U.S. Department of the Interior

Numerical Simulation of Ground-Water Withdrawals in the Southern Lihue Basin, Kauai, Hawaii

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 01-4200

Prepared in cooperation with the

COUNTY OF KAUAI DEPARTMENT OF WATER

USGS

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By Scot K. Izuka and Delwyn S. Oki

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Honolulu, Hawaii
2002

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Numerical Simulation of Ground-Water Withdrawals in the Southern Lihue Basin, Kauai, Hawaii

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Abstract

Numerical simulations indicate that ground-water withdrawals from the Hanamaulu and Puhi areas of the southern Lihue Basin will result in a decline in water levels and reductions in base flows of streams near proposed new water-supply wells. Most of the changes will be attained within 10 to 20 years of the start of pumping. Except for areas such as Puhi and Kilohana, the freshwater lens in most inland areas of the southern Lihue Basin is thick and model simulations indicate that changes in water level and the position of the freshwater-saltwater interface in response to pumping will be small relative to the present thickness of the freshwater lens. Effects of the proposed withdrawals on streamflow depend on withdrawal rate and proximity of the wells to streams. Placing pumped wells away from streams with low base flow and toward streams with high base flow can reduce the relative effect on individual streams.

Simulation of the 0.42-million-gallon-per-day increase in withdrawal projected for 2000 indicates that the resulting changes in water levels and interface position, relative to conditions prior to the withdrawal increase, will be small, and that stream base flow will be reduced by less than 10 percent. Simulation of the 0.83-million-gallon-per-day withdrawal projected for 2010 indicates further thinning of the freshwater lens in the Puhi area, where the lens already may be thin, as well as base-flow reduction in Nawiliwili Stream. Simulation of an alternative distribution of the 0.83-million-gallon-per-day withdrawal indicates that the effects can be reduced by shifting most of the new withdrawal to the Hanamaulu area where the freshwater lens is thicker and stream base flows are greater.

Simulation of the 1.16-million-gallon-per-day increase in withdrawal projected for 2020 indicates that if withdrawal is distributed only among Hanamaulu wells 1, 3, and 4, and Puhi well 5A, further thinning of the already-thin freshwater lens in the Puhi area would occur. Such a distribution would also exceed the maximum draft recommended by the water-systems standards used in Hawaii. Another simulation in which part of the 1.16 million gallons per day was distributed among three additional hypothetical wells in the Hanamaulu area showed that the pumping effects could be shifted from the Puhi area to the Hanamaulu area, where the freshwater lens is thicker, but that base flow in Hanamaulu Stream may decrease by as much as 16 percent.

INTRODUCTION

Projected increases in demand have compelled the Kauai County Department of Water (Kauai DOW) to explore for additional ground-water sources in the Lihue Basin, which includes the most populated areas on Kauai, Hawaii (fig. 1). The projected increases will come from and serve the southern Lihue Basin which, for the purposes of this study, is defined as the area of the Lihue Basin south of South Fork Wailua River (fig. 1). In 1990, Kauai's population was about 51,000, of which about 20 percent resided in the Lihue District (State of Hawaii, 1991). Total ground-water withdrawal from wells near Lihue in 1990 was estimated to be about

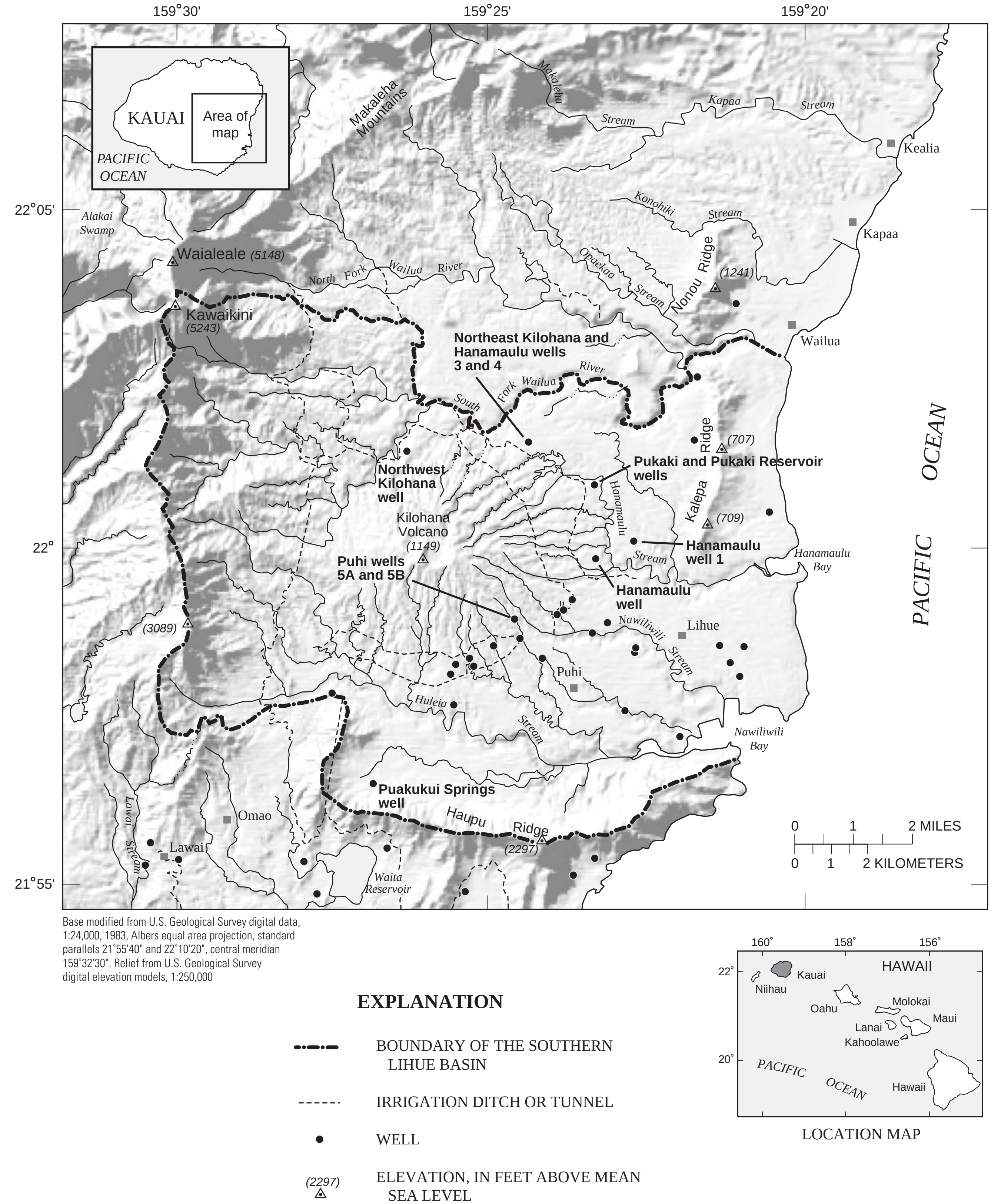


Figure 1. The southern Lihue Basin, Kauai, Hawaii.

Table 1. Kauai Department of Water projections for increases in water demand for Lihue, Kauai, Hawaii (Kauai County Department of Water, written commun., 2000)

Year	Projected additional ground-water withdrawal[1] (million gallons per day)
2000	0.42
2010	0.83
2020	1.16

[1] All values for additional withdrawal are relative to existing withdrawals prior to 2000

Table 2. Kauai Department of Water ground-water development projects in the Lihue area, Kauai, Hawaii (Kauai County Department of Water, written commun., 2000)
[gal/min, gallons per minute; Mgal/d, million gallons per day]

Well Project	Capacity (gal/min)	Capacity (Mgal/d)	Estimated completion date	Location
Hanamaulu well 1	50	0.07	2000	Hanamaulu
Hanamaulu well 3	160	0.23	2000	Hanamaulu
Hanamaulu well 4	300	0.43	2000	Hanamaulu
Pukaki well	120	0.17	2000	Hanamaulu
Puhi well 5A	400	0.58	2001	Puhi
Puhi well 5B[1]	700	1.01	2001	Puhi

[1]Puhi well 5B will be used as standby only, and therefore pumped infrequently (Gregg Fujikawa, Kauai County Department of Water, oral commun., 2000)

5 Mgal/d (Shade, 1995a). Since then, however, the Lihue Basin has undergone changes in land use accompanied by changes in water use. Since the mid-19th century, sugarcane cultivation grew to become the dominant land use in the Lihue Basin, but in the 1970's the sugarcane industry began a decline that ultimately led to the closure of the last plantation in 2000. Some former sugarcane lands have been converted to residential use or diversified agriculture.

The Kauai DOW recently projected water-demand increases of 1.16 Mgal/d by 2020 in the Lihue Basin (table 1). The Kauai DOW plans to meet the projected increases in water demand by constructing four new wells in the Hanamaulu area and two wells in the Puhi area during 2000 and 2001 (Kauai DOW, written commun., 2000) (table 2). Only the four wells in Hanamaulu and one well in Puhi (well 5A) will be pumped; the other well in Puhi (well 5B) will be a standby well for infrequent use (G. Fujikawa, Kauai DOW, oral commun., 2000). In this report, the term "pre-development," when applied to ground-water development, refers to the conditions (including existing pumped wells) prior to the addition of the proposed wells listed in table 2.

The Kauai DOW is concerned about the potential effects of the additional withdrawal, and whether the potential effects will limit well yields in the southern Lihue Basin. Increased ground-water withdrawal in a coastal area such as the southern Lihue Basin may lower the water table, raise the underlying saltwater, and reduce streamflow and discharge to the ocean. With a few exceptions, wells developing water in the southern Lihue Basin cause substantial depression of nearby water levels in the aquifer because of the low regional permeabilities of the basin's aquifers, but the effect of pumping on saltwater rise in Lihue is not known.

Ground-water discharge to streams in the southern Lihue Basin is substantial (Izuka and Gingerich, 1998a). Because of this ground-water/surface-water connection, ground-water withdrawals may reduce streamflows. State laws governing the reduction of flow in streams thus emerge as a potential limiting factor for ground-water development projects. However, the Hawaii State Water Code (Chapter 174C, Hawaii Revised Statutes) allows for streamflow reduction, provided the reduction does not cause flows to diminish below an "instream flow standard," which is defined as "the quantity or flow of water or depth of water which is required . . . to protect fishery, wildlife, recreational, aesthetic, scenic, and other beneficial instream uses." Although final instream flow standards were not yet established for the streams in the southern Lihue Basin at the time of this study, their eventual implementation will consider "existing and potential water developments including the economic impact of restriction of such use." Assessment of ground-water-development effects relative to instream flow standards requires quantitative estimates of streamflow reduction.

Purpose and Scope

To quantify the effects that may result from proposed ground-water development in the southern Lihue Basin, the U. S. Geological Survey (USGS), in cooperation with the Kauai DOW, undertook a study in which several proposed ground-water development scenarios were simulated using an existing numerical ground-water-flow model (Izuka and Gingerich, 1998a) of the southern Lihue Basin. This report summarizes the results of these simulations and their implications for ground-water development in the southern Lihue Basin.

Acknowledgments

The authors are grateful to the Kauai DOW Manager and Chief Engineer Ernest Lau, and the staff of the Kauai DOW for their cooperation and assistance.

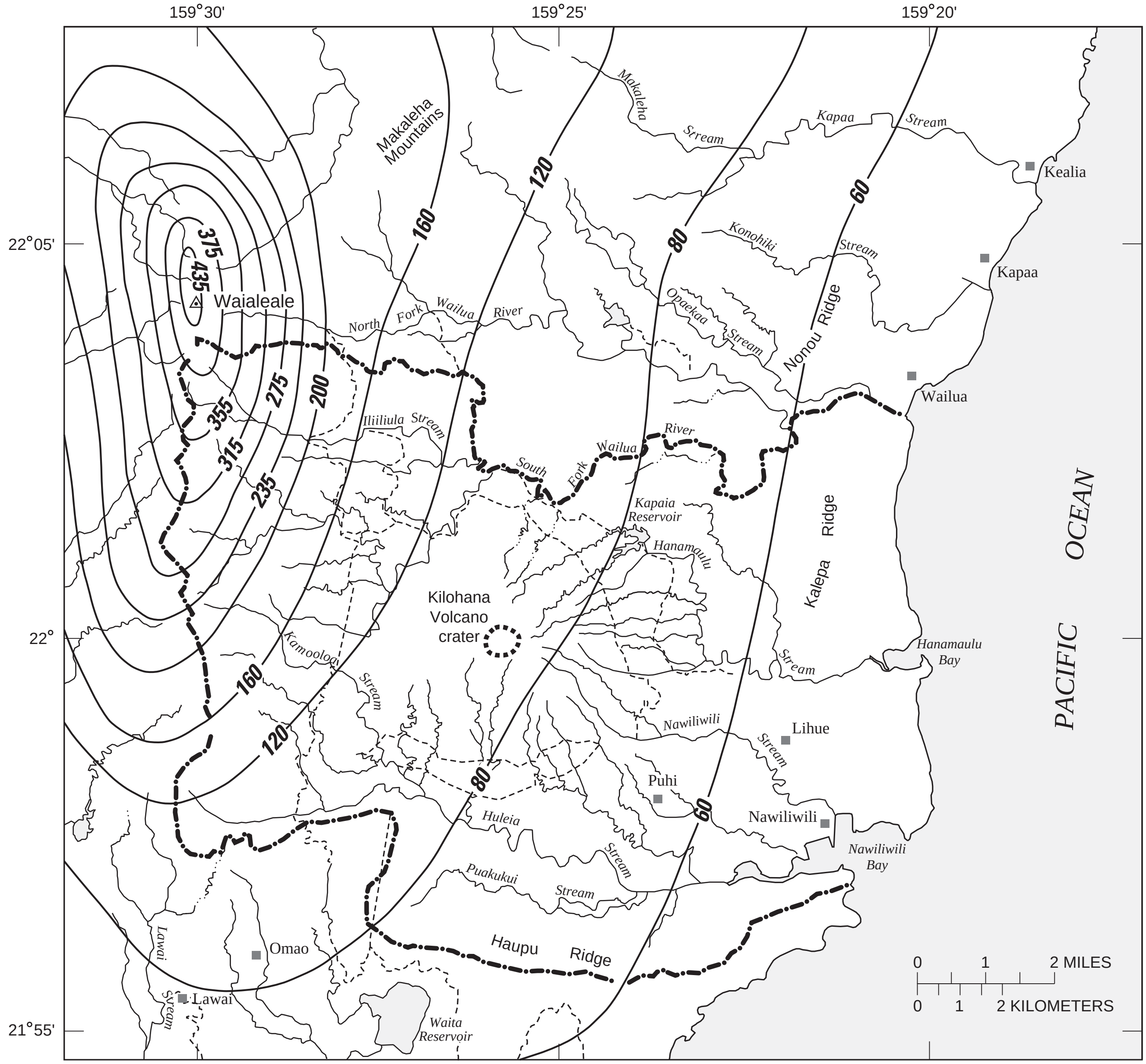
SETTING

The Lihue Basin is a large semicircular depression in southeastern Kauai, the fourth-largest island (553 mi^2) in the tropical, north-Pacific archipelago of Hawaii (fig. 1). The basin is bounded on the west by the high central mountains of Kauai, on the north by the Makaleha Mountains, on the south by Haupu Ridge, and on the east by the Pacific Ocean. In the south-central part of the basin lies the broad dome of Kilohana Volcano. Numerous streams and rivers drain from the Lihue Basin, but in the southern half of the basin where the town of Lihue is located, the smaller streams coalesce so that nearly all of the surface drainage empties into the ocean by three principal channels: the Wailua River, Hanamaulu Stream, and Huleia Stream. Rainfall distribution in the basin is influenced by the orographic effect (fig. 2). Rainfall is heaviest where the prevailing northeasterly trade winds encounter the windward flanks of Kauai's central mountains, forcing warm, moist air into the cool, higher elevations. Average annual rainfall ranges from about 50 in/yr at low-lying coastal areas to more than 400 in/yr near the crest of Kauai's central mountains (Giambelluca and others, 1986).

Much of the land in the Lihue Basin has historically been used for sugarcane cultivation. From the late 19th through the 20th century, ditches and reservoirs built by the sugar industry not only redistributed water within the Lihue Basin, but also transferred water to and from adjacent basins (Wilcox, 1996). Thus, the natural drainage pattern of the Lihue Basin has been modified into a network of natural stream channels crossed by irrigation ditches. Shade (1995a) estimated that in 1990, about 18.3 Mgal/d was diverted from surface-water sources within the combined drainage areas of Hanamaulu and Huleia Streams. Shade (1995a) also estimated that 30.56 Mgal/d was diverted from surface-water sources in the Wailua River drainage basin in 1990, but some of that water was used for hydroelectric power and returned back to the stream. A decline in Hawaii's sugar industry began in the 1970's and by the mid-1990's, Kauai was one of only two islands in the State that still had operational sugar plantations (Wilcox, 1996). Although some of the former sugarcane fields in the Lihue Basin had been taken out of sugar production, the largest of the sugar plantations in the Lihue Basin remained in operation through the remainder of the 20th century. That plantation, however, finally ceased operations in November 2000, leaving the future of the sugarcane fields and supporting irrigation infrastructure uncertain.

Geology

The Lihue Basin has undergone complex structural evolution. Present understanding of Kauai's geologic framework is the result of studies by numerous investigators, beginning with the early descriptions by Stearns (1946) and the comprehensive study of geology and water resources by Macdonald and others (1960), and later continuing with contributions by Krivoy and others (1965), Clague and Dalrymple (1988), Moore and others (1989), Holcomb and others (1997), and Reiners and others (1998). According to these studies, Kauai was formed during the Pliocene by mid-plate, hot-spot volcanism that created one or more large shield



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 21°55'40" and 22°10'20", central meridian 159°32'30"

EXPLANATION

— 80 —	LINE OF EQUAL AVERAGE ANNUAL RAINFALL--Interval, in inches, is variable
·—·—	BOUNDARY OF THE SOUTHERN LIHUE BASIN
-------	IRRIGATION DITCH OR TUNNEL

Figure 2. Distribution of rainfall in the Lihue Basin, Kauai, Hawaii (modified from Giambelluca and others, 1986).

volcanoes. Beginning in the shield-building stage, and continuing into a subsequent 0.5- to 1-million-year period of relative volcanic quiescence, erosion and faulting created large valleys, canyons, and other depressions (including the Lihue Basin). These depressions were later partly filled with sediments as well as lava flows and other igneous rocks from scattered rejuvenated volcanism in the late Pliocene and Pleistocene (fig. 3).

The origin of the circular Lihue Basin has been variously attributed to stream erosion (Stearns, 1946, 1985) or collapse (Macdonald and others, 1960; Holcomb and others, 1997). The Lihue Basin was subsequently partially filled with marine and terrigenous sediments and lava flows from rejuvenated volcanism (including Kilohana Volcano). Geochemical and stratigraphic evidence indicates that the sediments and rocks from rejuvenated volcanism are more than 1,000 ft thick in some places, and that the basement below these rocks has hundreds of feet of relief (Reiners and others, 1998).

The rocks of the Lihue Basin are divided into two geologic formations that are separated by an erosional unconformity (Macdonald and others, 1960; Langenheim and Clague, 1987). The Pliocene-age Waimea Canyon Basalt, which formed during the shield-building stage and constitutes most of the bulk of Kauai, forms the basement on which younger sediments and volcanic rocks of the Lihue Basin lie (figs. 3 and 4). The Waimea Canyon Basalt in the Lihue Basin consists mostly of thin lava flows. Most of the Waimea Canyon Basalt is obscured by the younger rocks of the basin, except at outcrops in the ridges and mountains surrounding and within the basin. In the ridges, the lava flows of the Waimea Canyon Basalt are intruded by numerous, near-vertical, sheet-like, volcanic dikes (Macdonald and others, 1960). Dikes are probably also present in the Waimea Canyon Basalt below the floor of the basin. However, dikes are rare in outcrops of the Waimea Canyon Basalt south of Mt. Waialeale and west and south of Haupu Ridge (Macdonald and others, 1960). At the northwest boundary of the basin near Mt. Waialeale is an outcrop of the thick-bedded lava flows that have been variously interpreted as caldera-filling lava (Macdonald and others, 1960) or lava that accumulated between multiple shield volcanoes (Holcomb and others, 1997).

Resting unconformably on the Waimea Canyon Basalt are volcanic rocks and intercalated sediments of the Pliocene- and Pleistocene-age Koloa Volcanics (Macdonald and others, 1960; Langenheim and Clague, 1987). The Koloa Volcanics is a heterogeneous unit that fills depressions in the Waimea Canyon Basalt. The volcanic rocks include variably weathered, thick, massive lava flows and pyroclastic deposits of highly alkalic mafic composition, erupted from edifices scattered over the old, eroded shield volcano during the rejuvenated stage of volcanism. Terrigenous and marine sediments are intercalated with the lava flows.

Overlying the Koloa Volcanics in some places are sediments of Pleistocene and Holocene age that form coastal plains and fill valley bottoms, but these deposits are relatively small in volume (Macdonald and others, 1960; Izuka and Gingerich, 1998a).

Hydraulic Properties of the Rocks

Most wells in the Lihue Basin develop water from the Koloa Volcanics. The volcanic rocks and sediments of the Koloa Volcanics are considered one hydrogeologic unit in this report because individual lava flows and sedimentary layers are too numerous and finely intercalated to be distinguished, and wells in the Koloa Volcanics penetrate both sedimentary and volcanic rock. Specific capacities of production wells indicate that permeability of the Koloa Volcanics varies widely. However, the predominance of low-productivity wells in the basin indicates that the regional permeability of the Koloa Volcanics is low, and that areas of high permeability are localized. Although wells in the localized high-permeability areas may have high initial yields, their long-term yields will ultimately be limited by the low regional permeability.

The permeability of an aquifer may be expressed in terms of its hydraulic conductivity. Whereas the ability of the aquifer to transmit a fluid depends on the properties of the fluid, hydraulic conductivity is a measure of the ability of an aquifer to transmit water under a hydraulic gradient. Analysis of aquifer-test data indicates that horizontal hydraulic conductivity (K_h) ranges from 0.042 ft/d to greater than 100 ft/d (Izuka and Gingerich, 1998a; Gingerich, 1999). Izuka and Gingerich (1998a) estimated that the regional K_h of the Koloa Volcanics is probably less than 1 ft/d and used a value of 0.275 ft/d in a numerical ground-water flow model of the basin. This regional hydraulic conductivity is one to four orders of magnitude lower than the regional

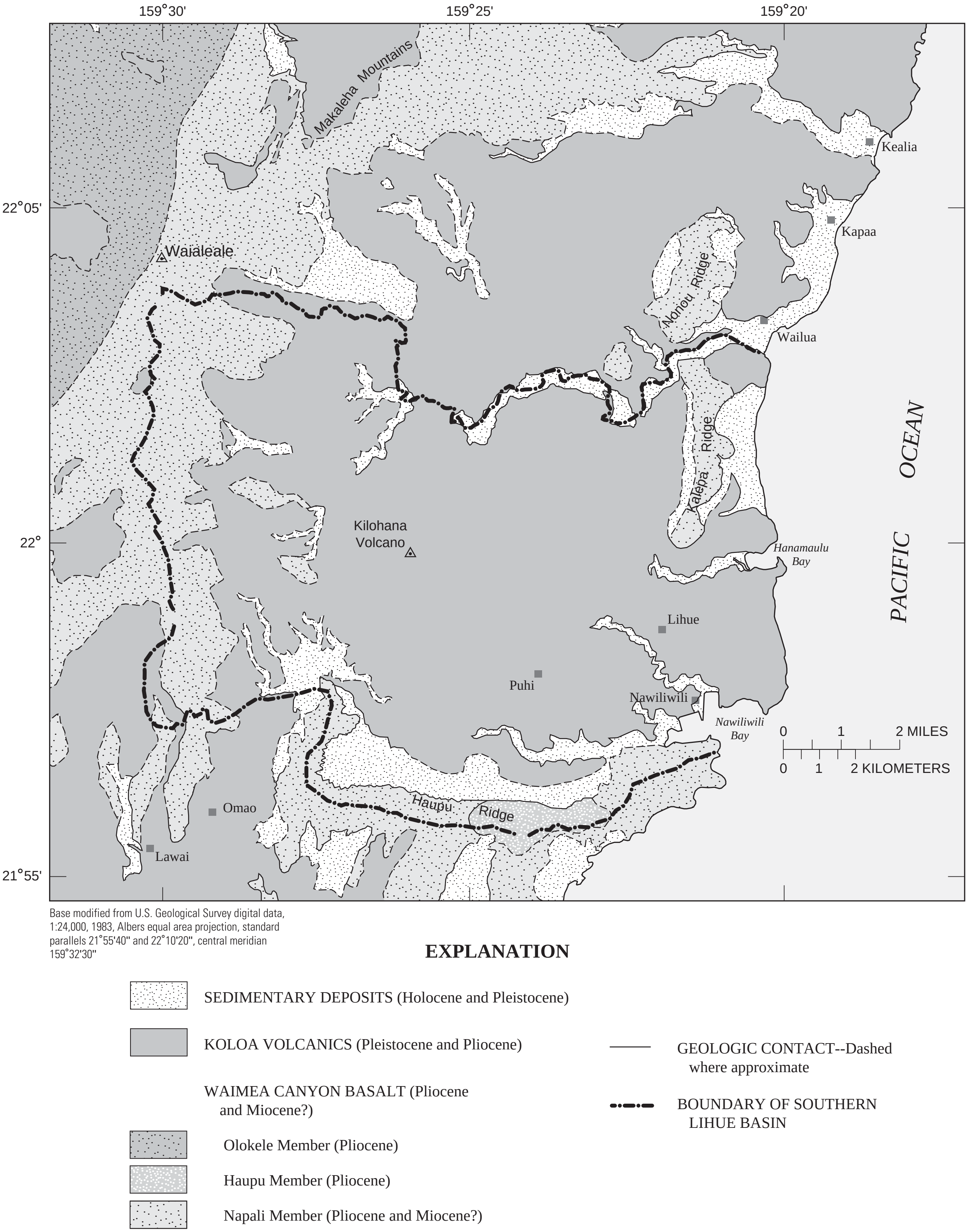


Figure 3. Geology of the Lihue Basin, Kauai, Hawaii (modified from Macdonald and others, 1960).

