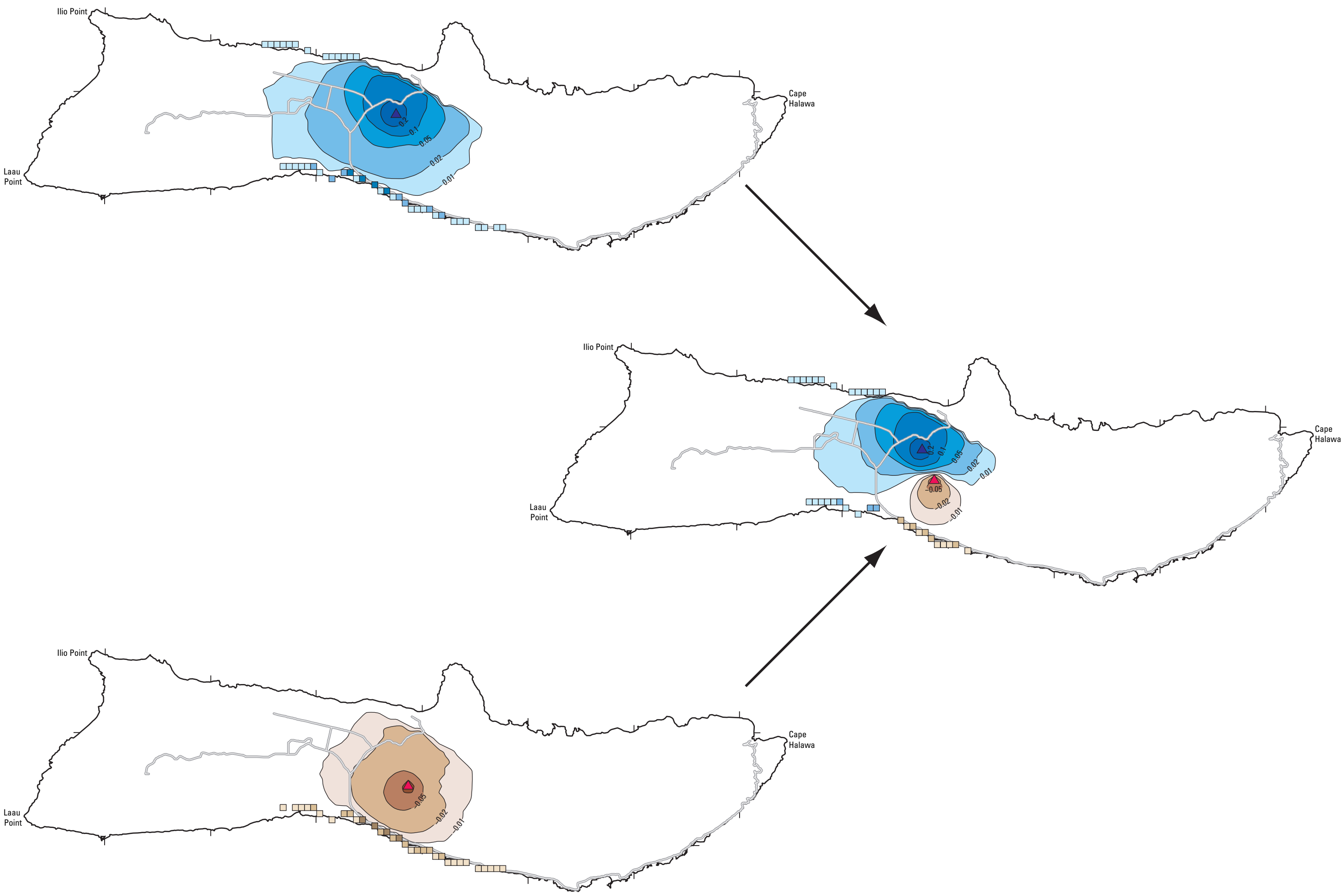
Prepared in Cooperation with the County of Maui Department of Water Supply

Numerical Simulation of the Hydrologic Effects of Redistributed and Additional Ground-Water Withdrawal, Island of Molokai, Hawaii



Scientific Investigations Report 2006–5177

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

COVER: Redistributed ground-water withdrawals on the Island of Molokai will cause a redistribution of water levels and coastal discharge. Water levels increase near sites of reduced withdrawal (blue triangles), and decrease near sites of increased withdrawal (red triangles), as shown by the contours of water-level change (in feet). Similarly, coastal discharge increases near sites of reduced withdrawal (blue squares), and decreases near sites of increased withdrawal (brown squares), as shown by the colored boxes. Ground-water discharge to coastal fishponds may be affected by a redistribution of ground-water withdrawals.

Numerical Simulation of the Hydrologic Effects of Redistributed and Additional Ground-Water Withdrawal, Island of Molokai, Hawaii

By Delwyn S. Oki

Prepared in Cooperation with the County of Maui Department of Water Supply

Scientific Investigations Report 2006–5177

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

U.S. Department of the Interior
Dirk Kempthorne, Secretary

U.S. Geological Survey
P. Patrick Leahy, Acting Director

U.S. Geological Survey, Reston, Virginia: 2006

For product and ordering information:
World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1–888–ASK–USGS

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov/
Telephone: 1–888–ASK–USGS

Suggested citation:
Oki, D.S., 2006, Numerical simulation of the hydrologic effects of redistributed and additional ground-water withdrawal, Island of Molokai, Hawaii: U.S. Geological Survey Scientific Investigations Report 2006–5177, 49 p.

Contents

Figures

Tables

Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

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

°F=(1.8×°C)+32

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

°C=(°F-32)/1.8

Vertical coordinate information is referenced to mean sea level.

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

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

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

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Numerical Simulation of the Hydrologic Effects of Redistributed and Additional Ground-Water Withdrawal, Island of Molokai, Hawaii

By Delwyn S. Oki

Abstract

Because of increased demand for water associated with a growing population, projected increases in demand over the next few decades, and rising salinity of the water pumped from some existing wells, the County of Maui Department of Water Supply (DWS) is currently (2006) considering drilling additional wells to replace or supplement existing wells on the Island of Molokai, Hawaii. Redistributed and additional ground-water withdrawals will affect ground-water levels, discharge of ground water to the nearshore environment, and, possibly, salinity of the water pumped from existing wells.

For this study, an existing numerical ground-water-flow model was used to estimate water-level and coastal-discharge changes, relative to 2005 base-case conditions, caused by withdrawals in the area between Kualapuu and Ualapue on Molokai. For most of the scenarios tested, total withdrawals were either equal to or 0.28 million gallons per day greater than those in the 2005 base case. Model results indicate that a redistribution of withdrawals causes a corresponding redistribution of water levels and coastal discharge. Water levels rose and coastal discharge increased near sites of reduced withdrawal, whereas water levels declined and coastal discharge decreased near sites of increased withdrawal. The magnitude and areal extent of hydrologic changes caused by a redistribution of withdrawals increased with larger changes in withdrawal rates. Simulated water-level changes were greatest at withdrawal sites and decreased outward with distance elsewhere. Simulated water-level declines at proposed withdrawal sites generally were less than 0.5 feet. The low-permeability dike complex of East Molokai Volcano impeded the spread of water-level changes to perennial streams in the northeastern part of the island, and discharge to these streams in the dike complex therefore was unaffected by the proposed withdrawals.

Simulated coastal-discharge changes generally were greatest immediately downgradient from sites of withdrawal change. Simulated coastal-discharge reductions generally were less than 30,000 gallons per day (and everywhere less than 75,000 gallons per day) within model elements for scenarios that excluded the Hawaii Department of Hawaiian Home Lands reservation (2.905 million gallons per day). (Model elements cover discrete 1,640- by 1,640-foot-square areas.) Simulated coastal-discharge reductions generally represented less than 5 percent change relative to 2005 base-case conditions. Simulated discharge to some fishponds and springs increased in response to decreased withdrawal at upgradient sites, and simulated discharge to other fishponds and springs decreased in response to increased withdrawal. Simulated water-level declines associated with the Hawaii Department of Hawaiian Home Lands reservation were as much as 4 feet at three arbitrarily selected withdrawal sites, and simulated reductions in coastal discharge between Umipaa and Kamiloloa along the south coast exceeded 200,000 gallons per day from several model elements.

Introduction

The resident population of the Island of Molokai, Hawaii (fig. 1), has grown by more than 20 percent from 1980 (population 6,049) to 2000 (population 7,404) (Hawaii Department of Business, Economic Development & Tourism, 2006). Because of increased demand for water associated with the growing population, projected increases in demand over the next few decades, and rising salinity of the water pumped from some existing wells, the County of Maui Department of Water Supply (DWS) is currently (2006) considering drilling additional wells to replace or supplement existing wells on Molokai.

In response to concerns over the water resources of Molokai, the Hawaii Commission on Water Resource Management (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 island's water resources. The CWRM has divided the island into 16 management areas or aquifer systems, primarily defined on the basis of geologic conditions and topographic divides (Mink and Lau, 1992) (fig. 2). Ground-water withdrawals on the island currently

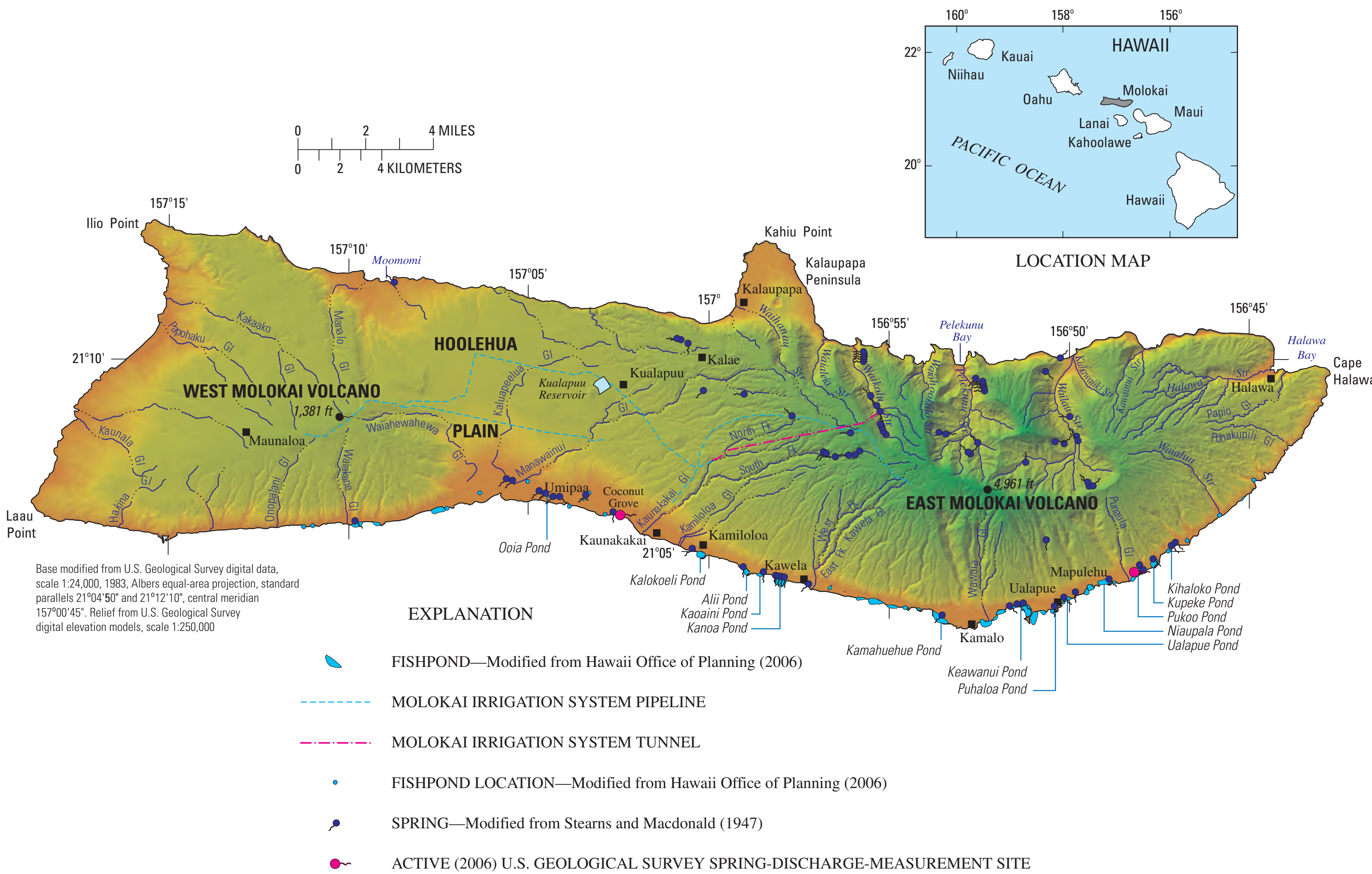
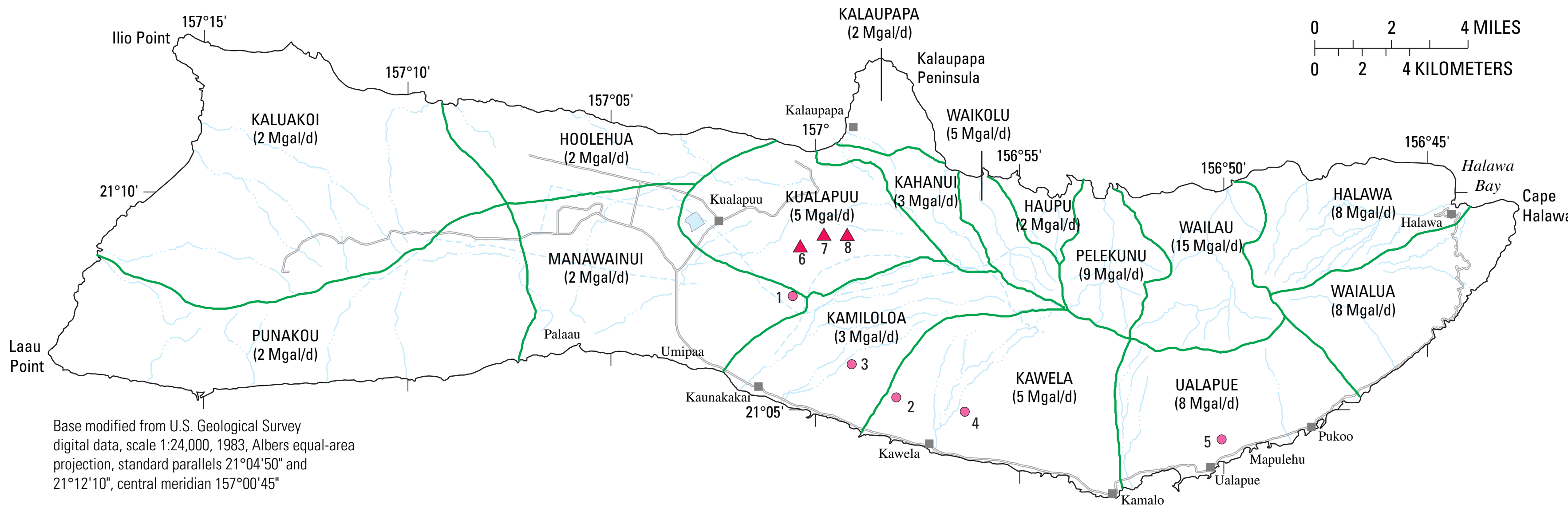


Figure 1. Island of Molokai, Hawaii, showing selected geographic features.



EXPLANATION

KUALAPUU (5 Mgal/d) — AQUIFER-SYSTEM BOUNDARY, AND NAME OF AQUIFER SYSTEM—State sustainable-yield estimate, in million gallons per day (Mgal/d), shown in parentheses.

2 — PROPOSED SITE FOR ADDITIONAL GROUND-WATER WITHDRAWAL AND SITE NUMBER

6 — ARBITRARY GROUND-WATER-WITHDRAWAL SITE FOR HAWAII DEPARTMENT OF HAWAIIAN HOME LANDS RESERVATION AND SITE NUMBER

Figure 2. Aquifer systems designated by the Hawaii Commission on Water Resource Management and sites for additional ground-water withdrawal proposed by the County of Maui Department of Water Supply, Island of Molokai, Hawaii.

are limited by sustainable-yield estimates for each of the 16 aquifer systems. As of May 2005, the CWRM had issued water-use permits authorizing a total of 8.077 million gallons per day (Mgal/d) of ground-water withdrawals from wells and tunnels on the island (table 1). In addition, the Hawaii Department of Hawaiian Home Lands (DHHL) has a reservation for 2.905 Mgal/d of ground water from the Kualapuu area (fig. 2; table 1).

Redistributed and additional ground-water withdrawals will affect ground-water levels and may cause the salinity of water pumped from existing wells to increase. Redistributed and additional ground-water withdrawals also will affect discharge of fresh and brackish water to the nearshore environment. Along the south coast, Native Hawaiians built dozens of fishponds in shallow coastal waters by constructing rock-wall enclosures extending from the shoreline (fig. 1). References to fishpond construction on Molokai date back to the 16th century, and the most recently constructed fishpond on the island was built about 1829 (Farber, 1997). Members of the community on Molokai have identified 31 fishponds that they would like to restore and maintain in a traditional manner for subsistence and small-business ventures (Farber, 1997). Discharge of fresh or brackish ground water to these fishponds may be a factor controlling productivity by providing nutrients for algae on which the fish feed (Farber, 1997). Stearns and Macdonald (1947, p. 56) suggested that fishponds along the south shore of Molokai indicate the presence of coastal springs, some of which discharge more than 0.5 Mgal/d. Thus, additional ground-water withdrawal may affect fishpond productivity.

In response to concerns over the possible effects of ground-water withdrawal on Molokai, the U.S. Geological Survey (USGS) undertook the present investigation, in cooperation with the DWS, to quantify the hydrologic effects of withdrawal from selected sites on ground-water levels and coastal discharge of ground water. An existing numerical ground-water-flow model (Oki, 1997) was used to estimate water-level declines and coastal-discharge reductions caused by redistributed and additional ground-water withdrawals in the area between Kualapuu and Ualapue on Molokai.

Purpose and Scope

The purpose of this report is to describe the results of model simulations that assess the hydrologic effects of redistributed or additional ground-water withdrawals relative to average or permitted 2005 withdrawal rates. No new data were collected as part of this study. An existing numerical ground-water-flow model (Oki, 1997) for Molokai was used to estimate the effects of different withdrawal scenarios on ground-water levels and coastal discharge.

Setting

The Island of Molokai, the fifth largest of the Hawaiian Islands, occupies an area of 260 mi^2 (Juvik and Juvik, 1998) between latitude 21°00′–21°15′ N. and longitude 157°20′–156°40′ W. (fig. 1). The island is composed mainly of two shield volcanoes (Stearns and Macdonald, 1947): the older West Molokai Volcano, which rises to an altitude of 1,381 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.

Climate

The climate on Molokai is characterized by mild temperatures, cool and persistent trade winds, a rainy winter season from October through April, and a dry summer season from May through September (Blumenstock and Price, 1967; Sanderson, 1993). The climate is controlled primarily by topography and the position of the North Pacific anticyclone and other migratory weather systems relative to the island. During the dry season, the stability of the North Pacific anticyclone produces persistent northeasterly winds known locally as trade winds. Summer trade winds blow 80 to 95 percent of the time. During the rainy season, frequent passage of migratory high-pressure systems by the Hawaiian Islands results in less persistent trade winds. Winter trade winds blow 50 to 80 percent of the time. Southerly winds associated with low-pressure systems can bring heavy rains to the island. The dry western and southern coastal areas receive much of their rainfall as a result of these low-pressure systems.

Rainfall

The windward (northeast) side of Molokai is wettest, a pattern controlled by the orographic lifting of moisture-laden northeasterly trade winds along the windward slope of East Molokai Volcano. The moisture-laden air mass cools as it rises up the slopes of the volcano, resulting in condensation, cloud formation, and high rainfall near the topographic crest of the mountains. West Molokai Volcano is considerably drier because it does not extend upward into the cloud-forming zone at higher altitudes.

Rainfall on Molokai is characterized by maxima at high altitudes and steep spatial gradients (fig. 3). Maximum mean annual rainfall is more than 150 in. near the summit of East Molokai Volcano in the northeastern part of the island (Giambelluca and others, 1986). Over West Molokai Volcano, maximum mean annual rainfall is about 25 in., and along the coastal areas of the southern and western parts of the island, mean annual rainfall is less than 16 in. Annual rainfall at Molokai Airport (rain gage 524, fig. 3) ranged from about 11 to 43 in. during the period 1975–2004 (fig. 4). In a wetter area to the east at Waikolu (rain gage 540, fig. 3), annual rainfall

Table 1. Ground-water-use permits effective in 2005 on the Island of Molokai, Hawaii.

[Data from the Hawaii Commission on Water Resource Management. Values in parentheses are 2005 mean annual withdrawal rates. Mgal/d, million gallons per day; --, no number available; MIS, Molokai Irrigation System]

Well	Name	Water-use permit (Mgal/d)	Aquifer system
0350–01	Keawanui salt	0.24	Ualapue
0350–05	Wescoatt	0.004	Ualapue
0350–07	Manawai No. 1	0.015	Ualapue
0350–09	Oceanic Institute salt	0.75	Ualapue
0352–09	Kamalo	0.01	Ualapue
0352–10	Kamalo-Curtis	0.012	Kawela
0352–11	Shige’s farm	0.004	Kawela
0352–12	Urauchi No. 1	0.001	Ualapue
0354–01	Meyer, Inc., No. 1	0.029	Kawela
0354–02	Meyer, Inc., No. 2	0.04	Kawela
0354–03	No. 3	0.017	Kawela
0354–04	Meyer, Inc., No. 4	0.005	Kawela
0354–07	Bostwick No. 1	0.045	Kawela
0447–02	Pukoo Farm	0.003	Ualapue
0448–01	Mapulehu Shaft No. 1	0.003	Ualapue
0448–03	Mapulehu Shaft	0.007	Ualapue
0449–01	Ualapue Shaft	0.185 (0.234)	Ualapue
0449–06	Kaluaaha-Shephard	0.008	Ualapue
0456–04, 0457–04	Breadfruit and AG No. 1	0.285	Kawela
0456–06, 0456–08, 0456–09	Kawela Plantation DW1–DW3	0.285	Kawela
0456–16	Kawela-Iaea No. 3	0.017	Kawela
0456–17	Johnson	0.016	Kawela
0457–01	Kawela Shaft	0.33 (0.348)	Kawela
0501–04	Kupa Shaft	0.056	Kamiloloa
0501–06	Home Pumehana	0.005	Kamiloloa
0501–07	Kaunakakai Park	0.075	Kamiloloa
0546–02	Puelelu	0.202	Waialua
0549–01	Mapulehu Tunnel	0.01	Ualapue
0601–01	Oloolo Kaunakakai	0.075	Kamiloloa
0602–03	Kalaiakamanu	0.005	Manawainui
0603–01	Umipaa	0.046	Manawainui
0605–01, 0605–02	ORCA Shaft Nos. 1 and 2	0.6	Manawainui
0605–03	ORCA No. 3	0.04	Manawainui
0705–05	Naiwa	0.012	Manawainui
0706–02	South Hoolehua	0.864	Manawainui
0706–03	Palaau salt	0.001	Manawainui
0759–01	Waiola No. 1	[1] 0.656	Kamiloloa
0801–01, 0801–02	Kualapuu Nos. 1 and 2	0.367	Kualapuu
0801–03	Kualapuu mauka	0.516 (0.605)	Kualapuu
0844–01	Puu O Hoku No. 1	[1] 0.235	Waialua
0855–01, 0855–02, 0855–03	Waikolu Tunnel 22–24	0.853	Waikolu
0901–01	No. 17	1.018	Kualapuu
1058–01	Waihanau No. 239	0.094	Kahanui
1059–01	Waikalae Tunnel	0.036	Kualapuu
—	DHHL reservation	2.905	Kualapuu
MIS Tunnel	Molokai Irrigation System Tunnel	[2] 1.822	Waikolu

[1] Not simulated.

[2] 1992–96 average withdrawal (Oki, 1997), equally distributed to two model nodes.

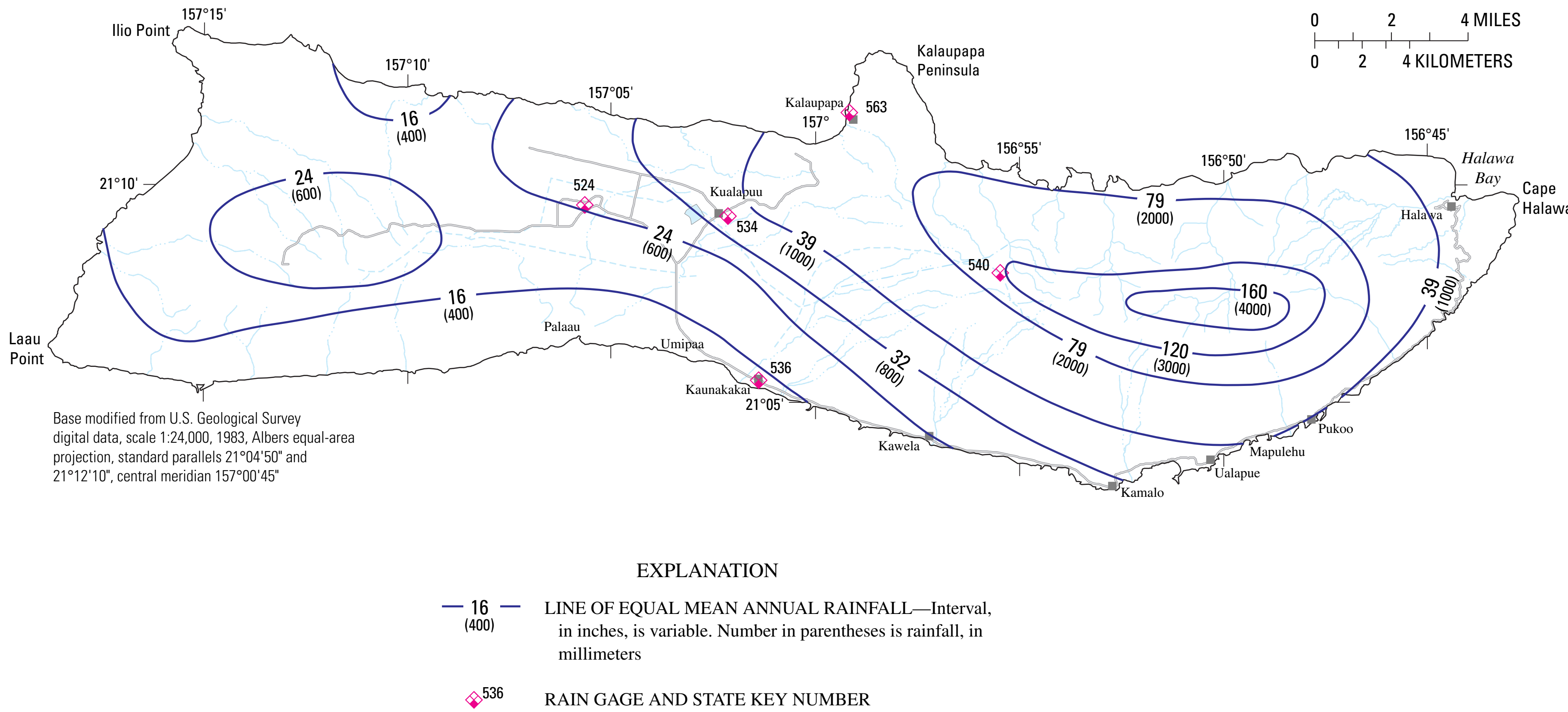


Figure 3. Mean annual rainfall on the Island of Molokai, Hawaii (modified from Giambelluca and others, 1986).

