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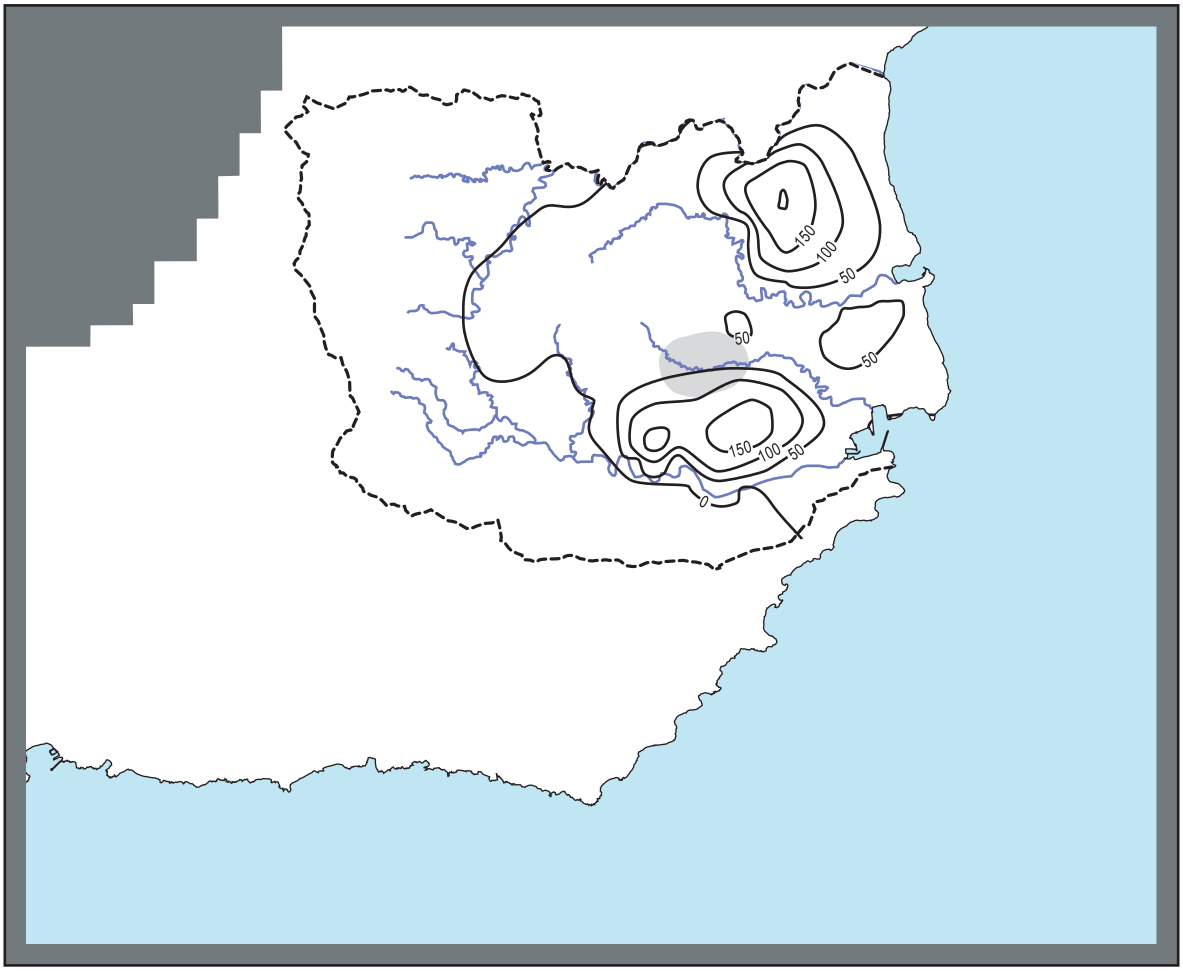
Effects of Irrigation, Drought, and Ground-Water Withdrawals on Ground-Water Levels in the Southern Lihue Basin, Kauai, Hawaii



Scientific Investigations Report 2006–5291

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

COVER

Simulated difference in ground-water levels between pre-development and 1981 conditions in the southern Lihue Basin, Kauai, Hawaii.

Effects of Irrigation, Drought, and Ground-Water Withdrawals on Ground-Water Levels in the Southern Lihue Basin, Kauai, Hawaii

By Scot K. Izuka

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U.S. Department of the Interior
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Contents

Figures

Tables

Conversion Factors

Multiply	By	To obtain
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

Vertical coordinate information is referenced to mean sea level.

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

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

Effects of Irrigation, Drought, and Ground-Water Withdrawals on Ground-Water Levels in the Southern Lihue Basin, Kauai, Hawaii

By Scot K. Izuka

Abstract

A numerical ground-water-flow model was used to investigate the effects of irrigation on ground-water levels in the southern Lihue Basin, Kauai, Hawaii, and the relation between declining ground-water levels observed in the basin in the 1990s and early 2000s and concurrent drought, irrigation reduction, and changes in ground-water withdrawal. Results of steady-state model simulations indicate that changing from pre-development to 1981 irrigation and ground-water-withdrawal conditions could, given enough time for steady state to be achieved, raise ground-water levels in some areas of the southern Lihue Basin by as much as 200 feet, and that changing from 1981 to 1998 irrigation and ground-water-withdrawal conditions could lower ground-water levels in some areas by as much as 100 feet. Transient simulations combining drought, irrigation reduction, and changes in ground-water withdrawal show trends that correspond with those observed in measured water levels.

Results of this study indicate that irrigation reduction was the primary cause of the observed decline in ground-water-levels. In contrast, ground-water withdrawal had a long-duration but small-magnitude effect, and drought had a widespread, high-magnitude but short-duration effect. Inasmuch as irrigation in the future is unlikely to return to the same levels as during the period of peak sugarcane agriculture, the decline in ground-water levels resulting from the reduction and ultimate end of sugarcane irrigation can be considered permanent. Assuming that irrigation does not return to the southern Lihue Basin and that, on average, normal rainfall persists and ground-water withdrawal remains at 1998 rates, model projections indicate that average ground-water levels in the Kilohana-Puhi area will continue to recover from the drought of 1998–2002 and eventually rise to within about 4 feet of the pre-drought conditions. Long-term climate trends, increases in ground-water withdrawal, or other factors not simulated in the model could also affect ground-water levels in the southern Lihue Basin in the future.

Introduction

About 31,000 people reside in the Lihue Basin, Kauai, Hawaii (fig. 1; U.S. Census Bureau, 2006). Most of the public drinking water in the basin comes from wells and tunnels that develop ground water from a volcanic-rock aquifer, much of which has a low regional permeability (Izuka and Gingerich, 1998). Ground-water levels in the Lihue Basin showed declining trends in the late 1990s and early 2000s. The declining water levels resulted in diminished yield from some wells and water tunnels, and raised questions about the causes of the decline and concerns about the future reliability of ground-water resources.

The observed decline in ground-water levels in the Lihue Basin was approximately concurrent with events that could have affected ground-water recharge, including a drought from 1998 to 2002 and a decrease in the volume of water diverted from surface-water sources for irrigation between 1981 and 2000. Analysis of the water budget of the Lihue Basin indicates that both events caused a substantial reduction in ground-water recharge (Izuka and others, 2005). The water-budget analysis did not, however, directly assess whether the recharge reductions actually caused the decline in ground-water levels that was observed in Lihue Basin wells in the late 1990s and early 2000s. Increases in ground-water withdrawals may also have contributed to this decline.

Ground-water-modeling studies in the Lihue Basin have shown that the introduction of a new production well may cause ground-water levels to continue to decline for decades before a new equilibrium is reached (Izuka and Oki, 2002). Therefore, wells that began production as early as the 1970s could have contributed to the decline in ground-water levels that was observed in the 1990s. Most of the highly productive wells in the Kilohana-Puhi well field (fig. 1) were constructed after 1970. Determining whether increases in ground-water withdrawals, reduction in ground-water recharge, or both were the primary cause of the observed decline in ground-water levels requires a comprehensive method of analysis, such as a numerical ground-water-flow model, that simultaneously considers these factors together with the hydrogeology of the basin.

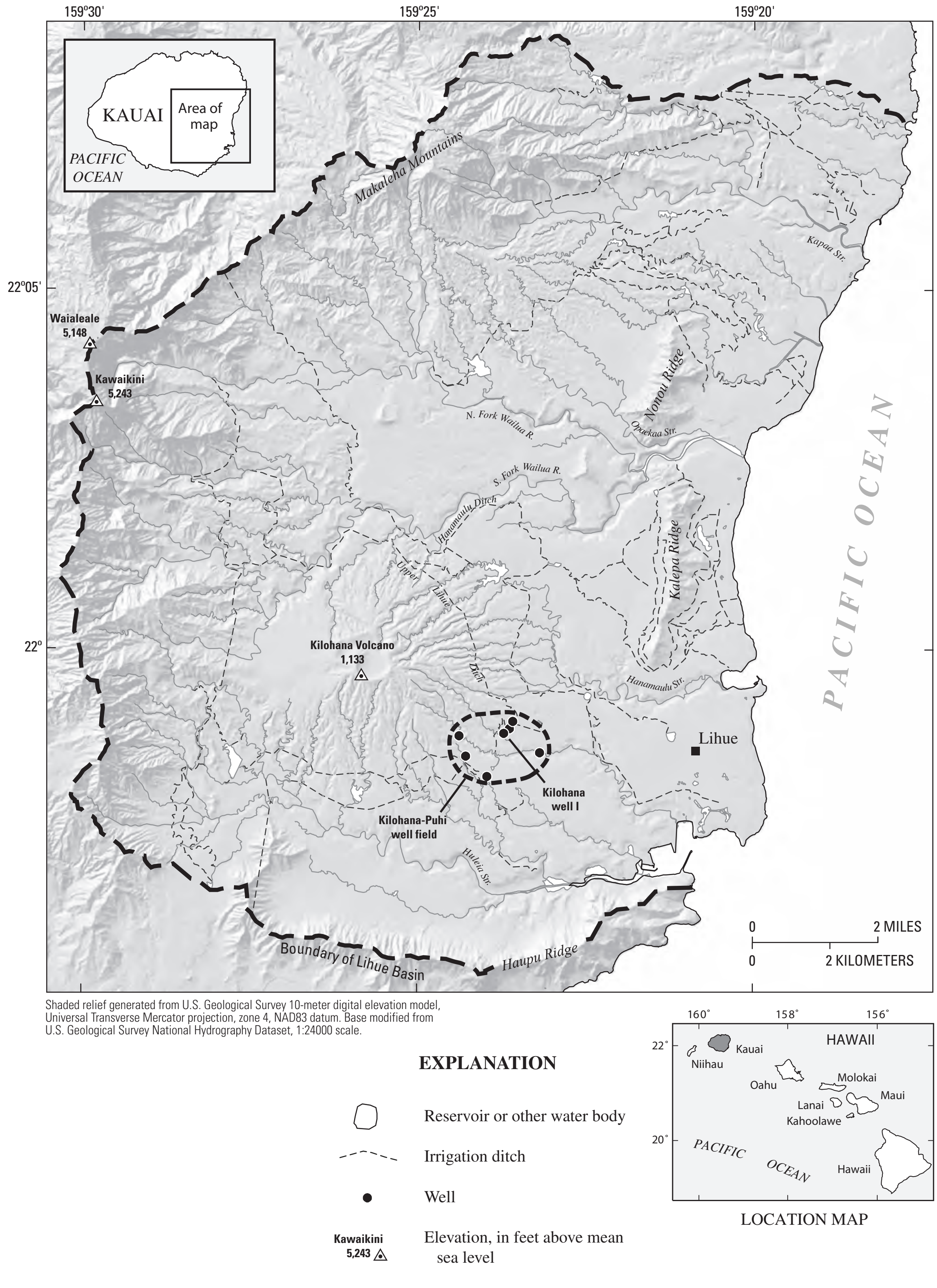


Figure 1. The Lihue Basin, Kauai, Hawaii.

Purpose and Scope

This report describes the results of a study, undertaken by the U.S. Geological Survey (USGS) in cooperation with the County of Kauai Department of Water (Kauai DOW), to assess the effects of drought, irrigation changes, and ground-water withdrawals on ground-water levels in the southern Lihue Basin. The southern Lihue Basin is the part of the basin that lies south of the South Fork Wailua River (fig. 1). A numerical ground-water model of the southern Lihue Basin was developed by Izuka and Gingerich (1998) and modified by Izuka and Oki (2002).

In this study, ground-water recharge estimates of Izuka and others (2005) and updated ground-water-withdrawal data were incorporated into the existing model of the southern Lihue Basin. This study addresses (1) whether the timing and location of the recharge reduction are consistent with the observed decline in ground-water levels, considering the rate of aquifer response to pumping and recharge stresses; and (2) the degree to which changes in ground-water withdrawals also contributed to the observed decline in ground-water levels. The study also looked backward historically to address how a century of irrigation in the southern Lihue Basin had altered the ground-water levels from pre-development conditions, and forward into the future to assess how ground-water levels will respond to the absence of irrigation.

Acknowledgments

Wynne Ushigome, acting Manager and Chief Engineer, Edward Tschupp, former Manager and Chief Engineer, and the staff of the Kauai DOW provided critical support for this study. The State of Hawaii Commission on Water Resource Management (CWRM) provided data on ground-water withdrawals. Delwyn S. Oki, Randall T. Hanson, and Connie M. Hoong of the USGS assisted in the preparation of this report.

Setting

The Lihue Basin is a 127-mi^2 semicircular depression on the eastern flank of Kauai, the fourth-largest (553 mi^2) island in the tropical North Pacific archipelago of Hawaii (fig. 1). The Lihue Basin is bounded on the west by the high central mountains of Kauai, which include the highest point on Kauai (Kawaikini Peak, elevation 5,243 ft), on the north by the Makaleha Mountains, on the south by Haupu Ridge, and on the east by the Pacific Ocean. A chain of smaller ridges, including Kalepa Ridge (elevation 708 ft) and Nonou Ridge (elevation 1,241 ft), lie near the eastern coast. In the south-central part of the basin lies the broad, dome-shaped Kilohana Volcano, which rises to an elevation of 1,133 ft.

Rainfall distribution in the Lihue 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. Rainfall averages range from about 50 in/yr in low-lying coastal areas to more than 400 in/yr near the crest of the central mountains (Giambelluca and others, 1986). Numerous perennial streams drain the Lihue Basin, especially near Kilohana Volcano, where many small streams flow radially off the flanks of the volcano (fig. 1). Most small streams, however, coalesce with a few principal watercourses, including Huleia Stream, Hanamaulu Stream, the Wailua River, and Kapaa Stream, before discharging into the Pacific Ocean.

From the late 19th through 20th centuries, much of the Lihue Basin was used for sugarcane agriculture. At its peak, the sugarcane industry in the basin diverted tens of billions of gallons of stream water to irrigate fields in the drier parts of the basin (Shade, 1995; Wilcox, 1996; Izuka and others, 2005). The water was diverted, transferred, and stored in a network of ditches, tunnels, and reservoirs that not only redistributed water within the Lihue Basin but also brought water in from, and took water out to, adjacent basins (fig. 1). Thus, throughout most of the 20th century, the natural drainage pattern of the Lihue Basin had been modified into a network of natural stream channels crossed by irrigation ditches, and in some areas, natural rainfall was supplemented by irrigation water (fig. 3). Hawaii's sugarcane industry began to decline in the 1970s, and by the end of the 20th century, sugarcane was being grown commercially in Hawaii only on Kauai and Maui. Sugarcane agriculture in the Lihue Basin ceased at the end of 2000, marking the end of sugarcane irrigation and a significant change in the water budget of the Lihue Basin.

Hydrogeology

The geology of Kauai and the Lihue Basin has been described by research spanning several decades, including studies by Stearns (1946, 1985), Macdonald and others (1960), Langenheim and Clague (1987), Clague and Dalrymple (1988), Holcomb and others, (1997), and Reiners and others (1999), which are summarized here. The bulk of Kauai was built by mid-oceanic-plate, hotspot volcanism that created one or more large shield volcanoes during the Miocene and Pliocene. Subsequent erosion and faulting of the shield volcanoes created large valleys, canyons, and other depressions, including the Lihue Basin. The eroded and faulted surface was partly filled with sediment and lava flows from rejuvenated-stage volcanism during the late Pliocene and Pleistocene. The rocks of rejuvenated-stage volcanism cover most of the surface of the Lihue Basin (fig. 4). Rejuvenated-stage volcanic vents generally follow two linear trends (fig. 5), one essentially north-south and the other approximately N. 60° E., that presumably correspond to rifts through which magma rose to supply the rejuvenated-stage eruptions.

The origin of the Lihue Basin remains enigmatic. Stearns (1946, 1985) attributed its formation to advanced stream erosion, whereas later researchers (for example, Macdonald and

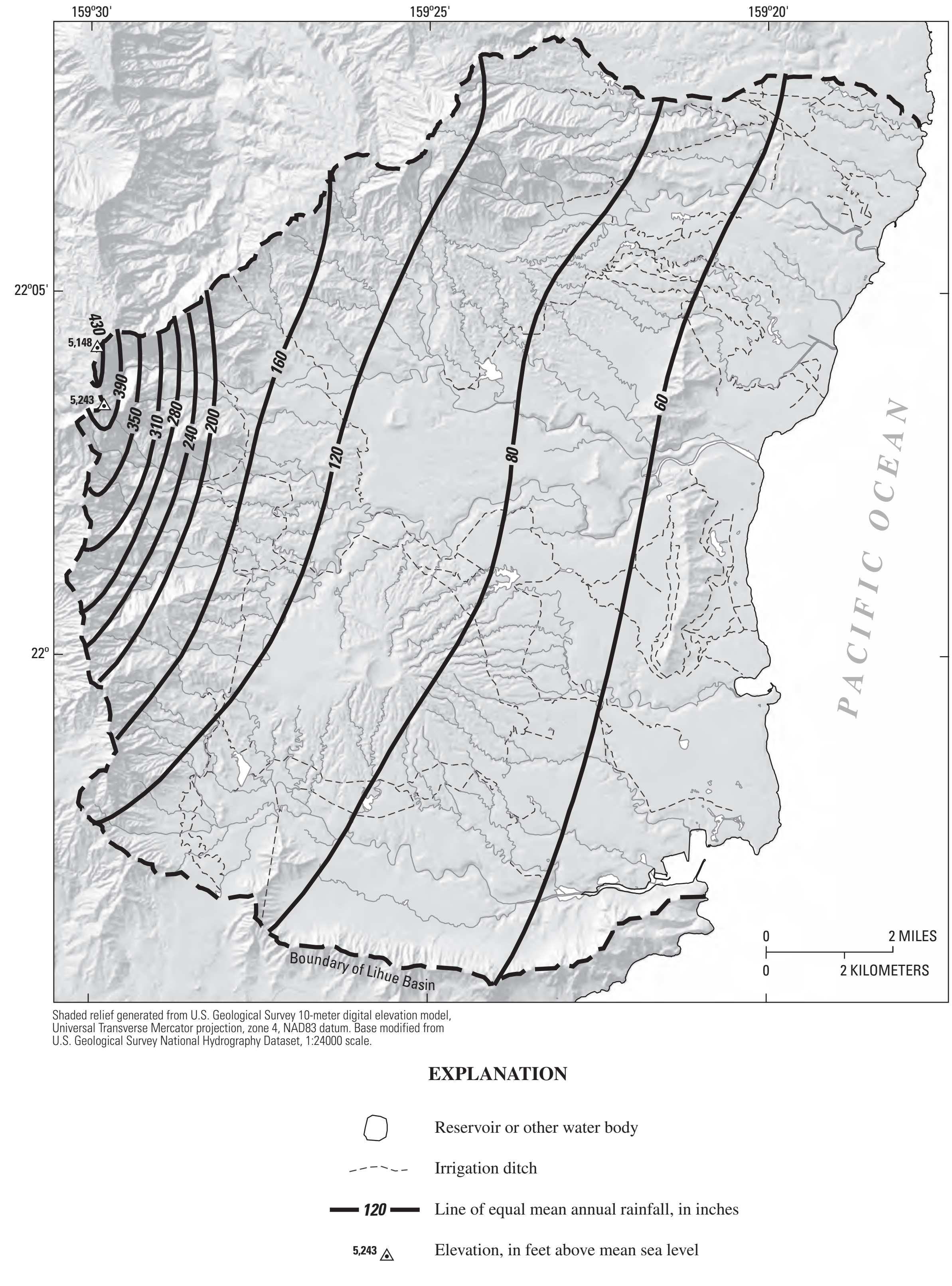
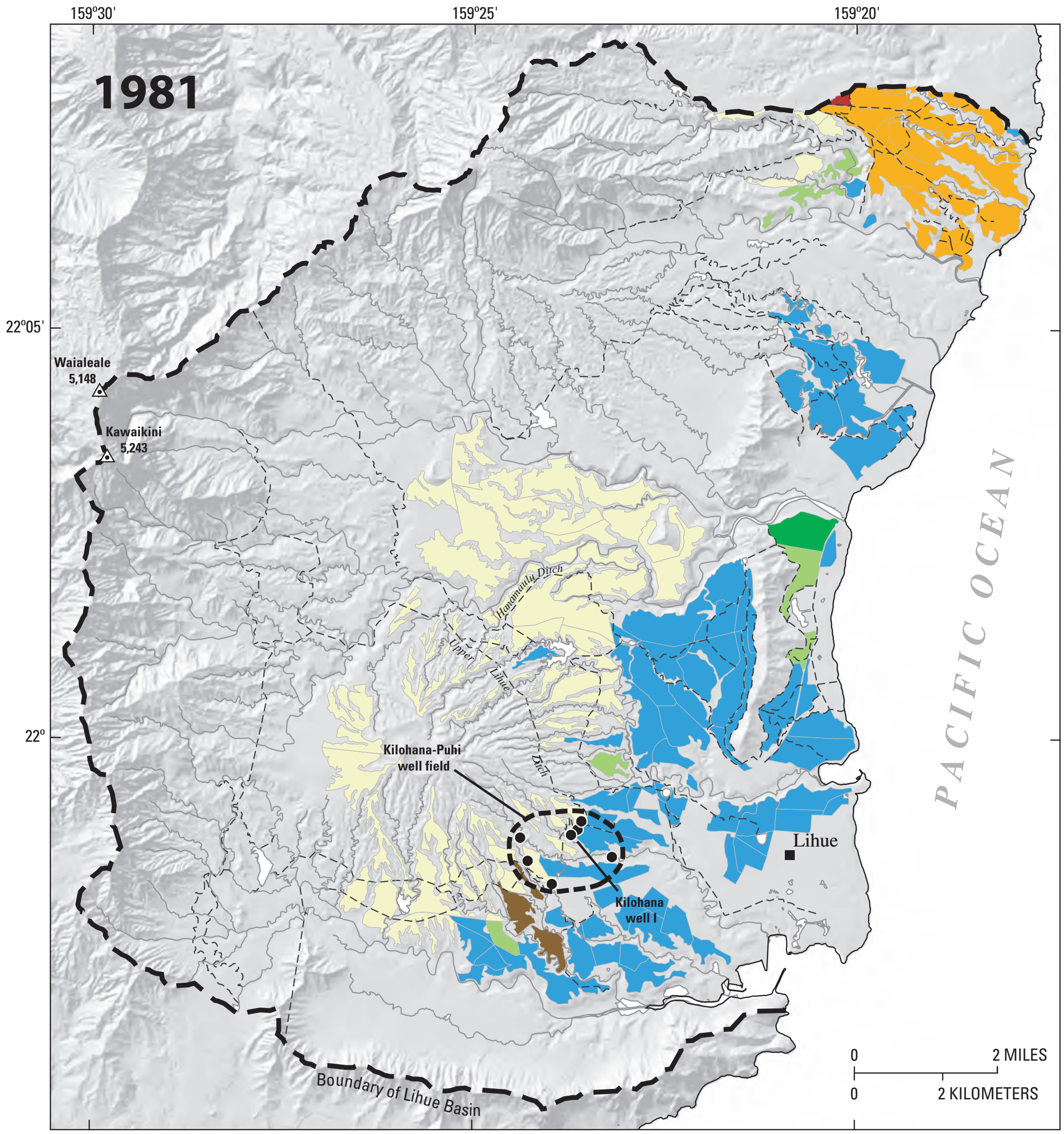


Figure 2. Mean annual rainfall in the Lihue Basin, Kauai, Hawaii. (Modified from Giambelluca and others, 1986.)



