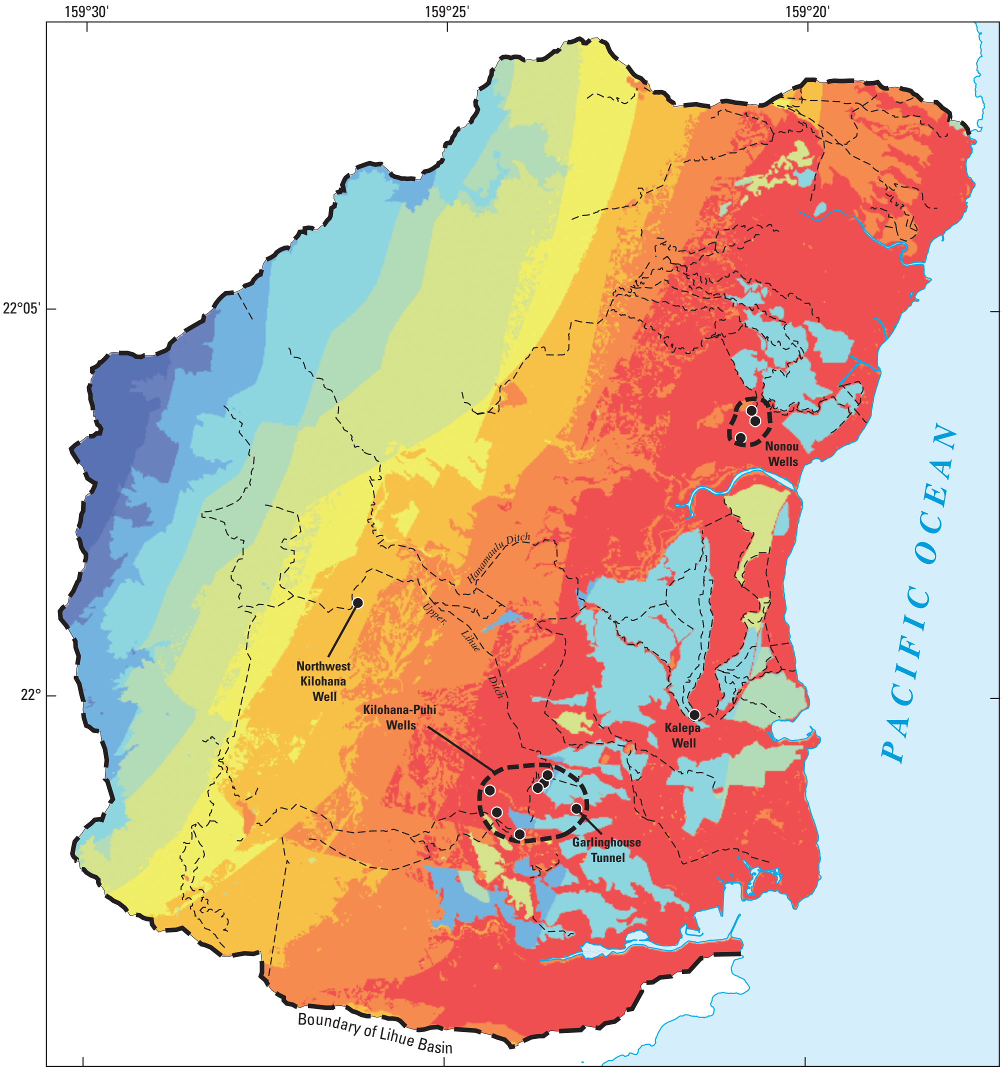
Prepared in cooperation with the County of Kauai Department of Water

Effects of Irrigation and Rainfall Reduction on Ground-Water Recharge in the Lihue Basin, Kauai, Hawaii



Scientific Investigations Report 2005-5146

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

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U.S. Department of the Interior
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Conversion Factors, Datums, and Acronyms

Conversion Factors

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

Datums

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.

Acronyms

Acronyms	Meaning
AWC	Available water capacity
CSC	NOAA Coastal Services Center
CWRM	Hawaii State Commission on Water Resource Management
DEM	Digital Elevation Model
Kauai DOW	County of Kauai Department of Water
GIS	Geographic Information System
HSPA	Hawaii Sugar Planters' Association
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
SPI	Standard precipitation index
USGS	U.S. Geological Survey

Effects of Irrigation and Rainfall Reduction on Ground-Water Recharge in the Lihue Basin, Kauai, Hawaii

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Abstract

Recent declines in water levels and productivity in some wells and tunnels in the Lihue Basin, Kauai, Hawaii, have raised concerns about the future reliability of ground-water sources. The trend of declining water levels coincides not only with increases in ground-water development, but also with decreases in applied irrigation and periods of lower-than-average rainfall. Water-balance computations indicate that the sugarcane industry had, at its peak, artificially increased recharge by about 25 percent over natural conditions. Periods of decreased precipitation and irrigation, concurrent with declines in observed ground-water-levels, caused substantial reductions in ground-water recharge relative to periods of normal rainfall and full irrigation. Simulations of recent decreases in irrigation, a recent drought, and hypothetical future scenarios of droughts and irrigation cessation indicated basin-wide recharge decreases of 7 to 83 percent relative to the condition of normal rainfall and full irrigation.

For the period during the observed decline in ground-water levels, the water-balance simulations indicate that the effect of the recent drought was greater than the effect of reduced irrigation. Effects of droughts, however, are temporary conditions that will eventually be mitigated by wet periods, whereas loss of irrigation in the Lihue Basin may be permanent and have a greater long-term effect. Effects of irrigation also may appear to be small relative to basin-wide recharge, but the effects of irrigation changes are concentrated in former irrigated sugarcane fields, and many wells with recent declining water levels are near these former sugarcane fields.

Introduction

The Lihue Basin (fig. 1) is the location of the seat of government and much of the industry on the island of Kauai. Nearly one-half of Kauai's population of 58,000 lives in the Lihue Basin (U.S. Census Bureau, 2005). Nearly all public drinking water supplied by the County of Kauai Department of Water (Kauai DOW) in the Lihue Basin comes from wells and tunnels that develop ground water from a volcanic-rock aquifer, much of which has low regional permeability (Izuka and Gingerich, 1998). The few high-producing wells and tunnels that exist are critical to public water supply in the Lihue Basin. Declining water levels and productivity in some of these high-producing wells and tunnels in recent years have raised concerns about the future reliability of ground-water sources. For example, productivity of the Garlinghouse Tunnel, a major source of drinking water, has decreased by about 50 percent since the 1980s. Water levels in other wells in the Kilohana-Puhi area and near Nonou Ridge, which include the most productive wells in the Lihue Basin, also have shown recent trends of declining water levels (fig. 2). Water levels in some non-pumped wells several miles from active production wells also show recent declines.

A number of natural and anthropogenic factors are approximately concurrent with the declining ground-water levels. For example, production in the Garlinghouse Tunnel decreased soon after construction of the other Kilohana-Puhi wells upgradient of the tunnel. The decrease in ground-water production from the tunnel, however, also was concurrent with extended periods of below-average precipitation, and a reduction in irrigation when the sugarcane industry converted to more efficient irrigation methods and later ceased operations. These events may have exacerbated the decline in ground-water levels by reducing ground-water recharge. To assess the effects of reductions in irrigation and rainfall on ground-water recharge in the Lihue Basin, the U.S. Geological Survey (USGS), in cooperation with the Kauai DOW, undertook a study to compute recharge for conditions that existed prior to and during the period of observed ground-water level decline, as well as for conditions that are plausible for the near future.

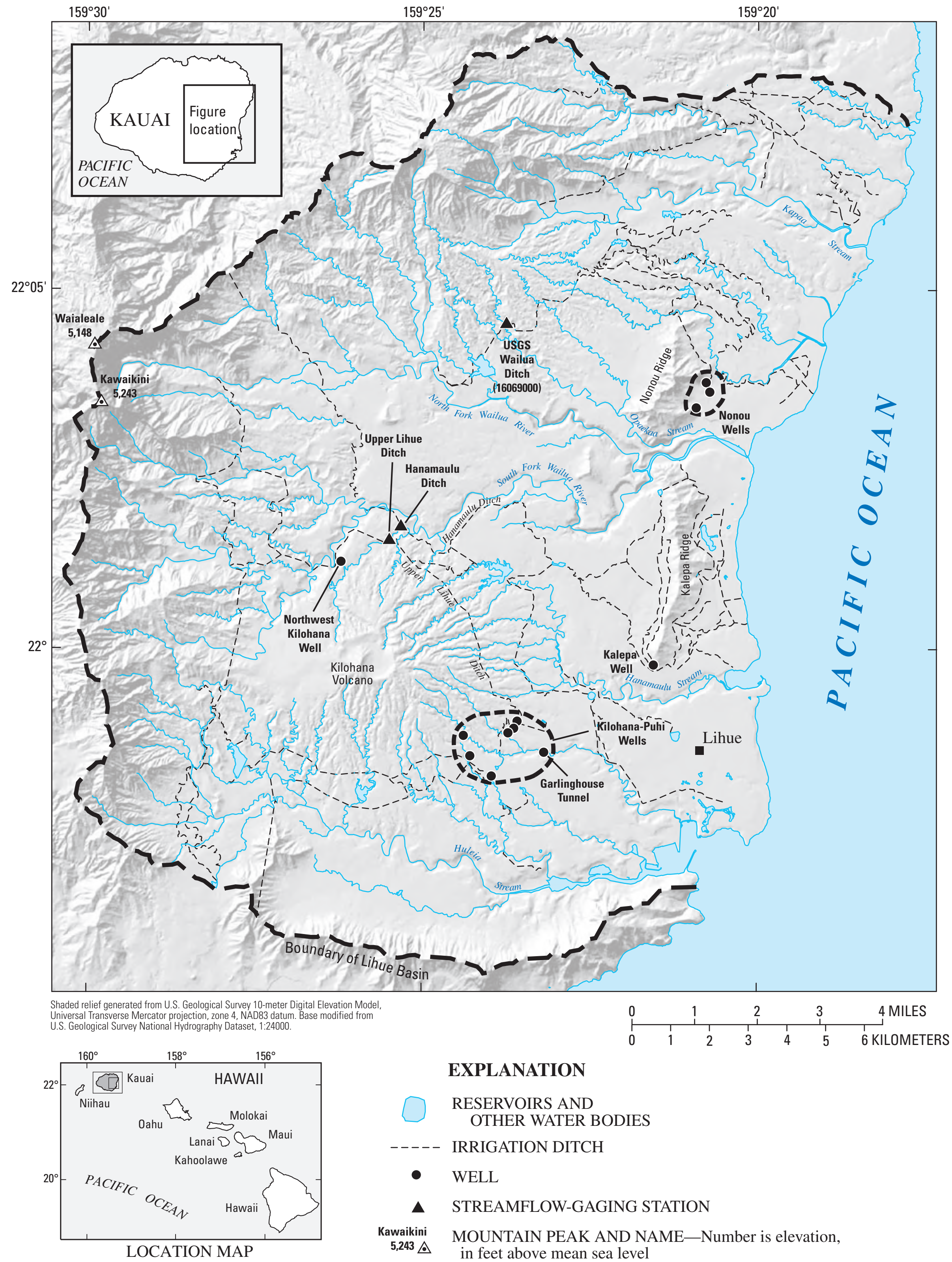


Figure 1. The Lihue Basin, Kauai, Hawaii.

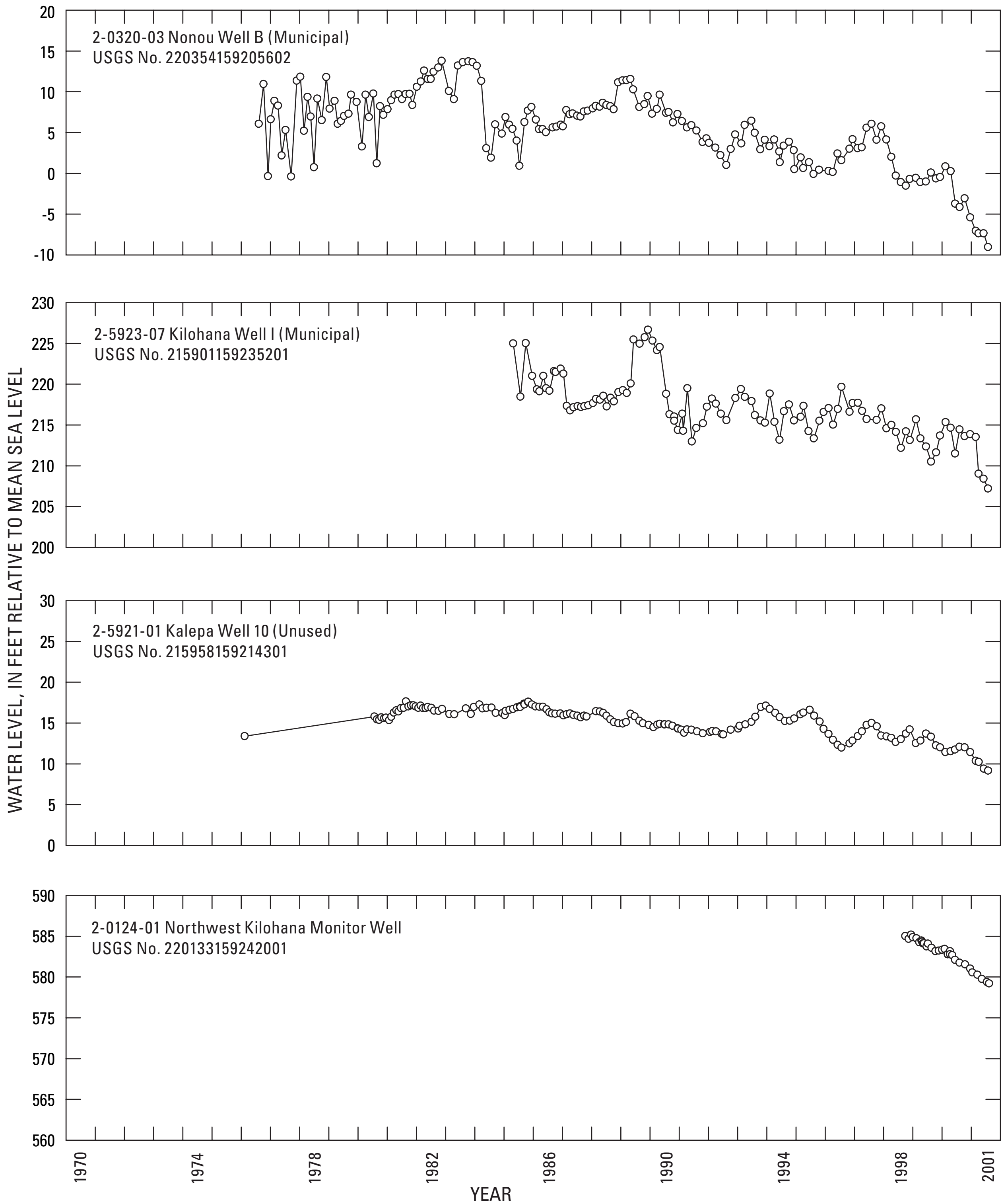


Figure 2. Water levels in selected wells in the Lihue Basin, Kauai, Hawaii.

