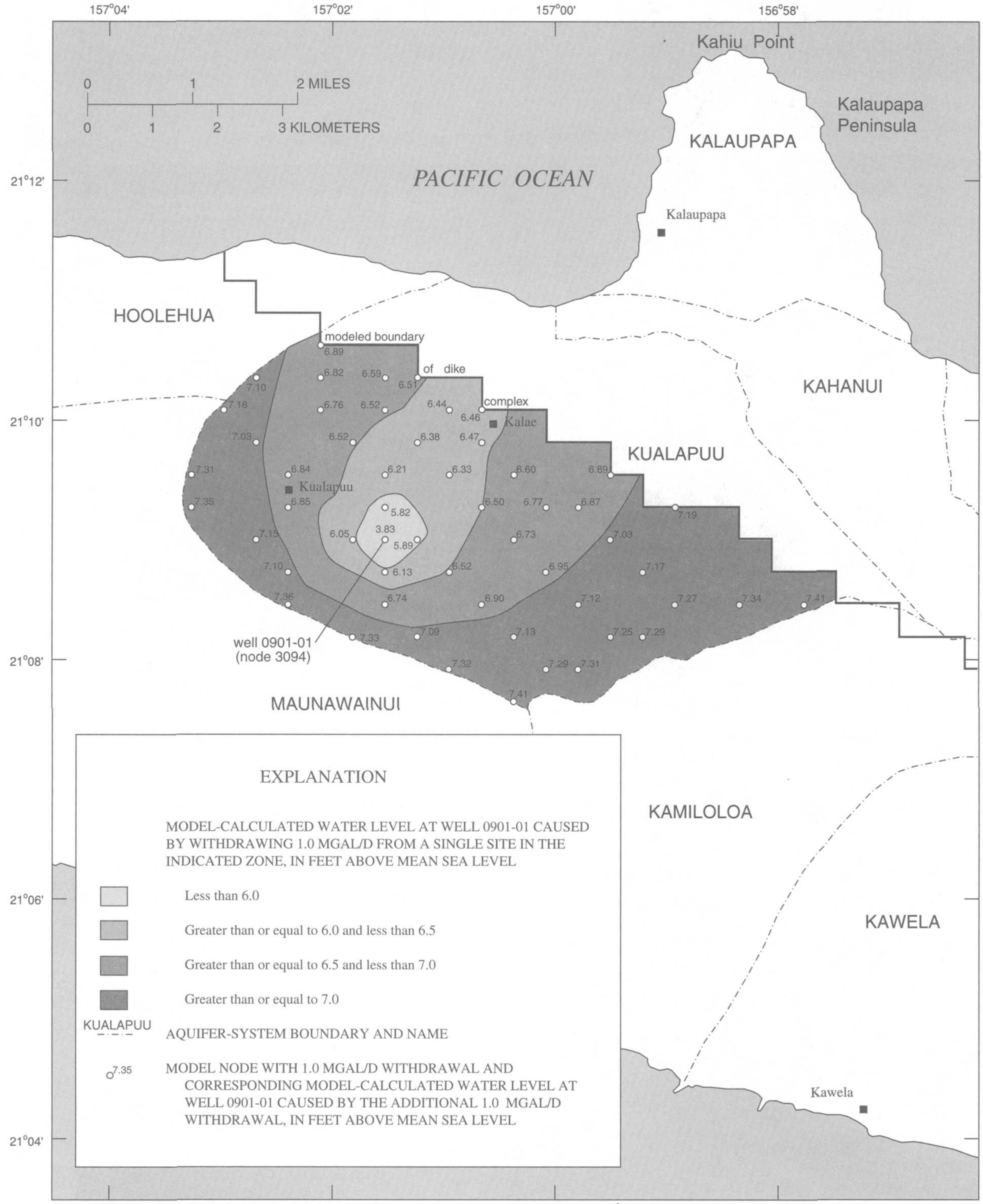
Model Limitations

The ground-water flow model of Molokai used in this study has several limitations. There are an insufficient number of monitor wells to define the spatial distribution of water levels in western Molokai, the inland parts of southeastern Molokai, and the dike complex of northeastern Molokai. Furthermore, the distribution of model-calculated water levels in the Kualapuu area is unverified in places.