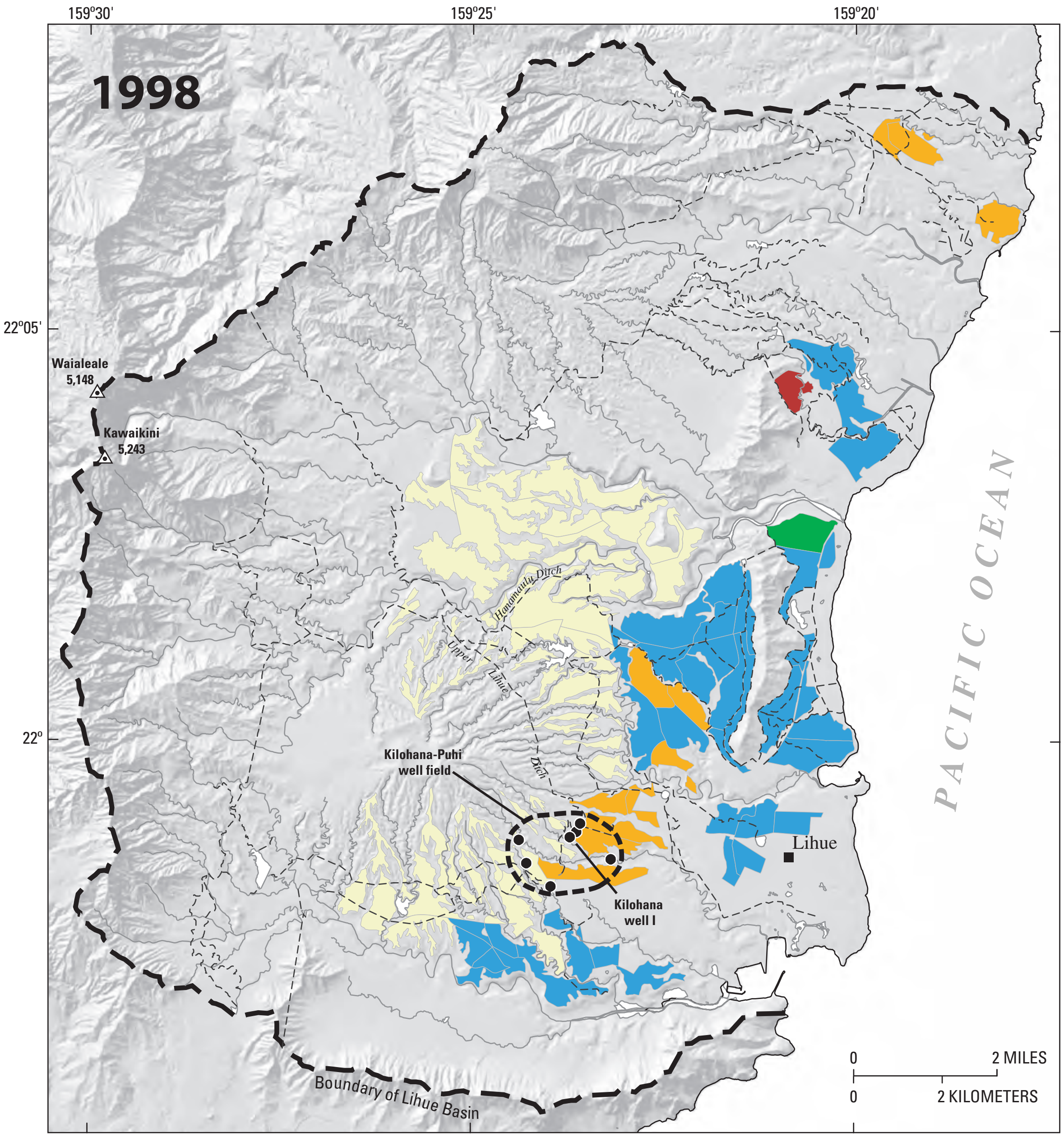
Shaded relief generated from U.S. Geological Survey 10-meter digital elevation model, Universal Transverse Mercator projection, zone 4, NAD83 datum. Base modified from U.S. Geological Survey National Hydrography Dataset, 1:24000 scale.

EXPLANATION

IRRIGATION METHOD
- Drip
- Drip and furrow
- Drip and unirrigated
- Furrow
- Unirrigated
- Unirrigated and furrow
- Unirrigated, furrow, and drip

- Irrigation ditch
- Well
- Kawaikini 5,243 — Elevation, in feet above mean sea level

Figure 3. Sugarcane fields (colored areas) in 1981 and 1998 in the Lihue Basin, Kauai, Hawaii. (From Izuka and others, 2005.)



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EXPLANATION

IRRIGATION METHOD
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- Well
- Kawaikini 5,243 — Elevation, in feet above mean sea level

Figure 3.—Continued.

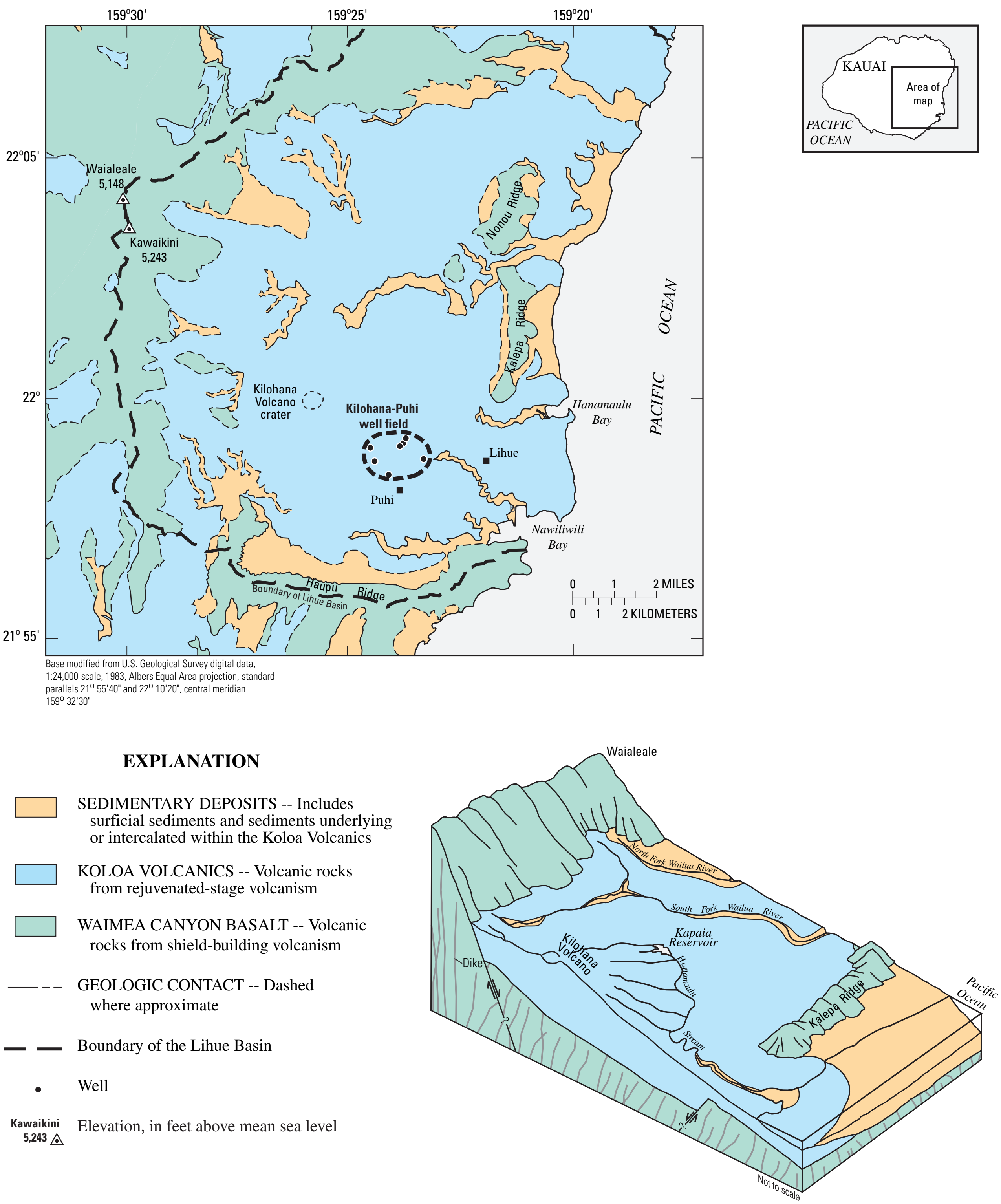


Figure 4. Geologic map and block diagram of the Lihue Basin, Kauai, Hawaii. (Modified from Macdonald and others, 1960, and Izuka and Gingerich, 2003.)

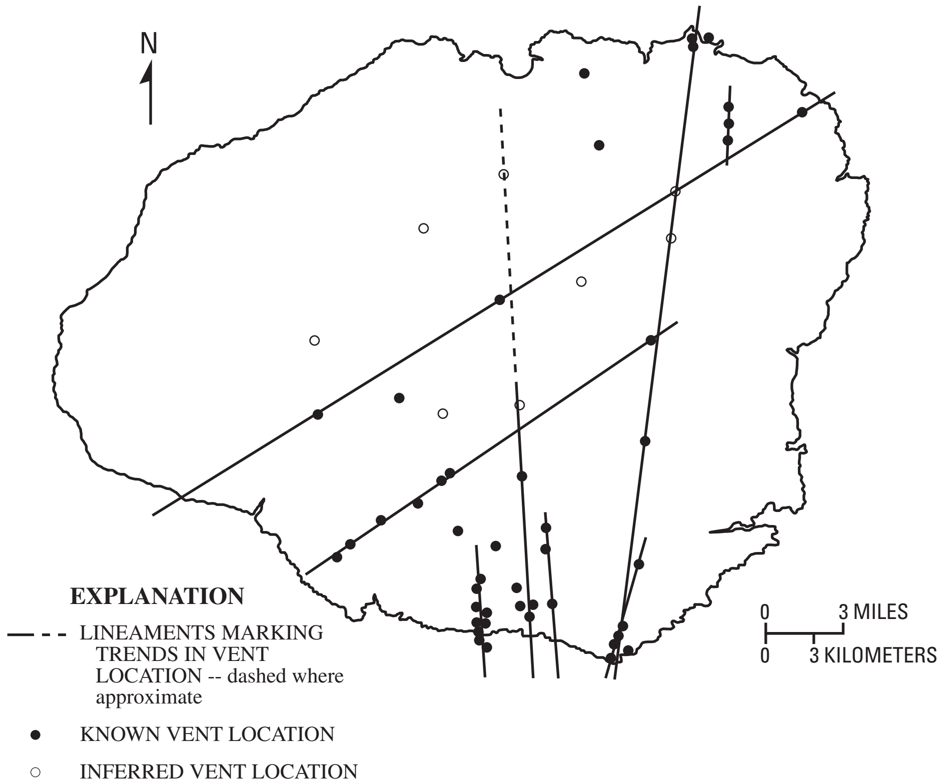


Figure 5. Vents of the Koloa Volcanics. (Modified from Macdonald and others, 1960.)

others, 1960; Holcomb and others, 1997) postulated some form of collapse. Exploratory drilling indicates that in some parts of the basin, the contact between the underlying shield volcano and the overlying basin-filling sediment and rejuvenated-stage volcanic rocks is hundreds of feet below present sea level (Gingerich and Izuka, 1997; Izuka and Gingerich, 1997a-d; Reiners and others, 1999). The broad, dome-shaped edifice of Kilohana Volcano in the southern Lihue Basin (fig. 1) is the largest single rejuvenated-stage structure on Kauai. Deep borings into the volcano's eastern flank penetrated marine and terrigenous sediment intercalated with lava flows (Izuka and Gingerich, 1997a, c), indicating that parts of the Lihue Basin had been submerged in the past and that multiple episodes of rejuvenated-stage volcanism built the floor of the basin above sea level.

Stratigraphy and Hydraulic Properties

The rocks of the Lihue Basin are divided into two principal units of formational rank separated by an erosional unconformity (fig. 4). The Pliocene Waimea Canyon Basalt, which includes the rocks of the shield volcanoes that form the bulk of Kauai, constitutes the basement on which younger rocks lie (Macdonald and others, 1960; Langenheim and Clague, 1987). Most of the Waimea Canyon Basalt consists of voluminous accumulations of thin lava flows that built the flanks of the shield volcanoes. In southern and western Kauai, flank lavas of the Waimea Canyon Basalt form some of the most permeable and productive aquifers on the island. Analogous flank lava flows on Oahu, Hawaii, have horizontal hydraulic conductivities (K_h) of hundreds to thousands of feet per day (Soroos, 1973). Vertical hydraulic conductivities (K_v) of aquifers in Hawaii are poorly known, but because of the distinctly layered structure of lava-flow aquifers, most investigators have presumed that the ratio of K_v to K_h is between 1:3 and 1:200 (Hunt, 1996).

In the Lihue Basin, the Waimea Canyon Basalt is mostly covered by younger rocks, but where it is exposed in the surrounding mountains and in smaller ridges within the basin, the formation is intruded by dense, near-vertical, sheetlike volcanic dikes (Macdonald and others, 1960). Dikes tend to reduce the overall K_h of the lava flows into which they intrude (Takasaki and Mink, 1985). An aquifer test in Haupu Ridge indicated a K_h of about 16 ft/d (Gingerich, 1999), but this value is probably higher than the regional bulk K_h of the dike-intruded Waimea Canyon Basalt of which the ridge is composed (Izuka and Oki, 2002). Dikes probably also intrude, and reduce the bulk permeability of, the Waimea Canyon Basalt beneath the floor of the basin (Izuka and Gingerich, 1998).

At the western boundary of the basin near Mount Waialeale (fig. 1, 4), the Waimea Canyon Basalt consists of thick lava flows that have been variously interpreted as caldera-filling lavas (Macdonald and others, 1960) or lavas that accumulated between multiple shield volcanoes (Holcomb and others, 1997). The hydraulic properties of this part of the Waimea Canyon Basalt are not known, but rocks formed in the caldera of the Koolau shield volcano on Oahu have very low permeability, owing to dike intrusion, thick ponded lava, hydrothermal alteration, and secondary mineralization (Stearns and Vaksvik, 1935; Takasaki and Mink, 1985).

Overlying the Waimea Canyon Basalt is the Koloa Volcanics, which is of Pliocene through Pleistocene age. The Koloa Volcanics consists mostly of rejuvenated-stage volcanic rocks but includes sediments that are intercalated with the lava flows, as well as sediments that lie directly over the eroded surface of the Waimea Canyon Basalt (Macdonald and others, 1960; Langenheim and Clague, 1987). The Koloa Volcanics has heterogeneous aquifer properties, probably owing to the presence or absence of dikes or sediments, or to variations in the thickness, degree of alteration, or secondary mineralization of lava flows. It is likely that dikes intrude the formation along the trends delineated by vents of the Koloa Volcanics (fig. 5). The specific capacity (well discharge divided by pumping drawdown) of wells in the Koloa Volcanics indicates that permeability in this formation varies widely. Aquifer tests indicate, however, that in most places the K_h of the Koloa Volcanics is less than 1.5 ft/d and may be as low as 0.042 ft/d; storage coefficients range from about 10^{-3} to 10^{-1} ft^{-1} (Gingerich, 1999).

Ground-Water Occurrence and Movement

Fresh ground water in Kauai, as in other oceanic islands, forms a lens-shaped body that is underlain by saltwater (fig. 6). The freshwater lens is buoyed by the density difference between saltwater and freshwater. The transition from freshwater to saltwater is a diffuse zone of mixing, but for simplicity, especially in the Lihue Basin where the freshwater lens is thick, the mixing zone can be envisioned as a sharp interface. Fresh ground water in the lens flows continuously from recharge areas to discharge areas. In the Lihue Basin, the freshwater lens is recharged primarily by infiltration of rainfall, although fog drip and irrigation enhance ground-water recharge in some places. Ground water in the freshwater lens flows generally from inland areas, where rainfall and recharge are highest, toward the coast, where it discharges to springs, streams, and the ocean.

Under pre-development conditions (that is, before the emplacement of wells or the application of irrigation), the freshwater lens is in a state of long-term average dynamic equilibrium in which the ground-water recharge rate is balanced by the ground-water discharge rate. This state of long-term equilibrium is commonly referred to as steady state. When the equilibrium is upset, whether by natural stresses such as prolonged droughts, or by artificial stresses such ground-water withdrawals (from production wells) or recharge from irrigation, the shape and size of the freshwater lens change. The rate of change depends on numerous factors, including the timing, location, and magnitude of the stresses and the hydraulic properties of the aquifer. During this period of change, the aquifer adjusts to the new stresses and is said to be in a transient state. Droughts and ground-water withdrawals cause the freshwater lens to shrink by lowering the water levels in the aquifer and by inducing the freshwater/saltwater interface to rise. On the other hand, enhancement of recharge by irrigation raises water levels and induces a downward shift of the freshwater/saltwater interface. Some stresses, such as droughts, will eventually pass, whereas other stresses, such as changes in ground-water withdrawal or irrigation, may persist for a long time. If stresses persist long enough, the freshwater lens will adjust toward a new steady state in which the total input (recharge from rainfall, fog, and irrigation) again equals the total output (ground-water withdrawal plus natural discharge).

The moist climate of the Lihue Basin and the low regional hydraulic conductivities of the Koloa Volcanics and the dike-intruded Waimea Canyon Basalt result in a freshwater lens that is thicker than in most other places in Hawaii (fig. 6). Freshwater saturates the aquifer to higher elevations, such that even some small, youthful streams with relatively shallow incision intersect and drain water from the upper part of the freshwater lens. Streams in the Lihue Basin thus play a substantial role in discharging water from the aquifer and shaping the water table (fig. 7). The low hydraulic conductivities result in steep horizontal and vertical hydraulic-head gradients that also contribute to the large areal variation in water-table elevations (Izuka and Gingerich, 2003).

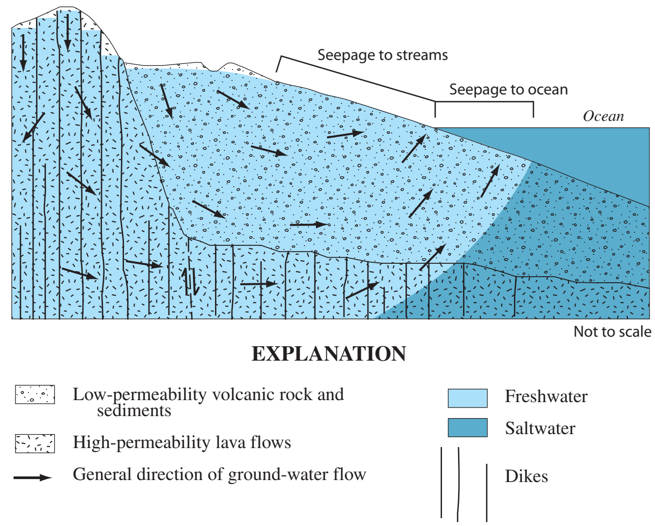


Figure 6. Conceptual model of ground-water occurrence in the southern Lihue Basin, Kauai, Hawaii. (From Izuka and Gingerich, 2003.)