Purpose and Scope

This report describes the effects of land-use changes, irrigation reduction, and drought on ground-water recharge in the Lihue Basin. Because the original motivation for the study was concern about the declining ground-water levels observed in some wells, the report begins with a comparison of ground-water levels to factors that affect those water levels, but the comparisons are limited to general trends. This report focuses on water-balance computations and resulting ground-water recharge estimates, and their implications for the effects of land-use changes, irrigation reduction, and drought on ground-water recharge in the Lihue Basin.

Acknowledgments

Edward Tschupp, current Manager and Chief Engineer, Ernest Lau, former Manager and Chief Engineer, and the staff of the Kauai DOW provided critical support and assistance for this study. Michael Furukawa (Grove Farm Inc. and the Lihue Land Company) and Dorothy Beckeart (formerly of Amfac Sugar – Lihue Plantation Company) assisted in accessing sugarcane plantation records and providing general information on irrigation practices. Neal Fujii and Kevin Gooding at the Hawaii State Commission on Water Resource Management (CWRM) provided data on ground-water development and withdrawals. Kevin Kodama, National Weather Service (NWS), provided rainfall data and analysis of the standard-precipitation index for the Lihue Airport. Richard A. Fontaine, Connie M. Hoong, Michael T. Moreo, and Jeff A. Perreault of the USGS contributed to the preparation of this report.

Description of Lihue Basin

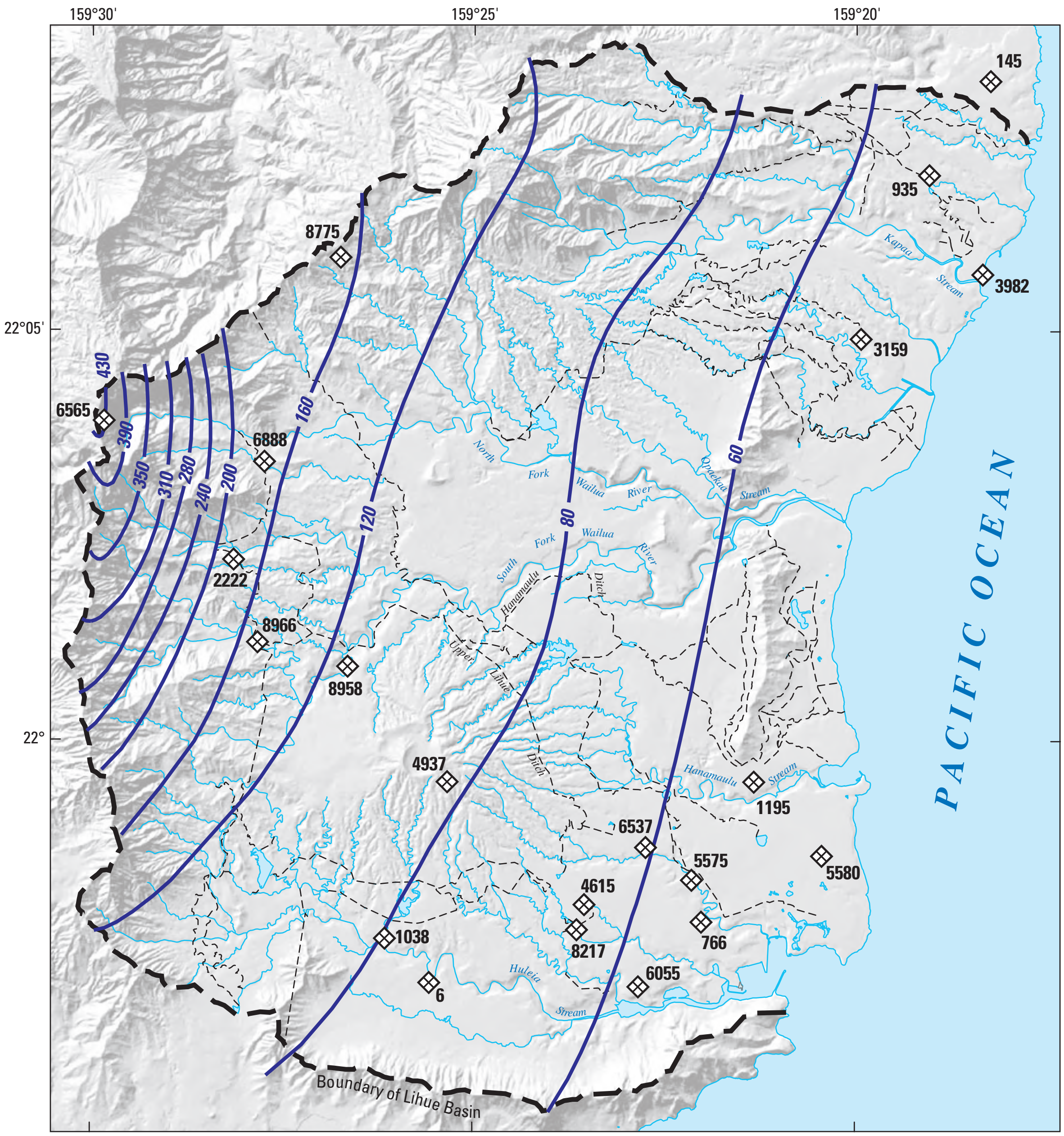
The Lihue Basin is a large semicircular depression in southeastern Kauai, a 553 mi^2 island in the tropical-Pacific Hawaiian Archipelago (fig. 1). The basin is encircled by mountains, some of which are several thousand feet in elevation, to the north, west, and south, and by the Pacific Ocean on the east. Kilohana Volcano, a broad, dome-shaped volcanic structure, covers much of the southern part of the Lihue Basin and rises to an elevation of 1,149 ft. A few smaller ridges and hills also lie within the basin. The natural drainage pattern in the Lihue Basin consists of numerous streams that coalesce into a few principal water courses, including Kapaa Stream, Wailua River, Hanamaulu Stream, and Huleia Stream.

Rainfall distribution in the basin is influenced by the orographic effect (fig. 3). Precipitation is highest where the prevailing northeasterly trade winds encounter the windward flanks of the hills and mountains, forcing warm, moist air into the cool, higher elevations. Mean annual rainfall ranges from about 50 in. at low-lying coastal areas to more than 430 in. at the crest of the mountains forming the western margin of the basin (Giambelluca and others, 1986).

From the late 19th century through the 20th century, much of the land in the Lihue Basin was used for sugarcane agriculture (Wilcox, 1996). Sugarcane plantations built numerous ditches and reservoirs to transport and store water for irrigation. The ditches and reservoirs not only redistributed water within the Lihue Basin, but also brought water in from, and took water out to, adjacent basins. As a result, surface-water drainage in the Lihue Basin consists of a complex network of natural drainage channels, irrigation ditches, and reservoirs. The sugarcane industry in Hawaii began to decline in the 1970s, and at the end of 2000, the last sugarcane plantation in the Lihue Basin closed. Some of the land formerly used for sugarcane cultivation has been urbanized or converted to diversified agriculture.

Hydrogeology

Current understanding of the complex geology of the Lihue Basin has been developed and revised on the basis of studies spanning several decades (Stearns, 1946; Macdonald and others, 1960; Langenheim and Clague, 1987, Clague and Dalrymple, 1988; Moore and others, 1989; Holcomb and others, 1997; and Reiners and others, 1998). These studies indicate that the Lihue Basin is a large depression formed by erosion and faulting of the large, basaltic shield volcanoes that formed Kauai (fig. 4). The basin is partly filled with sediments as well as lava flows and other igneous rocks from later, scattered rejuvenated volcanism. Rocks of the large shield volcanoes are known as the Waimea Canyon Basalt, which is of Pliocene age. Overlying rocks from the later rejuvenated volcanism and sedimentary deposits that partly fill the Lihue Basin are known as the Koloa Volcanics, which is of Pliocene-Pleistocene age. The Waimea Canyon Basalt forms the ridges surrounding the Lihue Basin as well as a few small ridges and hills within the basin. The Koloa Volcanics covers most of the floor of the basin and is more than 1,000 ft thick in some places. The Nonou wells penetrate into the Waimea Canyon Basalt at the base of Nonou Ridge; the Kilohana-Puhi wells penetrate the Koloa Volcanics. The Kalepa well is in the Waimea Canyon Basalt that forms Kalepa Ridge.



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.

0 1 2 3 4 MILES

0 1 2 3 4 5 6 KILOMETERS

EXPLANATION

RESERVOIRS AND OTHER WATER BODIES

IRRIGATION DITCH

120 LINE OF EQUAL MEAN ANNUAL RAINFALL, IN INCHES

6 RAIN GAGE AND NATIONAL WEATHER SERVICE NUMBER

Figure 3. Mean annual rainfall in the Lihue Basin, Kauai, Hawaii. (Modified from Giambelluca and others, 1986.)

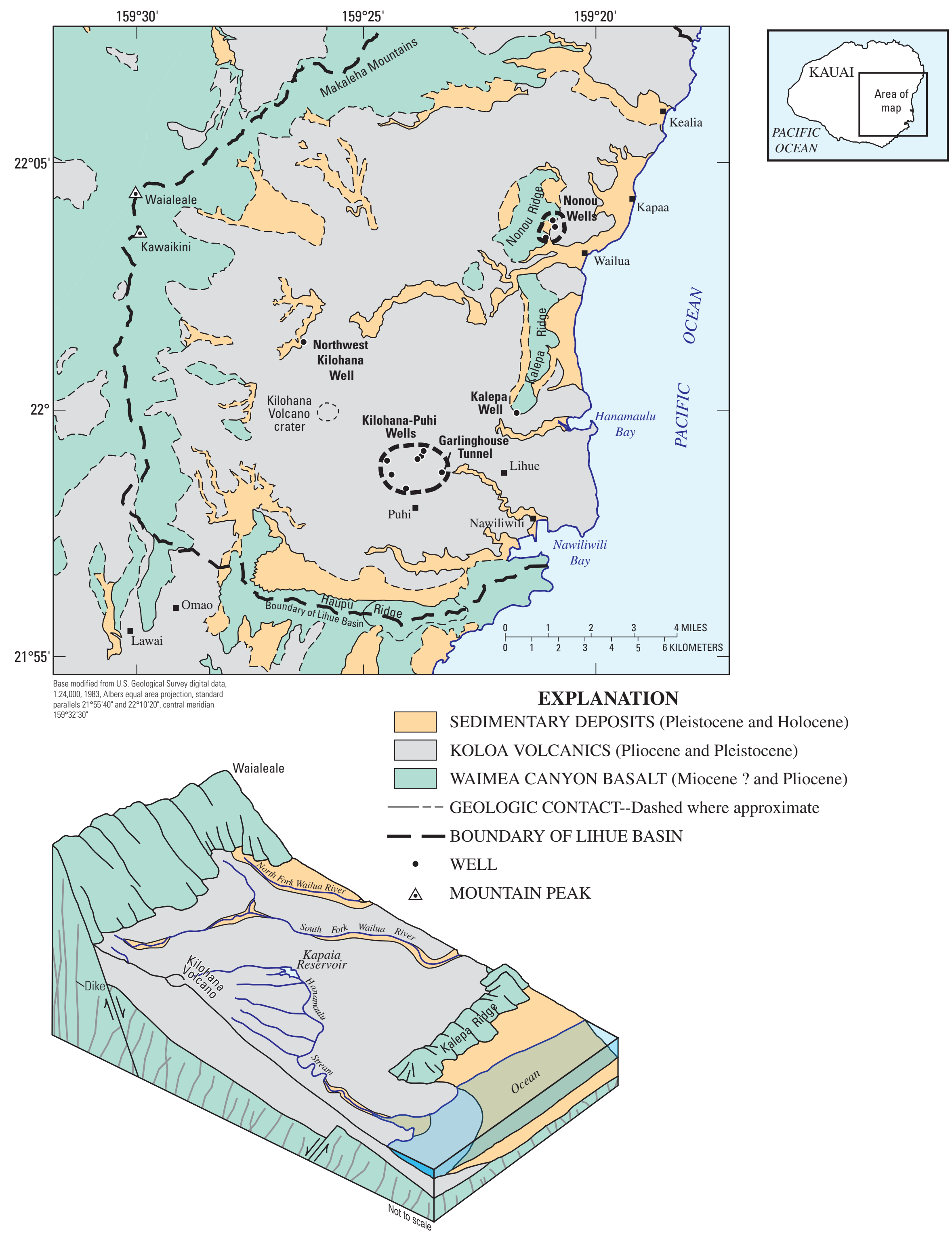


Figure 4. Geologic map and block diagram of the Lihue Basin, Kauai, Hawaii. (Modified from Macdonald and others, 1960; and Izuka and Gingerich, 2003.)

Changing water levels in wells are a manifestation of regional and local processes. Fresh ground water in the Lihue Basin, as in other coastal regions, forms a lens that overlies saltwater (fig. 5) (Izuka and Gingerich, 2003). This freshwater lens is mostly unconfined. Water from inland areas of recharge (mostly from infiltration of rainfall and irrigation water) flows toward discharge areas at streams, the coast, or pumped wells. The freshwater lens may attain a state of long-term dynamic equilibrium in which recharge equals discharge, but changes that affect recharge (such as droughts or changes in irrigation) and changes in discharge (such as changes in pumping rates at wells) can cause the lens to increase or decrease in size, thus water levels rise and decline in wells on a regional scale. Processes that can affect water levels at a local scale include the formation and spread of a cone of depression around a well when it is pumped, and local mounding caused by intensified recharge in a small area, as might be associated with the use of inefficient irrigation methods. Local processes commonly affect water levels on a shorter time scale than regional processes, but in either case, how quickly the effects occur depends in large part on geologic structure and hydraulic properties of the aquifer.

In the Lihue Basin, both the Waimea Canyon Basalt and the Koloa Volcanics are geologically complex, thus water levels in wells separated by only a short distance can be substantially different. The Waimea Canyon Basalt is one of the most permeable and productive aquifers on Kauai, but in the Lihue Basin, the formation is intruded by near-vertical sheets of dense, low-permeability volcanic dikes that reduce overall permeability (figs. 4 and 5). The Koloa Volcanics in the Lihue Basin is a thick (more that 1,000 ft in places) accumulation of heterogeneous rocks having low regional permeability and steep vertical and horizontal hydraulic-head gradients, but smaller areas of locally high permeability are within the formation (Izuka and Gingerich, 1998).

