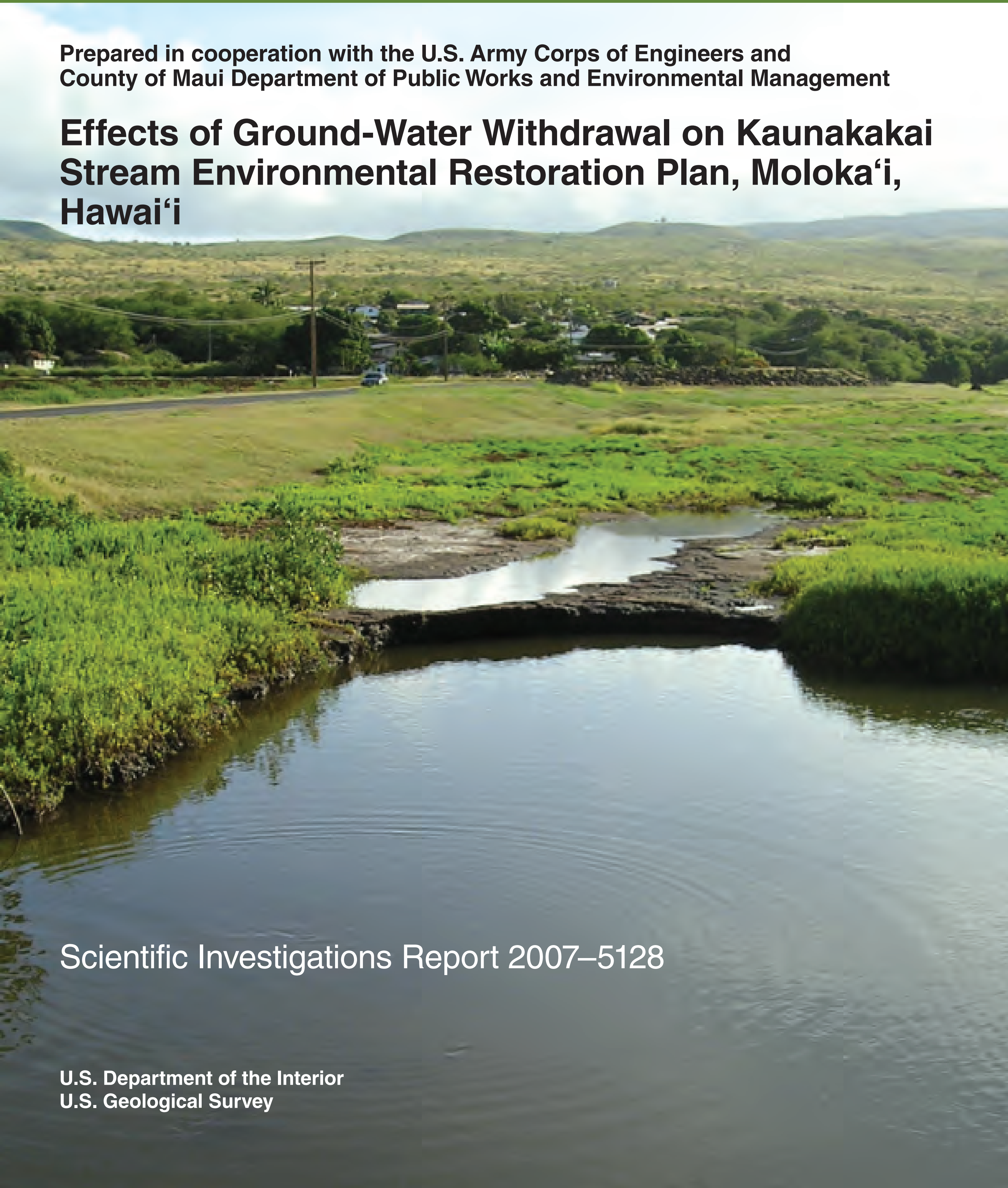
Prepared in cooperation with the U.S. Army Corps of Engineers and
County of Maui Department of Public Works and Environmental Management

Effects of Ground-Water Withdrawal on Kaunakakai Stream Environmental Restoration Plan, Molokaʻi, Hawaiʻi



Scientific Investigations Report 2007–5128

U.S. Department of the Interior
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COVER

The proposed habitat-restoration site near the mouth of Kaunakakai Stream will provide habitat for the native Hawaiian Stilt (*Himantopus mexicanus knudseni*). The U.S. Army Corps of Engineers is planning to create about 2.75 acres of wetland habitat in the area shown by removing sediment and lowering the streambed.

Effects of Ground-Water Withdrawal on Kaunakakai Stream Environmental Restoration Plan, Moloka‘i, Hawai‘i

By Delwyn S. Oki

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Contents

Figures

Tables

Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
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	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
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)

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

$$°F=(1.8×°C)+32$$

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

$$°C=(°F-32)/1.8$$

Vertical coordinate information is referenced to mean sea level.

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

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

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

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

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Effects of Ground-Water Withdrawal on Kaunakakai Stream Environmental Restoration Plan, Moloka‘i, Hawai‘i

By Delwyn S. Oki

Abstract

The U.S. Army Corps of Engineers, in cooperation with the County of Maui Department of Public Works and Environmental Management, has proposed to construct 2.75 acres of shallow ponds and mudflats near the mouth of Kaunakakai Stream, Moloka‘i, Hawai‘i to restore habitat for the endangered native Hawaiian Stilt. Kaunakakai Stream is ephemeral upstream from the habitat-restoration site. Where the pond and wetland bottoms are below the water table, the ponds and wetland will be sustained by ground-water discharge during dry-weather conditions. Because ground water is the main source of water for the proposed ponds and wetland, a reduction of ground-water level and discharge near the mouth of Kaunakakai Stream will have an effect on the availability of habitat.

In response to concerns about the possible effects of ground-water withdrawal on the habitat-restoration project near the mouth of Kaunakakai Stream, the U.S. Geological Survey undertook the present investigation to estimate, using an existing numerical ground-water-flow model, the changes in ground-water level and coastal discharge caused by redistributed and additional ground-water withdrawals. Steady-state water-level and coastal-discharge changes, relative to recent base-case conditions, were estimated for each of six withdrawal scenarios. Redistributed and additional ground-water withdrawals in the six scenarios were simulated from selected sites in the area between Kualapu‘u and ‘Ualapu‘e. For the scenarios tested, model results indicate that withdrawals from existing and proposed wells cause a water-level decline of about 0.1 feet in the vicinity of the Kaunakakai habitat-restoration site. In addition, model results indicate a reduction of ground-water discharge, ranging from 98,000 to 170,000 gallons per day, to the model element containing the habitat-restoration site, although the existing spatial discretization in the model is too coarse to reliably estimate the reduction of ground-water discharge to the stream. Reduction in discharge to the habitat-restoration site is likely less than the total indicated by the model element because the site covers a small fraction (about 5 percent) of the area of a model element.

Ground-water-level declines near the habitat-restoration site will reduce (1) the available wetted habitat area by an amount that is dependent on the bottom slope of the ponds near their edges, (2) the maximum water depth of the ponds by about 0.1 feet, and (3) the average water depth by an amount that is dependent on the bottom shape of the ponds. The salinity of ground water discharging into the wetland area likely will increase by an unknown amount in response to increased withdrawals upgradient from the site. A numerical model capable of simulating density-dependent flow and transport is needed to evaluate the effects of withdrawal on salinity in the area.

Introduction

The U.S. Army Corps of Engineers (USACE), Honolulu Engineering District, in cooperation with the County of Maui Department of Public Works and Environmental Management (DPWEM), has proposed improvements to the existing Kaunakakai Stream Flood Control Project near the mouth of Kaunakakai Stream, Moloka‘i, Hawai‘i (fig. 1) to restore habitat for the endangered native Hawaiian Stilt (*Himantopus mexicanus knudseni*). (Kaunakakai Stream also is commonly referred to as Kaunakakai Gulch, but for the purposes of this report it will be referred to as Kaunakakai Stream.) The Kaunakakai Stream Flood Control Project was completed in 1950 and consists of an enlarged stream channel with rock-lined levees on the stream banks. About 2.75 acres of wetland habitat, including shallow ponds and mudflats, would be created within the flood-control project limits by removing sediment and lowering the streambed (U.S. Army Corps of Engineers, 2004). Under the proposal, about 9,800 cubic yards of material would be excavated to create three ponds: pond A would extend upstream from the existing highway (route 460) bridge and would be excavated to an altitude of 1 ft below mean sea level; pond B would be adjacent to and extend upstream from pond A and would be excavated to mean sea level; pond C would extend upstream from pond B and be excavated to 1 ft above mean sea level (fig. 2). The study area is within Kaunakakai Stream channel and extends about 1,000 ft upstream of the highway bridge, which is about 1,500 ft inland from the coast.

Where the pond and wetland bottoms are below the water table, the ponds and wetland will be sustained by ground-water discharge during dry-weather conditions. Because ocean tides indirectly affect ground-water levels, tides also will affect water levels in the ponds and wetland. Upstream of the lowland coastal area, Kaunakakai Stream is ephemeral. Because ground water is the main source of water for the proposed ponds and wetland, a reduction of ground-water level and discharge near the mouth of Kaunakakai Stream will have an effect on the efficacy of the habitat-restoration project. Redistributed and additional ground-water withdrawals will affect ground-water levels, pond water levels, and discharge of fresh and brackish water to the near-shore environment.

Purpose and Scope

In response to concerns about the possible effects of ground-water withdrawal on the habitat-restoration project near the mouth of Kaunakakai Stream, the U.S. Geological Survey (USGS) undertook the present investigation, in cooperation with the USACE and DPWEM, 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 changes in water level and coastal discharge caused by redistributed and additional ground-water withdrawals in the area between Kualapuʻu and ʻUalapuʻe on Molokaʻi. This report describes the results of model simulations that assess the hydrologic effects of redistributed or additional ground-water withdrawals relative to 2006 average or May 2007 permitted withdrawal rates. No new data were collected as part of this study.

Setting

The Island of Molokaʻi, 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 Molokaʻi Volcano, which rises to an altitude of 1,381 ft, and the younger East Molokaʻi Volcano, which rises to an altitude of 4,961 ft. The town of Kaunakakai lies near the south coast of central Molokaʻi, about 0.25 mi east of Kaunakakai Stream, and on the south flank of East Molokaʻi Volcano (fig. 1).

Regional Hydrogeologic Setting

The geologic setting of the island of Molokaʻi has been described in detail 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 Molokaʻi. The exposed rocks of East Molokaʻi Volcano are named the East Molokaʻi Volcanics and the Kalaupapa Volcanics (Langenheim and Clague, 1987). Kaunakakai Stream flows over the East Molokaʻi Volcanics, which 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 (approximately 50–500 ft thick) veneer over the lower member (Stearns and Macdonald, 1947). The northeastern part of East Molokaʻi Volcano contains numerous intrusive volcanic dikes, which form a dike complex and reduce bulk permeability of the rocks in the area. The volcanic rocks of West Molokaʻi Volcano are known as the West Molokaʻi Volcanics (Langenheim and Clague, 1987) and are separated from the East Molokaʻi Volcanics by an erosional surface that forms a hydrologic confining unit over the West Molokaʻi Volcanics.