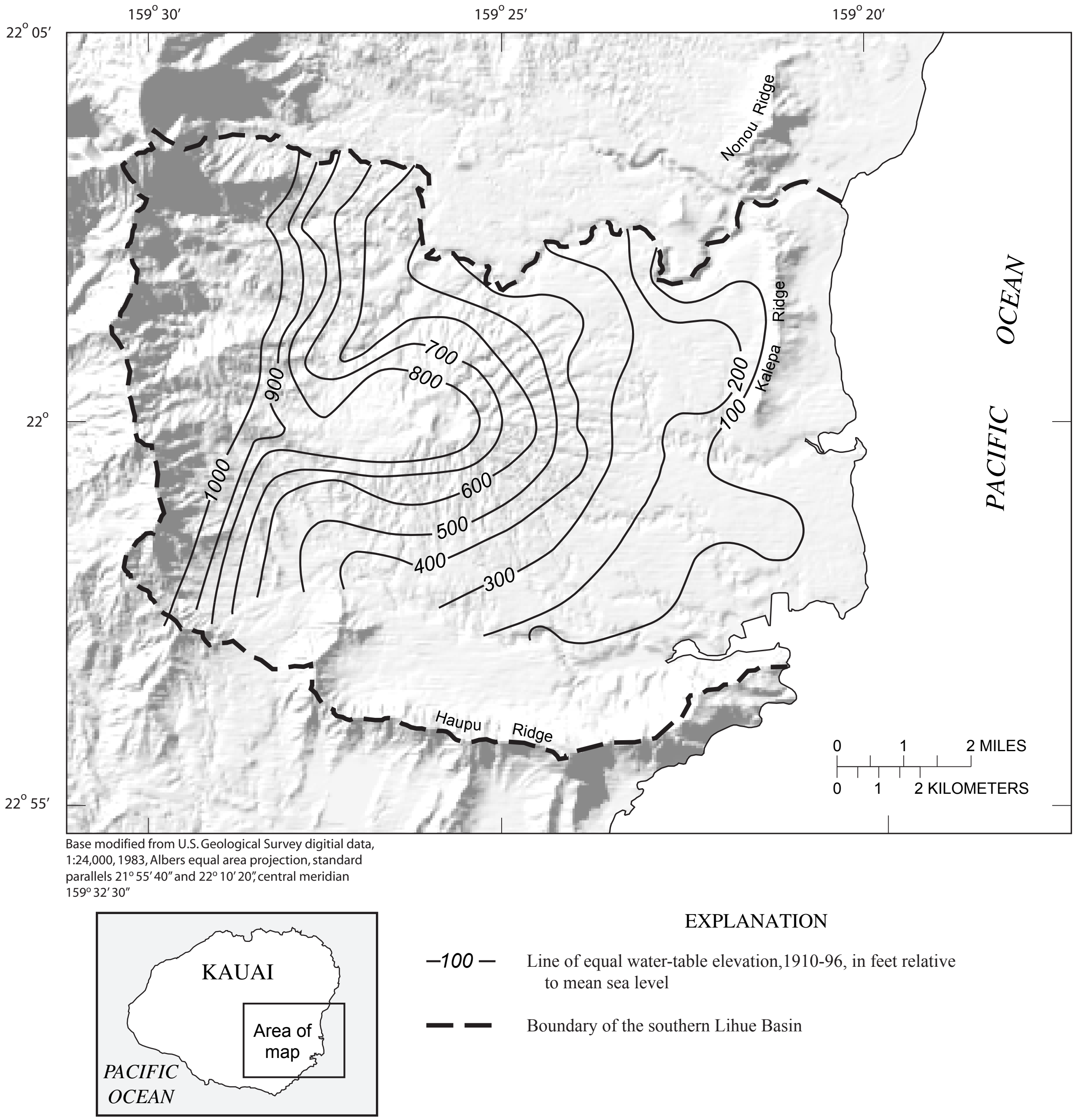


Figure 7. Generalized ground-water table map for the southern Lihue Basin, Kauai, Hawaii. (Modified from Izuka and Gingerich, 1998.)

Most of the wells and tunnels that provide water to the southern Lihue Basin develop ground water from the Koloa Volcanics. Although most of the Koloa Volcanics has low bulk K_h, a few exceptional wells, such as those of the Puhi-Kilohana well field (fig. 1), can produce as much as 1 Mgal/d. These few high-producing wells and tunnels are critical to the public water supply in the southern Lihue Basin, but a recent decline in ground-water levels has resulted in diminished yield in some wells and water tunnels. The decline in water levels was approximately concurrent with an extended period of lower-than-average rainfall and a decline in diversion of stream water for irrigation (fig. 8).

Effects of Irrigation and Drought on Ground-Water Recharge

Izuka and others (2005) used a daily soil-water-budget analysis to estimate ground-water recharge for various land-use and irrigation conditions that existed during hydrologically significant periods in the history of the Lihue Basin (table 1). These periods included (1) conditions in 1981, when the sugarcane industry was diverting billions of gallons of surface water per year for irrigation; (2) conditions in 1998, just before cessation of the sugarcane agriculture in the basin; and (3) no-irrigation conditions, which represent both pre-development conditions and conditions that are likely to persist after the closure of the sugarcane plantations in 2000.

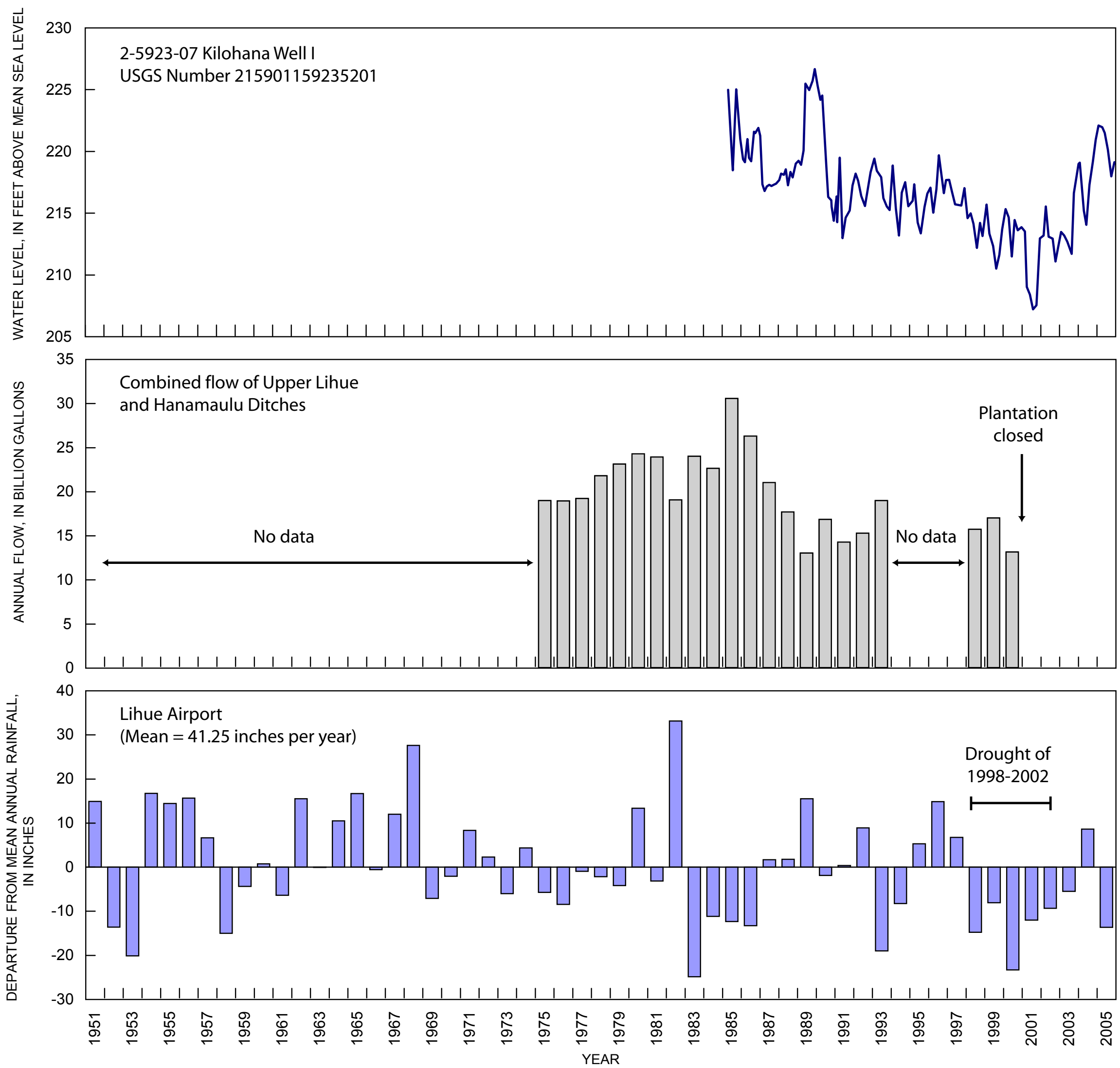


Figure 8. Water levels in Kilohana well I, mean annual rainfall at the Lihue Airport, and irrigation-ditch flows in the southern Lihue Basin, Kauai, Hawaii. (Rainfall data from National Climatic Data Center, 2006; ditch-flow data from records of the Lihue Plantation Company.)

Table 1. Estimates of ground-water recharge from water-budget analysis for various irrigation and rainfall conditions in the Lihue Basin, Kauai, Hawaii.

[From Izuka and others, 2005; Mgal/d, million gallons per day]

Scenario	Recharge (Mgal/d)
1981 irrigation, normal rainfall	264
1998 irrigation, normal rainfall	246
No irrigation, normal rainfall	212
1981 irrigation, with drought	131
1998 irrigation, with drought	114
No irrigation, with drought	84

Results of the water-budget analysis indicate that, assuming normal rainfall, ground-water recharge in the Lihue Basin was 264 Mgal/d under 1981 irrigation conditions and 246 Mgal/d under 1998 irrigation conditions (table 1). The decrease from 1981 to 1998 was partly due to a reduction in sugarcane irrigation as the industry in the basin neared its end. Also, some of the remaining fields were converted from furrow to drip irrigation, which significantly reduced the recharge-enhancing effect of irrigation. On the basis of irrigation-efficiency estimates used by the Hawaii Sugar Planters' Association, Izuka and others (2005) considered drip irrigation to be 2.8 to 3.0 times more efficient than furrow irrigation. Fields that were converted to drip irrigation between 1981 and 1998 included those near the Kilohana-Puhi well field, where declining ground-water levels were observed (fig. 3).

Results of the water-budget analysis also indicate that under no-irrigation conditions, ground-water recharge in the Lihue Basin was 212 Mgal/d (table 1). Comparison of this estimate with the recharge estimate for 1981 conditions indicates that irrigation had artificially increased ground-water recharge in the Lihue Basin by about 25 percent over no-irrigation conditions. The effects of irrigation on ground-water recharge were concentrated within the drier coastal areas, where irrigation was needed to supplement natural precipitation. All of the wells in the Lihue Basin that showed declining water levels are near irrigated areas.

Izuka and others (2005) also estimated ground-water recharge for various combinations of drought and irrigation (table 1). The severity of one of the droughts simulated in their analysis was comparable to that of the drought of 1998-2002 (fig. 8). Ground-water recharge under 1981 irrigation and drought conditions was estimated to be 131 Mgal/d (about 50 percent lower than under 1981 irrigation and normal rainfall conditions). Ground-water recharge under 1998 irrigation and drought conditions was estimated to be 114 Mgal/d (about 54 percent lower than under 1998 irrigation and normal rainfall conditions). Ground-water recharge under no-irrigation and drought conditions was estimated to be only 84 Mgal/d. These results indicate that a drought similar in magnitude to that of 1998-2002 could substantially reduce ground-water recharge in the Lihue Basin for a few years.

Unlike the effects of irrigation, the effects of drought on ground-water recharge in the Lihue Basin are widespread. Drought conditions in Hawaii are identified by statistically significant departures from normal rainfall, but the cause of droughts is commonly associated with quasi-periodic events, such as the El Niño Southern Oscillation (ENSO). Droughts are therefore expected to recur periodically but are balanced by higher-than-average rainfall periods. In contrast, irrigation in the Lihue Basin is not likely to return to the same magnitude as during the peak of sugarcane agriculture in the 20th century, when most sugarcane irrigation was by the furrow method. This inefficient and obsolete method returns much of the applied water to soil infiltration and ground-water recharge. Even if some form of agriculture replaces sugarcane in the Lihue Basin, it will probably use a more efficient method, such as drip irrigation, that contributes much less to ground-water recharge.

Ground-water recharge was significantly higher in the water-budget analysis of Izuka and others (2005) than it was in an earlier water-budget analysis by Shade (1995). Shade estimated that 19 percent of the total water input to the basin (sum of precipitation plus irrigation) went to ground-water recharge, whereas Izuka and others estimated that 34 percent of the total water input to the basin went to ground-water recharge (table 2). This discrepancy was too large to be attributed to the difference in periods analyzed by the two studies; in the Lihue Basin, the 1990 conditions analyzed by Shade were comparable to the 1998 irrigation and normal rainfall conditions analyzed by Izuka and others. Izuka and others attributed the discrepancy to differences in the methods used to distinguish between base flow (the component of streamflow that comes from ground-water discharge) and direct runoff in streamgage records. Shade used a flow-duration analysis that can overestimate runoff, and in turn underestimate ground-water recharge, in areas such as the Lihue Basin where a substantial part of the total streamflow is ground-water discharge. Izuka and others used a hydrograph-separation technique that more accurately assesses the base-flow characteristics of each stream. To improve the accuracy of their recharge estimate even more, Izuka and others incorporated details of the sugarcane irrigation process and crop water demands, and used a smaller time step (daily) than did Shade (monthly). For these reasons, the recharge estimates of Izuka and others were used in the following analyses of the effects of drought, irrigation, and ground-water withdrawal on ground-water levels in the southern Lihue Basin.

Table 2. Comparison of recharge estimates from previous water-budget studies.

[From Izuka and others (2005)]

Study	Conditions	Percent of total input (precipitation plus irrigation)		
		Runoff	Actual evapotranspiration	Recharge
Izuka and others (2005)	1998 irrigation, normal rainfall	30	36	34
Shade (1995)	1990 conditions	48	34	19

Effects of Irrigation, Drought, and Ground-Water Withdrawal on Ground-Water Levels

Assessing the link between the observed decline in ground-water levels and historical drought and changes in irrigation and ground-water withdrawals in the Lihue Basin requires simultaneous consideration of the variation of these factors in space and time together with the hydraulic properties of the rocks. Numerical ground-water-flow modeling is currently the most comprehensive method available for studying the complex, interrelated factors governing ground-water systems. Ground-water levels computed by the model simulate those in the real aquifer. Stresses such as drought and changes in ground-water withdrawals or irrigation can be simulated in the model, and simulated ground-water levels can be tracked to assess how ground-water levels in the real aquifer will be affected.

By incorporating recently revised recharge estimates and using updated information to compute historical changes in ground-water withdrawals, the numerical ground-water-flow model of the southern Lihue Basin created by Izuka and Gingerich (1998) can be adapted to determine which factors, or combination of factors, are likely to have caused the observed decline in ground-water levels in the Lihue Basin. Although the model covers only half the basin, it includes the Kilohana-Puhi well field (fig. 1), which is both an important source of drinking water and an area where declining water levels have threatened the productivity of wells (fig. 9).

Original Southern Lihue Basin Model

For discussion purposes, the numerical ground-water-flow model of the southern Lihue Basin constructed by Izuka and Gingerich (1998) is referred to as the original southern Lihue Basin model (or simply "original model") in this report. A detailed description of this model is given in the report by Izuka and Gingerich; a review of model features relevant to this study is given here. The original southern Lihue Basin model was created using a modified version of the finite-difference modeling program SHARP (Essaid, 1990), which allows quasi-three-dimensional simulation of the freshwater/saltwater systems in island and coastal aquifers. Freshwater and saltwater are treated as immiscible fluids separated by a sharp interface. Ground-water flow is governed by user-specified aquifer properties and distribution of model-calculated freshwater and saltwater heads. Streams and offshore areas were simulated using leaky confined cells. Ground-water seepage to streams and the ocean is governed by user-specified streambed and ocean-floor hydraulic properties and by 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. Head above a stream cell was set equal to the elevation of the stream cell as determined from topographic maps; head above an ocean-floor cell was set at sea-level equivalent freshwater head (head adjusted for the density difference between freshwater and saltwater and the depth of the cell below sea level, also determined from topographic maps).

Although the area of interest of the original southern Lihue Basin model lies entirely within the Lihue Basin, the model includes areas of southeastern Kauai that lie outside the basin (fig. 9). The model was extended beyond the limits of the basin so that model boundaries would not substantially affect ground-water flow within the basin (Izuka and Gingerich, 1998). Because areas outside the basin are not within the area of interest, it was not necessary to model them in as much detail as areas within the basin. The modeled area was divided into two layers, each layer having 2,475 cells, and each cell representing an area 2,000 ft by 2,000 ft. The upper layer extended 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 by Macdonald and others (1960). The lower layer extended from -500 ft to -6,000 ft elevation.

Recharge in the original model was 191 Mgal/d distributed over the modeled area according to the average annual recharge estimated by Shade (1995) on the basis of conditions that existed in 1990. Ground water in the Lihue Basin is developed from conventional vertical wells and from water

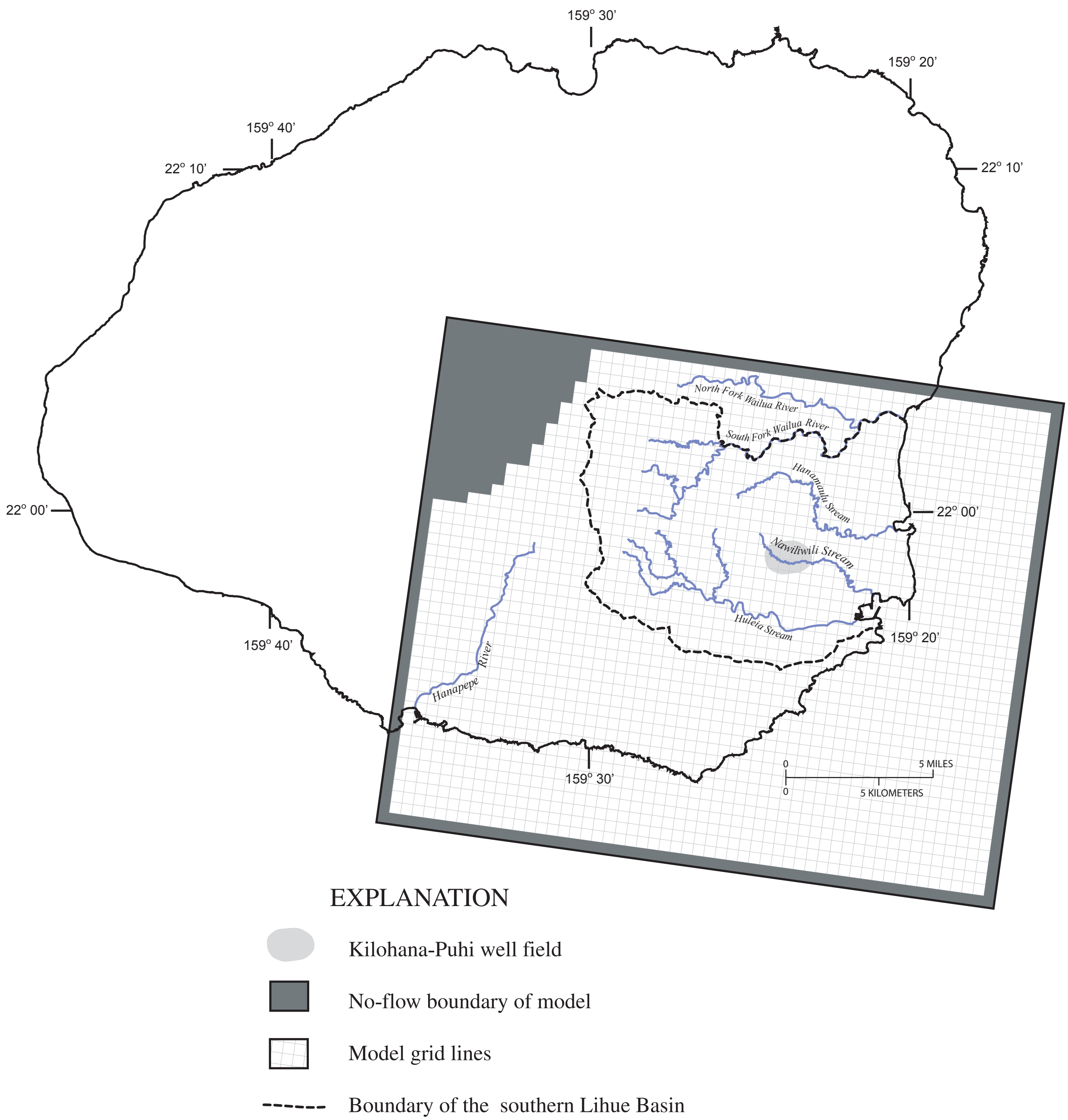


Figure 9. Boundaries of the numerical ground-water-flow model of the southern Lihue Basin, Kauai, Hawaii. (Modified from Izuka and Gingerich, 1998.)

tunnels (infiltration galleries that are driven parallel to the water table near streams). In the original model, withdrawals from conventional wells were based on water-use statistics obtained in 1993 from CWRM. Three water tunnels are within the active area of the original southern Lihue Basin model. Because these tunnels essentially intercept ground water that would normally have discharged to nearby streams, the tunnels were simulated using leaky confined aquifer cells.

Three hydrogeologic groups with contrasting hydraulic conductivities were included in the original model: (1) the Koloa Volcanics, with K_h of 0.275 ft/d and K_v of 5.5×10^{-4} ft/d; (2) the dike-free Waimea Canyon Basalt, with K_h of 200 ft/d and K_v of 1.0 ft/d; and (3) the dike-intruded Waimea Canyon Basalt with K_h of 1.11 ft/d and K_v of 1.1×10^{-2} ft/d.

Adjusting the Model to Revised Recharge Estimates

In any steady-state ground-water-flow model, a balance exists between simulated parameters such as hydraulic properties, water levels, and discharge. In constructing a model that is representative of an area of interest, values of model parameters that are known with the least certainty are adjusted until the values of other model parameters match known or measured values in the area of interest (a procedure commonly referred to as calibration). In the original southern Lihue Basin model, aquifer hydraulic properties were considered a parameter of greater uncertainty than ground-water recharge, water levels, or withdrawals, or stream base flow. Therefore, once a reliable estimate of ground-water recharge and well withdrawals was entered into the model, hydraulic properties were adjusted until (1) simulated water levels matched water levels measured in wells and (2) simulated ground-water discharge to streams matched base flows computed from streamgage records. Ground-water recharge in the original southern Lihue Basin model was based on the recharge estimates of Shade (1995). Because the recharge estimates are probably low, it was necessary for the purposes of this study to update the model using the revised recharge estimates of Izuka and others (2005). In this report, the model adjusted to the revised recharge estimates is referred to as the adjusted southern Lihue Basin model (or simply, “adjusted model”).