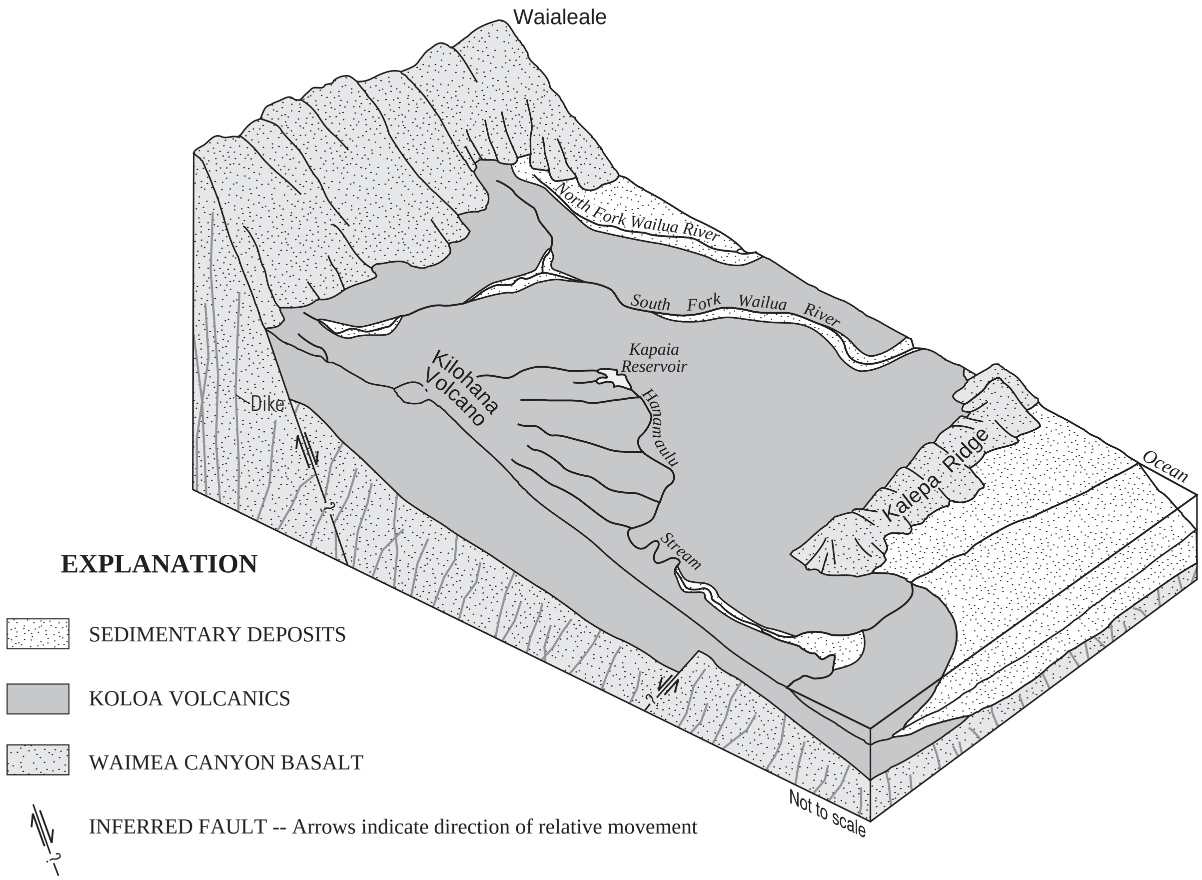


Figure 4. Block diagram showing the structure and stratigraphy of the southern Lihue Basin, Kauai, Hawaii (from Izuka and Gingerich, 1998a).

hydraulic conductivity of many other areas that have ground-water development in the Hawaiian Islands.

Some wells in the Lihue Basin, and most wells near but outside the basin, develop water from the shield-building lava flows of the Waimea Canyon Basalt. Within the basin, the Waimea Canyon Basalt crops out only in ridges that were left uncovered by the younger Koloa Volcanics. These ridges are intruded by low-permeability, sheet-like volcanic dikes that cut vertically or near vertically across the thin shield-building lava flows. The dikes reduce the regional permeability of the shield-building lava flows (Takasaki and Mink, 1985; Hunt, 1996). In some areas outside the basin, particularly on the southern flank of Haupu Ridge, dikes are apparently less numerous (Macdonald and others, 1960). Little information exists on the hydraulic properties of the Waimea Canyon Basalt underlying the Koloa Volcanics in the Lihue Basin, but it is likely that the Waimea Canyon Basalt is intruded by dikes as are the ridges surrounding the basin. Using curve-matching methods to analyze aquifer-test data, Gingerich (1999) estimated K_h for the Waimea Canyon Basalt of the northern flank of Haupu Ridge to be 15.8 to 16.1 ft/d, however, these estimates are probably higher than the regional K_h of the dike-intruded ridge because only the earliest part of the time-drawdown data was analyzed, which may not reflect the dikes that are likely to be at some distance from the test wells. Izuka and Gingerich (1998a) used a K_h of 1.11 ft/d for the dike-intruded Waimea Canyon Basalt in their numerical ground-water flow model of the southern Lihue Basin.

Dike-free shield-building lava flows on Oahu have K_h ranging from hundreds to thousands of feet per day (Soroos, 1973). The hydraulic conductivity of dike-free shield-building lava flows on Kauai is probably in the lower part of this range because the lava flows on Kauai are older and more altered. Izuka and Gingerich (1998a) used a K_h of 200 ft/d for dike-free Waimea Canyon Basalt in their numerical ground-water flow model of the southern Lihue Basin.

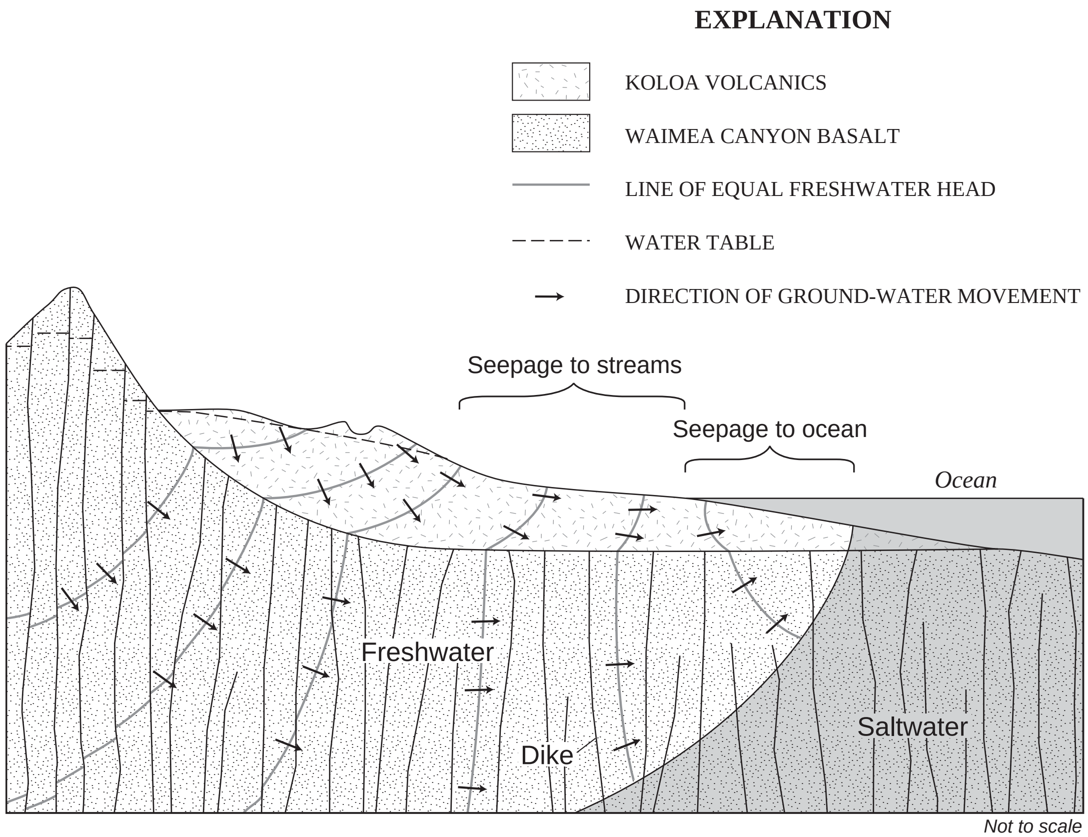


Figure 5. Diagrammatic representation of ground-water flow in the southern Lihue Basin, Kauai, Hawaii (from Izuka and Gingerich, 1998a).

Pleistocene and Holocene sediments in the basin are of small areal extent and have not been developed much for water or studied hydrologically, and therefore are not discussed as a separate hydrogeologic unit in this report.

Vertical hydraulic conductivity.--The vertical hydraulic conductivity (K_v) of an aquifer composed of gently dipping lava flows is likely to be substantially less than K_h. Estimates of K_v/K_h for lava flows in Hawaii range from 1/3 to 1/200 (Hunt, 1996). Whereas dike-free lava flows of the Waimea Canyon Basalt may have hydraulic properties similar to other basalts in Hawaii, the Koloa Volcanics probably has a lower value of K_v/K_h because it has thicker lava flows that are intercalated with sediments and weathered zones. Intrusion of dikes into the lava flows of the Waimea Canyon Basalt probably increases the value of K_v/K_h because dikes are essentially planar vertical structures that reduce the horizontal hydraulic conductivity of the intruded lava flows. In a numerical ground-water flow model of the southern Lihue Basin, Izuka and Gingerich (1998a) used K_v/K_h values of 1/200 for the dike-free lava flows of the Waimea Canyon Basalt, 1/100 for the dike-intruded part of the Waimea Canyon Basalt, and 1/500 for the Koloa Volcanics.

Ground-Water Occurrence and Movement

Fresh ground water in Kauai, as in other oceanic islands, forms a freshwater lens that is underlain by saltwater originating from the ocean (fig. 5). Freshwater in the lens moves downward in inland areas of recharge, horizontally toward the coast, and upward to be discharged to the ocean or at streams and springs on land.

The freshwater lens is buoyed by the density difference between saltwater and freshwater (the density of the saltwater in the aquifer is about 1.025 times the density of the freshwater). The transition from freshwater to saltwater is a diffuse zone of mixing, but for simplicity, especially in aquifers where the freshwater lens is thick, the mixing zone can be envisioned as a sharp interface (fig. 5). The Ghyben-Herzberg relation, which uses the density difference between freshwater and saltwater to estimate the thickness of the freshwater lens, indicates that the depth of the interface below sea level is about 40 times the elevation of the water table above sea level. The interface position computed by the Ghyben-Herzberg relation is commonly considered to be an approximation of the position of a 50-percent freshwater and 50-percent saltwater mixture in the transition zone, and the relation is commonly used to estimate freshwater-lens thickness in island and coastal aquifers. Because the Ghyben-Herzberg relation assumes hydrostatic conditions, however, the relation gives inaccurate freshwater-thickness estimates and does not accurately predict pumping-induced rises of the interface and saltwater intrusion in regions of the aquifer where ground-water flow has a substantial vertical component.

Ground water in the southern Lihue Basin originates mostly as recharge from rainfall. Ground water flows downward in the western part of the basin where recharge is highest, then flows to the north, east, and south where it discharges in streams or the ocean (fig. 5) or flows to adjacent ground-water areas. The ground-water system in the southern Lihue Basin is characterized by flow through low-permeability rock, a thick freshwater lens with a water table that is within a few tens of feet of the ground surface, steep horizontal and vertical hydraulic-head gradients, and a relatively large proportion of ground-water discharge to streams compared with most other places in Hawaii. The highest ground-water levels are found in the mountains at the western rim of the southern Lihue Basin where rainfall is highest and low-permeability intrusive dikes in the Waimea Canyon Basalt impound water to high elevations (figs. 5 and 6). In the central part of the basin, ground water saturates the Koloa Volcanics to elevations as high as 850 ft above sea level. The high heads in the saturated ground-water system in the southern Lihue Basin result from the low permeabilities of the Koloa Volcanics and dike-intruded Waimea Canyon Basalt. Because of the large flux of ground water through the basin and the high resistance to flow provided by the low-permeability rock, steep gradients result and fresh ground water saturates nearly to the land surface. Streams incising the upper part of the aquifer maintain water levels just below the land surface in interstream areas. The streams thus play an important part in shaping the water table in the southern Lihue Basin. Ground water that does not discharge to streams or springs eventually discharges at or beyond the coast. Water-budget calculations for the southern Lihue Basin indicate that at least 64 percent of recharge is eventually discharged to the streams; the remainder is withdrawn by wells or discharges directly into the ocean (Izuka and Gingerich, 1998a).

Effects Of Ground-Water Withdrawals

Prior to ground-water development, ground-water flow is in a state of long-term average dynamic equilibrium, commonly referred to as steady state. Seasonal variations may result in short-term imbalances, but in the long term, the average ground-water recharge rate is balanced by the average ground-water discharge rates to streams and the ocean.

When the pre-development equilibrium is upset by artificial withdrawals, such as pumping a well, the shape and size of the freshwater lens changes (fig. 7). During this period of change, the freshwater lens adjusts to the new stress presented by the withdrawal and the associated lowering of hydraulic head, and is said to be in a transient state. Artificial withdrawals cause the freshwater lens to shrink by lowering the water level (which is a measure of hydraulic head in the freshwater lens) in the well and the surrounding aquifer to form a cone of depression, and by inducing the freshwater/saltwater interface to rise and encroach inland. Lowering of water levels and rising of the interface continue as long as the cone of depression spreads.

With time, the cone of depression spreads to areas of natural ground-water discharge such as streams or the coast, where it causes a reduction in the rate of ground-water discharge. Ultimately, if pumping and recharge conditions remain the same for a sufficiently long time, the natural discharge to streams and the ocean will be reduced by an amount equal to the pumping rate, again establishing a new equilibrium and steady state. The ultimate magnitude of the water-level decrease and interface rise caused by the artificial withdrawals, the amount of time needed for a new steady state to become established, and where reductions in stream and coastal discharge will occur, depend on numerous factors including the withdrawal rate, distribution of wells, distance to areas of natural discharge, and the geometry and hydraulic properties of the aquifer.

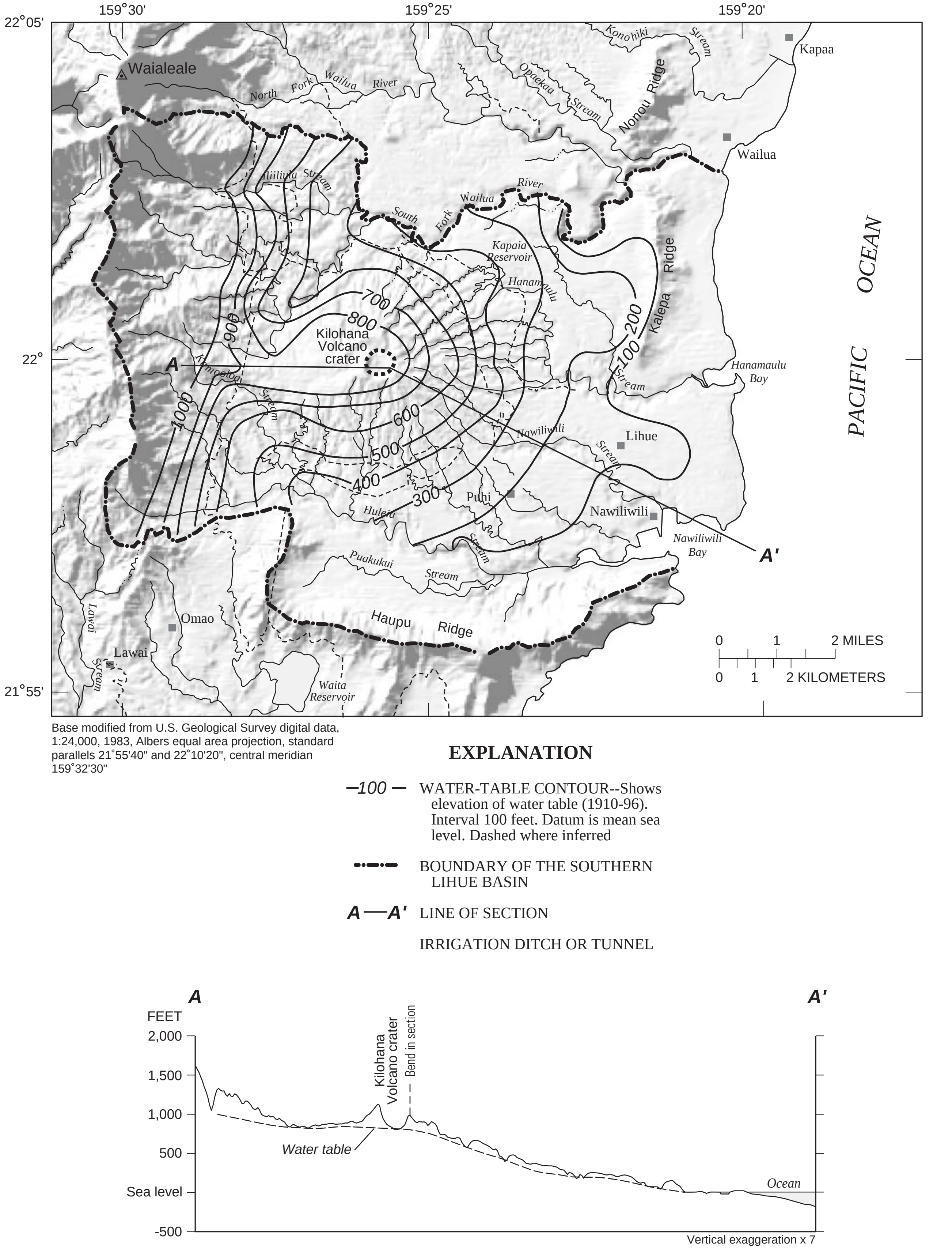


Figure 6. Generalized water-table map and profile for the southern Lihue Basin, Kauai, Hawaii (from Izuka and Gingerich, 1998a).

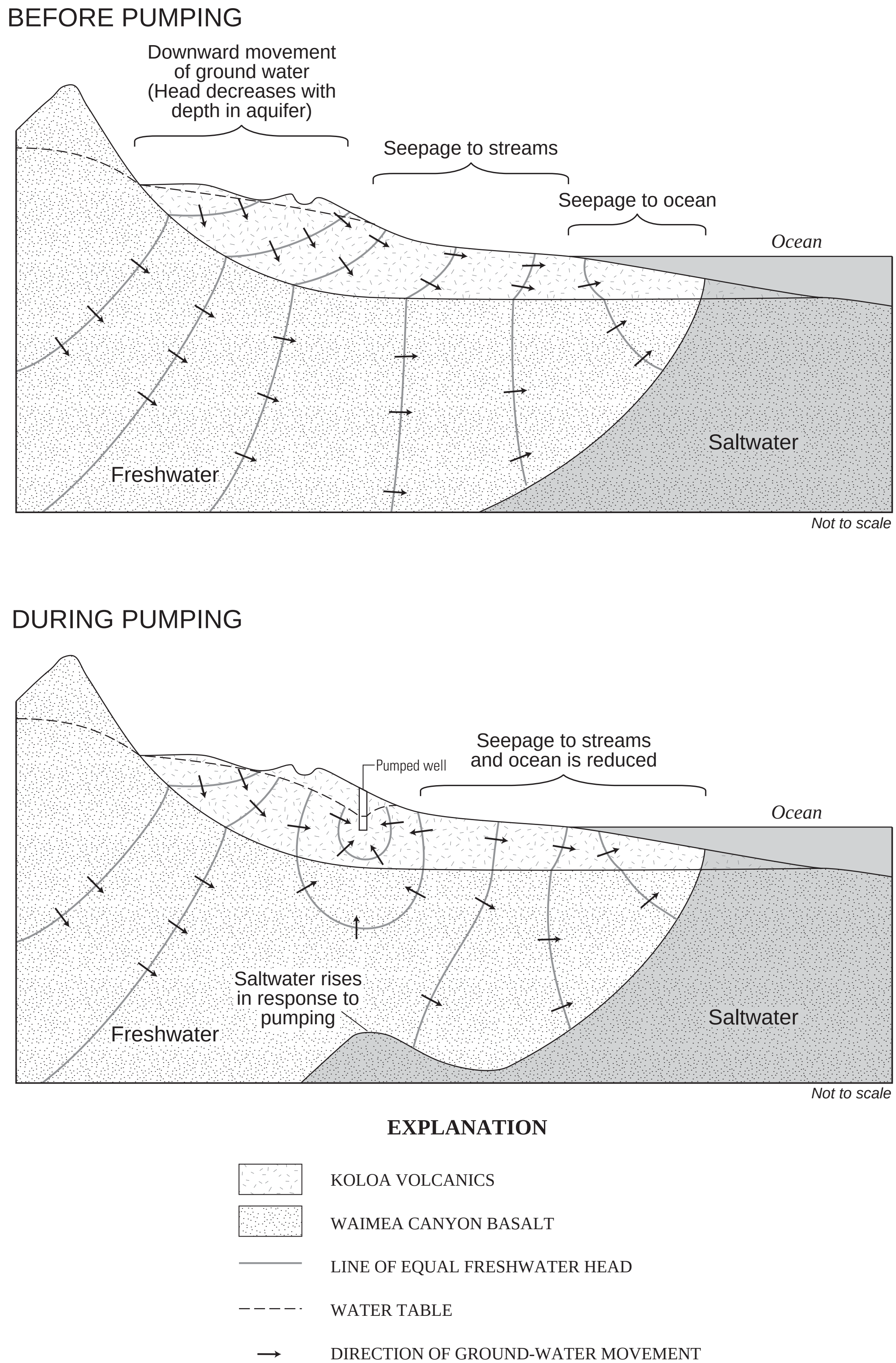


Figure 7. Generalized section showing the effects of ground-water withdrawals in the southern Lihue Basin, Kauai, Hawaii (from Izuka and Gingerich, 1998a).

NUMERICAL MODEL SIMULATION OF THE EFFECTS OF GROUND-WATER WITHDRAWALS

The factors governing the effects of ground-water withdrawals in an island aquifer such as the southern Lihue Basin, where substantial ground water discharges naturally to streams, include the spatial distribution of aquifer hydraulic properties, discharge boundaries, and recharge, and the flow of both saltwater and freshwater. Effects of ground-water withdrawal in such an environment include lowering of water levels, rise of the freshwater/saltwater interface, and reduction of ground-water discharge to streams and the ocean. Accurate assessment of the effects of ground-water withdrawals in the southern Lihue Basin requires simultaneous consideration of these factors and effects. Numerical ground-water-flow modeling is a comprehensive method for studying the factors governing the effects of ground-water withdrawal.

Original Numerical Model

With some modifications, the model of the southern Lihue Basin developed by Izuka and Gingerich (1998a) was used to study the effects of the ground-water withdrawals proposed for Hanamaulu and Puhi. The model was created using a modified version of the finite-difference modeling program SHARP (Essaid, 1990; Izuka and Gingerich, 1998a), which allows simulation of coupled freshwater and saltwater flow. A detailed description of the original southern Lihue Basin numerical model and its development is provided in Izuka and Gingerich (1998a); a synopsis of the aspects of the original model that are pertinent to the objectives of this study is provided here.

The SHARP program treats freshwater and saltwater as immiscible fluids separated by a sharp interface. Horizontal flow, vertical flow, and ground-water discharge to streams and the ocean are controlled by hydraulic-head gradients and hydraulic properties of the aquifer. Horizontal ground-water flow is computed from user-specified horizontal aquifer properties and the distribution of model-calculated freshwater and saltwater hydraulic heads. Vertical flow between layers is computed from user-specified vertical aquifer properties and differences between model-calculated heads in adjacent layers. Discharge of ground water to streams and the ocean is computed from user-specified streambed and ocean-floor hydraulic properties and the difference between model-calculated heads in the uppermost layer of the model and user-specified heads in the streams and at the ocean bottom.