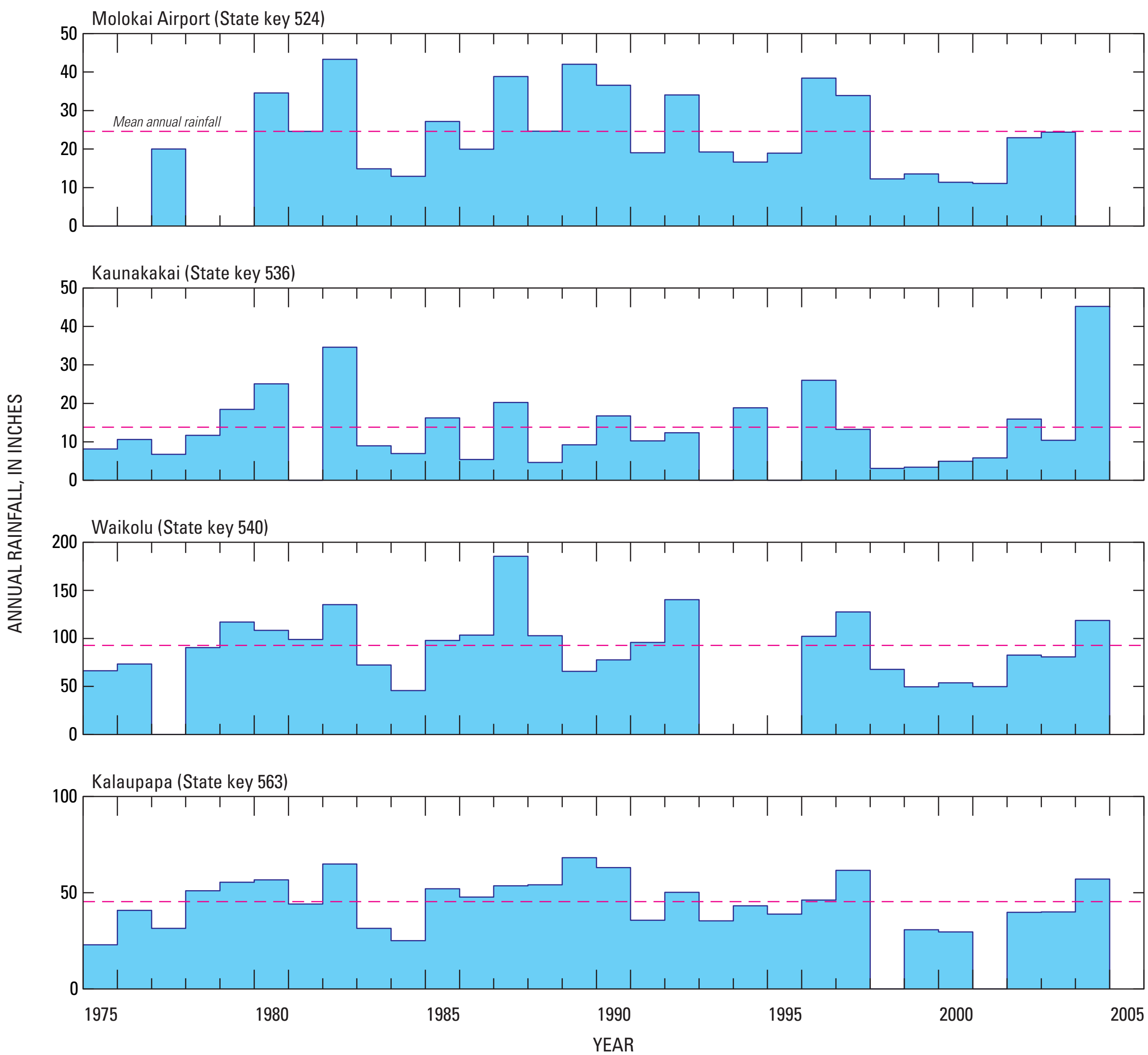


Figure 4. Annual rainfall at selected rain-gaging stations on the Island of Molokai, Hawaii, for the period 1975–2004. Mean annual rainfall values are for 1975–2004 and do not include missing or incomplete years (indicated as zero values). Data from National Climatic Data Center (2006).

ranged from about 46 to 185 in. during the same period (fig. 4). In comparison, mean annual rainfall over the open ocean is estimated at 22 to 28 in. (Dorman and Bourke, 1979; Elliot and Reed, 1984).

Evaporation

Published pan-evaporation records for Molokai are available at only three sites, two in the Hoolehua Plain and one near the town of Maunaloa in the western part of the island. Mean annual pan evaporation at the three sites ranges from 81 in. at Maunaloa to 118 in. near the Hoolehua Plain (Ekern and Chang, 1985). The high pan-evaporation rate on the dry, windy uplands of the central part of the island is attributed to 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 main eruptive stages: preshield, shield, postshield, and rejuvenated (Langenheim and Clague, 1987), although not all Hawaiian volcanoes have a postshield or rejuvenated stage. The preshield stage is the earliest, submarine phase of volcanic activity. Lava from this stage consists predominantly of alkalic basalt (basalt that is low in silica and rich in sodium and potassium). Lava from the principal, or shield, stage of volcano building consists of fluid tholeiitic basalt (silica saturated) that characteristically forms thin flows. This type of basalt forms during submarine and subaerial eruptions. A large central caldera can form during the shield stage and might later be partly or completely filled during subsequent eruptions. Typically, 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 penetrate 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 characteristics. Postshield-stage lava includes alkalic basalt and more viscous hawaiite, ankaramite, mugearite, and trachyte. Lava from this stage may erupt from sites outside the rift zones formed during the shield stage and form a veneer atop the shield-stage basalt. After a long period of quiescence, lava might issue from isolated vents on the volcano during the rejuvenated stage (also referred to as the posterosional stage).

Volcanic rocks of Hawaii can be divided into three main groups on the basis of their mode of emplacement: extrusive lava flows; intrusive dikes, sills, stocks, and plugs; and pyroclastic deposits. In general, lava flows that erupt from rift zones are less than 10 ft thick and consist of either pahoehoe, which is characterized by smooth or ropy surfaces, or aa, which contains a massive central core sandwiched between rubbly clinker layers (Wentworth and Macdonald, 1953). 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 central and marginal parts of rift zones of older volcanoes (see Takasaki and Mink, 1985), including West and East Molokai Volcanoes.

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

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 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 are formed by explosive volcanic activity and 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 total mass of a Hawaiian volcano (Wentworth and Macdonald, 1953). Cinder cones likely represent the surface expression of an intrusive body (dike) and may occur outside the central part of the rift zone.

The overall geology of Molokai has been described by numerous investigators (for example, Lindgren, 1903; Stearns and Macdonald, 1947; Beeson, 1976; Macdonald and others, 1983; Stearns, 1985). Langenheim and Clague (1987) described and renamed the stratigraphic framework of volcanic rocks on Molokai.

The Island of Molokai is formed primarily by shield- and postshield-stage volcanic rocks of the West and East Molokai Volcanoes, and secondarily by rejuvenated-stage volcanic rocks on the Kalaupapa Peninsula (Langenheim and Clague, 1987). Intrusive volcanic rocks in the form of dikes associated with rift zones and volcanic vents occur on both West and East Molokai Volcanoes. Coastal deposits consisting of sedimentary material and limestone reefs occur along the south coast.

West Molokai Volcano

The primary rift zones of West Molokai Volcano trend approximately northwest and southwest (fig. 5) in the direction of broad ridges that extend from near the summit of the volcano. A positive gravity anomaly that extends from near the summit region through Laau Point at the southwest tip of the island (Moore and Krivoy, 1965) suggests the presence of dense intrusive dikes associated with the southwestern rift zone. A few southeast-trending dikes exposed near the south coast may be evidence of a third rift zone associated with West Molokai Volcano. No surface evidence of a summit caldera has been observed on West Molokai Volcano (Beeson, 1976; Langenheim and Clague, 1987). Numerous fault scarps, 100 to 500 ft high, are exposed on the northeastern part of the volcano (Stearns and Macdonald, 1947). 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).

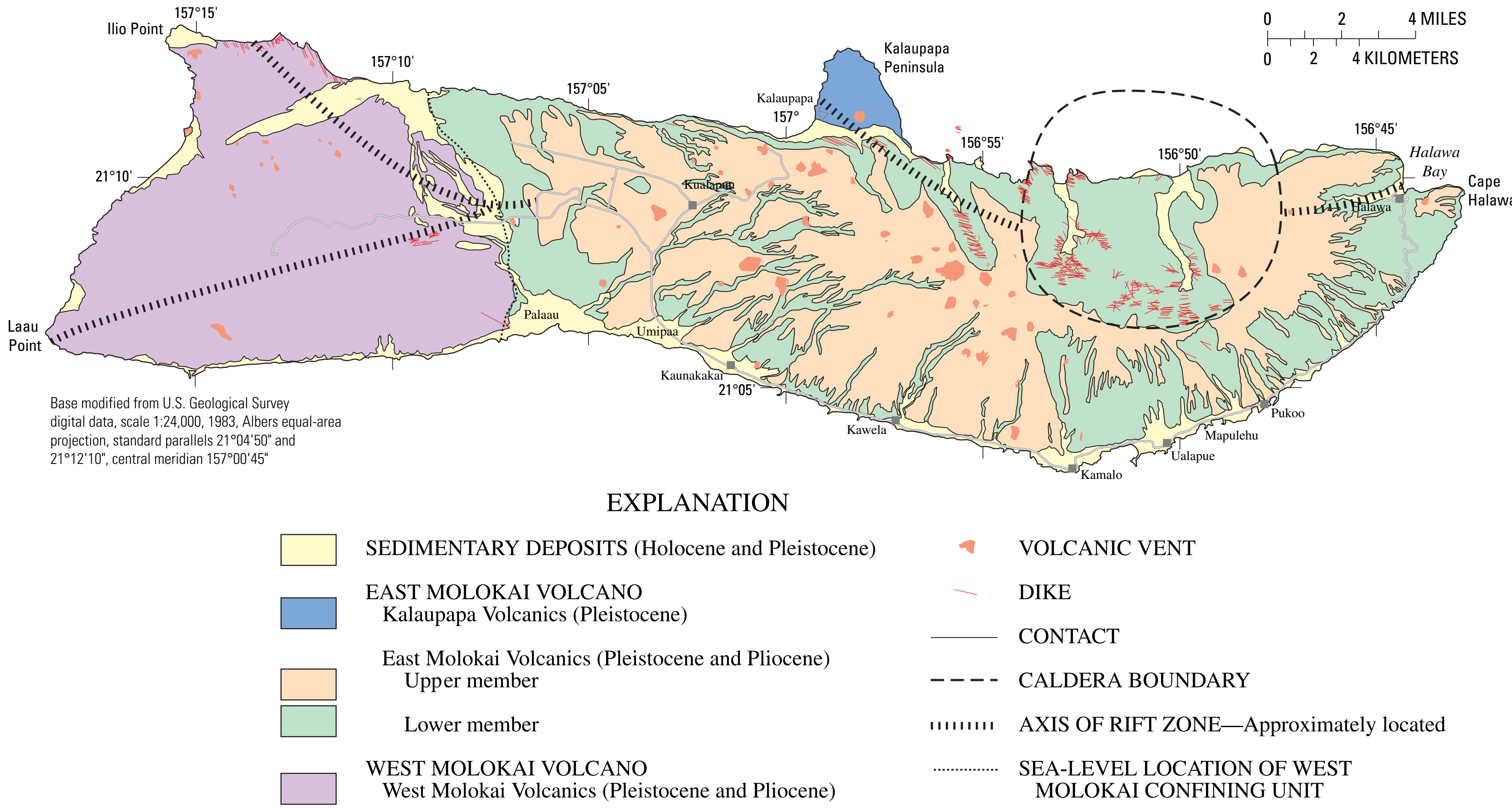


Figure 5. Generalized geologic map of the Island of Molokai, Hawaii (modified from Stearns and Macdonald, 1947, and Langenheim and Clague, 1987).

East Molokai Volcano

The primary rift zones of East Molokai Volcano trend northwest and east from a central caldera complex (fig. 5). Macdonald (1956) suggested a possible southern rift zone emanating from the caldera. Furthermore, Malahoff and Woollard (1966) interpreted results from a magnetic survey as indicating a possible southwestern rift zone emanating from the caldera complex. The northwestern and eastern rift zones are marked by numerous nearly vertical to vertical intrusive dikes (Stearns and Macdonald, 1947). The caldera complex of East Molokai Volcano is exposed in Pelekunu and Wailau stream valleys (fig. 5), and consists 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 west and south flanks of East Molokai Volcano (fig. 5). Many of these features do not appear to lie along the trends of the two primary rift zones of the volcano, possibly indicating the presence of (1) a marginal dike zone or (2) more than two primary rift zones.

The exposed rocks of East Molokai Volcano are named the East Molokai Volcanics and the Kalaupapa Volcanics (Langenheim and Clague, 1987). The East Molokai Volcanics is divided into two informal members: a lower member consisting of shield-stage tholeiitic, olivine-tholeiitic, and picritic-tholeiitic basalts and postshield-stage alkalic basalt; and an upper member consisting of postshield-stage mugearite and lesser amounts of hawaiite and trachyte (Langenheim and Clague, 1987). The upper member forms a relatively thin (approx. 50–500 ft thick) veneer over the lower member (Stearns and Macdonald, 1947); the upper member may obscure vent features associated with the lower member. The Kalaupapa Volcanics includes the rejuvenated-stage alkalic basalt and basanite that form Kalaupapa Peninsula (Clague and others, 1982; Langenheim and Clague, 1987).

Estimated ages of the rocks of West and East Molokai Volcanoes (McDougall, 1964; Naughton and others, 1980; Langenheim and Clague, 1987) indicate that the volcanoes may have formed contemporaneously. Stearns and Macdonald (1947) noted, however, that an erosional unconformity, which dips about 10° E., 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. This sequence indicates that the West Molokai Volcanics is older than the East Molokai Volcanics at the site of the exposed unconformity.

Coastal Deposits

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

Hydraulic Conductivity of the Rocks

Hydraulic conductivity is a quantitative measure of the capacity of a rock to transmit water and can be described qualitatively by permeability–the ease of fluid movement through a porous rock (see Domenico and Schwartz, 1990). The permeability of volcanic rocks varies with their mode of emplacement.

Lava Flows

In a layered sequence of subaerial, shield-stage lava flows of a volcano, where dike intrusions are absent, 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. On the basis of a numerical-model analysis, Oki (1997) estimated the horizontal hydraulic conductivity of the dike-free, shield-stage lava flows of Molokai at 1,000 ft/d.

Dikes

Although most dikes are less than 10 ft thick, they can extend vertically and laterally for thousands of feet and are hydrologically important because of their low permeability. Within a dike complex, dikes intersect at various angles and compartmentalize the more permeable intruded rock, impounding ground water 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 local-scale hydrologic effects of the dikes that fed the scattered vents of East Molokai Volcano near Kualapuu are unknown, these dikes intrude the aquifer and probably lower the overall permeability of the aquifer.

On the basis of a numerical-model analysis, Oki (1997) estimated the overall hydraulic conductivity of the dike complexes of West and East Molokai Volcanoes at 2 and 0.02 ft/d, respectively, and the horizontal hydraulic conductivity of the marginal dike zone near Kualapuu at 100 ft/d.

Weathering

Weathering generally reduces the permeability of 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 Volcanoes. In this report, this weathered zone is referred to as the West Molokai confining unit. 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 (Oki, 1998) on weathered volcanic rocks and a similar geohydrologic barrier, Oki (1997) estimated the hydraulic conductivity of the West Molokai confining unit at 1 ft/d.

Coastal Deposits

Coastal deposits and underlying weathered volcanic rocks impede the seaward discharge of freshwater near the southern part of the island. The permeability of the interbedded coastal deposits may vary widely, from low-permeability compacted alluvium to cavernous limestone deposits. Oki (1997) estimated the overall vertical hydraulic conductivity of the coastal deposits in the southern part of the island at 0.5–5 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 level. Water levels are highest in the mountainous interior parts of the island, particularly in the northeast, and lowest near the coast. Thus, ground water flows from the mountainous interior areas to coastal discharge areas. Ground water originating from the eastern and western parts of the island also flows toward the central Hoolehua Plain, from where it flows to either the north or south 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 the northeastern part of the island, 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.

Ground water on Molokai is unconfined in inland areas. Along the south coast, ground water may be confined by sedimentary deposits that impede the seaward discharge of fresh ground water. Fresh ground water on the island occurs 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 ten to hundreds of feet above sea level. Stearns and Macdonald (1947) also suggested that perched water exists on Molokai.

Recharge

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

Ground-water recharge on Molokai was estimated at 144 Mgal/d from an annual water budget (Hawaii Commission on Water Resource Management, 1990). More recently, Shade (1997) estimated ground-water recharge at 188.6 Mgal/d from a monthly water budget for natural-vegetation conditions, which represents an average of about 15 in/yr over the island. However, the ground-water recharge estimated by Shade varies areally from a minimum of near 0 in/yr in the western part to a maximum of about 100 in/yr in the northeastern part of the island.

Discharge to Streams

Streams on Molokai have steeper gradients in the mountainous, high-rainfall areas and flatter gradients near the coast. Streams in the windward, northeastern valleys are perennial throughout most of their lengths because they receive ground-water discharge from the dike-impounded ground-water body. In contrast, no perennial streams exist in the western part of the island or the central Hoolehua Plain. Most of the streams that drain to the south coast of East Molokai Volcano are perennial only in their upper reaches where rainfall is persistent or where water drains from marshes or springs. These streams generally are perennial only where they flow over lavas of the upper member of the East Molokai Volcanics. Where streams flow over more permeable lavas of the lower member, surface water is more readily lost to infiltration (Stearns and Macdonald, 1947, p. 47).

Water Levels

Measured water levels are available primarily in wells along the south coast and in the central plain (figs. 6, 7). 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 northwestern rift zone of East Molokai Volcano near Waikolu Stream, water levels in wells 0855–01, 0855–02, and 0855–03 (figs. 6 and 7) were about 900 ft above sea level in 1961. At the northern margin of the dike complex, near Kalaupapa Peninsula, the water level in well 1058–01 was reported to be 9 ft above sea level, which probably represents an upper limit for the water-table altitude in the Kalaupapa Volcanics. Results from an electrical-resistivity survey indicated that the freshwater zone in the Kalaupapa Volcanics is thin (Takasaki, 1986). In the West Molokai Volcanics, the

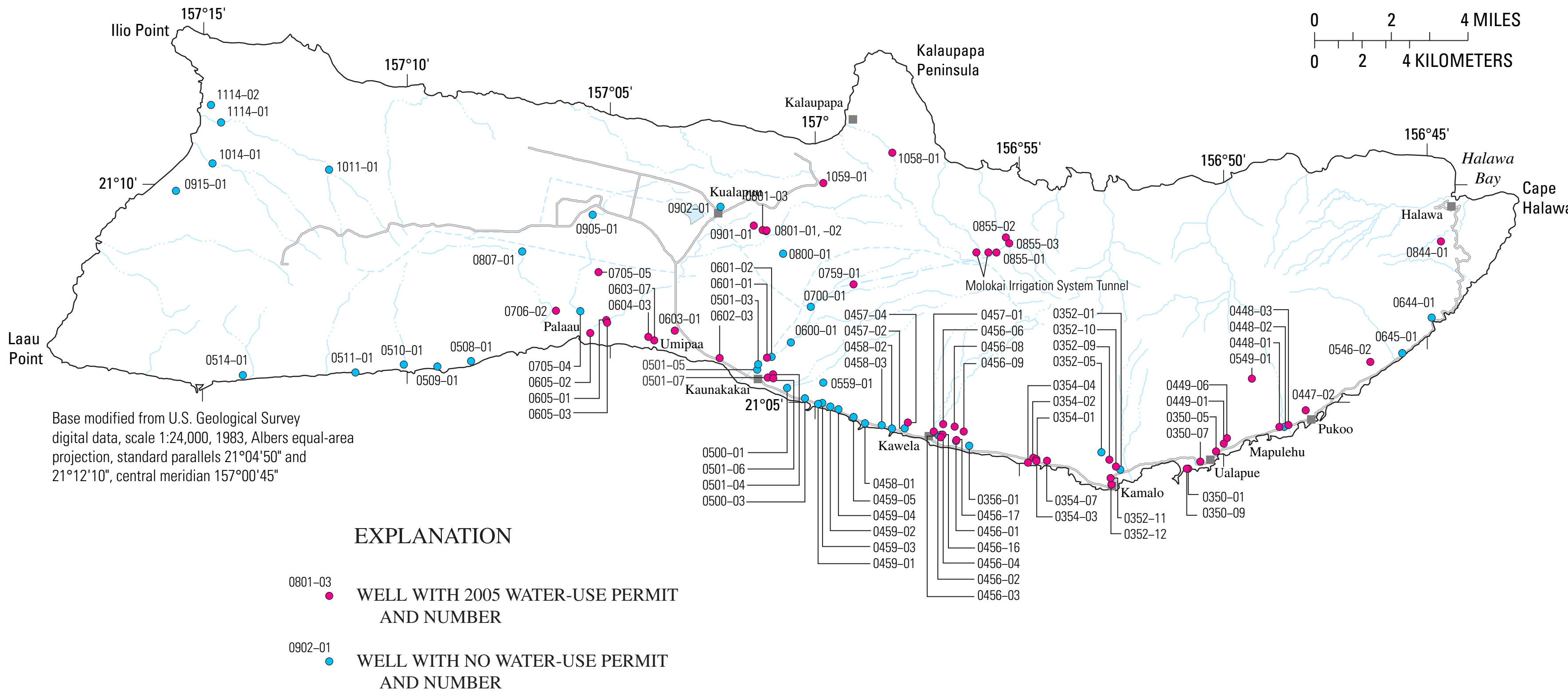
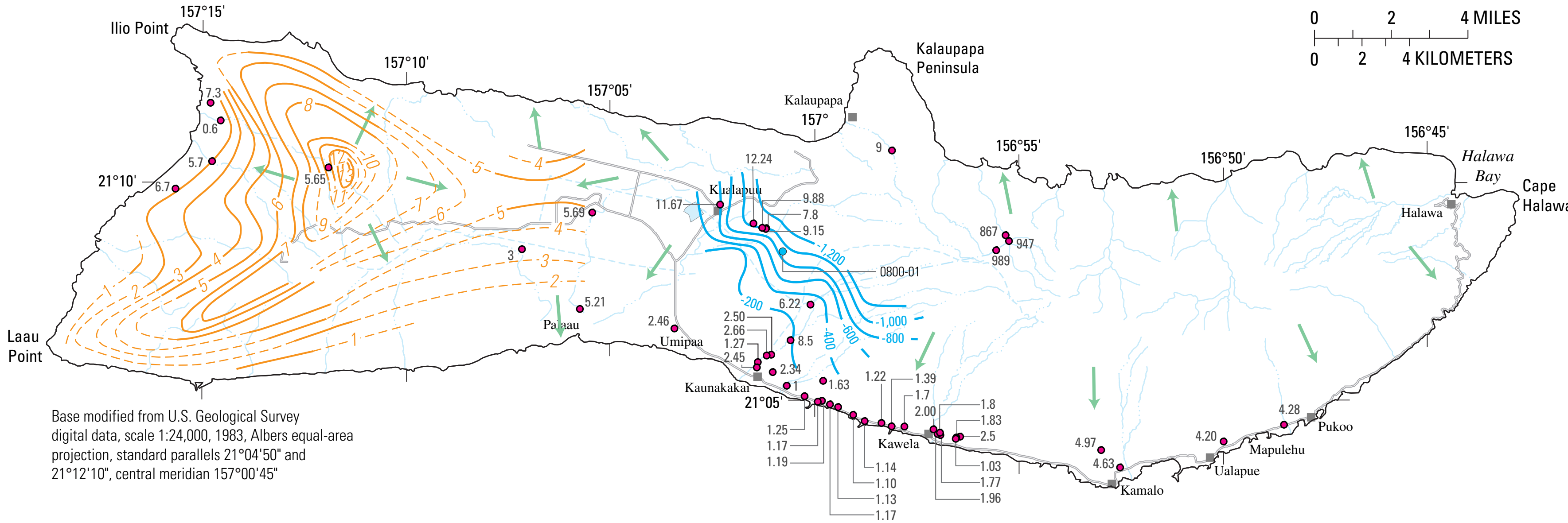


Figure 6. Locations of selected wells on the Island of Molokai, Hawaii.