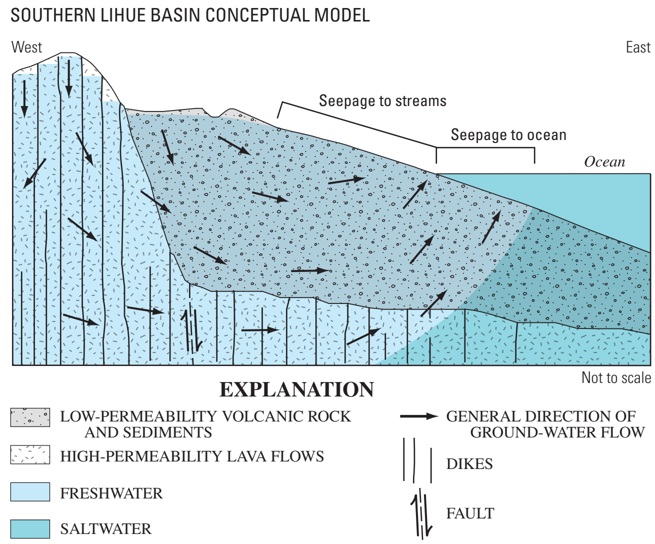


Figure 5. Diagram of conceptual model of ground-water occurrence in the Lihue Basin, Kauai, Hawaii. (From Izuka and Gingerich, 2003.)

Trends in Ground-Water Levels, Ground-Water Withdrawal, Irrigation, and Rainfall

Ground-water sources in the Lihue Basin include both conventional vertical wells and water tunnels (large-diameter horizontal galleries bored at the level of the water table). Two important ground-water production areas in the basin are the Nonou wells at the base of Nonou Ridge, and the Kilohana-Puhi wells on the southeast flank of Kilohana Volcano (fig. 1). Wells in both of these areas have shown recent water-level declines (fig. 2). In some cases, the declining water levels have affected well and tunnel production. For example, at the Garlinghouse Tunnel, one of the most productive sources of public water in the area of the Kilohana-Puhi wells, two pumps could be operated continuously prior to 1970, yielding about 1,500 gal/min for extended periods. By the 1990s, however, only one pump could be operated (at about 800 gal/min) without causing water levels to decline to the level of the pump intake. Water levels in some non-pumped monitor wells that are far from pumped wells also show recent declines. For example, water levels declined at the unused Kalepa well and the Northwest Kilohana monitor well (2.3 and 3.7 mi from the Kilohana-Puhi wells, respectively) (fig. 2).

The observed decline in ground-water levels in the Lihue Basin may be related to regional or local response of the ground-water system to (1) increasing ground-water withdrawals, (2) reductions in irrigation, and (3) below-average rainfall.

Increasing ground-water withdrawals.—Ground-water records at CWRM include wells in the Lihue Basin that date back to the 1890s, but records of ground-water withdrawals are not complete. An indication of historical ground-water production can be seen, however, in the number of wells listed as being in use. The number of wells in use increased sharply after 1960 (fig. 6). In the Lihue Basin, ground-water levels may take decades to adjust to increasing ground-water withdrawals (Izuka and Oki, 2002). Therefore, wells that began pumping in the 1970s–90s (such as all of the Kilohana-Puhi wells except the Garlinghouse Tunnel) and 1960s–80s (such as the Nonou wells) may have continued to affect ground-water levels through 2000.

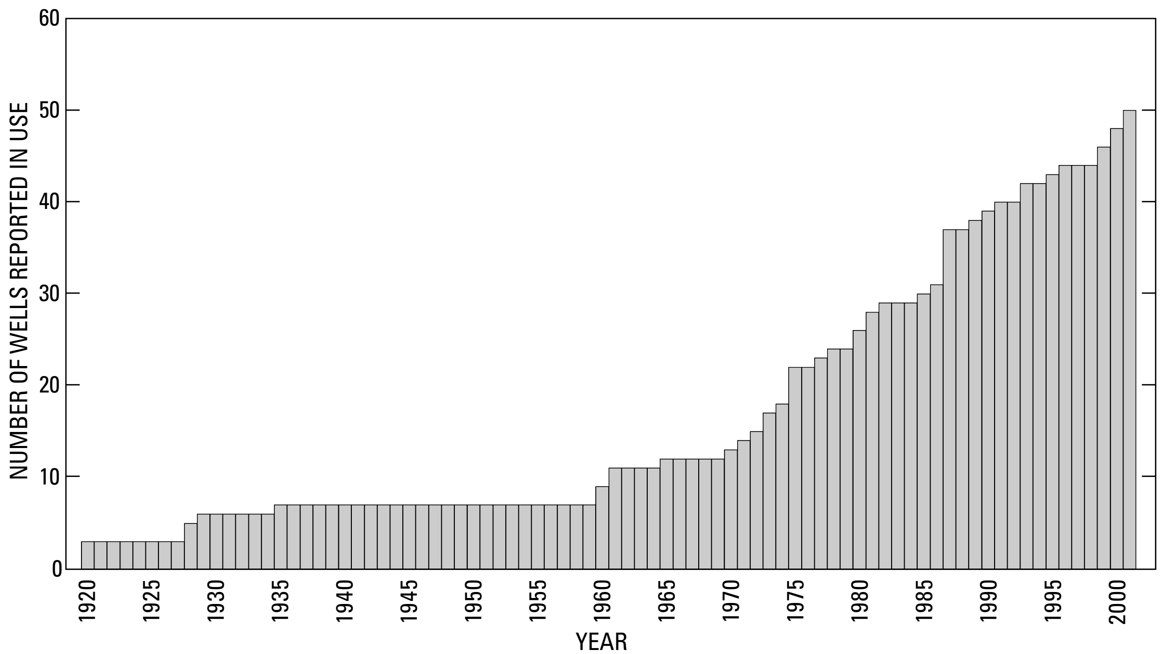


Figure 6. Growth in the number of production wells in the Lihue Basin, Kauai, Hawaii. (Based on data from the Hawaii State Commission on Water Resource Management, 2001.)

In both the Nonou and Kilohana-Puhi wells, short-term variations in water levels correspond inversely with rates of ground-water withdrawal (fig. 7). The Nonou wells show this correspondence clearly—when the pumping rates increase, water levels decline. Even so, ground-water withdrawals cannot account entirely for the overall trend of declining ground-water levels. The theoretical curve describing the decline of water levels with time in response to pumping a well, assuming the pumping rate is constant, is concave upward, becoming less steep with time. The observed ground-water decline in both the Kilohana-Puhi and Nonou wells, however, is concave downward, becoming increasingly steep with time (fig. 7). The concave-downward water-level trend also is seen in the Kalepa well, which is not being pumped and is not near any production wells (fig. 2). Withdrawal from wells certainly had an effect on local ground-water levels in the Kilohana-Puhi and Nonou wells, but other factors may have contributed to the observed water-level decline seen in the Kalepa well. The combined effects of withdrawal from numerous wells may have caused a regional depletion of water in the aquifer, and recharge may have been reduced by changes in irrigation and rainfall.

Changes in irrigation.—At its peak, the sugarcane industry in the Lihue Basin diverted tens of billions of gallons of water annually from streams for irrigation. The trends in irrigation water use for sugarcane fields near the Kilohana-Puhi wells can be seen in flows monitored by Lihue Plantation Company streamflow-gaging stations on the Hanamaulu and Upper Lihue Ditches; trends in water used to irrigate fields near the Nonou wells are indicated by the flow in the USGS Wailua Ditch streamflow-gaging station (number 16069000) (fig. 1). Water levels in wells show an overall correspondence with flows in ditches bringing water to fields near the wells (fig. 8). The general trend of declining water levels in the Kilohana-Puhi wells between 1985 and 2000 is approximately concurrent with a decline in flows in the Upper Lihue and Hanamaulu Ditches. Water levels at the Nonou wells and flows in the Wailua Ditch both show a general rise from 1975 to 1985 and decline from 1985 to 2000, although the ground-water-level pattern lags ditch flow by about 1.5 years. This correspondence indicates that ground-water levels may be linked to irrigation rates.

Sugarcane in the Lihue Basin was grown both with and without irrigation (figs. 9 and 10). Fields at higher elevations received enough rainfall and irrigation was not necessary. At the lower elevations, sugarcane fields were irrigated primarily by furrow methods prior to the 1980s, and a mix of furrow and drip methods from the mid-1980s through 2000. Drip irrigation was introduced to increase irrigation efficiency. Estimates for drip-irrigation efficiency (the ratio of water consumed by the crop to water applied to the field) for sugar plantations in Hawaii range from 80 to 95 percent, whereas estimates for furrow irrigation range from 30 to 70 percent (Dale, 1967; Fukunaga, 1978; Gibson, 1978; and Yamauchi and Bui, 1990).

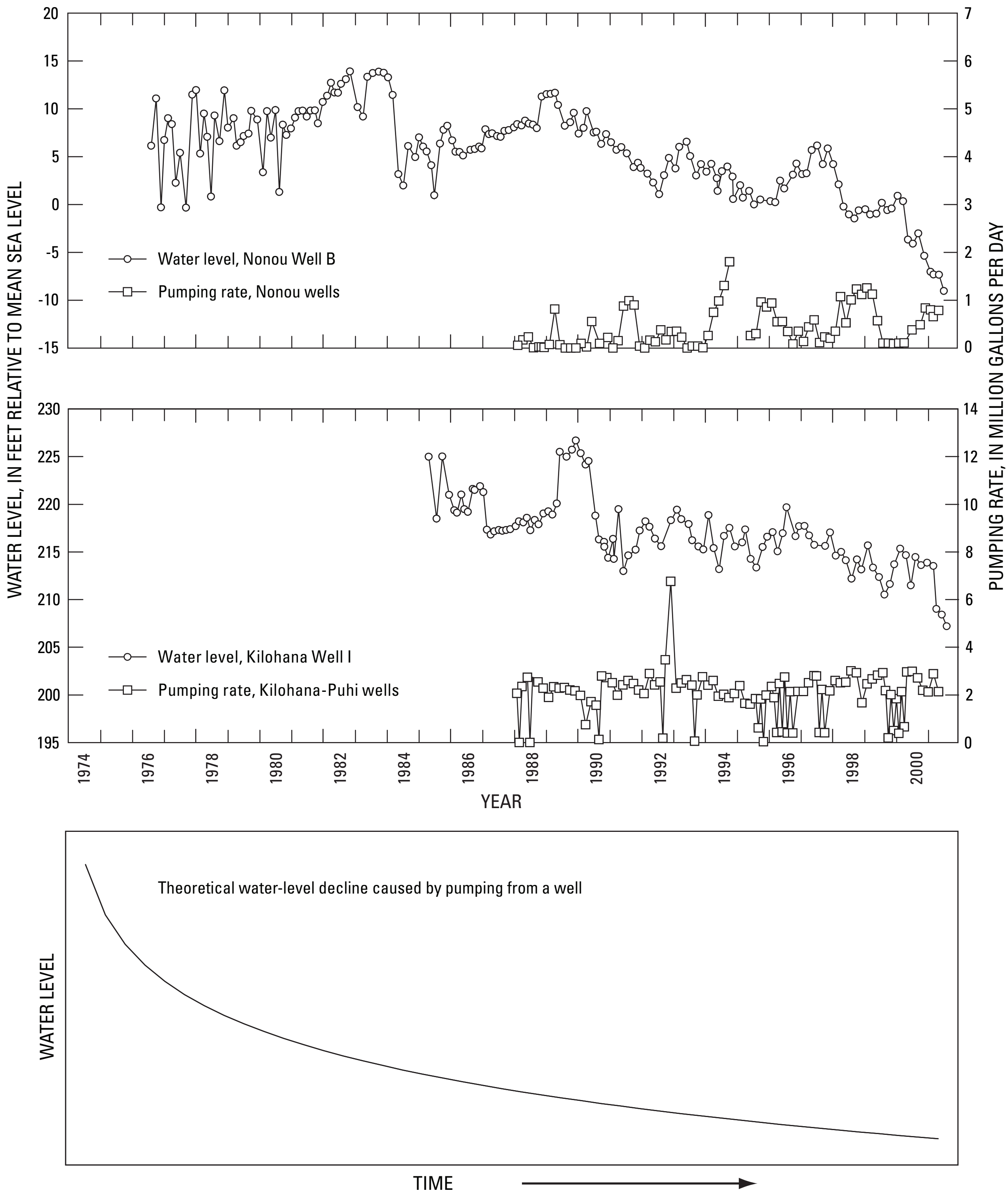


Figure 7. Pumping rate and water levels in the Nonou and Kilohana-Puhi wells, Kauai, Hawaii. (Pumping data provided by N.S. Fujii, Hawaii State Commission on Water Resource Management, written commun., 2001.)

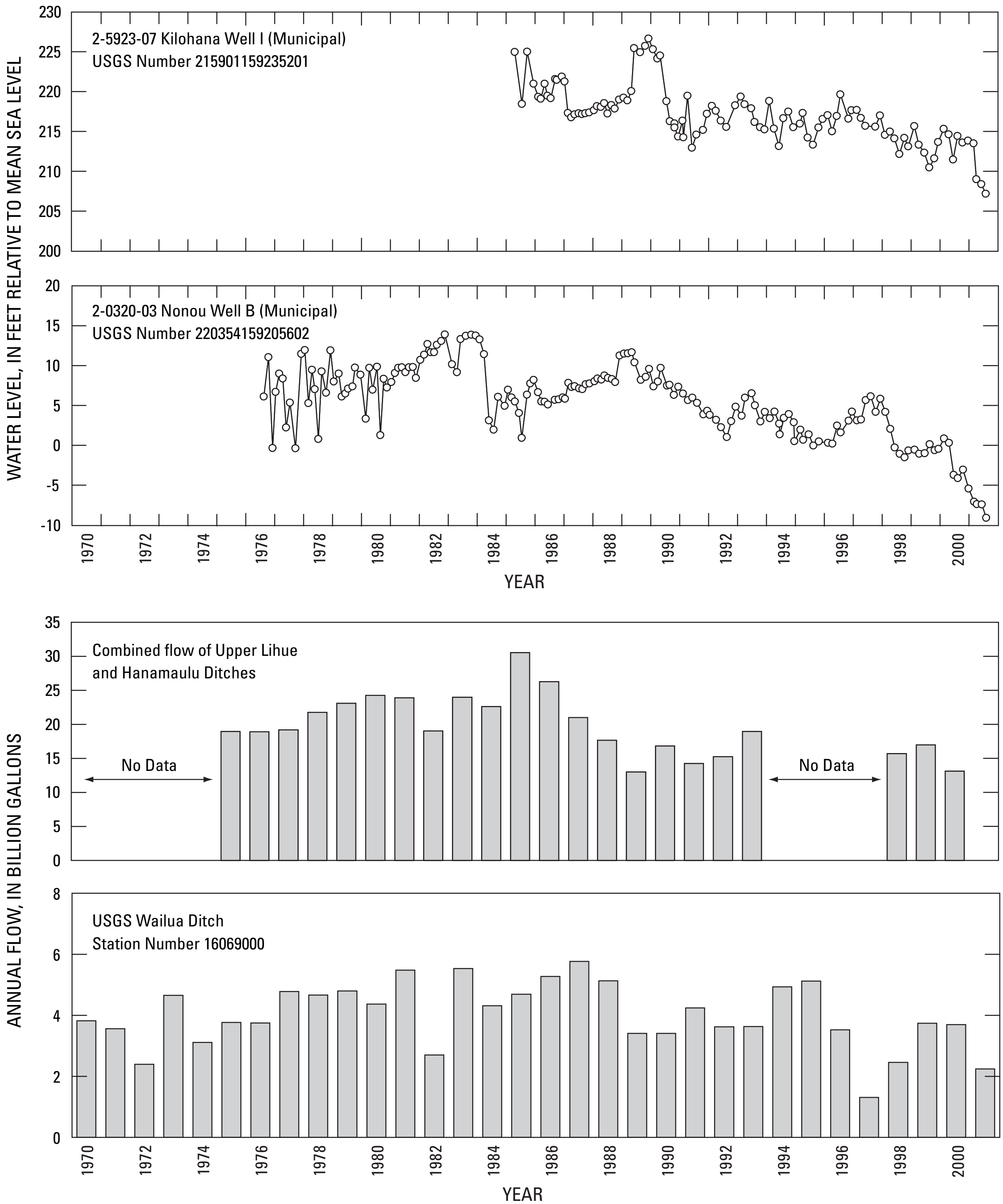


Figure 8. Ground-water levels and irrigation-ditch flow in the Lihue Basin, Kauai, Hawaii. (Data for the Upper Lihue and Hanamaulu Ditches are from records of the Lihue Plantation Company.)