The southern Lihue Basin model encompasses not only the southern Lihue Basin, but a 17.0-mi by 20.8-mi area in the southeast corner of Kauai and adjacent offshore areas (fig. 8). The modeled area was extended beyond the margins of the southern Lihue Basin so that the no-flow boundaries required at the periphery of the model would not substantially affect, or be affected by changes in, ground-water flow in the southern Lihue Basin. This is particularly important for testing hypothetical ground-water development scenarios. However, data from outside the basin are sparse, therefore the model may not accurately simulate conditions outside the basin. Areas outside the basin served only as gross approximations of the hydrologic system between the study area and the no-flow boundaries. The western and northern no-flow boundaries roughly parallel either the regional ground-water flow lines or ground-water divides. Ground-water withdrawal from the southern Lihue Basin is not likely to affect the location of these flow lines and divides because the propagation of the cones of depression will probably be halted by the large amount of water available through reduced ground-water discharge at rivers, streams, and coastal areas within the model. The southern and eastern no-flow boundaries of the ground-water model were placed in the ocean at a minimum of 2.5 mi from the coast to allow sufficient space for the freshwater lens in the model to extend seaward without impinging on the no-flow boundary (fig. 8). The no-flow boundary at the base of the model was set at an elevation of -6,000 ft, which is consistent with geophysical evidence from Kilauea Volcano, Hawaii, that indicates that porosity becomes nearly zero below 6,000 ft from the ground surface (Kauahikaua, 1993).

The simulated area was divided into two layers, each having 2,475 cells, and each cell representing an area 2,000 ft by 2,000 ft (fig. 8). The upper layer extends to an elevation of -500 ft, which corresponds to the depth of the contact between the Koloa Volcanics and the underlying Waimea Canyon Basalt as shown on the geologic map of Macdonald and others (1960). The lower layer extends from -500 ft to -6,000 ft elevation.

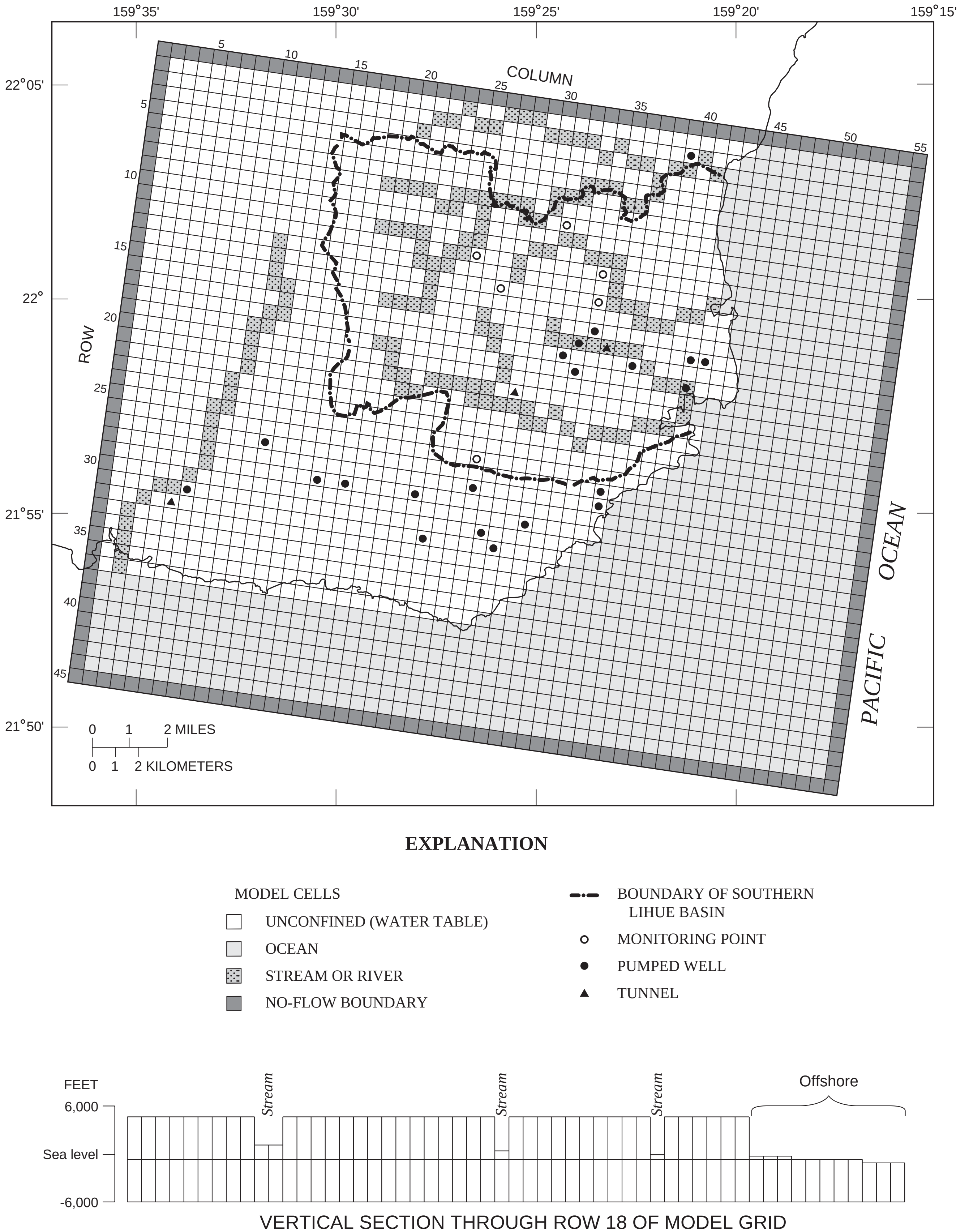


Figure 8. Model grid, boundaries, streams, pumped wells, and monitoring points used in the numerical ground-water flow model of the southern Lihue Basin, Kauai, Hawaii (from Izuka and Gingerich, 1998a).

In the model, the rocks of the southern Lihue Basin are divided into three hydrogeologic regions: (1) the Koloa Volcanics, (2) the dike-free lava flows of the Waimea Canyon Basalt, and (3) the dike-intruded lava flows of the Waimea Canyon Basalt (fig. 9). In the model, the Koloa Volcanics was assigned a K_h of 0.275 ft/d and a K_z of 5.5×10^{-4} ft/d, the dike-free lava flows of the Waimea Canyon Basalt were assigned a K_h of 200 ft/d and a K_z of 1.00 ft/d, and the dike-intruded lava flows of the Waimea Canyon Basalt were assigned a K_h of 1.11 ft/d and a K_z of 0.0111 ft/d. Recharge to the model was 191 Mgal/d distributed over the onshore area according to the average annual recharge estimated by Shade (1995b). Existing ground-water withdrawals in the model were based on water-use data obtained in 1993 from the Hawaii State Commission on Water Resource Management.

Uncertainties in Recharge

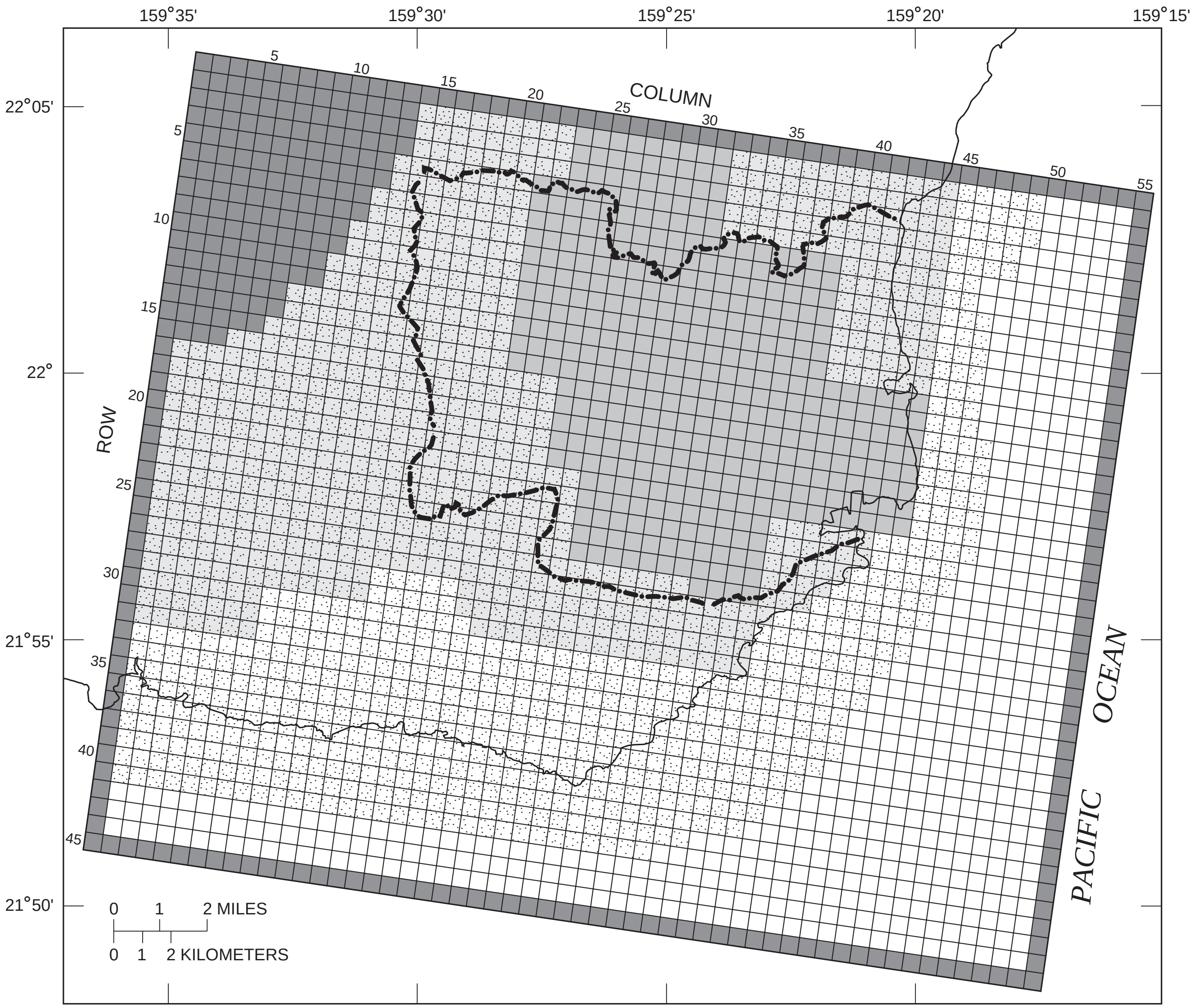
The original numerical ground-water model of the southern Lihue Basin used recharge estimates from a water budget computed by Shade (1995b). Izuka and Gingerich (1998a) concluded that the southern Lihue Basin model was sensitive to uncertainties in recharge, but did not quantify the uncertainties. Shade’s (1995b) method of accounting for evapotranspiration has the potential to overestimate recharge, which could lead to overestimation of ground-water availability. To assess the degree of uncertainty in the recharge estimates used in the southern Lihue Basin model, aspects of Shade's (1995b) water budget were investigated. The physical basis and computational procedures used for the uncertainty analysis are discussed in detail in the appendix; a synopsis is presented here.

Recharge in the original southern Lihue Basin model.--The water-budget approach to recharge estimation is based on the concept that part of the water that falls as precipitation runs off the land directly to the ocean; the remainder infiltrates the soil where the water is stored temporarily and is subject to evapotranspiration. Recharge to the aquifer occurs only when the soil's water-storing capacity is exceeded and the excess infiltrated water is passed to the underlying aquifer (Thornthwaite and Mather, 1955).

During a given precipitation event, how much water ultimately goes to recharge depends on the intensity of the precipitation and the amount of water already stored in the soil. If the soil moisture was nearly depleted by evapotranspiration prior to precipitation, much of the infiltrated water may remain in the soil, and little water passes to recharge. If the soil is nearly saturated prior to precipitation, more of the infiltrated water would become recharge. The water-budget method mimics this process by computing a water budget for short consecutive periods (such as days or months) using the amount of soil moisture at the end of one period as the input soil moisture for the next period. Accuracy of the recharge estimates is affected by the length of the individual consecutive periods in the water-budget computation. In general, daily water budgets more accurately estimate recharge than do monthly budgets.

The order in which evapotranspiration is assigned relative to recharge in the water-budget computation also affects the recharge estimate. Evapotranspiration may be subtracted from the infiltrated water initially, then if the remaining water exceeds soil-moisture storage capacity, the excess is assigned to recharge. Alternatively, infiltration in excess of soil-moisture storage capacity may be assigned first to recharge, then evapotranspiration acts only on the water remaining in the soil. Water budgets that assign evapotranspiration before recharge tend to underestimate recharge (Giambelluca and Oki, 1987; Rushton and Ward, 1979; Howard and Lloyd, 1979; Alley, 1984), whereas water budgets that account for recharge before evapotranspiration tend to overestimate recharge. The degree of overestimation or underestimation may be substantial for water budgets that are computed on a monthly or longer basis. For example, Shade (1997) computed monthly water budgets for the island of Molokai, Hawaii, and estimated a range for island-wide recharge of 140 Mgal/d (accounting for evapotranspiration before recharge) to 237 Mgal/d (accounting for recharge before evapotranspiration).

Recharge in the original southern Lihue Basin model totals 191 Mgal/d (Izuka and Gingerich, 1998a). The recharge for the model is based on a monthly calculation in which recharge was accounted for before evapotranspiration (Shade, 1995b), thus the estimate is expected to be high. The recharge estimate can be improved by computing a daily budget and accounting for evapotranspiration before recharge. In addition, the original water budget and recharge estimates could be improved by (1) using hydrograph-separation techniques to compute the runoff-to-rainfall ratio,



UPPER LAYER

EXPLANATION

MODEL CELLS

- Koloa Volcanics
- Dike-intruded Waimea Canyon Basalt
- Dike-free lava flows of the Waimea Canyon Basalt
- Ocean
- No-flow boundary
- BOUNDARY OF SOUTHERN LIHUE BASIN

Figure 9. Distribution of geology used in the numerical ground-water flow model of the southern Lihue Basin, Kauai, Hawaii (from Izuka and Gingerich, 1998a).

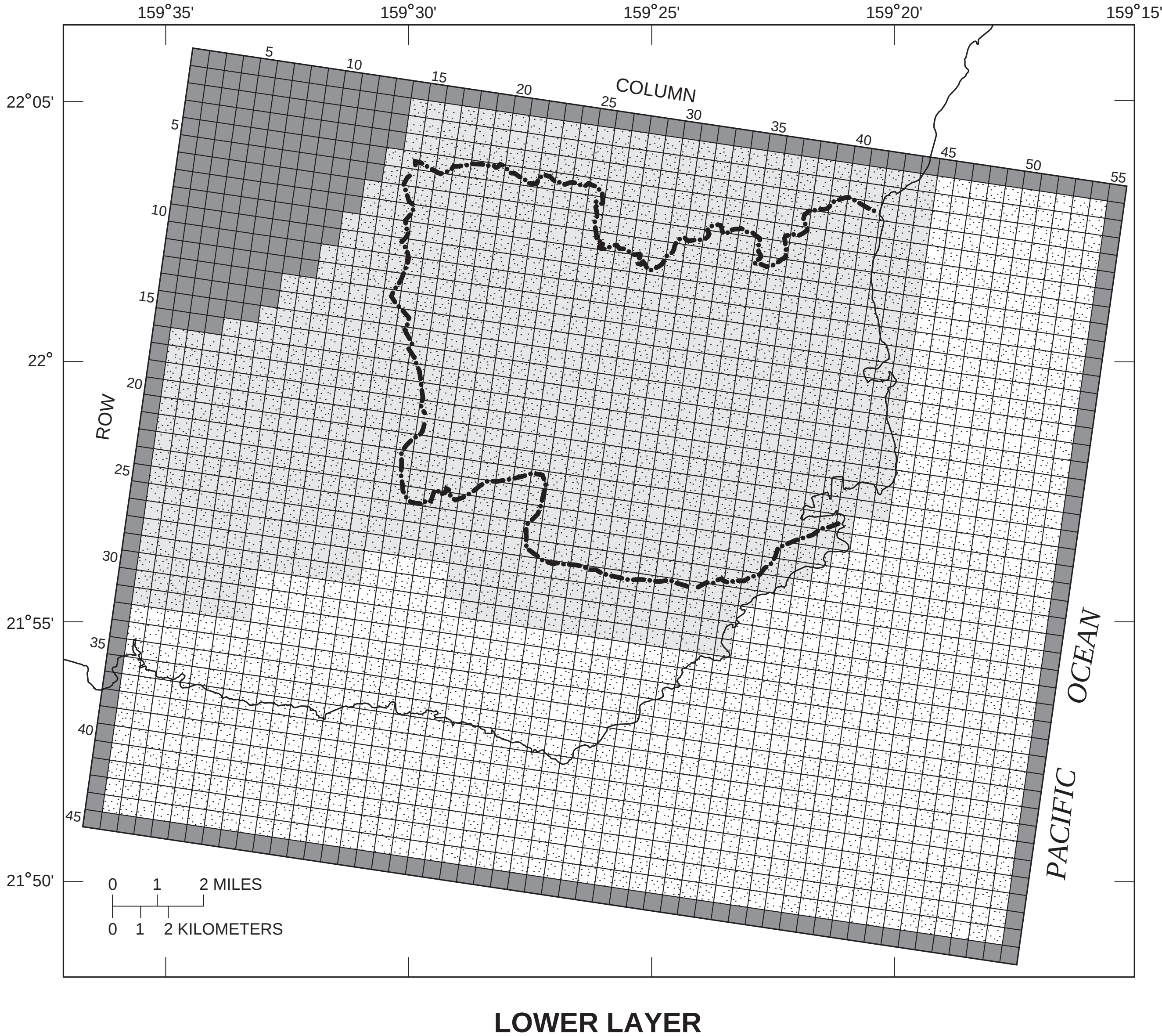


Figure 9. Distribution of geology used in the numerical ground-water flow model of the southern Lihue Basin, Kauai, Hawaii (from Izuka and Gingerich, 1998a)--*Continued*.

(2) accounting for fog drip, and (3) correcting for an apparent overestimation of evapotranspiration in irrigated areas.

Assessing the range of recharge uncertainty.--Recomputation of an entirely new water budget is beyond the scope of this report. Instead, daily water budgets were computed for selected sites with adequate data and compared with water budgets computed from the same data using the monthly techniques described by Shade (1995b). In the daily water budgets, the conservative approach of accounting for evapotranspiration before recharge was taken, and base-flow estimates from hydrograph-separation techniques (Izuka and Gingerich, 1998a) were used to compute the runoff-to-rainfall ratios. Regression equations were developed to describe the relation between average annual recharge estimated from a daily water budget and average annual recharge estimated from a monthly water budget. The regression equations were used to adjust recharge in each cell of the model. Adjustments to appropriate model cells for fog drip and for Shade's (1995b) apparent overestimation of evapotranspiration in irrigated areas were then made over a range of values, thus yielding a range of uncertainty in the recharge. These adjustments changed the magnitude and distribution of recharge in the model.

After the adjustments made in this study, the resulting estimated total recharge for the area of the southern Lihue Basin model ranged from a low of 167 Mgal/d to a high of 194 Mgal/d. The original 191 Mgal/d estimate is within the range of the adjusted estimates, but is near the high end of the range. The lower estimate in the range is 13 percent lower than the original 191 Mgal/d estimate for the modeled area, whereas the higher estimate is 2 percent higher. However, the actual recharge is unlikely to be as high or as low as either end members of the range. The original 191 Mgal/d estimate is only about 6 percent higher than the mean of the high and low estimates. Thus, although the analysis indicates that the original 191 Mgal/d may be high, it is probably high by only a few percent.

Although recomputed recharge estimates were a product of this analysis, the intent of the analysis was not to ultimately revise the recharge estimate. Thorough estimation of recharge requires extensive data collection, monitoring, and analyses that are not within the scope of this study. The analysis used in this study is tied to the original recharge estimate, and is therefore valid only for assessing uncertainty of the original estimate so that the southern Lihue Basin model could be tested over a range of recharge commensurate with the range of uncertainty.

Sensitivity of the model within the range.--The sensitivity of the southern Lihue Basin model to the recharge estimates was tested by substituting the high and low estimates of the recharge range into the model and running the simulations to steady state. Other parameters of the model were kept the same as the original model of Izuka and Gingerich (1998a). The water levels resulting from the simulations are shown in table 3. The absolute values of the differences between the observed and simulated water levels using the original recharge estimate of Shade (1995b) averaged 45 ft. Similarly, the absolute values of the differences between the observed and simulated water levels using the low recharge estimate also averaged 45 ft, as did the absolute values of the differences between the observed and simulated water levels using the high recharge estimate. As will be discussed in the “Model Limitations” section, the differences between simulated and observed heads can be partly attributed to averaging as a result of the coarseness of horizontal and vertical discretization (Izuka and Gingerich, 1998a).

Table 4 shows that when the original recharge estimate is used in the southern Lihue Basin model, the simulated base flow of Hanamaulu Stream is within the range of expected base flow determined by hydrograph separation (Izuka and Gingerich, 1998a), the simulated base flow of Huleia Stream is lower than expected by about 45 percent, and the simulated base flow of South Fork Wailua River is about 3 percent lower than the lowest expected base flow. When the high recharge estimate is used, the simulated base flow of Hanamaulu Stream is again within the range of expected base flow, the simulated base flow of Huleia Stream is lower by about 56 percent, and the simulated base flow of South Fork Wailua River is about 14 percent lower than the lowest expected base flow. The high recharge estimate, despite being slightly higher in total than the original recharge, results in lower simulated water levels in monitor wells (table 3) and lower base flows for Huleia Stream and South Fork Wailua River (table 4) because the high and original estimates differ in the way the recharge is distributed (see appendix).

When the low recharge estimate is used, all three streams had simulated base flows that were lower than

Table 3. Simulated steady-state water levels in the southern Lihue Basin, Kauai, Hawaii, for various estimates of recharge

[Mgal/d, million gallons per day; all water levels in feet above sea level]

Well name (and State well number)	Observed water level[a]	Location in model grid (row, column)	Simulated water levels from the numerical ground-water flow model of the Lihue Basin[b]		
			Using original recharge estimate (191Mgal/d)[c]	Using high recharge estimate (194 Mgal/d)	Using low recharge estimate (167 Mgal/d)
Puakukui Springs (2-5626-01)	173	26, 27	162	162	159
Northwest Kilohana (2-0126-01)	576	12, 25	686	634	634
Northeast Kilohana (2-0124-01)	428	9, 31	423	409	405
Hanamaulu (2-5923-08)	243	14, 34	296	289	279
Kilohana Crater [d]	820	14, 27	790	730	729
Pukaki Reservoir (2-0023-01)	252	12, 34	312	299	297

[a] From Izuka and Gingerich (1998a)

[b] Except for recharge, all parameters are the same as in the original model from Izuka and Gingerich (1998a). All simulated water levels are from upper layer of model.

[c] From Izuka and Gingerich (1998a), based on recharge calculated by Shade (1995b)

[d] Water level inferred from a marsh in the summit crater of Kilohana Volcano

Table 4. Simulated steady-state base flows of streams and rivers in the vicinity of the southern Lihue Basin, Kauai, Hawaii, for various estimates of recharge

[all base-flow values in million gallons per day (Mgal/d); n.d., not determined]

Stream or river	Expected base flow from analysis of gage records[a]	Simulated base flow from the numerical ground-water flow model of the Lihue Basin[b]		
		Using original recharge estimate (191 Mgal/d) [c]	Using high recharge estimate (194 Mgal/d)	Using low recharge estimate (167 Mgal/d)
North Fork Wailua River	n.d	21.60	24.6	22.8
South Fork Wailua River	57 to 74	55.34	49.3	45.6
Hanamaulu Stream	3 to 5	3.82	4.7	1.9
Nawiliwili Stream	n.d	1.09	1.5	0.3
Huleia Stream	22	12.10	9.6	8.0
Hanapepe Stream	46	44.95	42.5	37.7

[a] Estimated by hydrograph separation from Izuka and Gingerich (1998a)

[b] Except for recharge, all parameters are the same as in the original model from Izuka and Gingerich (1998a)

[c] Based on recharge calculated by Shade (1995b)

expected: simulated base flow of Hanamaulu Stream is 37 percent lower than the lowest value in the expected range, simulated base flow of Huleia Stream is 64 percent lower, and simulated base flow of South Fork Wailua River is about 20 percent lower than the lowest value in the expected range.

Recharge used for this study.--The foregoing analysis indicates that the original recharge used in the southern Lihue Basin model may be high, and therefore non-conservative. Simulated water levels and base flows in the southern Lihue Basin model are sensitive to recharge within the range of estimated uncertainty. However, the original recharge lies within the range estimated in the uncertainty analysis. Inasmuch as the original recharge is within the range of estimated uncertainty, and no recharge estimates of clearly better accuracy presently exist, the original recharge was used for simulating the effects of proposed ground-water withdrawals.

Model Limitations

The resolution of any numerical model is limited by the level of discretization used to create the model. The level of discretization used in the southern Lihue Basin model may be too coarse for studying effects at a local scale, but the discretization is adequate for studying ground-water withdrawal effects at the regional scale. For example, the model can only simulate major streams and rivers (fig. 8) and cannot indicate precisely which reaches of a stream or river will be most affected. However, the model can be used to study the overall effects on the major streams. The model also cannot predict precisely what the water-level decline in a particular well will be but can simulate the regional water-level decline in the aquifer. Actual water levels in individual pumped wells are likely to be lower than indicated by the model, depending on local aquifer properties, well construction, and well location.