Descriptions of the hydrologic setting and hydrologic data have been published previously (for example Lindgren, 1903; Stearns and Macdonald, 1947; Anthony, 1995; Oki, 1997, 2006; Oki and Bauer, 2001). Precipitation is the source of all freshwater on Molokaʻi. The windward (northeast) side of Molokaʻi is wettest, a pattern controlled by

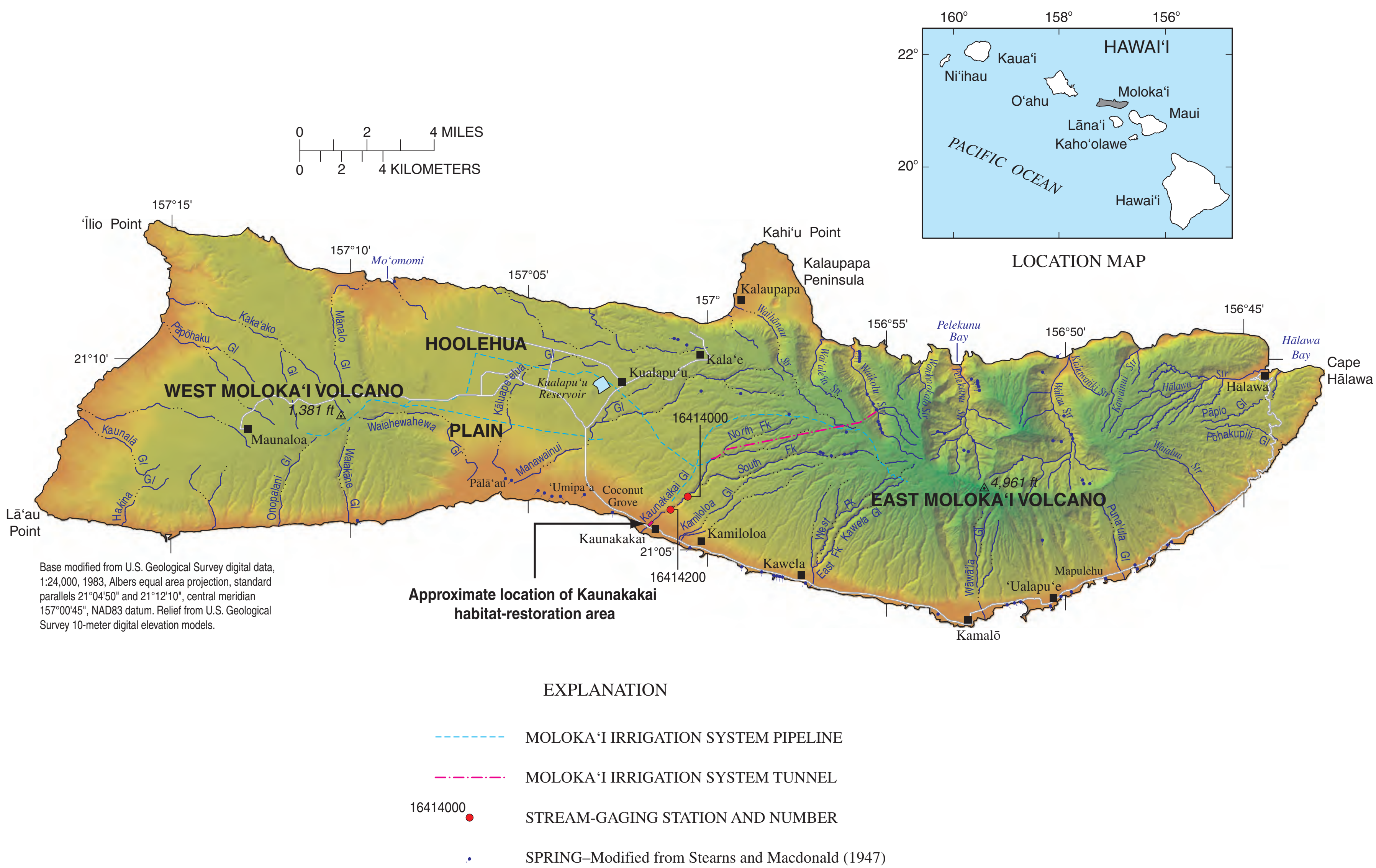


Figure 1. Map of Island of Molokaʻi, Hawaiʻi, showing proposed Kaunakakai habitat-restoration area and selected geographic features. Gl, gulch; Fk, fork; Str, stream.

Figure 2. Aerial photograph showing proposed Kaunakakai habitat-restoration area near the mouth of Kaunakakai Stream, Island of Moloka‘i, Hawai‘i (U.S. Army Corps of Engineers, 2004).

the orographic lifting of moisture-laden northeasterly trade winds along the windward slope of East Moloka‘i Volcano. West Moloka‘i Volcano is considerably drier because it does not extend upward into the cloud-forming zone at higher altitudes. Maximum mean annual rainfall is more than 150 in. near the summit of East Moloka‘i Volcano in the northeastern part of the island (Giambelluca and others, 1986). Over West Moloka‘i 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.

Rain that falls on the surface either (1) runs off, (2) evaporates or is transpired by vegetation, or (3) recharges the ground-water system. Total ground-water recharge on Moloka‘i was estimated from a monthly water budget to be 188.6 million gallons per day (Mgal/d), which represents an average of about 15 in/yr over the island (Shade, 1997). Ground-water recharge estimated by Shade (1997) varies spatially 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.

Water that recharges the ground-water system flows from zones of higher to lower hydraulic head, as measured by ground-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.

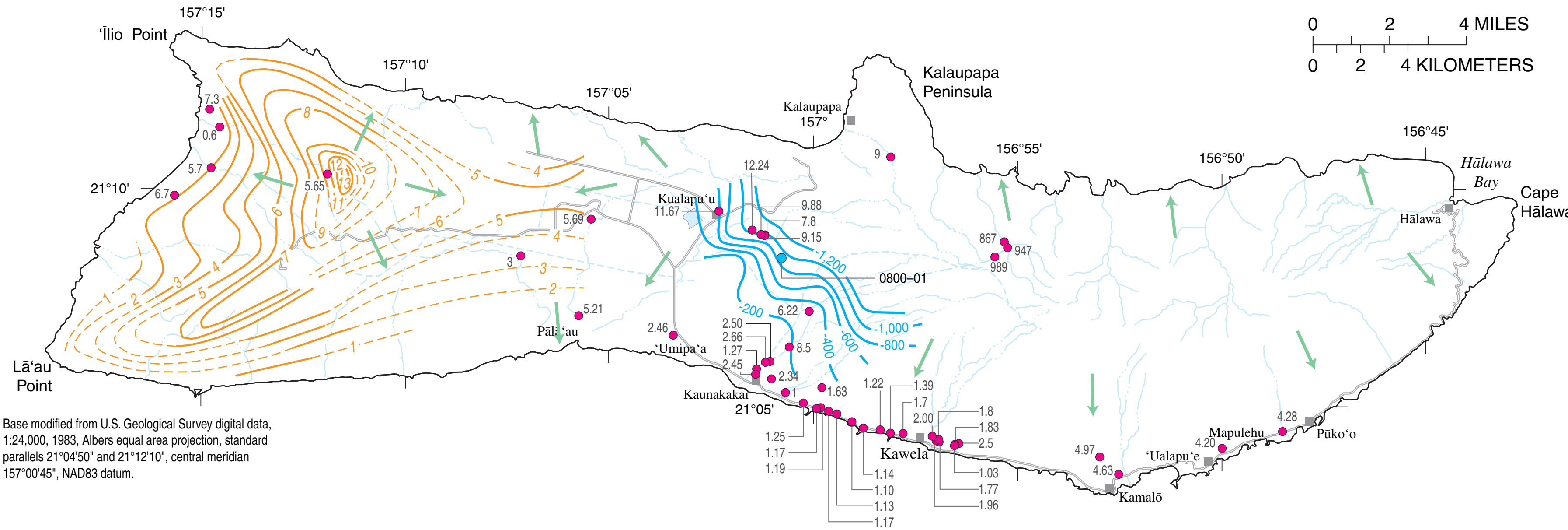
Measured water levels are available primarily in wells along the south coast and in the central plain (fig. 3). In the vicinity of Kualapu‘u, measured water levels are about 8 to 12 ft above sea level; along the south shore, water levels are 1 to 3 ft above sea level between ‘Umipa‘a and Kawela and 4 to 5 ft above sea level between Kamalō and Pūko‘o.

Available data are insufficient to develop a detailed contour map of water levels for the entire island. MacCarthy (1941) used electrical-resistivity measurements to determine the depth to saltwater, and then applied the Ghyben-Herzberg relation to estimate the altitude of the water table in the western part of the island (fig. 3). For hydrostatic conditions, and assuming a sharp interface between freshwater (specific gravity 1.000) and saltwater (specific gravity 1.025), the Ghyben-Herzberg relation predicts that every foot of freshwater above sea level must be balanced by 40 ft of freshwater below sea level. For dynamic conditions, the Ghyben-Herzberg 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. MacCarthy (1941) estimated that the water-table altitude in the western part of the island 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.

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. Ground water on Moloka‘i 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 rocks; and (2) as dike-impounded water ten to hundreds of feet above sea level.

Kaunakakai Hydrogeologic Setting

The Kaunakakai study area is located in the south-central coastal part of the island, where mean annual rainfall is less than 16 in. Near the inland reaches of Kaunakakai Stream, mean annual rainfall exceeds 120 in. (Giambelluca and others, 1986). Stearns and Macdonald (1947) observed small perched springs discharging from the upper member of the East Moloka‘i Volcanics in the north bank of the South Fork of Kaunakakai Stream, between altitudes of 2,450 and 3,150 ft, where the upper member overlies 3 to 5 ft of red ashy soil. Swamps upstream of the springs also may contribute flow to the South Fork of Kaunakakai Stream. During dry weather on October 9, 1945, total streamflow downstream of the springs was 0.12 ft^3/s; drainage from the swamps was 0.062 ft^3/s and discharge from the springs was estimated to be 0.054 ft^3/s (Stearns and Macdonald, 1947). On January 5, 1946, after three additional months of mostly dry weather, streamflow downstream of the springs was estimated to be 0.019 ft^3/s, all of which was attributed to the springs (Stearns and Macdonald, 1947). No springs have been mapped in the North Fork of Kaunakakai Stream. Discharge measurements are not available



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 DEPTH TO SALINE WATER BODY AS DETERMINED BY TIME-DOMAIN ELECTROMAGNETIC SURVEY (HAWAI‘I 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 3. Map showing average measured ground-water levels for the period 1938–97, ground-water levels from resistivity measurements, and altitude of top of saline water body determined from time-domain electromagnetic survey, Island of Moloka‘i, Hawai‘i (modified from Oki, 2006).

to characterize spring discharge for more recent conditions.

The North and South Forks of Kaunakakai Stream flow over the upper member of the East Molokaʻi Volcanics above altitudes of about 1,600 and 3,000 ft, respectively. Below these altitudes, the North and South Forks flow over the more permeable rocks of the lower member of the East Molokaʻi Volcanics. Stearns and Macdonald (1947) indicated that several streams on the southern slope of East Molokaʻi Volcano are perennial in their upper reaches, but do not flow continuously to the coast because of seepage losses and evaporation. These streams generally are perennial where they flow over lavas of the upper member of the East Molokaʻi Volcanics and where water discharges from springs or drains swamps. Where streams flow over the more permeable lower member, surface water more readily may be lost to infiltration. The South Fork of Kaunakakai Stream was described as perennial above an altitude of 1,900 ft (Stearns and Macdonald, 1947).