EXPLANATION

— 4 — LINE OF EQUAL WATER LEVEL AS DETERMINED BY RESISTIVITY MEASUREMENTS (MacCarthy, 1941)—Interval, 1 foot. Datum is mean sea level. Dashed where inferred

— -200 — LINE OF EQUAL ALTITUDE OF TOP OF SALINE WATER BODY AS DETERMINED BY TIME-DOMAIN ELECTROMAGNETIC SURVEY (HAWAII COMMISSION ON WATER RESOURCE MANAGEMENT, 1997)—Interval, 200 feet. Datum is mean sea level.

APPROXIMATE DIRECTION OF GROUND-WATER FLOW

2.46 WELL AND AVERAGE MEASURED WATER LEVEL, IN FEET ABOVE MEAN SEA LEVEL

Figure 7. Average measured water levels for period 1938–97, water levels from resistivity measurements, and altitude of top of saline water body determined from time-domain electromagnetic survey, Island of Molokai, Hawaii.

reported the water level in well 1011–01 was 5.65 ft above sea level in 1946 (Stearns and Macdonald, 1947, p. 65).

A detailed contour map of water levels for the entire island cannot be drawn from existing well data. MacCarthy (1941) used electrical-resistivity measurements to determine the depth to saltwater, then applied the Ghyben-Herzberg relation (see subsection below entitled “Freshwater Lens”) to estimate the altitude of the water table in the western part of the island (fig. 7). MacCarthy estimated that the water-table altitude there ranges from about 1 to 14 ft above sea level. The water-level estimates made from resistivity measurements are only approximate because use of the Ghyben-Herzberg relation to predict water levels from estimated depths to saltwater (1) ignores the freshwater-saltwater transition zone and (2) does not account for dynamic conditions in the aquifer where vertical flow is present. Unquantified errors probably are associated with the resistivity measurements and the geophysical models used to represent actual subsurface conditions.

Freshwater Lens

Water levels measured in wells drilled into the permeable dike-free lava flows on the island generally are less than 15 ft above sea level. Within these dike-free lava flows, a freshwater lens floats on denser, underlying saltwater. The source of the freshwater 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 freshwater lens (fig. 8; 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, creating a freshwater-saltwater transition zone.

Under hydrostatic conditions, the thickness of a freshwater lens can be estimated by using the Ghyben-Herzberg relation. If the specific gravities of freshwater and saltwater are assumed to be 1.000 and 1.025, respectively, and if the freshwater-saltwater transition zone is assumed to be a sharp interface, then the Ghyben-Herzberg relation predicts that every foot of freshwater above sea level must be balanced by

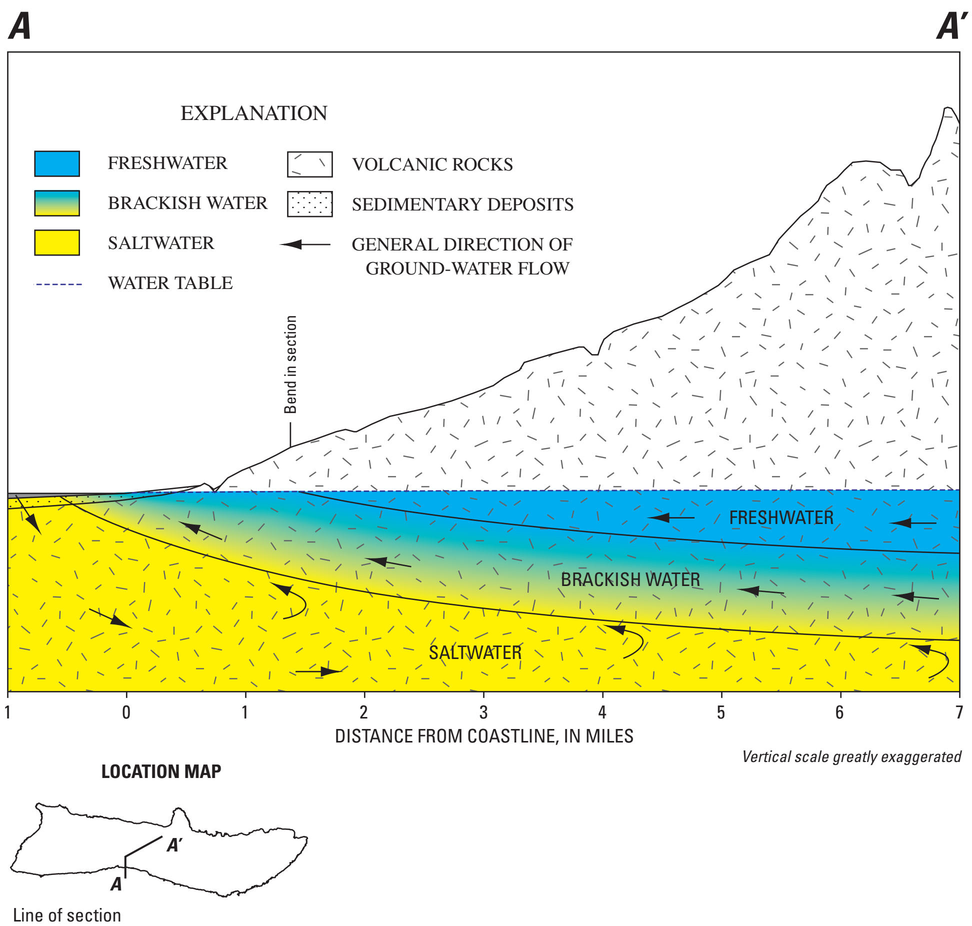


Figure 8. Schematic cross section of the ground-water-flow system on the Island of Molokai, Hawaii.

40 ft of freshwater below sea level. For dynamic conditions, the Ghyben-Herzberg relation generally underestimates the freshwater-lens thickness near the discharge zone and overestimates it near the recharge zone. The Ghyben-Herzberg relation is sometimes used to estimate the depth at which brackish water in the transition zone has a salinity about 50 percent that of seawater.

Dike-Impounded Ground Water

Within the dike complex of East Molokai Volcano, fresh ground water is impounded to high levels in the volcanic rocks between low-permeability dikes. In the valleys of the northeastern part of the island, the presence of springs indicates that ground water in the dike complex is probably impounded to altitudes higher than 2,000 ft above sea level (Stearns and Macdonald, 1947, p. 75). Because of low recharge rates in the western part of the island, 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, reducing 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.

Depth to Saline Water

Salinity profiles from deep open boreholes (deep monitor wells) commonly are used in Hawaii to estimate the thicknesses of the freshwater lens and freshwater-saltwater transition zone. The USGS drilled a deep monitor well (0800–01, fig. 6) in the Kualapuu area (Oki and Bauer, 2001) and collected salinity profiles from this well during the period 2001–4 (fig. 9). Measured salinity profiles indicate a freshwater lens, about 260 to 290 ft thick, defined by a fluid conductivity lower than 1,000 μS/cm. The thickness of this freshwater lens may vary over time because of changes in recharge or pumping rates. The upper part of the freshwater-saltwater transition zone, as indicated by fluid conductivity between 1,000 and 25,000 μS/cm, generally is about 150 ft thick.

Salinity profiles from deep open boreholes, such as well 0800–01 (fig. 6), may be affected by flow within the borehole (Paillet and others, 2002) caused by both natural and withdrawal-induced vertical-head differences in the aquifer. In areas where the head decreases with depth, downward borehole flow may occur, leading to an overestimate of the freshwater-lens thickness based on the recorded salinity profile. The head may increase with depth in the aquifer near partially penetrating pumped wells or coastal discharge areas, and an increase in head in the aquifer with depth may lead to upward flow within an open borehole. Upward borehole flow may cause saltwater to flow upward in the borehole, leading to an underestimate of the freshwater-lens thickness based on the recorded salinity profile.

The estimated thickness of the freshwater-saltwater transition zone may be unreliable if significant vertical flow causes mixing of water within the borehole. A flowmeter can be used to estimate the rate of vertical flow at different depths in an open borehole, although a flowmeter was not lowered into well 0800–01. 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.

A time-domain electromagnetic survey in the Kualapuu area was conducted by Blackhawk Geosciences, Inc. (Hawaii Commission on Water Resource Management, 1997) to estimate the depth to saline water (unspecified salinity). Results of the survey indicate that the altitude of the saline-water zone in the aquifer rises to the southwest (fig. 7). The results of this survey are consistent with the expected southwesterly decrease in water level. However, the estimated altitude of the saline-water zone from the survey is about 800 to 1,000 ft below sea level near well 0800–01 (fig. 6), deeper than where measured salinity profiles indicate fluid conductivity of 25,000 μS/cm (about 50 percent seawater) (fig. 9). In the Kualapuu area, estimated depths to saline water from the time-domain electromagnetic survey cannot be used to accurately predict water levels by using the Ghyben-Herzberg relation, mainly because the detected saline water does not correspond to 50 percent seawater.

Chloride Concentration

Chloride concentration is commonly used as an indicator of salinity, which may increase as a result of saltwater intrusion into a fresh ground-water body. The chloride concentration of water pumped from wells in the Kualapuu area generally has been less than 200 mg/L except in well 0902–01 (fig. 6). During the period 1950–61, the chloride concentration of water pumped from well 0902–01 ranged from 252 to 430 mg/L (Oki, 1997). For comparison, the chloride concentration of rainfall is typically less than 10 to 20 mg/L (Swain, 1973), and that of seawater about 19,500 mg/L (Wentworth, 1939).

During the 1990s, chloride concentrations of water pumped from wells 0801–01, 0801–02, 0801–03, and 0901–01 (fig. 6) in the Kualapuu area were less than 200 mg/L (fig. 10). During the same period, chloride concentrations of water pumped from well 0901–01 generally were about 50 mg/L, whereas chloride concentrations of water pumped from wells 0801–01, 0801–02, and 0801–03 generally ranged from 50 to 150 mg/L.

Before the early 1980s, chloride concentrations of water pumped from the Kawela Shaft (well 0457–01, fig. 6) were less than 100 mg/L (fig. 10). During 1996 through 1998, chloride concentrations of water pumped from Kawela Shaft ranged from 100 to 200 mg/L, and since 2002 chloride concentrations generally have been greater than 200 mg/L.

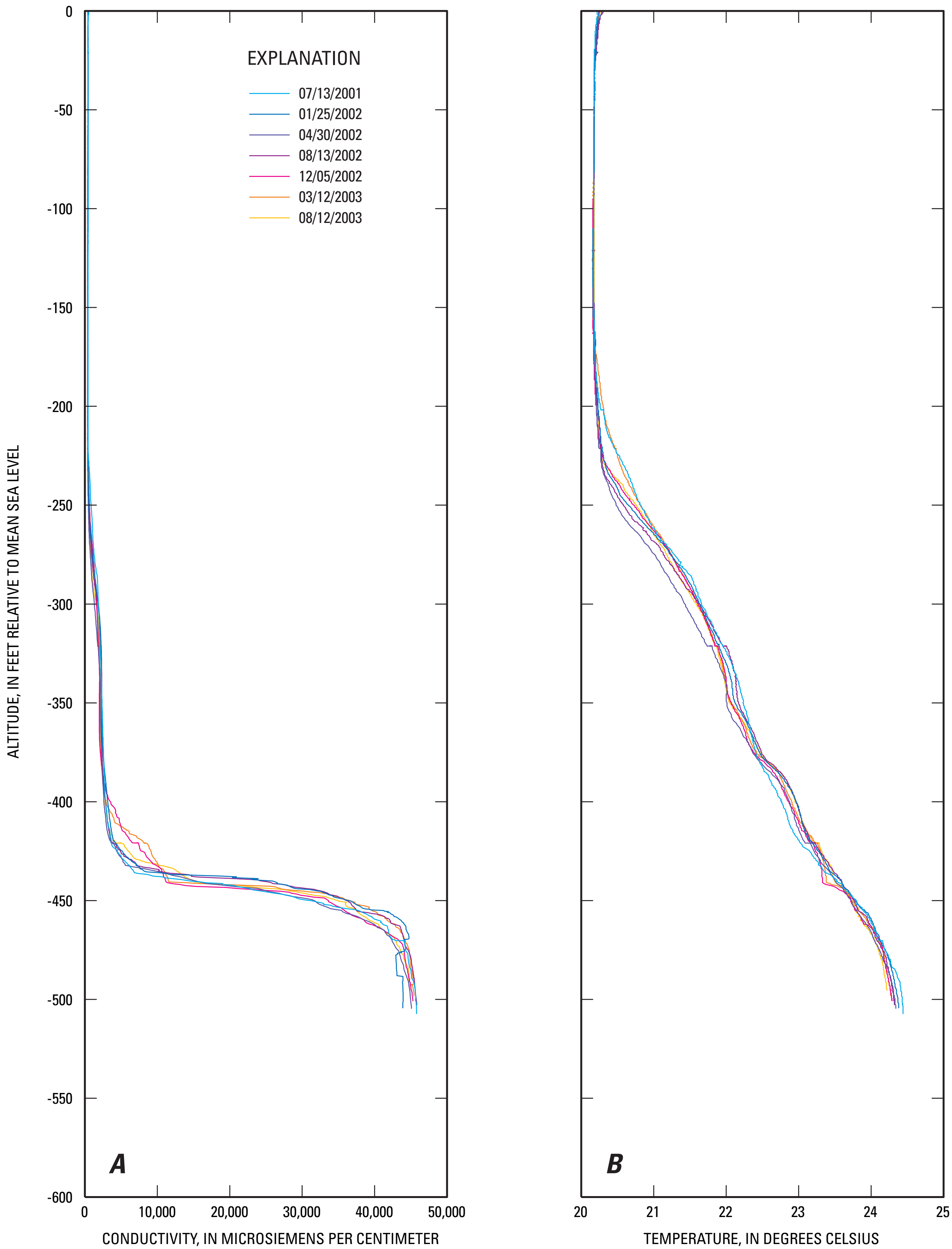


Figure 9. Fluid-conductivity (*A*) and fluid-temperature (*B*) profiles in the Kualapuu deep monitor well (0800–01) on the Island of Molokai, Hawaii.

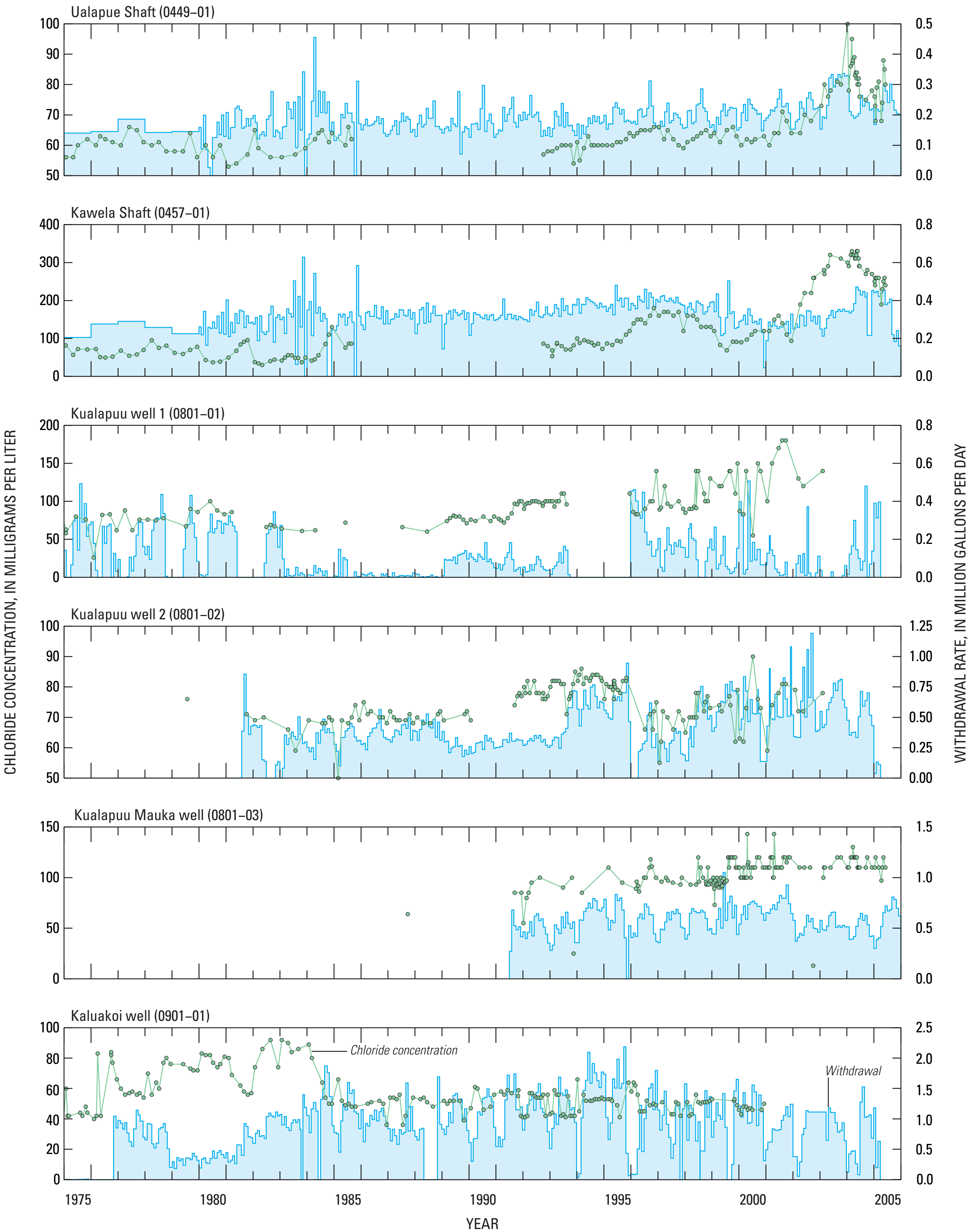


Figure 10. Chloride concentrations in water pumped from selected wells on the Island of Molokai, Hawaii (see fig. 6 for locations). Data from the U.S. Geological Survey and the County of Maui Department of Water Supply.

Before 2002, chloride concentrations of water pumped from the Ualapue Shaft (well 0449–01) generally were less than 70 mg/L (fig. 10); from 2003 through 2005, however, chloride concentrations generally were more than 70 mg/L, reaching a maximum of 100 mg/L during 2004.

Withdrawals

Most of the ground water withdrawn on Molokai is from the Kualapuu area, the southeast coastal area, and the dike complex in the northeastern part of the island. The reported mean annual withdrawal from wells (excluding the Molokai Irrigation System [MIS] Tunnel) on Molokai during the period 2000–2 was about 4.2 Mgal/d (computed from digital data supplied by Kevin Gooding, CWRM, written commun., 2005).

Five production wells (0801–01, 0801–02, 0801–03, 0901–01, and 0902–01, fig. 6) have been drilled in the Kualapuu area for either irrigation or domestic use. Wells 0901–01 and 0902–01, drilled in 1950 and 1946, respectively, originally were used to irrigate pineapple fields in the Hoolehua Plain area. Well 0902–01 was abandoned in 1964 when surface water from the MIS Tunnel (fig. 1) became available. Since 1976, water from well 0901–01 has been used for domestic and irrigation purposes in the western part of the island. Before the MIS Tunnel was completed, combined withdrawals from wells 0901–01 and 0902–01 varied seasonally from near 0 to about 1 Mgal/d (fig. 11). Kualapuu wells 0801–01 and 0801–02 (fig. 6) were completed in 1949 and 1979, respectively, and well 0801–03 (Kualapuu Mauka) was drilled in 1987. Monthly mean withdrawal rates from each of these three wells (0801–01, 0801–02, and 0801–03) generally have remained below 1 Mgal/d (fig. 11). During the period 2000–2, mean annual withdrawal from the four active wells in the Kualapuu area was about 2.2 Mgal/d. During 2005, mean annual withdrawal from well 0801–03 was 0.605 Mgal/d.

Near the south coast, 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 well (0457–01, fig. 6), near Kawela, was completed in 1921, and the other well (0449–01, fig. 6), near Ualapue, was completed in 1936. During the period 2000–2, mean annual withdrawals from Kawela Shaft (well 0457–01) and Ualapue Shaft (well 0449–01) were about 0.28 and 0.22 Mgal/d, respectively. During 2005, mean annual withdrawals from wells 0457–01 and 0449–01, respectively, were 0.348 and 0.234 Mgal/d. Total reported mean annual withdrawals from other wells near the south coast were less than 0.5 Mgal/d. Total unreported withdrawals from drilled wells and numerous shallow dug wells along the south coast are probably small.

Three production wells (0855–01, 0855–02, and 0855–03, fig. 6) drilled in 1961 withdraw water from the dike complex in the northeastern part of the island. Water from these wells enters the MIS. During the period 2000–2, mean annual withdrawal from these three wells was 0.99 Mgal/d.

Numerical Simulation of Additional Ground-Water Withdrawal

A numerical ground-water-flow model previously was constructed to simulate steady-state regional ground-water flow on Molokai (Oki, 1997). The same model was used in this study to estimate steady-state water-level and coastal-discharge changes caused by possible redistributed and additional ground-water withdrawals in the area between Kualapuu and Ualapue.

Model Description

The regional model uses the two-dimensional (areal), finite-element code AQUIFEM–SALT (Voss, 1984), which was designed to simulate the flow of confined or unconfined fresh ground water in systems that may have a freshwater lens. AQUIFEM–SALT simulates freshwater and saltwater as immiscible fluids separated by a sharp interface, the depth of which is determined by the Ghyben-Herzberg relation. In reality, a diffuse transition zone exists between the core of freshwater and underlying saltwater. AQUIFEM–SALT simulates the vertically averaged freshwater head in the aquifer and assumes that flow is entirely horizontal and that all wells fully penetrate the freshwater lens.

The model mesh, boundary conditions, hydraulic characteristics, and recharge used in this study are the same as those used in the original numerical model by Oki (1997), to which the reader is referred for a complete description of these features and construction details.

Model Application

The model by Oki (1997) was used in this study to estimate the steady-state hydrologic effects of ground-water withdrawals on ground-water levels and coastal discharge. The original model mesh consists of 6,432 nodes and 6,251 square elements (1,640 ft on a side). The mesh includes the entire Island of Molokai and extends offshore to include the entire coastal-discharge zone (fig. 12). The original mesh is therefore valid for testing the scenarios described in this study.

A base case defined mainly by 2005 mean annual withdrawal rates and May 2005 permitted withdrawal rates (table 1) was used to compute the water-level and coastal-discharge changes caused by redistributed or additional ground-water withdrawals. In this model, withdrawals were assigned to the node nearest to the withdrawal site. The hydraulic characteristics and long-term average recharge distribution used in the original model (Oki, 1997) were used for all simulations in this study.

Boundary conditions used in the original model include a no-flow boundary condition coinciding with the perimeter of the mesh and head-dependent-discharge boundary conditions used to simulate ground-water discharge to the ocean and

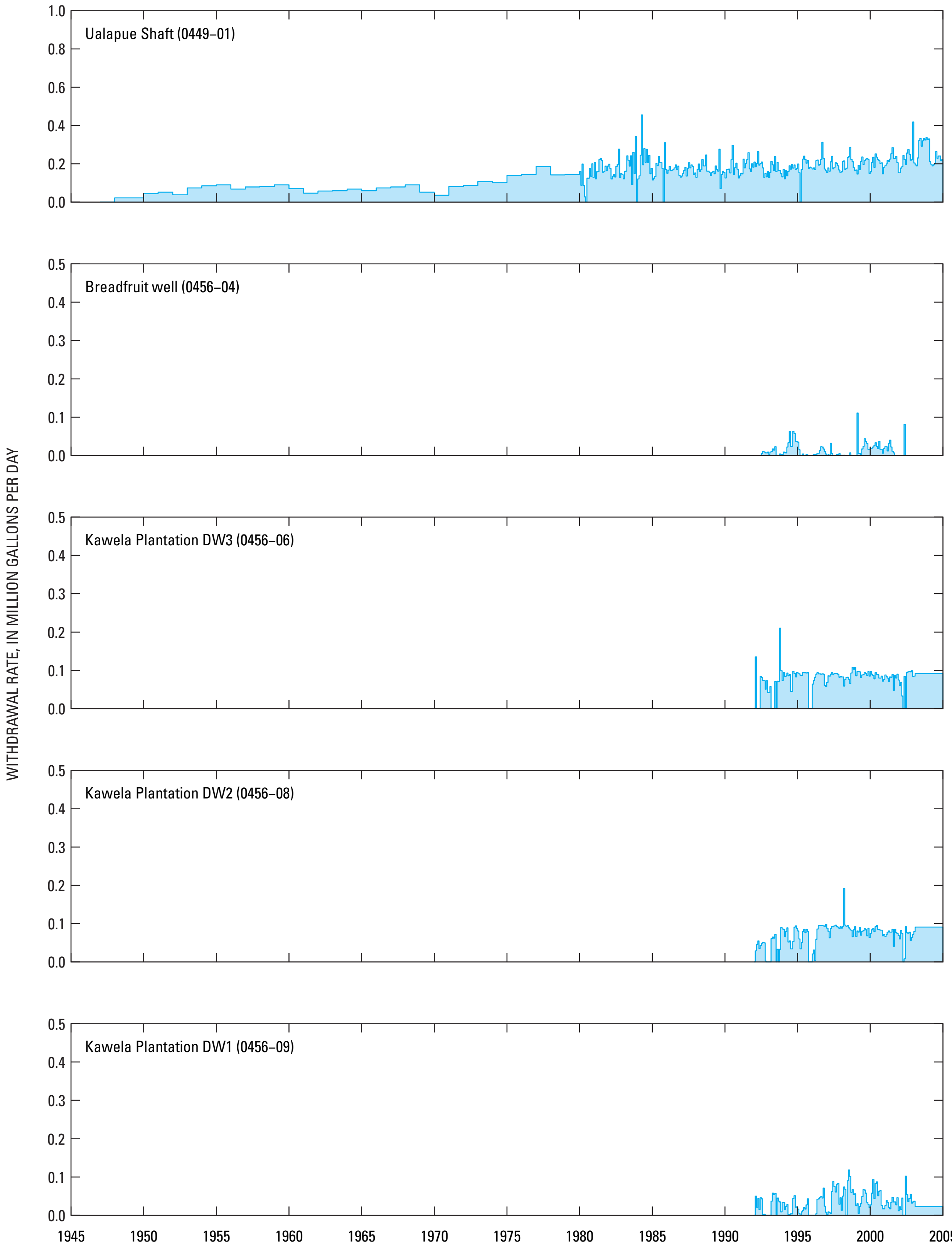


Figure 11. Reported ground-water withdrawal from selected wells on the Island of Molokai, Hawaii (see fig. 6 for locations). Data from the U.S. Geological Survey, the County of Maui Department of Water Supply, and the Hawaii Commission on Water Resource Management.