In the southern Lihue Basin, the limitations of discretization also become apparent when the simulated head in a model cell is compared to actual water-level measurements from a well located within the area represented by the cell (table 3). The simulated head in a cell is an average head in the area of the aquifer represented by the cell, whereas an actual water-level measurement from a well only represents the head over a small part of the area. Also, a water level in a well represents a vertically averaged head over the distance into the saturated aquifer the well penetrates, whereas the head in a cell is averaged over the entire saturated thickness of the cell. Because ground-water gradients in the southern Lihue Basin are steep in both the horizontal and vertical directions, the head within the volume of aquifer represented by the cell could vary by several tens of feet from place to place; likewise, an observed water level in a well may differ by several tens of feet from the head in the model cell. Although the model may not be able to resolve some local details in water levels or predict what the water levels in wells will be when the proposed withdrawal increases are implemented, the model can incorporate regional hydraulic conditions and boundaries to estimate regional-scale water-level declines.

Discretization also affects the simulated freshwater-saltwater interface position, which is a function of freshwater and saltwater head. In areas where local hydraulic complexities are too small to be resolved with the model’s degree of discretization, the model can only simulate the regional interface position, which may differ from the true interface position. Furthermore, the model cannot simulate pumping-induced movement of the interface beneath areas where the freshwater saturates to the no-flow boundary at the bottom of the model (that is, where the interface elevation is below -6,000 ft). In some areas (near Puhi well 5A, for example) where local hydrologic complexities are known to exist but are not incorporated in the model, the possibility of saltwater intrusion cannot be assessed from the model simulations alone and consideration of other criteria may be warranted. Despite the limitations of the southern Lihue Basin model, the simulated interface is regionally consistent with the hydrologic data, although the actual depth of the interface throughout most of the southern Lihue Basin is unknown.

The southern Lihue Basin ground-water model used in this study incorporated land-use conditions that existed in the 1990's. Thus, the model simulations show the effects of the proposed ground-water withdrawal increases relative to conditions that existed when much of the sugar industry in the southern Lihue Basin was still active. The recent demise of the sugar industry constitutes a substantial change in land use in the southern Lihue Basin, but the future of the former sugarcane lands, and how the land-use changes will affect ground water, is uncertain. Assessment of the potential effects resulting from land-use changes is beyond the scope of this study.

Uncertainties in recharge can result in uncertainties in hydraulic conductivities used in the model, the model-calculated water levels, and the model-calculated discharges. Underestimation of recharge will result in an underestimation of hydraulic conductivity and an overestimation of water-level declines caused by artificial ground-water withdrawals. Overestimation of recharge will result in an overestimation of hydraulic conductivity and an underestimation of water-level declines caused by artificial ground-water withdrawals. Uncertainties in the spatial distribution of estimated recharge can also affect model results. Although it is recognized that uncertainty in recharge exists, the southern Lihue Basin model is nevertheless the best tool currently available for assessing the effects of additional ground-water withdrawals on water levels and stream discharge.

STEADY-STATE SIMULATIONS OF PROPOSED WITHDRAWALS

Steady-state simulations were used to study the ultimate effects of the proposed withdrawals. The results of these simulations represent the new equilibrium (steady-state) conditions that would persist under the proposed ground-water withdrawal conditions, so long as those withdrawal conditions and recharge remain the same. The steady-state simulations do not address how long steady state would take to be achieved or how far the effects would have advanced at any time before steady state is achieved. Analysis of time-dependent ground-water withdrawal effects requires transient simulations, which are described in a later section.

Three ground-water development projections for the southern Lihue Basin were simulated with the numerical model: (1) 0.42 Mgal/d in 2000, (2) 0.83 Mgal/d in 2010, and (3) 1.16 Mgal/d in 2020. These withdrawals are projected increases over the ground-water withdrawals already in existence prior to 2000. Wells used in the simulations were based on the wells listed in the schedule of the Kauai DOW ground-water development projects (table 2). Simulated withdrawal for the 2000 projection was distributed among the four wells in the Hanamaulu area; simulated withdrawals for the 2010 and 2020 projections were distributed among the four wells in Hanamaulu (Hanamaulu wells 1, 3, and 4 and the Pukaki well) and one well in Puhi (well 5A). Puhi 5B was not simulated because it is intended as an infrequently used standby well (G. Fujikawa, Kauai Department of Water, oral commun., October 2000). Withdrawals were assigned to the cells in the model most closely representing the location and hydrologic conditions of the wells (fig. 10). Because Hanamaulu wells 3 and 4 will be located close to each other, their combined withdrawal was assigned to one cell in the model.

The effects of ground-water withdrawal on freshwater head were monitored at pumping locations as well as at a location representing the Lihue Town well field (fig. 10). Most of the wells in the Lihue Town well field lie within 2 mi of the coast, and therefore may be affected by saltwater intrusion resulting from upgradient ground-water development. Effects of ground-water withdrawals on the interface position were monitored beneath Hanamaulu well 1 and the Lihue Town well field, but could not be monitored at the other well sites because saltwater does not exist beneath these locations in the model.

Effects of the 2000 (0.42 Mgal/d) Projection

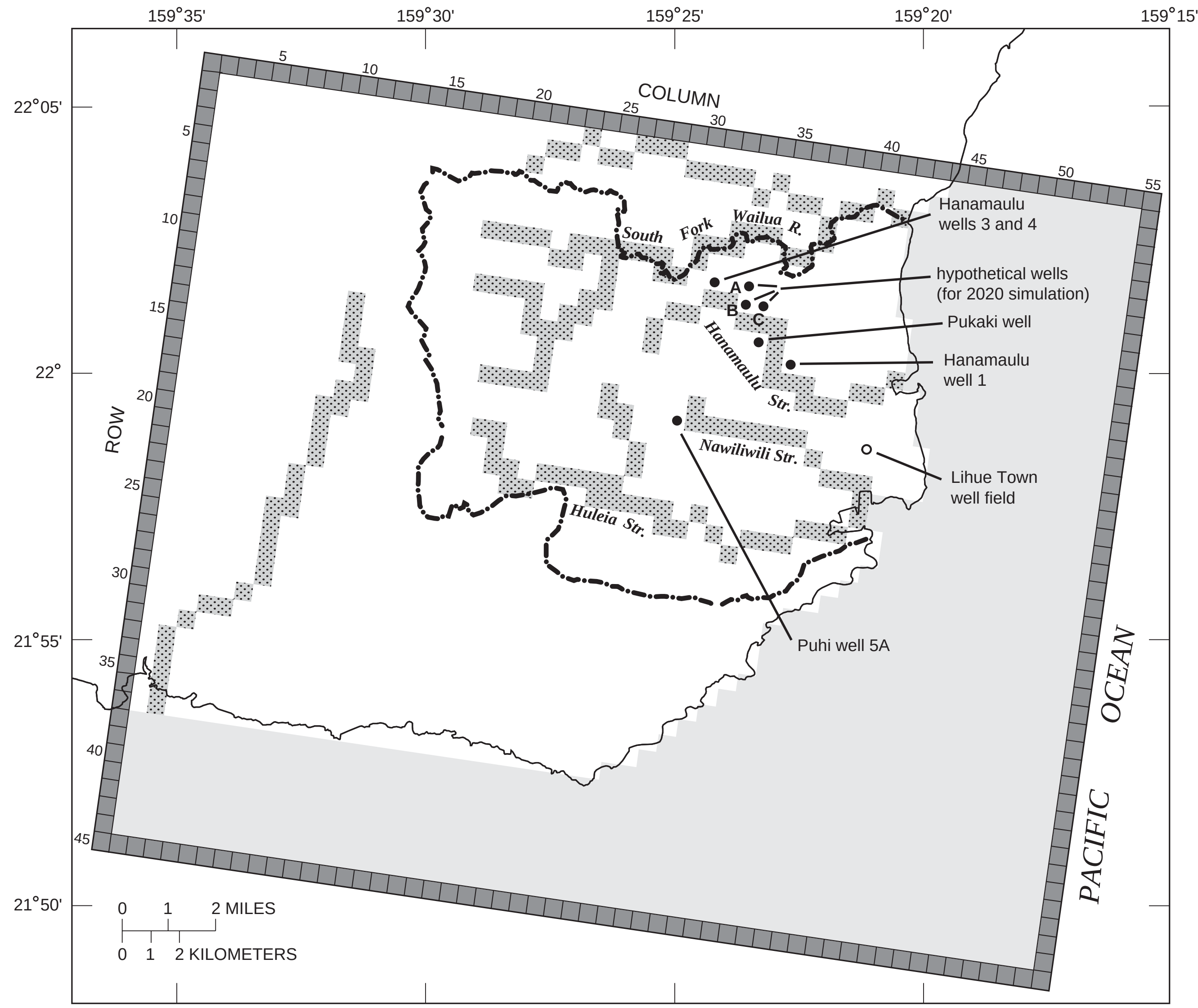
The future long-term average withdrawal of each new well in table 2 is not known. To simulate the 0.42 Mgal/d ground-water-withdrawal increase projected for 2000, an approximation of the future withdrawal distribution was obtained by setting withdrawal at an individual well on the basis of the proportion of the total pump capacity the well constituted:

$$Q_w = Q_t \times \frac{C_w}{C_t} \quad (1)$$

where: Q_w = simulated withdrawal for an individual well $[L^3/T]$,
Q_t = total projected new withdrawal $[L^3/T]$,
C_w = capacity of pump in the well $[L^3/T]$, and
C_t = total capacity of all new wells among which the projected withdrawal will be distributed $[L^3/T]$.

The combined withdrawal at Hanamaulu wells 3 and 4 constitutes 74 percent of the projected 0.42 Mgal/d increased withdrawal for 2000. Simulated water-level decrease in this location was 53 ft (fig. 11, table 5). Other wells had much smaller withdrawals and correspondingly smaller effects. Simulated water level in the vicinity of the Pukaki well declined by 15 ft. Simulated water level in the vicinity of Hanamaulu well 1 declined by 7 ft and the interface rose 1 ft. The ratio of the simulated interface rise to the simulated water-level decline differs from the 40:1 ratio implied by the Ghyben-Herzberg relation because the Ghyben-Herzberg relation ignores vertical hydraulic head gradients and therefore is not an accurate predictor of pumping-induced interface rise. The simulated withdrawal distribution for the 2000 projection did not result in any perceptible change in water-level or interface position in the Lihue Town well field.

The simulated changes in the water table and interface represent the regional effect of the proposed ground-water withdrawals. In reality, water levels in individual pumped wells are likely to be lower, depending on local aquifer properties, well construction, and well location. The measured water level is about 243 ft



EXPLANATION

MODEL CELL

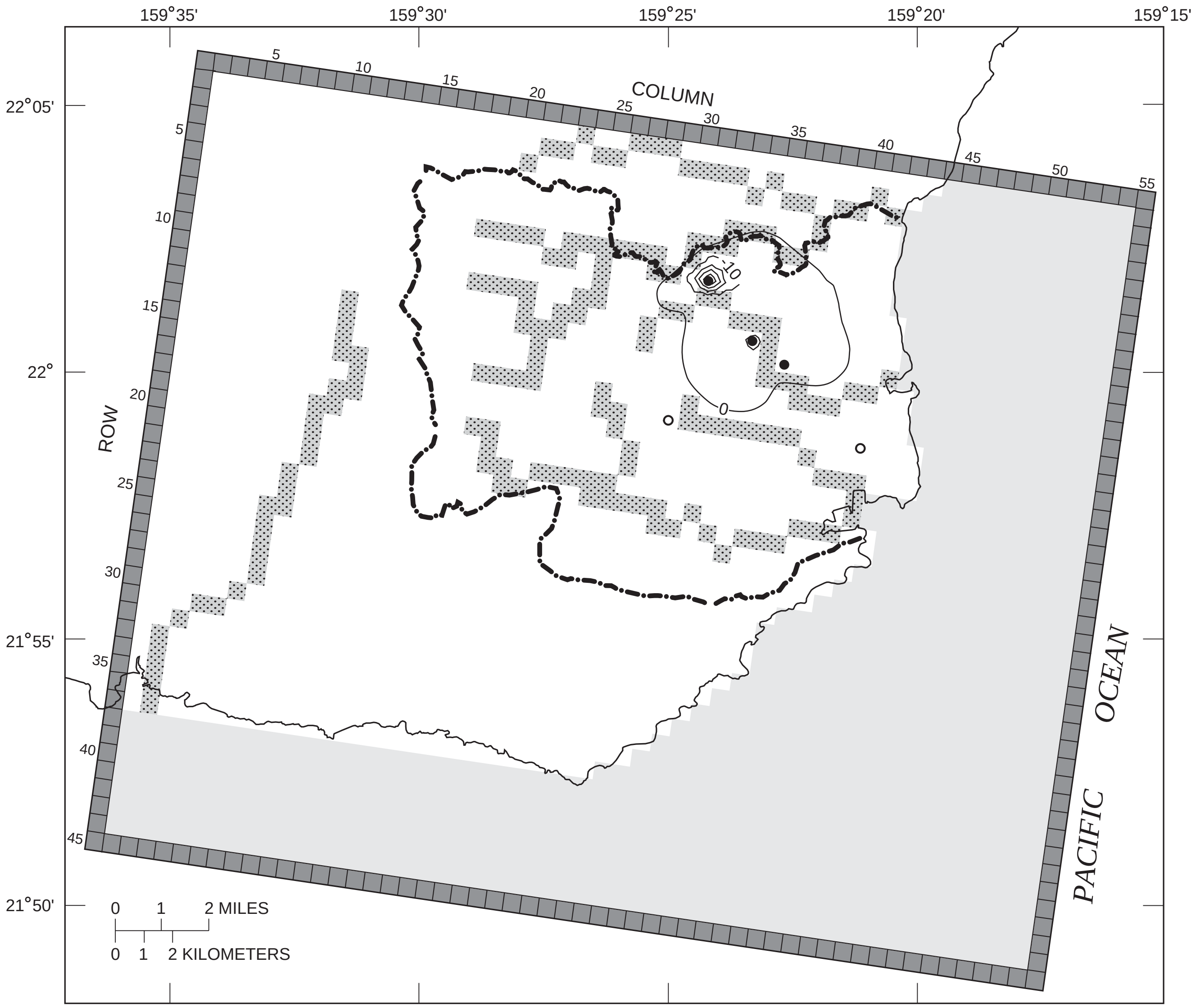
- Unconfined (water table)
- Ocean
- Stream or river
- No-flow boundary

BOUNDARY OF SOUTHERN LIHUE BASIN

MONITORING POINT

SIMULATED PROPOSED WELL

Figure 10. Simulated streams, wells, and monitoring points used in the steady-state simulations of projected increases in ground-water withdrawal in the southern Lihue Basin, Kauai, Hawaii.



EXPLANATION

MODEL CELL

Unconfined (water table)

Ocean

Stream or river

No-flow boundary

—-10— LINE OF EQUAL CHANGE IN WATER LEVEL IN UPPER LAYER OF MODEL --Interval is 10 feet

BOUNDARY OF SOUTHERN LIHUE BASIN

MONITORING POINT

SIMULATED PROPOSED WELL

Figure 11. Simulated steady-state changes in water levels resulting from the 0.42-million-gallon-per-day increase in ground-water withdrawal projected for 2000 in the southern Lihue Basin, Kauai, Hawaii.

Table 5. Conditions before, and simulated steady-state changes resulting from, the additional ground-water withdrawal of 0.42 million gallons per day projected for 2000 in the southern Lihue Basin, Kauai, Hawaii

[Mgal/d, million gallons per day; n.a., not applicable; n.d., not determined; <, less than; water-level and elevation datum is mean sea level]

Well and location (row, column) in model grid [a]	Pre-development		Steady-state condition with simulated 0.42 Mgal/d additional withdrawal		
	Measured water level (feet)	Simulated interface elevation [f] (feet)	Withdrawal (Mgal/d)	Water-level decrease [g] (feet)	Interface rise [f] (feet)
Hanamaulu 1 (13, 36)	249 [c]	-5,430	0.03	7	1
Hanamaulu 3 and 4 (9, 31)	243 [d]	< -6,000	0.31	53	n.d.[h]
Pukaki (12, 34)	252 [d]	< -6,000	0.08	15	n.d.[h]
Puhi [b] (17, 30)	65 [e]	< -6,000	n.a.	0	n.d.[h]
Lihue Town well field [b] (17, 41)	n.a.	-3,171	n.a.	0	0

[a] All wells are in upper layer of model
[b] For monitoring purposes only; no part of the 0.42 Mgal/d is pumped at this site
[c] Measured on 10/1/98. Data from well files at the U.S. Geological Survey, Honolulu
[d] From Izuka and Gingerich (1998a)
[e] Measured on 4/12/97. Data from well files at the U.S. Geological Survey, Honolulu
[f] Computed from interface elevations in lower layer of model
[g] Computed from freshwater heads in upper layer of model
[h] Cannot be determined because the pre-development interface is deeper than the bottom of the model

Table 6. Simulated steady-state stream base flow and changes resulting from the additional ground-water withdrawal of 0.42 million gallons per day projected for 2000 in the southern Lihue Basin, Kauai, Hawaii

[Mgal/d, million gallons per day]

Stream or river	Simulated pre-development base flow (Mgal/d)	Steady-state base flow with simulated withdrawal (Mgal/d)	Base-flow decrease (Mgal/d)
South Fork Wailua	55.34	55.20	0.14
Hanamaulu	3.82	3.55	0.27
Nawiliwili	1.09	1.08	0.01
Huleia	12.10	12.10	0

above sea level in the vicinity of Hanamaulu wells 3 and 4 and 252 ft above sea level in the vicinity of the Pukaki well (Izuka and Gingerich, 1998a), and water levels near Hanamaulu well 1 are about 249 ft above sea level (data in ground-water files at the USGS, Honolulu). Model simulations indicate that the freshwater extends several thousand feet below sea level at all three of these locations. By comparison, the simulated water-level changes and interface rise that would result from withdrawing 0.42 Mgal/d of ground water from the Hanamaulu area are small.

With the distribution of the 0.42 Mgal/d withdrawal as shown in table 5, the stream that is most affected is Hanamaulu Stream (table 6), which is closest to the wells. Simulated base flow in Hanamaulu Stream was reduced by 0.27 Mgal/d, which is 64 percent of the total effect of the proposed withdrawal on natural ground-water discharge. Although Hanamaulu Stream has the largest simulated change, the reduction in the base flow is only 5 to 9 percent of the estimated pre-development base flow or 7 percent of the simulated pre-development base flow of the stream (compare tables 4 and 6). Simulated base flow in South Fork Wailua River was reduced by 0.14 Mgal/d, and simulated base flow at Nawiliwili Stream was reduced by 0.01 Mgal/d. The simulated base-flow reduction in these streams accounts for all of the 0.42 Mgal/d withdrawn from the wells; the effects of ground-water withdrawal apparently do not extend beyond these streams or to coastal areas (fig. 11). This is consistent with the lack of change in simulated head and interface position in the Lihue Town well field.

Effects of the 2010 (0.83 Mgal/d) Projection

Initial simulation of the 0.83 Mgal/d withdrawal projected for 2010 used the withdrawal distribution among the four wells in Hanamaulu and Puhi well 5A determined by equation 1; withdrawal values for each well are shown in table 7. The largest withdrawals in this simulation were the combined withdrawal at Hanamaulu wells 3 and 4 (45 percent) and the withdrawal at Puhi well 5A (39 percent). Simulated water-level decline was 65 ft in the vicinity of Hanamaulu wells 3 and 4, and 58 ft in the vicinity of Puhi well 5A (fig. 12, table 7). Other wells had smaller simulated withdrawals and water-level decreases. Simulated water-level decrease near Hanamaulu well 1 was 8 ft and the interface rose 2 ft. The effect of the 0.83-Mgal/d withdrawal on water levels in the Lihue Town well field was imperceptible in the model, but resulted in a 1-ft rise of the simulated interface.

When compared to the pre-development measured water level, the simulation results indicate that the distribution of ground-water withdrawals shown in table 7 will lower the water-level in the vicinity of Puhi well 5A to within 7 ft of sea level, which raises the possibility of saltwater intrusion. Although the model-simulated interface does not extend beneath Puhi well 5A, a high degree of uncertainty is associated with the simulated interface position. Puhi well 5A lies in an anomalous area where water-level declines during drilling indicate a steep vertical head gradient complicated by intercalated low- and high-permeability horizons (Izuka and Gingerich, 1998a). When the well was shallow, measured water-level elevations were about 375 ft, which is comparable to the simulated water-level elevation (483 ft) prior to the proposed ground-water withdrawal, but the water-level elevation measured when the well was completed was only 65 ft. This anomaly cannot be resolved with the level of vertical discretization in the southern Lihue Basin model, but the anomaly is of small areal extent (Izuka and Gingerich, 1998a) and its omission from the model does not affect the model's ability to assess regional effects of the proposed ground-water withdrawal increases in most areas. However, the model's ability to simulate interface rise directly beneath Puhi well 5A is limited. The Ghyben-Herzberg relation indicates a water level of 65 ft above sea level would have a pre-development interface elevation of -2,600 ft, but the relation ignores vertical head gradients. Extrapolating the vertical gradient measured in Puhi well 5A during drilling indicates a pre-pumping interface elevation of about -1,700 ft (Izuka and Gingerich, 1998b), but this estimate assumes that the head gradient in the well persists to the interface. Neither the Ghyben-Herzberg relation nor the method of Izuka and Gingerich (1998b) can determine pumping-induced interface rise. Because the location and pumping-induced interface rise is uncertain, and because Puhi well 5A extends hundreds of feet below sea level, saltwater intrusion remains a possibility.

Although the southern Lihue Basin model cannot predict whether saltwater will actually be pumped at Puhi well 5A, the model can be used to examine the effects of shifting the stress of the ground-water withdrawals away from the Puhi area and toward parts of the aquifer where the freshwater lens is thicker. An alternative withdrawal distribution is discussed in a later section of this report.

With the initial distribution of withdrawal (as shown in table 7), 0.79 Mgal/d of the 0.83-Mgal/d withdrawal was accounted for by reductions in base flows of South Fork Wailua River and Hanamaulu, Nawiliwili, and Huleia Streams (table 8). The largest effect is on Hanamaulu Stream, where base flow was reduced by 0.34 Mgal/d or 41 percent of the total effect of the ground-water withdrawals on natural ground-water discharge. Base flow in South Fork Wailua River was reduced by 0.17 Mgal/d, base flow at Nawiliwili Stream was reduced by 0.19 Mgal/d, and base flow at Huleia Stream was reduced by 0.09 Mgal/d. With the exception of Nawiliwili Stream, reductions of base flows caused by the 2010 projected withdrawals are less than 10 percent of the simulated pre-development base flows of the streams. The relative base-flow reduction in Nawiliwili Stream is higher (17 percent) because the stream has a small pre-development base flow and projected withdrawal at nearby Puhi well 5A is high. The alternative withdrawal distribution discussed below will examine whether shifting withdrawal toward Hanamaulu can reduce the base-flow reduction in Nawiliwili Stream.