Because of the lack of sufficient water-level data, the model developed for this study is not unique. That is, it is possible that different distributions of hydraulic conductivity and leakance can be used in a model to produce equally acceptable model-calculated water levels. A model zone was created to represent the marginal dike zone of East Molokai Volcano, and two coastal discharge zones were created for southern Molokai. Although this zonation is plausible, it is probable that other zonation geometries could produce similar results. The model developed for this study can be refined and a better representation of the flow system can be obtained as more data become available to constrain the model.

Because the ground-water flow model contains only a single layer, vertical hydraulic gradients cannot be simulated and model-calculated drawdown caused by additional withdrawals underestimates actual drawdown near partially penetrating wells. In addition, the model should not be viewed as a quantitatively precise predictive tool because of the uncertainty in the hydraulic-conductivity distribution of the model. The model is, nevertheless, the best available tool for analyzing the possible regional hydrologic effects of additional withdrawals on Molokai for steady-state conditions. The transient hydrologic effects of additional withdrawals were not modeled in this study.

The AQUIFEM-SALT code, which assumes a sharp interface between freshwater and saltwater, was used to simulate the regional flow system on Molokai. No deep monitor wells exist on Molokai which can provide information on the thickness of the transition zone between freshwater and underlying saltwater. A deep monitor well would provide information that is necessary to evaluate (1) the extent to which the sharp-



Base modified from U. S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 21°04'50" and 21°12'10", central meridian 157°00'45"

Figure 22. Model-calculated steady-state water levels at well 0901-01 (model node 3094) caused by withdrawing 1.0 million gallons per day, above the March 1999 total allocated withdrawal rate, from the Kualapuu area (outside of modeled dike complex), Molokai, Hawaii. The model-calculated water levels at well 0901-01 are shown adjacent to the selected sites where the additional 1.0 million gallons per day withdrawal was simulated. In all simulations, the 1.0 million gallons per day additional withdrawal was assumed to be from a single site.