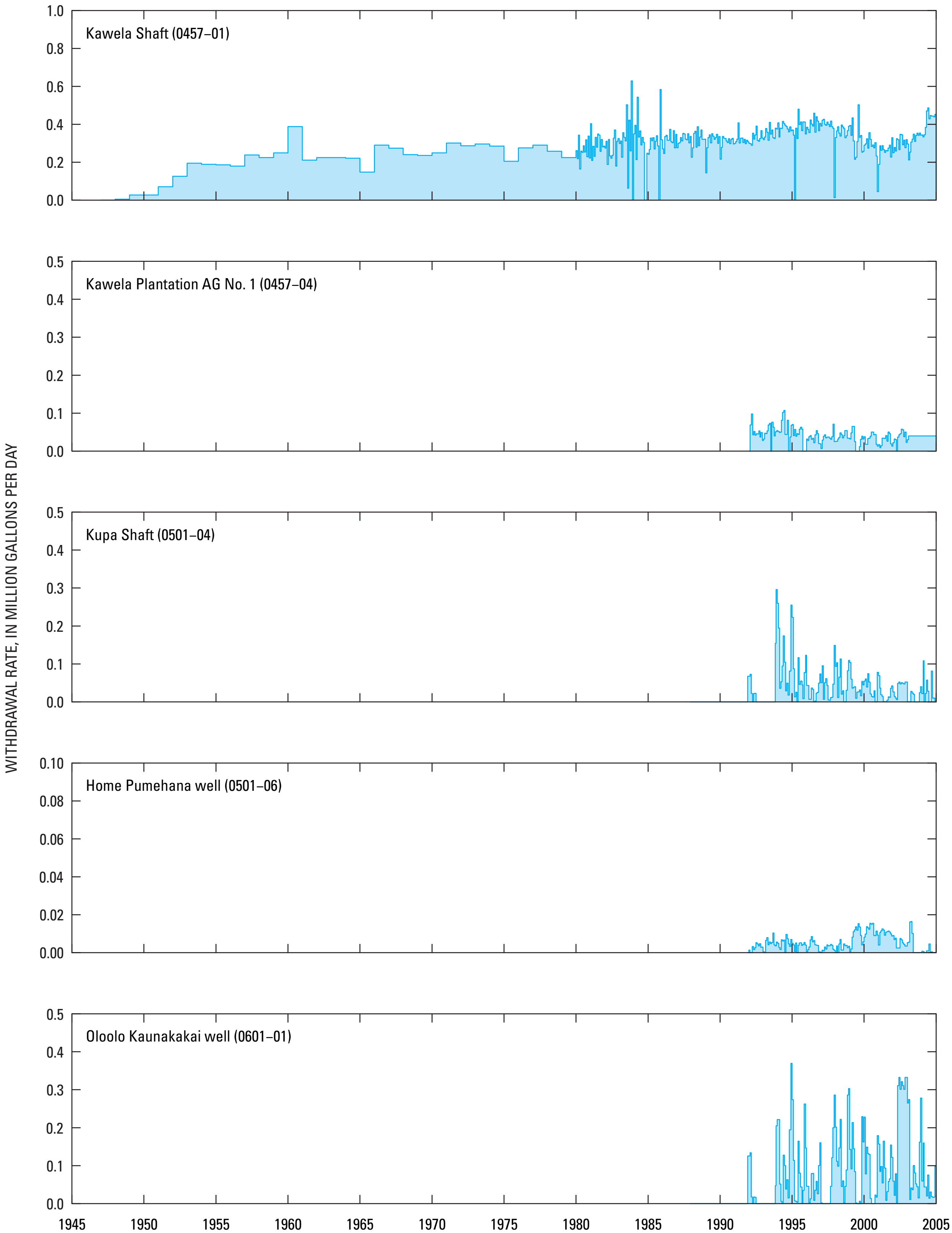


Figure 11. Reported ground-water withdrawal from selected wells on the Island of Molokai, Hawaii (see fig. 6 for locations). Data from the U.S. Geological Survey, the County of Maui Department of Water Supply, and the Hawaii Commission on Water Resource Management—*Continued*.

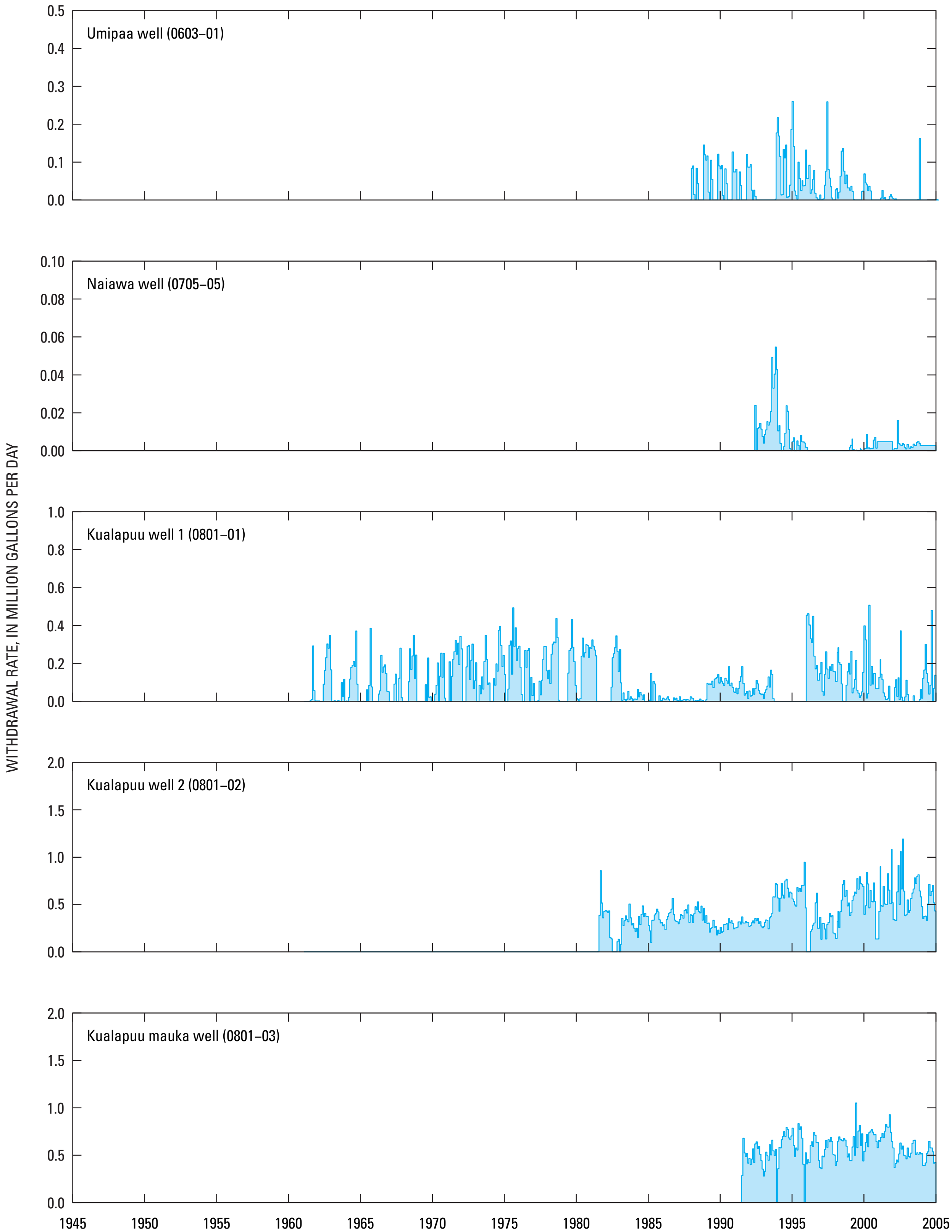


Figure 11. Reported ground-water withdrawal from selected wells on the Island of Molokai, Hawaii (see fig. 6 for locations). Data from the U.S. Geological Survey, the County of Maui Department of Water Supply, and the Hawaii Commission on Water Resource Management—*Continued*.

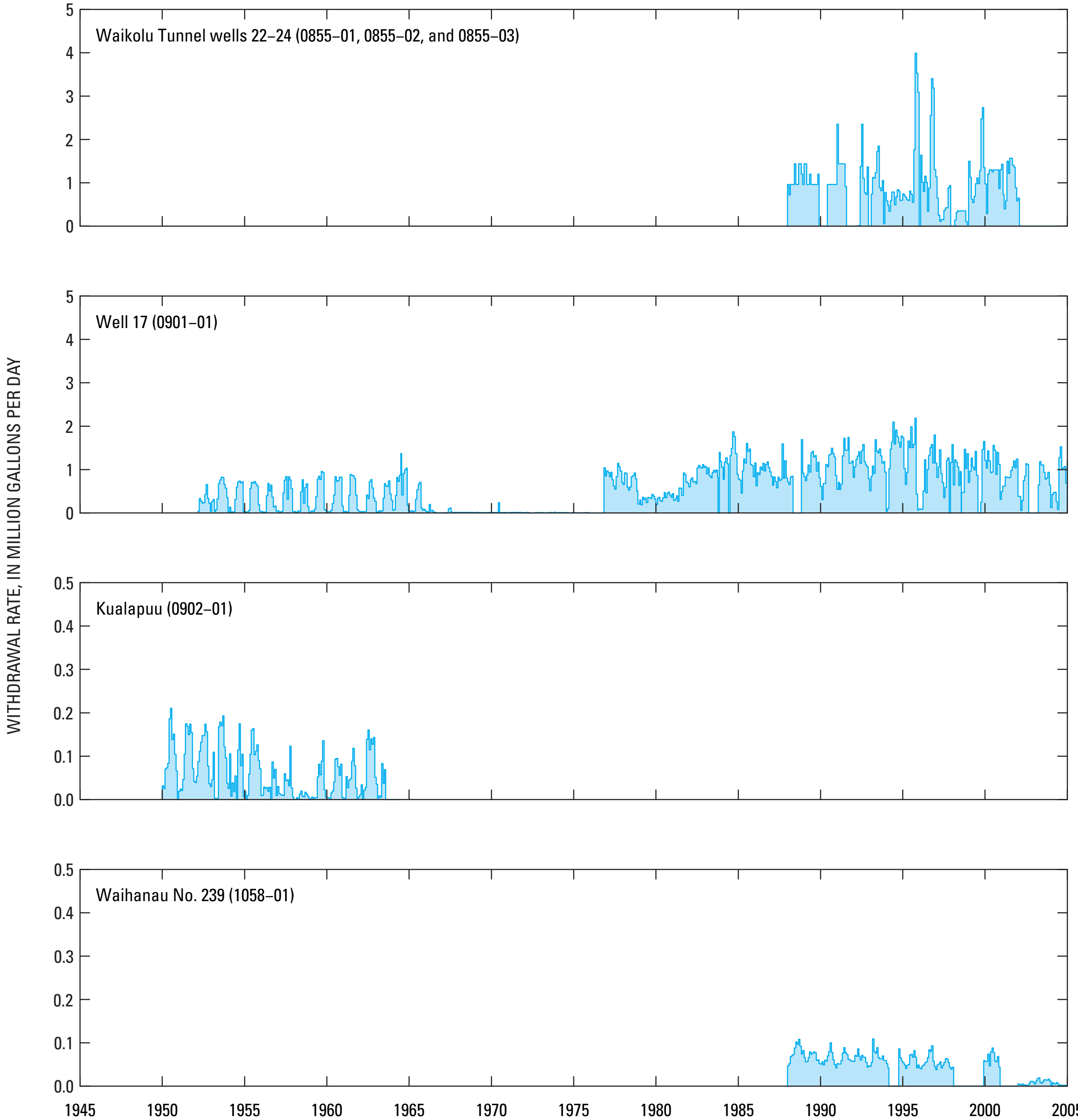


Figure 11. Reported ground-water withdrawal from selected wells on the Island of Molokai, Hawaii (see fig. 6 for locations). Data from the U.S. Geological Survey, the County of Maui Department of Water Supply, and the Hawaii Commission on Water Resource Management—*Continued*.

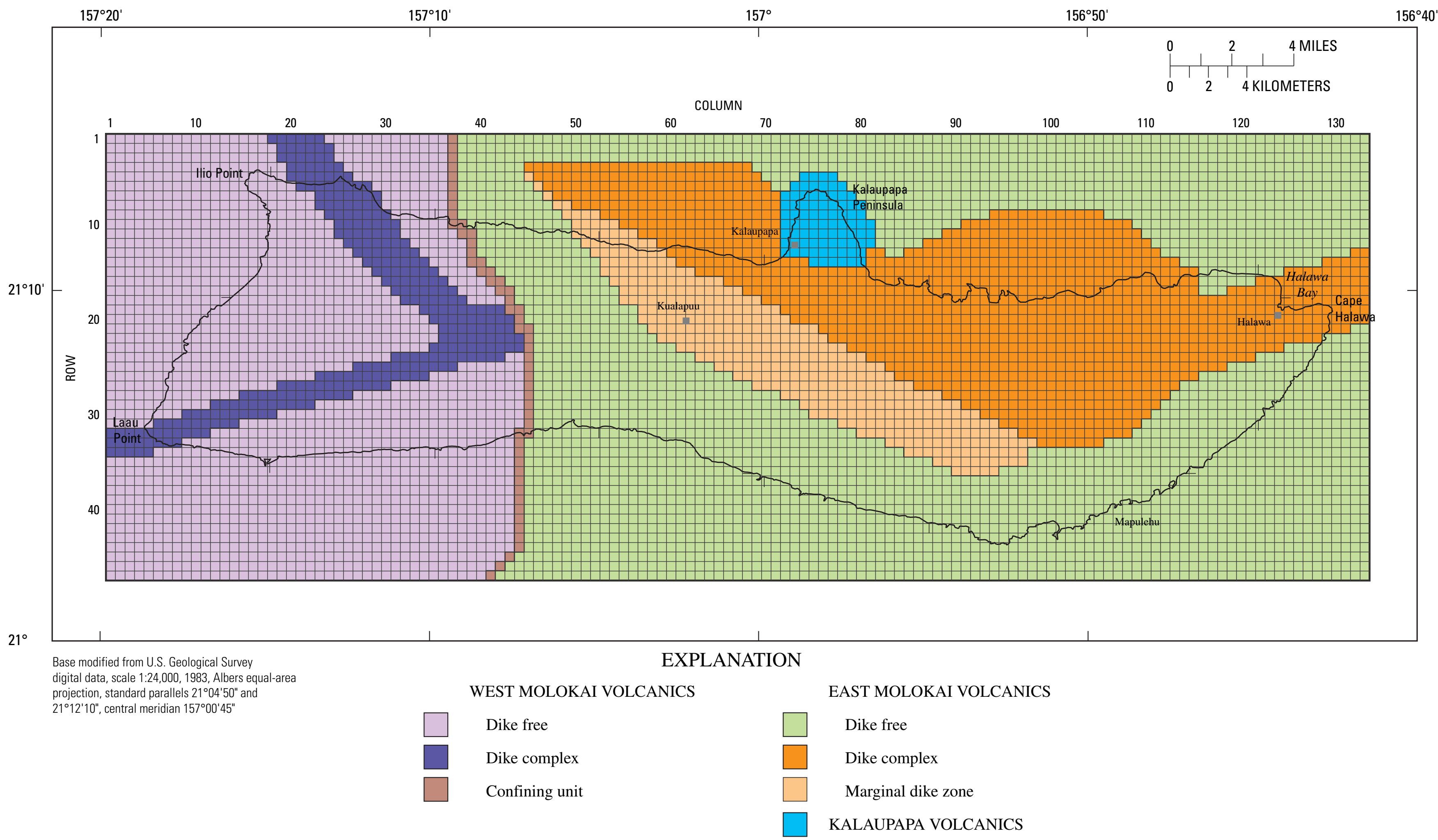


Figure 12. Model mesh and hydraulic-conductivity zones used in the ground-water-flow model for the Island of Molokai, Hawaii.

streams. Because ocean levels, coastal bathymetry, and stream-channel altitudes have not changed sufficiently, the original boundary conditions (Oki, 1997) were used in this study.

The water level in Puu O Hoku No. 1 well (0844–01, fig. 6), which was drilled after the model was constructed, is about 9 ft above mean sea level (Hawaii Commission on Water Resource Management, unpub. data, 2006), indicating that the well site is probably not in the dike complex as originally modeled. Thus, the model is not used to specifically assess the hydrologic effects of ground-water withdrawal from this well, which is located near the east end of the island, outside the main area of interest between Kualapuu and Ualapue.

Description of Model Scenarios

The 2005 base-case scenario was used as a reference for computing steady-state water-level and coastal-discharge changes caused by redistributed or additional ground-water withdrawals. The withdrawal rates used in the 2005 base case were mean 2005 withdrawal rates at wells 0449–01 (Ualapue Shaft), 0457–01 (Kawela Shaft), and 0801–03 (Kualapuu Mauka), the May 2005 permitted withdrawal rates at other wells (excluding Puu O Hoku No. 1, Waiola No. 1, and the DHHL reservation), and the 1.822-Mgal/d withdrawal rate from the MIS Tunnel (Oki, 1997) near Waikolu Stream (fig. 6; table 1). Proposed Waiola No. 1 well (0759–01) is not likely to be drilled (Charley F. Ice, CWRM, written commun., 2006), and so it was omitted from the model. The DHHL reservation was omitted from the base case, although it was simulated in a scenario described below. The 2005 base-case withdrawal rates range from 0.001 Mgal/d (well 0352–12) to 1.822 Mgal/d (MIS Tunnel) and total 9.164 Mgal/d (fig. 6; table 1). The total base-case withdrawal exclusive of the MIS Tunnel is 7.342 Mgal/d, or about 75 percent higher than the reported 2000–2 mean annual withdrawal of 4.2 Mgal/d (excluding the MIS Tunnel). Total withdrawal represented in the base case is 5 percent of recharge (187 Mgal/d).

The DWS provided five proposed withdrawal sites (Manawainui, Kawela 1, Kawela 2, Kamiloloa, and Ualapue) to be tested in the model (fig. 2; table 2). A total of 15 scenarios, excluding the base case, were tested. In scenarios 1 through 13, withdrawals from existing wells 0449–01, 0457–01, and 0801–03 (fig. 6) were fully or partially redistributed to one to four of the proposed withdrawal sites. In scenarios 1 through 8, the total withdrawal equals the base-case withdrawal, whereas in scenarios 9 through 13 the total withdrawal exceeds the base-case withdrawal by 0.28 Mgal/d. Scenarios 9 through 13 incorporate an increased water demand forecast for 2030 by the DWS. Scenario 14 is similar to scenario 11 but includes the 2.905-Mgal/d withdrawal from the DHHL reservation arbitrarily assigned to three sites in the Kualapuu area. Scenario 15 corresponds to natural conditions without any withdrawals. For all simulations, recharge in the model was 187 Mgal/d.

Model Results

For each of the scenarios tested, the steady-state distributions of water-level and coastal-discharge changes were determined relative to the 2005 base-case, steady-state distributions of water levels and coastal discharges. Simulated water-level changes are greatest at withdrawal sites and decrease outward with distance elsewhere. Within the zone where water levels rise because of decreased withdrawal, the salinity of water pumped from existing wells may decrease, although the extent of the decrease cannot be predicted accurately with the sharp-interface model used in this study. Similarly, within the zone where water levels decline because of increased withdrawal, the salinity of water pumped from existing wells may increase by an unknown amount. The change in the salinity of water pumped from existing wells is dependent on the amount of water-level change and the location of the well relative to the freshwater-saltwater transition zone. Greater water-level changes (all other factors being equal) are expected to cause

Table 2. Proposed ground-water-withdrawal sites on the Island of Molokai, Hawaii.

[DHHL, Hawaii Department of Hawaiian Home Lands]

Site	Name	Approximate altitude (feet)	Aquifer system
1	Manawainui	925	Manawainui
2	Kawela 1	700	Kawela
3	Kamiloloa	700	Kamiloloa
4	Kawela 2	700	Kawela
5	Ualapue	400	Ualapue
6	DHHL reservation 1	1,200	Kualapuu
7	DHHL reservation 2	1,600	Kualapuu
8	DHHL reservation 3	1,800	Kualapuu

greater salinity changes. Deep wells or wells near the coast may be located near a source of brackish ground water (transition zone) and affected to a greater extent than shallow or inland wells.

Simulated coastal-discharge changes generally are greatest immediately downgradient from sites of withdrawal change, and areas of coastal-discharge changes may correspond to sites of mapped fishponds or springs (fig. 1). In general, coastal-discharge changes are difficult to directly measure except at onshore spring sites where discharge is channelized. Thus, the numerical model is used in this study to provide regional estimates of coastal-discharge changes caused by redistributed or additional ground-water withdrawals. In this study, coastal-discharge changes are represented over areas defined by model elements (1,640 by 1,640 ft). Coastal-discharge changes less than or equal to 1,000 gal/d within model elements are considered too small to be represented accurately by the regional model and therefore are not shown; however, coastal-discharge changes greater than 1,000 gal/d generally account for about 95 percent of the total simulated change in discharge. Simulated coastal-discharge changes may not accurately reflect actual local-scale changes because of the level of spatial discretization and because local-scale heterogeneities in the hydraulic characteristics of the rocks are not represented in the model.

Scenarios 1 Through 8—Redistribution of Withdrawals

In each of scenarios 1 through 8, withdrawals from existing wells 0449–01, 0457–01, and 0801–03 (fig. 6) were partially or fully redistributed to one to four proposed withdrawal sites (fig. 2; table 3), and the total withdrawal from all sites equals the total 2005 base-case withdrawal. In scenarios 1 through 8, the total combined withdrawal from proposed withdrawal sites and wells 0449–01, 0457–01, and 0801–03 is 1.187 Mgal/d. In these eight scenarios, withdrawal from well 0801–03 was reduced by 0.232 or 0.432 Mgal/d, and withdrawals from wells 0449–01 and 0457–01 were maintained at 2005 base-case rates or set equal to zero.

In scenario 1, in which the withdrawal from well 0801–03 (fig. 6) is reduced by 0.232 Mgal/d and the withdrawal from proposed withdrawal site 1 is increased by the same amount, the hydrologic effects of each well are first simulated separately (figs. 13, 14) and then combined (fig. 15). Reducing the withdrawal from well 0801–03 by 0.232 Mgal/d without increasing the withdrawal from proposed withdrawal site 1 causes water levels and coastal discharge to increase (fig. 13). The water level at well 0801–03 rises by 0.63 ft, and water-level rises decrease outward with distance from well 0801–03. Coastal discharge increases mainly along the south

Table 3. Summary of withdrawal scenarios simulated with the ground-water-flow model for the Island of Molokai, Hawaii.

[Values in **red bold** indicate that withdrawal rate differs from base-case withdrawal at the site; Mgal/d, million gallons per day; DHHL, Hawaii Department of Hawaiian Home Lands]

Scenario	Simulated withdrawal (Mgal/d)									
	Well 0801–03 (Kualapuu Mauka)	Well 0457–01 (Kawela Shaft)	Well 0449–01 (Ualapue Shaft)	Proposed site 1 (Manawainui)	Proposed site 2 (Kawela 1)	Proposed site 3 (Kamiloloa)	Proposed site 4 (Kawela 2)	Proposed site 5 (Ualapue)	DHHL	Total
Base case	0.605	0.348	0.234	0	0	0	0	0	0	1.187
1	**0.373**	0.348	0.234	**0.232**	0	0	0	0	0	1.187
2	**0.373**	**0**	0.234	**0.232**	**0.348**	0	0	0	0	1.187
3	**0.373**	**0**	**0**	**0.232**	**0.348**	0	0	**0.234**	0	1.187
4	**0.173**	0.348	0.234	**0.432**	0	0	0	0	0	1.187
5	**0.173**	**0**	0.234	**0.432**	**0.348**	0	0	0	0	1.187
6	**0.173**	**0**	**0**	**0.432**	**0.348**	0	0	**0.234**	0	1.187
7	**0.173**	**0**	**0**	**0.232**	**0.348**	**0.200**	0	**0.234**	0	1.187
8	**0.173**	**0**	**0**	**0.232**	**0.348**	0	**0.200**	**0.234**	0	1.187
9	**0.465**	**0.392**	**0.378**	**0.232**	0	0	0	0	0	**1.467**
10	**0.465**	**0**	**0.378**	**0.232**	**0.392**	0	0	0	0	**1.467**
11	**0.465**	**0**	**0**	**0.232**	**0.392**	0	0	**0.378**	0	**1.467**
12	**0.173**	**0**	**0**	**0.232**	**0.392**	**0.292**	0	**0.378**	0	**1.467**
13	**0.173**	**0**	**0**	**0.232**	**0.392**	0	**0.292**	**0.378**	0	**1.467**
14	**0.465**	**0**	**0**	**0.232**	**0.392**	0	0	**0.378**	**2.905**	**4.372**
15	**0**	**0**	**0**	0	0	0	0	0	0	**0**

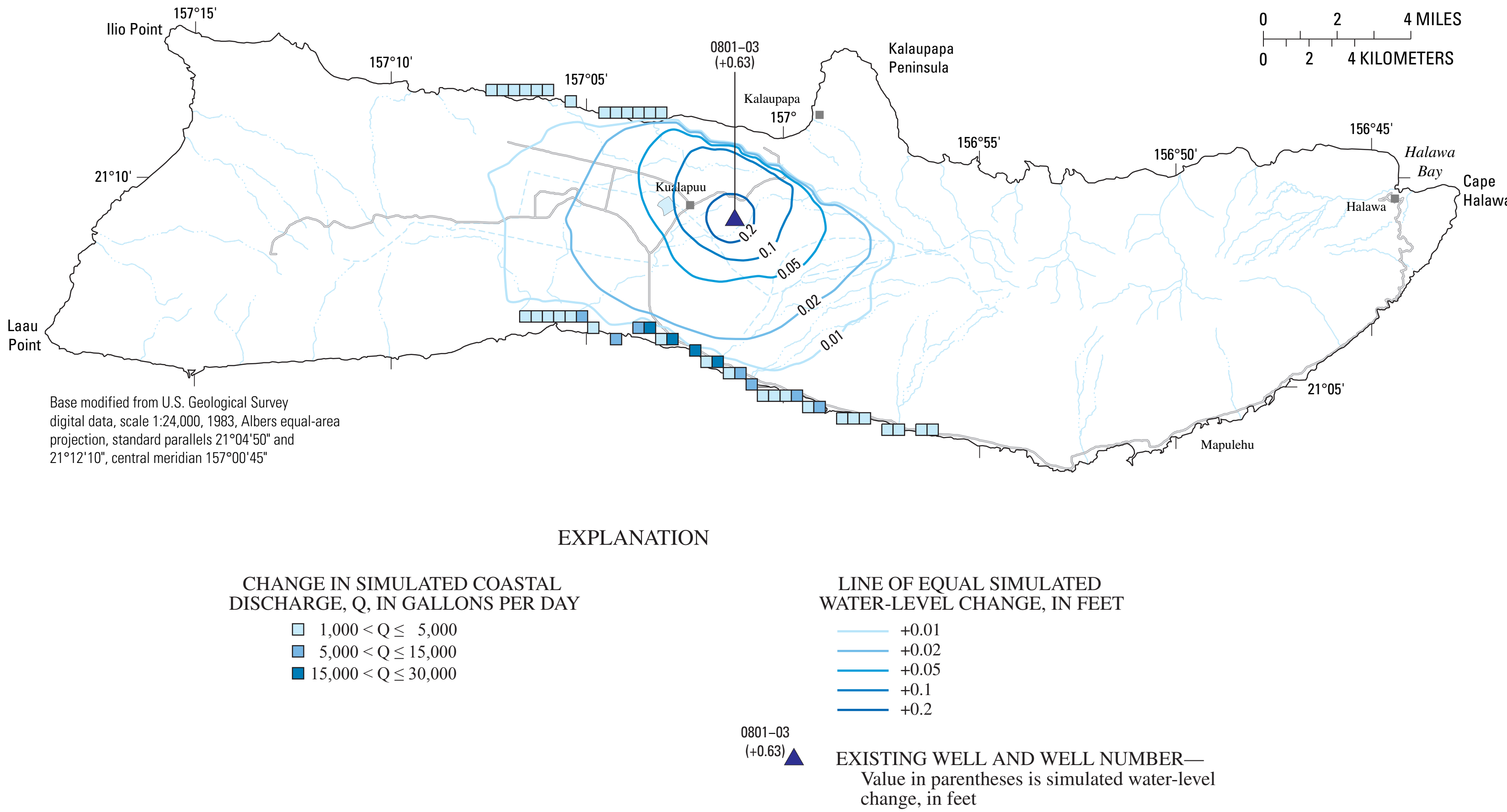


Figure 13. Simulated changes in water level and coastal discharge (relative to base-case conditions) caused by decreasing withdrawal by 0.232 million gallons per day from the existing Kualapuu well (0801–03), Island of Molokai, Hawaii.