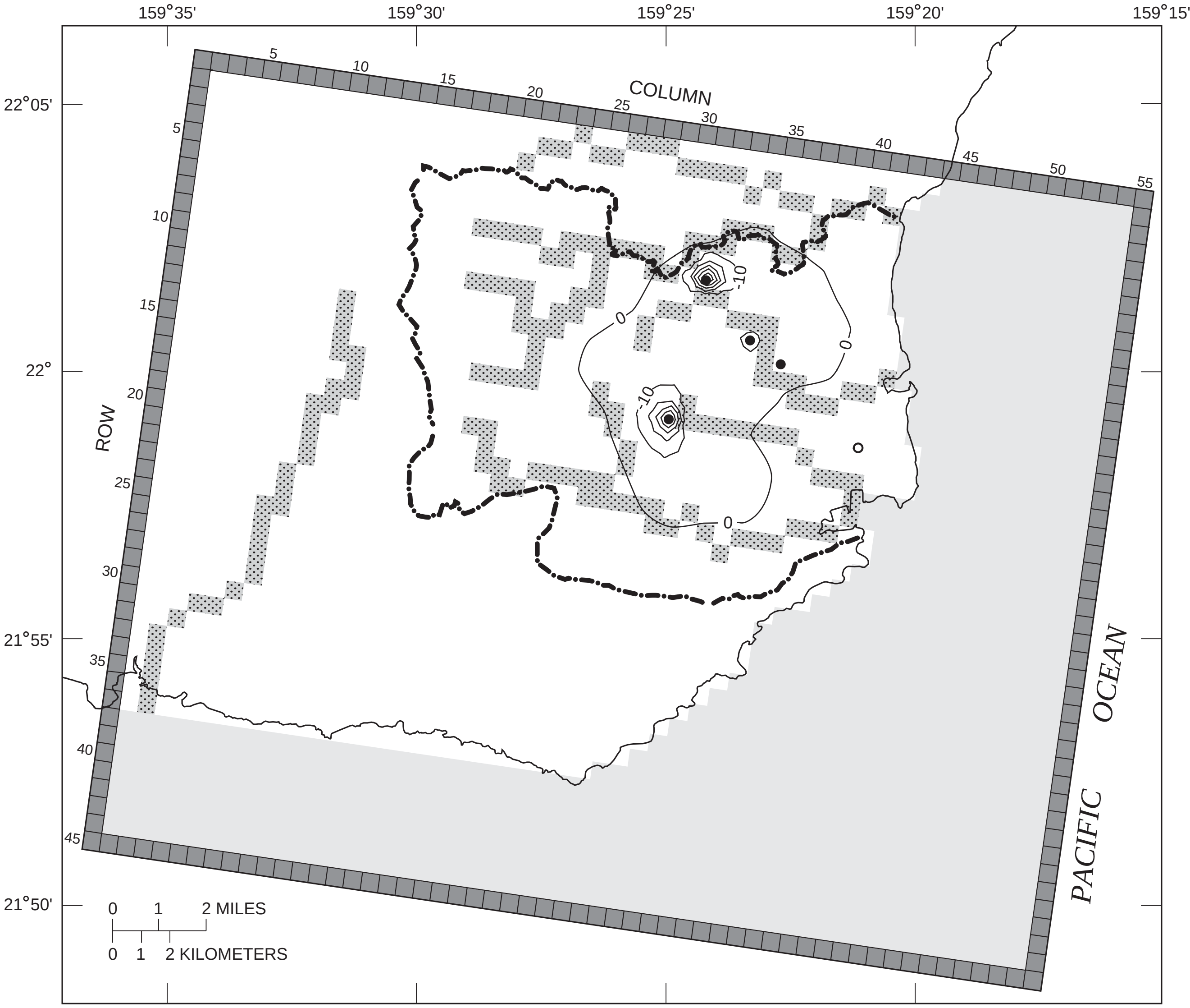
Table 7. Conditions before, and simulated steady-state changes resulting from, the additional ground-water withdrawal of 0.83 million gallons per day projected for 2010 in the southern Lihue Basin, Kauai, Hawaii
[Mgal/d, million gallons per day; n.a., not applicable; n.d., not determined; <, less than; water-level and elevation datum is mean sea level]

Well and location (row, column) in model grid [a]	Pre-development		Steady-state condition with simulated 0.83 Mgal/d additional withdrawal		
	Measured water level (feet)	Simulated interface elevation[f] (feet)	Withdrawal (Mgal/d)	Water-level decrease[g] (feet)	Interface rise [f] (feet)
Hanamaulu 1 (13, 36)	249 [c]	-5,430	0.04	8	2
Hanamaulu 3 and 4 (9, 31)	243 [d]	< -6,000	0.37	65	n.d.[h]
Pukaki (12, 34)	252 [d]	< -6,000	0.10	18	n.d.[h]
Puhi 5A (17, 30)	65 [e]	< -6,000	0.32	58	n.d.[h]
Lihue Town well field [b] (17, 41)	n.a.	-3,171	n.a.	0	1

[a] All wells are in upper layer of model
[b] For monitoring purposes only; no part of the 0.83 Mgal/d is pumped at this site
[c] Measured on 10/1/98. Data from well files at the U.S. Geological Survey, Honolulu
[d] From Izuka and Gingerich (1998a)
[e] Measured on 4/12/97. Data from well files at the U.S. Geological Survey, Honolulu
[f] Computed from interface elevations in lower layer of model
[g] Computed from freshwater heads in upper layer of model
[h] Cannot be determined because the pre-development interface is deeper than the bottom of the model

Table 8. Simulated steady-state stream base flow and changes resulting from the additional ground-water withdrawal of 0.83 million gallons per day projected for 2010 in the southern Lihue Basin, Kauai, Hawaii
[Mgal/d, million gallons per day]

Stream or river	Simulated pre-development base flow (Mgal/d)	Steady-state base flow with simulated withdrawal (Mgal/d)	Base-flow decrease (Mgal/d)
South Fork Wailua	55.34	55.17	0.17
Hanamaulu	3.82	3.48	0.34
Nawiliwili	1.09	0.90	0.19
Huleia	12.10	12.01	0.09



EXPLANATION

MODEL CELL

- Unconfined (water table)
- Ocean
- Stream or river
- No-flow boundary

-10 LINE OF EQUAL CHANGE IN WATER LEVEL IN UPPER LAYER OF MODEL --Interval is 10 feet

BOUNDARY OF SOUTHERN LIHUE BASIN

MONITORING POINT

SIMULATED PROPOSED WELL

Figure 12. Simulated steady-state changes in water levels resulting from the 0.83-million-gallon-per-day increase in ground-water withdrawal projected for 2010 in the southern Lihue Basin, Kauai, Hawaii.

An alternative distribution of the 0.83 Mgal/d ground-water withdrawal.--Because Puhi well 5A penetrates deep into a part of the freshwater lens that is thin relative to elsewhere in the Lihue Basin, and because proximity of the well to Nawiliwili Stream can cause significant reduction in the stream's base flow if withdrawal at the well is high, an alternative distribution of ground-water withdrawal wherein withdrawals were moved away from the Puhi area and toward Hanamaulu was simulated in the southern Lihue Basin model. Table 9 and figure 13 summarize the results of a simulation in which withdrawal at each of the Hanamaulu area wells was increased to 67 percent of the pump capacity. This represents the maximum withdrawal from the Hanamaulu wells for the given pump capacity according to the State of Hawaii Water System Standards (County Departments of Water Supply, State of Hawaii, 1985), which recommend that wells have pumps large enough to meet the maximum daily demand by pumping not more than 16 hours per day. Maximizing the withdrawal in the Hanamaulu wells allowed withdrawal at Puhi well 5A to be reduced to 69 percent of the withdrawal assigned to this well in the initial withdrawal distribution.

The resulting water-level decrease in the vicinity of Puhi well 5A is 40 ft, which is 18 ft less than in the initial distribution (compare tables 7 and 9). The alternative distribution of ground-water withdrawal caused water levels to decrease by an additional 13 ft in the vicinity of Hanamaulu wells 3 and 4, by an additional 3 ft in the vicinity of Pukaki well, and by an additional 1 ft in the vicinity of Hanamaulu well 1 relative to the water-level decreases in the initial withdrawal distribution. However, the pre-development water table is hundreds of feet above sea level in the vicinity of these wells. Relative to the initial distribution of ground-water withdrawal, the simulated interface position in the alternative distribution was 7 ft higher at Hana-maulu well 1 and 3 ft higher at the Lihue Town well field, but the simulated interface positions in these areas are still thousands of feet below sea level.

The alternative withdrawal distribution resulted in a base-flow reduction of 0.14 Mgal/d at Nawiliwili Stream; this effect is 0.05 Mgal/d less than with the initial 0.83-Mgal/d-withdrawal distribution (table 10). The effect of the alternative withdrawal distribution on base flow in Huleia Stream was also less than the effect of the initial 0.83-Mgal/d-withdrawal distribution. Effects on Hanamaulu Stream and South Fork Wailua River were larger with the alternative withdrawal distribution, but the effects on these streams relative to their larger base flows are relatively small. The simulation indicates that base flow will decrease by 13 percent in Nawiliwili Stream, 10 percent in Hanamaulu Stream, and less than 1 percent each at Huleia Stream and South Fork Wailua River.

Effects of the 2020 (1.16 Mgal/d) Projection

The simulations for the 2010 projection showed that by distributing most of the proposed pumping stress on the Hanamaulu wells, the potential of saltwater entering Puhi well 5A is reduced. Therefore, the first of two simulations of the 1.16 Mgal/d withdrawal projected for 2020 used a distribution that is proportionally similar to the alternative distribution of the 2010 scenario, wherein most (73 percent) of the proposed withdrawal comes from the Hanamaulu wells (table 11). The simulation indicates that water levels in the vicinity of Hanamaulu wells 3 and 4 would decrease by 110 ft, and water levels in the vicinity of the Pukaki well and Hanamaulu well 1 would decrease by 30 and 13 ft, respectively (table 11, fig. 14). The simulated interface beneath Hanamaulu well 1 rose 11 ft as a result of the proposed ground-water withdrawal and the simulated interface at the Lihue Town well field rose 5 ft. The simulated water-level declines and interface rises in the Hanamaulu area are small relative to the simulated thickness of fresh-water below sea level. However, the simulation indicates that water levels in the vicinity of Puhi well 5A would decrease by 56 ft; because the lens is thinner in this area and the well is deep, the potential for saltwater to rise into the well exists. The simulation indicates that most of the changes to stream base flow resulting from the 1.16 Mgal/d withdrawal proposed for 2020 would occur at Hanamaulu Stream and South Fork Wailua River (table 12), which is consistent with the greater withdrawal in the Hanamaulu area compared to the Puhi area.

To maintain the distribution of ground-water withdrawal projected for 2020, pumps in the proposed Hanamaulu wells would be operating at 94 to 100 percent of the proposed pump capacities (compare tables 11 and 2). Such high pumping exceeds the maximum draft of 16 hours of pumping per well per day

Table 9. Conditions before, and simulated steady-state changes resulting from, an alternative distribution of the additional ground-water withdrawal of 0.83 million gallons per day projected for 2010 in the southern Lihue Basin, Kauai, Hawaii

[Mgal/d, million gallons per day; n.a., not applicable; n.d., not determined; <, less than; water-level and elevation datum is mean sea level]

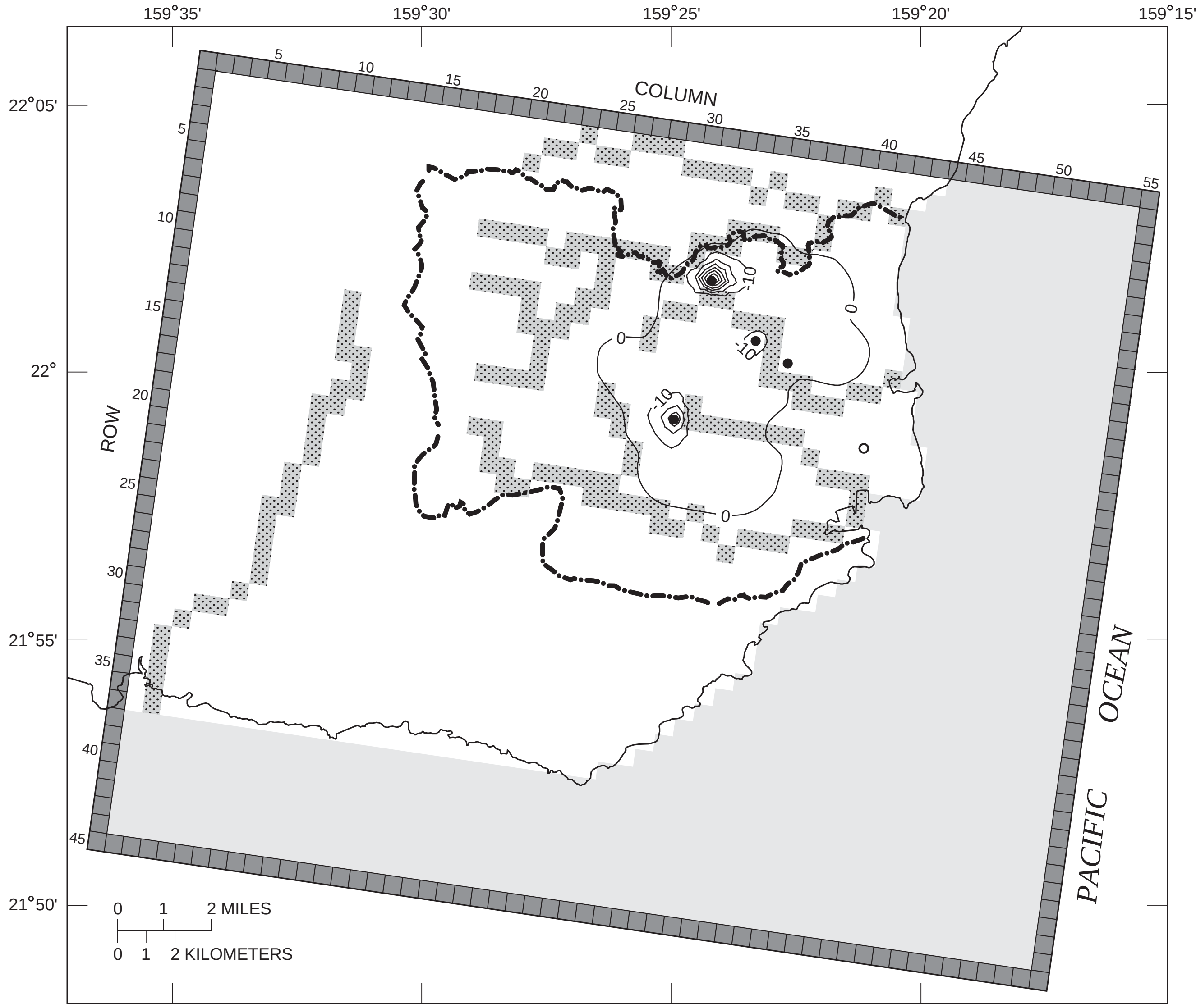
Well and location (row, column) in model grid [a]	Pre-development		Steady-state condition with simulated 0.83 Mgal/d additional withdrawal		
	Measured water level (feet)	Simulated interface elevation [f] (feet)	Withdrawal (Mgal/d)	Water-level decrease [g] (feet)	Interface rise [f] (feet)
Hanamaulu 1 (13, 36)	249 [c]	-5,430	0.05	9	9
Hanamaulu 3 and 4 (9, 31)	243 [d]	< -6,000	0.44	78	n.d.[h]
Pukaki (12, 34)	252 [d]	< -6,000	0.12	21	n.d.[h]
Puhi 5A (17, 30)	65 [e]	< -6,000	0.22	40	n.d.[h]
Lihue Town well field [b] (17, 41)	n.a.	-3,171	n.a.	0	4

[a] All wells are in upper layer of model
[b] For monitoring purposes only; no part of the 0.83 Mgal/d is pumped at this site
[c] Measured on 10/1/98. Data from well files at the U.S. Geological Survey, Honolulu
[d] From Izuka and Gingerich (1998a)
[e] Measured on 4/12/97. Data from well files at the U.S. Geological Survey, Honolulu
[f] Computed from interface elevations in lower layer of model
[g] Computed from freshwater heads in upper layer of model
[h] Cannot be determined because the pre-development interface is deeper than the bottom of the model

Table 10. Simulated steady-state stream base flow and changes resulting from an alternative distribution of the additional ground-water withdrawal of 0.83 million gallons per day projected for 2010 in the southern Lihue Basin, Kauai, Hawaii

[Mgal/d, million gallons per day]

Stream or river	Simulated pre-development base flow (Mgal/d)	Steady-state base flow with simulated withdrawal (Mgal/d)	Base-flow decrease (Mgal/d)
South Fork Wailua	55.34	55.14	0.20
Hanamaulu	3.82	3.42	0.40
Nawiliwili	1.09	0.95	0.14
Huleia	12.10	12.04	0.06



EXPLANATION

MODEL CELL

- Unconfined (water table)
- Ocean
- Stream or river
- No-flow boundary

—-10— LINE OF EQUAL CHANGE IN WATER LEVEL IN UPPER LAYER OF MODEL --Interval is 10 feet

BOUNDARY OF SOUTHERN LIHUE BASIN

MONITORING POINT

SIMULATED PROPOSED WELL

Figure 13. Simulated steady-state changes in water levels resulting from the alternative distribution of the 0.83-million-gallon-per-day increase in ground-water withdrawal projected for 2010 in the southern Lihue Basin, Kauai, Hawaii.

Table 11. Conditions before, and simulated steady-state changes resulting from, the additional ground-water withdrawal of 1.16 Mgal/d projected for 2020 in the southern Lihue Basin, Kauai, Hawaii
[Mgal/d, million gallons per day; n.a., not applicable; n.d., not determined; <, less than; water-level and elevation datum is mean sea level]

Well and location (row, column) in model grid [a]	Pre-development		Steady-state condition with simulated 1.16 Mgal/d additional withdrawal		
	Measured water level (feet)	Simulated interface elevation [f] (feet)	Withdrawal (Mgal/d)	Water-level decrease [g] (feet)	Interface rise [f] (feet)
Hanamaulu 1 (13, 36)	249 [c]	-5,430	0.07	13	11
Hanamaulu 3 and 4 (9, 31)	243 [d]	< -6,000	0.62	110	n.d.[h]
Pukaki (12, 34)	252 [d]	< -6,000	0.16	30	n.d.[h]
Puhi 5A (17, 30)	65 [e]	< -6,000	0.31	56	n.d.[h]
Lihue Town well field [b] (17, 41)	n.a.	-3,171	n.a.	0	5

[a] All wells are in upper layer of model

[b] For monitoring purposes only; no part of the 1.16 Mgal/d is pumped at this site

[c] Measured on 10/1/98. Data from well files at the U.S. Geological Survey, Honolulu

[d] From Izuka and Gingerich (1998a)

[e] Measured on 4/12/97. Data from well files at the U.S. Geological Survey, Honolulu

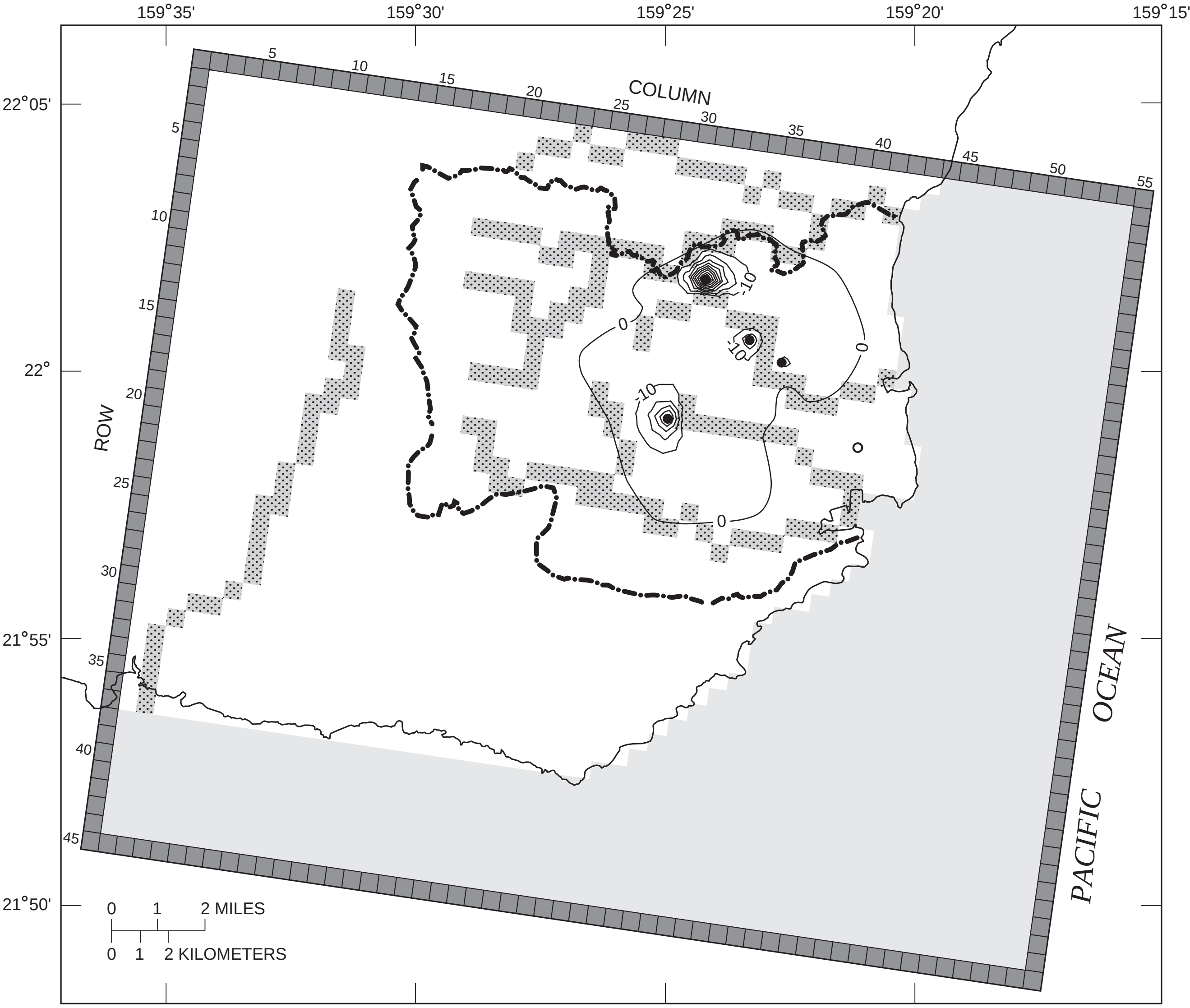
[f] Computed from interface elevations in lower layer of model

[g] Computed from freshwater heads in upper layer of model

[h] Cannot be determined because the pre-development interface is deeper than the bottom of the model

Table 12. Simulated steady-state stream base flow and changes resulting from the additional ground-water withdrawal of 1.16 million gallons per day projected for 2020 in the southern Lihue Basin, Kauai, Hawaii
[Mgal/d, million gallons per day]

Stream or river	Simulated pre-development base flow (Mgal/d)	Steady-state base flow with simulated withdrawal (Mgal/d)	Base-flow decrease (Mgal/d)
South Fork Wailua	55.34	55.05	0.29
Hanamaulu	3.82	3.26	0.56
Nawiliwili	1.09	0.89	0.20
Huleia	12.10	12.01	0.09



EXPLANATION

MODEL CELL

Unconfined (water table)

Ocean

Stream or river

No-flow boundary

-10 LINE OF EQUAL CHANGE IN WATER LEVEL IN UPPER LAYER OF MODEL --Interval is 10 feet

BOUNDARY OF SOUTHERN LIHUE BASIN

MONITORING POINT

SIMULATED PROPOSED WELL

Figure 14. Simulated steady-state changes in water levels resulting from the 1.16-million-gallon-per-day increase in ground-water withdrawal projected for 2020 in the southern Lihue Basin, Kauai, Hawaii.

recommended by the State of Hawaii Water Systems Standards (County Departments of Water Supply, State of Hawaii, 1985). Indeed, if all of the 1.16 Mgal/d projected for 2020 were withdrawn only from the Pukaki well, Hanamaulu wells 1, 3, and 4, and Puhi well 5A with the pump sizes given in table 2, the maximum recommended draft would be exceeded regardless of distribution. The total pump capacity for these wells is 1.48 Mgal/d; if each well is limited to an average 16 hours of withdrawal per day, the maximum average withdrawal would be only 0.99 Mgal/d. To maintain withdrawal at each well below the recommended maximum and to lower withdrawal at Puhi well 5A to reduce the risk of saltwater intrusion, either the size of the pumps in the Hanamaulu wells would have to be increased or new wells would be needed.

An alternative distribution of the 1.16 Mgal/d ground-water withdrawal.--To simulate the 1.16 Mgal/d additional withdrawal projected for 2020 without exceeding the maximum-withdrawal guidelines, three wells (wells A, B, and C in table 13 and fig. 10) were added to the Hanamaulu area of the model. The pump capacity of these hypothetical wells was assumed to be 120 gal/min (0.17 Mgal/d), which is equal to the pump capacity of the nearby Pukaki well.

In this simulation, 80 percent of the total proposed withdrawal came from wells in the Hanamaulu area, thus placing most of the stress of the proposed withdrawal where the freshwater lens is thick. Simulated water-level decreases in this area ranged from 82 ft in the vicinity of Hanamaulu wells 3 and 4 to 10 ft in the vicinity of Hanamaulu well 1, whereas pre-development measured water levels in these areas are more than 200 ft above sea level (table 13, fig. 15). Simulated withdrawal at Puhi well 5A, where the freshwater lens is thinner, accounted for 20 percent of the total proposed withdrawal, and simulated water-level decrease in the vicinity of this well was 41 ft. The simulated interface beneath Hanamaulu well 1 rose 10 ft as a result of the proposed ground-water withdrawal and the simulated interface beneath the Lihue Town well field rose 5 ft. These simulated interface rises are small relative to the simulated thickness of freshwater below sea level at these sites.

Most of the changes to stream base flow resulting from the simulated 1.16 Mgal/d withdrawal for 2020 occurred at Hanamaulu Stream and South Fork Wailua River (table 14), which is consistent with the greater withdrawal in the Hanamaulu area compared to the Puhi area. Change in base flow at Hanamaulu Stream alone accounted for more than half of the proposed additional withdrawal. Hanamaulu Stream also ranked highest in terms of relative change, with a simulated base flow decrease of 16 percent relative to simulated pre-development base flows. Nawiliwili Stream decreased by 14 percent, and Huleia Stream and South Fork Wailua River decreased by less than 1 percent relative to pre-development base flows.

Implications of the Steady-State Simulations

The steady-state simulations indicate that with respect to stream base flow, the effects of the projected withdrawal increases will be greatest on streams nearest the location of the proposed wells. Redistributing withdrawal can change the effect on individual streams, but because streams are so numerous in the southern Lihue Basin, it is difficult to shift the net effect away from streams as a whole. Although the net effect on streams cannot be substantially reduced, the proportional effects can be partially mitigated by shifting ground-water withdrawal away from streams with low base flow and toward streams with high base flow.