After the revised recharge estimates were incorporated into the model, two aspects of the model — namely, the representation of streams and the distribution of hydraulic conductivity — were adjusted until simulated ground-water levels matched measured ground-water levels and simulated ground-water discharge to streams matched computed stream base flows. Ground-water levels used for matching purposes were the same as those used in the original model; pumping conditions were also kept the same as those simulated in the original model during the matching procedure. Ground-water recharge computed by Izuka and others (2005) for 1998 irrigation and normal rainfall conditions (table 1) was used in the adjustment because these conditions are similar to those on which the original model was based.

Izuka and others (2005) computed recharge only for areas within the Lihue Basin. The original southern Lihue Basin model, however, includes areas that are outside the basin (fig. 9). To estimate recharge for areas outside the basin, regression equations relating ground-water recharge to mean annual soil infiltration (precipitation minus runoff) were developed from the results of Izuka and others (see Appendix). Mean annual soil infiltration for areas outside the basin was entered into the regression equations to compute ground-water recharge. Mean annual soil infiltration was determined using an approach similar to that used by Izuka and others for areas within the basin. Using a geographic information system (GIS), mean annual precipitation was determined from the mean-annual rainfall map of Kauai by Giambelluca and others (1986). Fog contribution of 0.18 times mean annual rainfall was added to precipitation in areas above 2,000 ft elevation. A runoff-to-rainfall ratio of 0.28 was computed for the drainage area of stream gage 16049000 on the Hanapepe River and applied to the mean annual rainfall map of Giambelluca and others to determine the distribution of mean annual runoff. Mean annual runoff was subtracted from mean annual precipitation to determine mean annual soil infiltration, which was, in turn, used in the regression equation to determine mean annual ground-water recharge. The resulting total recharge within the active model area for 1998 irrigation and normal rainfall conditions was 304 Mgal/d (table 3), which is about 54 percent higher than in the original model.

Table 3. Recharge rates used in model simulations of various drought and irrigation scenarios in the ground-water-flow model of the southern Lihue Basin, Kauai, Hawaii.

Scenario	Recharge in model (million gallons per day)
1981 irrigation, normal rainfall	315
1998 irrigation, normal rainfall	304
No irrigation, normal rainfall	274
1998 irrigation, with drought	144
No irrigation, with drought	118

Result of Model Adjustment

To a large extent, the representation of streams in the adjusted model is the same as that in the original model. Some simulated streams were lengthened or shortened (fig. 10) to more accurately represent streams in the southern Lihue Basin, and the heads overlying some stream cells were adjusted to more precisely represent stream-channel elevations shown on topographic maps. A single value of 2.3×10^{-5} day^{-1} was used for both stream-bed and ocean-floor leakance (K_v of a stream cell divided by one-half the vertical thickness of the cell), which is equal to the value used by Izuka and Gingerich (1998) in the original model.

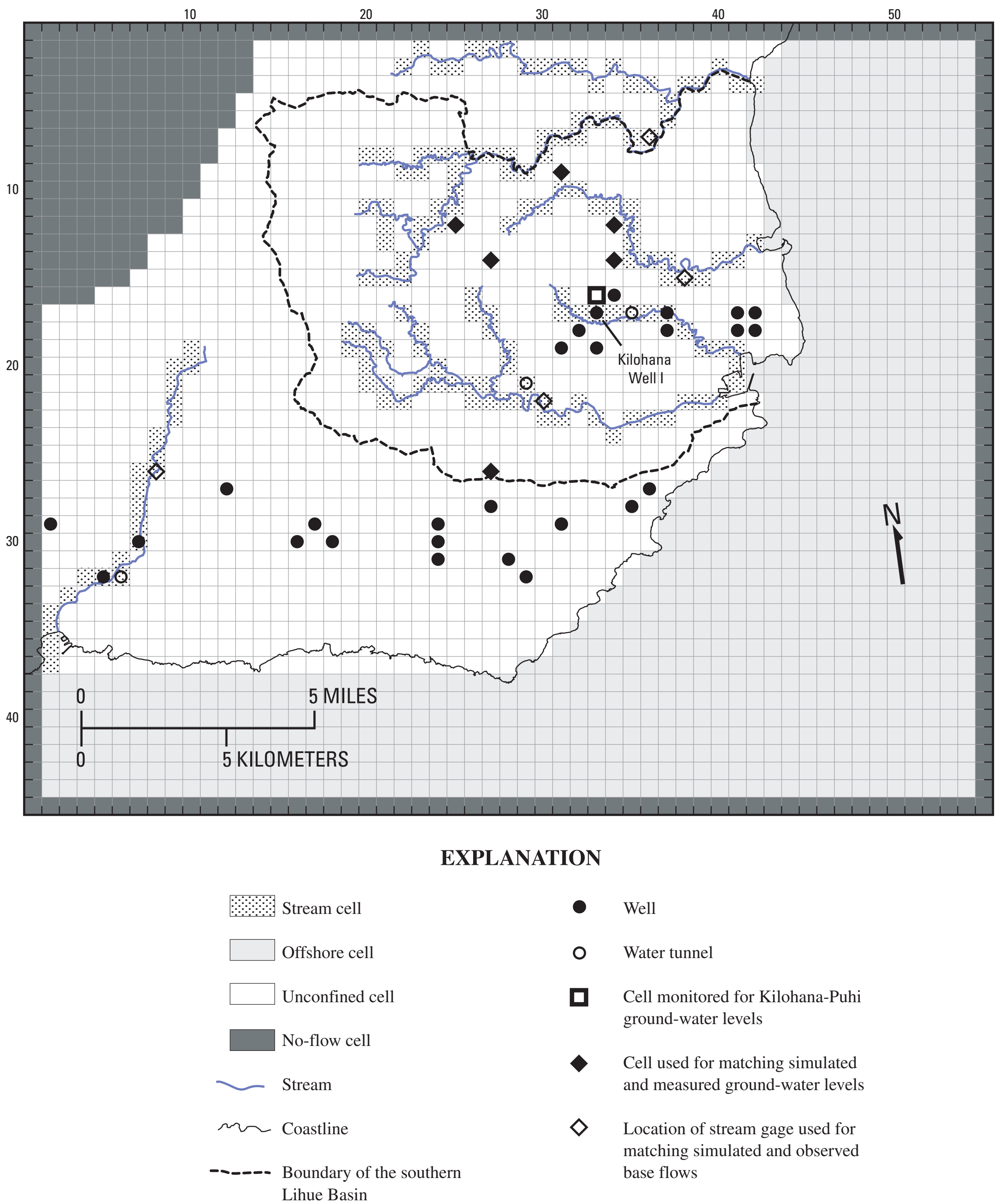


Figure 10. Cells used to simulate streams, submarine areas, wells, and water tunnels in the adjusted model of the southern Lihue Basin, Kauai, Hawaii.

The distribution of hydraulic conductivities in the adjusted model is also similar to those in the original model, except that some detail was added to improve consistency with the geologic map by Macdonald and others (1960), and to more accurately represent the relative positions of rock types and streams. In the original model, the Waimea Canyon Basalt was divided into dike-intruded and dike-free units with different hydraulic properties, but the Koloa Volcanics was modeled as a single hydrogeologic unit with uniform hydraulic properties. In the adjusted model, both the Koloa Volcanics and the Waimea Canyon Basalt are divided into dike-intruded and dike-free units (fig. 11). In the adjusted model, distribution of dike-intruded and dike-free Waimea Canyon Basalt is based on dikes shown on the geologic map by Macdonald and others. The distribution of dike-intruded and dike-free Koloa Volcanics in the adjusted model is based on the locations of lineaments and associated volcanic vents depicted by Macdonald and others, and the premise that dikes probably intrude the Koloa Volcanics along fissures marked by lineaments and reduce the bulk hydraulic conductivity of the region. The lineaments and associated volcanic vents are limited to the western two-thirds of the Lihue Basin; thus, in the adjusted model, the Koloa Volcanics in the western two-thirds of the basin was presumed to be intruded by dikes and given a lower hydraulic conductivity than the Koloa Volcanics in the eastern part of the basin (fig. 11).

The values of hydraulic conductivity in the adjusted model are, in most areas, equal to or higher than those in the original model; this is expected because the recharge in the adjusted model is higher than the recharge in the original model. Values of hydraulic conductivity for the dike-intruded Koloa Volcanics in the adjusted model are equal to or slightly lower than the values for the Koloa Volcanics in the original model, whereas the values of hydraulic conductivity for the dike-free Koloa Volcanics are higher than in the original model. Hydraulic conductivities of all parts of the Koloa Volcanics in the adjusted model are, however, within the range determined by Gingerich (1999) from aquifer-test analyses. Values of hydraulic conductivity for the dike-intruded Waimea Canyon Basalt are higher in the adjusted model than in the original model. Values of hydraulic conductivity for the dike-free Waimea Canyon Basalt are the same in the adjusted model and the original model.

The overall distribution of simulated ground-water levels in the adjusted model matched measured water levels at monitor points more closely than did the simulated water levels in the original model (fig. 12). The distribution of simulated ground-water levels in the upper layer of the adjusted model (fig. 13) is consistent with the distribution of measured water levels in the southern Lihue Basin (fig. 7) and similar to the distribution of ground-water levels in the original model.

The agreement between total simulated ground-water discharge (table 4) and total simulated ground-water recharge (equal to ground-water recharge for 1998 irrigation, normal rainfall conditions in table 3) confirms that the adjusted model represents steady-state conditions. As a whole, simulated stream base flows in the adjusted model match observed base flows of streams in the modeled area more closely than did simulated base flows in the original model (fig 12). As in the original model, a larger fraction of ground-water flow discharges at streams than at the coast. Of the 304 Mgal/d total ground-water discharge in the adjusted model, 181 Mgal/d (60 percent) discharges at streams, 108 Mgal/d (35 percent) discharges to the ocean, and 15 Mgal/d (5 percent) is withdrawn from wells.

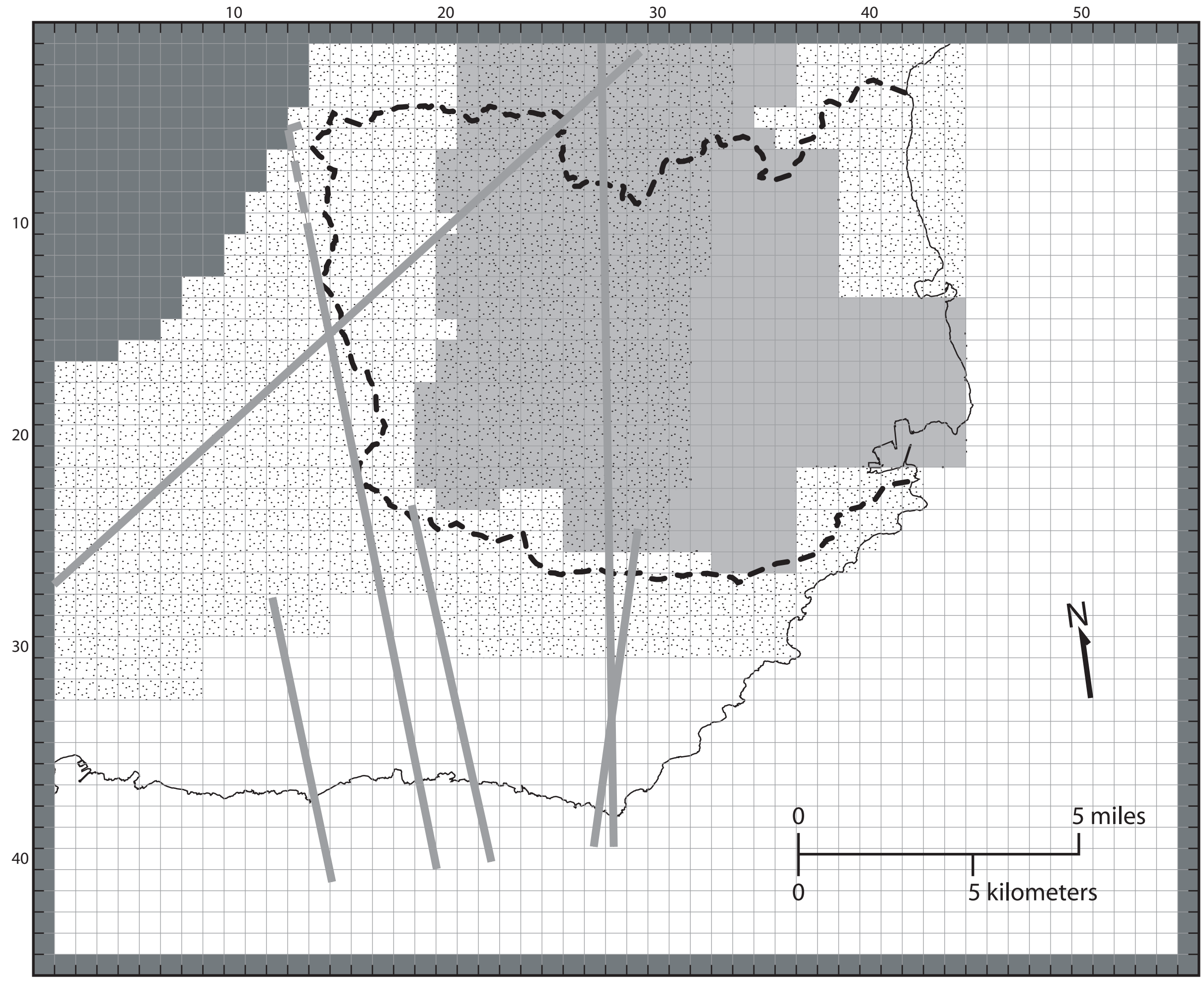
Table 4. Simulated ground-water discharge in the adjusted model of the southern Lihue Basin, Kauai, Hawaii.

[Actual values from Izuka and Gingerich (1988). NA, not applicable]

Discharge location	Ground-water discharge (million gallons per day)	
	Model	Actual
Hanapepe Stream	46	46
Huleia Stream	16	22
Hanamaulu Stream	5	5
South Fork Wailua River	59	57
Other streams	55	NA
Total for streams	181	NA
Ocean	108	NA
Wells	15	15
Total ground-water discharge	304	NA

Model-simulated ground-water discharges at the Hanapepe Pump 3, Kokolau, and Garlinghouse tunnels differ substantially from average recorded withdrawals (table 5), but the discrepancies do not affect the results of the adjusted model as they relate to the objectives of this study. The discrepancies result because tunnels are so close to streams that the model cells representing the tunnels incorporate some seepage to and from nearby streams. In some cases (Hanapepe Pump 3, for example), simulated tunnel discharge is less than recorded draft because the tunnel develops both ground water and surface water from the nearby stream (Izuka and Gingerich, 1998). In other cases (Kokolau, for example), simulated tunnel discharge is greater than recorded draft because the model cell representing the tunnel probably incorporates some seepage from the nearby stream.

The level of discretization in both the original and adjusted models precludes closer matching of simulated to observed ground-water levels and stream base flows, especially where horizontal hydraulic gradients are steep, as in most areas of the basin. Whereas a measured ground-water level is characteristic of the water level at a single point on a



UPPER LAYER

EXPLANATION

DIKE-INTRUDED KOLOA VOLCANICS -- K_h = 0.220 to 0.275 feet per day, K_v = 0.0009 to 0.0011 feet per day

DIKE-FREE KOLOA VOLCANICS -- K_h = 1.10 feet per day, K_v = 0.0022 feet per day.

DIKE-INTRUDED WAIMEA CANYON BASALT -- K_h = 3.89 feet per day, K_v = 0.0389 feet per day.

DIKE-FREE WAIMEA CANYON BASALT -- K_h = 200 feet per day, K_v = 1.00 foot per day.

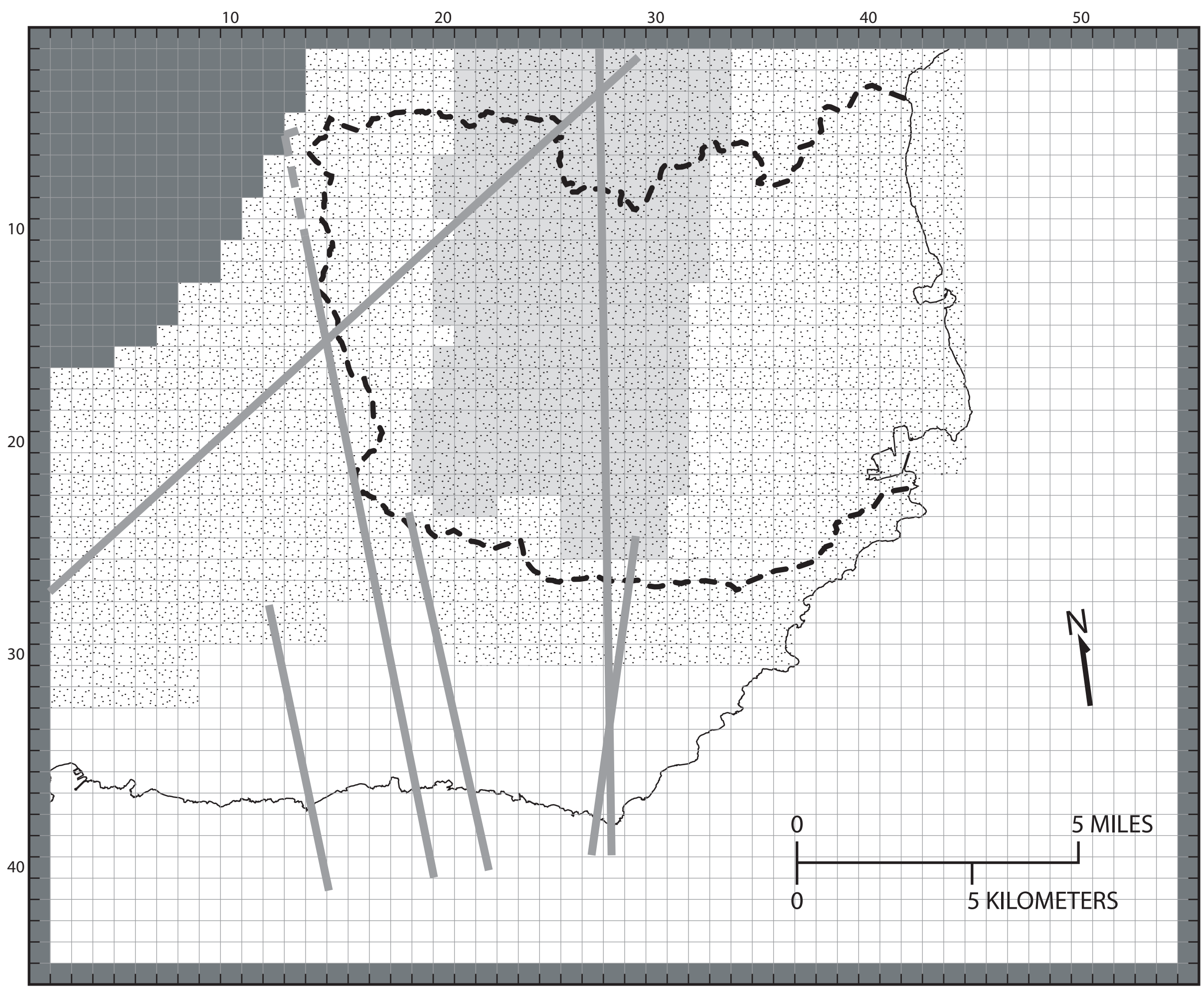
No-flow cell

Coastline

Boundary of the southern Lihue Basin

LINEAMENTS MARKING TRENDS IN LOCATION OF VENTS OF THE KOLOA VOLCANICS -- Dashed where approximate. Modified from Macdonald and others (1960)

Figure 11. Distribution of hydraulic conductivities in the adjusted numerical model of the southern Lihue Basin, Kauai, Hawaii. Lineaments tracing vents of the Koloa Volcanics are shown for comparison. K_h is horizontal hydraulic conductivity, and K_v is vertical hydraulic conductivity.



LOWER LAYER

EXPLANATION

DIKE-INTRUDED WAIMEA CANYON BASALT, INNER BASIN -- includes dikes from Waimea Canyon Basalt and Koloa Volcanics K_h = 0.220 to 0.275 feet per day, K_v = 0.0009 to 0.0011 feet per day.

DIKE-INTRUDED WAIMEA CANYON BASALT -- K_h = 3.89 feet per day, K_v = 0.0389 feet per day.

DIKE-FREE WAIMEA CANYON BASALT -- K_h = 200 feet per day, K_v = 1.00 foot per day.

No-flow cell

Coastline

Boundary of the southern Lihue Basin

LINEAMENT MARKING TREND IN LOCATION OF VENTS OF THE KOLOA VOLCANICS -- Dashed where approximate. Modified from Macdonald and others (1960)

Figure 11.—Continued.