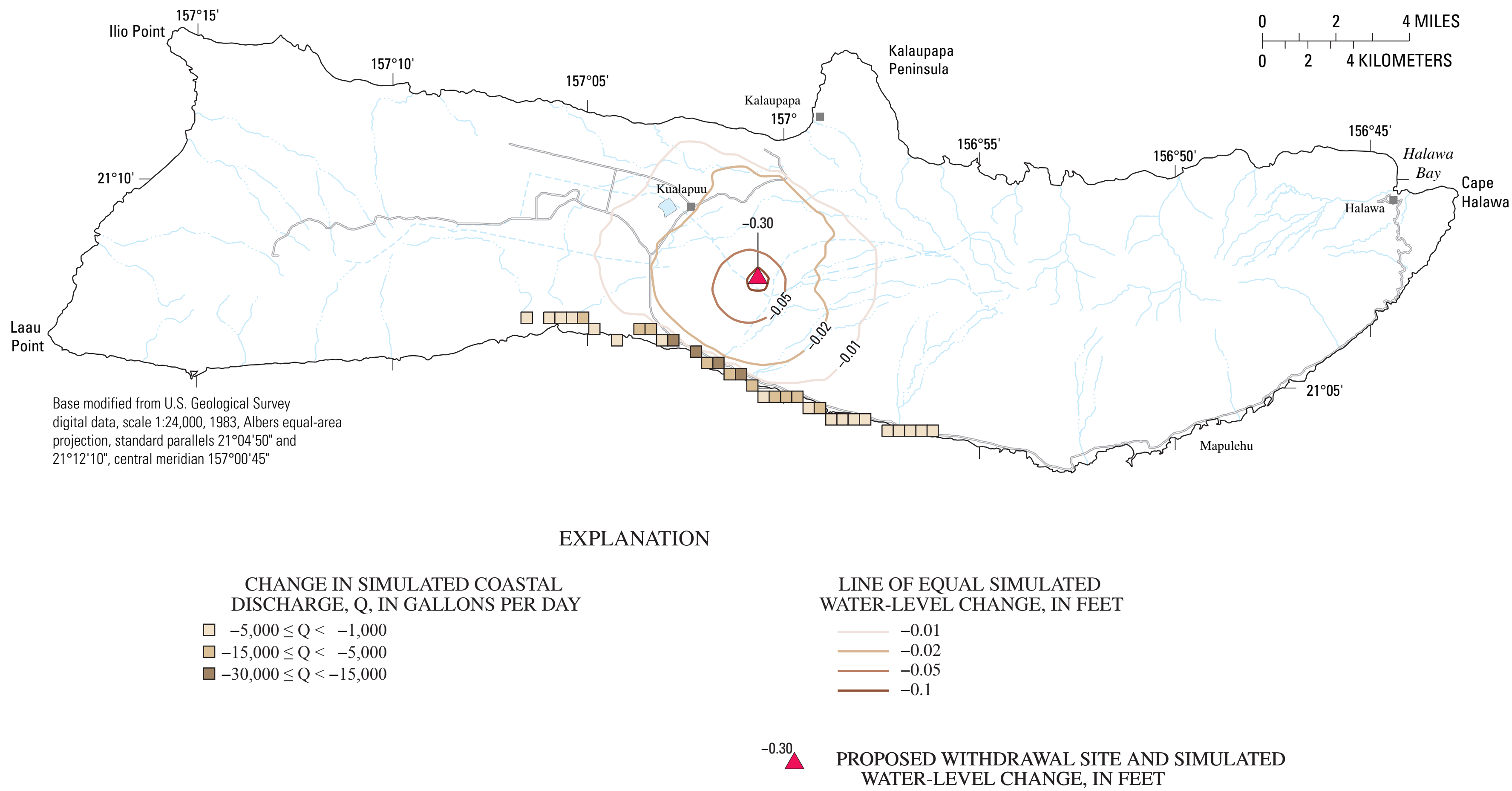


Figure 14. Simulated changes in water level and coastal discharge (relative to base-case conditions) caused by withdrawing 0.232 million gallons per day from proposed site 1 (Manawainui), Island of Molokai, Hawaii.

Scenario 1

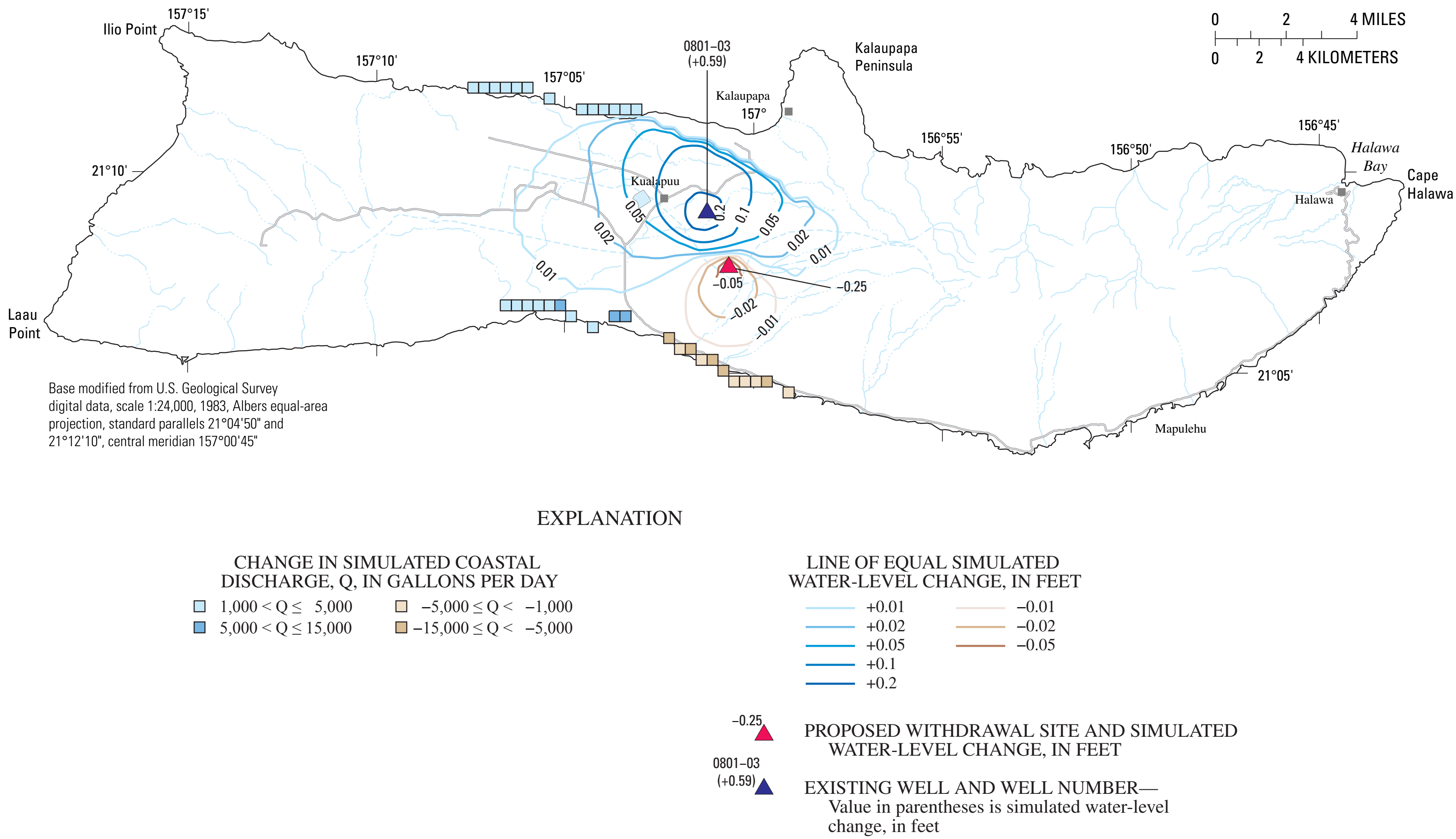


Figure 15. Scenario 1 of ground-water-flow model for the Island of Molokai, Hawaii, showing simulated changes in water level and coastal discharge (relative to base-case conditions) caused by decreasing withdrawal by 0.232 million gallons per day from the existing Kualapuu well (0801–03) and withdrawing 0.232 million gallons per day from proposed site 1 (Manawainui).

coast from Palaau to Kawela but also along the north coast, northwest of well 0801–03. Withdrawing 0.232 Mgal/d from proposed withdrawal site 1 without reducing the withdrawal from well 0801–03 causes water levels and coastal discharge to decrease (fig. 14). The water level at proposed withdrawal site 1 declines by 0.30 ft, and water-level declines decrease outward from proposed withdrawal site 1. Coastal discharge decreases along the south coast from Palaau to Kawela. The scenario 1 combination of reducing withdrawal from well 0801–03 by 0.232 Mgal/d and withdrawing the same amount from proposed site 1 causes the water level at well 0801–03 to rise by 0.59 ft and the water level at proposed site 1 to decline by 0.25 ft (fig. 15). Thus, the water-level changes simulated in scenario 1 are reduced relative to those caused by the individual withdrawals. In addition, the zone where coastal discharge increases because of reduced withdrawal from well 0801–03 is smaller if the withdrawal from proposed site 1 is 0.232 Mgal/d rather than 0. Similarly, the zone where coastal discharge decreases because of increased withdrawal from proposed withdrawal site 1 is smaller if the withdrawal from well 0801–03 is reduced by 0.232 Mgal/d rather than 0.

In scenarios 1 through 8, simulation results indicate that a redistribution of withdrawals causes a corresponding redistribution of water levels and coastal discharge. Water levels rise and coastal discharge increases near sites of reduced withdrawal, whereas water levels decline and coastal discharge decreases near sites of increased withdrawal (figs. 15–22). The magnitude and areal extent of the hydrologic changes caused by redistributing ground-water withdrawals increase with larger withdrawal changes. The magnitude of hydrologic changes also generally decreases with distance from the withdrawal sites.

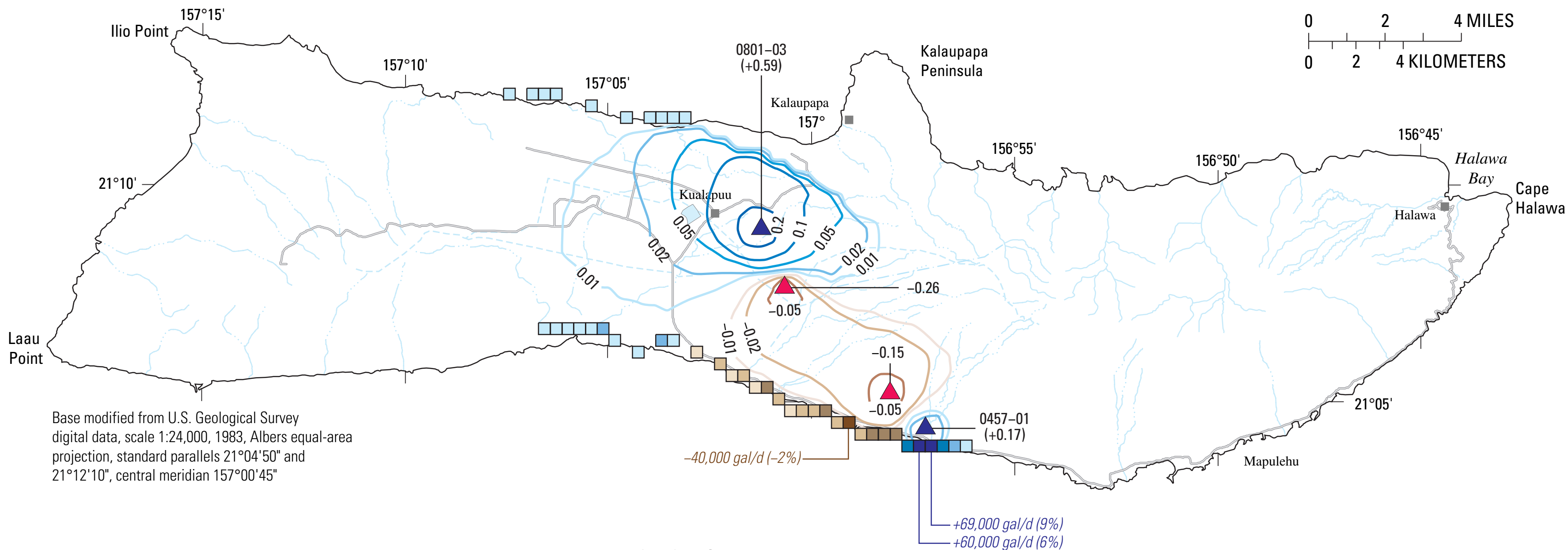
At existing wells where withdrawal rates are reduced, simulated water levels rise by 0.08 ft at well 0449–01 (Ualapue Shaft in scenarios 3, 6, 7, and 8) to 1.10 ft at well 0801–03 (Kualapuu Mauka in scenarios 7 and 8) (table 4). At proposed sites where withdrawals are increased, simulated water levels decline by 0.07 ft at site 5 (Ualapue in scenarios 3, 6, 7, and 8) to 0.48 ft at site 1 (Manawainui in scenarios 5 and 6) (table 4). Simulated water-level changes decrease with distance from withdrawal sites. The magnitudes of simulated water-level changes increase with larger withdrawal changes. For example, simulated water-level changes (relative to the base case) in scenario 4 (fig. 18) are greater than those in scenario 1 (fig. 15) because the magnitudes of withdrawal changes simulated in scenario 4 are greater than in scenario 1 at common sites. In scenario 1, the simulated water level at well 0801–03 rises by 0.59 ft in response to a withdrawal reduction of 0.232 Mgal/d (fig. 15), whereas in scenario 4 the water level at well 0801–03 rises by 1.08 ft in response to a withdrawal reduction of 0.432 Mgal/d (fig. 18). Similarly, in scenario 1, the simulated water level at proposed withdrawal site 1 declines by 0.25 ft in response to withdrawal of 0.232 Mgal/d (fig. 15), whereas in scenario 4 the water level at site 1 declines by 0.47 ft in response to withdrawal of 0.432 Mgal/d (fig. 18).

The areal extent of simulated water-level change, as indicated by the ±0.01-ft line of equal water-level change, is dependent on the magnitude of the withdrawal change and the location of the withdrawal site relative to low-permeability features, the coast, and other withdrawal sites. Larger withdrawal changes cause more widespread water-level changes (for example, compare scenarios 1 and 4). Low-permeability features represented in the regional model affect the simulated distribution of water-level changes. The areal extent of simulated water-level changes is limited in the northeast by the dike complex of East Molokai Volcano and, in some cases, in the west by the confining unit separating the West and East Molokai Volcanics (for example, figs. 18–22). In general, withdrawal sites farther inland, away from areas of coastal discharge, create more extensive areas of water-level change. For example, a withdrawal reduction of 0.232 Mgal/d from well 0801–03 (scenario 1), located in the inland Kualapuu area, creates a more extensive area of water-level change than a withdrawal reduction of 0.234 Mgal/d from the Ualapue Shaft (scenario 3), located near the coast (figs. 15, 17). The areal extent of water-level rise caused by reduced withdrawal from an existing well is limited by the effects of increased withdrawal from nearby proposed sites. For example, in scenario 1, the areal extent of water-level rise caused by reduced withdrawal from well 0801–03 does not extend to the coast immediately south of the well because of the effects of increased withdrawal from proposed site 1 (fig. 15). Reducing the withdrawal from well 0801–03 by 0.232 Mgal/d without withdrawing 0.232 Mgal/d from proposed site 1 will create a larger areal extent of water-level rise relative to that simulated in scenario 1 (compare figs. 13 and 15). Reduced withdrawal from well 0801–03 may lead to decreased salinity of the water pumped from existing wells in the Kualapuu area, although the extent of improvement cannot be predicted accurately with a sharp-interface model.

For steady-state conditions, the zero net change in withdrawal simulated in scenarios 1 through 8 will cause a zero net change in coastal discharge. Local increases and decreases in coastal discharge are simulated in scenarios 1 through 8, although the sum of the increases equals the sum of the decreases. In scenarios 1 through 8, coastal-discharge changes within model elements (1,640 ft on a side) do not exceed 70,000 gal/d (table 5). The simulated reductions in coastal discharge generally are less than 5 percent (table 5). In the regional model, the low-permeability dike complex of East Molokai Volcano impedes the simulated spreading of water-level changes to perennial streams in the northeastern part of the island, and discharge to these streams in the dike complex therefore is unaffected by proposed withdrawals.

In scenarios 1 and 4, the withdrawal from well 0801–03 (fig. 6) is partly redistributed to proposed withdrawal site 1 (Manawainui). Reducing the withdrawal from well 0801–03 by 0.232 Mgal/d (scenario 1) or 0.432 Mgal/d (scenario 4) causes the simulated coastal discharge to increase along both the south and north coasts, southwest and northwest of well 0801–03 (figs. 15, 18). Within individual model ele-

Scenario 2



EXPLANATION

CHANGE IN SIMULATED COASTAL DISCHARGE, Q, IN GALLONS PER DAY (gal/d)

- 1,000 < Q ≤ 5,000
- 5,000 < Q ≤ 15,000
- 15,000 < Q ≤ 30,000
- 30,000 < Q
- −5,000 ≤ Q < −1,000
- −15,000 ≤ Q < −5,000
- −30,000 ≤ Q < −15,000
- Q < −30,000

Discharge changes greater than 30,000 gal/d are indicated (values in parentheses are percentage change relative to base-case discharge)

LINE OF EQUAL SIMULATED WATER-LEVEL CHANGE, IN FEET

- +0.01
- +0.02
- +0.05
- +0.1
- +0.2
- −0.01
- −0.02
- −0.05

−0.26 PROPOSED WITHDRAWAL SITE AND SIMULATED WATER-LEVEL CHANGE, IN FEET

0801–03 (+0.59) EXISTING WELL AND WELL NUMBER—Value in parentheses is simulated water-level change, in feet

Figure 16. Scenario 2 of ground-water-flow model for the Island of Molokai, Hawaii, showing simulated changes in water level and coastal discharge (relative to base-case conditions) caused by decreasing withdrawal by 0.232 million gallons per day from the existing Kualapuu well (0801–03), decreasing withdrawal to zero from the existing Kawela Shaft (well 0457–01), withdrawing 0.232 million gallons per day from proposed site 1 (Manawainui), and withdrawing 0.348 million gallons per day from proposed site 2 (Kawela 1).

Scenario 3

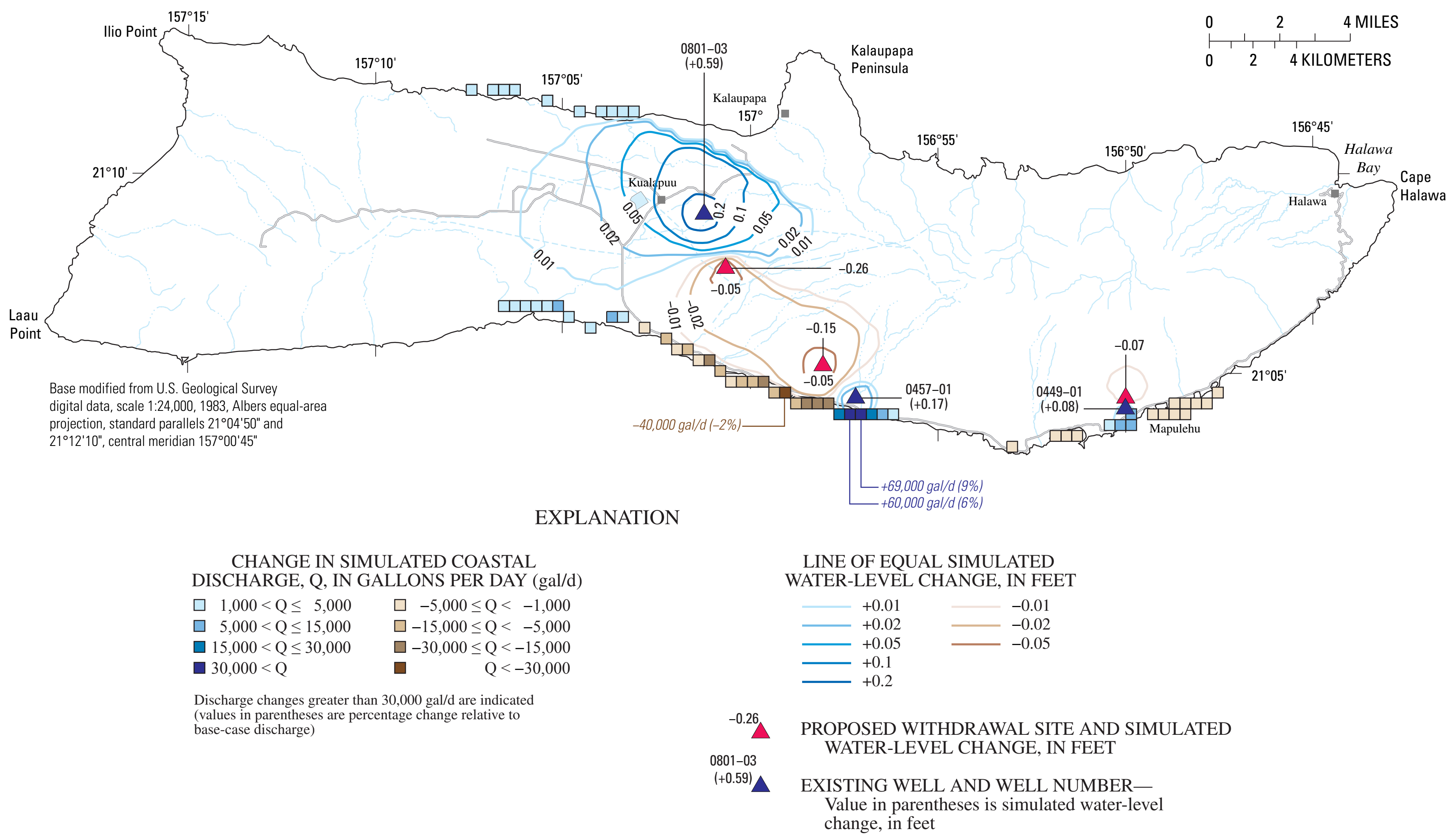


Figure 17. Scenario 3 of ground-water-flow model for the Island of Molokai, Hawaii, showing simulated changes in water level and coastal discharge (relative to base-case conditions) caused by decreasing withdrawal by 0.232 million gallons per day from the existing Kualapuu well (0801–03), decreasing withdrawals to zero from the existing Kawela Shaft (well 0457–01) and the existing Ualapue Shaft (well 0449–01), withdrawing 0.232 million gallons per day from proposed site 1 (Manawainui), withdrawing 0.348 million gallons per day from proposed site 2 (Kawela 1), and withdrawing 0.234 million gallons per day from proposed site 5 (Ualapue).