Estimates of streamflow reductions provided by the model simulations will allow quantitative comparisons when final instream flow standards are established and implemented as mandated by the Hawaii Water Code. Quantitative effects estimated by the simulations in this study or by additional simulations can be used to help identify pumping distributions that meet both the need to provide drinking water as well as the need to maintain instream flow standards.

The steady-state simulations indicate that in most inland areas of the southern Lihue Basin, with the exception of the Puhi area, the depression of the water table and rise of the interface caused by the proposed ground-water withdrawal will be small relative to the pre-development thickness of freshwater above and below sea level. In the Puhi area, the model simulations cannot assess with certainty the rise of the interface because layered heterogeneities that exist in the area are too small to be resolved given the level of vertical discretization of the model. The heterogeneities in this area appear to be anomalous, however, and limited to the Puhi and Kilohana areas (Izuka and Gingerich, 1998a). Throughout most inland areas of the southern Lihue

Table 13. Conditions before, and simulated steady-state changes resulting from, an alternative distribution of the additional ground-water withdrawal of 1.16 million gallons per day projected for 2020 in the southern Lihue Basin, Kauai, Hawaii

[Mgal/d, million gallons per day; n.a., not applicable; n.d., not determined; <, less than; water-level and elevation datum is mean sea level]

Well and location (row, column) in model grid [a]	Pre-development		Steady-state condition with simulated 1.16 Mgal/d additional withdrawal		
	Measured water level (feet)	Simulated interface elevation [f] (feet)	Withdrawal (Mgal/d)	Water-level decrease [g] (feet)	Interface rise [f] (feet)
Hanamaulu 1 (13, 36)	249 [c]	-5,430	0.05	10	10
Hanamaulu 3 and 4 (9, 31)	243 [d]	< -6,000	0.45	82	n.d.[h]
Pukaki (12, 34)	252 [d]	< -6,000	0.12	22	n.d.[h]
Puhi 5A (17, 30)	65 [e]	< -6,000	0.23	41	n.d.[h]
Well A (9, 33)	n.a.	< -6,000	0.10	45	n.d.[h]
Well B (10, 33)	n.a.	< -6,000	0.11	35	n.d.[h]
Well C (10, 34)	n.a.	< -6,000	0.10	35	n.d.[h]
Lihue Town well field [b] (17, 41)	n.a.	-3,171	n.a.	0	5

[a] All wells are in upper layer of model

[b] For monitoring purposes only; no part of the 1.16 Mgal/d is pumped at this site

[c] Measured on 10/1/98. Data from well files at the U.S. Geological Survey, Honolulu

[d] From Izuka and Gingerich (1998a)

[e] Measured on 4/12/97. Data from well files at the U.S. Geological Survey, Honolulu

[f] Computed from interface elevations in lower layer of model

[g] Computed from freshwater heads in upper layer of model

[h] Cannot be determined because the pre-development interface is deeper than the bottom of the model

Table 14. Simulated steady-state stream base flow and changes resulting from an alternative distribution of the additional ground-water withdrawal of 1.16 million gallons per day projected for 2020 in the southern Lihue Basin, Kauai, Hawaii

[Mgal/d, million gallons per day]

Stream or river	Simulated pre-development base flow (Mgal/d)	Steady-state base flow with simulated withdrawal (Mgal/d)	Base-flow decrease (Mgal/d)
South Fork Wailua	55.34	55.06	0.29
Hanamaulu	3.82	3.19	0.63
Nawiliwili	1.09	0.94	0.15
Huleia	12.10	12.04	0.06

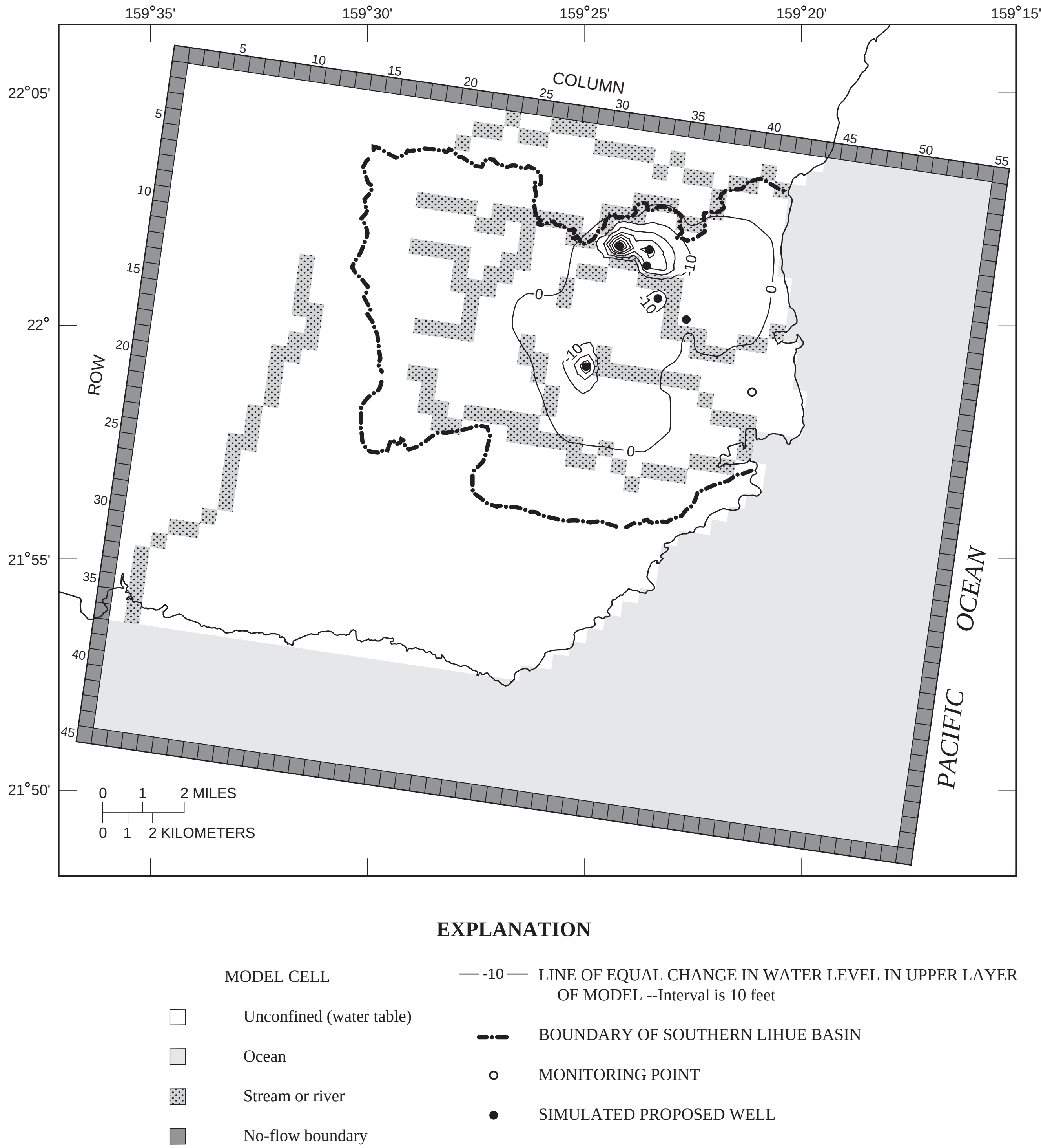


Figure 15. Simulated steady-state changes in water levels resulting from the alternative distribution of the 1.16-million-gallon-per-day increase in ground-water withdrawal projected for 2020 in the southern Lihue Basin, Kauai, Hawaii.

Table 15. Storage coefficients and specific-storage values from aquifer tests in the Lihue Basin, Kauai, Hawaii

Well number	Well name	Storage coefficient[a]	Assumed aquifer thickness[a] (feet)	Specific storage (feet^{-1})
2-0023-01	Pukaki Reservoir	8.2×10^{-2}	975	8.4×10^{-5}
2-0124-01	Northeast Kilohana	1.6×10^{-2}	924	1.7×10^{-5}
2-0126-01	Northwest Kilohana	8.5×10^{-4}	916	9.3×10^{-7}

[a] From Gingerich, 1999

Basin, where the freshwater lens is thick and hydraulic conductivities are low, the rise of the interface in response to ground-water withdrawal is relatively small.

RATE OF DEVELOPMENT OF THE EFFECTS OF THE PROPOSED GROUND-WATER WITHDRAWALS

Whereas the steady-state simulations indicate the full effects of constant ground-water withdrawal that will ultimately be attained given enough time, transient simulations can show how the effects develop over time. To study the rate at which the effects caused by the proposed ground-water withdrawal will develop, the southern Lihue Basin model was modified to allow transient simulations. The rate at which an aquifer responds to withdrawal is a function of aquifer storage. Other parameters being equal, the lower the storage, the faster the response to withdrawal will be. The transient simulations thus require estimates of aquifer storage. Because aquifer storage is not precisely known, the proposed withdrawals were tested using a range of storage values.

The storage of an aquifer is the volume of water the aquifer will yield per unit area as a result of a unit decline in head in the aquifer. The amount of water released depends on the effective porosity and compressibility of the aquifer, the expandability of water, and whether the aquifer is confined or unconfined. In an unconfined aquifer, the amount of water released comes mainly from draining of pore spaces. Water released as a result of aquifer compression or water expansion is relatively small. Porosity in the lava-flow aquifers in Hawaii, as determined from laboratory procedures or photo analysis, ranges from about 5 to 50 percent, but these values represent total porosity; effective porosity may be lower by a factor of 10 (Hunt, 1996). Massive lava flows, such as those in the southern Lihue Basin, are likely to have even lower porosities. For the transient simulations in this report, porosities of 1 and 10 percent were used, which is consistent with the lower total porosities measured for dense basalt in Hawaii (Hunt, 1996) and recognizes that effective porosity will be lower than total porosity.

In a confined aquifer, where the pore space is not drained, the aquifer yields water as the rock compresses and water expands. The storage in a confined aquifer is thus a function of aquifer elasticity and water compressibility, and is expressed in terms of specific storage. Aquifer-test analyses yield storage in terms of storage coefficient, which is related to specific storage by

$$S_s = \frac{S}{b}, \qquad (2)$$

where: S_s = specific storage (L^{-1}),
S = storage coefficient (dimensionless), and
b = aquifer thickness (L).

Gingerich (1999) analyzed aquifer-test data from several wells in the southern Lihue Basin and determined storage coefficients ranging from 8.2×10^{-2} to 8.5×10^{-4} (table 15). To derive specific storage, which is the parameter needed for the transient simulations, the storage coefficients in Gingerich (1999) were divided by the assumed aquifer thicknesses. The resulting specific-storage values ranged from 8.4×10^{-5} ft^{-1} to 9.3×10^{-7} ft^{-1}. The transient simulations were tested over a similar range of specific storage (rounded to the nearest whole power of 10) of 10^{-4} ft^{-1} to 10^{-6} ft^{-1}.

The rate of response of stream base flow also depends on how the withdrawal is distributed relative to the streams. The transient simulations used the same withdrawal distributions as in the steady-state simulations. Different combinations of S_s, porosity, and withdrawal distribution used in the transient simulations yielded a range of rates for water-level decreases and base-flow reductions.

Transient Simulations of the 2000 (0.42 Mgal/d) Projection

Graphs of the simulated effects of the 0.42 Mgal/d ground-water withdrawal projected for 2000 (using the distribution of ground-water withdrawal described in table 5) on water levels and stream base flows (figs. 16 and 17) show how the rate at which the effects will develop depends on S_s and porosity. The combination of low S_s (10^{-6} ft^{-1}) and low porosity (1 percent) in one simulation resulted in such rapid declines in water levels and base flows that the full effects (as indicated by the steady-state simulation of the same withdrawal distribution) were attained within the first 20 years of the start of withdrawal. Simulated changes using the higher values of S_s (10^{-4} ft^{-1}) and porosity (10 percent) were more gradual. Still, the simulation indicates that 95 percent of the full effects on water levels in the vicinity of Hanamaulu wells 3 and 4 (31 ft), and 80 to 87 percent of the full effect on base flow in the nearest streams (Hanamaulu Stream and South Fork Wailua River) would be attained within 20 years.

Transient simulations combining the higher S_s value (10^{-4} ft^{-1}) with the lower porosity value (1 percent), gave virtually the same results as simulations combining the lower S_s value (10^{-6} ft^{-1}) with the higher porosity value (10 percent). These simulations indicate intermediate rates of change: within 20 years, 99 percent of the full water-level effects in the vicinity of Hanamaulu wells 3 and 4, and 92 to 94 percent of the full base-flow effects in Hanamaulu Stream and South Fork Wailua River, were attained (figs. 16 and 17).

Transient Simulations of the 2010 (0.83 Mgal/d, Alternative Distribution) Projection

Transient simulation of the 0.83 Mgal/d ground-water withdrawal projected for 2010 (table 9) using the lower values of S_s and porosity, indicates that the full effects on water levels at these sites would be attained within 5 years from the start of withdrawal (fig. 18). Even if the higher values of S_s and porosity are used, the transient simulations indicate that 96 percent of the ultimate water-level decrease in the vicinity of Hanamaulu wells 3 and 4, and 90 percent of the full effect on water levels in the vicinity of Puhi well 5A would be attained within 20 years. Transient simulations combining the higher S_s value with the lower porosity and combining the lower S_s value with higher porosity indicate that within 20 years, 99 percent of the full effects on water levels in the vicinity of Hanamaulu wells 3 and 4, and about 95 percent of the full effect on water levels in the vicinity of Puhi well 5A, would be attained.

The transient simulations also indicate that within the first 20 years of the start of ground-water withdrawal, streams near the pumped wells (in this case Nawiliwili Stream, which is near Puhi well 5A, and Hanamaulu Stream and South Fork Wailua River, which are near the Hanamaulu wells) nearly attain the full base-flow reductions indicated by the steady-state simulations (fig. 19). In the simulation showing the fastest response to ground-water withdrawal, the full effects on base flows at these streams were attained within 11 years from the start of withdrawal. In the simulation showing the slowest response to ground-water withdrawal, 74 to 86 percent of the full effects on base flows were attained within 20 years. In the simulations showing intermediate rates of response, 84 to 93 percent of the full effects on base flows were attained within 20 years.

Transient Simulations of the 2020 (1.16 Mgal/d, Alternative Distribution) Projection

In the transient simulations of the alternative distribution of the 1.16 Mgal/d additional withdrawal projected for 2020 (table 13) the fastest response to ground-water withdrawal indicates that the full effects on water levels would be attained in about 2 years at Hanamaulu wells 3 and 4, and about 4 years at Puhi well 5A (fig. 20). The simulation showing the slowest response indicates that in 20 years, more than 90 percent of the full effects on water levels at these locations would be attained. In the simulations showing intermediate rates of response, 96 to 99 percent of the full effects on water levels at these sites was attained within 20 years.

In the simulation showing the fastest response to ground-water withdrawal, the full effects on base flows were attained in about 6 to 7 years in Hanamaulu and Nawiliwili Streams, and South Fork Wailua River (fig. 21). In the simulation showing the slowest response to ground-water withdrawal, 84 percent of the full

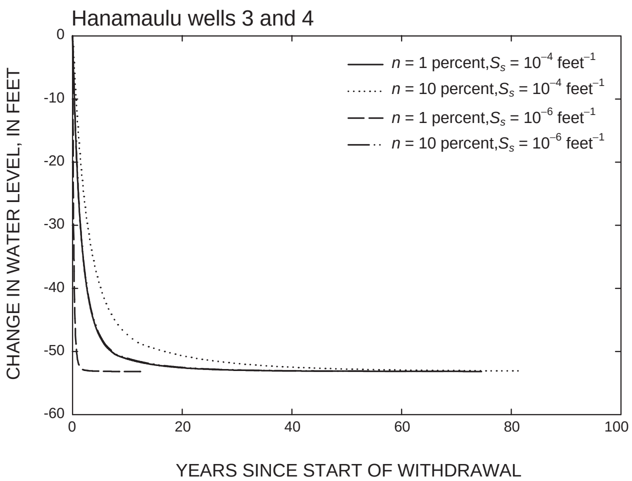


Figure 16. Simulated water-level changes with time since start of withdrawal of the 0.42 million gallons per day projected for the southern Lihue Basin, Kauai, Hawaii, in 2000 (n, porosity; S_S, specific storage).

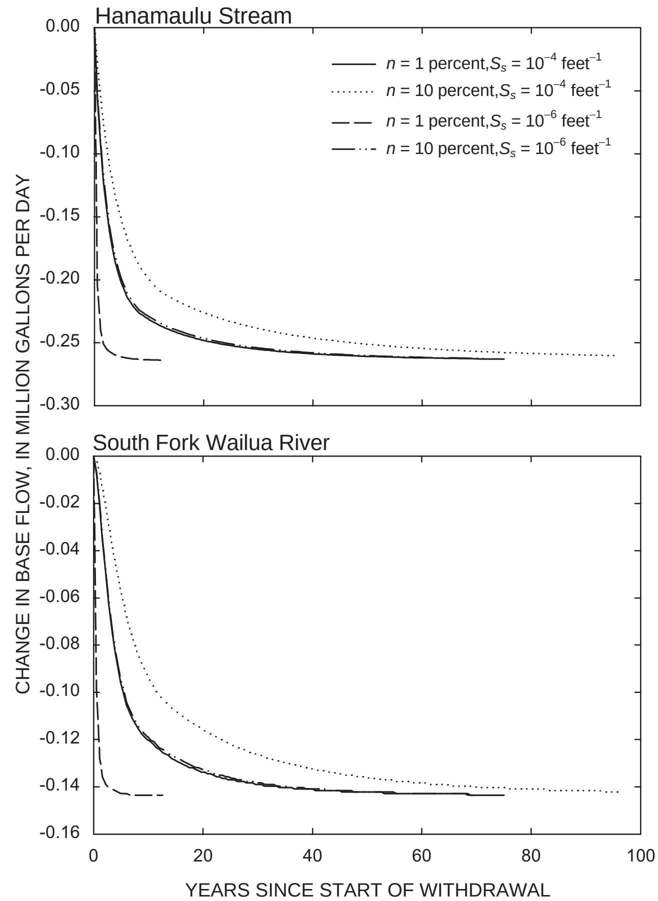


Figure 17. Simulated stream base-flow changes with time since start of withdrawal of the 0.42 million gallons per day projected for the southern Lihue Basin, Kauai, Hawaii, in 2000 (n, porosity; S_S, specific storage).

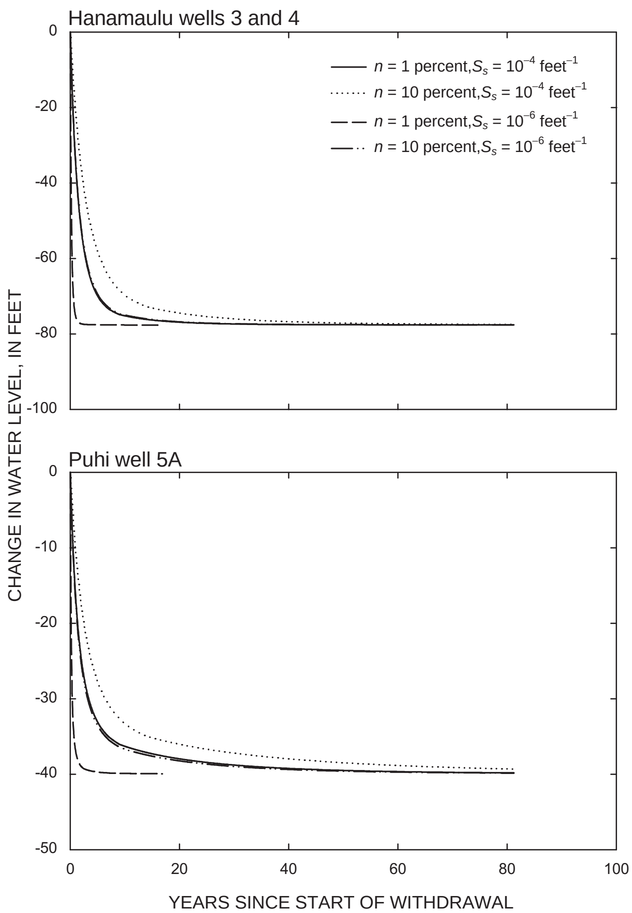


Figure 18. Simulated water-level changes with time since start of withdrawal of the 0.83 million gallons per day (alternative distribution) projected for the southern Lihue Basin, Kauai, Hawaii, in 2010 (n, porosity; S_s, specific storage).

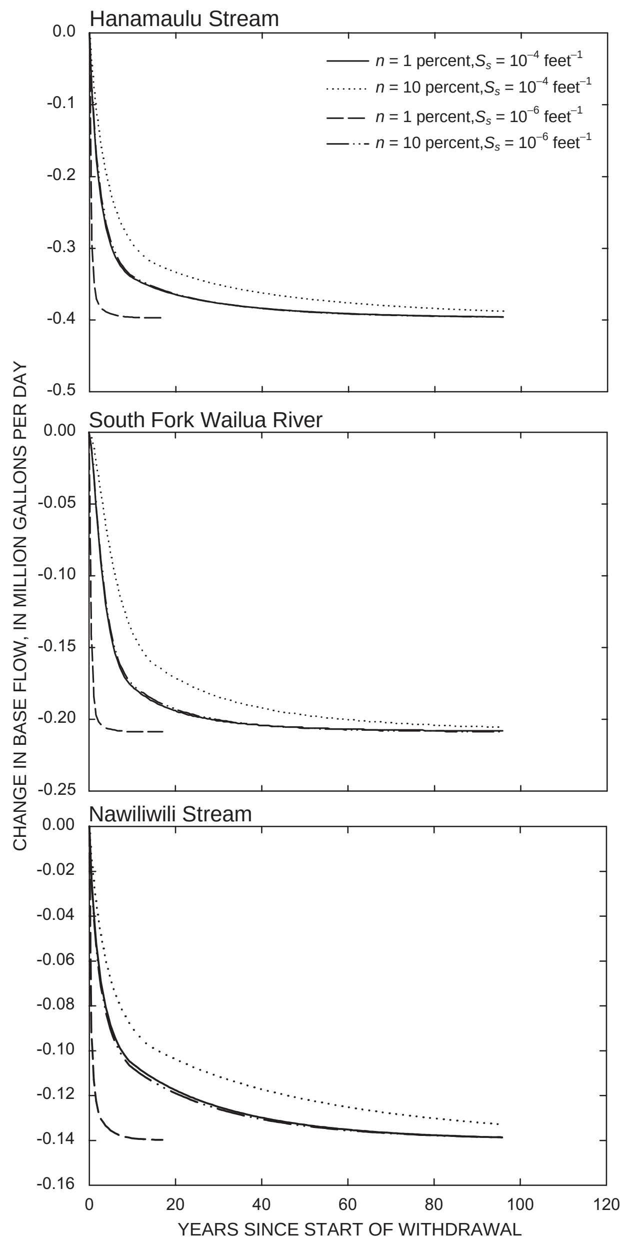


Figure 19. Simulated stream base-flow changes with time since start of withdrawal of the 0.83 million gallons per day (alternative distribution) projected for the southern Lihue Basin, Kauai, Hawaii, in 2010 (n, porosity; S_s, specific storage).

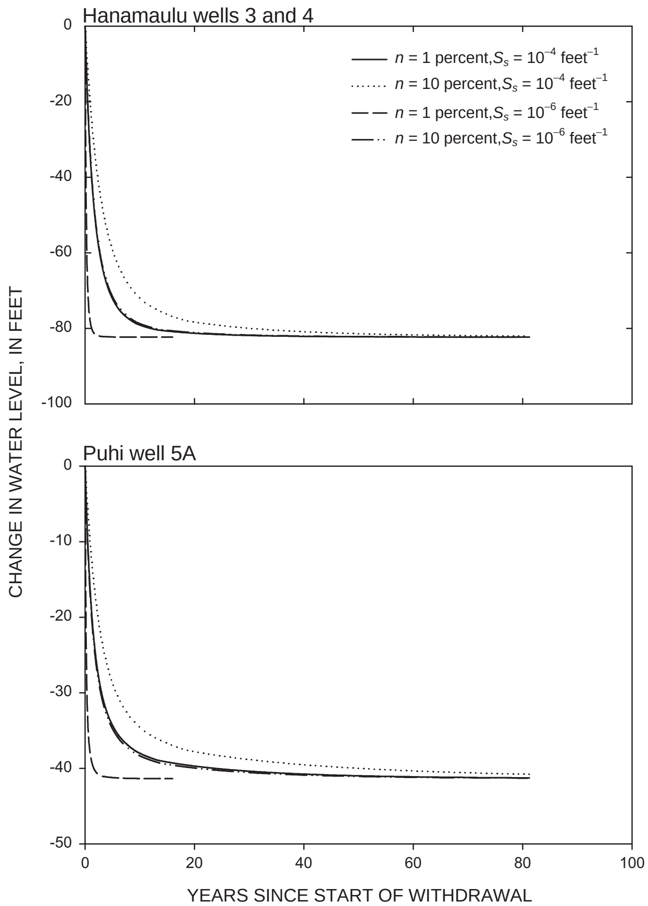


Figure 20. Simulated water-level changes with time since start of withdrawal of the 1.16 million gallons per day (alternative distribution) projected for the southern Lihue Basin, Kauai, Hawaii, in 2020 (*n*, porosity; S_S, specific storage).