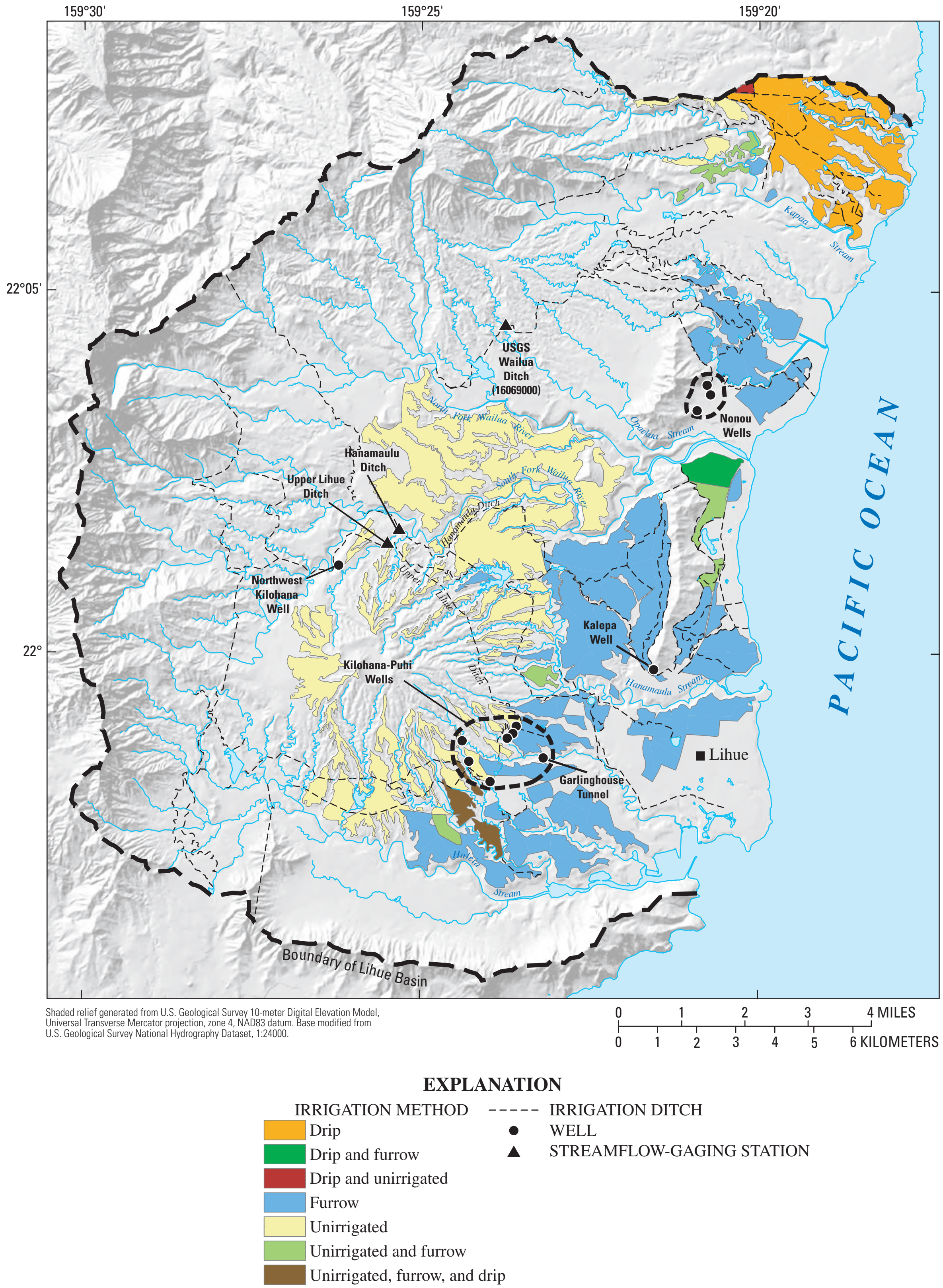


Figure 9. Sugar-plantation fields in 1981 in the Lihue Basin, Kauai, Hawaii. (Field outlines modified from maps in State of Hawaii, 1991; irrigation classification for 1981 from records of the Lihue Plantation Company.)

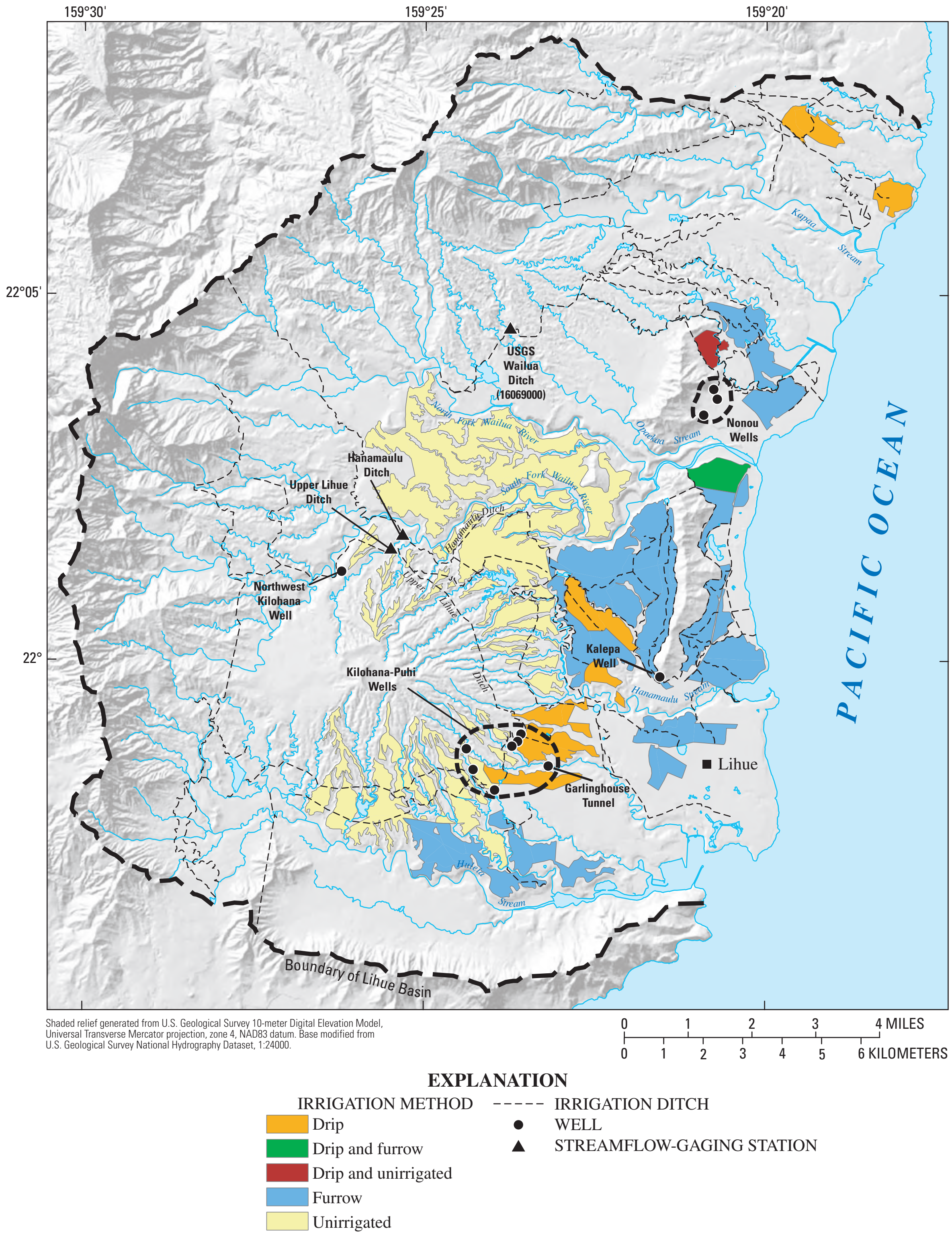


Figure 10. Sugar-plantation fields in 1998 in the Lihue Basin, Kauai, Hawaii. (Field outlines modified from maps in State of Hawaii, 1991; irrigation classification for 1998 from records of the Lihue Plantation Company.)

The conversion from furrow to drip irrigation was not widespread in the Lihue Basin, but sugarcane fields immediately adjacent to the Kilohana-Puhi wells were converted to drip irrigation beginning in the early 1990s (figs. 9 and 10). Concurrent with the conversion was a steep decline in water levels at the Kilohana wells. The rate of water-level decline steepened even more, however, beginning in about 1998, several years after the conversion was completed (fig. 8).

Only a small part of the sugarcane fields near the Nonou wells was converted from furrow to drip irrigation, but in the mid to late 1990s, some of the area was completely taken out of sugarcane production (figs. 9 and 10). This reduction in sugarcane production near the Nonou wells coincides with observed declines in ground-water levels (fig. 8).

Variations in rainfall.—Rain-gage records for the Lihue Basin extend back to the late 19th century, but not all rain gages have long, continuous records. The rainfall records at the USGS rain gage on Mt. Waialeale and the NWS rain gage at the Lihue Airport were used to evaluate trends because they are among the longest, most complete records in the Lihue Basin. The Lihue Airport rain gage also is one of the rain gages that the NWS uses to monitor droughts in Hawaii.

Annual rainfall totals at the rain gages on Mt. Waialeale and at the Lihue Airport were below average during most of the 1990s, especially from 1995 through 2002 at Mt. Waialeale and from 1998 through 2002 at the Lihue Airport (fig. 11). Periods of below-average rainfall also occurred in the 1970s and 1980s. The periods of below-average rainfall in the 1980s and 1990s coincide with the period of observed declines in ground-water levels in the Lihue Basin. The apparent water-level decline in the Northwest Kilohana Well (fig. 2), which is far from production wells and irrigated sugarcane fields, indicates decreased rainfall is at least partly the cause of water-level declines in the Lihue Basin.

Changes in Ground-Water Recharge

Recent declines in water levels observed in some wells in the Lihue Basin correspond with increased ground-water withdrawal, reduced irrigation, and periods of below-average rainfall. Whereas increasing ground-water withdrawal will certainly and directly lower water levels to some degree, reduction of irrigation and periods of low rainfall can affect water levels indirectly by reducing ground-water recharge. To quantify the effects irrigation and rainfall may have on ground-water recharge, a water-balance model of the Lihue Basin was developed and used to simulate several scenarios representing historical conditions prior to and during the period of observed water-level decline, and for hypothetical conditions that could develop in the near future. The scenarios examined three different land-use conditions: (1) conditions that existed in 1981, when sugarcane cultivation occupied 16,600 acres in the Lihue Basin and most fields used furrow irrigation; (2) conditions that existed in 1998, when the area used for sugarcane cultivation had declined by 25 percent from 1981 and some fields were converted from furrow to drip irrigation; and (3) a hypothetical condition in which there is no irrigation. For each of the land-use conditions, four rainfall conditions were examined, including a base case using historical mean rainfall, and three drought conditions (described in a later section).

Estimating Ground-Water Recharge

Ground-water recharge in this study was estimated using a modification of the mass-balance method of Thornthwaite and Mather (1955) (see appendix A for details). The method operates on the premise that part of the water that falls on the land surface as rain runs off to the ocean via streams while the remainder infiltrates the soil. In the Lihue Basin, fog and irrigation also add to the amount of water in the soil. Water is temporarily stored in the soil where it is subject to evapotranspiration (fig. 12). Recharge to the aquifer occurs when more water infiltrates than can be held in the soil given its water-storing capacity, antecedent water content, and losses from evapotranspiration. The excess infiltrated water is then passed to the aquifer underlying the soil. The method thus constitutes a balance of input (precipitation and irrigation), output (runoff, evapotranspiration, and recharge), and water storage in the plant-soil system. In the water balance, the water-storage capacity of the soil is determined by the thickness of the soil within the root zone (root depth) and the available water capacity of the soil.

Timing of the input, output, and storage of water also affects computed recharge. If precipitation is frequent, evapotranspiration has less time to deplete the water stored in the soil, hence soil moisture may be kept near the water-storage capacity of the soil and even a small amount of infiltration may result in recharge to the aquifer. If precipitation is infrequent and evapotranspiration has a long time to reduce the antecedent soil moisture, even a large precipitation event may result in small volumes of recharge. In this study, the water-balance was computed on a daily basis, which is more accurate than computing on a monthly or longer basis because it allows more realistic simulation of short-duration events such as daily irrigation and episodic rainfall. The water balance was computed by stepping through consecutive days, using the ending soil moisture for one day as the antecedent soil moisture for the next day. The analysis required assuming initial soil-moisture conditions, but by computing the water balance for thousands of consecutive days (in this study, the equivalent of 50 years), the water balance converged on a long-term average recharge value.