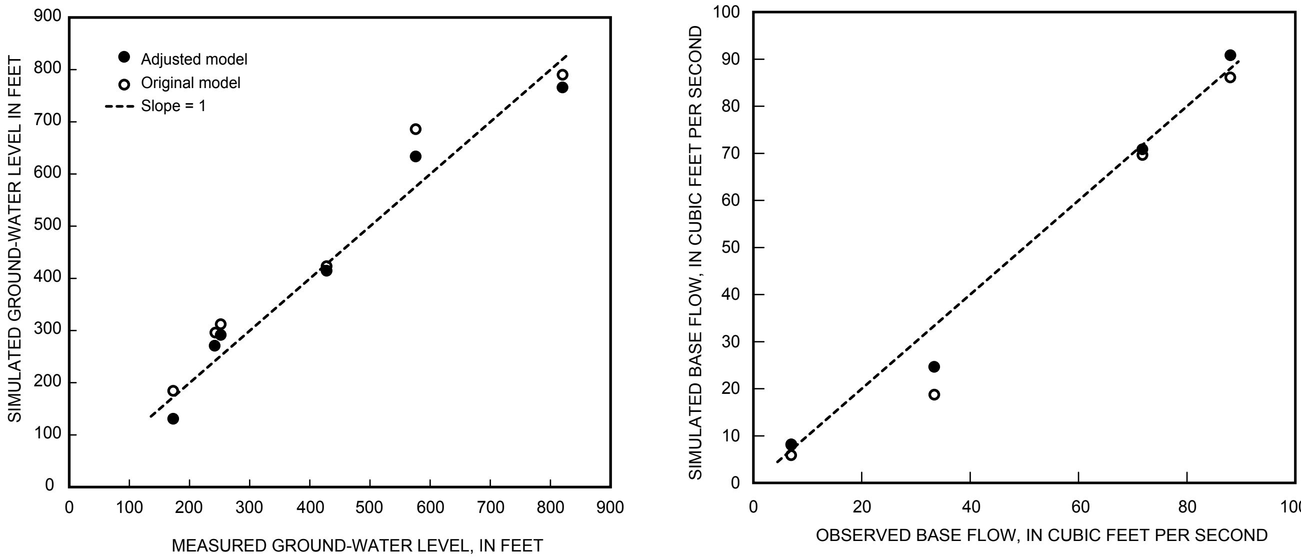


Figure 12. Observed ground-water levels and stream base flows compared with simulated ground-water levels and stream base flows in the adjusted numerical ground-water model of the southern Lihue Basin, Kauai, Hawaii.

Table 5. Water tunnels in the area simulated by the ground-water model of the southern Lihue Basin, Kauai, Hawaii.

[Data on reported draft from K. Gooding, Hawaii State Commission on Water Resource Management, written commun., 2005; Mgal/d, million gallons per day]

Well number	Tunnel	Year built	Location	Average reported draft		Simulated discharge in adjusted model (Mgal/d)
				Rate (Mgal/d)	Period of record	
5534-01	Hanapepe Pump 3	1899	Outside basin	10.505	1983-2001	1.071
5725-01	Kokolau	1928	In basin	0.288	1987-2005	0.602
5823-01	Garlinghouse	1935	In basin	0.715	1987-2005	0.474

steep gradient, a simulated ground-water level represents an average ground-water level in a 4-million-square-foot area near the observation point in the model. Similarly, the aquifer properties, aquifer water level, and stream elevation simulated in a stream cell are each an average of these properties within the area represented by the cell. Actual stream properties, especially stream elevation, can vary greatly within the 2,000-ft by 2,000-ft area of a model cell.

Simulation of the Effects of Irrigation, Drought, and Ground-Water Withdrawal

The adjusted southern Lihue Basin model was used for steady-state and transient simulations to study the relations between the observed decline in ground-water levels and historical irrigation, drought, and ground-water withdrawals. Various conditions of rainfall and irrigation were simulated in the model by incorporating the recharge estimates of Izuka and others (2005). Recharge for areas outside the basin was estimated using the regression method described previously.

Changes in ground-water withdrawal from conventional wells (water tunnels were simulated as leaky confined-aquifer cells, as discussed earlier) for the periods represented by the recharge scenarios of Izuka and others (2005) were also computed and incorporated into the adjusted model. Ground-water withdrawals representative of 1981 and 1998 were computed from records at the CWRM. The records consist of withdrawal rates reported periodically (about monthly). Most wells have some records, but these records are not always complete for the entire period the well was in use (K. Gooding, CWRM, oral commun., 2005), especially before adoption of the Hawaii State Water Code in 1987. For this study, estimates of the average ground-water-withdrawal rates in the southern Lihue Basin for 1981 and 1998 were computed on the basis of reported pumping rates and dates indicating when

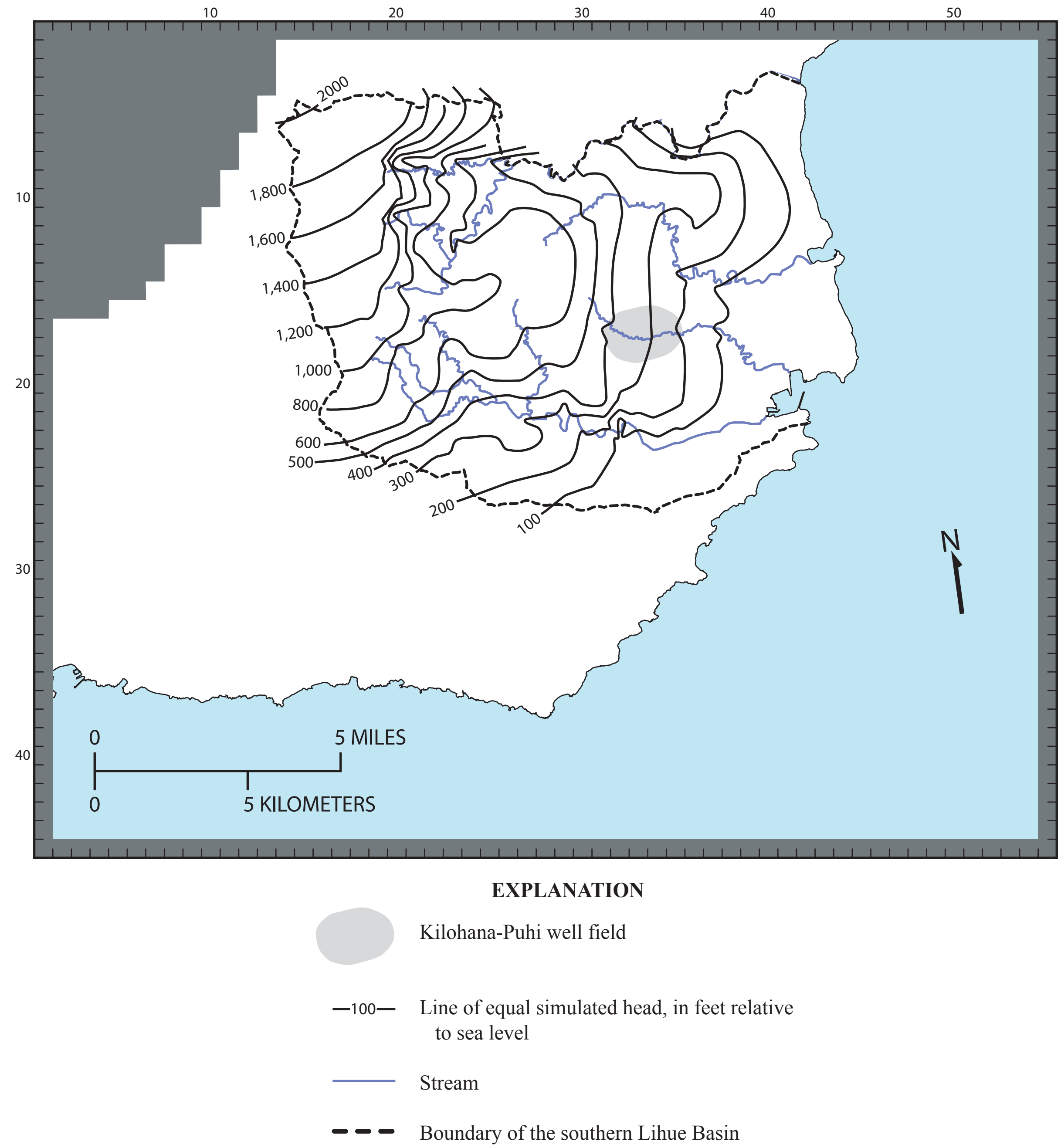


Figure 13. Distribution of simulated ground-water levels in the upper layer of the adjusted model of the southern Lihue Basin, Kauai, Hawaii.

the well was in use, such as (1) the date of the first and last reported withdrawal; (2) the date of well construction; (3) the date of pump installation; (4) the "draft" date, which is the date an approximate average withdrawal from the well was reported; and (5) the "use" date, which is the date the use of well's water was reported. For example, if the date of the first reported draft, pump-installation date, or the "use" or "draft" date for a given well is earlier than 1981, and the last reported draft is after 1981, the well was presumed to have been in use in 1981, whether or not any draft was reported for 1981. If the date of the first reported draft is after 1981 and no pump-installation date or "draft" date is listed, then the date of well construction was considered. If the well was completed more than 4 years before 1981 and there is a record of the well having been in use after 1981, then the well was assumed to have been in use in 1981. A similar procedure was used to determine which wells were in use in 1998. Once a well was determined to have been in use in 1981 or 1998, a withdrawal rate equivalent to the average of the reported draft rates was simulated in the ground-water model (tables 6, 7).

Table 6. Production wells and estimated draft used in the numerical-model simulation of 1981 conditions in the southern Lihue Basin, Kauai, Hawaii.

[Data from K. Gooding, Hawaii State Commission on Water Resource Management, written commun., 2005; Mgal/d, million gallons per day]

Well number	Name	Year built	Simulated draft (Mgal/d)
In basin			
5822-01	Sugar mill	1965	0.032
5822-02	Grammar school	1961	0.083
5824-01	Puhi 1	1975	0.158
5923-01	Kilohana A	1974	0.248
		Total	0.521
Outside basin			
5427-01	Koloa A	1953	0.177
5425-11	Mahaulepu 11	1927	0.924
5426-03	Koloa	1953	2.263
5523-01	Kipu Kai	1950	0.011
5523-02	Kipu Kai	1960	0.209
5526-01	Kaluahonu	1966	0.118
5527-01	Kahoano	1966	0.444
5427-02	Koloa B	1964	0.311
5529-01	Huinawai Reservoir	1950	1.690
5530-03	Lawai 1	1962	0.193
5533-01	Hanapepe Valley A	1974	0.552
5534-03	Hanapepe Town	1966	0.029
5631-01	Kalaheo A-Diesel	1974	0.403
5635-01	Domestic Water	1947	1.373
5635-02	500 H.P. Irrigation	1969	0.806
		Total	9.503

Table 7. Production wells and estimated draft used in the numerical-model simulation of 1998 conditions in the southern Lihue Basin, Kauai, Hawaii.

[Data from K. Gooding, Hawaii State Commission on Water Resource Management, written commun., 2005; Mgal/d, million gallons per day]

Well number	Name	Year built	Simulated draft (Mgal/d)
In basin			
5820-01	Westin 3	1987	0.065
5821-03	Westin 1	1987	0.032
5821-04	Westin 2	1987	0.107
5821-05	Westin 4	1987	0.107
5821-06	Westin 5	1987	0.098
5822-02	Grammar school	1961	0.083
5824-01	Puhi 1	1975	0.158
5824-03	Puhi 2	1980	0.033
5824-05	Puhi 3	1990	0.213
5824-06	Puhi 4	1993	0.096
5923-01	Kilohana A	1974	0.248
5923-02	Kilohana B	1977	0.280
5923-03	Kilohana C	1978	0.057
5923-04	Kilohana F	1980	0.031
5923-05	Kilohana G	1981	0.150
5923-07	Kilohana I	1982	0.652
		Total	2.410
Outside basin			
5426-04	Koloa C	1977	0.575
5426-05	Koloa D	1981	0.770
5427-01	Koloa A	1953	0.177
5427-02	Koloa B	1964	0.311
5529-01	Huinawai Reservoir	1950	1.690
5530-03	Lawai 1	1962	0.193
5530-04	Lawai 2	1986	0.162
5533-01	Hanapepe Valley A	1974	0.552
5533-02	Hanapepe Valley B	1980	0.287
5534-03	Hanapepe Town	1966	0.029
5631-01	Kalaheo A-Diesel	1974	0.403
5631-02	Kalaheo B	1985	0.067
5635-01	Domestic Water	1947	1.373
5635-02	500 H.P. Irrigation	1969	0.806
		Total	7.395

Steady-State Simulations

Steady-state simulations represent the ground-water levels that would ultimately develop under a given set of conditions (rainfall, irrigation, and ground-water withdrawal), assuming enough time is allowed to achieve equilibrium. Three steady-state conditions were simulated in this study: (1) pre-development conditions, when no irrigation was applied in the study area and no ground water was being withdrawn from wells; (2) 1981 irrigation and ground-water-withdrawal conditions; and (3) 1998 irrigation and ground-water-withdrawal conditions. Normal rainfall was used in all three steady-state simulations. As discussed earlier, the level of discretization, together with the steep hydraulic gradients characteristic of the study area, limits the precision to which model ground-water levels can be made to match actual ground-water levels. The adjusted model simulates ground-water-level *differences*, however, with sufficient accuracy for the purposes of this study.

Figure 14 shows the difference in simulated steady-state ground-water levels between pre-development and 1981 conditions. Ground-water levels in the lowland areas between major streams are substantially higher in the simulation of 1981 conditions as a result of the recharge-enhancing effects of furrow irrigation (fig. 3). Steady-state ground-water levels beneath some irrigated areas are as much as 200 ft higher in the 1981 simulation than in the pre-development simulation. In some parts of the Kilohana-Puhi well field (fig. 1), irrigation raised simulated water levels by more than 50 ft. In areas of the southern Lihue Basin unaffected by furrow irrigation, ground-water levels in the 1981 simulation are slightly lower (as indicated by values less than zero in fig. 14) as a result of ground-water withdrawal. The effect of irrigation on simulated ground-water levels is, however, overwhelmingly greater than the effect of ground-water withdrawal.

Figure 15 shows the difference in simulated steady-state ground-water levels between 1981 and 1998 conditions. The largest difference is in the area between Huelia and Nawiliwili Streams, where water levels in the 1998 steady-state simulation are as much as 100 ft lower than in the 1981 steady-state simulation. This area corresponds to a part of the aquifer underlying fields that were taken out of sugarcane production between 1981 and 1998. The area is also downgradient from fields that were converted from furrow to drip irrigation between 1981 and 1998, and the Kilohana-Puhi wells, most of which were built from the 1970s to 1990s (fig. 3). In the area south of Huleia Stream, ground-water levels in the 1998 simulation are slightly higher than in the 1981 simulation. The higher water levels result from the decrease in ground-water withdrawal after pumping from an irrigation well south of the Lihue Basin was halted.

The steady-state simulations indicate that irrigation changes from pre-development to 1981 and from 1981 to 1998 had an overwhelming effect on ground-water levels in the southern Lihue Basin. In contrast, the changes in ground-water withdrawals during those periods had a much smaller effect on regional ground-water levels. The steady-state simulations represent the ground-water levels that would ultimately result if enough time is available for steady state to be achieved, but in reality, the ground-water system may not fully adjust to changes that occur quickly, or to stresses (such as droughts) that are of short duration. For example, it is possible that the difference in simulated ground-water levels between 1981 and 1998 shown in figure 15 did not, in reality, develop fully before conditions again changed with the onset of drought in 1998 and the end of sugarcane irrigation in 2000. Effects of this relatively rapid succession of changes are more effectively studied using transient simulations.

Transient Simulations

Transient simulations show how effects on ground-water levels develop over time. The rate at which an aquifer responds to irrigation, drought, and ground-water withdrawal is a function of aquifer porosity and storage — lower porosity and storage values correspond to faster aquifer response. Because aquifer porosity and storage are not precisely known, the effects were tested using a range of values. Laboratory testing and photograph analysis indicate that total porosity in the lava-flow aquifers in Hawaii ranges from about 5 to 50 percent, but effective porosity (n) may be lower by a factor of 10 (Hunt, 1996). Massive lava flows, such as those of the Koloa Volcanics and dike-intruded Waimea Canyon Basalt in the Lihue Basin, are likely to have even lower n. For the transient simulations in this report, n values of 1 and 10 percent were used. Specific storage (S_s) was varied between 10^{-6} ft^{-1} and 10^{-4} ft^{-1}, which is consistent with aquifer-test analyses by Gingerich (1999) and similar to the values used by Izuka and Oki (2002) in their transient simulations of ground-water withdrawals in the Lihue Basin.

Three sets of transient simulations, each representing a given combination of drought, irrigation, and ground-water-withdrawal conditions, were tested in this study. Within each set, values of n and S_s were varied. In all cases, the results of the steady-state simulation of 1981 conditions with normal rainfall were used as initial conditions, and various combinations of drought, irrigation, and ground-water withdrawal were applied as stresses. Changes in water level in an upper-layer cell (row 16, column 33) of the model were monitored to represent water-level changes in the Kilohana-Puhi well field. Changes in this water level were tracked through model-simulated time to study the rate of aquifer response to simulated stresses.

Independent effects of irrigation reduction and changes in ground-water withdrawal.—In the first set of transient simulations, the effect of irrigation reduction from 1981 to 1998 was isolated from the effects of drought and changes in ground-water withdrawal. Beginning with the results from the simulation of steady-state 1981 conditions with normal rainfall, recharge distribution was changed to that of 1998 irrigation and normal rainfall. Ground-water withdrawal was kept at 1981 rates, which is the same as that of the initial conditions. The simulation results indicate that the change

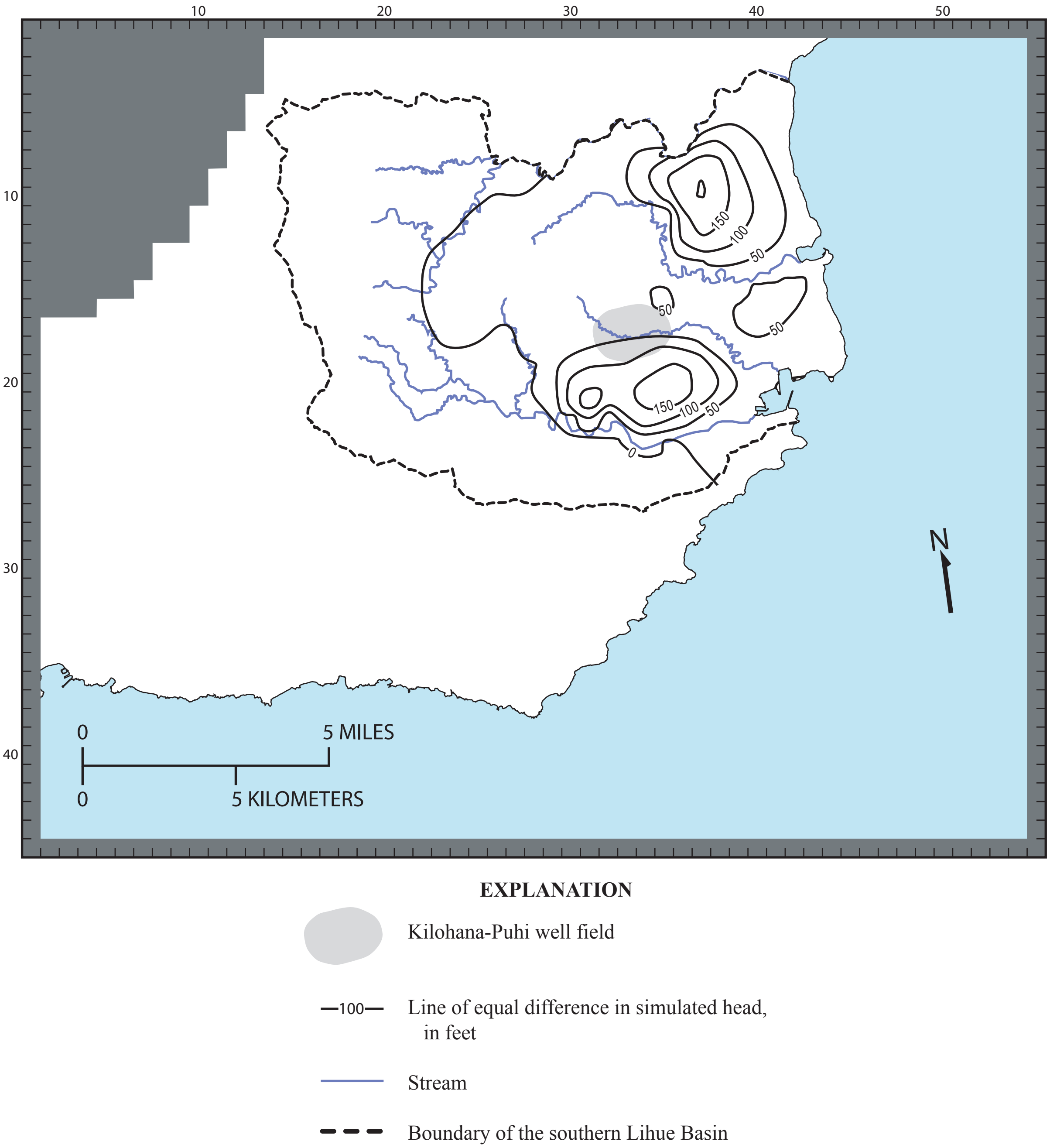


Figure 14. Difference in simulated steady-state ground-water levels between pre-development and 1981 conditions in the adjusted model of the southern Lihue Basin, Kauai, Hawaii. Positive values indicate that 1981 steady-state ground-water levels are higher than pre-development steady-state ground-water levels.