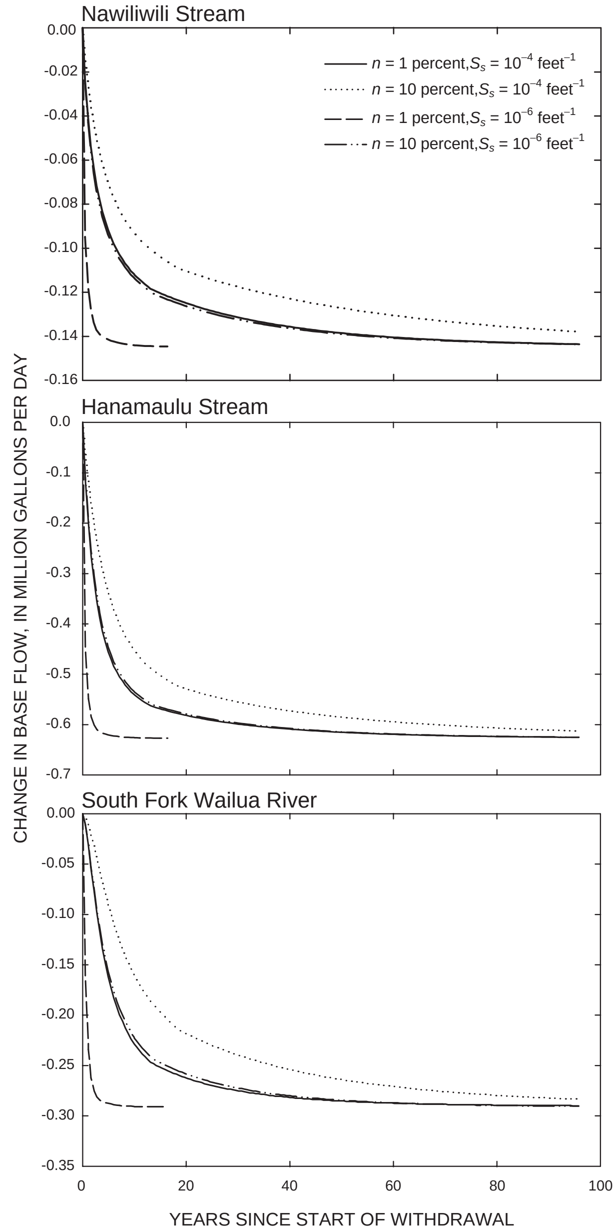


Figure 21. Simulated stream base-flow changes with time since start of withdrawal of the 1.16 million gallons per day (alternative distribution) projected for the southern Lihue Basin, Kauai, Hawaii, in 2020 (*n*, porosity; S_S, specific storage).

base-flow effect on Hanamaulu Stream, 75 percent of the full base-flow effect on South Fork Wailua River, and 77 percent of the full base-flow effect on Nawiliwili Stream were attained in 20 years. In the simulations showing intermediate rates of response, 87 to 93 percent of the full effects on base flows of these streams was attained within 20 years.

Implications of the Transient Simulations

The transient simulations indicate that most of the changes resulting from the projected increase in ground-water withdrawal from the Hanamaulu and Puhi areas of the southern Lihue Basin will develop within 10 to 20 years of the start of ground-water withdrawal. Even assuming the slowest expected aquifer response, 90 percent or more of the water-level declines at pumped wells will be attained within 20 years, and 75 percent or more of the ultimate base-flow reductions will be attained in streams nearest the ground-water withdrawals, and these streams will ultimately undergo the greatest changes. This relatively quick response of streamflow to ground-water withdrawal is consistent with the proximity of the wells to streams. Because the southern Lihue Basin has so many streams, it is difficult to construct a well that is not near a stream.

SUMMARY AND CONCLUSIONS

Numerical simulations indicate that ground-water withdrawals from the Hanamaulu and Puhi areas of the southern Lihue Basin will result in depression of water levels and reductions in stream base flows in and near proposed new water-supply wells. Except for areas such as Puhi and Kilohana, which have unique hydraulic characteristics that are of limited extent, the freshwater lens in most inland areas of the southern Lihue Basin is thick and hydraulic conductivities are low. Model simulations indicate that the rise of the interface in response to ground-water withdrawal in most areas of the southern Lihue Basin will be small relative to the pre-development thickness of freshwater. Effects of the projected withdrawals on streams depend on the withdrawal rate and proximity of the pumped wells to streams. Because the southern Lihue Basin has so many streams, it is difficult to construct a well that is not near a stream. However, shifting ground-water withdrawals away from streams with small base flow and toward streams with large base flow can reduce the relative effect on individual streams.

Quantitative streamflow-reduction estimates, such as those provided by the model simulations, are needed to assess the effects of ground-water development relative to final instream flow standards mandated by the Hawaii State Water Code. Model simulations can help identify pumping distributions that meet both the need to provide drinking water as well as the need to maintain the environmental, aesthetic, and recreational qualities of streams.

Simulation of the projected 0.42 Mgal/d increased withdrawal for 2000 included withdrawals from proposed new water-supply wells in Hanamaulu. The simulation indicates that the resulting depression of water levels and rise of the interface will be small in comparison to the pre-development freshwater thickness. Virtually all of the 0.42 Mgal/d pumped from the wells will ultimately come from base-flow reductions in Hanamaulu Stream, South Fork Wailua River, and Nawiliwili Stream. The largest proportional change in the simulation occurred at Hanamaulu Stream, where base flow was reduced by about 7 percent.

Simulation of the 0.83 Mgal/d withdrawal projected for 2010 included withdrawal from wells in Hanamaulu as well as from Puhi well 5A. Because Puhi well 5A penetrates deep into a relatively thin freshwater lens, the potential exists that saltwater will enter the well. The model simulation cannot assess with certainty the rise of the interface beneath the Puhi area because of vertical heterogeneities that are apparently limited to the Puhi and Kilohana areas, but simulations indicate that thinning of the already-thin freshwater lens in the Puhi area can be reduced by shifting most of the new withdrawal to the Hanamaulu area where the freshwater lens is thicker. The shift of withdrawal to the Hanamaulu area will also reduce the effect on Nawiliwili Stream, which already has small base flow, and increase the effect on the larger streams and rivers in the Hanamaulu area.

The increased withdrawal of 1.16 Mgal/d projected for 2020 cannot be obtained from the combination of Hanamaulu wells 1, 3, and 4, the Pukaki well, and Puhi well 5A without exceeding the recommended maximum rates for the pumps planned for these wells. Therefore, simulation of the 2020 projection included three additional hypothetical wells in the Hanamaulu area, such that 80 percent of the total proposed withdrawal came from wells in the Hanamaulu area. Resulting water-level decline and interface rise were small relative to the simulated thickness of freshwater below sea level at these sites. The simulation indicates that base flow will decrease by 16 percent in Hanamaulu Stream, 13 percent in Nawiliwili Stream, and 1 percent in South Fork Wailua River.

Most of the changes in water level and streamflow will develop within 10 to 20 years of the start of ground-water withdrawals. Even assuming the slowest expected aquifer response, 75 percent or more of the ultimate base-flow reductions in streams nearest the new ground-water withdrawals, and 90 percent or more of the water-level declines at pumped wells will be attained within 20 years. This relatively quick response of streams to ground-water withdrawals is consistent with the proximity of the wells to streams.

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APPENDIX

RECHARGE UNCERTAINTY IN THE LIHUE BASIN AREA, KAUAI

Ground-water recharge used in the original numerical model of the southern Lihue Basin by Izuka and Gingerich (1998a) was estimated by Shade (1995b) using a water-budget approach. The water-budget approach to recharge estimation is based on the concept that part of the water that falls as precipitation runs off the land directly to the ocean; the remainder infiltrates the soil where the water is stored temporarily and is subject to evapotranspiration. Recharge to the aquifer occurs only when the soil's water-storing capacity is exceeded and the excess infiltrated water is passed to the underlying aquifer (Thornthwaite and Mather, 1955). How much water ultimately goes to recharge depends on the intensity of the precipitation and the amount of water already stored in the soil. If the soil moisture was nearly depleted by evapotranspiration prior to precipitation, much of the infiltrated water may remain in the soil, and little water passes to recharge. If the soil is nearly saturated prior to precipitation, a greater part of the infiltrated water would become recharge. The water-budget method mimics this process by computing a water budget for short consecutive periods (such as days or months) using the amount of soil moisture at the end of one period as the input soil moisture for the next period. Accuracy of the recharge estimates is affected by the length of the individual consecutive periods in the water-budget computation. Daily water budgets can account for intra-month variability in rainfall and evapotranspiration and therefore provide more accurate recharge estimates than monthly water budgets.

The order in which evapotranspiration is assigned relative to recharge in the water-budget computation also affects the recharge estimate. Evapotranspiration may be subtracted from the infiltrated water initially, then if the remaining water exceeds soil-moisture storage capacity, the excess is assigned to recharge. Alternatively, infiltration in excess of soil-moisture storage capacity may be assigned first to recharge, then evapotranspiration acts only on the water left in the soil. Water budgets that assign evapotranspiration before recharge tend to underestimate recharge (Giambelluca and Oki, 1987; Rushton and Ward, 1979; Howard and Lloyd, 1979; Alley, 1984), whereas water budgets that account for recharge before evapotranspiration tend to overestimate recharge. The degree of overestimation or underestimation may be substantial for water budgets that are computed on a monthly or longer basis. For example, Shade (1997) computed monthly water budgets for the island of Molokai, Hawaii, and estimated a range for island-wide recharge of 140 Mgal/d (assigning evapotranspiration before recharge) to 237 Mgal/d (assigning recharge before evapotranspiration). Ground-water recharge used in the numerical model of the southern Lihue Basin was estimated from a monthly water budget that accounts for recharge before evapotranspiration (Shade, 1995b), and is thus expected to be higher and less accurate than recharge estimated from a daily water budget.

This study assesses the potential inaccuracy of the recharge used in the original model of the southern Lihue Basin by comparing average annual recharge estimated using a daily water-budget approach versus recharge estimated using a monthly water-budget approach. Both the daily and monthly water budgets were computed using the same data from the same selected sites in and near the Lihue Basin. The monthly water-budget computation assigned recharge before evapotranspiration, which is the method used by Shade (1995b). In contrast, the daily water-budget computation accounted for evapotranspiration before recharge, which is a more conservative approach, and used base flows computed from hydrograph-separation techniques in the computation of the runoff-to-rainfall ratios. Regression equations relating average annual recharge estimates from the two methods were developed and used to adjust the original recharge in each cell of the southern Lihue Basin ground-water model so that a daily-water-budget-based recharge distribution could be obtained for the model. This distribution was further refined by including fog drip, and correcting for an apparent overestimation of evapotranspiration in irrigated areas of the original Lihue Basin water budget. Adjustments for fog and the apparent overestimation of evapotranspiration in irrigated areas were then made over a range of values, thus yielding a range of uncertainty in the recharge estimate.

Data

To develop equations relating average annual recharge estimated from a daily water budget and average annual recharge estimated from a monthly water budget, available pan-evaporation (Ekern and Chang,

1985) and daily rainfall data (Hydrosphere, 1996) from stations in and near the Lihue Basin (fig. A1, table A1) were used. The same rainfall and pan-evaporation data were used in a daily water budget and a monthly water budget. For the monthly water budget, daily rainfall and pan-evaporation values were aggregated into monthly totals. Pan evaporation was used as an estimate of potential evapotranspiration (Shade, 1995b) in the water budgets.

Only stations with at least 1 year of daily rainfall data were considered for the analysis, and all but two of these stations had daily or monthly pan-evaporation data. Only annual pan-evaporation data were available for stations 1045 and 1047, but these two stations were included in the analysis because (1) these were the only two stations meeting the other selection criteria that had an average annual rainfall value greater than 100 in., (2) the annual pan-evaporation rates are probably adequate because persistent orographic clouds reduce seasonal variations in pan-evaporation rates (Ekern and Chang, 1985), and (3) the estimated annual pan-evaporation rate at these two sites is less than 20 percent of the annual rainfall and therefore evapotranspiration is a less important component of the water budget than at drier sites. For these stations, the annual pan-evaporation total was uniformly distributed throughout the year. At station 1020.1, concurrent daily rainfall and pan-evaporation data were used. For all stations other than 1020.1, 1045, and 1047, the available daily rainfall and monthly pan-evaporation data were not from concurrent periods. At these sites, monthly pan evaporation was estimated from mean monthly pan evaporation adjusted by an annual solar radiation factor (Ekern and Chang, 1985, p. 11), and the monthly pan-evaporation total was uniformly distributed throughout the month.

Daily Water Budget

The water-budget method that was used in this study is a variant of the Thornthwaite and Mather (1955) bookkeeping procedure. For a given area, daily runoff was assumed to be a constant fraction of daily rainfall for a given month (table A2). Daily runoff was subtracted from daily rainfall, and the remaining volume was added to the beginning soil-moisture storage for the day to determine interim soil-moisture storage:

$$X_i = P_i - R_i + S_{i-1}, \qquad \text{(A1)}$$

where: X_i = interim soil-moisture storage for current day [L],
S_{i-1} = ending available soil-moisture storage from previous day (i–1), equal to the beginning available soil-moisture storage for current day (i) [L],
P_i = precipitation for current day [L],
R_i = runoff for current day [L], and
i = subscript designating current day number.

All volumes of water are expressed as an equivalent depth of water over an area by dividing by the total area. Available soil-moisture storage, expressed as a depth of water, is equal to the root depth multiplied by the difference between the existing volumetric soil-moisture content within the root zone and the volumetric wilting-point moisture content.

$$S_{i-1} = D \times (\theta_{i-1} - \theta_{wp}), \qquad \text{(A2)}$$

where: D = plant root depth [L],
θ_{i-1} = ending volumetric soil-moisture content from previous day (i–1), equal to the beginning volumetric soil-moisture content for current day (i) [L^3/L^3], and
θ_{wp} = volumetric wilting-point moisture content [L^3/L^3].

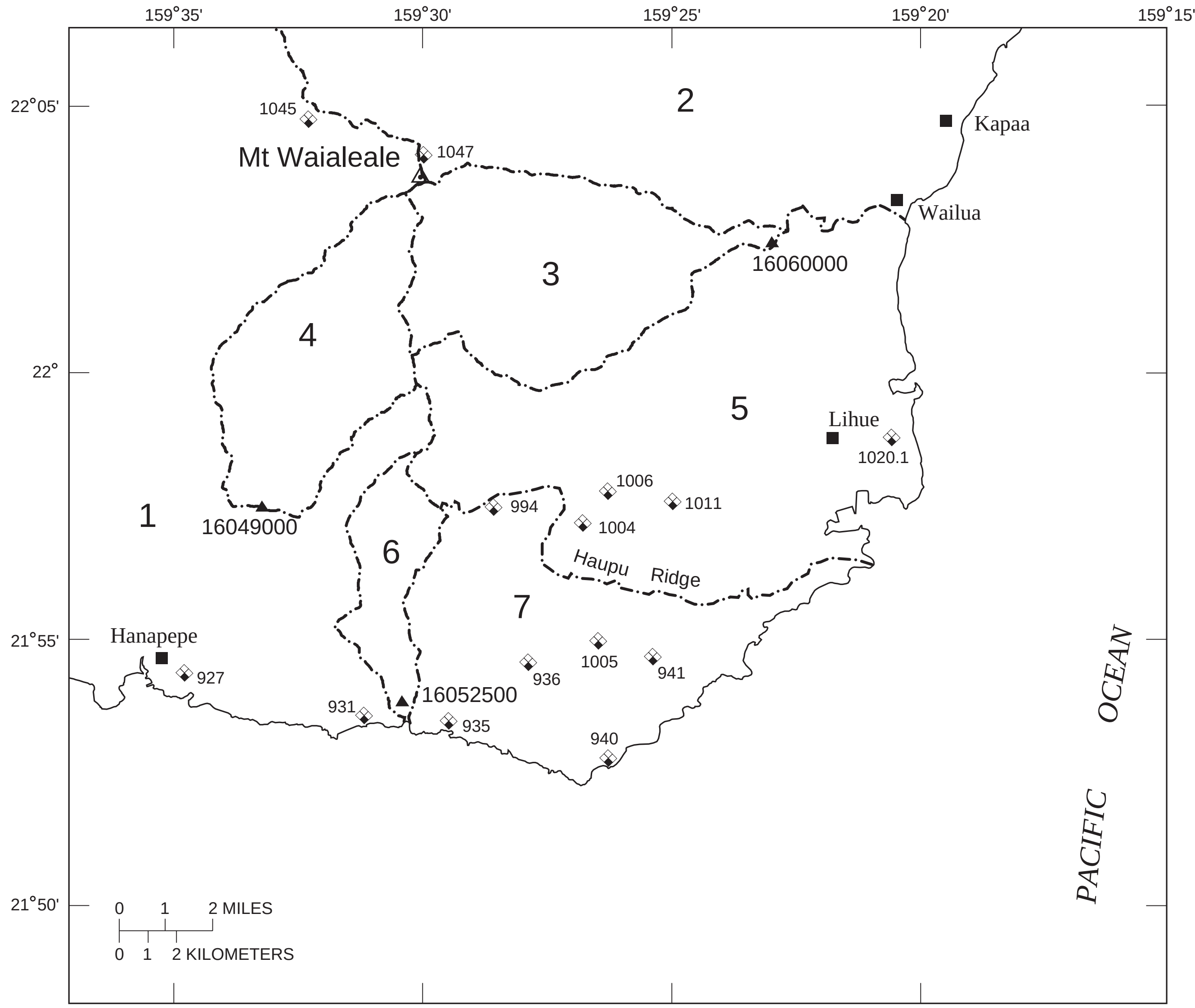
The maximum soil-moisture storage, expressed as a depth of water, is equal to the root depth multiplied by the available water capacity, which is the difference between the volumetric field-capacity moisture content and the volumetric wilting-point moisture content.

$$S_m = D\,\phi,$$

$$\phi = \theta_{fc} - \theta_{wp}, \qquad \text{(A3)}$$

where: S_m = maximum soil-moisture storage [L],
ϕ = available water capacity [L^3/L^3], and
θ_{fc} = volumetric field-capacity moisture content [L^3/L^3].

For a given day, evapotranspiration was subtracted from the interim soil-moisture storage, and any soil moisture remaining above the maximum soil-moisture storage was assumed to be recharge. Evapotranspiration



EXPLANATION

—·—·—	BOUNDARY OF AREA WITH UNIFORM RUNOFF-TO-RAINFALL RATIOS
▲16052500	STREAM-GAGING STATION AND NUMBER
◈ 1020.1	RAIN-GAGING STATION AND STATE NUMBER
1	MAP DESIGNATION OF AREA USED IN WATER-BUDGET COMPUTATION--see table A2

Figure A1. Areas with different runoff-to-rainfall ratios in the southern Lihue Basin, Kauai, Hawaii.

Table A1. Rainfall and pan-evaporation stations used in the water-budget analysis, Lihue Basin area, Kauai

Station number	Period of daily rainfall record used	Average annual rainfall[a] (inches)	Pan evaporation[b]	
			Type of data available	Average annual (inches)
927	3/1/1951-6/30/1956	35	monthly	104
931	10/1/1949-9/30/1955	43	monthly	90
935	4/1/1950-8/31/1953	37	monthly	88
936	2/1/1955-1/31/1956	82	monthly	53
940	10/1/1949-11/30/1954	37	monthly	93
941	11/1/1950-4/30/1953	62	monthly	92
994	10/1/1949-2/29/1952	91	monthly	66
1004	12/1/1951-9/30/1953	75	monthly	63
1005	2/1/1954-6/30/1956	97	monthly	75
1006	10/1/1949-8/31/1952	78	monthly	61
1011	3/1/1954-6/30/1956	81	monthly	70
1020.1	1/1/1979-11/30/1991	41	daily	99
1045	7/1/1995-9/30/1999	160	annual	30
1047	4/1/1997-9/30/1999	349	annual	30

[a] Averages for period computed from data in Hydrosphere (1996)
[b] Monthly and annual data from Ekern and Chang (1985); daily data from Hydrosphere (1996)

Table A2. Runoff-to-rainfall ratios used in the monthly and daily water budgets
[nc, not computed]

Area (fig. A1)	Ratio of runoff-to-rainfall												
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Monthly water budget													
1	0.330	0.373	0.398	0.313	0.213	0.175	0.215	0.228	0.135	0.203	0.398	0.393	nc
2	0.714	0.621	0.689	0.675	0.612	0.404	0.469	0.447	0.323	0.486	0.791	0.705	nc
3[a]	0.639	0.457	0.550	0.444	0.369	0.251	0.280	0.303	0.307	0.338	0.545	0.547	0.43
4[b]	0.376	0.485	0.505	0.383	0.320	0.284	0.343	0.350	0.247	0.266	0.406	0.420	0.37
5	0.595	0.518	0.638	0.635	0.580	0.403	0.383	0.360	0.358	0.440	0.698	0.613	nc
6[c]	0.251	0.241	0.185	0.274	0.123	0.070	0.057	0.059	0.070	0.056	0.283	0.311	0.18
7	0.595	0.518	0.638	0.635	0.580	0.403	0.383	0.360	0.358	0.440	0.698	0.613	nc
Daily water budget													
1[d,f]	0.315	0.406	0.423	0.321	0.268	0.238	0.287	0.293	0.207	0.223	0.340	0.352	nc
1[e,f]	0.167	0.161	0.123	0.183	0.082	0.047	0.038	0.039	0.047	0.037	0.189	0.207	nc
2	0.654	0.468	0.563	0.454	0.378	0.257	0.287	0.310	0.314	0.346	0.558	0.560	nc
3	0.654	0.468	0.563	0.454	0.378	0.257	0.287	0.310	0.314	0.346	0.558	0.560	0.44
4	0.315	0.406	0.423	0.321	0.268	0.238	0.287	0.293	0.207	0.223	0.340	0.352	0.31
5	0.654	0.468	0.563	0.454	0.378	0.257	0.287	0.310	0.314	0.346	0.558	0.560	nc
6	0.167	0.161	0.123	0.183	0.082	0.047	0.038	0.039	0.047	0.037	0.189	0.207	0.12
7	0.167	0.161	0.123	0.183	0.082	0.047	0.038	0.039	0.047	0.037	0.189	0.207	nc

[a] area 3 corresponds to the drainage basin for station 16060000
[b] area 4 corresponds to the drainage basin for station 16049000
[c] area 6 corresponds to the drainage basin for station 16052500
[d] runoff-to-rainfall ratios from area 4
[e] runoff-to-rainfall ratios from area 6
[f] for area 1, runoff-to-rainfall ratios from areas 4 and 6 were used to compute recharge with a daily water budget, and the average recharge value was used

was determined as a function of potential evapotranspiration and soil moisture. At all sites, potential evapotranspiration was assumed to be equal to pan evaporation. For soil-moisture contents greater than or equal to a threshold value, C_i, the rate of evapotranspiration was assumed to be equal to the potential evapotranspiration rate. For soil-moisture contents below C_i, the rate of evapotranspiration was assumed to occur at a reduced rate that declines linearly with soil-moisture content:

for $S \geq C_i$,

$$E = PE_i,$$

and for $S < C_i$,

$$E = S \times PE_i / C_i, \qquad \text{(A4)}$$

where: E = instantaneous rate of evapotranspiration [L/T],
PE_i = potential evapotranspiration rate for current day [L/T],
S = instantaneous soil moisture [L], and
C_i = threshold soil-moisture content below which evapotranspiration is reduced below the potential evapotranspiration rate [L].

The threshold soil moisture, C_i, was estimated from a model having the form:

for $[a + bD + cPE_i] < 1$,

$$C_i = [a + bD + cPE_i] \times S_m,$$

and for $[a + bD + cPE_i] \geq 1$,

$$C_i = S_m. \qquad \text{(A5)}$$

The calibration coefficients a, b, and c were determined by Giambelluca (1983) on the basis of lysimeter studies from Hawaii (Ekern, 1966). For D expressed in mm, and PE_i expressed in mm per day, the calibration coefficients were determined to be:

for $PE_i \leq 6$ mm/d,
$a = 1.25$,
$b = -1.87 \times 10^{-3}$,
$c = 5.20 \times 10^{-2}$,

and for $PE_i > 6$ mm/d,
$a = 1.41$,
$b = -1.87 \times 10^{-3}$,
$c = 2.20 \times 10^{-2}$.

By recognizing that $E = -dS/dt$, the total depth of water lost to evapotranspiration during a day, E_i, was determined as:

for $X_i > C_i$, $t_i < 1$,

$$E_i = PE_i t_i + C_i\{1\text{-}\exp[-PE_i(1\text{-}t_i)/C_i]\},$$

for $X_i > C_i$, $t_i \geq 1$,

$$E_i = PE_i\ ,$$

and for $X_i \leq C_i$,

$$E_i = X_i\{1\text{-}\exp[-PE_i/C_i]\}, \qquad \text{(A6)}$$

where: E_i = depth of water lost to evapotranspiration during the day [L], and
$t_i = (X_i - C_i)/PE_i$, which is the time during which soil moisture storage is above C_i [T].