During water years 1951–98, mean discharge of Kaunakakai Stream near an altitude of 240 ft was 1.9 ft^3/s measured at USGS stream-gaging station 16414000 (Kaunakakai Gulch at Kaunakakai, Molokaʻi, Hawaiʻi), downstream of the confluence of the North and South Forks. (Data from stream gaging-station 16414000 are available on the world-wide web at *http://waterdata.usgs.gov/hi/nwis/nwisman/?site_no=16414000&agency_cd=USGS*.) Recorded daily mean discharge at gaging station 16414000 was zero about 88 percent of the time during water years 1951–98, indicating that, at this site, Kaunakakai Stream probably flows only in response to rainfall. Farther downstream, recorded daily mean discharge at gaging station 16414200 (Kaunakakai Gulch at 75 feet) was zero about 91 percent of the time during water years 2004–6 (*http://waterdata.usgs.gov/hi/nwis/nwisman/?site_no=16414200&agency_cd=USGS*). No known diversions exist upstream from the gaging stations, although discharge from the Molokaʻi Irrigation System (MIS) Tunnel into Kaunakakai Stream sometimes may augment streamflow.

Near the mouth of Kaunakakai Stream, where habitat restoration is being proposed, Kaunakakai Stream is perennial where it is hydraulically connected to the ground-water system. Near the coast, the main ground-water-flow system consists of a freshwater-lens system (Gingerich and Oki, 2000) within dike-free rocks. In general, a freshwater-lens system includes a lens-shaped freshwater body, an intermediate transition zone of brackish water, and underlying saltwater (fig. 4). Within a freshwater-lens system, fresh ground water generally moves from inland areas to the coast. A saltwater circulation system exists beneath the freshwater lens (Cooper and others, 1964; Souza and Voss, 1987). Saltwater flows landward in the deeper parts of the aquifer, rises and mixes with seaward flowing freshwater forming a brackish-water transition zone, and then discharges to the ocean. The thicknesses of freshwater and the brackish-water transition zone are controlled by factors including aquifer permeability, recharge rate, ground-water-withdrawal rate, and extent of mixing between freshwater and underlying saltwater. The freshwater-lens system is recharged mainly by inflow from upgradient areas and also by direct infiltration of precipitation and irrigation water. Near the study area, discharge from the freshwater-lens system is by diffuse seepage near the coast, to springs, to Kaunakakai Stream, to the atmosphere by evapotranspiration, and to withdrawal wells.

In the study area, the freshwater-lens system exists in the dike-free volcanic rocks and sedimentary deposits near the coast. Alluvium overlies the volcanic rocks near the mouth of Kaunakakai Stream, where ground-water levels probably range from near sea level to about 2 ft above mean sea level (fig. 3). Both ground-water levels and stream stage are expected to be affected by ocean tides and longer-term variations in sea level. On the basis of water-quality information from nearby wells, the salinity of ground water near the mouth of Kaunakakai Stream is likely brackish because of mixing with saltwater from the ocean.

Withdrawals

In response to concerns about the water resources of Molokaʻi, the State of Hawaiʻi 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 Molokaʻi through a permitting process to protect the island's water resources. The CWRM has divided the island into 16 management areas or aquifer systems (Hawaiʻi Commission on Water Resource Management, 1990), primarily defined on the basis of geologic conditions and topographic divides (fig. 5) (Mink and Lau, 1992). Limits on ground-water withdrawals on the island currently are based on sustainable-yield estimates for each of the 16 aquifer systems. As of May 2007, the CWRM had issued water-use permits authorizing a total of 8.077 Mgal/d of ground-water withdrawals from wells and tunnels on the island (table 1), although reported withdrawals are less than this total. In addition to

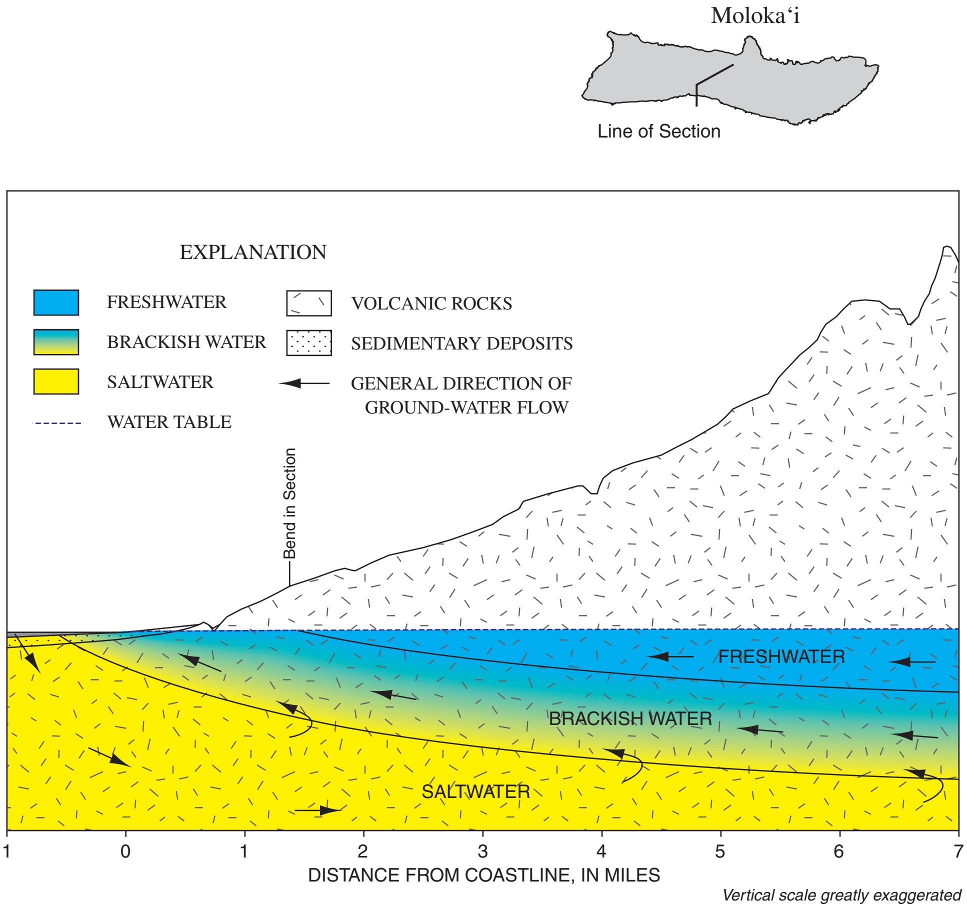


Figure 4. Schematic cross section of the ground-water-flow system on the Island of Moloka‘i, Hawai‘i (modified from Oki, 2006).

the 8.077 Mgal/d of water-use permits, the State of Hawai‘i Department of Hawaiian Home Lands (DHHL) has a reservation for 2.905 Mgal/d of ground water from the Kualapu‘u area (fig. 5; table 1), and the MIS Tunnel develops ground water, estimated to be about 1.822 Mgal/d during 1992–96 (Oki, 1997).

Most of the ground water withdrawn on Moloka‘i is from the Kualapu‘u area, the southeast coastal area, and the dike complex in the north-eastern part of the island. On the basis of complete monthly reports during 2006, the annual mean withdrawal from wells (excluding the MIS Tunnel) on Moloka‘i during 2006 was about 2.917 Mgal/d (computed from digital data supplied by Lenore Nakama, Hawai‘i Commission on Water Resource Management, written commun., 2007). This total is not representative of island-wide withdrawal during 2006—incompletely reported monthly withdrawals from some wells and unreported withdrawals from other wells and tunnels would probably increase the total by several million gallons per day.

Five production wells (0801–01, 0801–02, 0801–03, 0901–01, and 0902–01, fig. 5) have been drilled in the Kualapu‘u 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 17 (0901–01) has been used for domestic supply and irrigation in the western part of the island. During 2006, mean withdrawal from Well 17 (0901–01) was 0.902 Mgal/d. Kualapu‘u wells 0801–01 and 0801–02 (fig. 5) were completed in 1949 and 1979, respectively, and well 0801–03 (Kualapu‘u Mauka) was drilled in 1987. During 2006, annual mean withdrawals from wells 0801–01, 0801–02, and 0801–03 were 0.213, 0.465, and 0.712 Mgal/d, respectively.

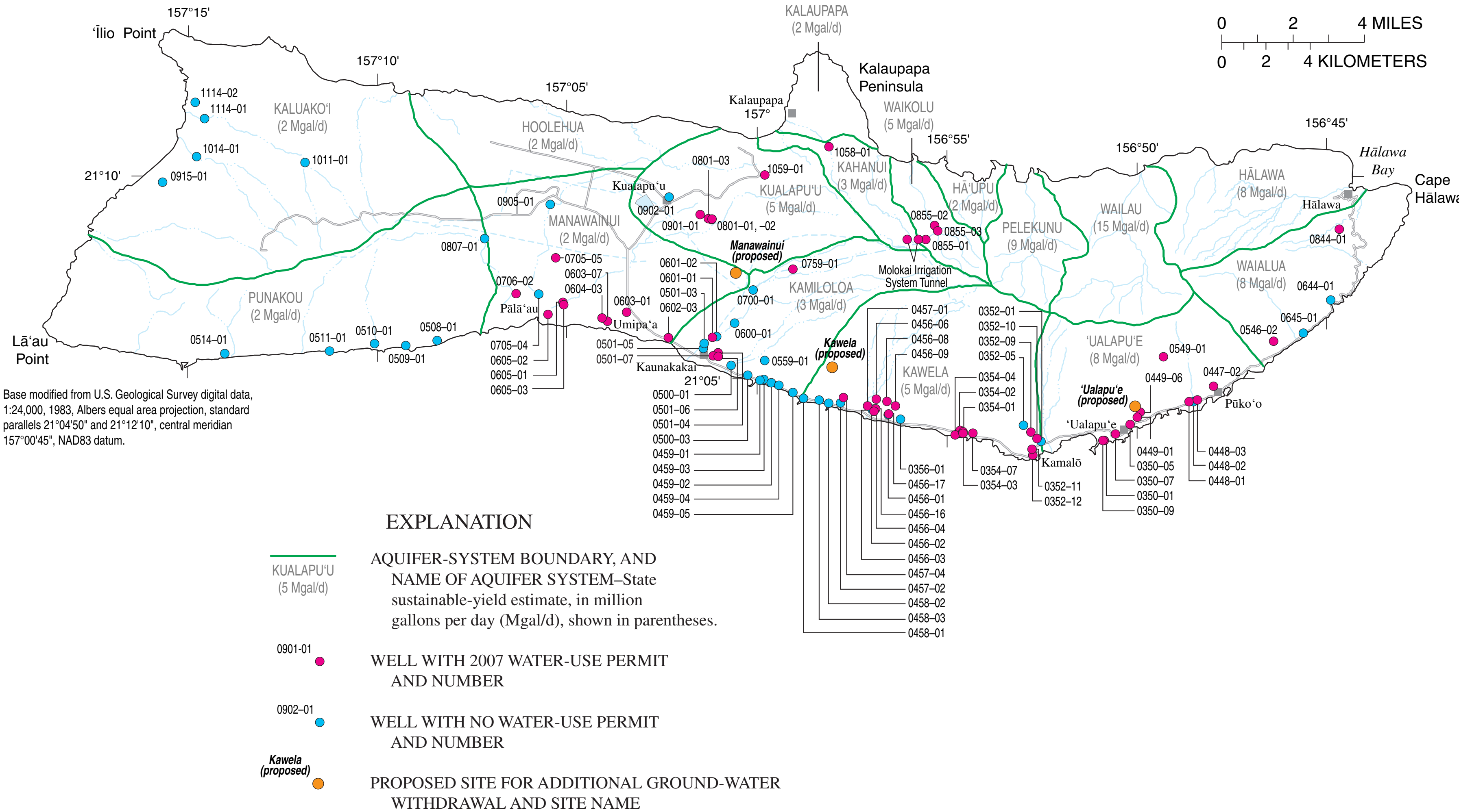


Figure 5. Map showing aquifer systems designated by the State of Hawaiʻi Commission on Water Resource Management and locations of selected wells on the Island of Molokaʻi, Hawaiʻi.