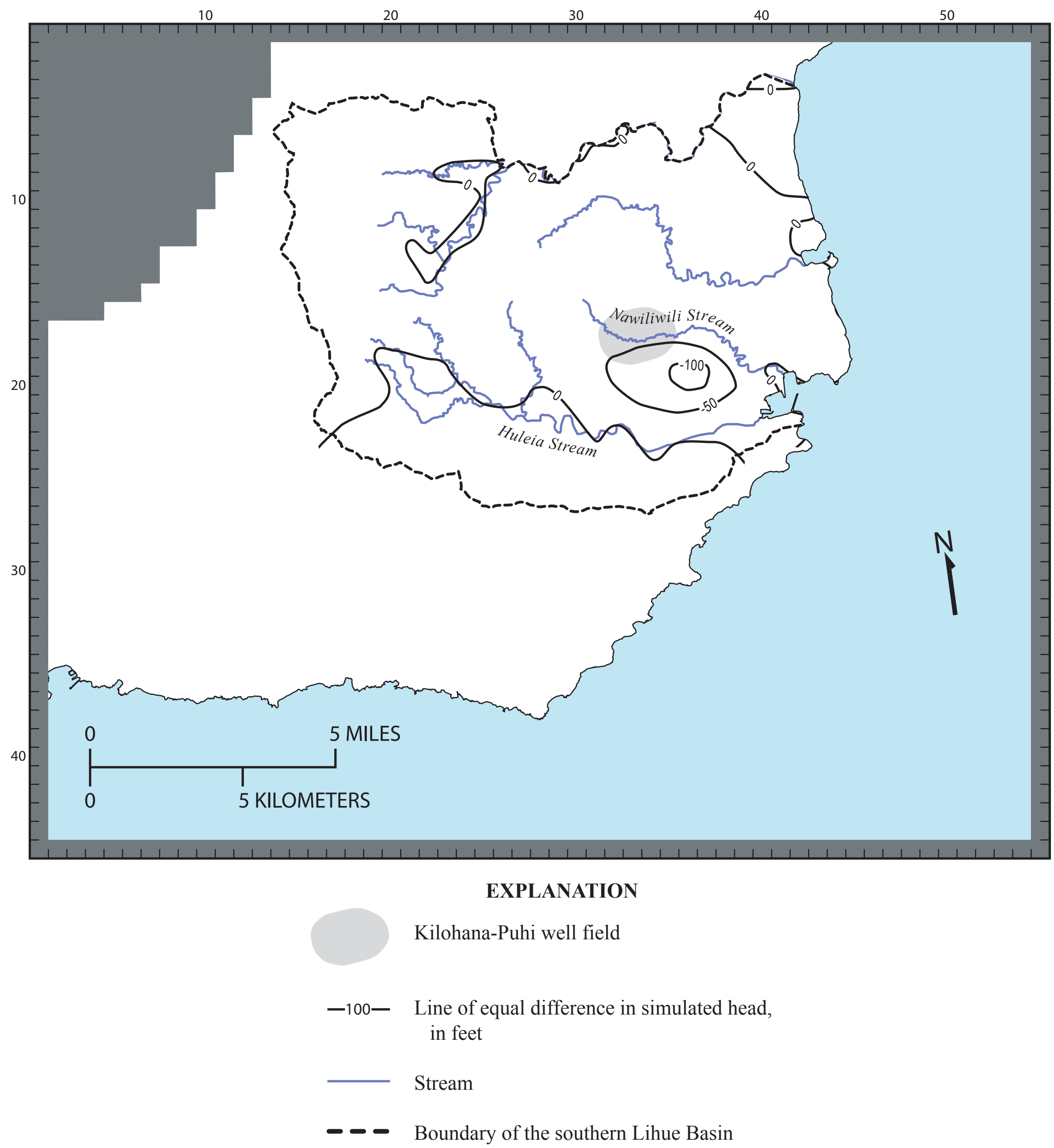


Figure 15. Difference in simulated steady-state ground-water levels between 1981 and 1998 conditions in the adjusted model of the southern Lihue Basin, Kauai, Hawaii. Negative values indicate that 1998 steady-state ground-water levels are lower than 1981 steady-state ground-water levels.

from 1981 to 1998 irrigation rates would cause water levels in the Kilohana-Puhi well field to decline by about 17 ft (fig. 16). With a simulated *n* of 1 percent and simulated S_s of 10^{-6} ft^{-1}, the decline would take about 2 years. With a simulated *n* of 10 percent and simulated S_s of 10^{-4} ft^{-1}, the water level would decline more gradually, achieving a decrease of 12 ft in 5 years and 16 ft in 10 years. Other combinations of *n* and S_s correspond to intermediate rates of decline.

In the second set of transient simulations, the effect of changing from 1981 to 1998 ground-water withdrawal rates was isolated from other effects (fig. 16). Recharge was maintained at the 1981 rate, which is the same as in the initial conditions. The simulations indicate that the change from 1981 to 1998 ground-water withdrawal rates would cause water levels in the Kilohana-Puhi well field to decline by less than 3 ft if this rate persisted for 20 years. These results indicate that the change in ground-water withdrawal between 1981 and 1998 had a smaller effect on ground-water levels in the Kilohana-Puhi well field than did the change in irrigation during the same period. These results are consistent with those of the steady-state simulations, which show that the recharge-enhancing effect of irrigation overwhelms the effect of changes in ground-water withdrawal.

Combined effects of drought, irrigation reduction, and changes in ground-water withdrawal.—The third set of transient simulations combined the effects of irrigation reduction, ground-water withdrawal changes, and drought in the sequence in which they occurred in history (table 8). The simulation results can be compared to actual measured water levels in the Kilohana-Puhi well field to assess whether the general trends and the timing of changes in trends were consistent. More than 20 years of water-level measurements are available from Kilohana well I, but water levels in the well show high-frequency fluctuations because the well is actively being pumped and is affected by pumping from nearby wells (Taogoshi and others, 2002). The measured water levels in Kilohana well I represent a single point in the well field, whereas the simulated ground-water levels represent an average of water levels within the area of a cell near Kilohana well I (fig. 10). To compare measured with simulated ground-water levels, the data from Kilohana well I were transformed by subtracting the average water level of Kilohana well I for the period of record from the individual water-level measurements, and smoothing the results using a moving average of the preceding 12 records (the average interval between records is 58 days). The simulated ground-water levels were also transformed by subtracting the average, but the results were not smoothed.

Figure 17 compares the transformed simulated ground-water levels with the curve of the transformed and smoothed water-level data from Kilohana well I. The discretization of recharge and ground-water withdrawal into blocks of time (table 8) contributes to the discrepancy between simulated and measured ground-water levels. Even so, the trends and timing of changes in trends shown in the model agree with those shown in the data from Kilohana well I. Both show a declining trend before 1998 that corresponds with reductions in irrigation resulting from removing nearby sugarcane fields from production and conversion of some fields from furrow to drip irrigation (fig. 3), and with increasing ground-water withdrawals from the Kilohana-Puhi well field. Near 1998, the downward trend of both the Kilohana well I and simulated water-level curves becomes steeper with the onset of drought. At the end of 2000, the downward trend of the simulated and measured ground-water levels becomes even steeper when irrigation was completely halted while the drought was still in effect. The combined effects of the drought and loss of irrigation, however, had only a brief effect on ground-water levels. After the end of the drought, both the measured and model-simulated water levels show a rise.

The transient simulations can also be used to assess how ground-water levels in the southern Lihue Basin will be affected in the future. Projecting the model simulations beyond the present shows that simulated water levels in the Kilohana-Puhi area continue to recover from the 1998-2002 drought and eventually attain a level that is within about 4 ft of

Table 8. Periods of irrigation, ground-water withdrawal, and rainfall in transient simulations of the adjusted ground-water model of the southern Lihue Basin, Kauai, Hawaii.

[NA, not applicable]

Conditions during simulated period	Duration (years)	Dates represented
Starting conditions (normal rainfall, 1981 irrigation rates, 1981 ground-water withdrawal rates)	NA	Pre-1982
Normal rainfall[1] 1998 irrigation rates, 1998 ground-water withdrawal rates	16	1982-1997
Drought, 1998 irrigation rates, 1998 ground-water withdrawal rates	3	1998-2000
Drought, no irrigation, 1998 ground-water withdrawal rates	2	2001-2002
Normal rainfall, no irrigation, 1998 ground-water withdrawal rates	38	2003-2040

[1] Rainfall in 1982-1987 at the Lihue Airport (National Climatic Data Center, 2006) averaged 41.11 inches per year, which is comparable to the long-term average for this gage (41.25 inches per year).

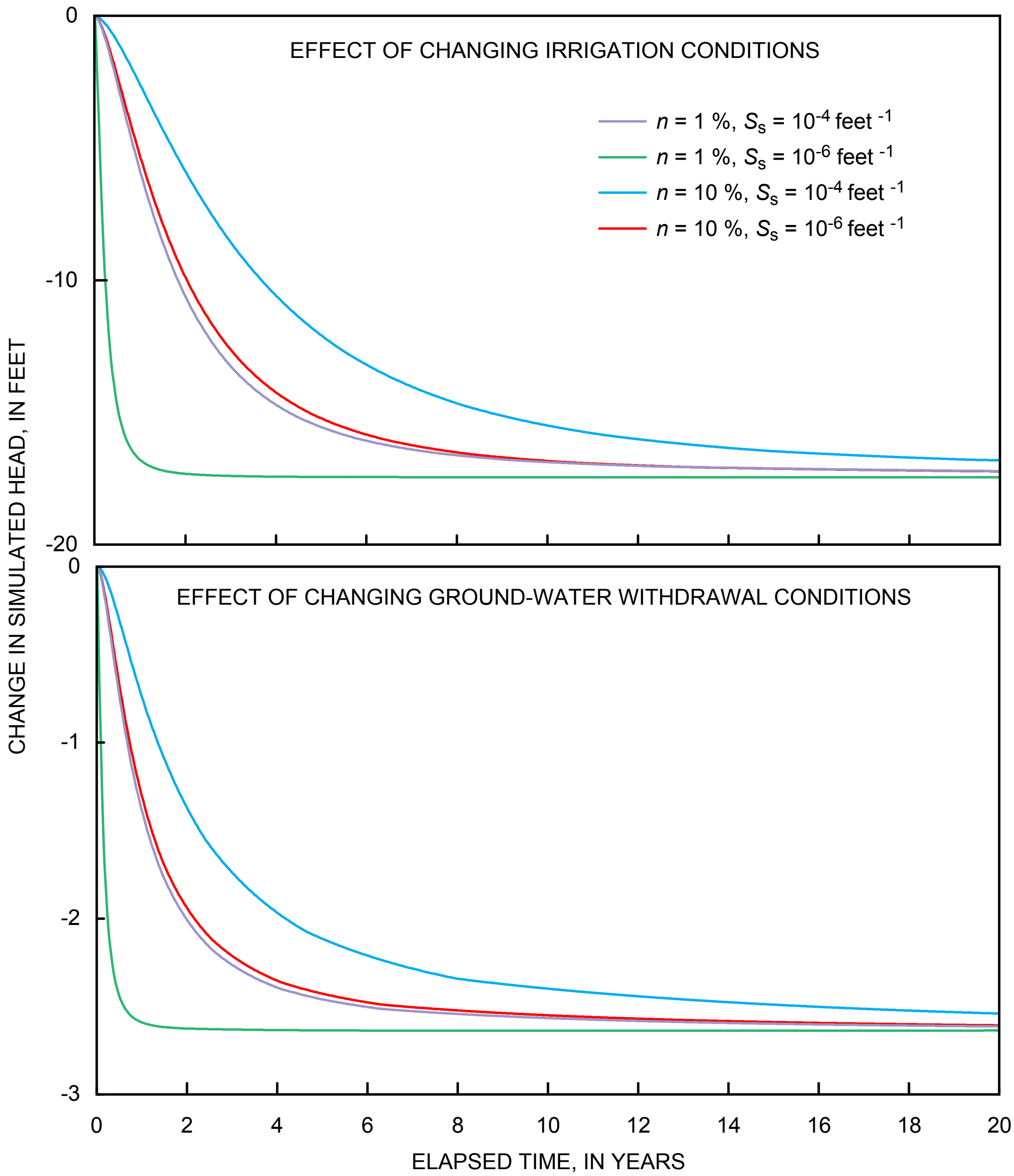


Figure 16. Simulated changes in water level in the Kilohana-Puhi well field resulting from reductions in irrigation and changes in ground-water withdrawals that occurred between 1981 and 1998. *n* is effective aquifer porosity, % is percent, and S_s is aquifer specific storage.

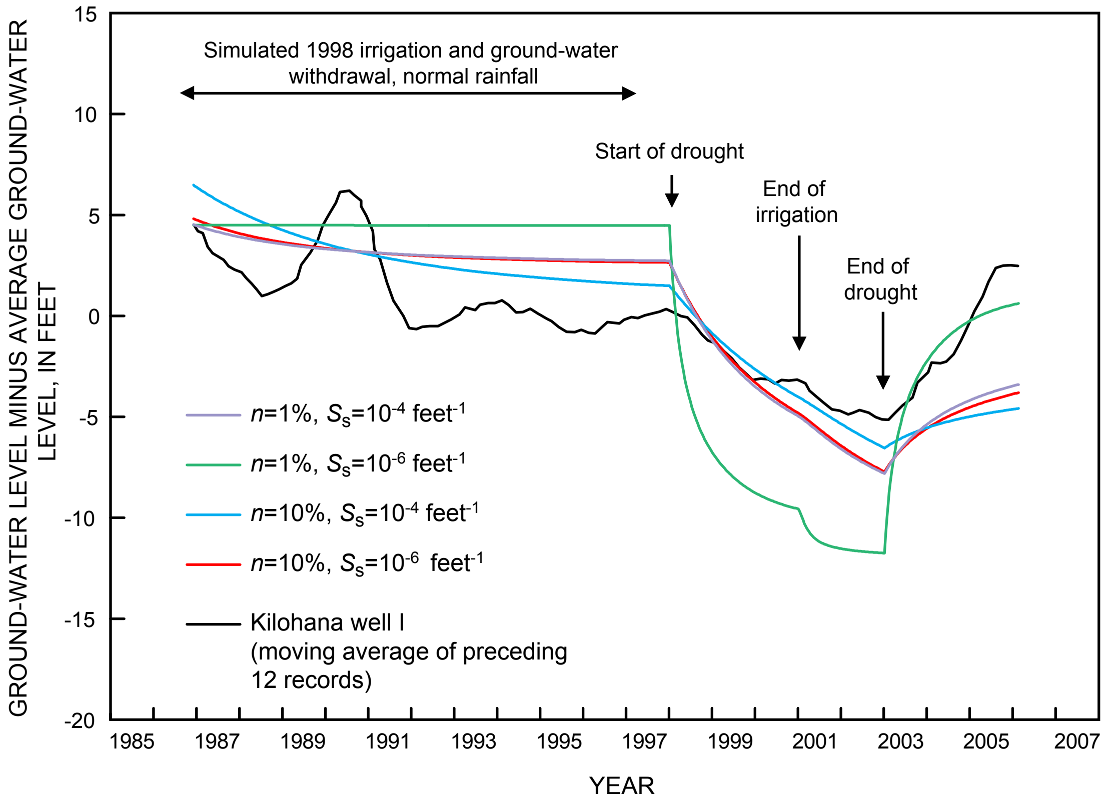


Figure 17. Comparison of measured water levels in Kilohana well I and model-simulated changes in water level at the Kilohana-Puhi well field, Kauai, Hawaii. *n* is effective aquifer porosity, % is percent, and S_s is aquifer specific storage.

the pre-drought conditions (fig. 18). The water levels do not recover fully to the pre-drought conditions, however, because of the loss of sugarcane irrigation. These projections assume that the last set of conditions simulated in the transient model (1998 ground-water withdrawal rates, normal rainfall, and no irrigation) persist for a long time. It is likely, however, that at least rainfall will vary on a cyclic basis, and droughts as well as high-rainfall periods will recur with corresponding fluctuations in ground-water levels.

Study Implications and Limitations

The steady-state and transient simulations both indicate that of the three factors examined in this study (drought, irrigation, and ground-water withdrawal), irrigation changes resulted in the largest effects on water levels in the area near the Kilohana-Puhi well field, when both magnitude and duration are considered. The drought of 1998-2002 contributed to the decline in simulated ground-water levels, but the effect was of limited duration; the simulations show (and recent measurements indicate) that ground-water levels in the area have risen with the return of normal and higher-than-normal rainfall. Ground-water withdrawal, despite increasing over the decades, had a much smaller effect on average water levels in the Kilohana-Puhi well field. These findings are consistent with the large effect irrigation had on ground-water recharge compared to the relatively small historical ground-water withdrawal in the Lihue Basin. Estimated ground-water recharge in the Lihue Basin under 1981 irrigation conditions was 52 Mgal/d greater than under pre-development conditions (table 1), whereas ground-water withdrawal from the entire Lihue Basin is currently only about 7 Mgal/d (Izuka and others, 2005).

These results indicate that the primary cause of the observed decline in water levels, at least in the Kilohana-Puhi wells, was the reduction and ultimate cessation of sugarcane irrigation in the late 20th century. Inasmuch as irrigation in the future will probably not return to the same levels as during the period of sugarcane agriculture, the decline in ground-water levels resulting from the reduction and loss of sugarcane irrigation can be considered permanent.

The possibility exists that long-term trends in climate will affect ground-water recharge, water levels, and availability of ground water in the future. Recent statistical analyses indicate that ground-water discharge to streams has decreased

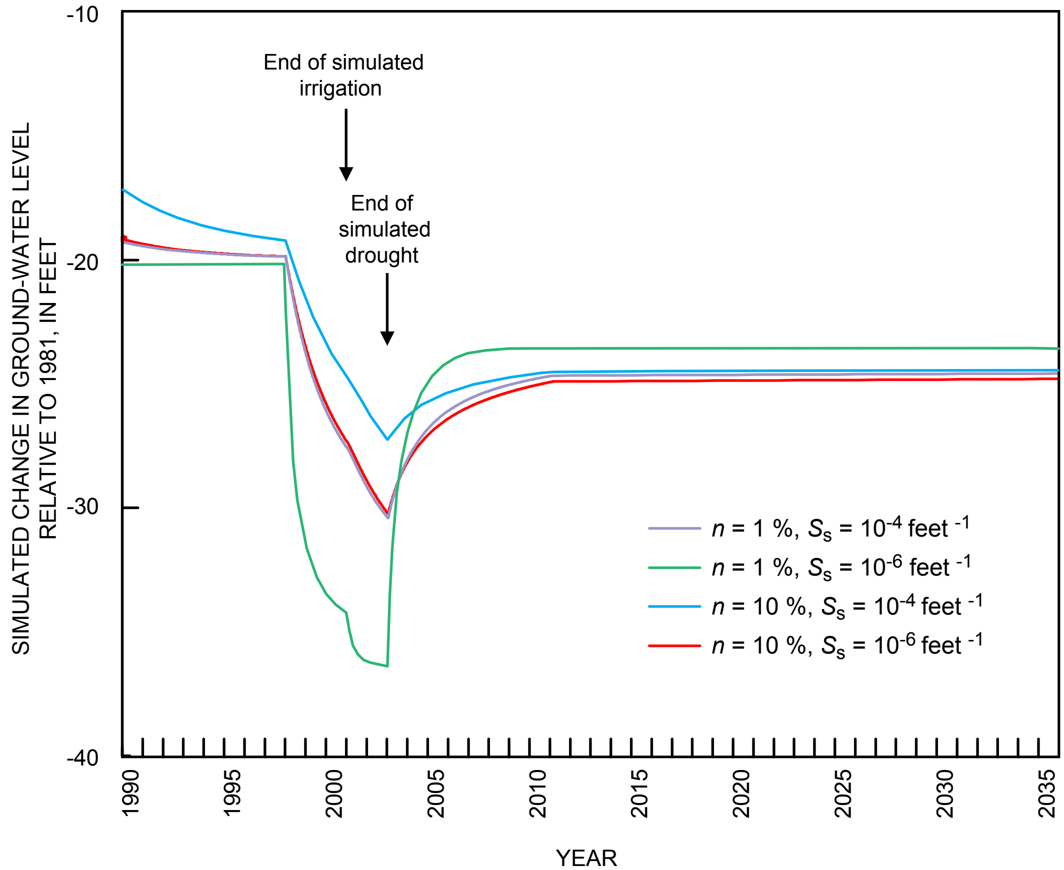


Figure 18. Projected future changes in water level in the Kilohana-Puhi well field, Kauai, Hawaii, assuming conditions that existed in 2003 remain unchanged. Changes are relative to 1981 water levels. *n* is effective aquifer porosity, % is percent, and S_s is aquifer specific storage.

from 1913 to 2002; the decrease is coincident with a downward trend in rainfall, and may indicate a long-term decline in ground-water storage and recharge (Oki, 2004). This potential downward trend was not simulated in the model.

The effect of increasing ground-water withdrawals beyond 1998 levels also was not simulated in this study. An increase in ground-water withdrawals would affect ground-water levels in the immediate vicinity of pumped wells, especially in the low-permeability rocks of the Lihue Basin. Whether or not regional ground-water levels will be substantially affected depends on the magnitude and location of the increases. The Kauai DOW and private landowners have worked cooperatively to develop surface-water resources in the Lihue Basin, which will reduce reliance on ground water as the source of drinking water.

Summary and Conclusions

Updated ground-water-withdrawal data and recharge estimates for various historical conditions were incorporated into a numerical ground-water-flow model of the southern Lihue Basin to determine whether the decline in ground-water levels observed in the 1990s to early 2000s is related to drought, decreases in sugarcane irrigation, and changes in ground-water withdrawal. Steady-state model simulations indicate that, given enough time, the recharge-enhancing effect of furrow-irrigation methods used in 1981 could have raised ground-water levels in some areas of the southern Lihue Basin by as much as 200 ft over pre-development levels. The increase in ground-water withdrawals during that same period would tend to lower ground-water levels, but the model simulations indicate that the effect is small relative to the overwhelming effect of irrigation. The steady-state simulations also indicate that, given enough time, the decrease in irrigation that occurred between 1981 and 1998 could theoretically lower ground-water levels in parts of the southern Lihue Basin by as much as 100 ft.

Transient simulations in which irrigation effects are examined independently from other effects indicate that the reduction in irrigation from 1981 to 1998 would have caused water levels in the Kilohana-Puhi well field to decline by about 17 ft; this decline would take from 2 to more than 20 years, depending on aquifer properties. Transient simulations in which ground-water-withdrawal effects are examined independently indicate that the changes in ground-water withdrawal between 1981 and 1998 would cause water levels in the Kilohana-Puhi well field to decline by less than 3 ft, even if this rate persisted for 20 years. These results are consistent with the overwhelming irrigation effect shown by the steady-state simulations.

Transient simulations combining historical irrigation reduction, ground-water withdrawal changes, and drought show trends in ground-water levels that correspond with trends in measured water levels in the Kilohana-Puhi well field. In both the measured and simulated ground-water levels, a declining trend between 1981 and 1998 corresponds to reductions in irrigation and increases in ground-water withdrawals. The downward trend becomes steeper at the onset of drought in 1998, and even steeper when sugarcane irrigation was halted in 2000. Measured and simulated ground-water levels both show a rise corresponding to the end of the drought in 2002. If the final conditions in the transient simulations (1998 ground-water withdrawal rates, normal rainfall, and no irrigation) persist, model projections indicate that water levels in the Kilohana-Puhi area will continue to recover from the drought and eventually attain a level that is within about 4 ft of the pre-drought conditions. Water levels on average will remain below pre-drought conditions, however, because of the loss of sugarcane irrigation.