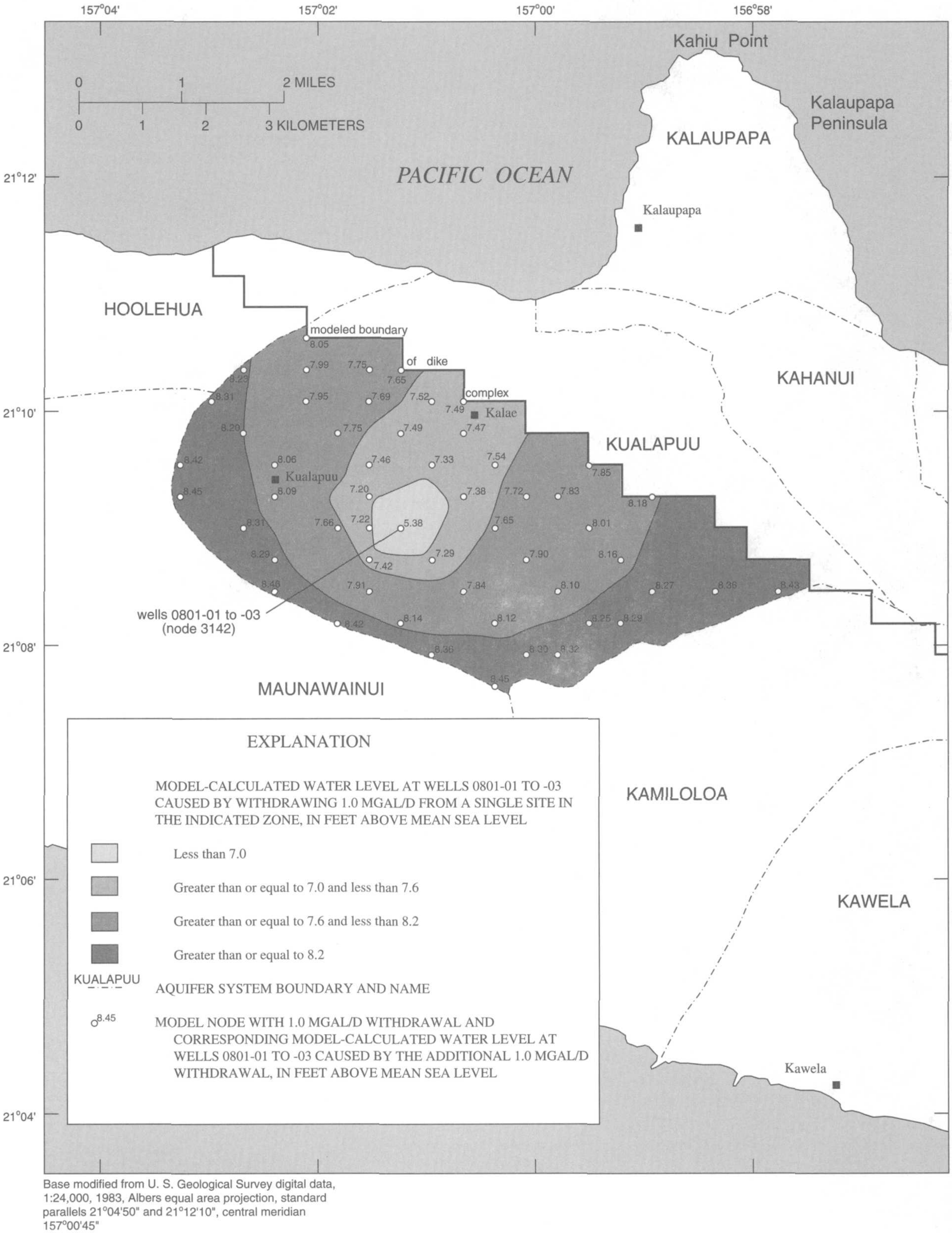


Figure 23. Model-calculated steady-state water levels at wells 0801-01 to -03 (model node 3142) caused by withdrawing 1.0 million gallons per day, above the March 1999 total allocated withdrawal rate, from the Kualapuu area (outside of modeled dike complex), Molokai, Hawaii. The model-calculated water levels at wells 0801-01 to -03 are shown adjacent to the selected sites where the additional 1.0 million gallons per day withdrawal was simulated. In all simulations, the 1.0 million gallons per day additional withdrawal was assumed to be from a single site.