Table 1. May 2007 ground-water-use permits for the Island of Moloka‘i, Hawai‘i.

[Mgal/d, million gallons per day; --, 2006 withdrawal information incomplete or not reported to the Hawai‘i Commission on Water Resource Management]

Well	Name	May 2007 water-use permit, in Mgal/d	2006 average reported withdrawal, in Mgal/d	Aquifer system
0350–01	Keawanui salt	0.240	--	‘Ualapu‘e
0350–05	Wescoatt	0.004	--	‘Ualapu‘e
0350–07	Manawai no. 1	0.015	--	‘Ualapu‘e
0350–09	Oceanic Institute salt	0.750	--	‘Ualapu‘e
0352–09	Kamalō	0.010	--	‘Ualapu‘e
0352–10	Kamalō-Curtis	0.012	--	Kawela
0352–11	Shige’s farm	0.004	--	Kawela
0352–12	Urauchi No. 1	0.001	--	‘Ualapu‘e
0354–01	Meyer, Inc., no. 1	0.029	--	Kawela
0354–02	Meyer, Inc., no. 2	0.040	--	Kawela
0354–03	Well no. 3	0.017	--	Kawela
0354–04	Meyer, Inc., no. 4	0.005	--	Kawela
0354–07	Keonekuino-Teves	0.045	--	Kawela
0447–02	Pūko‘o Farm	0.003	--	‘Ualapu‘e
0448–01	Mapulehu	0.003	--	‘Ualapu‘e
0448–03	Mapulehu Shaft	0.007	--	‘Ualapu‘e
0449–01	‘Ualapu‘e Shaft	0.185	0.272	‘Ualapu‘e
0449–06	Kalua‘aha-Shephard	0.008	--	‘Ualapu‘e
0456–04, 0457–04	Breadfruit well 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	0.330	0.237	Kawela
0501–04	Kupa Shaft	0.056	0.035	Kamiloloa
0501–06	Home Pumehana	0.005	--	Kamiloloa
0501–07	Kaunakakai Park	0.075	--	Kamiloloa
0546–02	Pū‘elelū	0.202	--	Waialua
0549–01	Mapulehu Tunnel	0.010	--	‘Ualapu‘e
0601–01	Oloolo	0.075	0.081	Kamiloloa
0602–03	Kalaiakamanu Hou	0.005	--	Manawainui
0603–01	‘Umipa‘a	0.046	0.000	Manawainui
0605–01, 0605–02	ORCA Shaft no. 1 and no. 2	0.600	--	Manawainui
0605–03	ORCA no. 3	0.040	--	Manawainui
0705–05	Nā‘iwa	0.012	--	Manawainui
0706–02	South Hoolehua	0.864	--	Manawainui
0706–03	Pālā‘au salt	0.001	--	Manawainui
0759–01	Waiola no. 1	[1]0.656	--	Kamiloloa
0801–01, 0801–02	Kualapu‘u DHHL 1 and 2	0.367	0.678	Kualapu‘u
0801–03	Kualapu‘u mauka	0.516	0.712	Kualapu‘u
0844–01	Pu‘u O Hoku no. 1	[1]0.235	--	Waialua
0855–01, 0855–02, 0855–03	Waikolu Tunnel 22–24	0.853	--	Waikolu
0901–01	Well no. 17	1.018	0.902	Kualapu‘u
1058–01	Waihānau no. 239	0.094	--	Kahanui
1059–01	Waikalae Tunnel	0.036	0.00036	Kualapu‘u
DHHL reservation	DHHL reservation	[1]2.905	--	Kualapu‘u
MIS Tunnel	Moloka‘i Irrigation System Tunnel	[2]1.822	--	Waikolu

[1]Not simulated.

[2]No water-use permit; value is 1992–96 average withdrawal (Oki, 1997), equally distributed to two model nodes.

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. 5), near Kawela, was completed in 1921, and the other well (0449–01, fig. 5), near ‘Ualapu‘e, was completed in 1936. During 2006, annual mean withdrawals from wells 0457–01 and 0449–01, respectively, were 0.237 and 0.272 Mgal/d. Total reported annual mean withdrawals, on the basis of complete records, from other wells near the south coast were about 0.116 Mgal/d. Incompletely reported and unreported withdrawals from drilled wells and numerous shallow dug wells along the south coast probably are less than a few million gallons per day.

Three production wells (0855–01, 0855–02, and 0855–03, fig. 5) drilled in 1961 withdraw water from the dike complex in the northeastern part of the island. Water from these wells enters the MIS. Although withdrawals during 2006 from wells 0855–01, 0855–02, and 0855–03 were not reported to the CWRM, from the most recently reported data during the period 2000–2, mean withdrawal from these three wells was 0.99 Mgal/d.

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, water purveyors on Moloka‘i have considered increasing withdrawals from existing wells, drilling additional wells, and redistributing withdrawals among wells. The County of Maui Department of Water Supply (DWS) is considering drilling additional wells to (1) replace existing sources that have increasing salinity, (2) reduce withdrawals in the Kualapu‘u area, and (3) meet anticipated future water demand (Oki, 2006). Moloka‘i Properties Limited, the largest private landowner on Moloka‘i, is considering using brackish water from the existing Kākalahale well (0700–01) for nonpotable needs and using water developed from Well 17 (0901–01) for potable uses only (PBR Hawaii and Associates, Inc., 2006). Excess water available from Well 17 could be made available to communities outside of Moloka‘i Properties Limited lands (PBR Hawaii and Associates, Inc., 2006).

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 Moloka‘i (Oki, 1997). The model was used in another study to estimate changes in steady-state water level and coastal discharge caused by possible redistributed and additional ground-water withdrawals in the area between Kualapu‘u and ‘Ualapu‘e (Oki, 2006) and also is used for the present study.

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 other details regarding development of the regional flow model.

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 domain includes the entire Island of Moloka‘i and offshore coastal-discharge zone. The model domain was discretized using a finite-element mesh consisting of 6,432 nodes and 6,251 square elements (1,640 ft on a side). The original mesh is valid for testing the scenarios described in this study.

A base case defined by 2006 annual mean withdrawal rates, if completely reported, and May 2007 permitted withdrawal rates, otherwise, (table 1) was used to compute changes in water level and coastal discharge caused by redistributed or additional ground-water withdrawals. In the model, withdrawals were assigned to the node nearest to the withdrawal site. The hydraulic characteristics and the magnitude and distribution of long-term average recharge 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 streams. Because ocean levels, coastal bathymetry, and stream-channel altitudes have not changed significantly, the original boundary conditions (Oki, 1997) were used in this study. Modification of model coastal leakance near the mouth of Kaunakakai Stream, where sediment will be excavated to create habitat, was considered unnecessary because (1) the excavated area represents less than 5 percent of the area of a model element, (2) the estimated confining-unit thickness (25 ft) in the excavated area likely would change by less than 10 percent, and (3) the resulting area-weighted confining-unit thickness and leakance value for the model element therefore would change by less than 1 percent.

The water level in Puʻu O Hoku No. 1 well (0844–01, fig. 5), which was drilled after the original model was constructed, is about 9 ft above mean sea level (Hawaiʻi Commission on Water Resource Management, unpub. data, 2006), indicating that the well site probably is 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 withdrawals between Kualapuʻu and ʻUalapuʻe.

Description of Model Scenarios

The base-case scenario was used as a reference for computing changes in steady-state water level and coastal discharge caused by redistributed or additional ground-water withdrawals. The withdrawal rates used in the base case were 2006 mean reported withdrawal rates, if completely reported, an estimated 1.822 Mgal/d withdrawal from the MIS Tunnel (Oki, 1997), and May 2007 permitted withdrawal rates, otherwise (excluding Puʻu O Hoku No. 1, Waiola No. 1, and the DHHL reservation). Puʻu O Hoku No. 1 (0844–01) was not simulated because of uncertainty described previously. The proposed Waiola No. 1 well (0759–01) likely will not be drilled (Charley F. Ice, Hawaiʻi Commission on Water Resource Management, written commun., 2006), and was omitted from the model. The DHHL reservation was omitted from the base case because of uncertainty as to feasible well locations. The base-case withdrawal rates range from 0.001 Mgal/d (well 0352–12) to 1.822 Mgal/d (MIS Tunnel) and total 9.296 Mgal/d (table 1). Total withdrawal represented in the base case is 5 percent of recharge (187 Mgal/d). Recharge in the model (187 Mgal/d) differs slightly from 188.6 Mgal/d estimated by Shade (1997) because discretization near the shoreline causes the modeled land area to differ slightly from the actual land area.

Withdrawal rates simulated in scenarios 1–6 were determined during discussions with the USACE and were based on published information and preliminary plans of various water purveyors (table 2). In scenario 1, withdrawal from the Kākalahale well (0700–01) was increased from zero (base case) to 1.0 Mgal/d (PBR Hawaii and Associates, Inc., 2006). Scenario 2 is similar to scenario 1 but includes increased withdrawal from Well 17 (0901–01), increasing from 0.902 to 1.7 Mgal/d. Scenarios 3 and 5 are similar to scenario 1, but withdrawals from three existing wells (0449–01, 0457–01, and 0801–03) were fully or partially redistributed to three proposed wells (ʻUalapuʻe, Kawela, and Manawainui) (Oki, 2006). Scenarios 4 and 6 are similar to scenario 2, but withdrawals from three existing wells (0449–01, 0457–01, and 0801–03) also were fully or partially redistributed to three proposed wells (ʻUalapuʻe, Kawela, and Manawainui). In scenarios 1, 3, and 5, total withdrawal exceeds the base-case withdrawal by 1.0 Mgal/d, whereas in scenarios 2, 4, and 6, total withdrawal exceeds the base-case withdrawal by 1.798 Mgal/d.

Model Results

For each of the scenarios tested, the changes in water level and coastal discharge were determined relative to the base case. Simulated water-level changes are greatest at withdrawal sites and decrease outward with distance elsewhere. Within the zone where water levels decline because of increased withdrawal, the salinity of water pumped from existing wells may increase, although the extent of the increase cannot be predicted accurately with the sharp-interface model used in this study. Similarly, within the zone where water levels rise because of decreased withdrawal, the salinity of water pumped from existing wells may decrease by an unknown amount. The change in the salinity of water pumped from existing wells is dependent on

Table 2. Summary of withdrawal scenarios simulated with the ground-water-flow model for the Island of Molokaʻi, Hawaiʻi.

[Values in red bold indicate that withdrawal rate differs from base-case withdrawal at the site; Mgal/d, million gallons per day]

Scenario	Simulated withdrawal from selected wells (Mgal/d)								
	Kākalahale (0700–01)	Well 17 (0901–01)	Kualapuʻu Mauka (0801–03)	Kawela Shaft (0457–01)	ʻUalapuʻe Shaft (0449–01)	Manawainui proposed	Kawela proposed	ʻUalapuʻe proposed	Total
Base case	0	0.902	0.712	0.237	0.272	0	0	0	2.123
1	**1.0**	0.902	0.712	0.237	0.272	0	0	0	**3.123**
2	**1.0**	**1.7**	0.712	0.237	0.272	0	0	0	**3.921**
3	**1.0**	0.902	**0.480**	**0**	**0**	**0.232**	**0.237**	**0.272**	**3.123**
4	**1.0**	**1.7**	**0.480**	**0**	**0**	**0.232**	**0.237**	**0.272**	**3.921**
5	**1.0**	0.902	**0.280**	**0**	**0**	**0.432**	**0.237**	**0.272**	**3.123**
6	**1.0**	**1.7**	**0.280**	**0**	**0**	**0.432**	**0.237**	**0.272**	**3.921**

the amount of water-level change and the location of the open interval of the well relative to the depth of the freshwater-saltwater transition zone. Greater water-level changes (all other factors being equal) are expected to cause 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 changes in coastal discharge generally are greatest immediately downgradient from sites of simulated changes in withdrawal. In general, changes in coastal discharge are difficult to measure directly except at onshore springs where discharge is channelized. Thus, the numerical model is used in this study to provide estimates of changes in coastal discharge caused by redistributed or additional ground-water withdrawals. In this study, the changes are represented over areas defined by model elements (1,640 by 1,640 ft). 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, changes greater than 1,000 gal/d generally account for about 95 percent of the total simulated change in discharge. Simulated changes in coastal discharge 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.