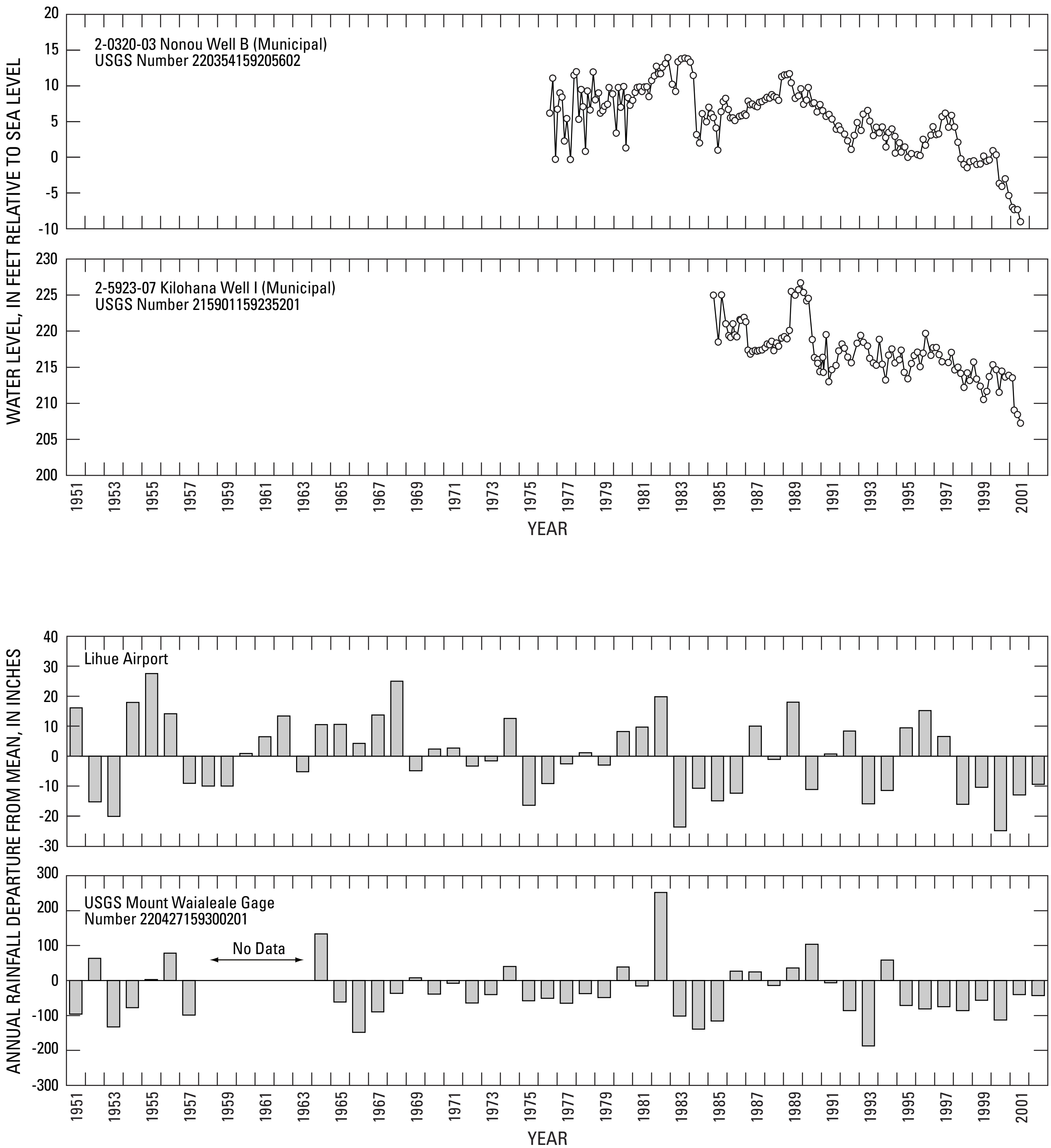


Figure 11. Ground-water levels and rainfall in the Lihue Basin, Kauai, Hawaii.
Mean annual rainfall for each rain gage determined on entire period of record, which is 1912 to 2002 for Mt. Waialeale and 1951 to 2002 for the Lihue Airport. (Rainfall data for the Lihue Airport for 1951 to 2001 from National Climatic Data Center, 2002; for 2002 from K. Kodama, National Weather Service, written commun., 2004; other data from the U.S. Geological Survey.)

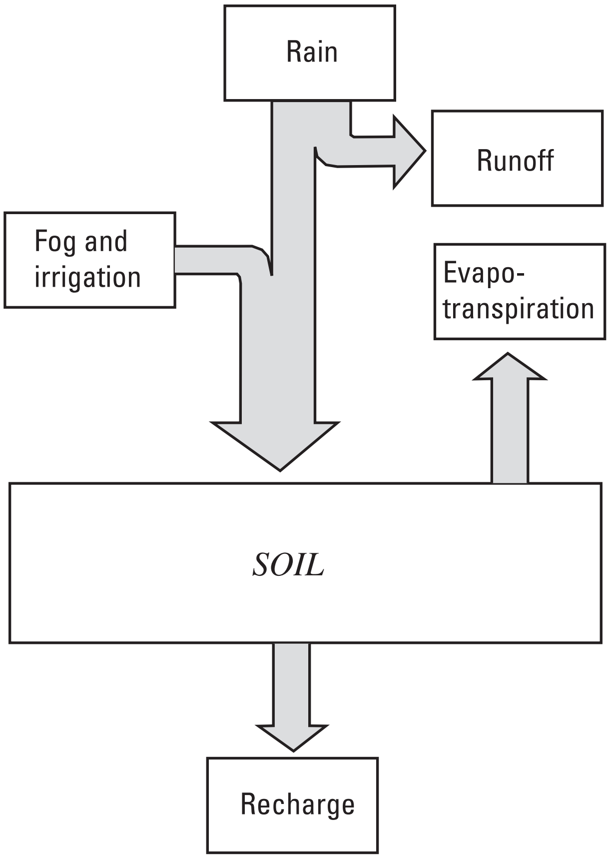


Figure 12. Water-balance flow chart showing water input (rain, fog, and irrigation minus runoff) and loss (evapotranspiration and recharge) from the plant-soil system.

Although the water-balance computes the water budget over a 50-year period, the computation is not intended to show how recharge varied over the 50-year period (that is, it is not a transient simulation). Each scenario is a steady-state simulation for a given set of conditions, assuming that those conditions persisted long enough for recharge to have achieved a steady state. Only the recharge at the end of the 50 years is considered valid. The sole purpose of stepping through daily water-balance computations for 50 years is to allow time for recharge to achieve a steady state for the conditions being simulated.

The water-balance was computed for the entire Lihue Basin (fig. 1). The daily water balance was computed for subareas within the basin having homogeneous precipitation, sugarcane cultivation and irrigation, runoff, and evapotranspiration characteristics. These areas were defined by merging geographic-information-system (GIS) spatial datasets (coverages) created from published and unpublished maps and other data (see appendix A).

Factors Affecting Ground-Water Recharge

Spatial and temporal variations in precipitation, irrigation, runoff, and evapotranspiration affect ground-water recharge. Each of these factors constitutes a parameter in the water-balance computations of recharge. Some parameters may have considerable uncertainty associated with them because a range of values are plausible, although one of the values in the range is usually considered most plausible. This section describes only the most plausible values selected for the water-balance computation; parameter uncertainty (i.e. plausible values other than the ones used) and its implications on recharge computations are discussed in a later section of this report.

Precipitation

Rainfall.—In this study, the daily rainfall distribution required for the water-balance computations was synthesized from the mean monthly rainfall distribution maps of Giambelluca and others (1986). These maps depict mean monthly rainfall as lines of equal rainfall, based on rain-gage data from 1916 to 1983. To convert lines on the maps to the areal rainfall distribution needed for the water-balance computation, areas between adjacent rainfall lines were assigned a mean monthly value equal to the average values of the two lines. In areas that were bounded by only one rainfall line (such as near the coast) or completely encircled by a single rainfall line (such as near the peaks of mountains), the mean value of rain gages within the area was assigned. If no rain gages were within a given area, the area was assigned the average of the value of the existing rainfall line and the value of the line that would logically have been next in the sequence of existing lines on the map.

The daily rainfall needed for the water-balance computation was synthesized from the mean monthly rainfall using the method of fragments (see Oki, 2002, for example). In this method, month-by-month patterns of daily rainfall (fragments) derived from the records of selected individual rain gages were imposed on the mean monthly rainfall distribution (fig. 13). In this study, data for fragments were obtained from daily rainfall data compiled by the National Climatic Data Center (2002, 2003) for the period from 1905 through 2001. Nineteen rain gages in the Lihue Basin had sufficient daily data for creating fragments. The fragments were created by dividing the rainfall of each day by the total for the month (fig. 13). Fragments were applied to the areas of equal mean monthly rainfall as defined by the mean monthly rainfall lines. Only fragments from rain gages lying within an area were applied to the rainfall for that area. If an area had no rain gages, fragments from the rain gages that were in the next closest area were used. Table 1 lists the areas of equal mean monthly rainfall and the corresponding rain gages from which fragments were derived.

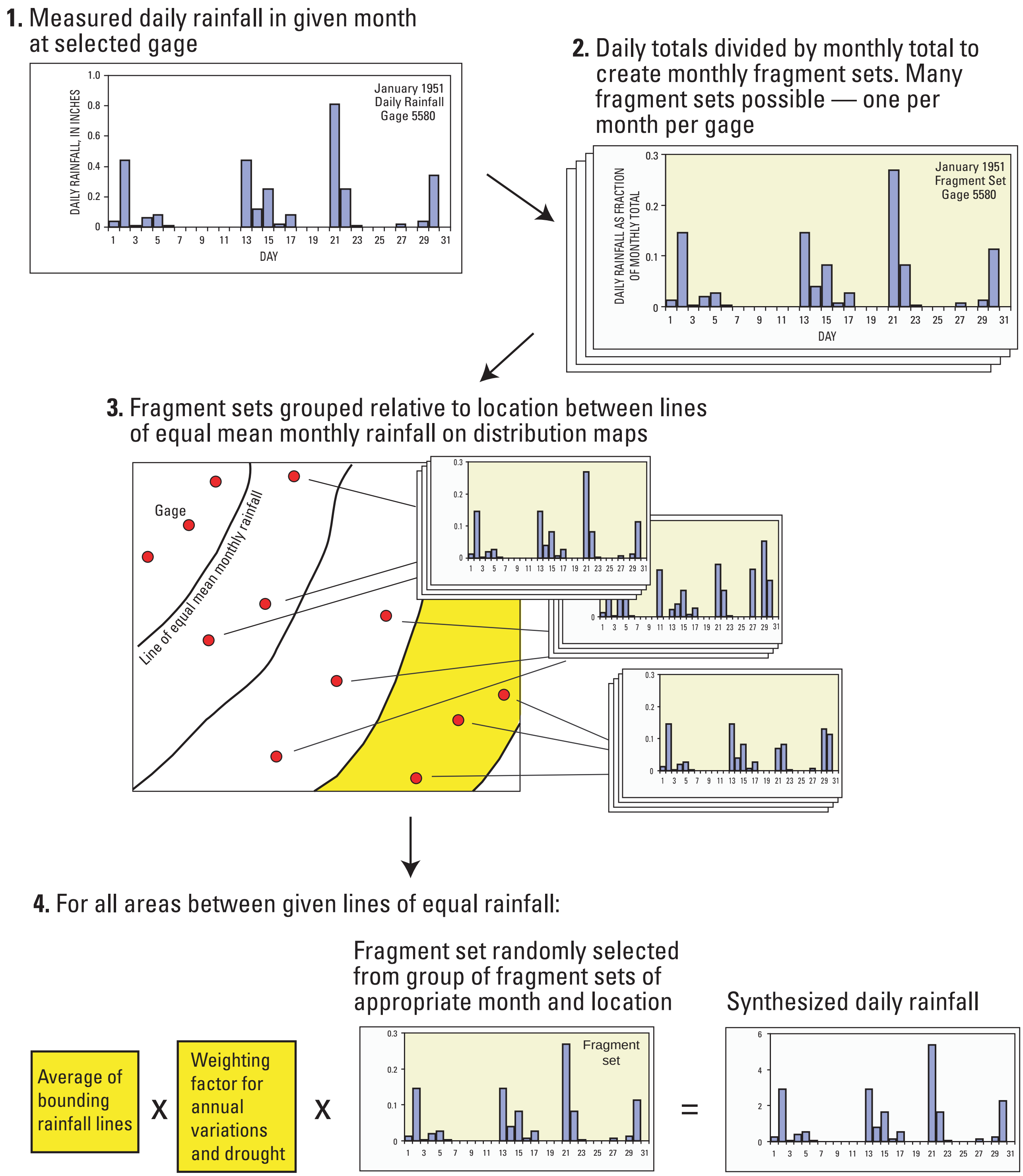


Figure 13. Synthesis of daily rainfall from mean monthly rainfall maps using method of fragments.

Table 1. Rain gages used to derive fragments for areas of equal rainfall in the water-balance computation for the Lihue Basin, Kauai, Hawaii.

[Gage numbers shown are National Weather Service rain-gage numbers (see figure 3 for locations). **Abbreviations:** OPAE, U.S. Geological Survey Opaekaa rain gage, number 220443159235601; NA, not applicable]

Bounding lines of equal mean monthly rainfall (inches)	Mean monthly rainfall in area between bounding lines (inches)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Less than 2	Average of gages in area. If no gages, then 1.5	NA	NA	NA	NA	NA	5580 0145 0935 3982	0145 0935 3982 5580	5580	NA	NA	NA	NA
2 to 3	2.5	NA	NA	NA	NA	3982	1195 3159 5575 6537 0766 6055	0145 0935 3982 5580	0145 1195 3159 0935 3982	0145 1195 3159 5580 0935 3982 0766	NA	NA	NA
3 to 4	3.5	NA	NA	NA	5580 3982	0145 1195 3159 5575 5580 0935 0766 6055	4615 8217	1195 3159 5575 0766 6537 6055	5575 6537 0766 6055	5575 6537 4615 8217 6055	3892	NA	NA
4 to 6	5.0	NA	0145 1195 3159 5575 5580 0935 3982 6537 4615 8217 0766 6055	0145 1195 5575 5580 3982 0766 6055	0145 1195 3159 5575 0935 6537 0766 4615 8217 6055	6537 4615 8217 0006	4937 1038 0006	8217 4615	0006 8217 4615	OPAE 0006 1038 4937	1195 5580 5575 3159 0145 0935 0766 6055 6537	0145 5580 0766 3982	0145 5580 3982
6 to 8	7.0	0145 1195 3159 5580 5575 0935 6537 4615 8217 6055 0766 3982	OPAE 4937 1038 0006	3159 0935 6537 4615 8217 0006	1038 0006	4937 1038	8958 OPAE	OPAE 0006 1038 4937	OPAE 4937 1038	8958	4615 8217 0006 1038 4937	5575 1195 3159 0935 6537 4615 8217 6055 0006	1195 5575 3159 0935 0766 6537 4615 8217 6055 0006
8 to 12	10.0	OPAE 8958 4937 1038 0006	8958 8966	OPAE 8958 4937 1038	OPAE 8958 4937	OPAE 8958 8966	8966 2222 6888 8775	8958	8958	8966 2222 6888 8775	8958 OPAE	OPAE 1038 4937 8958	OPAE 8958 4937 1038

Table 1. Rain gages used to derive fragments for areas of equal rainfall in the water-balance computation for the Lihue Basin, Kauai, Hawaii.—Continued

[Gage numbers shown are National Weather Service rain-gage numbers (see figure 3 for locations). **Abbreviations:** OPAE, U.S. Geological Survey Opaekaa rain gage, number 220443159235601; NA, not applicable]