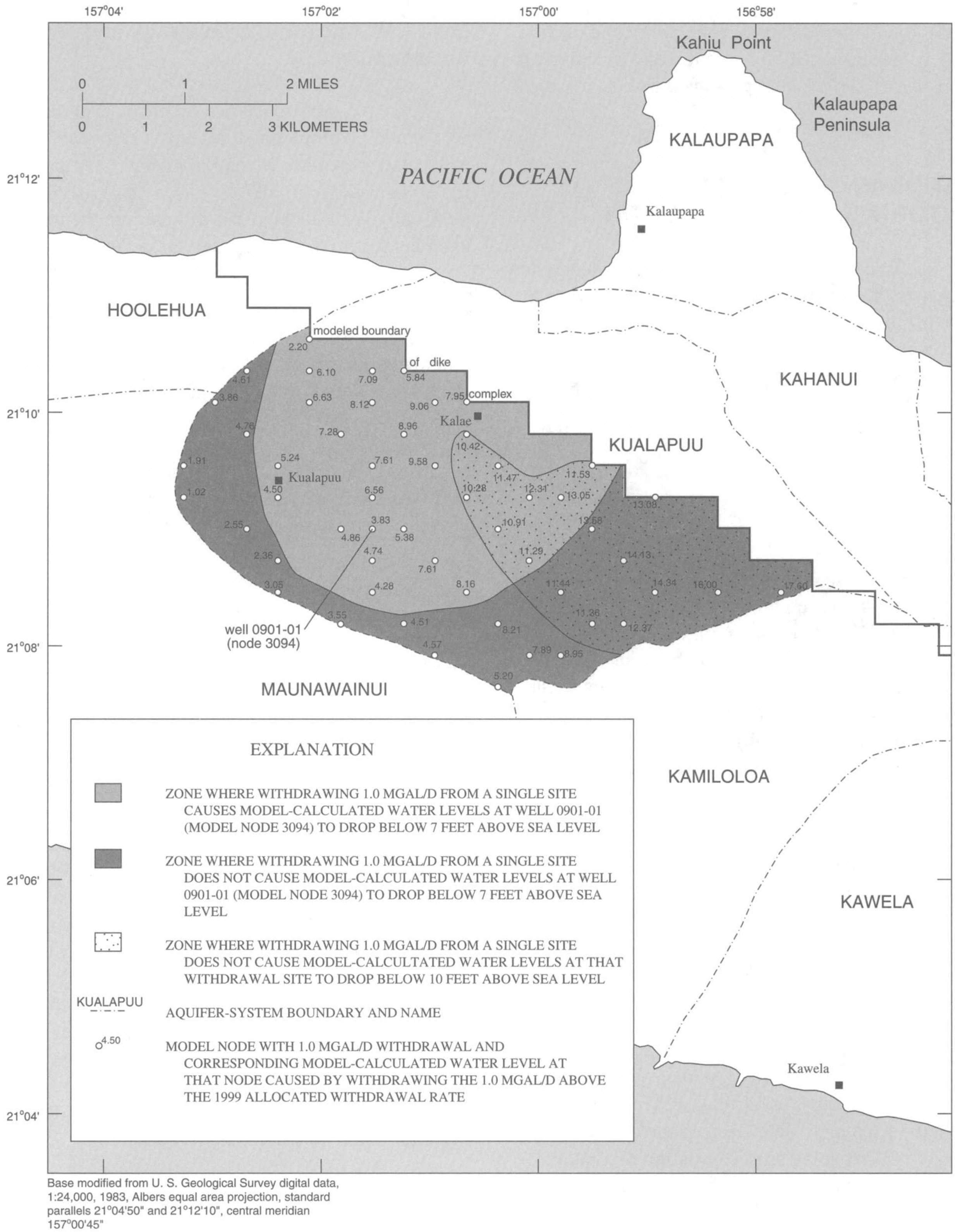


Figure 24. Model-calculated zone where withdrawing 1.0 million gallons per day from a single site does not cause the steady-state water level at the withdrawal site to drop below 10 feet above sea level, and model calculated zone where withdrawing 1.0 million gallons per day from a single site does not cause the water level at well 0901-01 (model node 3094) to drop below 7 feet above sea level, Kualapuu area (outside of modeled dike complex), Molokai, Hawaii.

interface assumption deviates from reality and (2) how accurately the surface of 50-percent seawater salinity in the transition zone can be represented by a sharp interface.

ADDITIONAL CRITERIA FOR DEEP MONITOR WELL SITE SELECTION

In addition to possible sites of future ground-water development, factors to be considered in selecting a site for a deep monitor well in the Kualapuu area include (1) ground-water level, (2) ground-surface altitude, (3) land classification, ownership, and accessibility, (4) geology, (5) locations of existing production wells, and (6) historical ground-water quality information. Each of these additional factors is discussed below.

Ground-Water Level

Measured water levels in existing production wells in the Kualapuu area are between about 8 and 12 ft above sea level. Thus, a deep monitor well drilled in an area with water levels of 8 to 12 ft above sea level may provide hydrologic information that is relevant to the existing production wells. The depth to saline water has been estimated from a geophysical survey (State of Hawaii, 1997) and is a function of the water-level altitude.

Ground-Surface Altitude

Drilling at ground-surface altitudes significantly greater than 1,000 ft will result in increased costs and the well may be located in the dike complex or conservation district (fig. 5), which presents additional problems (see following sections). Existing water-level information indicates that wells drilled at ground-surface altitudes significantly less than 1,000 ft will likely have lower water levels than existing production wells in the Kualapuu area. Ground-surface altitudes are about 1,000 ft at the sites of existing production wells in the Kualapuu area. Because model-calculated water-level contours (Oki, 1997) generally are aligned with the topographic contours, a deep monitor well drilled at an altitude of about 1,000 to 1,100 ft in the Kualapuu area may provide hydrologic information that is relevant to the existing production wells.