Scenario 1

In scenario 1, withdrawal of 1.0 Mgal/d from the Kākalahale well (0700–01) causes water levels and coastal discharge to decrease relative to base-case conditions (fig. 6, tables 3, 4). The simulated water-level decline at the Kākalahale well is 0.61 ft, and water-level declines decrease outward from the well. The areal extent of simulated water-level decline, as indicated by the –0.01-ft line of equal water-level change, is from the Hoolehua Plain in the west to Kawela in the east (fig. 6). The areal extent of simulated water-level decline is limited in the northeast by the dike complex of East Molokaʻi Volcano and in the west by the confining unit separating the West and East Molokaʻi Volcanics. Near the Kaunakakai Stream habitat-restoration site, the simulated water-level decline is 0.08 ft (table 3).

Coastal discharge decreases mainly along the south coast from Pālāʻau in the west to beyond Kawela in the east, but also along the north coast, northwest of the Kākalahale well. The total reduction in coastal discharge simulated in scenario 1 is equal to the withdrawal from the Kākalahale well (1.0 Mgal/d). In general, the simulated decrease in coastal discharge caused by withdrawal from the Kākalahale well is greatest in the coastal area immediately downgradient from the well. Within individual model elements, coastal discharge is reduced by as much as 110,000 gal/d south-southwest of the Kākalahale well and east of Kaunakakai Stream. Near the Kaunakakai Stream habitat-restoration site, the simulated reduction in coastal discharge from the model element closest to the site is 98,000 gal/d, which is a 7-percent reduction relative to base-case conditions (fig. 6, table 4). This reduction in coastal discharge may overestimate the reduction in ground-water discharge to Kaunakakai Stream, and thus the reduction in streamflow, because the stream covers a small fraction of the area represented by the model element.

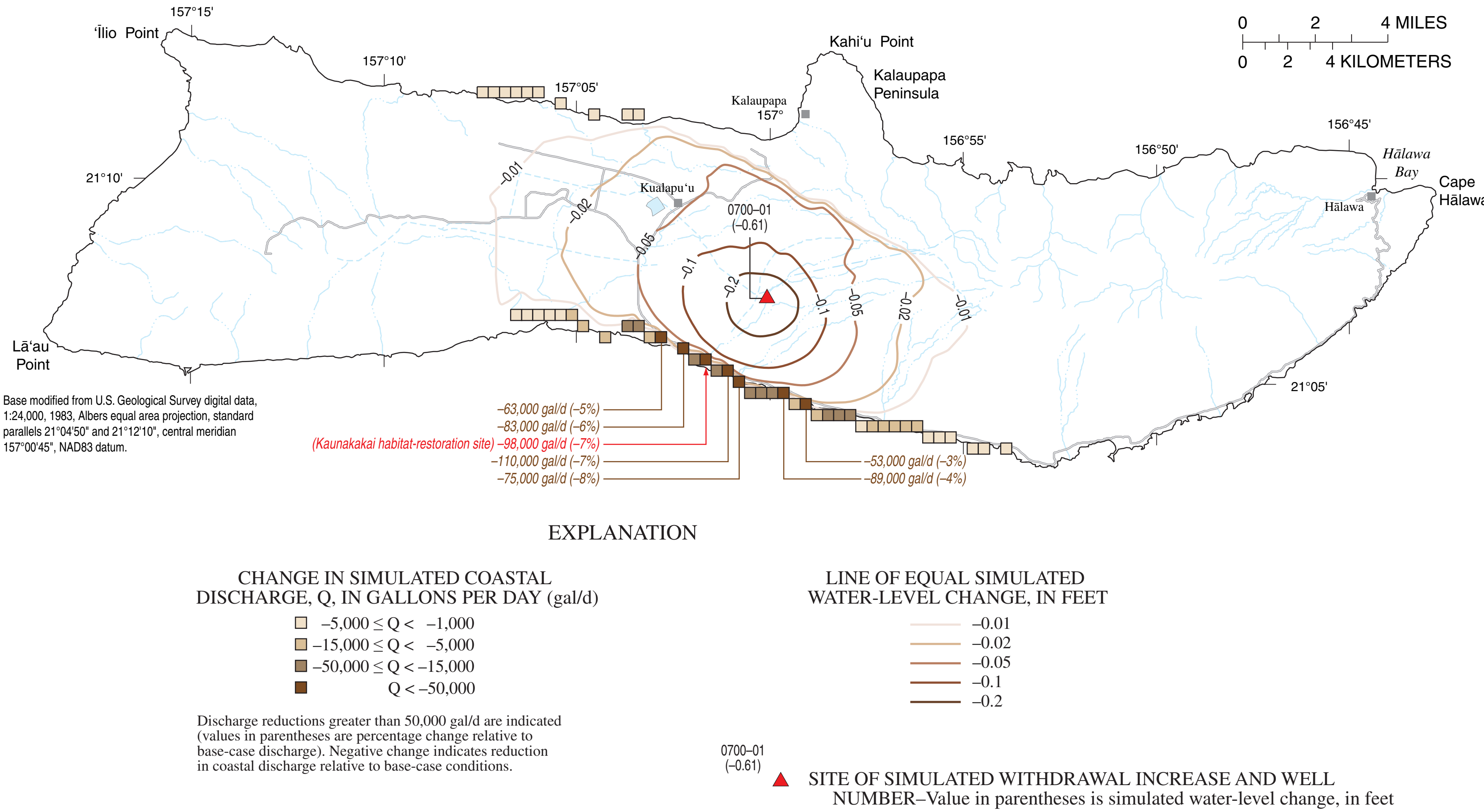


Figure 6. Scenario 1 of ground-water-flow model for the Island of Molokaʻi, Hawaiʻi, showing simulated changes in steady-state ground-water level and coastal discharge (relative to base-case conditions) caused by withdrawing 1.0 million gallons per day from the Kākalahale well (0700–01).

Table 3. Summary of changes in steady-state ground-water level simulated with the ground-water-flow model for the Island of Molokaʻi, Hawaiʻi.

[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]

	Simulated water-level change (feet)								
Scenario	Kākalahale (0700–01)	Well 17 (0901–01)	Kualapuʻu Mauka (0801–03)	Kawela Shaft (0457–01)	ʻUalapuʻe Shaft (0449–01)	Manawainui proposed	Kawela proposed	ʻUalapuʻe proposed	Kaunakakai Stream habitat-restoration site
[1]Base case	5.98	6.89	7.34	2.95	3.64	6.13	4.86	4.75	1.38
1	**–0.61**	–0.09	–0.09	–0.01	0.00	–0.22	–0.04	0.00	–0.08
2	**–0.71**	**–3.40**	–1.45	–0.02	0.00	–0.38	–0.06	0.00	–0.12
3	**–0.65**	0.26	**0.57**	**0.10**	**0.09**	**–0.49**	**–0.14**	**–0.08**	–0.09
4	**–0.74**	**–2.81**	**–0.65**	**0.10**	**0.09**	**–0.65**	**–0.16**	**–0.08**	–0.13
5	**–0.67**	0.54	**1.11**	**0.10**	**0.09**	**–0.72**	**–0.14**	**–0.08**	–0.09
6	**–0.77**	**–2.35**	**–0.03**	**0.10**	**0.09**	**–0.89**	**–0.16**	**–0.08**	–0.13

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

Table 4. Summary of changes in steady-state coastal discharge simulated with the ground-water-flow model for the Island of Molokaʻi, Hawaiʻi.

[Overall maximum changes in coastal discharge are within an individual model element. Model elements are square areas 1,640 feet on a side. Only model elements with base-case coastal discharge greater than 1,000 gal/d considered. gal/d, gallons per day; --, not applicable]

Scenario	[1]Reduction in coastal discharge near Kaunakakai Stream habitat-restoration site (gal/d)	Overall maximum absolute change in coastal discharge (gal/d)		Overall maximum relative change in coastal discharge (percent)		[2]Number of model elements with coastal-discharge change greater than 5 percent	
		Increase	Decrease	Increase	Decrease	Increase	Decrease
1	98,000	--	110,000	--	22	--	13 (7)
2	149,000	--	150,000	--	63	--	25 (12)
3	110,000	37,000	123,000	4	25	0	14 (8)
4	161,000	33,000	164,000	4	57	0	23 (12)
5	118,000	37,000	132,000	4	27	0	14 (9)
6	170,000	33,000	172,000	4	51	0	24 (12)

[1]Simulated reduction in coastal discharge near Kaunakakai Stream habitat-restoration site is from the entire model element nearest the site.

[2]Values in parentheses indicate number of elements with change in steady-state coastal discharge greater than 5 percent and greater than 50,000 gal/d.

Scenario 2

Withdrawals simulated in scenario 2 are similar to those in scenario 1 except that withdrawal from Well 17 (0901–01) was increased from 0.902 to 1.7 Mgal/d. Increased withdrawal from Well 17 causes greater declines in water level and greater reductions in coastal discharge relative to scenario 1 (fig. 7, tables 3, 4). The simulated water-level decline is 3.40 ft at Well 17 and 0.71 ft at the Kākalahale well. The water-level declines decrease outward from Well 17 and the Kākalahale well (0700–01). In scenario 2, the areal extent of simulated water-level decline, as indicated by the –0.01-ft line of equal water-level change, is greater than the extent in scenario 1. Near the Kaunakakai Stream habitat-restoration site, the simulated water-level decline is 0.12 ft in scenario 2 (table 3), which is 0.04 ft greater than the simulated decline in scenario 1.

In scenario 2, coastal discharge decreases mainly along the south coast from Pālā‘au in the west to beyond Kawela in the east, but also along the north coast, northwest of Well 17. Because of increased withdrawal from Well 17 in scenario 2 relative to scenario 1, overall coastal-discharge reduction and reduction at common sites is greater in scenario 2. Within individual model elements, coastal discharge is reduced by as much as 150,000 gal/d along the south coast east of Kaunakakai Stream. Near the Kaunakakai Stream habitat-restoration site, the simulated reduction in coastal discharge from the model element closest to the site is 149,000 gal/d in scenario 2, which is an 11-percent reduction relative to base-case conditions (fig. 7, table 4) and which is greater than the simulated reduction in scenario 1 (98,000 gal/d). This reduction in coastal discharge may overestimate the discharge reduction in Kaunakakai Stream, which covers a small fraction of the area represented by the model element.

Scenario 3

Total withdrawal simulated in scenario 3 is equal to the total withdrawal simulated in scenario 1, but scenario 3 includes a redistribution (full or partial) of withdrawals from existing wells to proposed wells. DWS is considering reducing withdrawal from well 0801–03 to reduce the possibility of saltwater intrusion in the Kualapuu area, where several existing wells are closely spaced. Because of increasing salinity in water pumped from wells 0457–01 and 0449–01 (Oki, 2006), DWS also is considering replacing these wells with wells located farther inland. In scenario 3, withdrawal from well 0801–03 was reduced by 0.232 Mgal/d, and withdrawal from the proposed Manawainui well was increased from zero to 0.232 Mgal/d; withdrawal from well 0457–01 was reduced from 0.237 Mgal/d to zero, and withdrawal from the proposed Kawela well was increased from zero to 0.237 Mgal/d; withdrawal from well 0449–01 was reduced from 0.272 Mgal/d to zero, and withdrawal from the proposed ‘Ualapu‘e well was increased from zero to 0.272 Mgal/d.