Recharge and soil-moisture storage at the end of a given day were assigned according to the following equations:

for $X_i - E_i \leq S_m$,

$$Q_i = 0,$$

$$S_i = X_i - E_i, \qquad \text{(A7)}$$

and for $X_i - E_i > S_m$,

$$Q_i = X_i - E_i - S_m,$$

$$S_i = S_m, \qquad \text{(A8)}$$

where: Q_i = ground-water recharge during the day [L], and
S_i = soil-moisture storage [L] at the end of the current day, i.

Monthly Water Budget

The monthly water-budget method used for this study was identical to the method described by Shade (1995b). Daily rainfall data from the selected stations (table A1) were aggregated into monthly values, and these monthly values were used as input to the monthly water budget. Unlike the daily water budget, the monthly water budget was computed by assuming that recharge occurs before evapotranspiration. In addition, evapotranspiration was assumed to occur at the potential evapotranspiration rate for soil moisture above the wilting point, and was assumed to be zero for soil moisture below the wilting point. Monthly runoff, assumed to be a constant fraction of monthly rainfall (table A2), was subtracted from monthly rainfall, and this volume was added to the beginning soil-moisture storage for the month to determine interim soil-moisture storage:

$$X_j = P_j - R_j + S_{j-1}, \qquad \text{(A9)}$$

where: X_j = interim soil-moisture storage for current month [L],
S_{j-1} = ending soil-moisture storage from previous month (j–1), equal to the beginning soil-moisture storage for current month (j) [L],
P_j = precipitation for current month [L],
R_j = runoff for current month [L], and
j = subscript designating current month number.

All volumes of water are expressed as an equivalent depth of water over an area by dividing by the total area. Recharge was assumed to occur only for interim soil-moisture storage values in excess of the maximum soil-moisture storage, S_m:

for $X_j \le S_m$,

$$Q_j = 0,$$

and for $X_j > S_m$,

$$Q_j = X_j - S_m, \qquad \text{(A10)}$$

where: Q_j = ground-water recharge during the month [L].

In the monthly water budget, evapotranspiration was assigned last and was determined as a function of potential evapotranspiration and available soil moisture:

for $X_j - Q_j < PE_j$,

$$E_j = X_j - Q_j,$$

$$S_j = 0,$$

and for $X_j - Q_j \ge PE_j$,

$$E_j = PE_j,$$

$$S_j = X_j - Q_j - PE_j, \qquad \text{(A11)}$$

where: E_j = evapotranspiration during the current month [L],
PE_j = potential evapotranspiration for the current month [L], and
S_j = ending soil-moisture storage for the current month (j) [L].

Runoff-to-Rainfall Ratios

Essential to the determination of direct runoff and runoff-to-rainfall ratios is the separation of base flow from total flow measured at a stream gage. A commonly used method of determining base flow is to conduct a flow-duration analysis and assume that base flow is equal to the discharge that is equaled or exceeded 90 percent of the time (known as Q90). Shade (1995b) used this method to determine base flow for the water budget on which the recharge for the southern Lihue Basin model is based. However, the use of Q90 is arbitrary, and may not be appropriate for all drainage basins. Izuka and Gingerich (1998a) estimated base flow for selected streams in the Lihue Basin using a hydrograph-separation computer program by Wahl and Wahl (1995). For U.S. Geological Survey gages 16049000 (Hanapepe River), 16052500 (Lawai Stream), and 16060000 (South Fork Wailua River), mean annual runoff-to-rainfall ratios computed using the base flows from Izuka and Gingerich (1998a) differ from the runoff-to-rainfall ratios computed by Shade (1995b).

To relate the recharge estimates from Shade (1995b) to recharge estimates from a daily water budget, it was necessary to retain the runoff-to-rainfall ratios from Shade (1995b) (table A2) in the monthly water budget used in this analysis. However, for the daily water budget, the original runoff-to-rainfall ratios (Shade, 1995b) were adjusted to reflect more recent estimates of base flow (Izuka and Gingerich, 1998a). For the drainage basin of station 16049000, the annual runoff-to-rainfall ratio determined by Shade (1995b) is 0.37, whereas the annual runoff-to-rainfall ratio using the base-flow estimate from Izuka and Gingerich (1998a) is 0.31. For the drainage basin of station 16049000, the monthly ratios of runoff-to-rainfall from Shade (1995b) were multiplied by a factor of 31/37 to reflect the more recent base-flow estimates. Similarly, for the drainage basins of stations 16052500 and

16060000, the monthly ratios of runoff-to-rainfall from Shade (1995b) were multiplied respectively by factors of 12/18 and 44/43. In ungaged areas or areas where Izuka and Gingerich (1998a) did not estimate base flow, runoff-to-rainfall ratios were assumed to be the same as in adjacent gaged basins in similar climatologic settings (fig. A1, table A2). Thus, areas 2 and 5 (fig. A1) on the windward side of Kauai were assigned the same runoff-to-rainfall ratios as the drainage basin for gage 16060000 (area 3), which is also on the windward side. Area 7, which lies leeward of Haupu Ridge, was assigned the same runoff-to-rainfall ratio as the drainage basin for gage 16052500 (area 6). For area 1 in figure A1, runoff-to-rainfall ratios from areas 4 and 6 (basins of gages 16049000 and 16052500, respectively) were used to compute two different recharge distributions, and the two distributions were averaged.

Comparison of Recharge from Daily and Monthly Water Budgets

For each of the gaged and ungaged areas (fig. A1) in the vicinity of the Lihue Basin, daily and monthly water budgets were computed using all of the selected rainfall and pan-evaporation data (table A1) and the appropriate runoff-to-rainfall ratios for the area (table A2). Within the Lihue Basin area, maximum soil-moisture storage values are generally about 1 to 3 in. (Shade, 1995b), thus, the daily and monthly water budgets were computed for maximum soil-moisture storage values of 1, 2, and 3 in. Maximum soil-moisture storage in the daily budget is the product of available water capacity and root depth (equation A3). For each value of maximum soil-moisture storage tested, available-water-capacity values of 0.10, 0.13, and 0.16 were used in the daily water budget. The root depths were adjusted such that the desired maximum soil-moisture storage values of 1, 2, and 3 in. were obtained.

Estimated annual recharge from the daily and monthly water budgets were compared for each of the gaged and ungaged areas in the vicinity of the Lihue Basin (fig. A2). Using the water-budget methods described above, the total recharge from a daily water budget will be less than the total recharge from a monthly budget, given the same runoff-to-rainfall ratios. In some areas, the runoff-to-rainfall ratios used in the daily budget were less than the ratios used in the monthly budget. For this condition, total recharge from a daily budget could exceed the total recharge from a monthly budget.

Each of the relations between annual recharge computed from a daily budget and annual recharge computed from a monthly budget were generalized by fitting (least-square error) a second-degree polynomial curve to the data (fig. A2). The appropriate second-degree polynomial equation was used to adjust the original annual recharge estimates (computed from a monthly budget) in the Lihue model grid. For each model cell, given the annual recharge estimate from a monthly water budget, the corresponding annual recharge estimate from a daily water budget was determined by using the appropriate second-degree polynomial equation appropriate for the area in which the model cell was located. By applying the appropriate equations, total recharge over the modeled area was estimated to be 149 Mgal/d, which is 23 percent lower than the original estimate of 191 Mgal/d.

Fog Drip

Cloud vapor that is intercepted by vegetation and drips to the ground, also known as fog drip, can be a significant component of the water budget in an area (see for example Ekern, 1964; Juvik and Ekern, 1978). Ekern (1983) collected fog on the leeward side of the Koolau Range on the island Oahu, and his data indicate a fog-to-rain ratio of 0.06. On the windward side of Mauna Loa on the island of Hawaii, the average annual fog-to-rain ratio at an altitude of about 5,000 ft was 0.30 (Juvik and Ekern, 1978). However, average annual rainfall at the Mauna Loa site was about 100 in., which is considerably less than annual rainfall at comparable altitudes on Kauai. For wet months with rainfall exceeding 20 in., the fog-to-rain ratio at the Mauna Loa site ranged from 0.17 to 0.19, which is lower than the average annual value (Juvik and Ekern, 1978).

No fog-collection studies are available for the island of Kauai. For this study, fog drip was assumed to occur above an altitude of 2,000 ft, which is consistent with data from Oahu (Ekern, 1983). The fog-to-rain ratio above an altitude of 2,000 ft was assumed to decrease from the windward to leeward side of the island crest (fig. A3). Because of the uncertainty in fog-drip estimates for Kauai, upper and lower estimates for the fog-to-rain ratio were tested. For the lower estimate, fog-to-rain ratios of 0.03 and 0.10 were used for

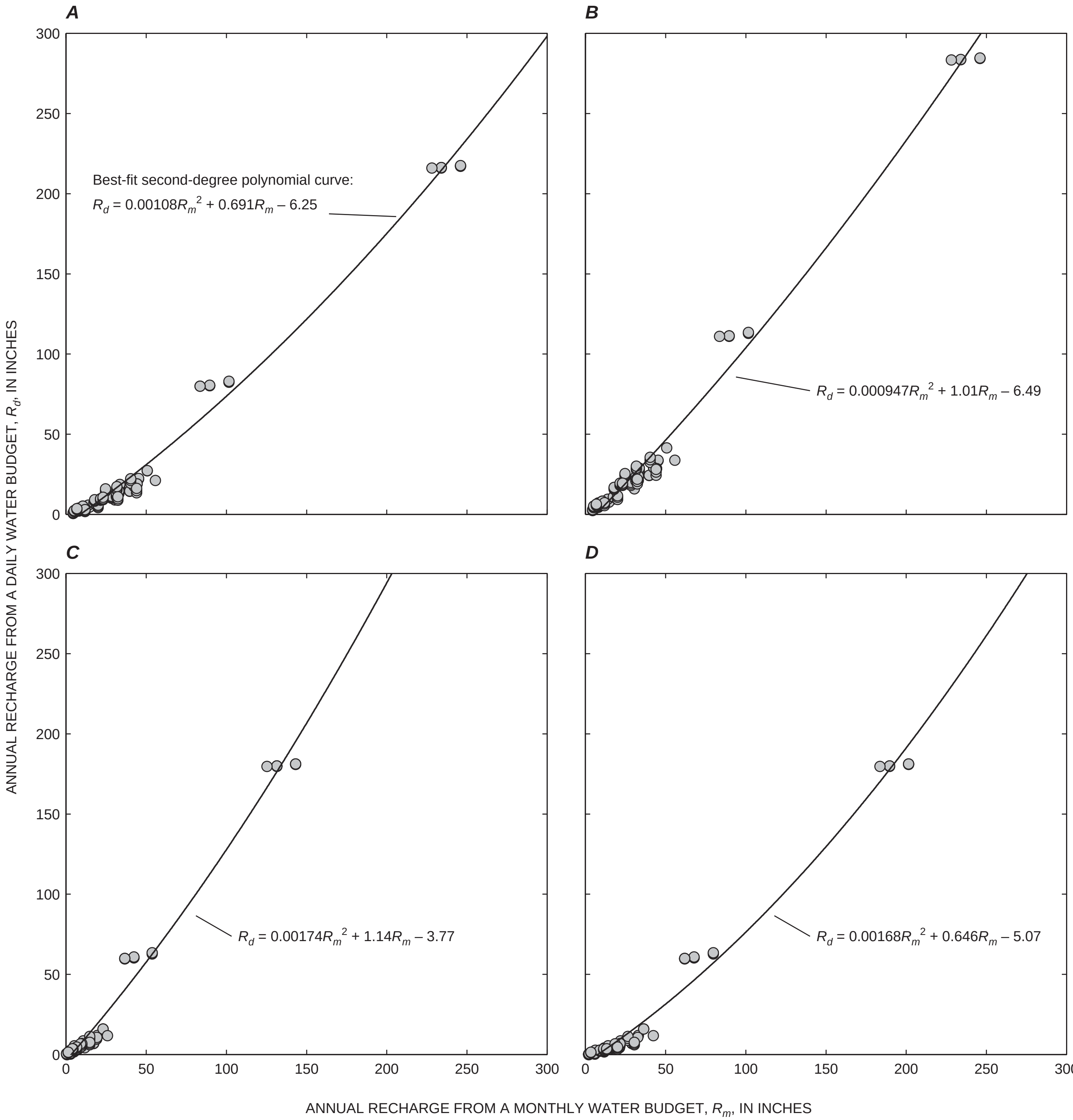


Figure A2. Relation between recharge from a monthly water budget and recharge from a daily water budget for the Lihue Basin area, Kauai, Hawaii using various runoff-to-rainfall ratios: (***A***) area 1 with runoff-to-rainfall ratios in the daily water budget from area 4; (***B***) area 1 with runoff-to-rainfall ratios in the daily water budget from area 6; (***C***) area 2; (***D***) area 3; (***E***) area 4; (***F***) area 5; (***G***) area 6; and (***H***) area 7. Areas 1 to 7 are shown in figure A1, and runoff-to-rainfall ratios are given in table A2.

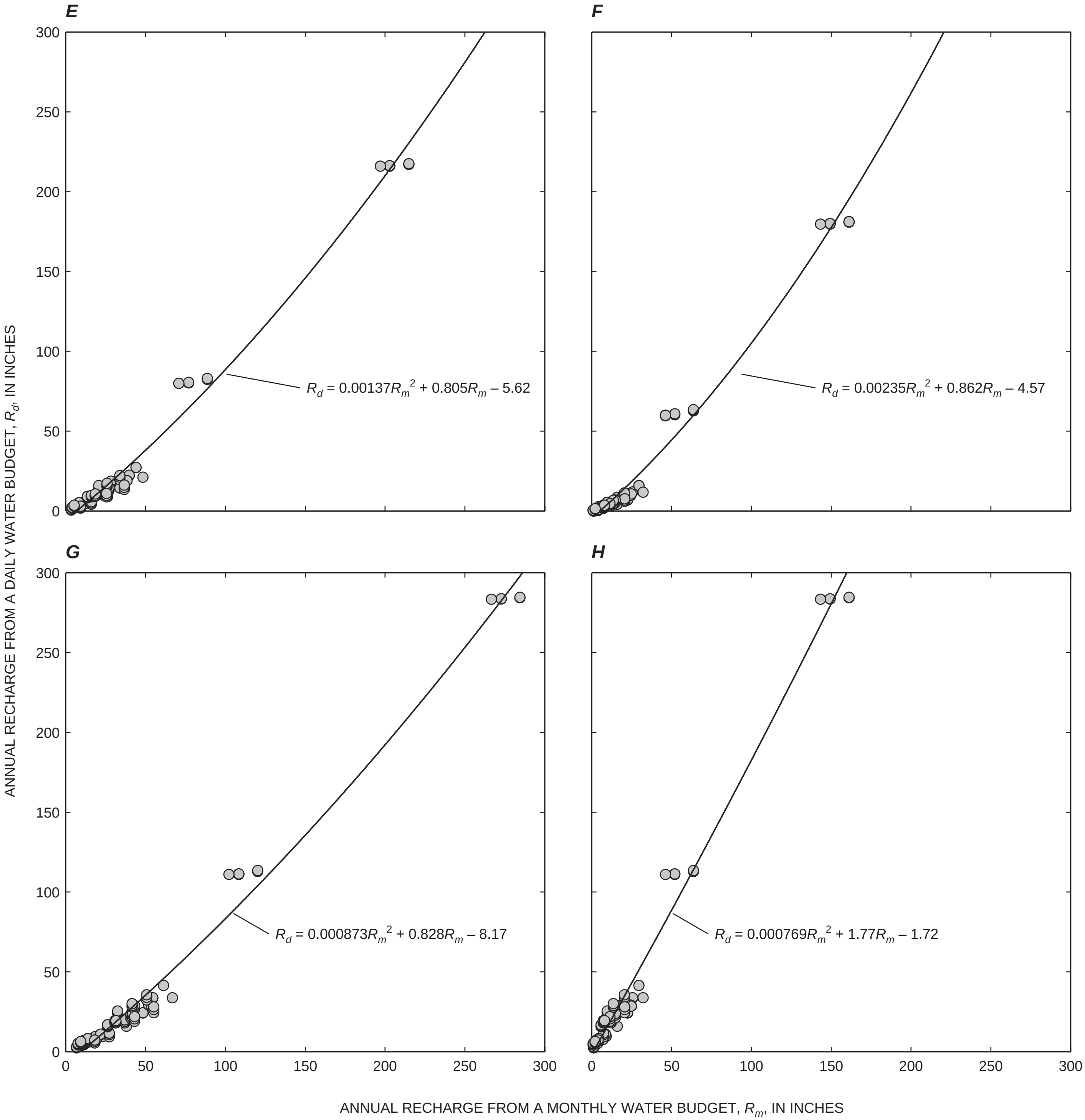
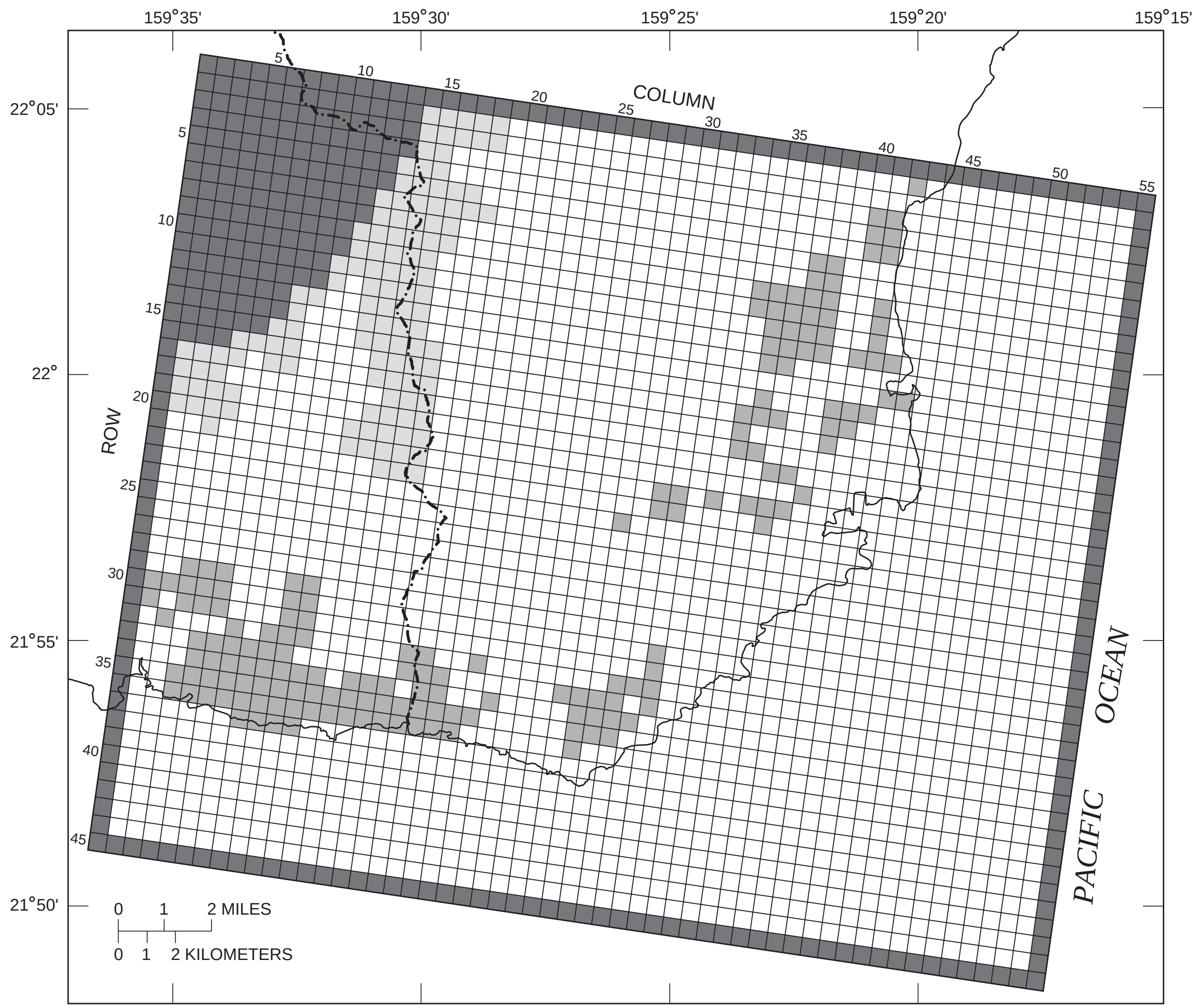


Figure A2. Relation between recharge from a monthly water budget and recharge from a daily water budget for the Lihue Basin area, Kauai, Hawaii using various runoff-to-rainfall ratios: (***A***) area 1 with runoff-to-rainfall ratios in the daily water budget from area 4; (***B***) area 1 with runoff-to-rainfall ratios in the daily water budget from area 6; (***C***) area 2; (***D***) area 3; (***E***) area 4; (***F***) area 5; (***G***) area 6; and (***H***) area 7. Areas 1 to 7 are shown in figure A1, and runoff-to-rainfall ratios are given in table A2--*Continued*.



EXPLANATION

MODEL CELL

- Fog drip
- Irrigated agriculture
- No fog drip or irrigation
- No-flow boundary
- ISLAND CREST AND DRAINAGE DIVIDE

Figure A3. Cells with fog drip and irrigation recharge added to recharge used in original ground-water flow model of the southern Lihue Basin, Kauai, Hawaii.

leeward and windward areas, respectively. For the upper estimate, fog-to-rain ratios of 0.06 and 0.15 were used for leeward and windward areas, respectively.

Fog drip was computed for each model cell above an altitude of 2,000 ft from the product of mean annual rainfall (Giambelluca and others, 1986) and the assumed fog-to-rain ratio. Because annual rainfall in the model cells above an altitude of 2,000 ft is generally more than twice the annual pan-evaporation rate, it was assumed that rainfall is sufficient to meet the evaporative demand and that all of the fog drip contributes to recharge. Estimated recharge from fog drip in the modeled area ranges from 11.8 to 19.2 Mgal/d.

Evapotranspiration in Irrigated Areas

In the original monthly water budget for Kauai (Shade, 1995b), evapotranspiration and recharge in irrigated sugarcane areas were computed in two steps. First, a monthly water budget that accounted for rainfall but not irrigation was computed, and then additional recharge and evapotranspiration were estimated from the volume of applied irrigation water. The additional evapotranspiration associated with the applied irrigation water was set equal to potential evapotranspiration in irrigated sugarcane areas. The additional recharge associated with the applied irrigation water was then computed from the difference between applied irrigation water and potential evapotranspiration. This computational procedure can lead to overestimation of evapotranspiration in irrigated sugarcane for two reasons: (1) summing evapotranspiration associated with rainfall and potential evapotranspiration associated with irrigation in the same area applies the evapotranspiration effect twice on the water budget for that area, and (2) the assumption that evapotranspiration is equal to the potential rate is only valid if water is always available for crop use, which may not be true on a day-to-day basis.

Because evapotranspiration appears to be overestimated in the irrigated areas, recharge should be increased by an amount equal to the overestimated evapotranspiration. The increase in recharge in the irrigated areas should be at least equal to the estimated evapotranspiration from the monthly water budget that accounts for rainfall and not irrigation. (An additional increase could be justified on the basis that evapotranspiration may not occur at the potential rate.) In the monthly water budget (Shade, 1995b), the maximum monthly evapotranspiration is equal to the maximum soil-moisture storage. Within the Lihue Basin area, the maximum soil-moisture storage in irrigated areas generally is 2 in. or more. For a maximum soil-moisture storage value of 2 in., the maximum annual evapotranspiration rate would be 24 in. For values of maximum soil-moisture storage greater than 2 in., the maximum annual evapotranspiration rate would be greater than 24 in. In the monthly water budget without irrigation, the monthly evapotranspiration is probably less than the maximum soil-moisture storage value because low monthly rainfall may limit evapotranspiration.

Because it was not possible to verify the original evapotranspiration estimates associated with rainfall in irrigated areas (Shade, 1995b), a lower and upper estimate was used for this study. For the irrigated areas, estimated lower and upper values for evapotranspiration were 6 and 24 in., respectively. Thus, annual recharge in model cells representing irrigated areas (fig. A3) was increased by either 6 or 24 in. The estimated increase in recharge in irrigated areas ranges from 6.4 to 25.7 Mgal/d.

Results and Discussion

A number of sources of uncertainty in the original recharge estimate of 191 Mgal/d for the modeled Lihue Basin area were identified in this study. Total recharge over the modeled area was estimated to range from 167 to 194 Mgal/d after accounting for (1) differences between a daily water budget and a monthly water budget, (2) the most recent runoff-to-rainfall ratio estimates, (3) fog drip, and (4) overestimation of evapotranspiration in irrigated areas in the original water budget (Shade, 1995b). The adjusted recharge values range from 13 percent lower to 2 percent higher than the original 191 Mgal/d estimate for the modeled area (Izuka and Gingerich, 1998a). Although the adjusted recharge values should not be viewed as rigorously derived estimates, it does appear that the originally estimated recharge value of 191 Mgal/d is reasonable. A daily water budget computed over the Lihue Basin area would provide a refined estimate of recharge.