Land Classification, Ownership, and Accessibility

A deep monitor well drilled in a conservation district would be problematic because (1) the well would be located at an altitude significantly greater than 1,000 ft, (2) the well would likely be located in the dike complex, and (3) it may be difficult to secure the necessary legal permits to drill on conservation land.

Land ownership is an additional consideration. Access to a deep monitor well located on privately owned property may be lost if the property is sold or the landowner no longer desires the well on the property. Locating a well on government-owned land, particularly DHHL or DWS land, would probably minimize the possibility of losing access to the well in the future because (1) land ownership is less likely to change, and (2) both DHHL and DWS have expressed an interest in drilling a deep monitor well in the Kualapuu area.

From a logistical standpoint, accessibility to the proposed drilling site is a factor to consider. Locating a deep monitor well near an existing road would reduce the costs associated with drilling the well and future monitoring of water levels and the vertical distribution of salinity in the well.

Geology

Existing production wells in the Kualapuu area were drilled in the East Molokai Volcanics and are located outside of the dike complex. Within the dike complex near the eastern part of the Kualapuu area, water levels probably are at least several tens of feet above sea level, which is considerably higher than the water levels of 8 to 12 ft measured at existing wells. Thus, a deep monitor well drilled within the dike complex may not provide useful information that is relevant to the existing wells. Furthermore, there are no plans to drill additional pumped wells in the dike complex within the Kualapuu area that would make a deep monitor well in the dike complex relevant.

Because hydrologic conditions in the immediate vicinity of the volcanic vents may differ from conditions near the existing production wells, a deep monitor well drilled near a volcanic vent may not provide relevant information. Existing production wells in the Kualapuu area are located about a mile from known volcanic vents.

Locations of Existing Production Wells

Limited information on the vertical distribution of salinity in DHHL well 1 (0801-01) indicates that pumping from nearby wells can cause borehole flow, and thereby affect the salinity profile, in a deep monitor well. A salinity profile obtained from an ideal deep monitor well would be an exact representation of the vertical distribution of salinity in the aquifer. Because of borehole flow, however, the salinity profile obtained from a deep monitor well may not correspond to the salinity distribution in the aquifer. Although borehole flow in a deep monitor well can exist even in the absence of nearby pumping, information from DHHL well 1 (0801-01) indicates that pumped wells located within about 1,000 ft from the monitor well can further enhance borehole flow. Pumped wells located farther than 1,000 ft from a deep monitor well can also cause borehole flow in the monitor well depending on pumping rate and the permeability of the aquifer.

To reduce the possible effects of borehole flow, a deep monitor well in the Kualapuu area would ideally be located as far as possible from existing or proposed production wells. On the other hand, a deep monitor well that is located in the vicinity of existing or proposed wells, and that is not affected by borehole flow induced by pumping from other wells, would provide the most relevant information.