Reduced withdrawal from well 0801–03 causes the water level near the well to increase by 0.57 ft (fig. 8). Because of the increased withdrawals from the proposed Manawainui and Kawela wells, the simulated water-level decline at the Kākalahale well in scenario 3 (0.65 ft) is greater than the simulated decline in scenario 1 (0.61 ft). In scenario 3, the areal extent of simulated water-level decline around the Kākalahale well (0700–01), as indicated by the –0.01-ft line of equal water-level change, is less than the extent in scenario 1 because of the decreased withdrawal from well 0801–03. Near the Kaunakakai Stream habitat-restoration site, the simulated water-level decline is 0.09 ft in scenario 3 (table 3), which is 0.01 ft greater than the simulated decline in scenario 1. The effects of redistributing withdrawal from well 0449–01 to the proposed ‘Ualapu‘e well do not extend to Kaunakakai Stream.

In scenario 3, coastal discharge increases slightly along the north coast, northwest of well 0801–03, because of the reduced withdrawal from that well. Local increases in coastal discharge also are simulated near other sites of reduced withdrawal (wells 0457–01 and 0449–01). Within individual model elements, coastal discharge is reduced by as much as 123,000 gal/d along the south coast east of Kaunakakai Stream. Near the Kaunakakai Stream habitat-restoration site, the simulated reduction in coastal discharge from the model element closest to the site is 110,000 gal/d in scenario 3 (fig. 8, table 4), which is an 8-percent reduction relative to base-case conditions and which is greater than the simulated reduction in scenario 1 (98,000 gal/d).

Scenario 4

Total withdrawal simulated in scenario 4 is equal to the total withdrawal simulated in scenario 2, but scenario 4 includes a redistribution (full or partial) of withdrawals from existing wells to proposed wells identical to the redistribution described in scenario 3. Reduced withdrawal from well 0801–03 causes the water-level decline at Well 17 to decrease from 3.40 ft (scenario 2) to 2.81 ft (scenario 4). In contrast, the increased withdrawals from the proposed Manawainui and Kawela wells

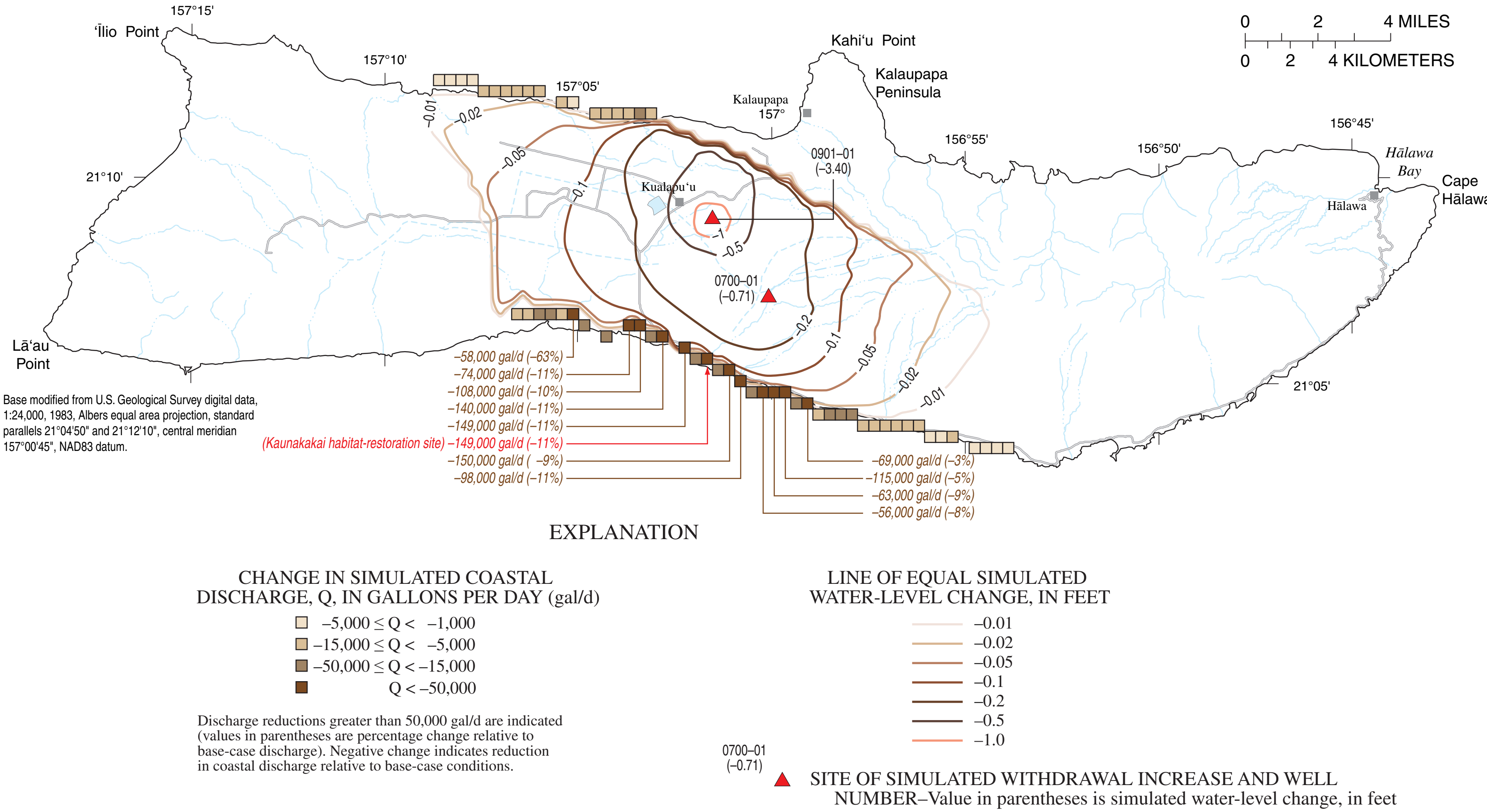


Figure 7. Scenario 2 of ground-water-flow model for the Island of Molokaʻi, Hawaiʻi, showing simulated changes in steady-state ground-water level and coastal discharge (relative to base-case conditions) caused by withdrawing 1.0 million gallons per day (Mgal/d) from the Kākalahale well (0700–01) and increasing withdrawal from Well 17 (0901–01) from 0.902 to 1.7 Mgal/d.

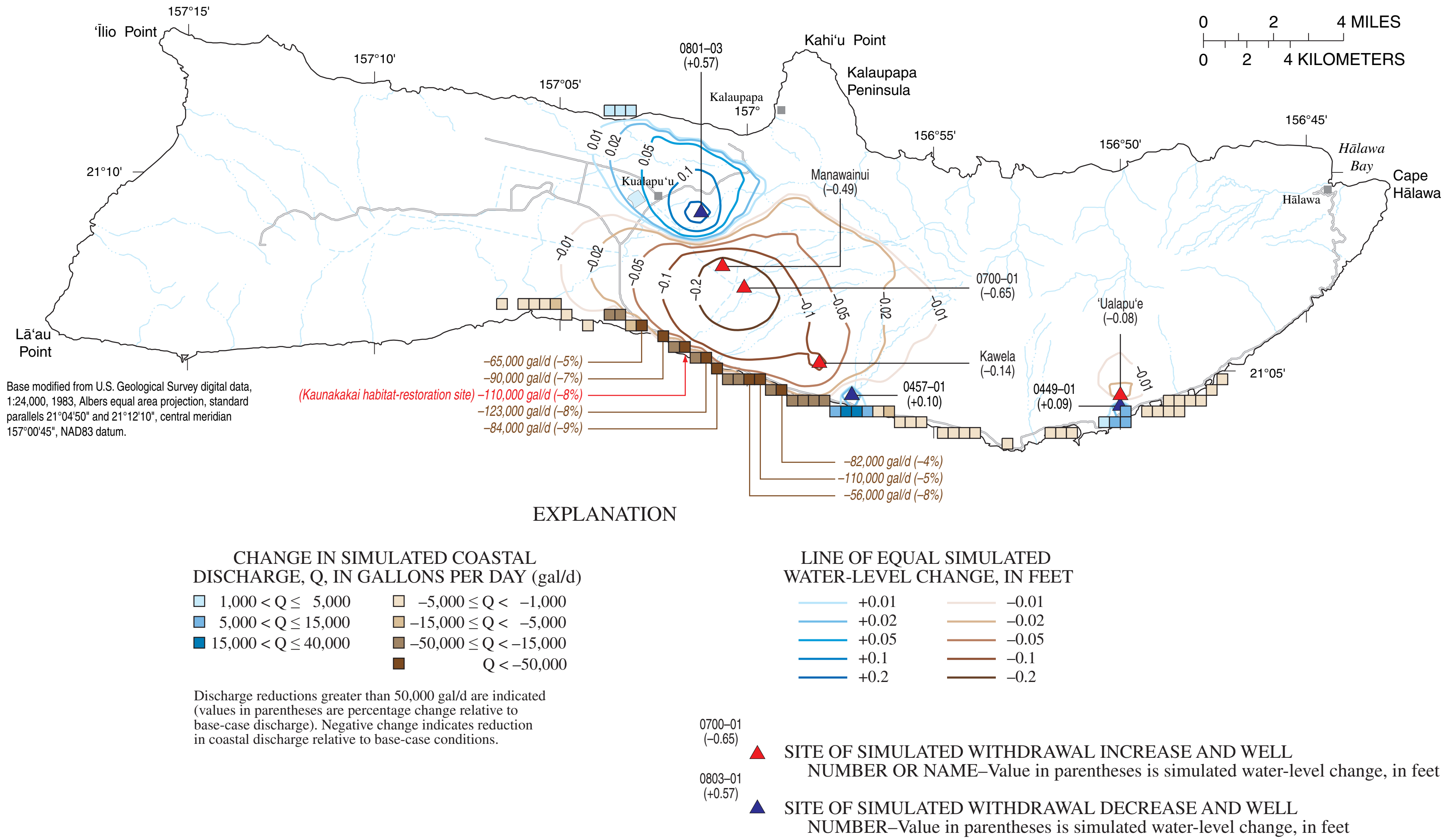


Figure 8. Scenario 3 of ground-water-flow model for the Island of Molokaʻi, Hawaiʻi, showing simulated changes in steady-state ground-water level and coastal discharge (relative to base-case conditions) caused by withdrawing 1.0 million gallons per day (Mgal/d) from the Kākalahale well (0700–01), and redistributing (fully or partially) withdrawal from existing wells to proposed wells. Withdrawal from well 0801–03 was reduced by 0.232 Mgal/d, and withdrawal from the proposed Manawainui well was increased from zero to 0.232 Mgal/d; withdrawal from well 0457–01 was reduced from 0.237 Mgal/d to zero, and withdrawal from the proposed Kawela well was increased from zero to 0.237 Mgal/d; withdrawal from well 0449–01 was reduced from 0.272 Mgal/d to zero, and withdrawal from the proposed ʻUalapuʻe well was increased from zero to 0.272 Mgal/d.

cause the water-level decline at the Kākalahale well (0700–01) to increase from 0.71 ft (scenario 2) to 0.74 ft (scenario 4). Near the Kaunakakai Stream habitat-restoration site, the simulated water-level decline is 0.13 ft in scenario 4 (table 3), which is 0.01 ft greater than the simulated decline in scenario 2.