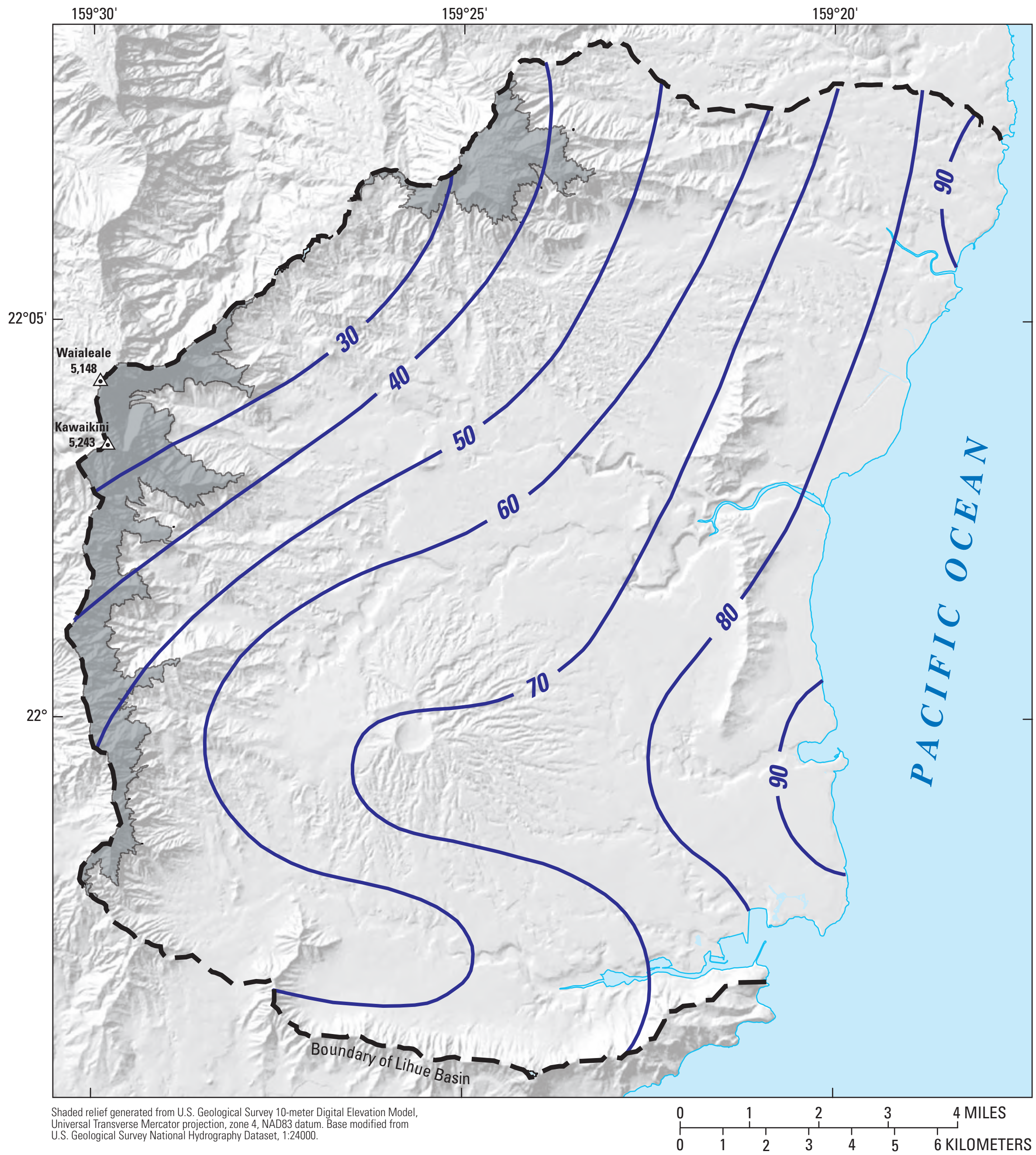
Bounding lines of equal mean monthly rainfall (inches)	Mean monthly rainfall in area between bounding lines (inches)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
12 to 16	14.0	2222 6888 8966 8775	2222 6888 8775	2222 8966	8966 8775	2222 6888 8775	8966 2222 6888 8775	6888 2222 8966 8775	8966 2222 6888 8775	8966 2222 6888 8775	8966 2222 6888 8775	8966 8775	8966 8775
16 to 20	18.0	2222 6888 8966 8775	2222 6888 8775	6888 8775	2222 6888	2222 6888 8775	6565	6888 2222 8966 8775	8966 2222 6888 8775	6565	8966 2222 6888 8775	2222 6888	2222 6888
20 to 24	22.0	6565	2222 6888 8775	6888 8775	2222 6888	2222 6888 8775	6565	6565	8966 2222 6888 8775	6565	6565	2222 6888	2222 6888
24 to 28	26.0	6565	6565	6565	6565	6565	6565	6565	6565	6565	6565	6565	2222
Greater than 28	Average of gages in area. If no gages, then 30.0	6565	6565	6565	6565	6565	6565	6565	6565	6565	6565	6565	6565

For the base-case scenarios, the mean monthly rainfall was multiplied by a weighting factor to account for annual rainfall variations (fig. 13). The weighting factors were derived from the 50-year period, beginning in 1950, of the historical rainfall record at the NWS rain gage at the Lihue Airport. The factors were computed by dividing the annual rainfall for a given year by the mean annual rainfall for the period 1950 to 2001. For drought scenarios, lower-than-average weighting factors were used (computation of weighting factors for droughts is discussed in more detail in a later section).

An example computation helps illustrate the computation of daily rainfall using the weighting factors and method of fragments. The month of June 1960 and the area having mean monthly rainfall of 5.0 in. is used in this example. For this area and time, the value of 5.0 in. is multiplied by the weighting factor for 1960 (the factor is 1.021, indicating that rainfall in 1960 was slightly higher than average) yielding an estimated monthly value of 5.105 in. of rainfall in June 1960. A rainfall fragment set (fragments based on one June) is then randomly selected from among the fragment sets computed for June from rain gages within the 5.0-in. rainfall area (as seen in table 1, those rain gages are 4937, 1038, and 0006). The daily rainfall pattern represented by the fragment set is then imposed on the estimated June 1960 value by multiplying it by the fragment set.

Fog drip.—Fog is water that exists in the liquid phase but in droplets too small to fall as rain. Some of this water is intercepted by plants and drips or flows along branches and stems to the ground, thus adding to the overall water balance of the soil. The sparse fog data for Hawaii is commonly expressed as a ratio of fog to concurrent rainfall. This ratio is used to estimate fog precipitation in areas having rainfall but no fog data, such as the Lihue Basin. The fog-to-rain ratio varies, however, with elevation, seasons, topography, and climate regimes, so it is important that the fog-to-rain ratios used are reasonably representative of conditions in the Lihue Basin. In Hawaii, maximum fog development coincides with the position of the tropical temperature inversion (usually at about 6,600 ft), but fog may develop at elevations as low as about 2,000 ft (Juvik and Ekern, 1978).

For this study, fog contribution was added to all areas in the Lihue Basin at elevations above 2,000 ft (fig. 14). Juvik and Ekern (1978) reported a fog-to-rain ratio of 0.28 for the Kulani Camp Station (on Mauna Loa, on the island of Hawaii), which has a windward orographic climate regime comparable to that in the Lihue Basin. The Lihue Basin has a maximum elevation of 5,208 ft, which is comparable to the elevation of the Kulani Camp Station (5,183 ft), but most of the fog zone in the Lihue Basin is at a lower elevation than the Kulani Camp Station, and lower than the level of maximum fog development at the tropical temperature inversion. In the water-balance computation for this study, a single fog-to-rain ratio of 0.18 was used for all areas higher than 2,000 ft elevation. This value was selected on the assumption that the fog-to-rain ratio in the Lihue Basin ranges from zero at 2,000 ft to about 0.3 at the highest elevation, and that areas above 2,000 ft elevation probably have a mean fog-to-rain ratio about midway between 0 and 0.3.



EXPLANATION

FOG ZONE

90 — LINE OF EQUAL ANNUAL PAN EVAPORATION, IN INCHES

Kawaikini 5,243 — MOUNTAIN PEAK AND NAME—Number is elevation, in feet above mean sea level

Figure 14. Distribution of mean annual pan evaporation (modified from Ekern and Chang, 1985) and area of fog contribution in the water balance for the Lihue Basin, Kauai, Hawaii.

Sugarcane Cultivation and Irrigation

Timing of irrigation application.—The typical sugarcane growing cycle in the Lihue Basin was 24 months. In a field that was irrigated, water was applied during only part of the cycle. The sugarcane was irrigated throughout the first 20 months of the cycle, which constituted the growing period. Over a period of about 40 days just before the end of the growing period, irrigation was reduced gradually until at the end of the growing period, the sugarcane received no irrigation water. The growing period was followed by a 50-day ripening period without irrigation, after which the sugarcane was harvested. After harvest, the field lay fallow for about 2 months while it was prepared for the next crop. In the water balance, the growing cycle was simplified to eliminate the need to simulate the gradual reduction of irrigation during the last 40 days of the growing period prior to ripening (table 2).

Plantations planned the growing cycles of the fields so that about one-half of the fields would be harvested in alternating years. To simulate this practice in the water-balance calculation, the fields were randomly divided into two groups such that half of the area of active cultivation began the 24-month cycle at the start of the computation period, and the other half started the irrigation cycle 12 months later.

In furrow-irrigated fields, water was periodically diverted from irrigation ditches to flood furrows dug in the crop fields. In an idealized irrigation schedule, each furrow-irrigated field would be flooded once every 14 to 16 days. In drip irrigated fields, water carried in hoses or pipes was dripped slowly into soil near the roots of the sugarcane. Ideally, water would be applied frequently in small amounts, but in practice, water was applied to drip-irrigated fields for two to three consecutive days each week, with no water applied during the remainder of the week. For the water-balance calculation, sugarcane fields were identified as having either drip, furrow, or no irrigation, and in some cases, combinations of these, based on plantation records (figs. 9, 10). Water was applied to furrow-irrigated fields on days 1 and 15 of each month, and to drip-irrigated fields on days 1, 2, 3, 8, 9, 10, 15, 16, 17, 22, 23, 24, and 28 of each month.

Table 2. Irrigation rates during periods in the growing cycle of sugarcane in the water-balance computation for the Lihue Basin, Kauai, Hawaii.

Period	Irrigation	Actual duration (days)	Duration in water-balance analysis (days)
Growing	Full	580	608
Last 40 days of growing [1]	Gradual reduction	40	0
Ripening	None	50	61
Fallow	None	60	61
Total number of days in cycle		730	730

[1] Not simulated in water-balance computation

Amount of water applied: furrow versus drip irrigation.—The water-balance computation requires mean monthly volumes of applied irrigation water per unit area of drip-irrigated fields (Q_D) and furrow-irrigated fields (Q_F). For this study, the distribution of sugarcane fields and the irrigation method used at each field was determined from records acquired from the Lihue Plantation Company after they had ceased operation in 2000. Records of how much irrigation water was actually applied to each field were not available, but a time-averaged estimate of Q_D and Q_F could be computed from monthly irrigation-ditch flow data. For this estimate, all water measured at the streamflow-gaging stations on ditches was assumed to have been actually applied to the fields served by the ditches (all irrigation also was assumed to have come from stream diversions; some small areas may have been irrigated with ground water, but this irrigation is insignificant compared to the amount of stream water diverted to irrigate sugarcane). In reality, some water probably was lost in transit between the gaging stations and the fields as a result of leakage and evaporation. The ditch-and-reservoir system, in a sense, has a water balance of its own, with evapotranspiration and recharge components that differ somewhat from, but are analogous to, that of sugarcane fields. The difference in the water balances of the ditch-and-reservoir system and the sugarcane fields probably have a negligible effect on the overall water balance of the Lihue Basin because the area occupied by the ditch-and-reservoir system is small. The applied irrigation per unit area within the Lihue Basin also was assumed to be virtually the same for all fields on which the same irrigation method was used. This allowed values of Q_D and Q_F to be computed based on fields having the most complete records of area in cultivation, irrigation method, and ditch flow. These values of Q_D and Q_F could then be applied to all fields in the basin, including those having insufficient data.

Because furrow irrigation is less efficient than drip irrigation, more water is applied per acre to a furrow-irrigated field than to a drip-irrigated field (assuming crop needs are the same). As discussed previously, estimates for drip-irrigation efficiency for sugar plantations in Hawaii range from 80 to 95 percent, whereas estimates for furrow irrigation range from 30 to 70 percent. The ratio of drip efficiency to furrow efficiency (R_{DF}) thus ranges from 1.1 to 3.2 (that is, a unit area of furrow-irrigated field uses 1.1 to 3.2 times more water than a drip-irrigated field). The Hawaii Sugar Planters' Association (HSPA) generally considered furrow irrigation to be about 30 percent efficient and drip irrigation to be 85 to 90 percent efficient (Michael Furukawa, oral commun., 2002), which indicates a range in R_{DF} of 2.8 to 3.0.

The quantity R_{DF} can be used to estimate monthly Q_D and Q_F from monthly irrigation ditch flows. For a given month, the total monthly irrigation (I_T) applied to a region with both furrow-irrigated and drip-irrigated fields is given by:

$$I_T = Q_D A_D + Q_F A_F \,, \qquad (1)$$

where

I_T is total monthly irrigation applied to an area of mixed furrow- and drip-irrigated fields [L^3],

Q_D is monthly volume of water applied per unit area of drip-irrigated fields [L],

A_D is total area of furrow-irrigated fields [L^2],

Q_F is monthly volume of water applied per unit area of furrow-irrigated fields [L], and

A_F is total area of furrow-irrigated fields [L^2].

The value of Q_F can be expressed in terms of Q_D if the ratio of drip efficiency to furrow efficiency (R_{DF}) is known:

$$Q_F = R_{DF} Q_D \,, \qquad (2)$$

where

R_{DF} is the ratio of drip efficiency to furrow efficiency [dimensionless].

Substituting equation 2 into equation 1 and solving for Q_D gives:

$$Q_D = I_T \,/ (A_D + R_{DF} A_F) \,. \qquad (3)$$

Monthly values of Q_D and Q_F can thus be computed from equations 2 and 3 for any region having adequate records of monthly I_T (for example from monthly ditch-flow records), A_D , and A_F .

Relatively continuous monthly ditch-flow records exist for the Upper Lihue and Hanamaulu Ditches for the period between 1980 and 2000. These ditches supplied water to furrow- and drip-irrigated sugarcane fields between the South Fork Wailua River and Huleia Stream (figs. 9 and 10). The records of irrigation methods also are nearly complete for these fields. Monthly ditch flows for the Upper Lihue Ditch were added to those for the Hanamaulu Ditch and the composite flows used together with a value of 3.0 for R_{DF} to compute monthly Q_D and Q_F . Mean monthly Q_D and Q_F were then computed from the monthly values (table 3).