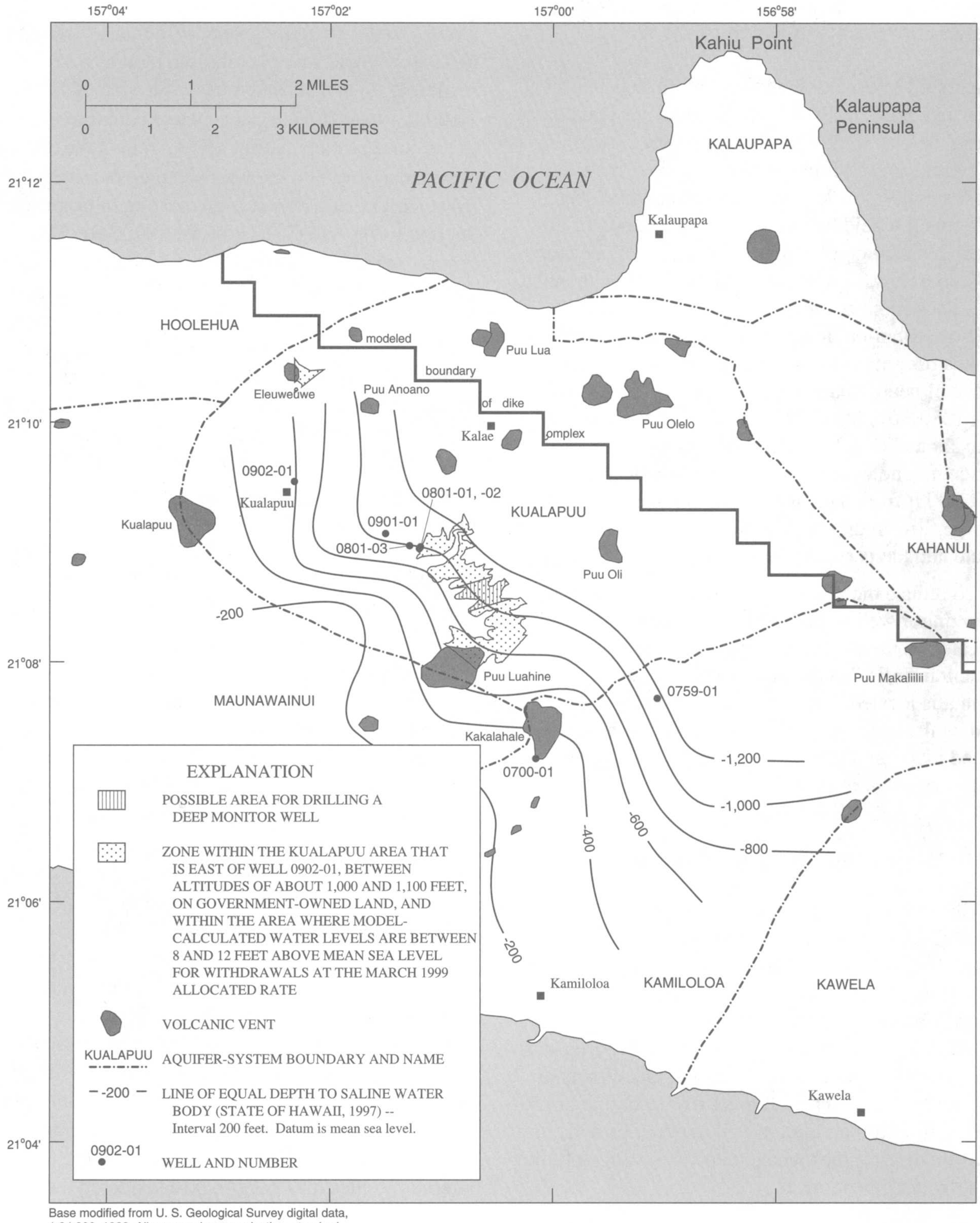
Historical Ground-Water Quality Information

Chloride concentrations of pumped water from well 0902-01 indicate that chloride concentrations near the western part of the Kualapuu area may exceed 250 mg/L. Thus, it is unlikely that future drinking-water wells will be drilled in the Kualapuu area west of well 0902-01. Locating a deep monitor well in the area west of well 0902-01 would reduce the possible effects of borehole flow caused by pumping from existing or proposed wells, but the monitor well may not provide useful information for the management of existing or future ground-water development.

SITE SELECTION FOR A DEEP MONITOR WELL

As discussed previously, a deep monitor well in the Kualapuu area will be most useful if it is located (1) in the vicinity of future ground-water development, (2) in an area where water levels are about 8 to 12 ft above sea level, (3) at a ground-surface altitude of 1,000 to 1,100 ft, (4) on government-owned land that is outside of the conservation district, (5) outside of the dike complex and as far from known volcanic vents as possible, (6) at least about 1,000 ft from existing or proposed production wells, and (7) east of well 0902-01. The intersection of the areas defined by (1) model-calculated water levels between 8 and 12 ft above sea level (with withdrawal rates equal to the March 1999 allocated rates), (2) ground-surface altitudes between 1,000 and 1,100 ft, (3) government-owned property that is outside of the dike complex, and (4) the area east of well 0902-01 forms two zones; a smaller intersection zone north of well 0902-01 and a larger intersection zone mostly southeast of the existing production wells in the Kualapuu area (fig. 25). The intersection zone to the north of well 0902-01 is near a volcanic vent, Eleuweuwe, and is thus ruled out as a possible site for a deep monitor well because of geological considerations.