In scenario 4, coastal discharge decreases mainly along the south coast, but also along the north coast, northwest of Well 17 (0901–01). Local increases in coastal discharge are simulated near sites of reduced withdrawal (wells 0457–01 and 0449–01). Within individual model elements, coastal discharge is reduced by as much as 164,000 gal/d along the south coast east of Kaunakakai Stream. Near the Kaunakakai Stream habitat-restoration site, the simulated reduction in coastal discharge from the model element closest to the site is 161,000 gal/d in scenario 4 (fig. 9, table 4), which is an 11-percent reduction relative to base-case conditions and which is greater than the simulated reduction in scenario 2 (149,000 gal/d).

Scenario 5

Simulated withdrawal in scenario 5 is similar to withdrawal in scenario 3, except that withdrawal from 0801–03 is further reduced by 0.2 Mgal/d and withdrawal from the proposed Manawainui well is increased by an equal amount. In scenario 5, the water level at well 0801–03 increases by 1.11 ft relative to the base case, compared to an increase of 0.57 ft in scenario 3. Because of the increased withdrawal from the proposed Manawainui well, the simulated water-level decline at the Manawainui well in scenario 5 (0.72 ft) is greater than the simulated decline in scenario 3 (0.49 ft). Near the Kaunakakai Stream habitat-restoration site, the simulated water-level decline is 0.09 ft in scenario 5 (table 3), which is equal to the simulated decline in scenario 3.

In scenario 5, coastal discharge increases slightly along the north coast, northwest of well 0801–03, because of the reduced withdrawal from that well. Local increases in coastal discharge also are simulated near other sites of reduced withdrawal (wells 0457–01 and 0449–01). Within individual model elements, coastal discharge is reduced by as much as 132,000 gal/d along the south coast east of Kaunakakai Stream. Near the Kaunakakai Stream habitat-restoration site, the simulated reduction in coastal discharge from the model element closest to the site is 118,000 gal/d in scenario 5 (fig. 10, table 4), which is an 8-percent reduction relative to base-case conditions and which is greater than the simulated reduction in scenario 3 (110,000 gal/d).

Scenario 6

Simulated withdrawal in scenario 6 is similar to withdrawal in scenario 4, except that withdrawal from 0801–03 is further reduced by 0.2 Mgal/d and withdrawal from the proposed Manawainui well is increased by an equal amount. In scenario 6, the water level at well 0801–03 decreases by 0.03 ft relative to the base case, compared to a decrease of 0.65 ft in scenario 4. Because of the increased withdrawal from the proposed Manawainui well, the simulated water-level decline at the Manawainui well in scenario 6 (0.89 ft) is greater than the simulated decline in scenario 4 (0.65 ft). Near the Kaunakakai Stream habitat-restoration site, the simulated water-level decline is 0.13 ft in scenario 6 (table 3), which is equal to the simulated decline in scenario 4.

In scenario 6, coastal discharge decreases mainly along the south coast, but also along the north coast, northwest of Well 17 (0901–01). Local increases in coastal discharge are simulated near sites of reduced withdrawal (wells 0457–01 and 0449–01). Within individual model elements, coastal discharge is reduced by as much as 172,000 gal/d along the south coast east of Kaunakakai Stream. Near the Kaunakakai Stream habitat-restoration site, the simulated reduction in coastal discharge from the model element closest to the site is 170,000 gal/d in scenario 6 (fig. 11, table 4), which is a 12-percent reduction relative to base-case conditions and which is greater than the simulated reduction in scenario 4 (161,000 gal/d).

Effects on Kaunakakai Habitat-Restoration Site

Model results indicate that withdrawals (within the ranges tested) from Well 17 (0901–01), the Kākalahale well (0700–01), and the proposed Manawainui and Kawela wells cause a water-level decline of about 0.1 ft in the vicinity of the Kaunakakai habitat-restoration site. This reduction in ground-water level will cause a reduction of ground-water discharge to Kaunakakai Stream, but the existing spatial discretization in the model is too coarse to reliably estimate the reduction. The simulated reductions of discharge in the model element containing the habitat-restoration site range from 98,000 to 170,000 gal/d. Reduction in discharge to the habitat-restoration site likely is less than the total indicated by the model element because the

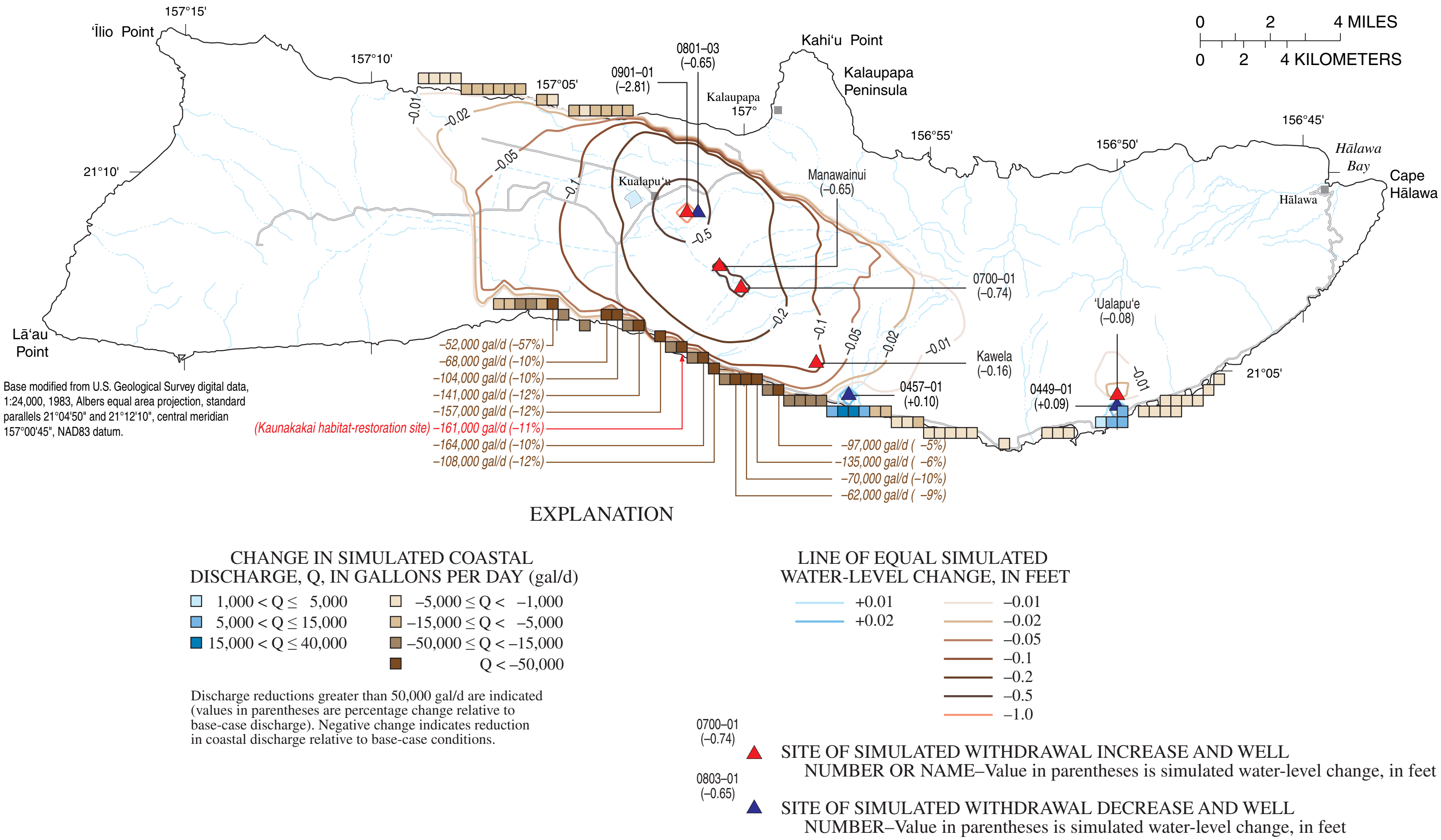


Figure 9. Scenario 4 of ground-water-flow model for the Island of Molokaʻi, Hawaiʻi, showing simulated changes in steady-state ground-water level and coastal discharge (relative to base-case conditions) caused by withdrawing 1.0 million gallons per day (Mgal/d) from the Kākalahale well (0700–01), increasing withdrawal from Well 17 (0901–01) from 0.902 to 1.7 Mgal/d, and redistributing (fully or partially) withdrawal from existing wells to proposed wells. Withdrawal from well 0801–03 was reduced by 0.232 Mgal/d, and withdrawal from the proposed Manawainui well was increased from zero to 0.232 Mgal/d; withdrawal from well 0457–01 was reduced from 0.237 Mgal/d to zero, and withdrawal from the proposed Kawela well was increased from zero to 0.237 Mgal/d; withdrawal from well 0449–01 was reduced from 0.272 Mgal/d to zero, and withdrawal from the proposed ʻUalapuʻe well was increased from zero to 0.272 Mgal/d.