Runoff and Infiltration

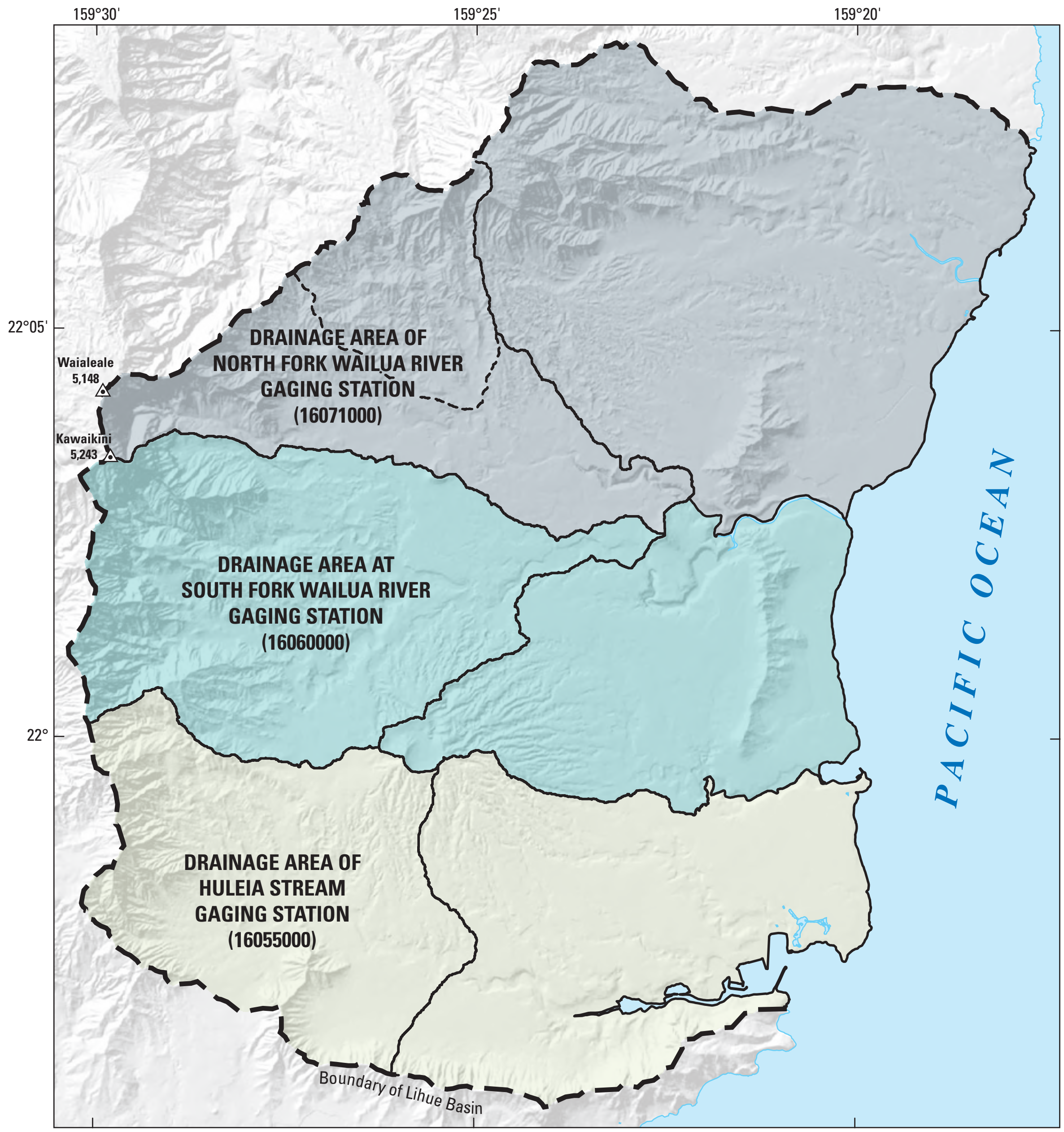
The volume of water that infiltrates the soil after a period of rainfall can be estimated by subtracting the amount of direct runoff (water that flows over the land surface and shallow subsurface into the stream) from rainfall (fig. 12).

Table 3. Monthly irrigation used in the water budget for drip-irrigated (Q_D) and furrow-irrigated (Q_F) fields in the Lihue Basin, Kauai, Hawaii.

Month	Q_D (inches)	Q_F (inches)
January	2.96	8.89
February	2.77	8.30
March	3.41	10.24
April	3.83	11.50
May	4.18	12.53
June	3.67	11.00
July	4.43	13.29
August	4.41	13.23
September	3.69	11.06
October	4.09	12.27
November	3.60	10.80
December	2.96	8.89

Direct runoff for the drainage basins of some streams in the Lihue Basin can be determined from long-term gaging-station records. Flow recorded at a streamflow-gaging station includes both direct-runoff and base-flow (ground water that discharges into the stream) components from within the drainage area of the station. In this study, the direct-runoff component was separated from the base-flow component for selected streams by using the hydrograph-separation program of Wahl and Wahl (1995). The mean monthly direct-runoff values were then divided by the mean monthly rainfall (derived from the rainfall-distribution maps of Giambelluca and others, 1986) within the drainage area of each gaging station to obtain monthly ratios of runoff to rainfall. The monthly runoff-to-rainfall ratios were then used to compute infiltration in the water balance.

Runoff-to-rainfall ratios could not be computed for all areas in the Lihue Basin. The hydrograph-separation program is designed for continuous-record streamflow-gaging stations with no upstream controls such as diversions, additions, or reservoirs. Not all areas within the Lihue Basin were covered by the drainage areas of continuous-record streamflow-gaging stations, and most of the streams with gaging stations have been affected by diversions for irrigation. Direct runoff could, however, be computed for gaged streams that also have concurrent records of the water put into and taken from the stream. In these cases, the hydrograph-separation program was run on the composite hydrographs of the concurrent parts of the records of the gaging stations. Direct runoff and runoff-to-rainfall ratios were computed for the drainage areas of gaging stations 16060000 on the South Fork Wailua River, 16071000 on the North Fork Wailua River, and 16055000 on Huleia Stream (fig. 15 and table 4). Other areas in the Lihue Basin were assigned runoff-to-rainfall ratios of the nearest gaged basins.



EXPLANATION

RUNOFF-TO-RAINFALL RATIO BASED ON DATA FROM

- North Fork Wailua River gaging station
- South Fork Wailua River gaging station
- Huleia Stream gaging station

DRAINAGE AREA OF EAST BRANCH NORTH FORK WAILUA RIVER GAGING STATION (16086000)--Used in sensitivity analysis only

Kawaikini 5,243 MOUNTAIN PEAK AND NAME—Number is elevation, in feet above mean sea level

Figure 15. Areas used in the computation and assignment of runoff-to-rainfall ratios for the water balance of the Lihue Basin, Kauai, Hawaii.

Table 4. Monthly runoff-to-rainfall ratios for selected drainage basins in the Lihue Basin, Kauai, Hawaii.

[**East Branch North Fork Wailua River:** used in sensitivity tests only. **Gaging stations:** abbreviated U.S. Geological Survey gaging-station numbers. To obtain full number, append "16" before and "00" after number shown.]

	Huleia Stream	South Fork Wailua River	North Fork Wailua River	East Branch North Fork Wailua River
Gaging stations used to compute composite flow	[1]0550, 0534, 0536, 0544	[1]0600, 0570, 0580	[1]0710, 0700, 0620, 0610, 1000	[1]0680
Period of record used in computation	1968–70	1913, 1918	1966–72	1912–2004
Monthly runoff-to-rainfall ratios				
January	0.36	0.32	0.42	0.49
February	.41	.26	.33	.34
March	.40	.62	.31	.41
April	.17	.60	.37	.37
May	.24	.43	.35	.32
June	.17	.29	.31	.20
July	.11	.30	.21	.23
August	.11	.24	.21	.24
September	.12	.16	.23	.27
October	.19	.23	.17	.31
November	.41	.17	.25	.44
December	.83	.60	.52	.41
Average	.29	.35	.31	.34

[1]Indicates the gaging station that defines the drainage area of basin.

The mean monthly direct runoff values are not really mean monthly values in the strict sense. The mean monthly direct runoff for January, for example, would normally be the average of all direct-runoff means for January over the period of record, and only Januarys with complete data would be used in the average. The periods of concurrent record for most streams in the Lihue Basin are short, however, and would be even shorter if incomplete months were eliminated from analysis. Therefore, in this study, the monthly direct runoff for January was computed by averaging all direct runoff values for all January days, regardless of whether or not those days belong to complete months. This gave an average daily discharge (in cubic feet per second) for all January days; a similar computation was made for all other months. An adjustment was necessary for March at the South Fork Wailua River gaging station because available data from that station indicated that the mean monthly direct runoff was more than mean monthly rainfall. This inconsistency results because the period of concurrent record for the gaging stations used in the computation was short and included the anomalously high flows of March 11–13, 1918, with daily mean flows in excess of 2,900 ft^3/s. Because such flows are not typical and tended to skew the mean, they were eliminated from the average.

Rate of Evapotranspiration

In the water-balance analysis, evapotranspiration takes place within the soil. Potential evapotranspiration is the amount of water that would be evaporated or transpired from a well-vegetated soil if sufficient water is always available. The actual amount of water that is evaporated or transpired (actual evapotranspiration) is usually less because natural precipitation and soil-moisture storage do not always provide sufficient water for evapotranspiration at the potential rate. Even in sugarcane-growing areas where irrigation supplements natural precipitation, evapotranspiration may be less than the potential rate during ripening, harvesting, and fallow periods between crops when irrigation is reduced or completely withheld. Potential evapotranspiration is controlled by climate and the physiological water requirements of vegetation, whereas actual evapotranspiration also is affected by availability of water in the soil and soil depth.

Potential evapotranspiration.—A relatively large volume of pan-evaporation data is available for Hawaii because of monitoring conducted by sugarcane plantations, but pan evaporation may differ from potential evapotranspiration depending on vegetation type and percentage of ground area covered by the vegetation. Because the pan-evaporation data constitute the most widespread, readily available indicator of evapotranspiration, it is common in water-balance studies in Hawaii to express the uptake of water by vegetation as a ratio to pan evaporation (pan coefficient).

Research on sugarcane in Hawaii indicates that the ratio of evapotranspiration from fully grown sugarcane to pan evaporation is about 1.0 to 1.2 (Jones, 1980). Pan coefficients for other vegetation types are less well known. In a water-balance study on Oahu, Hawaii, Giambelluca (1983) considered evapotranspiration for most types of vegetation to be equal to that of fully grown sugarcane, except in persistently wet forests. In a series of water-balance computations for several areas in Hawaii, Shade (1995a, 1995b, 1997a, 1997b, 1999) used a pan coefficient of 1.0 based on published lysimeter studies in Hawaii sugarcane fields. For the Kohala Mountain on the island of Hawaii, Oki (2002) used a pan coefficient of 0.85 for all areas except wet forested areas below the fog zone.

In this study, potential evapotranspiration was derived from the map of annual pan evaporation by Ekern and Chang (1985) (fig. 14). The same methods described above for converting the lines of equal rainfall to an areal rainfall distribution were used to convert the lines of equal pan evaporation to areal evaporation distribution. Tabled monthly data in Ekern and Chang (1985) indicate that pan evaporation varies seasonally, with peaks in July–August, and lows in December–January. To better represent monthly variations, monthly weighting factors were derived from the mean monthly values and applied to the areal pan-evaporation distribution (table 5). The pan-evaporation distribution was converted to potential-evapotranspiration distribution by applying the pan coefficients. All non-agricultural areas were assigned a pan coefficient of 0.85 except for wetlands (1.0) and bare, rocky, or unconsolidated land (0.2). In agricultural areas, potential evapotranspiration (and hence pan coefficients) varies depending on the stage of growth of the crop (Allen and others, 1998). In this study, the crop cycle for sugarcane fields was divided into stages and pan coefficients for sugarcane fields were assigned as shown in figure 16 based on information in Fukunaga (1978). Evapotranspiration varies depending on whether the soil is at field capacity, nearly depleted (near the wilting point), or at some point between these conditions. In the water-balance computations used in this study, the method of Allen and others (1998) was used to model the change in evapotranspiration between field capacity and wilting point.

Availability of water in the soil.—For a given amount of infiltration, the availability of water in the soil is a function of the soil's ability to store water for uptake by plants. The maximum amount of water that can be stored in the soil and used by plants is known as the available water capacity. In the water-balance analysis for this study, the distribution of available water capacity of soils in the Lihue Basin is based on soil surveys described in Foote and others (1972) and U.S. Department of Agriculture (2001). For most types of soil, values of available water capacity were reported as ranges.

Table 5. Weighting factors used to account for the monthly variation in pan evaporation in the water-balance computation for the Lihue Basin, Kauai, Hawaii.

Month	Weighting factor
January	0.0643
February	.0661
March	.0797
April	.0850
May	.0948
June	.0974
July	.1036
August	.1024
September	.0918
October	.0831
November	.0692
December	.0626

For the water-balance computation, the median value of the range was used. For many soil types, different ranges were reported for different depths. In these cases, the water-balance computation used the depth-weighted mean available water capacity for all soil layers within the root depth. For a small number of soil types in the Lihue Basin, a value of zero was reported in the available-water-capacity data from the U.S. Department of Agriculture (2001). Because an available water capacity of zero is unrealistic, a default minimum value of 0.03 was assigned to any soil type and layer having a reported value of zero.

Soil thickness (root depth).—In the water-balance analysis, evapotranspiration from soil is assumed to take place only within the reach of roots. Root depths were estimated for various types of vegetation land cover. The distribution of vegetation type used in this study was based on a land-cover map for Kauai produced by the National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center (CSC) on the basis of remote-sensing satellite imagery taken in 2000 (National Oceanic and Atmospheric Administration, 2000). The NOAA map showed 13 categories of land cover in the study area (table 6). The NOAA land-cover classification did not always agree with aerial photographs, plantation maps, and ground-based knowledge of the area. In particular, areas of active sugarcane cultivation at the time the satellite imagery was acquired were in some cases classified as "grassland" and in other cases as "cultivated land," presumably based on how the land appeared at the time of the satellite imaging. From above, recently plowed or planted fields have the appearance of actively cultivated land, whereas mature sugarcane has the appearance of grass. In areas where there were discrepancies, the areas of known active sugarcane cultivation as indicated by plantation maps and records took precedence over the NOAA classification.