Scenario 4

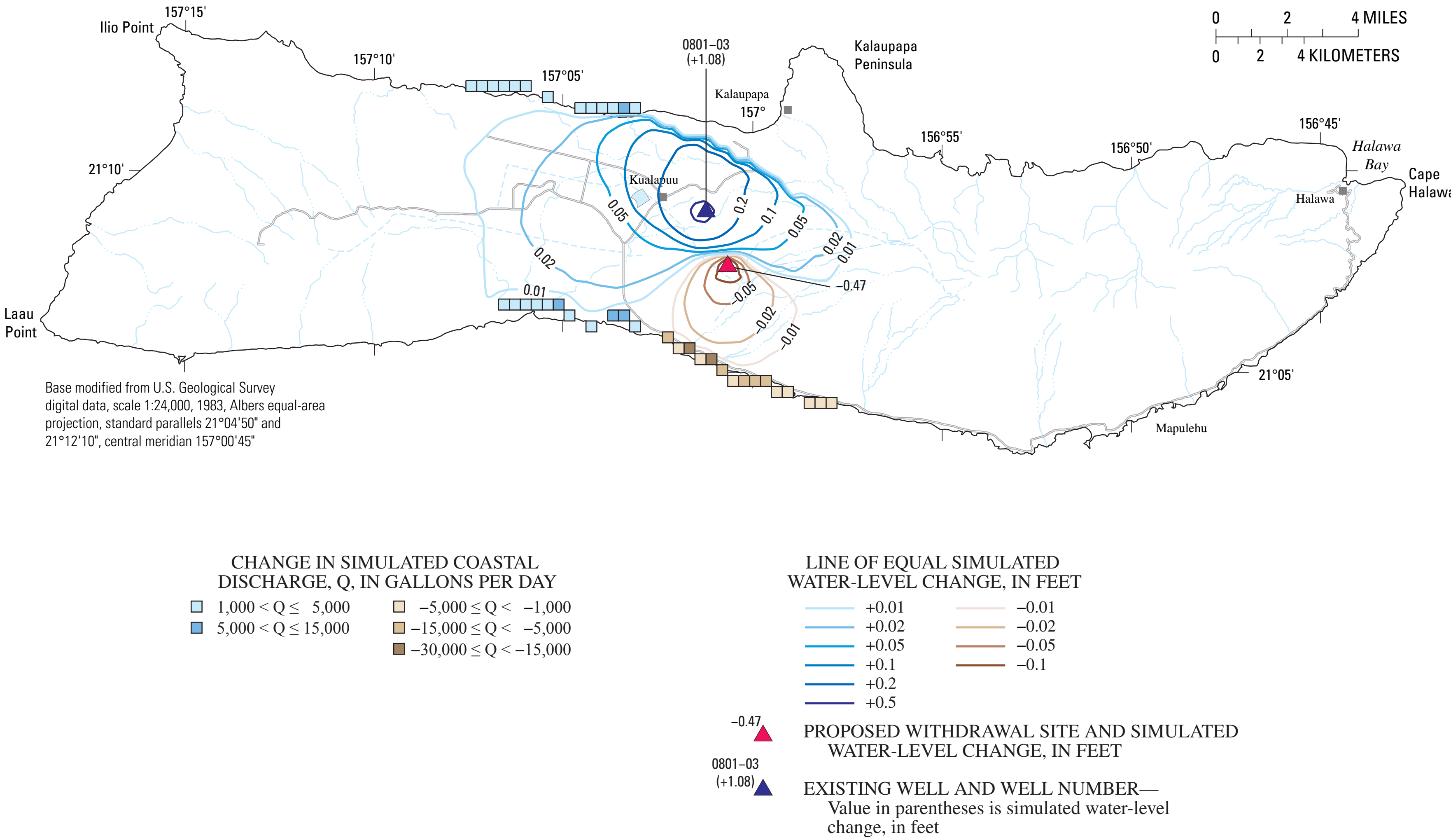


Figure 18. Scenario 4 of ground-water-flow model for the Island of Molokai, Hawaii, showing simulated changes in water level and coastal discharge (relative to base-case conditions) caused by decreasing withdrawal by 0.432 million gallons per day from the existing Kualapuu well (0801–03) and withdrawing 0.432 million gallons per day from proposed site 1 (Manawainui).

Scenario 5

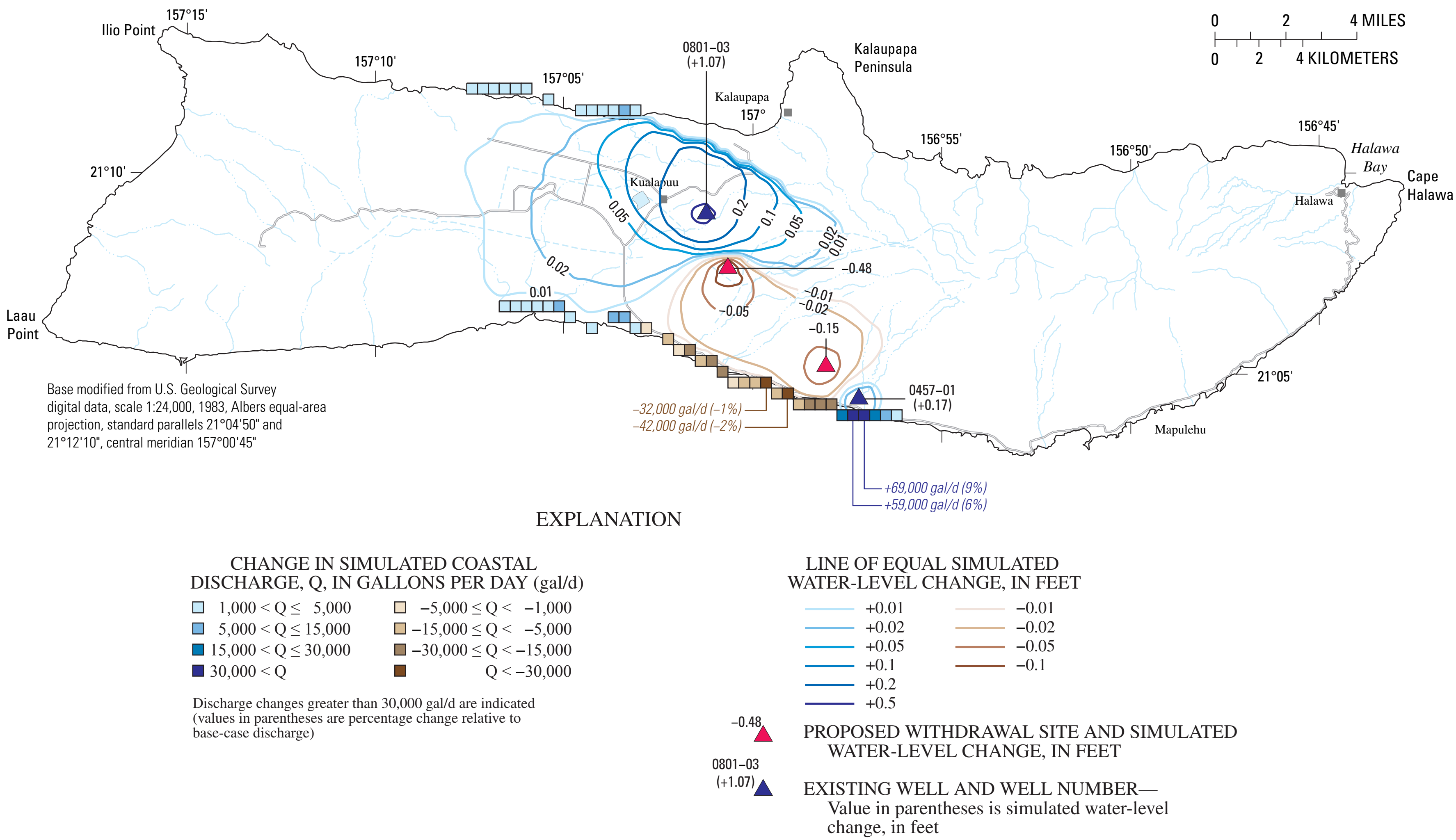
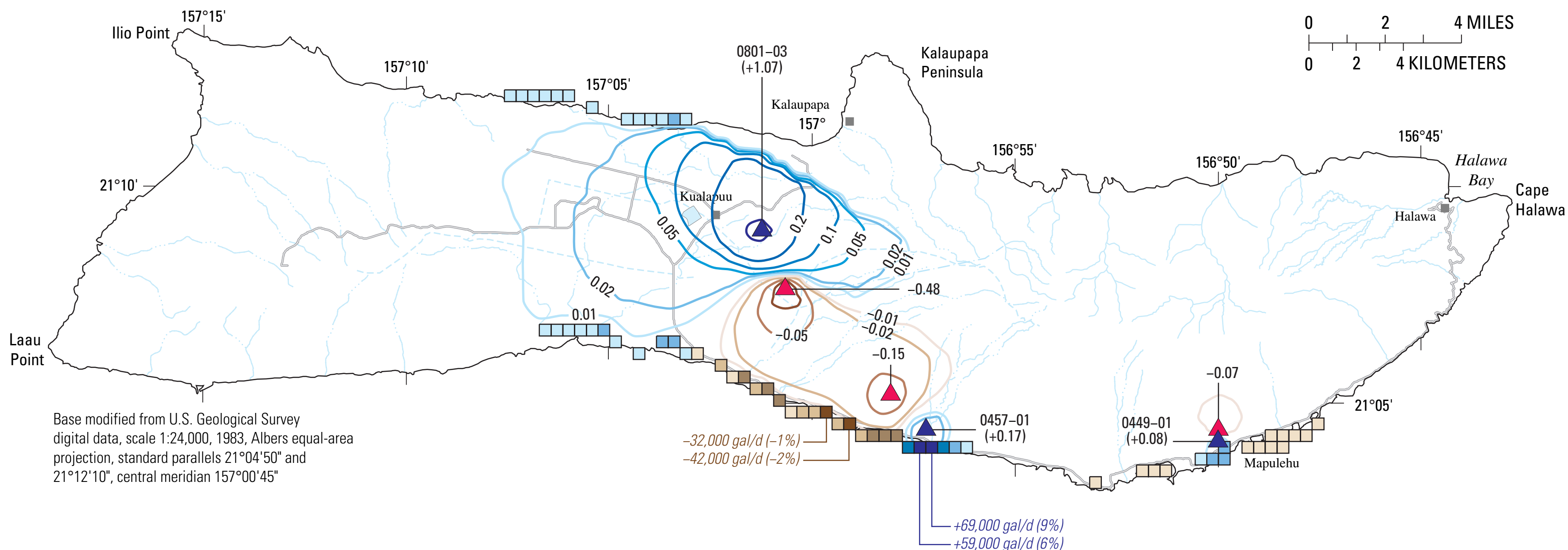


Figure 19. Scenario 5 of ground-water-flow model for the Island of Molokai, Hawaii, showing simulated changes in water level and coastal discharge (relative to base-case conditions) caused by decreasing withdrawal by 0.432 million gallons per day from the existing Kualapuu well (0801–03), decreasing withdrawal to zero from the existing Kawela Shaft (well 0457–01), withdrawing 0.432 million gallons per day from proposed site 1 (Manawainui), and withdrawing 0.348 million gallons per day from proposed site 2 (Kawela 1).

Scenario 6



EXPLANATION

CHANGE IN SIMULATED COASTAL DISCHARGE, Q, IN GALLONS PER DAY (gal/d)

- 1,000 < Q ≤ 5,000
- 5,000 < Q ≤ 15,000
- 15,000 < Q ≤ 30,000
- 30,000 < Q
- −5,000 ≤ Q < −1,000
- −15,000 ≤ Q < −5,000
- −30,000 ≤ Q < −15,000
- Q < −30,000

Discharge changes greater than 30,000 gal/d are indicated (values in parentheses are percentage change relative to base-case discharge)

LINE OF EQUAL SIMULATED WATER-LEVEL CHANGE, IN FEET

- +0.01
- +0.02
- +0.05
- +0.1
- +0.2
- +0.5
- −0.01
- −0.02
- −0.05
- −0.1

−0.48 PROPOSED WITHDRAWAL SITE AND SIMULATED WATER-LEVEL CHANGE, IN FEET

0801–03 (+1.07) EXISTING WELL AND WELL NUMBER—Value in parentheses is simulated water-level change, in feet

Figure 20. Scenario 6 of ground-water-flow model for the Island of Molokai, Hawaii, showing simulated changes in water level and coastal discharge (relative to base-case conditions) caused by decreasing withdrawal by 0.432 million gallons per day from the existing Kualapuu well (0801–03), decreasing withdrawals to zero from the existing Kawela Shaft (well 0457–01) and the existing Ualapue Shaft (well 0449–01), withdrawing 0.432 million gallons per day from proposed site 1 (Manawainui), withdrawing 0.348 million gallons per day from proposed site 2 (Kawela 1), and withdrawing 0.234 million gallons per day from proposed site 5 (Ualapue).

Scenario 7

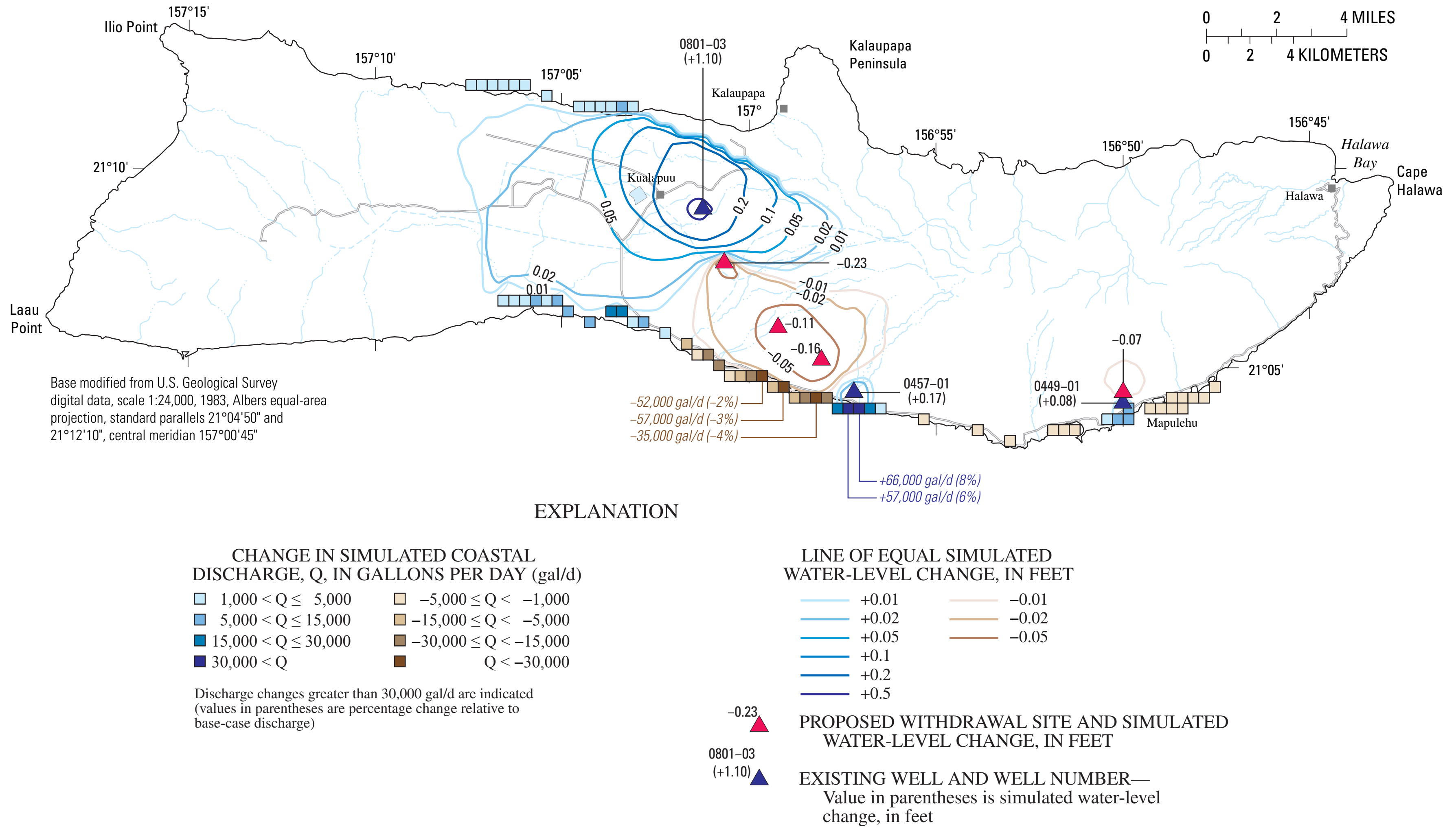
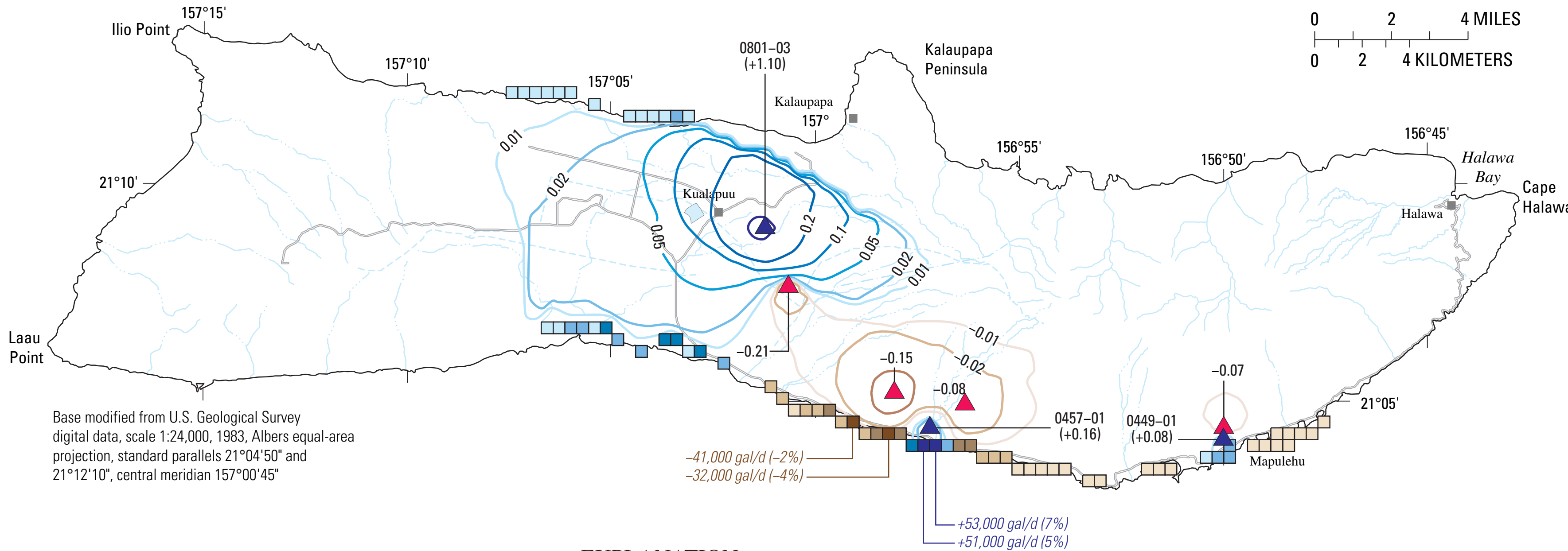


Figure 21. Scenario 7 of ground-water-flow model for the Island of Molokai, Hawaii, showing simulated changes in water level and coastal discharge (relative to base-case conditions) caused by decreasing withdrawal by 0.432 million gallons per day from the existing Kualapuu well (0801–03), decreasing withdrawals to zero from the existing Kawela Shaft (well 0457–01) and the existing Ualapue Shaft (well 0449–01), withdrawing 0.232 million gallons per day from proposed site 1 (Manawainui), withdrawing 0.348 million gallons per day from proposed site 2 (Kawela 1), withdrawing 0.200 million gallons per day from proposed site 3 (Kamiloloa), and withdrawing 0.234 million gallons per day from proposed site 5 (Ualapue).

Scenario 8



EXPLANATION

CHANGE IN SIMULATED COASTAL DISCHARGE, Q, IN GALLONS PER DAY (gal/d)

- $1{,}000 < Q \le 5{,}000$
- $5{,}000 < Q \le 15{,}000$
- $15{,}000 < Q \le 30{,}000$
- $30{,}000 < Q$
- $-5{,}000 \le Q < -1{,}000$
- $-15{,}000 \le Q < -5{,}000$
- $-30{,}000 \le Q < -15{,}000$
- $Q < -30{,}000$

Discharge changes greater than 30,000 gal/d are indicated (values in parentheses are percentage change relative to base-case discharge)

LINE OF EQUAL SIMULATED WATER-LEVEL CHANGE, IN FEET

- +0.01
- +0.02
- +0.05
- +0.1
- +0.2
- +0.5
- –0.01
- –0.02
- –0.05

–0.21 PROPOSED WITHDRAWAL SITE AND SIMULATED WATER-LEVEL CHANGE, IN FEET

0801–03 (+1.10) EXISTING WELL AND WELL NUMBER—Value in parentheses is simulated water-level change, in feet

Figure 22. Scenario 8 of ground-water-flow model for the Island of Molokai, Hawaii, showing simulated changes in water level and coastal discharge (relative to base-case conditions) caused by decreasing withdrawal by 0.432 million gallons per day from the existing Kualapuu well (0801–03), decreasing withdrawals to zero from the existing Kawela Shaft (well 0457–01) and the existing Ualapue Shaft (well 0449–01), withdrawing 0.232 million gallons per day from proposed site 1 (Manawainui), withdrawing 0.348 million gallons per day from proposed site 2 (Kawela 1), withdrawing 0.200 million gallons per day from proposed site 4 (Kawela 2), and withdrawing 0.234 million gallons per day from proposed site 5 (Ualapue).

Table 4. Summary of water-level changes simulated with the ground-water-flow model for the Island of Molokai, Hawaii.

[Values in **red bold** indicate that withdrawal rate differs from base-case withdrawal at the site; positive values indicate an increase in water level, whereas negative values indicate a decrease in water level; DHHL, Hawaii Department of Hawaiian Home Lands]

Scenario	Simulated water-level change (feet)								
	Well 0801–03 (Kualapuu Mauka)	Well 0457–01 (Kawela Shaft)	Well 0449–01 (Ualapue Shaft)	Proposed site 1 (Manawainui)	Proposed site 2 (Kawela 1)	Proposed site 3 (Kamiloloa)	Proposed site 4 (Kawela 2)	Proposed site 5 (Ualapue)	DHHL (range for three sites)
[1]Base case	8.38	2.89	3.66	6.19	4.87	5.37	5.67	4.76	12.48–16.75
1	**0.59**	0	0	**–0.25**	0	–0.01	0	0	0.04–0.10
2	**0.59**	**0.17**	0	**–0.26**	**–0.15**	–0.03	0	0	0.03–0.10
3	**0.59**	**0.17**	**0.08**	**–0.26**	**–0.15**	–0.03	0	**–0.07**	0.03–0.10
4	**1.08**	0	0	**–0.47**	0	–0.01	0	0	0.07–0.19
5	**1.07**	**0.17**	0	**–0.48**	**–0.15**	–0.03	0	0	0.07–0.18
6	**1.07**	**0.17**	**0.08**	**–0.48**	**–0.15**	–0.03	0	**–0.07**	0.07–0.18
7	**1.10**	**0.17**	**0.08**	**–0.23**	**–0.16**	**–0.11**	0	**–0.07**	0.08–0.20
8	**1.10**	**0.16**	**0.08**	**–0.21**	**–0.15**	–0.02	**–0.08**	**–0.07**	0.09–0.21
9	**0.35**	**–0.03**	**–0.08**	**–0.27**	0	–0.01	0	–0.02	0.01–0.05
10	**0.35**	**0.17**	**–0.08**	**–0.28**	**–0.17**	–0.04	0	–0.02	0.01–0.04
11	**0.35**	**0.17**	**0.04**	**–0.28**	**–0.17**	–0.04	0	**–0.13**	0.01–0.04
12	**1.09**	**0.16**	**0.04**	**–0.24**	**–0.19**	**–0.16**	–0.01	**–0.13**	0.08–0.20
13	**1.10**	**0.15**	**0.04**	**–0.22**	**–0.18**	–0.03	**–0.12**	**–0.13**	0.08–0.21
14	**–1.89**	**0.12**	**0.04**	**–1.11**	**–0.30**	–0.31	–0.05	**–0.13**	**–3.64 to –3.99**
15	**3.51**	**0.29**	**0.18**	0.45	0.14	0.19	0.12	0.08	0.63–1.07

[1]Simulated base-case water level, in feet.

ments, coastal discharge increases by as much as 6,000 gal/d (scenario 1, fig. 15) and 12,000 gal/d (scenario 4, fig. 18). In general, the simulated increase in coastal discharge caused by reducing the withdrawal from well 0801–03 decreases with distance from the well. Increasing the withdrawal from proposed withdrawal site 1 causes coastal discharge to decrease along the south coast and limits the eastward extent of the zone where coastal discharge increases because of the reduced withdrawal from well 0801–03 (figs. 15, 18). Within individual model elements, coastal discharge decreases by as much as 10,000 gal/d (scenario 1) and 18,000 gal/d (scenario 4) south of proposed withdrawal site 1.

Scenarios 2 and 5 (figs. 16, 19) include the redistributed withdrawals in scenarios 1 and 4, respectively, as well as the additional redistributed withdrawal from the Kawela Shaft (well 0457–01, fig. 6) to proposed withdrawal site 2 (Kawela 1). In scenarios 2 and 5, withdrawal of 0.348 Mgal/d from the Kawela Shaft is entirely redistributed to proposed withdrawal site 2. Shutting off the Kawela Shaft causes water levels and coastal discharge to increase in the immediate vicinity of the shaft, and withdrawing 0.348 Mgal/d from proposed withdrawal site 2 causes water levels and coastal discharge to decrease in the vicinity of that site. In scenarios 2 and 5, water levels increase by 0.17 ft at the Kawela Shaft and decrease by 0.15 ft at proposed withdrawal site 2. In scenarios 2 and 5, coastal discharge within model elements increases by as much as 69,000 gal/d immediately south of the Kawela Shaft and decreases by as much as 40,000 gal/d (scenario 2, fig. 16) and 42,000 gal/d (scenario 5, fig. 19) immediately southwest of proposed withdrawal site 2.