The ground-water model simulations indicate that when both magnitude and duration are considered, the loss of irrigation had a larger effect on ground-water levels than either drought or increases in ground-water withdrawal, especially in the area near the Kilohana-Puhi well field in the southern Lihue Basin. Ground-water withdrawal effects are long in duration but small in magnitude, whereas drought effects are high in magnitude and widespread but of short duration. These results indicate that the primary cause of the observed decline in ground-water levels, at least in the Kilohana-Puhi wells, was irrigation reduction. Inasmuch as irrigation in the future will probably not return to the high levels prevalent during the 20th century, the decline in ground-water levels resulting from the reduction and loss of sugarcane irrigation can be considered permanent.

The possibility exists that long-term trends in climate will affect ground-water recharge, levels, and availability in the future. A possibility also exists that ground-water withdrawals will increase in the future. The effects of these changes on ground-water levels in the southern Lihue Basin were not addressed in this study.

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Appendix: Estimating Ground-Water Recharge for Areas Outside the Lihue Basin

Introduction

The ground-water recharge estimates of Izuka and others (2005) were limited to areas within the Lihue Basin. The numerical ground-water model of the southern Lihue Basin (Izuka and Gingerich, 1998), however, extended to areas outside of the basin (see fig. 10 in main text). In this study, estimates of ground-water recharge for areas outside the basin were computed using a regression analysis that relates recharge to mean annual rainfall. Rainfall is the primary form of precipitation on Kauai; fog can contribute significant amounts, but only in areas of limited extent. As a result, recharge is strongly correlated with mean annual rainfall. The strong correlation suggests that mean annual rainfall can be used as a predictor of recharge outside the basin if appropriate regression models can be developed from the recharge-rainfall relation of the water-budget analysis within the basin. The key premise of this approach is that regression equations developed from one area can be used to estimate recharge in another area. The transferability of equations from one area to another probably depends on the similarities in climate, land use, vegetation, and soil between the two areas. If these physical conditions differ from one area to another, the differences can be mitigated by adjustments or refinements to the regression equations.

Shade and Nichols (1996) used a similar approach to estimate ground-water recharge in parts of southern Oahu, Hawaii. Their analysis developed regression equations from an existing detailed water-budget analysis for southern Oahu by Giambelluca (1983, 1986). Shade and Nichols developed separate rainfall-recharge regression equations for both natural conditions and for conditions where significant additional water was brought in by irrigation or where xerophytic pineapple plants were present. They could ignore the effects of other factors, such as basin runoff characteristics, soil type, or contributions from other forms of precipitation, because their use of the equations was limited to estimating recharge in areas that were in close proximity to the water-budget study area.

Development of Regression Equations

Bivariate plots and regression equations for estimating ground-water recharge were developed on the basis of a detailed water-budget computed by Izuka and others (2005) for the Lihue Basin. The water-budget analysis of Izuka and others (2005) used a geographic-information-system (GIS) procedure to divide the Lihue Basin into 77,000 subareas (commonly referred to as polygons) having homogeneous precipitation, agriculture, runoff, and evapotranspiration characteristics. A daily water budget was computed for each subarea. These subareas were the basis for the regression analysis, one subarea constituting one data point in the regression. For the regression analysis, the number of subareas was reduced by eliminating subareas for which land use was unclassified or classified as bare land, unconsolidated shore, or water bodies. The number of subareas in the regression analysis was further reduced by eliminating multiple occurrences of identical X- and Y-value pairs.

The results of the 1981-irrigation, normal-rainfall scenario of Izuka and others (2005) were used to generate a bivariate plot of recharge versus mean annual rainfall (fig. A1). Data points tended to cluster along five main trends defined principally by five land-use/climate conditions: (1) non-agricultural subareas outside the fog zone, (2) non-agricultural subareas within the fog zone, (3) furrow-irrigated subareas, (4) drip-irrigated subareas, and (5) subareas with two or more irrigation methods.

Within the five major trends, data points tend to group even further, probably in relation to discretized parameters such as runoff-to-rainfall ratios, soil-water capacity, root depths, and evapotranspiration. Although most water-budget parameters in nature vary continuously from one location to the next, in the water-budget analysis by Izuka and others (2005) the parameters were discretized into regions of uniform value. For example, the trend of data points representing subareas within the fog zone has a different slope than does the trend of data points for areas outside the fog zone. This difference is primarily an artifact resulting from determining fog as a percentage of rainfall. To remove the artifacts resulting from discretizing runoff-to-rainfall ratios and fog distribution, fog was added and runoff subtracted from rainfall to yield mean annual soil infiltration. A plot of recharge versus mean annual soil infiltration (fig. A2) shows fewer groups, tighter clustering of data points, and a stronger correlation than the bivariate plot of recharge versus simple mean annual rainfall.

Figures A1 and A2 both show natural groupings of data points that reflect the presence or absence of irrigation, or differences in method of irrigation. Subareas of furrow-irrigated sugarcane plot along a trend that indicates significantly higher recharge than in other subareas, which is consistent with the known inefficiency of the furrow-irrigation method. On the other hand, data points representing drip-irrigated subareas plot in a cluster that is not much different from non-agricultural areas, which indicates that drip irrigation does not substantially enhance recharge. Subareas with mixed irrigation methods plot between the furrow-irrigation group and drip-irrigation group.

A closer look at the low-infiltration end of the bivariate plot of recharge versus infiltration shows that for non-agricultural areas, the data trend above a mean annual soil infiltration of about 50 in/yr has a steeper slope than below 50 in/yr

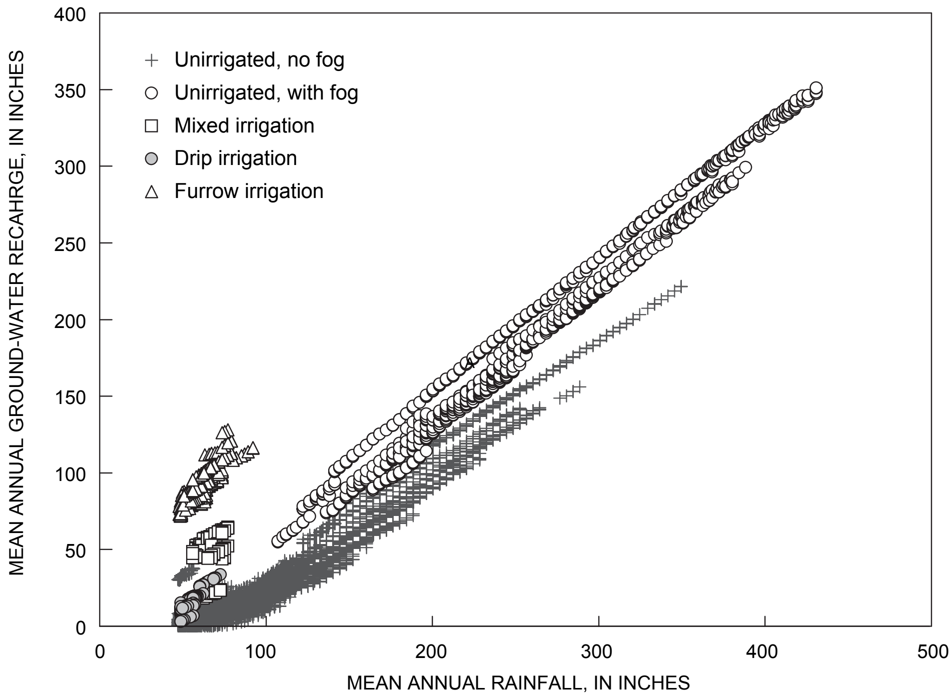

Figure A1. Bivariate scatter plot of ground-water recharge versus mean annual rainfall for subareas in the Lihue Basin, Kauai, Hawaii, from the water-budget analysis of Izuka and others (2005).

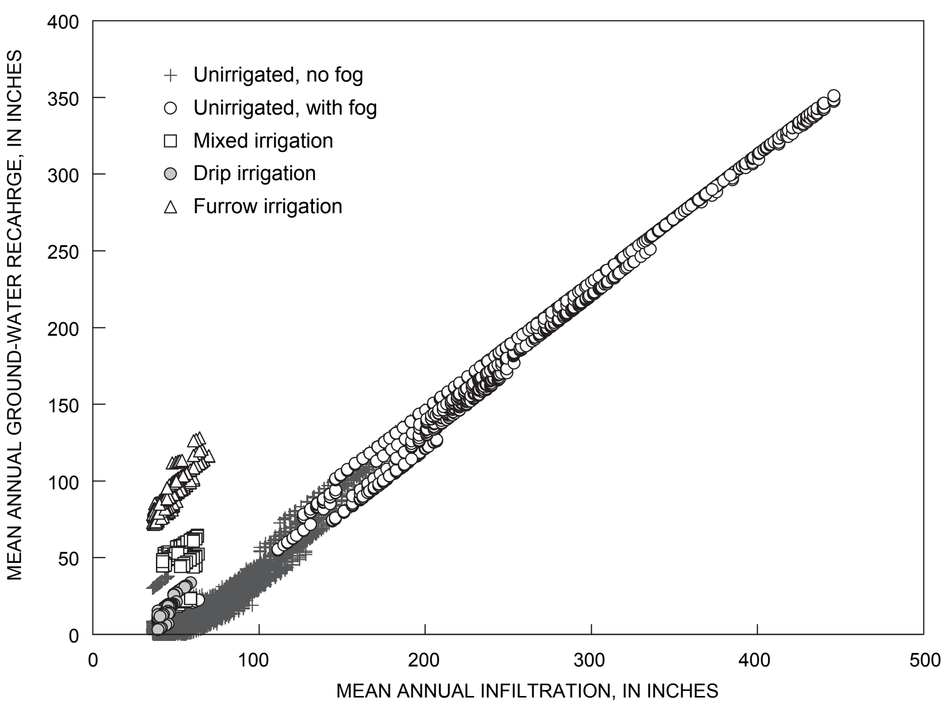

Figure A2. Bivariate scatter plot of ground-water recharge versus mean annual soil infiltration (rainfall plus fog minus runoff), for subareas in the Lihue Basin, Kauai, Hawaii, from the water-budget analysis of Izuka and others (2005).

(fig. A3), indicating that more than one regression line may be needed to adequately describe the infiltration-recharge relation. Previous studies have used multi-segment regression lines to describe the relation between rainfall and recharge in other areas of Hawaii. Shade and Nichols (1996) used as many as four regression line segments to describe the rainfall-recharge relation for non-agricultural areas of southern Oahu. Their regression line segments were discontinuous at the endpoints, however, which can lead to additional uncertainties beyond those inherent in normal continuous-function linear regression.

For the purpose of estimating ground-water recharge for areas of the model outside the Lihue Basin, regression equations were developed using mean annual soil infiltration as the independent variable. Regression equations were computed separately for (1) furrow-irrigated subareas, (2) drip-irrigated subareas, and (3) non-agricultural subareas. For non-agricultural subareas, a two-segment linear regression equation was developed. The two segments of the relation share a common breakpoint, thus eliminating the added uncertainty associated with the discontinuous equation of Shade and Nichols (1996). The equations for each segment were determined by testing all combinations of values for the X-axis intercept (from 0 to 100 in/yr, in increments of 1 in/yr) and X-value breakpoint separating the two linear segments (from X-axis intercept plus 1 to 200 in/yr, in increments of 1 in/yr). Slopes for each line segment were determined by least-squared-error analysis. The values for the X-axis intercept and X-value breakpoint that produced the highest R^2 value were selected. Coefficients for the three analyses developed in this study are summarized in table A1.

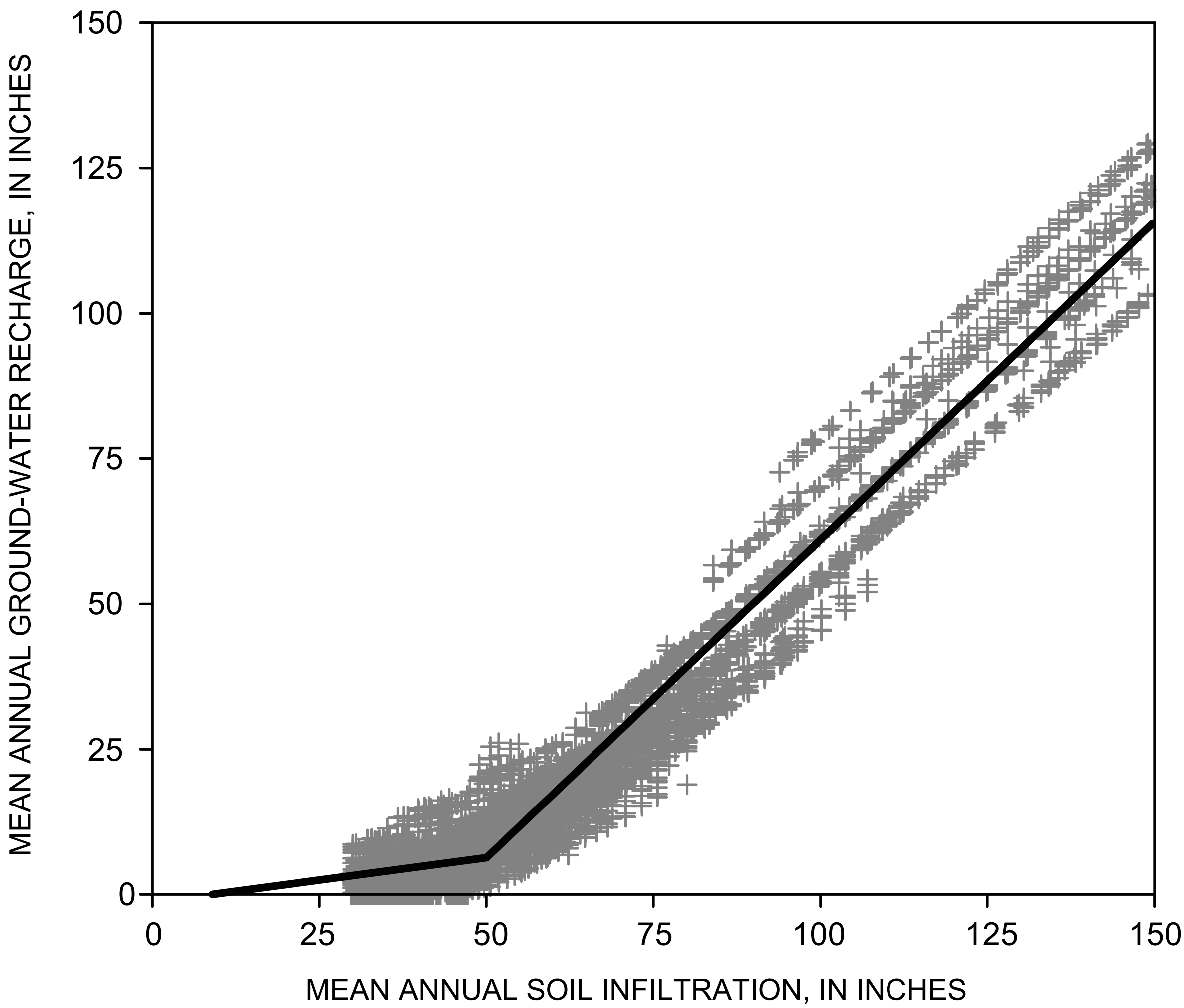

Figure A3. Bivariate scatter plot of ground-water recharge versus low values of mean annual soil infiltration (rainfall plus fog minus runoff), for subareas in the Lihue Basin, Kauai, Hawaii, from the water-budget analysis of Izuka and others (2005).

Table A1. Coefficients for regression equations to estimate ground-water recharge based on water-budget analysis by Izuka and others (2005) for the Lihue Basin, Kauai, Hawaii.

Regression equation	Regression		
	Slope	Intercept (inches)	R^2
Drip-irrigated subareas	1.571	-41.84	0.86
Furrow-irrigated subareas	1.647	24.94	0.83
Non-agricultural subareas	----	----	0.99
Mean annual infiltration greater than 9 inches and less than or equal to 50 inches	0.154	-1.38	----
Mean annual infiltration greater than 50 inches	1.095	-48.30	----

Testing the Regression Equations

Before using the regression equations to compute ground-water recharge for areas outside the Lihue Basin, the equations were tested to see how closely they could replicate the water-budget-based recharge results of Izuka and others (2005). Recharge was computed for the four scenarios shown in table A2 using the regression equations in table A1. Mean annual rainfall used as input to the regression analysis was based on maps by Giambelluca and others (1986). Mean annual infiltration was computed by adding fog drip to mean annual rainfall and subtracting runoff. Fog drip was computed as a fraction (0.18) of mean annual rainfall in areas higher than 2,000 m above sea level, which is the method Izuka and others (2005) used to estimate fog drip. Runoff was computed by multiplying mean annual rainfall by the average of the monthly runoff-to-rainfall ratios used by Izuka and others (2005); these ratios ranged from 0.29 to 0.35, depending on location in the basin. For drought scenarios, mean annual rainfall was reduced by multiplying by a factor of 0.64, which is equal to the factor Izuka and others (2005) used to simulate a moderate drought. To compute ground-water recharge for a given area, equations were selected depending on the presence or absence of irrigation, or the method of irrigation. If an area had more than one irrigation type, recharge was computed using the equations of all irrigation methods present in that area, and the results were averaged.

Table A2 summarizes results of the regression-based recharge analysis for the Lihue Basin and compares them with the results of the water-budget analysis of Izuka and others (2005). In two out of the four scenarios, the discrepancy between the regression-based and water-budget-based recharge estimates is less than 4 percent. Only in the scenarios representing drought conditions was the discrepancy greater than 4 percent; even so, the discrepancy was not large.

Using the Regression Equations to Estimate Ground-Water Recharge Outside the Lihue Basin

The area of the ground-water-flow model outside the Lihue Basin lies between Haupu Ridge and the Hanapepe River (see fig. 10 in text). This area was included in the model only so that the model boundaries would coincide with defensible hydrologic boundaries (Izuka and Gingerich, 1998). Because the area was coarsely discretized and the hydrologic parameters were broadly generalized, only a broadly generalized representation of the recharge distribution is required for this part of the model. The regression-based approach for estimating recharge is considered adequate for this purpose.

Table A2. Comparison of regression-based and water-budget-based estimates of ground-water recharge for 1981 irrigation conditions in the Lihue Basin, Kauai, Hawaii.

Recharge scenario	Recharge (million gallons per day)		Percent difference
	Water budget analysis of Izuka and others (2005)	Regression	
1981 irrigation, normal rainfall	264	261	-1.1
1981 irrigation with drought	131	125	-4.6
No irrigation, normal rainfall	212	211	-0.5
No irrigation with drought	84	88	4.8

Furrow irrigation is not currently used in this area, and the irrigation of coffee in the area probably contributes only a minor amount to ground-water recharge. Therefore, the equation developed for non-agricultural subareas (table A1) is adequate for estimating the broadly generalized recharge distribution needed for this section of the ground-water-flow model. The distribution of soil infiltration required for the regression analysis was computed by adding fog drip and subtracting runoff from the mean annual rainfall distribution maps of Giambelluca and others (1986). Infiltration was computed for both normal rainfall and drought conditions. For normal rainfall conditions, the mean annual rainfall distribution of Giambelluca and others (1986) was left unchanged. For drought conditions, mean annual rainfall was multiplied by a factor of 0.64. Contribution from fog drip was estimated by multiplying rainfall by a factor of 0.18 for all areas above 2,000-ft elevation. Runoff was estimated by applying a runoff-to-rainfall ratio (0.28), computed for the Hanapepe River using hydrograph-separation results for USGS stream gages 1604900 and 1604300 (Izuka and Gingerich, 1998), to rainfall within the drainage area estimated from the maps of Giambelluca and others (1986).

A GIS was used to merge the regression-based estimates with the water-budget-based estimates of Izuka and others (2005) for areas within the Lihue Basin. The GIS was also used to merge the recharge distribution with the grid of the ground-water-flow model and compute the recharge for each cell in the grid by taking the area-weighted average of all recharge subareas (polygons) within the cell. Resulting distributions of recharge used for simulating various combinations of irrigation and rainfall conditions in the adjusted southern Lihue Basin model are shown in figure A4 .