The intersection zone that is southeast of the existing Kualapuu production wells is outside of the modeled dike complex and near the area where future ground-water development is possible. Within this southeastern intersection zone, a site must be chosen that is as far from known volcanic vents as possible, and at least about 1,000 ft from existing production wells. A viable area for drilling a deep monitor well is located about a half mile southeast of existing wells 0801-01 to -03 and a half mile north of the central part of a known volcanic vent, Puu Luahine (fig. 25). This area represents the central part of the intersection zone that is southeast of existing Kualapuu production wells. In this central area, existing geophysical information indicates that the saline water is about 1,000 ft below sea level, which is the same depth indicated at the existing production wells (fig. 25). Although there are unimproved roads leading to this central area, existing topography may make access difficult for large vehicles. Thus, alternative sites may need to be considered that are outside of the central area but that are within the intersection zone that is southeast of existing Kualapuu production wells.



Base modified from U. S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 21°04'50" and 21°12'10", central meridian 157°00'45"

Figure 25. Possible area for drilling a deep monitor well in the Kualapuu area, Molokai, Hawaii. The possible area for drilling represents the central part of the zone within the Kualapuu area that is southeast of well 0901-01, between altitudes of about 1,000 and 1,100 feet, on government-owned property, and within the area where model-calculated water levels are between 8 and 12 feet above mean sea level for withdrawals at the March 1999 allocated rate.

SUMMARY AND CONCLUSIONS

Projected demand for ground water is high in the Kualapuu area of Molokai, which lies in the central part of the island. The northeastern part of the Kualapuu area is within the dike complex of the northwest rift zone of East Molokai Volcano. No wells have been drilled in the northeastern part of the Kualapuu area, but ground water there is probably impounded to high levels (tens to hundreds of feet above sea level) in the volcanic rocks between low-permeability dikes. Within the Kualapuu area, ground water generally flows from the northeast to the southwest. Measured water levels from wells that are outside of the dike complex are about 8 to 12 feet above sea level. In the Kualapuu area and outside of the dike complex, a freshwater body of unknown thickness overlies a brackish-water transition zone of unknown thickness, which in turn overlies saltwater.

Results of a time-domain electromagnetic survey indicate that the altitude of the saline-water zone in the Kualapuu area rises in a southwesterly direction. The results of the time-domain electromagnetic survey are consistent with the expected increase in water levels in a northeasterly direction.

As of mid-1999 no deep monitor wells existed on Molokai. There is an acute need for such wells on Molokai, and in the Kualapuu area in particular, to evaluate the thickness of the freshwater body and brackish-water transition zone. Management of the ground-water resources in the Kualapuu area is hindered because of the uncertainty in the vertical salinity structure in the aquifer.

The main factors to be considered in selecting a site for a deep monitor well in the Kualapuu area include (1) possible sites of future ground-water development, (2) ground-water level, (3) ground-surface altitude, (4) land classification, ownership, and accessibility, (5) geology, (6) locations of existing production wells, and (7) historical ground-water quality information.

A deep monitor well near an area of possible future ground-water development would provide useful information related to the availability of freshwater in the area. A numerical ground-water flow model (Oki, 1997) that was developed to simulate steady-state regional ground-water flow on Molokai was used in this study to determine areas of possible future ground-water development in the Kualapuu area of Molokai.

The numerical model was used to estimate ground-water levels that result from pumping at rates equal to and in excess of the March 1999 allocated rates from existing and hypothetical wells in the Kualapuu area. Withdrawal rates of 0.5 and 1.0 Mgal/d in excess of the March 1999 total allocation rate were simulated at selected individual sites in the Kualapuu area, outside of the modeled dike complex.

Model results indicate that the southeastern part of the Kualapuu area is a possible area of future ground-water development because (1) withdrawals from this area have a small effect on water levels at existing wells in the Kualapuu area (relative to effects from withdrawals in other parts of the Kualapuu area that are outside of the dike complex), and (2) model-calculated water levels in this part of the Kualapuu area are high relative to water levels in other parts of the Kualapuu area that are outside of the dike complex. Although it may be possible to successfully withdraw additional ground water from other parts of the Kualapuu area, model results indicate that the effects on existing wells will be greater, water levels at the site of the additional pumping will be lower, or both.