Scenarios 3 and 6 (figs. 17, 20) include the redistributed withdrawals in scenarios 2 and 5, respectively, as well as additional redistributed withdrawal from the Ualapue Shaft (well 0449–01, fig. 6) to proposed withdrawal site 5 (Ualapue), immediately inland from the shaft. In scenarios 3 and 6, withdrawal of 0.234 Mgal/d from the Ualapue Shaft is entirely redistributed to proposed withdrawal site 5. Shutting off the Ualapue Shaft causes water levels and coastal discharge to increase in the immediate vicinity. Withdrawing 0.234 Mgal/d from proposed withdrawal site 5 causes water levels to decrease in the immediate vicinity and coastal discharge to decrease to the southwest and southeast, bracketing the area where coastal discharge increases in response to shutting off the Ualapue Shaft (figs. 17, 20). The simulated hydrologic effects of redistributing withdrawal from the Ualapue Shaft to proposed withdrawal site 5 mainly are limited to the area between Kamalo and Pukoo. In scenarios 3 and 6, water levels

Table 5. Summary of coastal-discharge changes simulated with the ground-water-flow model for the Island of Molokai, Hawaii.

[Maximum changes are within an individual model element. Model elements are square areas 1,640 feet on a side. gal/d, gallons per day; --, not applicable]

Scenario	Maximum absolute change in coastal discharge (gal/d)		Maximum relative change in coastal discharge (percent)		Number of model elements with coastal-discharge change greater than 5 percent	
	Increase	Decrease	Increase	Decrease	Increase	Decrease
1	6,000	10,000	6	2	1	0
2	69,000	40,000	9	5	4	0
3	69,000	40,000	9	5	4	0
4	12,000	18,000	11	4	1	0
5	69,000	42,000	11	5	4	0
6	69,000	42,000	11	5	4	0
7	66,000	57,000	14	7	4	2
8	53,000	41,000	15	5	3	0
9	2,000	18,000	2	3	0	0
10	66,000	48,000	8	5	3	2
11	66,000	48,000	8	5	3	2
12	63,000	72,000	14	10	4	2
13	44,000	49,000	15	6	3	2
14	30,000	240,000	4	85	0	34
15	960,000	– – –	706	– –	68	– –

increase by 0.08 ft at Ualapue Shaft and decrease by 0.07 ft at proposed withdrawal site 5. Coastal discharge within model elements increases by as much as 69,000 gal/d immediately south of the Ualapue Shaft and decreases by less than 5,000 gal/d immediately southwest and southeast of proposed withdrawal site 5 (figs. 17, 20).

Scenarios 7 and 8 (figs. 21, 22) are similar to scenario 3 but include a further reduction in the withdrawal (0.200 Mgal/d) from well 0801–03, redistributed to either site 3 (Kamiloloa in scenario 7) or site 4 (Kawela 2 in scenario 8). Scenarios 7 and 8 indicate a further increase in water levels in the Kualapuu area relative to scenario 3. The simulated water level at well 0801–03 increases by 1.10 ft (scenarios 7 and 8) compared to 0.59 ft (scenario 3) (table 1). In scenarios 7 and 8, the zone where coastal discharge increases because of reduced withdrawal from well 0801–03 extends farther eastward than in scenario 3, and the zone where coastal discharge decreases because of withdrawal from proposed withdrawal sites 1 through 4 mainly is between Kaunakakai and Kamalo. Within model elements, coastal discharge decreases by as much as 57,000 gal/d (scenario 7, fig. 21) and 41,000 gal/d (scenario 8, fig. 22) southwest of proposed withdrawal site 2.

Scenarios 9 Through 13—Additional Ground-Water Withdrawal

In each of scenarios 9 through 13, the total withdrawal from all sites was 0.28 Mgal/d greater than the total 2005 base-case withdrawal of 9.164 Mgal/d. In these five scenarios, the combined withdrawal from proposed sites and wells 0449–01, 0457–01, and 0801–03 equals 1.467 Mgal/d (table 3). In these scenarios, the withdrawal from well 0801–03 was reduced by 0.140 or 0.432 Mgal/d relative to the average 2005 withdrawal rate, and the withdrawals from wells 0449–01 and 0457–01 were increased by 0.044 and 0.144 Mgal/d, respectively, or set equal to zero.

At existing wells where withdrawals are changed, simulated water levels change by –0.08 ft at well 0449–01 (Ualapue Shaft in scenarios 9 and 10) to 1.10 ft at well 0801–03 (Kualapuu Mauka in scenario 13) (figs. 23–27; table 4). At proposed withdrawal sites where withdrawals are increased, simulated water levels decline by 0.12 ft at site 4 (Kawela 2 in scenario 13) to 0.28 ft at site 1 (Manawainui in scenarios 10 and 11) (table 3).

For the steady-state conditions simulated in scenarios 9 through 13 (figs. 23–27), a net increase in withdrawal of 0.28 Mgal/d relative to the 2005 base case causes a net decrease of 0.28 Mgal/d in coastal discharge. Local increases and

Scenario 9

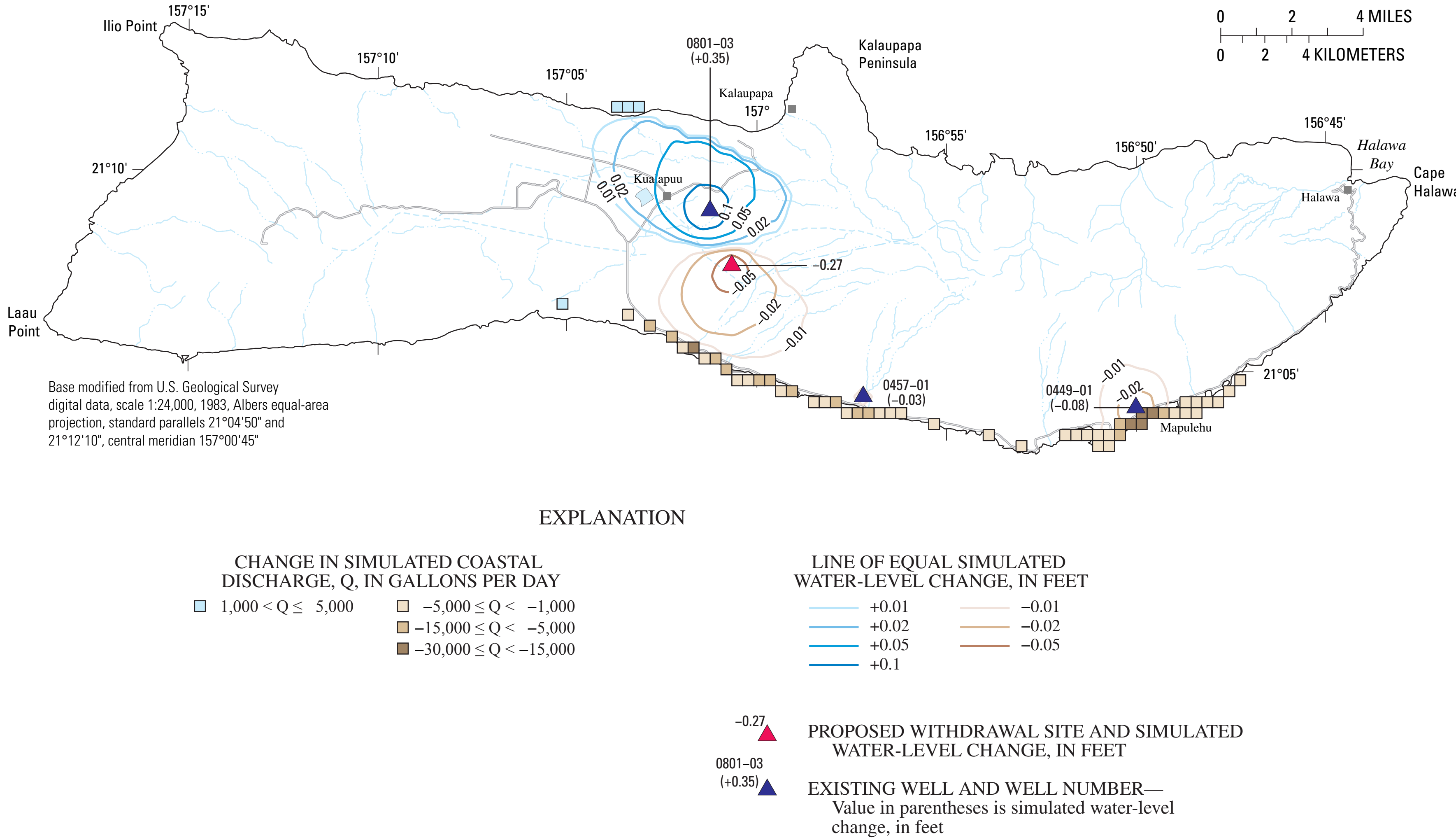


Figure 23. Scenario 9 of ground-water-flow model for the Island of Molokai, Hawaii, showing simulated changes in water level and coastal discharge (relative to base-case conditions) caused by decreasing withdrawal by 0.140 million gallons per day from the existing Kualapuu well (0801–03), increasing withdrawal by 0.044 million gallons per day from the existing Kawela Shaft (well 0457–01), increasing withdrawal by 0.144 million gallons per day from the existing Ualapue Shaft (well 0449–01), and withdrawing 0.232 million gallons per day from proposed site 1 (Manawainui).

Scenario 10

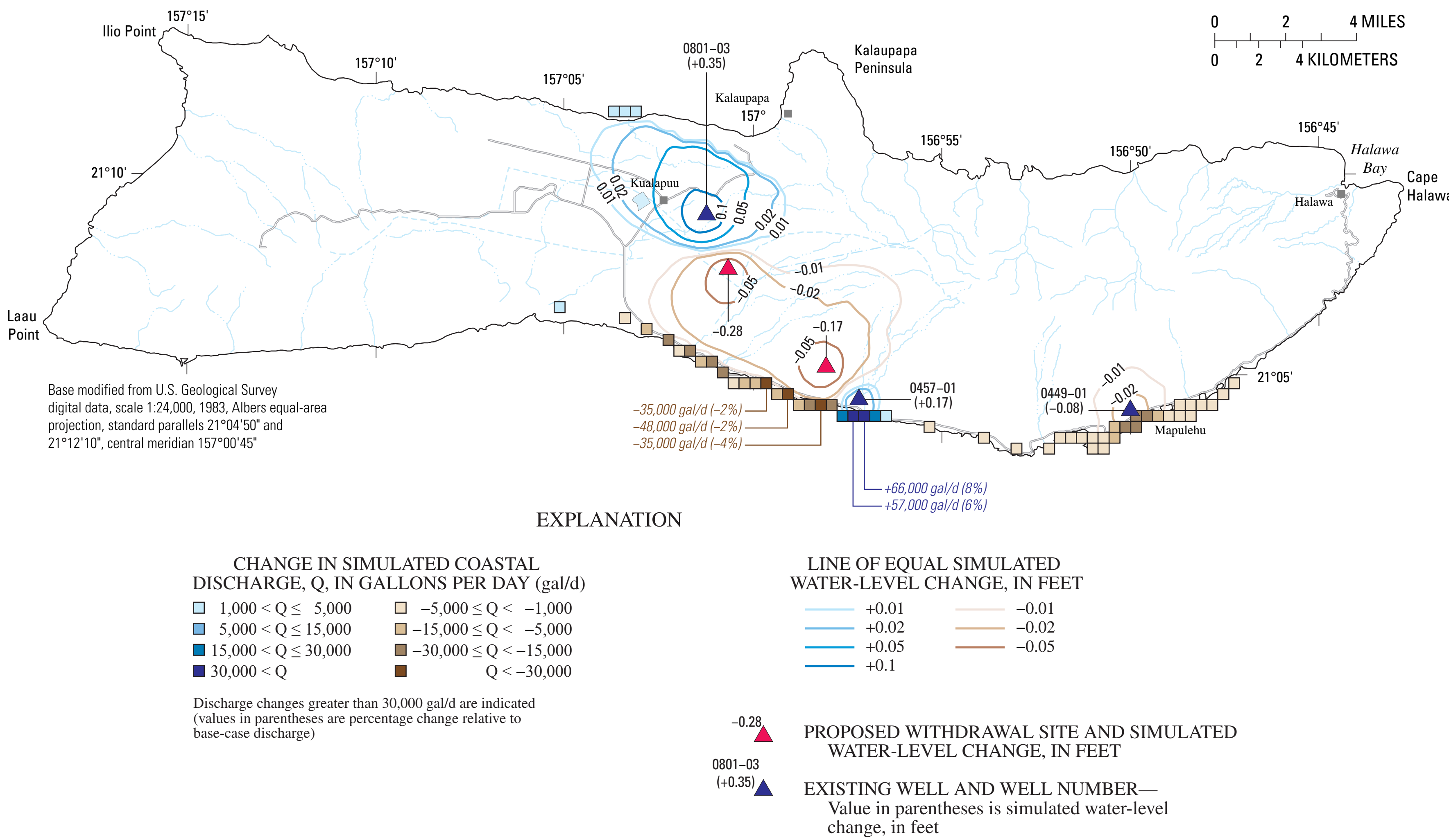


Figure 24. Scenario 10 of ground-water-flow model for the Island of Molokai, Hawaii, showing simulated changes in water level and coastal discharge (relative to base-case conditions) caused by decreasing withdrawal by 0.140 million gallons per day from the existing Kualapuu well (0801–03), decreasing withdrawal to zero from the existing Kawela Shaft (well 0457–01), increasing withdrawal by 0.144 million gallons per day from the existing Ualapue Shaft (well 0449–01), withdrawing 0.232 million gallons per day from proposed site 1 (Manawainui), and withdrawing 0.392 million gallons per day from proposed site 2 (Kawela 1).

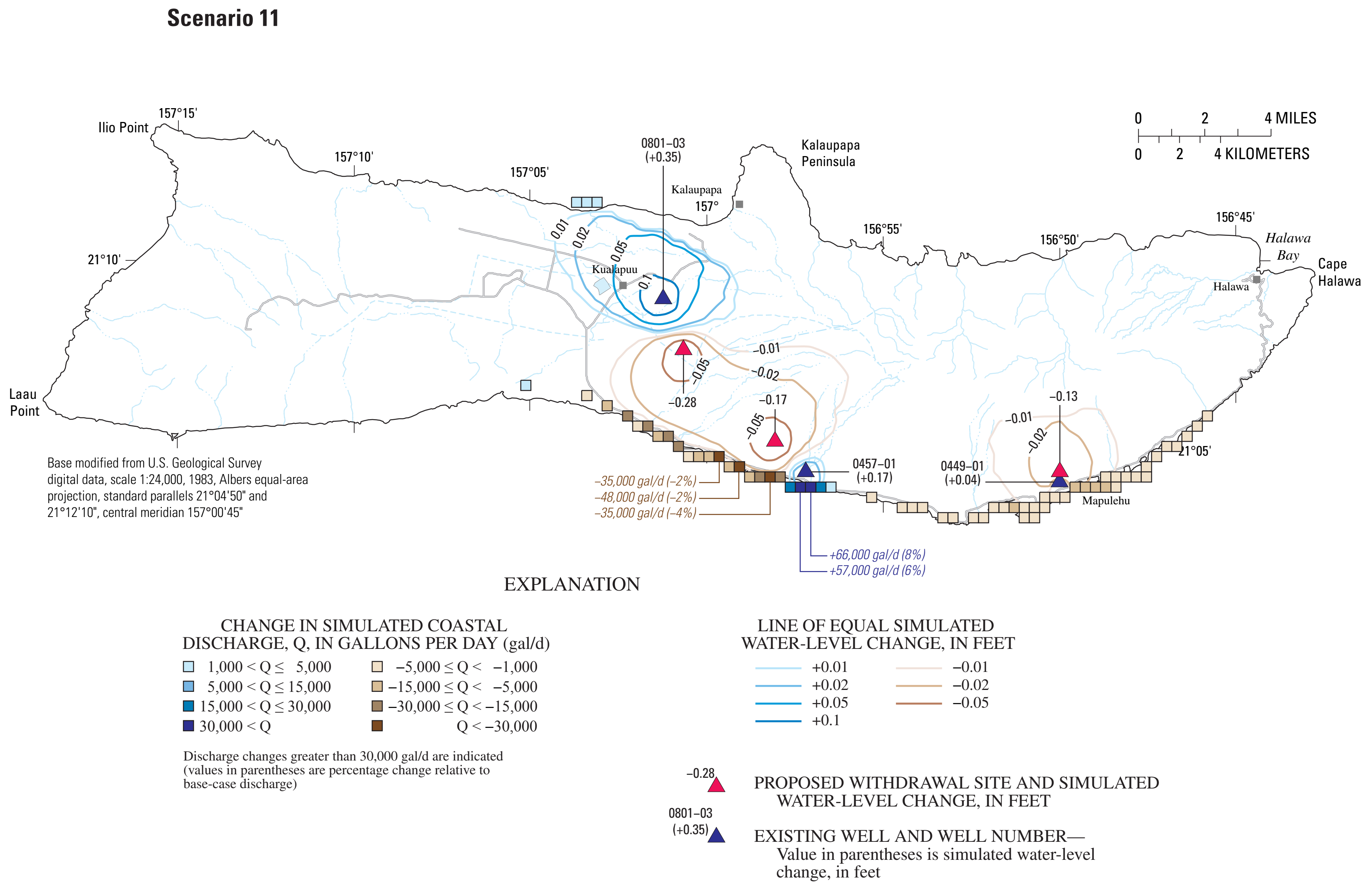


Figure 25. Scenario 11 of ground-water-flow model for the Island of Molokai, Hawaii, showing simulated changes in water level and coastal discharge (relative to base-case conditions) caused by decreasing withdrawal by 0.140 million gallons per day from the existing Kualapuu well (0801–03), decreasing withdrawals to zero from the existing Kawela Shaft (well 0457–01) and the existing Ualapue Shaft (well 0449–01), withdrawing 0.232 million gallons per day from proposed site 1 (Manawainui), withdrawing 0.392 million gallons per day from proposed site 2 (Kawela 1), and withdrawing 0.378 million gallons per day from proposed site 5 (Ualapue).

Scenario 12

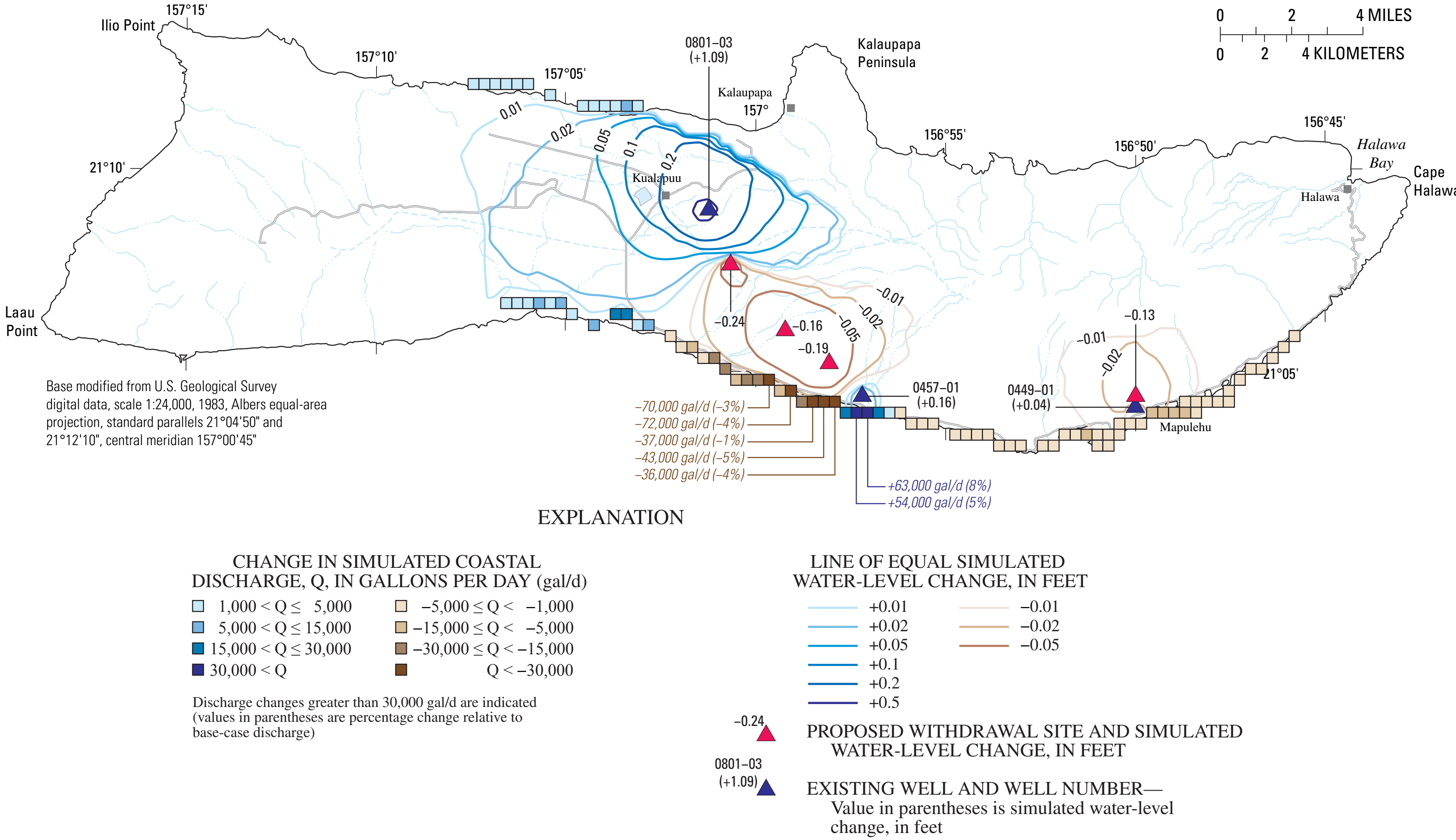


Figure 26. Scenario 12 of ground-water-flow model for the Island of Molokai, Hawaii, showing simulated changes in water level and coastal discharge (relative to base-case conditions) caused by decreasing withdrawal by 0.342 million gallons per day from the existing Kualapuu well (0801–03), decreasing withdrawals to zero from the existing Kawela Shaft (well 0457–01) and the existing Ualapue Shaft (well 0449–01), withdrawing 0.232 million gallons per day from proposed site 1 (Manawainui), withdrawing 0.392 million gallons per day from proposed site 2 (Kawela 1), withdrawing 0.292 million gallons per day from proposed site 3 (Kamiloloa), and withdrawing 0.378 million gallons per day from proposed site 5 (Ualapue).

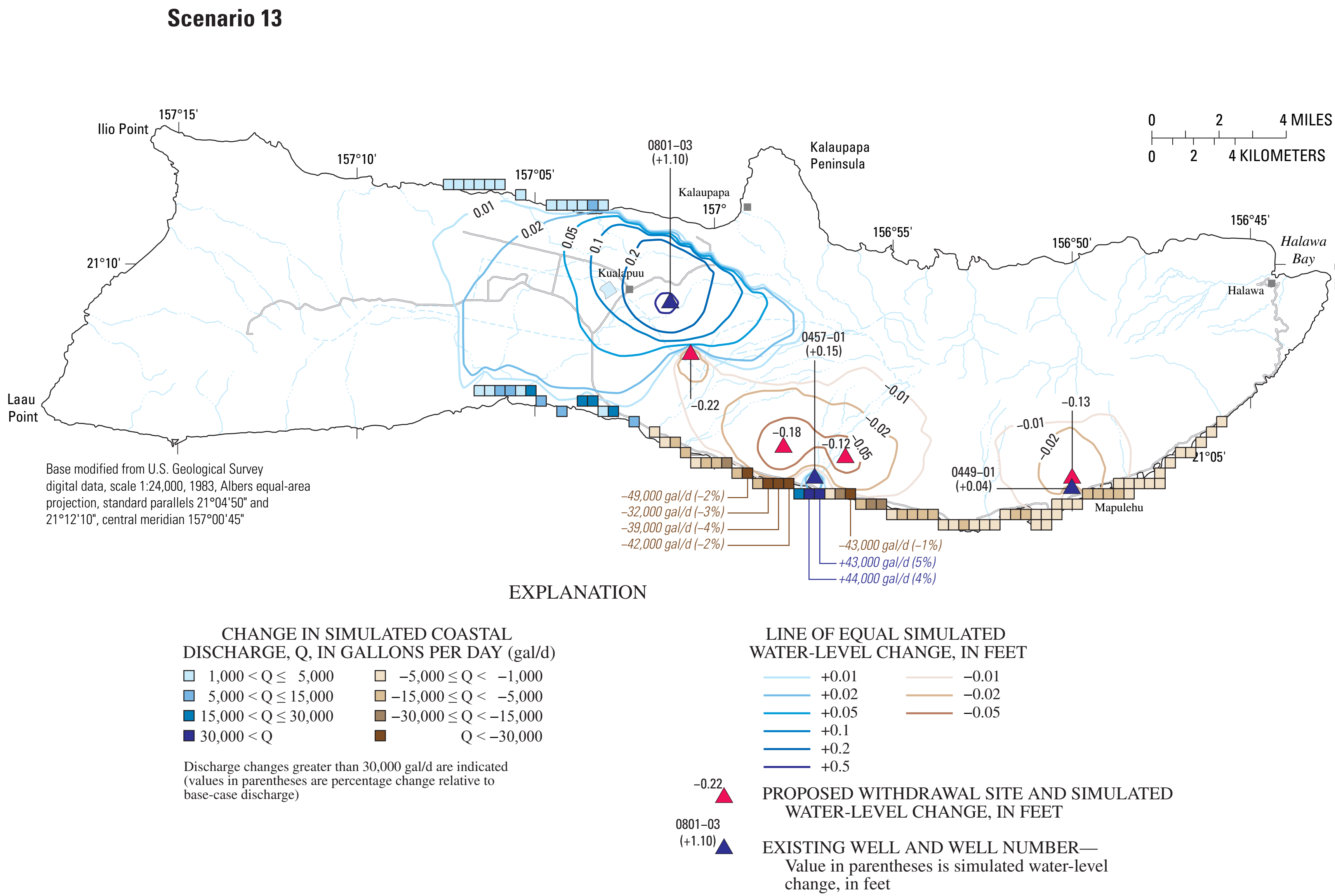


Figure 27. Scenario 13 of ground-water-flow model for the Island of Molokai, Hawaii, showing simulated changes in water level and coastal discharge (relative to base-case conditions) caused by decreasing withdrawal by 0.342 million gallons per day from the existing Kualapuu well (0801–03), decreasing withdrawals to zero from the existing Kawela Shaft (well 0457–01) and the existing Ualapue Shaft (well 0449–01), withdrawing 0.232 million gallons per day from proposed site 1 (Manawainui), withdrawing 0.392 million gallons per day from proposed site 2 (Kawela 1), withdrawing 0.292 million gallons per day from proposed site 4 (Kawela 2), and withdrawing 0.378 million gallons per day from proposed site 5 (Ualapue).

decreases in coastal discharge are simulated in these five scenarios, although the sum of the decreases exceeds the sum of the increases by 0.28 Mgal/d. Reducing withdrawal from well 0801–03 by 0.140 Mgal/d (scenarios 9–11) or 0.432 Mgal/d (scenarios 12–13) causes simulated coastal discharge to increase along both the north and south coasts (figs. 23–27). Shutting off the Kawela Shaft and withdrawing 0.392 Mgal/d from site 2 (scenarios 10–13) causes coastal discharge immediately downgradient from Kawela Shaft to increase by as much 66,000 gal/d in model elements (scenarios 10, 11, figs. 24–25). However, shutting off the Ualapue Shaft and withdrawing 0.378 Mgal/d from site 5 (scenarios 11–13, figs. 25–27) does not result in an increase in coastal discharge immediately downgradient from the shaft. In scenarios 9 through 13, reductions in coastal discharge in model elements generally are less than 5 percent (table 5), and maximum reductions in coastal discharge in model elements range from 18,000 gal/d (scenario 9, fig. 23) to 72,000 gal/d (scenario 12, fig. 26).