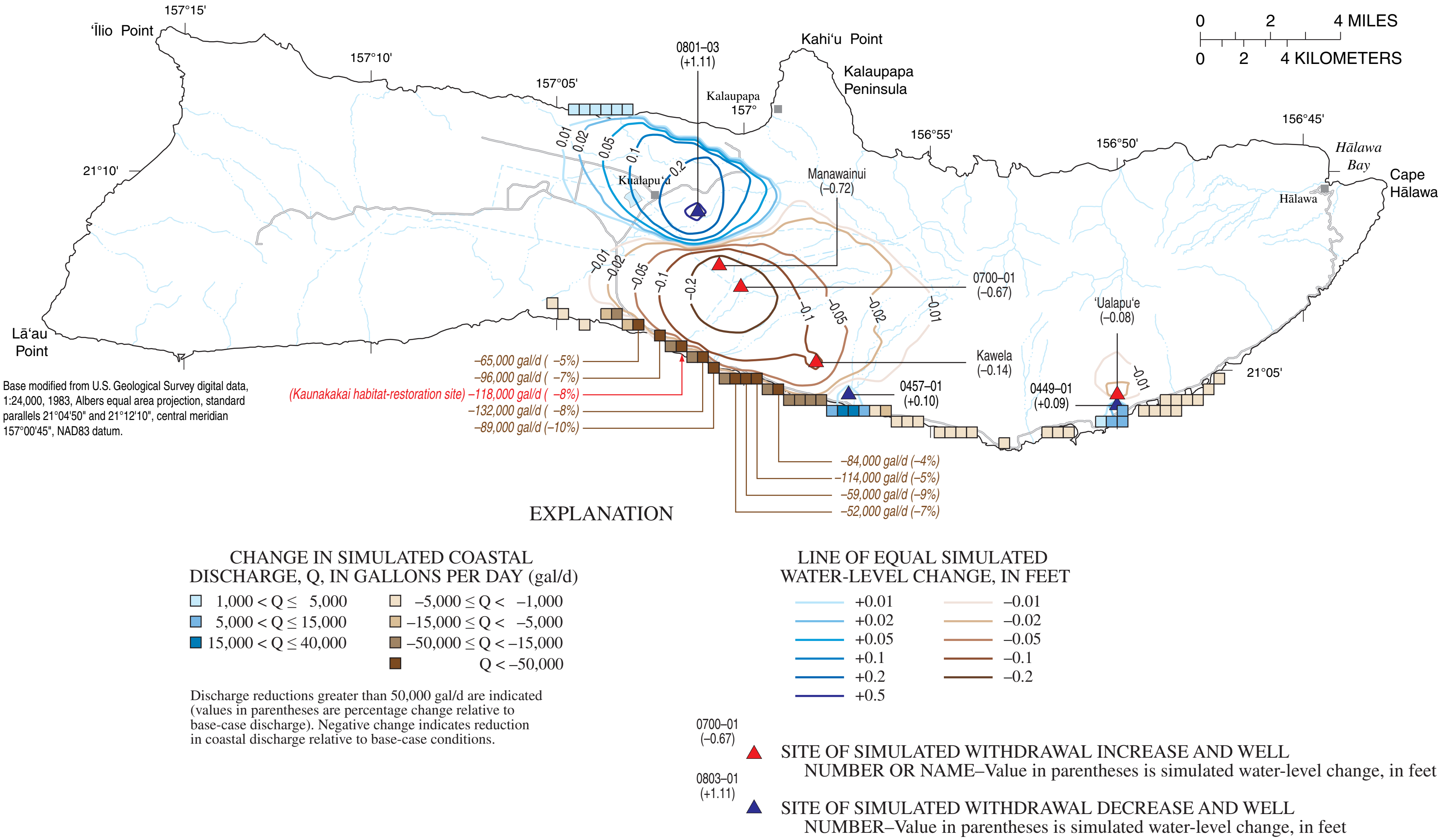


Figure 10. Scenario 5 of ground-water-flow model for the Island of Molokaʻi, Hawaiʻi, showing simulated changes in steady-state ground-water level and coastal discharge (relative to base-case conditions) caused by withdrawing 1.0 million gallons per day (Mgal/d) from the Kākalahale well (0700–01), and redistributing (fully or partially) withdrawal from existing wells to proposed wells. Withdrawal from well 0801–03 was reduced by 0.432 Mgal/d, and withdrawal from the proposed Manawainui well was increased from zero to 0.432 Mgal/d; withdrawal from well 0457–01 was reduced from 0.237 Mgal/d to zero, and withdrawal from the proposed Kawela well was increased from zero to 0.237 Mgal/d; withdrawal from well 0449–01 was reduced from 0.272 Mgal/d to zero, and withdrawal from the proposed ʻUalapuʻe well was increased from zero to 0.272 Mgal/d.

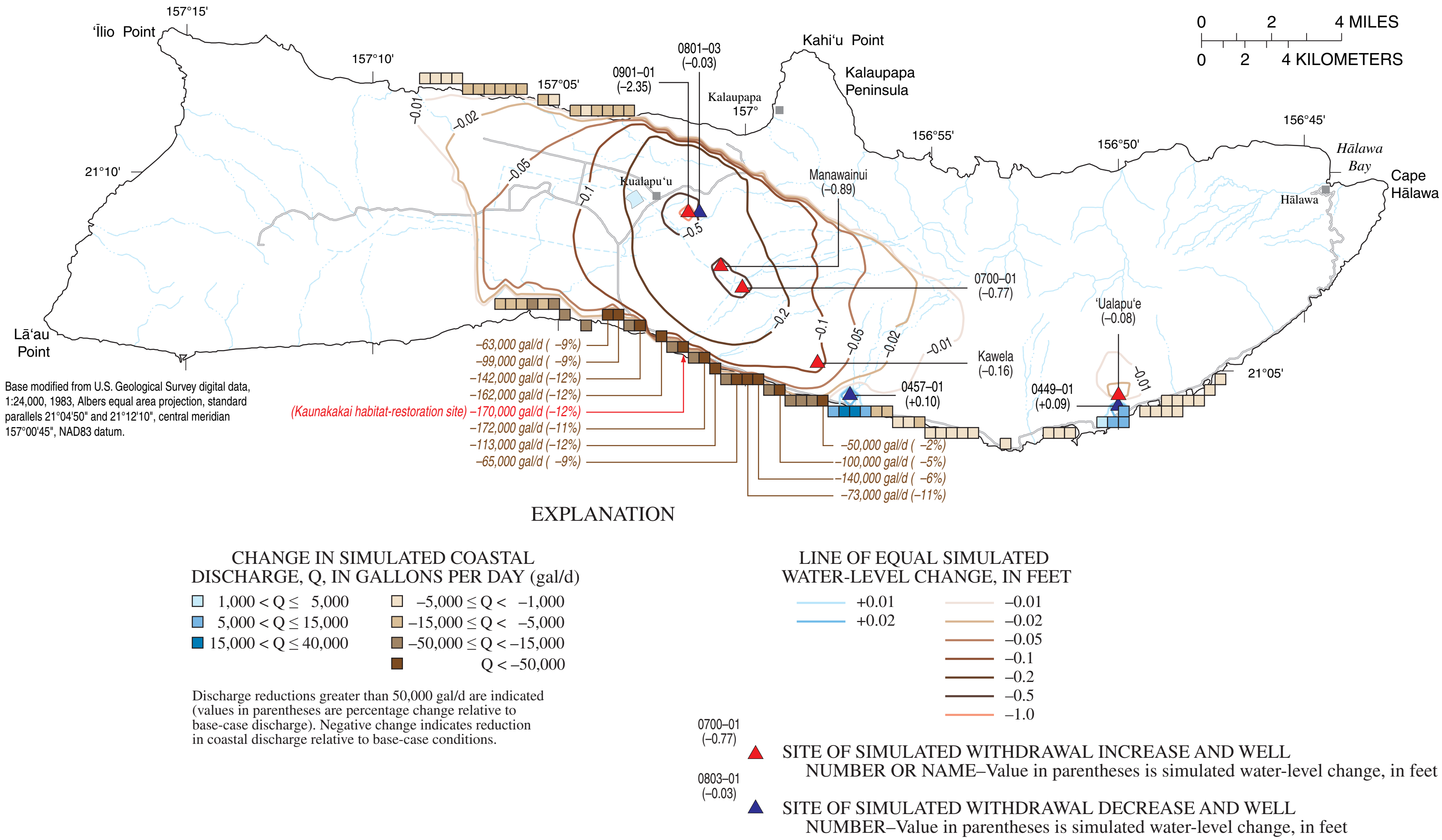


Figure 11. Scenario 6 of ground-water-flow model for the Island of Moloka‘i, Hawai‘i, showing simulated changes in steady-state ground-water level and coastal discharge (relative to base-case conditions) caused by withdrawing 1.0 million gallons per day (Mgal/d) from the Kākalahale well (0700–01), increasing withdrawal from Well 17 (0901–01) from 0.902 to 1.7 Mgal/d, and redistributing (fully or partially) withdrawal from existing wells to proposed wells. Withdrawal from well 0801–03 was reduced by 0.432 Mgal/d, and withdrawal from the proposed Manawainui well was increased from zero to 0.432 Mgal/d; withdrawal from well 0457–01 was reduced from 0.237 Mgal/d to zero, and withdrawal from the proposed Kawela well was increased from zero to 0.237 Mgal/d; withdrawal from well 0449–01 was reduced from 0.272 Mgal/d to zero, and withdrawal from the proposed ‘Ualapu‘e well was increased from zero to 0.272 Mgal/d.

site covers a small fraction (about 5 percent) of the area of the model element.

The reduction of ground-water level near the habitat-restoration site also may reduce the wetted habitat area available to the native species. The extent of reduction in wetted habitat area is controlled by the slope of the ponds near their edges, which will be affected by channel scour associated with large storms and sedimentation. The maximum water depth of the proposed ponds will be reduced by about 0.1 ft, and the average water depth also will be reduced by an amount that is dependent on the bottom shape of the ponds. The salinity of ground water discharging into the wetland area likely will increase by an unknown amount in response to increased withdrawals upgradient from the site. A numerical model capable of simulating density-dependent flow and transport is needed to evaluate the effects of withdrawal on salinity in the area.

Model Limitations

The ground-water-flow model of Moloka‘i 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 Moloka‘i 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, 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 relatively coarse spatial discretization and because local-scale heterogeneities in the hydraulic characteristics of the rocks are not represented. Furthermore, changes to the hydraulic characteristics of the system, caused for example by excavation or filling near sites of ground-water discharge, may not be represented accurately in the model.

Summary

The U.S. Army Corps of Engineers, in cooperation with the County of Maui Department of Public Works and Environmental Management, has proposed to construct 2.75 acres of shallow ponds and mudflats near the mouth of Kaunakakai Stream, Moloka‘i, Hawai‘i to restore habitat for the endangered native Hawaiian Stilt. Where the pond and wetland bottoms are below the water table, the ponds and wetland will be sustained by ground-water discharge during dry-weather conditions. Upstream of the lowland coastal area where Kaunakakai Stream is hydraulically connected to the ground-water system, Kaunakakai Stream is ephemeral. Because ground water is the main source of water for the proposed ponds and wetland, a reduction of ground-water level and discharge near the mouth of Kaunakakai Stream will have an effect on the efficacy of the habitat-restoration project. Redistributed and additional ground-water withdrawals will affect ground-water levels and discharge of fresh and brackish water near the project.

In response to concerns about the possible effects of ground-water withdrawal on the habitat-restoration project near the mouth of Kaunakakai Stream, the USGS undertook the present investigation to quantify the hydrologic effects of withdrawal from selected sites on ground-water levels and coastal discharge. An existing numerical ground-water-flow model was used to estimate changes in ground-water level and coastal discharge caused by redistributed and additional ground-water withdrawals in the area between Kualapu‘u and ‘Ualapu‘e.

The ground-water-flow model was used to quantify changes, relative to base-case conditions, in steady-state ground-water level and coastal discharge for each of six withdrawal scenarios. Withdrawals simulated in the base case were average 2006 withdrawal rates, if completely reported, and May 2007 permitted rates otherwise. Simulated changes in ground-water level are greatest at withdrawal sites and decrease outward with distance elsewhere. Simulated changes in coastal discharge generally are greatest immediately downgradient from sites of withdrawal change. For the scenarios tested, hydrologic changes caused by withdrawals were limited to areas outside the low-permeability dike complex of East Moloka‘i Volcano and to areas east of the confining unit separating West and East Moloka‘i Volcanics. Water-level declines at withdrawal sites were as much as 3.40 ft at Well 17 (0901–01), and coastal-discharge reductions in individual model elements (square areas 1,640 ft on a side) were as much as 170,000 gal/d along the south coast.

For the scenarios tested, model results indicate that withdrawals from existing and proposed wells cause a water-level decline of about 0.1 ft in the vicinity of the Kaunakakai habitat-restoration site. In addition, model results indicate a reduction of ground-water discharge to the stream, although the spatial discretization in the existing model is too coarse to accurately estimate the reduction of ground-water discharge to the stream. Reduction of discharge in the model element containing the habitat-restoration site ranges from 98,000 to 170,000 gal/d. Reduction in discharge to the habitat-restoration site is likely less than the total indicated because the site covers a small fraction (about 5 percent) of the model element.

The reduction of ground-water level near the habitat-restoration site will reduce (1) the available wetted habitat area by an amount that is dependent on the bottom slope of the ponds near their edges, (2) the maximum water depth of the ponds by about 0.1 ft, and (3) the average water depth by an amount that is dependent on the bottom shape of the ponds. The salinity of ground water discharging into the wetland area likely will increase by an unknown amount in response to increased withdrawals upgradient from the site. A numerical model capable of simulating density-dependent flow and transport is needed to evaluate the effects of withdrawal on salinity in the area.

The ground-water-flow model simulates the regional effects of additional withdrawal on water level and coastal discharge. The actual reduction in water level and coastal discharge on a local scale may not be accurately represented by the model because of the relatively coarse spatial discretization used in the model and because local-scale heterogeneities in the hydraulic characteristics of the rocks are not represented. Furthermore, human-induced changes to the hydraulic characteristics of the system, caused for example by excavation or filling near sites of ground-water discharge, may not be represented accurately in the model.

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