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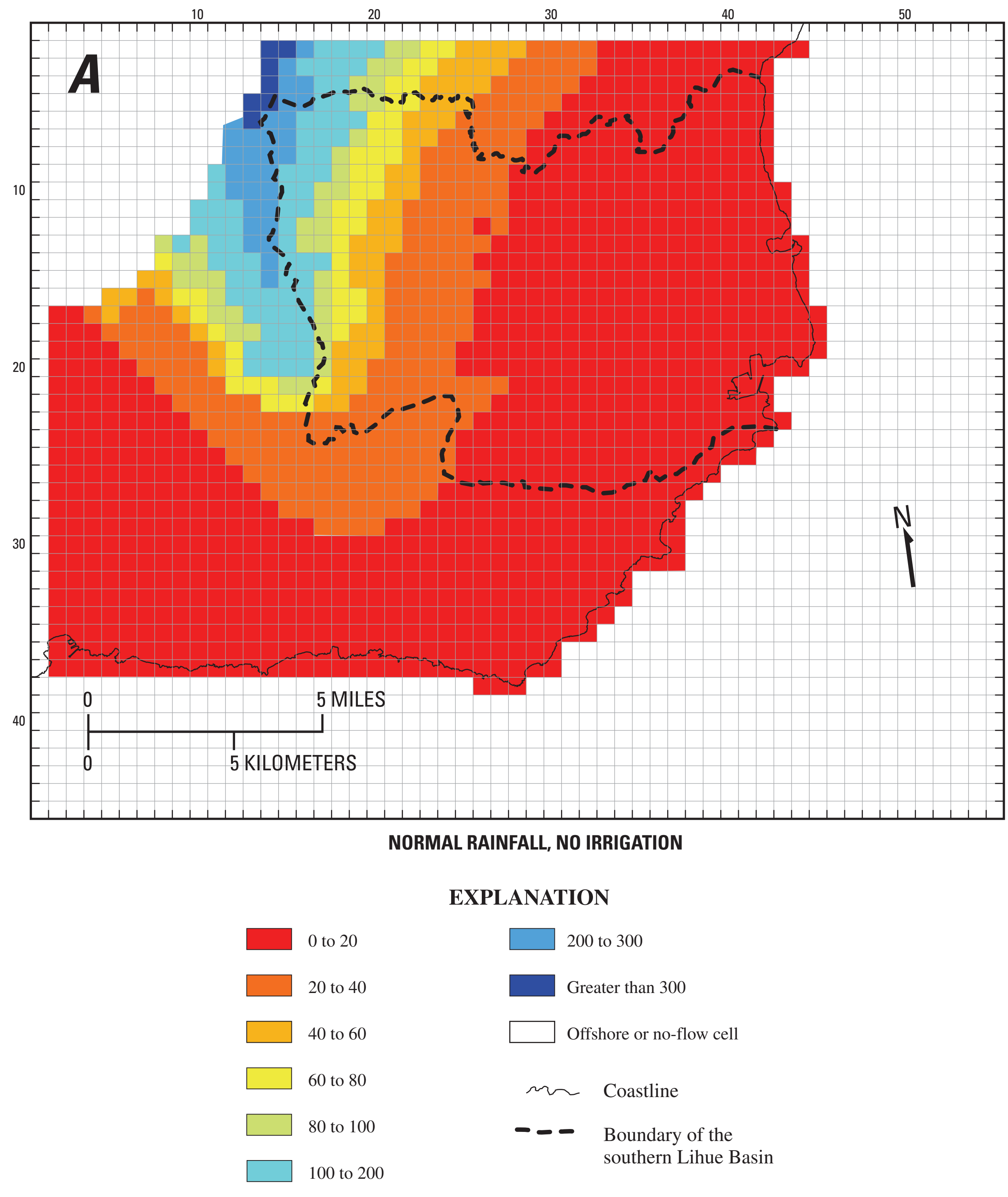
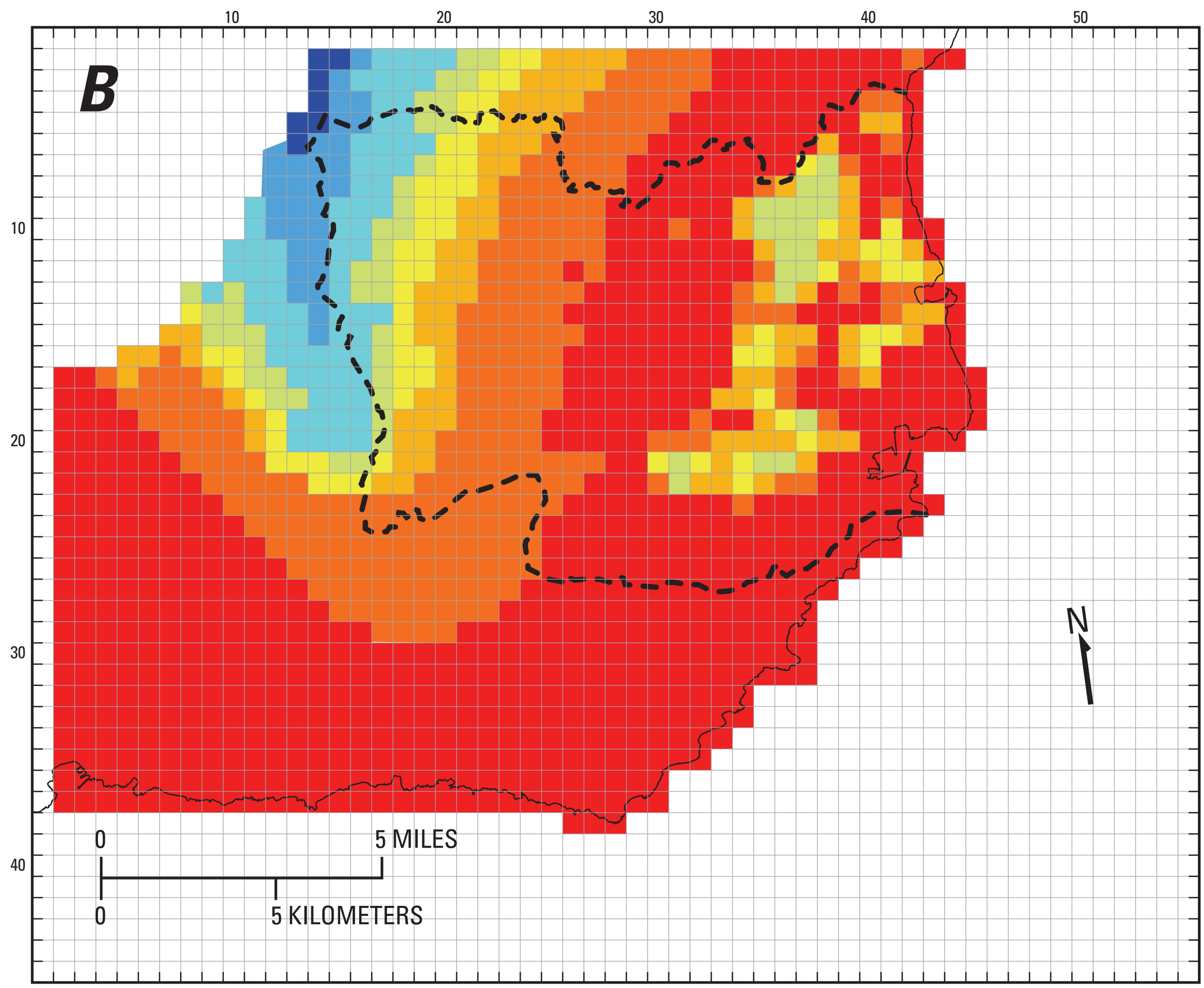


Figure A4. Distributions of ground-water recharge (in inches per year) in adjusted ground-water model of the southern Lihie Basin, Kauai, Hawaii, used to simulate conditions of normal rainfall with no irrigation (*A*), normal rainfall and 1981 irrigation (*B*), normal rainfall and 1988 irrigation (*C*), drought with no irrigation (*D*), drought and 1981 irrigation (*E*), and drought and 1988 irrigation (*F*).



NORMAL RAINFALL, 1981 IRRIGATION

EXPLANATION

- 0 to 20
- 20 to 40
- 40 to 60
- 60 to 80
- 80 to 100
- 100 to 200
- 200 to 300
- Greater than 300
- Offshore or no-flow cell
- Coastline
- Boundary of the southern Lihue Basin

Figure A4.—Continued.

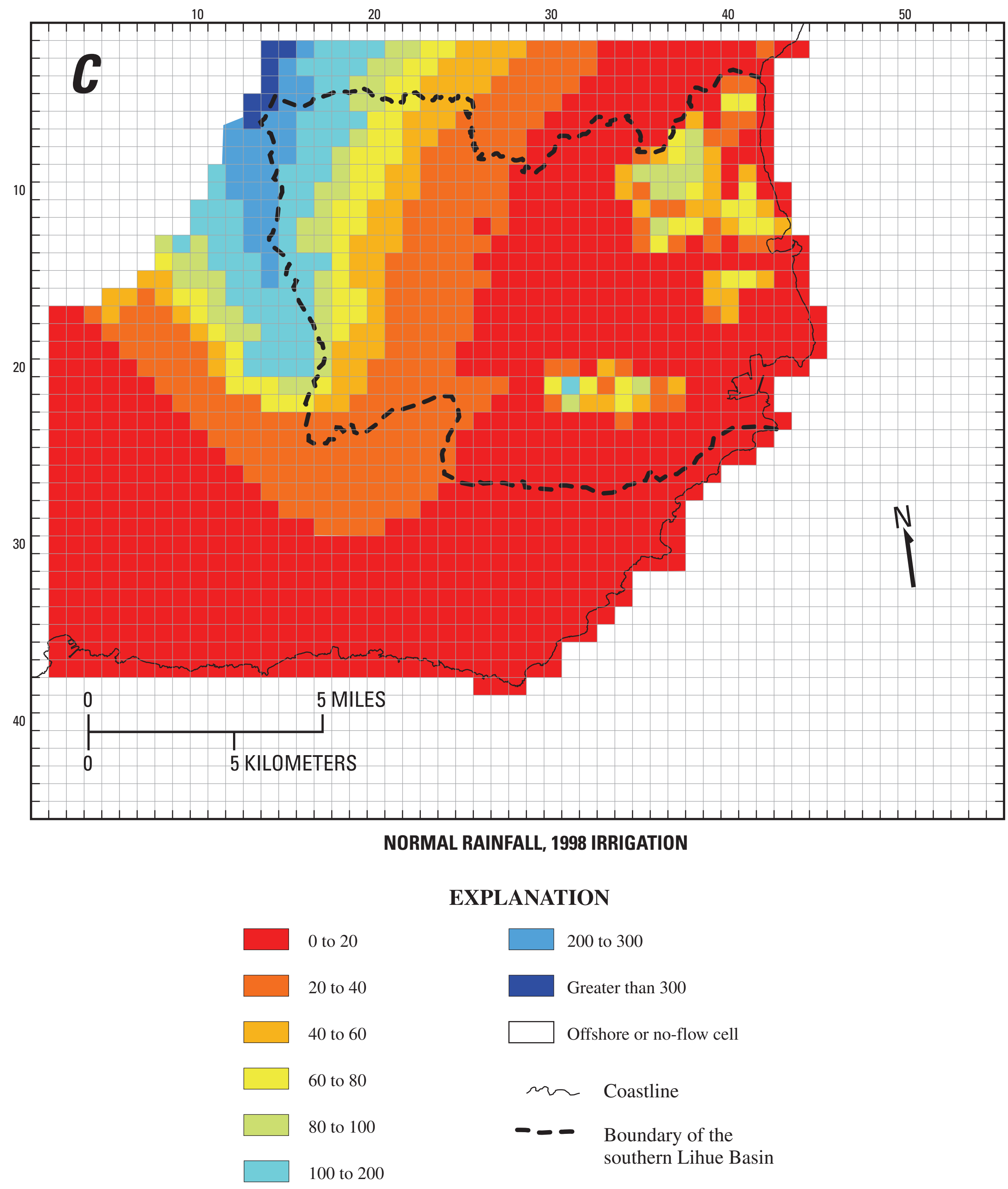
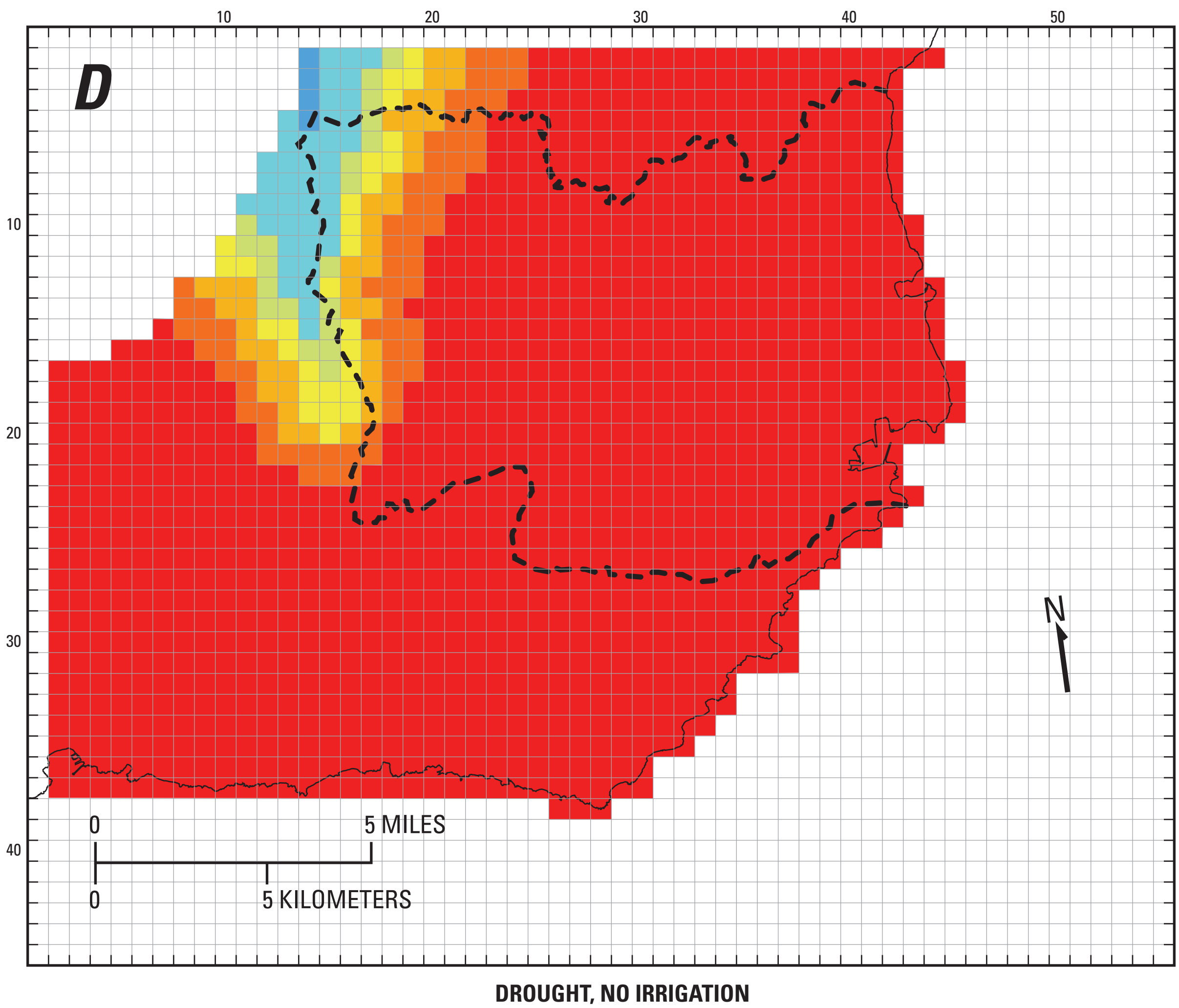


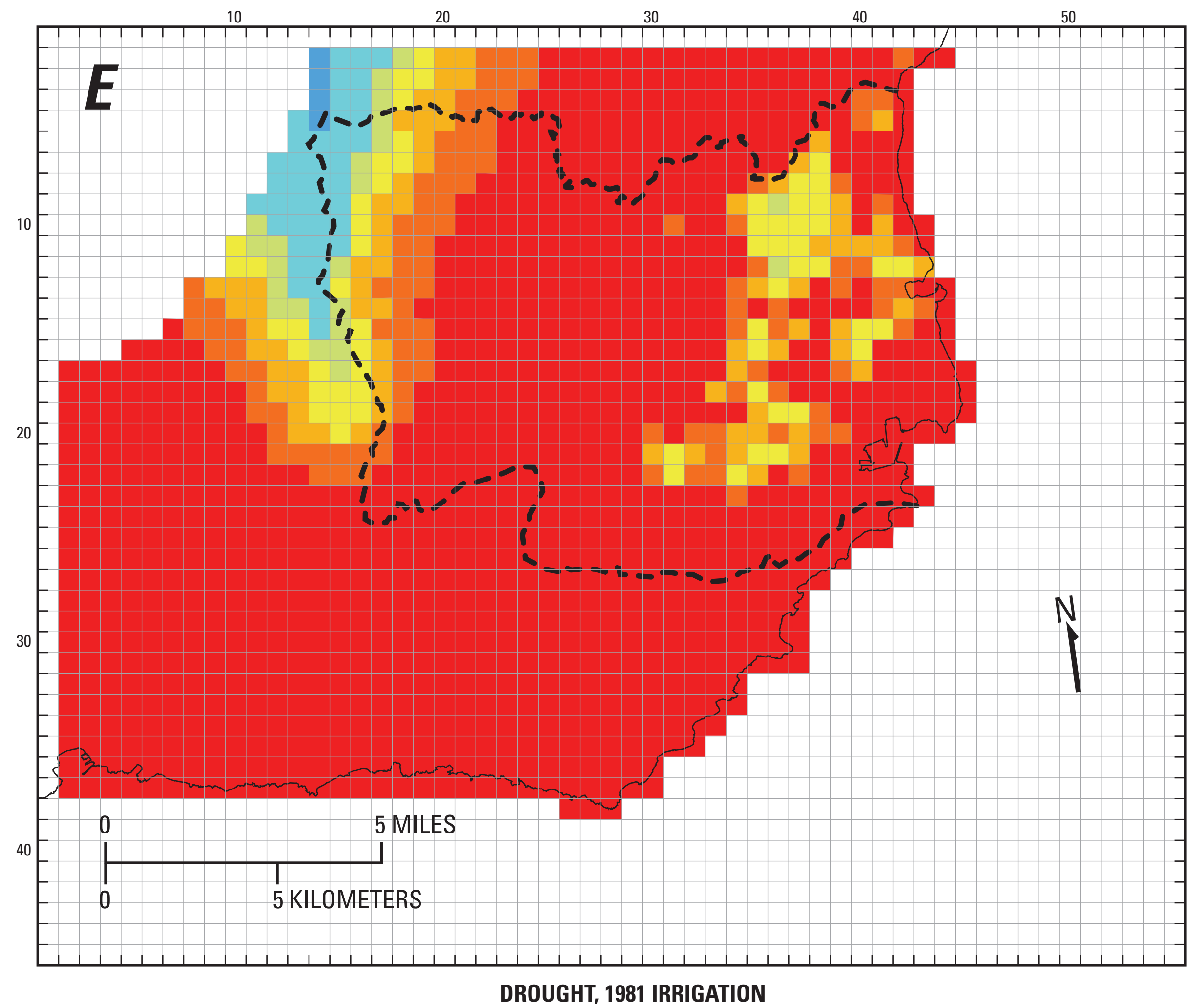
Figure A4.—Continued.



EXPLANATION

- 0 to 20
- 20 to 40
- 40 to 60
- 60 to 80
- 80 to 100
- 100 to 200
- 200 to 300
- Greater than 300
- Offshore or no-flow cell
- Coastline
- Boundary of the southern Lihue Basin

Figure A4.—Continued.



EXPLANATION

0 to 20
20 to 40
40 to 60
60 to 80
80 to 100
100 to 200
200 to 300
Greater than 300
Offshore or no-flow cell
Coastline
Boundary of the southern Lihue Basin

Figure A4.—Continued.

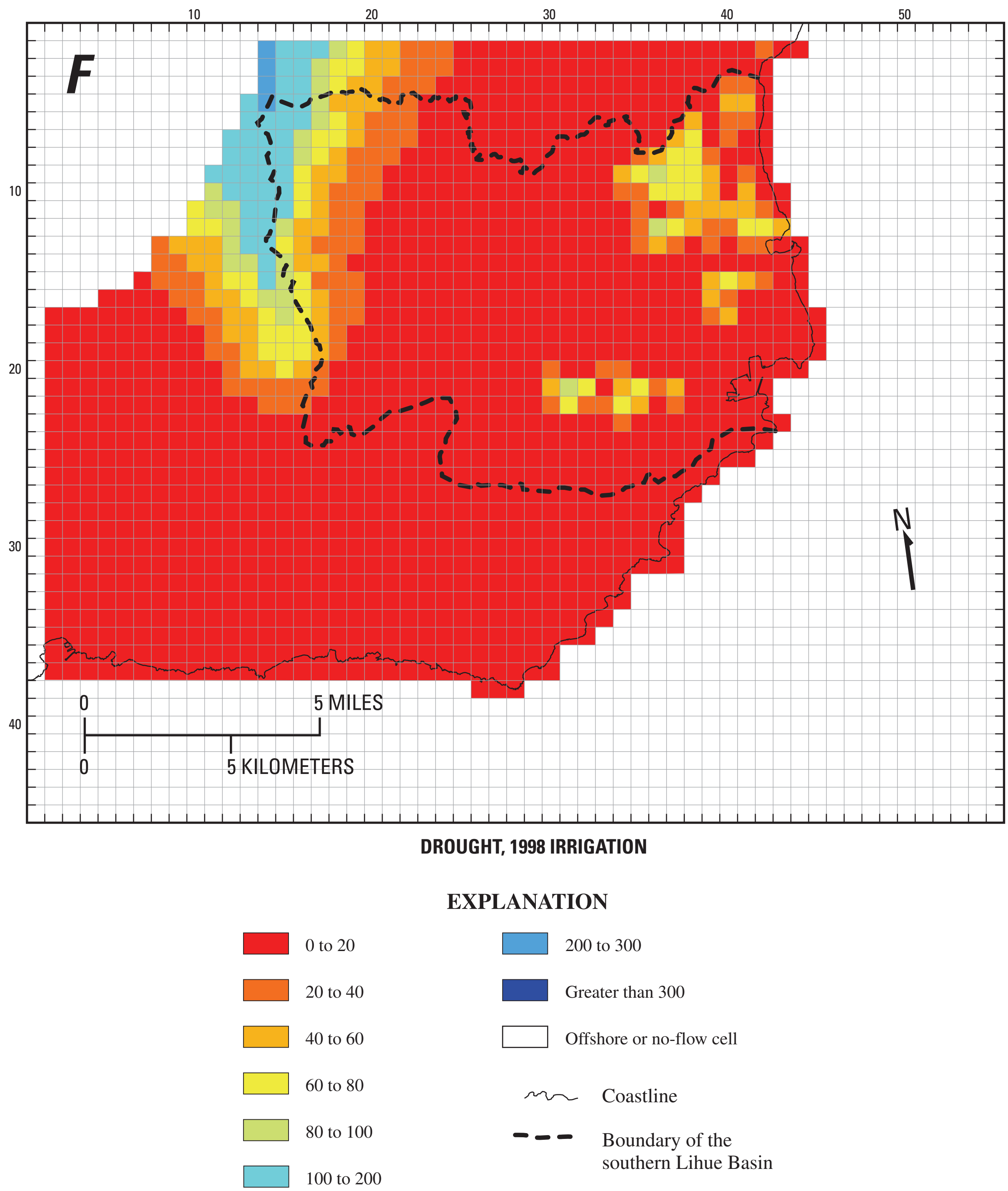


Figure A4.—Continued.

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