Measured water levels in existing production wells in the Kualapuu area are between about 8 and 12 ft above sea level. Thus, a deep monitor well drilled in an area with water levels of about 8 to 12 ft above sea level may provide hydrologic information that is relevant to the existing production wells.

Drilling at ground-surface altitudes significantly greater than 1,000 ft will result in increased costs, whereas drilling at ground-surface altitudes significantly less than 1,000 ft will likely be in an area with water levels that are not representative of those measured at exiting production wells. Ground-surface altitudes are about 1,000 ft at the sites of existing production wells in the Kualapuu area. Because model-calculated water-level contours (Oki, 1997) generally are aligned with the topographic contours, a deep monitor well drilled at an altitude of about 1,000 to 1,100 ft in the Kualapuu area may provide hydrologic information that is relevant to the existing production wells.

Access to a deep monitor well located on privately owned property may be lost if the property is sold or the landowner no longer desires the well on the property. Locating a well on government-owned land, particularly DHHL or DWS land, would probably minimize the possibility of losing access to the well in the future because (1) land ownership is less likely to change, and (2) both DHHL and DWS have expressed an interest in drilling a deep monitor well in the Kualapuu area.

Existing production wells in the Kualapuu area were drilled in the East Molokai Volcanics and are located outside of the dike complex. A deep monitor well will be most useful if it is drilled in a similar hydrogeologic setting as the existing production wells. Because hydrologic conditions in the immediate vicinity of volcanic vents may differ from conditions near the existing production wells, a deep monitor well will probably be most relevant if it is drilled as far from known volcanic vents as possible.

Limited information on the vertical distribution of salinity in DHHL well 1 (0801-01) indicates that pumping from nearby wells can cause borehole flow, and thereby affect the salinity profile, in a deep monitor well. A salinity profile obtained from an ideal deep monitor well would be an exact representation of the vertical distribution of salinity in the aquifer. Because of borehole flow, however, the salinity profile obtained from a deep monitor well may not correspond to the salinity distribution in the aquifer. Although borehole flow in a deep monitor well can exist even in the absence of nearby pumping, information from DHHL well 1 indicates that pumped wells located within about 1,000 ft of the monitor well can further enhance borehole flow. Pumped wells located farther than 1,000 ft from a deep monitor well can also cause borehole flow in the monitor well depending on pumping rate and the permeability of the aquifer. To reduce the possible effects of borehole flow, a deep monitor well in the Kualapuu area would ideally be located as far as possible from existing or proposed production wells. On the other hand, a deep monitor well that is in the vicinity of existing or proposed wells, and that is not affected by borehole flow induced by pumping from other wells, would provide the most relevant information.

Chloride concentrations of pumped water from well 0902-01 indicate that ground-water quality near the western part of the Kualapuu area may exceed 250 mg/L. Thus, it is uncertain whether future drinking-water wells will be drilled in the Kualapuu area west of well 0902-01. Locating a deep monitor well in the area west of well 0902-01 would reduce the possible effects of borehole flow caused by pumping from existing or proposed wells, but because it would be far from existing or future wells, it may not provide useful information for management of the water resources.

A viable area for drilling a deep monitor well is about a half mile southeast of existing wells 0801-01 to -03 and a half mile north of a known volcanic vent, Puu Luahine. In this area, existing geophysical information indicates that the saline water is at about the same depth as at wells 0801-01 to -03. Although there are unimproved roads leading to this area, existing topography may make access difficult for large vehicles. Thus, nearby sites may need to be considered that are within the zone that is southeast of existing Kualapuu production wells, between model-calculated water levels of 8 and 12 ft above sea level, between altitudes of 1,000 and 1,100 ft, on government-owned property, and east of well 0902-01.

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☆ U.S. GOVERNMENT PRINTING OFFICE: 2000 — 589-387 / 16004 Region No. 10

Oki—SITE SELECTION FOR A DEEP MONITOR WELL, KUALAPUU, MOLOKAI, HAWAII—WRIR 99-4291

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