Scenario 14—the DHHL Reservation

Scenario 14 is similar to scenario 11 with the addition of the 2.905-Mgal/d withdrawal from the DHHL reservation equally distributed among three arbitrary withdrawal sites in the Kualapuu area (fig. 28). In scenario 14, (1) simulated water levels at the three arbitrary withdrawal sites in the Kualapuu area are 3.64 to 3.99 ft lower than in the base case, (2) the simulated water level at well 0801–03 is 1.89 ft lower than in the base case and 1.54 (1.89 – 0.35) ft lower than in scenario 11, and (3) simulated water levels at proposed withdrawal sites 1 and 2 are 1.11 and 0.30 ft lower than in the base case, respectively, and 0.83 and 0.25 ft lower than in scenario 11. In comparison, simulated water levels in scenarios 1 through 13 decline less than 0.5 ft relative to the base case.

Total withdrawal in scenario 14 is 3.185 Mgal/d greater than in the base case. Thus, simulated steady-state coastal discharge in scenario 14 is 3.185 Mgal/d less than in the base case. In scenario 14, coastal discharge increases only in the area immediately downgradient from the Kawela Shaft (by as much as 30,000 gal/d in one model element; fig. 28). Coastal discharge decreases along both the north and south coasts. South of the Kualapuu area, between Umipaa and Kamiloloa (fig. 1), the reduction of coastal discharge in several model elements is greater than 200,000 gal/d (fig. 28). The simulated reduction of coastal discharge in model elements is less than 75,000 gal/d in scenarios 1 through 13. Comparison of scenarios 11 and 14 indicates that the 2.905-Mgal/d withdrawal from the DHHL reservation in the Kualapuu area at the three selected sites has little effect on water levels and coastal discharge east of Mapulehu.

Scenario 15—Natural Conditions (Zero Withdrawals)

In scenario 15, all withdrawals were set to zero, causing water levels and coastal discharge to increase over much of the central and eastern parts of the island relative to base-case conditions (fig. 29). Eliminating all withdrawal causes regional increases in water levels and coastal discharge to natural, predevelopment conditions. Water levels and coastal discharge increase along the south coast from Palaau eastward to Halawa (figs. 1, 29). Water levels and coastal discharge increase along the north coast from Moomomi eastward to Kalaupapa (fig. 29). Simulated discharge to streams in the dike complex of East Molokai Volcano also increases in response to eliminating withdrawals from wells 0855–01, 0855–02, and 0855–03 and the MIS Tunnel (fig. 29), which are located in the dike complex of East Molokai Volcano near Waikolu Stream.

Model Limitations

The ground-water-flow model of Molokai used in this study has several limitations. The number of monitor wells is insufficient to define the spatial distribution of water levels in inland areas in the southeastern part of the island, in the western part of the island, and in the dike complex in the northeastern part of the island. Thus, the distribution of simulated water levels is unverified in some places. Furthermore, the thickness of the freshwater lens is poorly known in most parts of the island, including areas of proposed additional ground-water withdrawal.

Because of a lack of sufficient water-level data used to constrain the simulations, the model used in this study is not unique—that is, different distributions of hydraulic conductivity could be used to construct a model that produces equally acceptable simulated water levels. The model used in this study can be refined, and the ground-water-flow system can be better represented, 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 the simulated drawdown caused by additional withdrawal underestimates the 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. The model is, nevertheless, the best available tool for analyzing the possible regional hydrologic effects of ground-water withdrawals on Molokai under steady-state conditions. Transient hydrologic effects of withdrawals were not considered in this study.

The AQUIFEM–SALT model simulates a sharp interface between freshwater and saltwater. Simulated freshwater thickness from AQUIFEM–SALT overestimates the actual freshwater thickness. In reality, freshwater is separated from underlying saltwater by a freshwater-saltwater transition zone,

Scenario 14

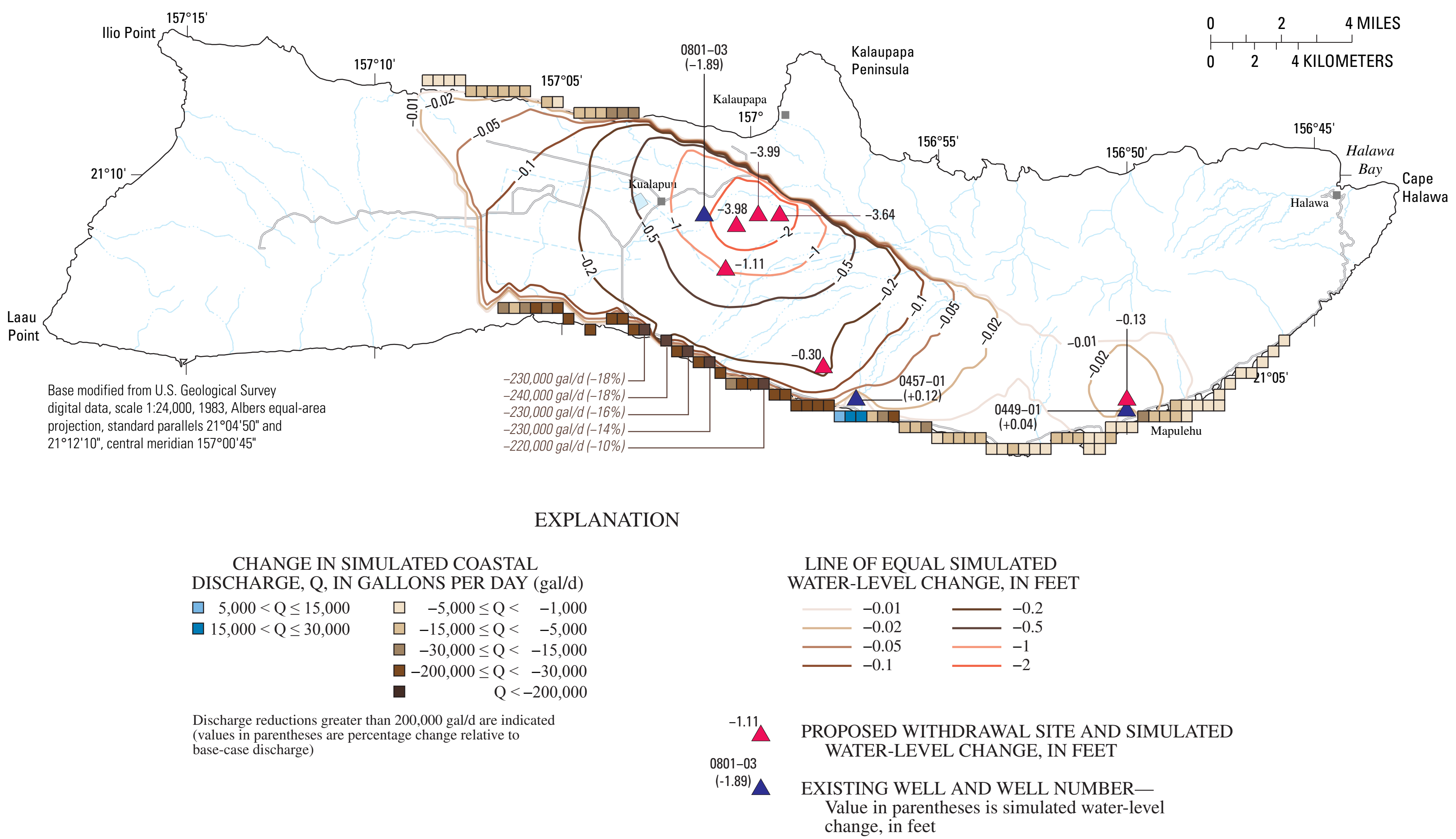
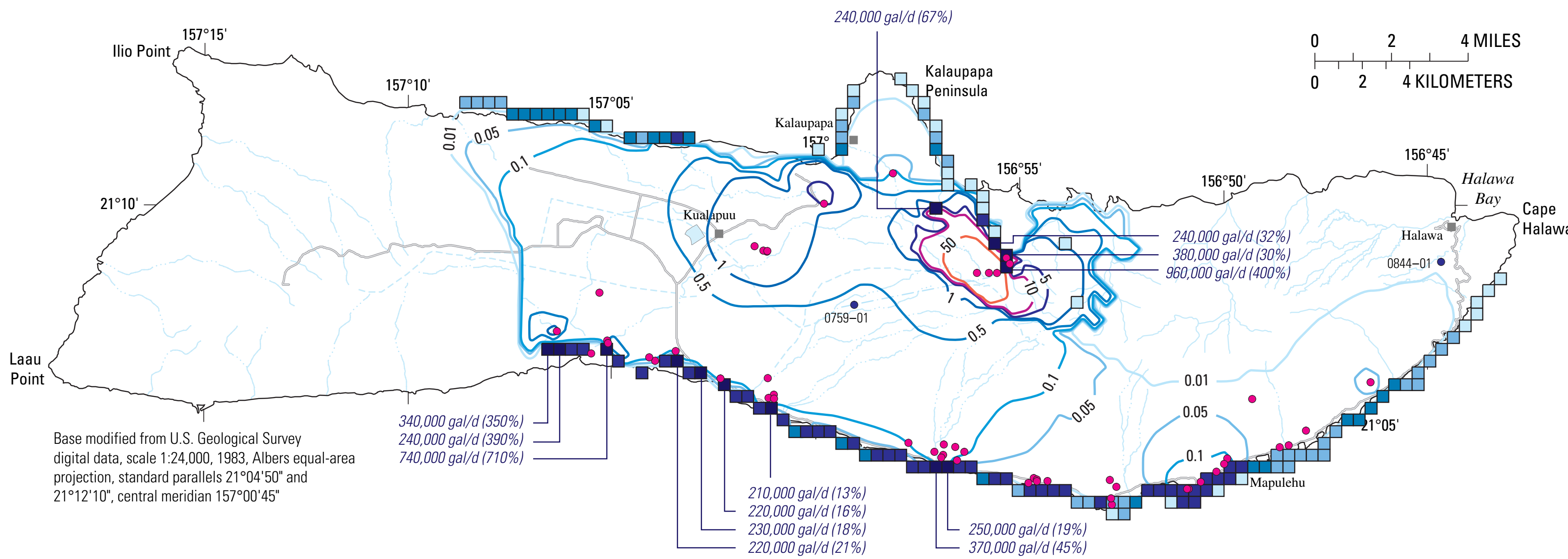


Figure 28. Scenario 14 of ground-water-flow model for the Island of Molokai, Hawaii, showing simulated changes in water level and coastal discharge (relative to base-case conditions) caused by decreasing withdrawal by 0.140 million gallons per day from the existing Kualapuu well (0801–03), decreasing withdrawals to zero from the existing Kawela Shaft (well 0457–01) and the existing Ualapue Shaft (well 0449–01), withdrawing 0.232 million gallons per day from proposed site 1 (Manawainui), withdrawing 0.392 million gallons per day from proposed site 2 (Kawela 1), withdrawing 0.378 million gallons per day from proposed site 5 (Ualapue), and withdrawing 0.968 million gallons per day from each of three hypothetical wells in the Kualapuu area.

Scenario 15



EXPLANATION

CHANGE IN SIMULATED COASTAL DISCHARGE, Q, IN GALLONS PER DAY (gal/d)

- 1,000 < Q ≤ 5,000
- 5,000 < Q ≤ 15,000
- 15,000 < Q ≤ 30,000
- 30,000 < Q ≤ 200,000
- 200,000 < Q

Discharge reductions greater than 200,000 gal/d are indicated (values in parentheses are percentage change relative to base-case discharge)

LINE OF EQUAL SIMULATED WATER-LEVEL CHANGE, IN FEET

- 0.01
- 0.05
- 0.1
- 0.5
- 1
- 5
- 10
- 50

WITHDRAWAL SITE SIMULATED IN THE 2005 BASE CASE

WITHDRAWAL SITE WITH 2005 WATER-USE PERMIT NOT SIMULATED IN THE 2005 BASE CASE

Figure 29. Scenario 15 of ground-water-flow model for the Island of Molokai, Hawaii, showing simulated changes in water level and coastal discharge (relative to base-case conditions) caused by setting all withdrawals to zero.

which can be represented by using a model capable of simulating density-dependent ground-water flow and transport.

The ground-water-flow model simulates the regional effects of additional withdrawal on coastal discharge. The actual reduction in coastal discharge on a local scale may not be accurately represented by the model because of the level of spatial discretization and because local-scale heterogeneities in the hydraulic characteristics of the rocks are not represented.

Summary

Because of the increasing demand for water associated with a growing population, projected increases in demand over the next few decades, and the increasing salinity of water pumped from some existing wells, the DWS is currently (2006) considering drilling additional wells to replace or supplement existing wells on Molokai. Redistributed and additional ground-water withdrawals would affect water levels, might affect the salinity of water pumped from existing wells, and would affect the discharge of ground water to the nearshore environment. In response to concerns over the possible effects of ground-water withdrawals on Molokai, the USGS undertook this investigation, in cooperation with the DWS, to quantify the hydrologic effects of ground-water withdrawal from selected sites on water levels and coastal discharge. An existing numerical ground-water-flow model was used to estimate water-level and coastal-discharge changes caused by redistributed and additional ground-water withdrawals in the area between Kualapuu and Ualapue.

The model by Oki (1997) was used in this study to estimate the steady-state hydrologic effects of redistributed and additional ground-water withdrawals. A base case defined by 2005 mean annual withdrawal rates from wells 0449–01 (Ualapue Shaft), 0457–01 (Kawela Shaft), and 0801–03 (Kualapuu Mauka), May 2005 permitted withdrawal rates from other wells (excluding Waiola No. 1, Puu O Hoku No. 1, and the DHHL reservation of 2.905 Mgal/d), and the 1.822-Mgal/d withdrawal from the MIS Tunnel was used to calculate water-level and coastal-discharge changes caused by redistributed and additional ground-water withdrawals. The 2005 base-case withdrawal rates range from 0.001 to 1.822 Mgal/d and total 9.164 Mgal/d. Total withdrawal represented in the base case is 5 percent of island recharge. The hydraulic characteristics and long-term average recharge distribution (187 Mgal/d) used in the original numerical model were used for all the simulations in this study.

A total of 15 scenarios were tested. Results of the scenarios of redistributed and additional ground-water withdrawals indicate that (1) redistribution of ground-water withdrawals causes a corresponding redistribution of water levels and coastal discharge; (2) water levels rise and coastal discharge increases near sites of reduced withdrawal, whereas water levels decline and coastal discharge decreases near sites of increased withdrawal; (3) the magnitude and areal extent of hydrologic changes caused by redistributed ground-water withdrawals increase with larger withdrawal changes; (4) simulated hydrologic changes are greatest near and downgradient from withdrawal sites and decrease with distance elsewhere; (5) simulated water-level declines are less than 0.5 ft (for scenarios in which the DHHL reservation is omitted); (6) simulated coastal-discharge reductions generally are less than 30,000 gal/d (and everywhere less than 75,000 gal/d) within discrete 1,640- by 1,640-ft-square areas (for scenarios in which the DHHL reservation is omitted), generally representing less than 5 percent change; (7) the low-permeability dike complex of East Molokai Volcano impedes the spread of water-level changes to perennial streams in the northeastern part of the island, and discharge to these streams in the dike complex therefore is unaffected by proposed withdrawals; and (8) discharge to some fishponds and springs increases in response to decreased withdrawal at upgradient sites, and discharge to other fishponds and springs decreases in response to increased withdrawal. Simulated withdrawal of the DHHL reservation (2.905 Mgal/d) causes water levels in the Kualapuu area to decline by almost 4 ft. Eliminating all withdrawal causes regional increases in water levels and coastal discharge to natural, predevelopment levels. In addition, eliminating withdrawals from existing wells and the MIS Tunnel in the dike complex increases ground-water discharge to streams in the northeastern part of the island.

The ground-water-flow model of Molokai used in this study has several limitations. Because of insufficient information on water levels in many areas, including areas of proposed withdrawal, the distribution of simulated water levels cannot be verified in some places. The regional model may not accurately represent local-scale reductions in coastal discharge caused by withdrawals. A better representation of the ground-water-flow system using a three-dimensional, density-dependent model can be constructed as more data become available.

References Cited

Beeson, M.H., 1976, Petrology, mineralogy, and geochemistry of the East Molokai Volcanic Series, Hawaii: U.S. Geological Survey Professional Paper 961, 53 p.

Blumenstock, D.I., and Price, Saul, 1967, Climate of Hawaii, *in* Climates of the States, no. 60–51, Climatography of the United States: Washington, D.C., U.S. Department of Commerce.

Clague, D.A., Dao-gong, Chen, Murnane, Richard, Beeson, M.H., Lanphere, M.A., Dalrymple, G.B., Friesen, Walter, and Holcomb, R.T., 1982, Age and petrology of the Kalaupapa Basalt, Molokai, Hawaii: Pacific Science, v. 36, no. 4, p. 411–420.

Cooper, H.H., Jr., Kohout, F.A., Henry, H.R., and Glover, R.E., 1964, Sea water in coastal aquifers: U.S. Geological Survey Water-Supply Paper 1613–C, 84 p.

Domenico, P.A., and Schwartz, F.W., 1990, Physical and chemical hydrogeology: New York, John Wiley, 824 p.

Dorman, C.E., and Bourke, R.H., 1979, Precipitation over the Pacific Ocean, 30°S to 60°N: Monthly Weather Review, v. 107, no. 7, p. 896–910.

Ekern, P.C., and Chang, J.-H., 1985, Pan evaporation; State of Hawai‘i, 1894–1983: Hawaii Department of Land and Natural Resources Report R74, 172 p.

Elliot, W.P., and Reed, R.K., 1984, A climatological estimate of precipitation for the world ocean: Journal of Applied Meteorology, v. 23, no. 3, p. 434–439.

Farber, J.M., 1997, Ancient Hawaiian fishponds; can restoration succeed on Moloka‘i?: Encinitas, Calif., Neptune House, 99 p.

Giambelluca, T.W., Nullet, M.A., and Schroeder, T.A., 1986, Rainfall atlas of Hawai‘i: Hawaii Department of Land and Natural Resources Report R76, 267 p.

Hawaii Commission on Water Resource Management, 1990, Hawaii water plan, v. 1–2 *of* Water resources protection plan: Honolulu, variously paginated.

Hawaii Commission on Water Resource Management, 1997, Contested case hearing on water use, well construction and pump installation permit applications filed by Wai‘ola O Molokai, Inc. and Molokai Ranch, Limited: case CCH–MO96–1, exhibit A–18, 1 p.

Hawaii Department of Business, Economic Development & Tourism, 2006, 2004 State of Hawaii data book: URL http://www.hawaii.gov/dbedt/info/economic/databook/db2004/ [accessed May 16, 2006].

Hawaii Office of Planning, 2006, Hawaii statewide GIS program: URL http://www.hawaii.gov/dbedt/gis/fishponds.htm [accessed Apr. 5, 2006].

Juvik, S.O., and Juvik, J.O., 1998, Atlas of Hawai‘i (3d ed.): Honolulu, University of Hawaii Press, 333 p.

Langenheim, V.A.M., and Clague, D.A., 1987, The Hawaiian-Emperor volcanic chain, part II, stratigraphic framework of volcanic rocks of the Hawaiian Islands, chap. 1 *of* Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 55–84.

Lindgren, Waldemar, 1903, The water resources of Molokai, Hawaiian Islands: U.S. Geological Survey Water-Supply and Irrigation Paper 77, 62 p.

Lockwood, J.P., and Lipman, P.W., 1987, Holocene eruptive history of Mauna Loa Volcano, chap. 18 *of* Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 509–535.

MacCarthy, G.R., 1941, Geophysical studies on the island of Molokai, Territory of Hawaii: U.S. Department of the Interior Press Release 160579, October 3, 1941, 2 p.

Macdonald, G.A., 1956, The structure of Hawaiian volcanoes: Verhandelingen Van Het Koninklijk Nederlandsh Geologisch Mijnbouwkundig Genootschap, v. 16, p. 1–22.

Macdonald, G.A., Abbott, A.T., and Peterson, F.L., 1983, Volcanoes in the sea; the geology of Hawaii (2d ed.): Honolulu, University of Hawaii Press, 517 p.

Malahoff, Alexander, and Woollard, G.P., 1966, Magnetic surveys over the Hawaiian Islands and their geologic implications: Pacific Science, v. 20, no. 3, p. 265–311.

Mathewson, C.C., 1970, Submarine canyons and the shelf along the north coast of Molokai Island, Hawaiian Ridge: Pacific Science, v. 24, no. 2, p. 235–244.

McDougall, Ian, 1964, Potassium-argon ages from lavas of the Hawaiian islands: Geological Society of America Bulletin, v. 75, no. 2, p. 107–128.

Mink, J.F., and Lau, L.S., 1992, Aquifer identification and classification for Moloka‘i; groundwater protection strategy for Hawaii: University of Hawaii, Water Resources Research Center Technical Report 187, 31 p.

Moore, J.G., and Krivoy, H.L., 1965, A reconnaissance gravity survey of the island of Molokai, Hawaii: Pacific Science, v. 19, no. 3, p. 343–345.

National Climatic Data Center, 2006, Annual climatological summary: National Oceanic and Atmospheric Administration, URL http://hurricane.ncdc.noaa.gov/ancsum/ACS [accessed Apr. 12, 2006].

Naughton, J.J., Macdonald, G.A., and Greenberg, V.A., 1980, Some additional potassium-argon ages of Hawaiian rocks; the Maui Volcanic Complex of Molokai, Maui, Lanai and Kahoolawe: Journal of Volcanology and Geothermal Research, v. 7, no. 3–4, p. 339–355.

Oki, D.S., 1997, Geohydrology and numerical simulation of the ground-water flow system of Molokai, Hawaii: U.S. Geological Survey Water-Resources Investigations Report 97–4176, 62 p.

Oki, D.S., 1998, Geohydrology of the central Oahu, Hawaii, ground-water flow system and numerical simulation of the effects of additional pumping: U.S. Geological Survey Water-Resources Investigations Report 97–4276, 132 p.

Oki, D.S., and Bauer, G.R., 2001, Drilling, construction, water-level, and water-quality information for the Kualapuu deep monitor well 4–0800–01, Molokai, Hawaii: U.S. Geological Survey Open-File Report 01–350, 19 p.

Paillet, F.L., Williams, J.H., Oki, D.S., and Knutson, K.D., 2002, Comparison of formation and fluid-column logs in a heterogeneous basalt aquifer: Ground Water, v. 40, no. 6, p. 577–585.

Sanderson, Marie, ed., 1993, Prevailing trade winds; weather and climate in Hawai‘i: Honolulu, University of Hawaii Press, 126 p.

Seckel, G.R., 1962, Atlas of the oceanographic climate of the Hawaiian Islands region: U.S. Fish and Wildlife Service Fishery Bulletin 193, v. 61, p. 373–427.

Shade, P.J., 1997, Water budget for the island of Molokai, Hawaii: U.S. Geological Survey Water-Resources Investigations Report 97–4155, 20 p.

Souza, W.R., and Voss, C.I., 1987, Analysis of an anisotropic coastal aquifer system using variable-density flow and solute transport simulation: Journal of Hydrology, v. 92, p. 17–41.

Stearns, H.T., 1985, Geology of the State of Hawaii (2d ed.): Palo Alto, Calif., Pacific Books, 335 p.

Stearns, H.T., and Macdonald, G.A., 1947, Geology and ground-water resources of the island of Molokai, Hawaii: Hawaii Division of Hydrography Bulletin 11, 113 p.

Stearns, H.T., and Vaksvik, K.N., 1935, Geology and ground-water resources of the island of Oahu, Hawaii: Hawaii Division of Hydrography Bulletin 1, 479 p.

Swain, L.A., 1973, Chemical quality of ground water in Hawaii: Hawaii Department of Land and Natural Resources Report R48, 54 p.

Takasaki, K.J., 1986, Results of exploratory drilling for water in Waihanau Valley, Molokai, Hawaii: U.S. Geological Survey Water-Resources Investigations Report 85–4332, 26 p.

Takasaki, K.J., and Mink, J.F., 1985, Evaluation of major dike-impounded ground-water reservoirs, island of Oahu: U.S. Geological Survey Water-Supply Paper 2217, 77 p.

Voss, C.I., 1984, AQUIFEM–SALT; a finite-element model for aquifers containing a seawater interface: U.S. Geological Survey Water-Resources Investigations Report 84–4263, 37 p.

Wentworth, C.K., 1939, The specific gravity of sea water and the Ghyben-Herzberg ratio at Honolulu: University of Hawaii Bulletin, v. 18, no. 8, 24 p.

Wentworth, C.K., and Macdonald, G.A., 1953, Structures and forms of basaltic rocks in Hawaii: U.S. Geological Survey Bulletin 994, 98 p.