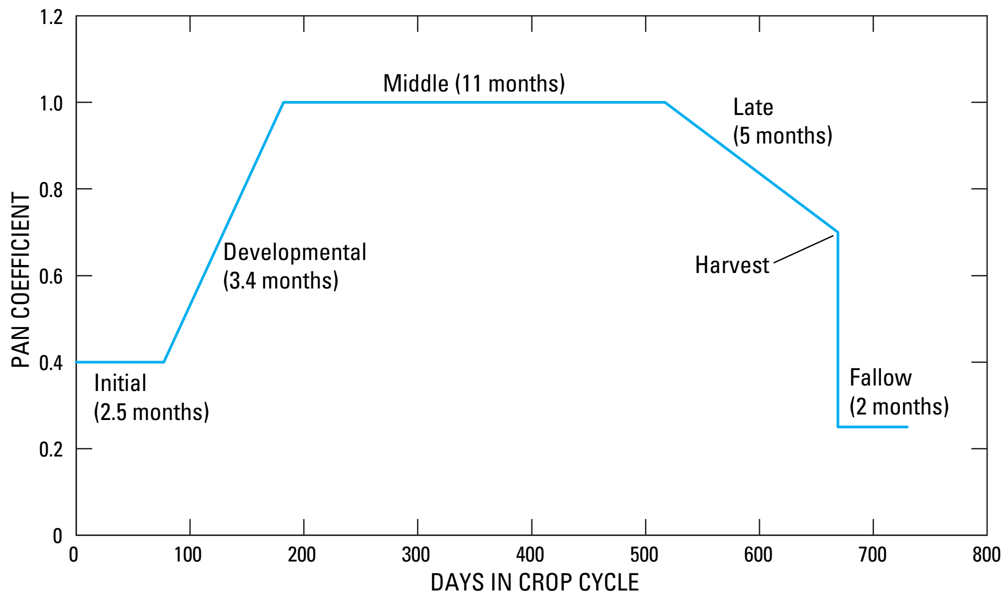


Figure 16. Pan coefficients in the water-balance computation for different growth stages of sugarcane.

In this study, sugarcane was assigned a root depth of 24 in. based on the results of Lee (1927), who found that in field studies and controlled experiments, 85 percent or more of the roots in mature sugarcane were in the uppermost 24 in. of soil (table 6). Grasslands were assigned a root depth of 20 in., which is similar to the root depth assigned to pasture lands by Oki (2002). Areas of scrub and shrub, which in the Lihue Basin are mostly sloping areas where soil thickness and vegetation growth is limited by mass wasting, were assigned a root depth of 12 in., which is consistent with values reported in Scott (1975). Vegetation in high- and low-intensity developed areas, which in the Lihue Basin consist primarily of urban and residential lands, was assumed to be short grass with a root depth of 12 in. Fifty percent of any area classified as high-intensity developed and 20 percent of any area classified as low-intensity developed were assumed to be impervious to water. Areas classified as “evergreen forest” in the NOAA map were assigned a root depth of 36 in., based on reported root depths for forest soils in Foote and others (1972). Other land-cover categories, for which root depths are unknown, were assigned arbitrary values of 6 to 16 in., but the total land area in these categories is relatively small.

Table 6. Land-cover categories, root depths, and pan coefficients used in this study.

[**Land-cover category**: Data from National Oceanic and Atmospheric Administration (2001)]

Land-cover category	Root depth (inches)	Pan coefficient
Sugarcane	24	See fig. 16
Bare land	6	0.20
Cultivated land	16	.85
Estuarine forested wetland	6	1.00
Evergreen forest	36	.85
Grassland	20	.85
High intensity developed	12	.85
Low intensity developed	12	.85
Palustrine emergent wetland	6	1.00
Palustrine forested wetland	6	1.00
Palustrine scrub/shrub wetland	6	1.00
Scrub/shrub	12	.85
Unconsolidated shore	6	.20
Unclassified	6	.85

Other Input Data

In addition to the principal data sets described above, the water-balance computation required other data that generally have a smaller influence on estimates of ground-water recharge because the data (1) pertain to only a small area in the Lihue Basin, (2) affect a minor computational adjustment in the water balance, or (3) represent starting conditions whose initial values become irrelevant as the daily water balance is computed over a period of many decades. The values assigned to these parameters in the water-balance computation for the Lihue Basin are listed in table 7.

Recharge Estimates

1981 base case.—In 1981, 16,600 acres in the Lihue Basin were used for sugarcane production (fig. 9). Most of the sugarcane fields that were irrigated used the furrow-irrigation method. In this scenario, the basin received a total water input of 750 Mgal/d, 665 Mgal/d (89 percent) of which came from rainfall, 70 Mgal/d (9 percent) from irrigation, and 15 Mgal/d (2 percent) from fog (table 8). Of this total input, 220 Mgal/d (29 percent) went to stream runoff. The estimated basin-wide recharge in this scenario was 264 Mgal/d, or about 35 percent of the total water input to the basin. The distribution pattern of recharge (fig. 17) parallels the distributions of rainfall (fig. 3) and evapotranspiration (fig. 14), with highest recharge per unit area at the inland margin of the Lihue Basin, and lowest recharge near the coast. Much of the coastal area receives 10 in/yr or less of recharge, except in areas of active sugarcane fields, where irrigation has raised recharge in most fields to more than 80 in/yr.

Table 7. Values of miscellaneous parameters in the computation of the water balance for the Lihue Basin, Kauai, Hawaii.

Parameter	Value
Starting soil-moisture storage	50 percent of capacity
Soil depth for non-vegetated areas	6 inches
Impervious surface interception capacity	50 percent
Recharge rate under surface-water bodies	12 inches per year
Percentage of pervious area in:	
High-intensity developed areas	50 percent
Low-intensity developed areas	80 percent
Depletion fraction for evapotranspiration method of Allen and others (1998)[1]	0.65 for sugarcane, 0.50 for all other types of vegetation

[1]See appendix A for explanation.

Table 8. Results of water-balance computations for various land-use and climate conditions in the Lihue Basin, Kauai, Hawaii.

[**Abbreviation:** n.r., not relevant]

Scenario	Water-balance components (million gallons per day)						Percent difference in recharge relative to	
	Rain	Fog	Irrigation	Runoff	Actual evapotrans-piration	Recharge	1981 base case	1998 base case
1981 base case	665	15	70	220	266	264	n.r.	7
1998 base case	665	15	46	220	260	246	-7	n.r.
No-irrigation base case	665	15	0	220	247	212	-20	-14
1981 condition, moderately dry	419	9	70	139	229	131	-50	n.r.
1981 condition, very dry	343	8	70	113	208	100	-62	n.r.
1981 condition, extremely dry	298	7	70	99	193	84	-68	n.r.
1998 condition, moderately dry	419	9	46	139	222	114	n.r.	-54
1998 condition, very dry	343	8	46	113	199	84	n.r.	-66
1998 condition, extremely dry	298	7	46	99	184	69	n.r.	-72
No irrigation, moderately dry	419	9	0	139	205	84	-68	-66
No irrigation, very dry	343	8	0	114	182	56	-79	-77
No irrigation, extremely dry	298	7	0	99	165	41	-84	-83

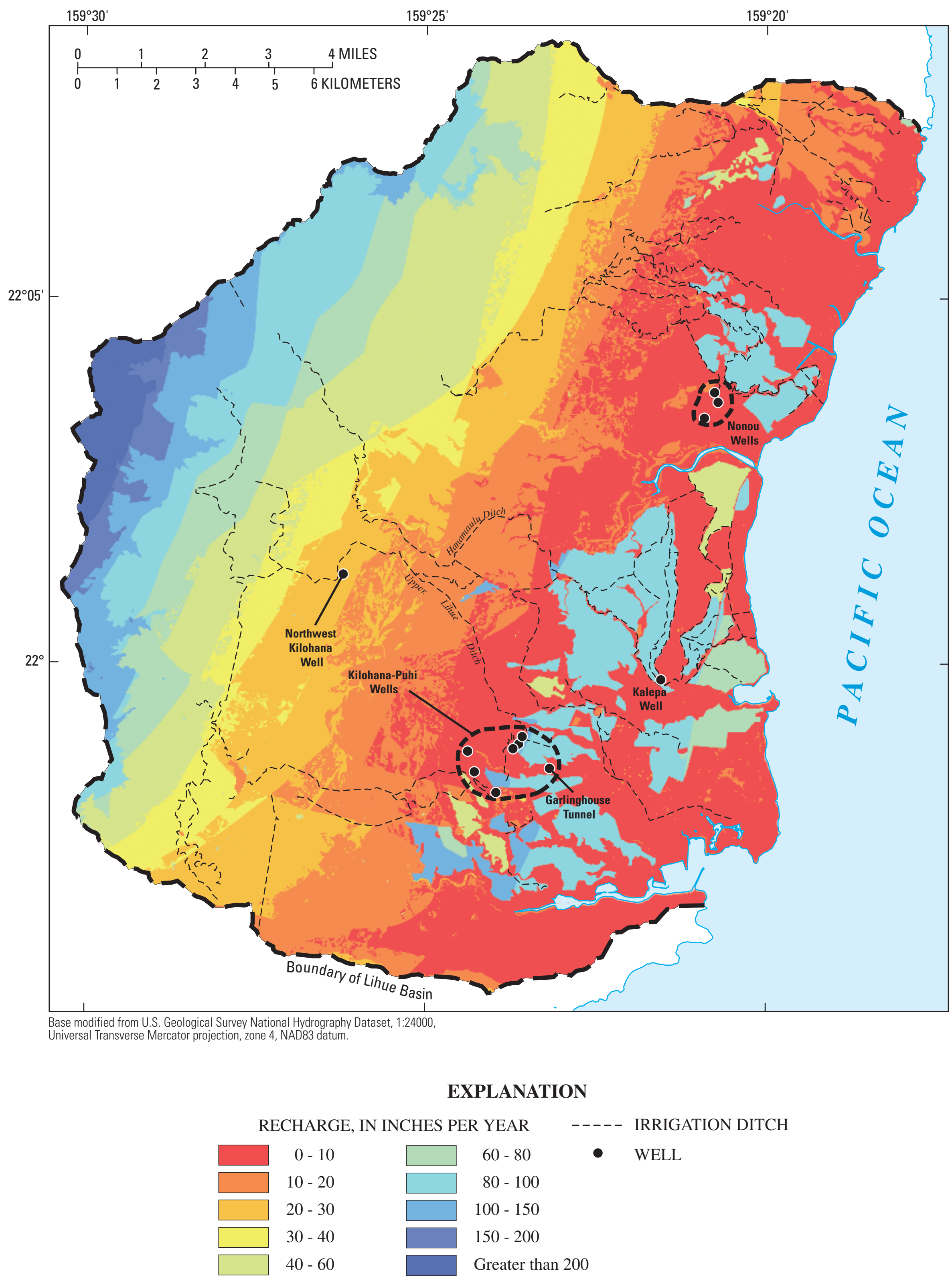


Figure 17. Distribution of estimated recharge for 1981 land-use conditions in the Lihue Basin, Kauai, Hawaii.

1998 base case.—Between 1981 and 1998, agriculture in the Lihue Basin changed in hydrologically significant ways. Plantation records for 1998 had the most complete irrigation information available for years near the closing of sugarcane operations. In 1998, the total area used for sugarcane production was 12,400 acres, about 25 percent less than in 1981 (fig. 10). Also, some sugarcane fields were converted from furrow irrigation to more efficient drip irrigation in the 1980s and 1990s. These changes resulted in a reduction in irrigation of 24 Mgal/d (relative to 1981 conditions), or about 3 percent reduction in total water input to the Lihue Basin. For the land-use conditions that existed in 1998, the water-balance analysis yielded a recharge estimate of 246 Mgal/d in the Lihue Basin, which is 18 Mgal/d less than the estimated recharge for 1981 land-use conditions (table 8). The pattern of recharge distribution for the 1998 base case (fig. 18) is similar to the distribution for the 1981 base case (fig. 17) except for differences associated with irrigation changes that took place between these times (figs. 9 and 10). Recharge is less in areas that changed from furrow to drip irrigation and in areas removed from sugarcane production.

No-irrigation base case.—Since the closure of the sugarcane industry in the Lihue Basin in 2000, other agricultural activities have replaced sugarcane in some areas, but most of the former sugarcane lands are currently unused. Although the future of agriculture in the Lihue Basin is unknown, the amount of irrigation water used in the near future probably will be substantially less than the amount used to irrigate sugarcane. In this scenario, distribution of sugarcane fields was based on 1998 land-use conditions. When the sugarcane plantations ceased operation in 2000, fields probably were left in various stages of the planting cycle, from recently harvested fallow fields to fields with mature sugarcane. It is therefore difficult to determine what the water demands (pan coefficients) would have been since the closing of the plantation, or what they will be in the future. For this reason, the water balance was allowed to cycle through the pan coefficients as if the sugarcane was still present, but irrigation was completely withheld. In the 1981 and 1998 land-use scenarios, irrigation provided 70 and 46 Mgal/d, respectively, or 9 and 6 percent of the total water input to the basin-wide water balance (table 8). With this water completely removed from the water balance, basin-wide recharge was 212 Mgal/d, which constitutes a 52 Mgal/d decrease relative to the 1981 base case and 34 Mgal/d decrease relative to 1998 base case. The pattern of recharge distribution for this scenario (fig. 19) shows that without irrigation, nearly all coastal areas, including the areas near the Nonou and Kilohana-Puhi wells, would receive recharge of 10 in/yr or less.

1981 and 1998 land-use conditions with drought.—To examine how a period of low precipitation may have affected recharge, a water balance was computed for a hypothetical case using the 1981 and 1998 land-use conditions combined with various degrees of drought. For this study, drought conditions were imposed on the water-balance computation by using a lower-than-normal annual-rainfall weighting factor. Drought conditions were defined on the basis of the 12-month standard precipitation index (SPI) (Guttman, 1999). The 12-month SPI for rainfall data from 1952 to 2003 for the Lihue Airport rain gage was computed and placed into “moderately dry,” “very dry,” and “extremely dry” categories by the NWS (Kevin Kodama, written commun., May 20, 2004). To obtain the annual rainfall weights representative of each category, the average rainfall for all 12-month periods in the category was divided by the mean annual rainfall for 1950–2001 (table 9).

The average of the 12-month periods classified as moderately dry, very dry, and extremely dry was 26.6, 21.8, and 18.9 in., respectively, which yielded weighting factors of 0.64, 0.53, and 0.46 (table 9). Using these weighting factors to compute rainfall for droughts of varying severity and applying this to 1981 land-use conditions resulted in computed recharge ranging from 131 to 84 Mgal/d (table 8). This represents a decrease of 133 to 180 Mgal/d (50 to 68 percent) relative to the 1981 base case. Using 1998 land-use conditions, the computed recharge ranged from 114 to 69 Mgal/d, or 132 to 177 Mgal/d (54 to 72 percent) less than the 1998 base case. Under moderately dry conditions, the area of the basin receiving 10 in/yr or less of recharge is about twice the size that it is under normal rainfall conditions (compare figs. 20 and 21 with figs. 17 and 18). Most furrow-irrigated areas, however, still would receive 60 in/yr or more of recharge.

Table 9. Mean rainfall for 12-month periods classified as near normal to extremely dry using the standard precipitation index (SPI) for the rain gage at the Lihue Airport, Kauai, Hawaii.

[Data and SPI analysis for 1951 through 2003 provided by Kevin Kodama, National Weather Service, written commun., May 20, 2004]

Category	Mean rainfall for 12-month periods classified in category (inches)	Weighting factor
Near normal	40.3	Not applicable
Moderately dry	26.6	0.64
Very dry	21.8	.53
Extremely dry	18.9	.46

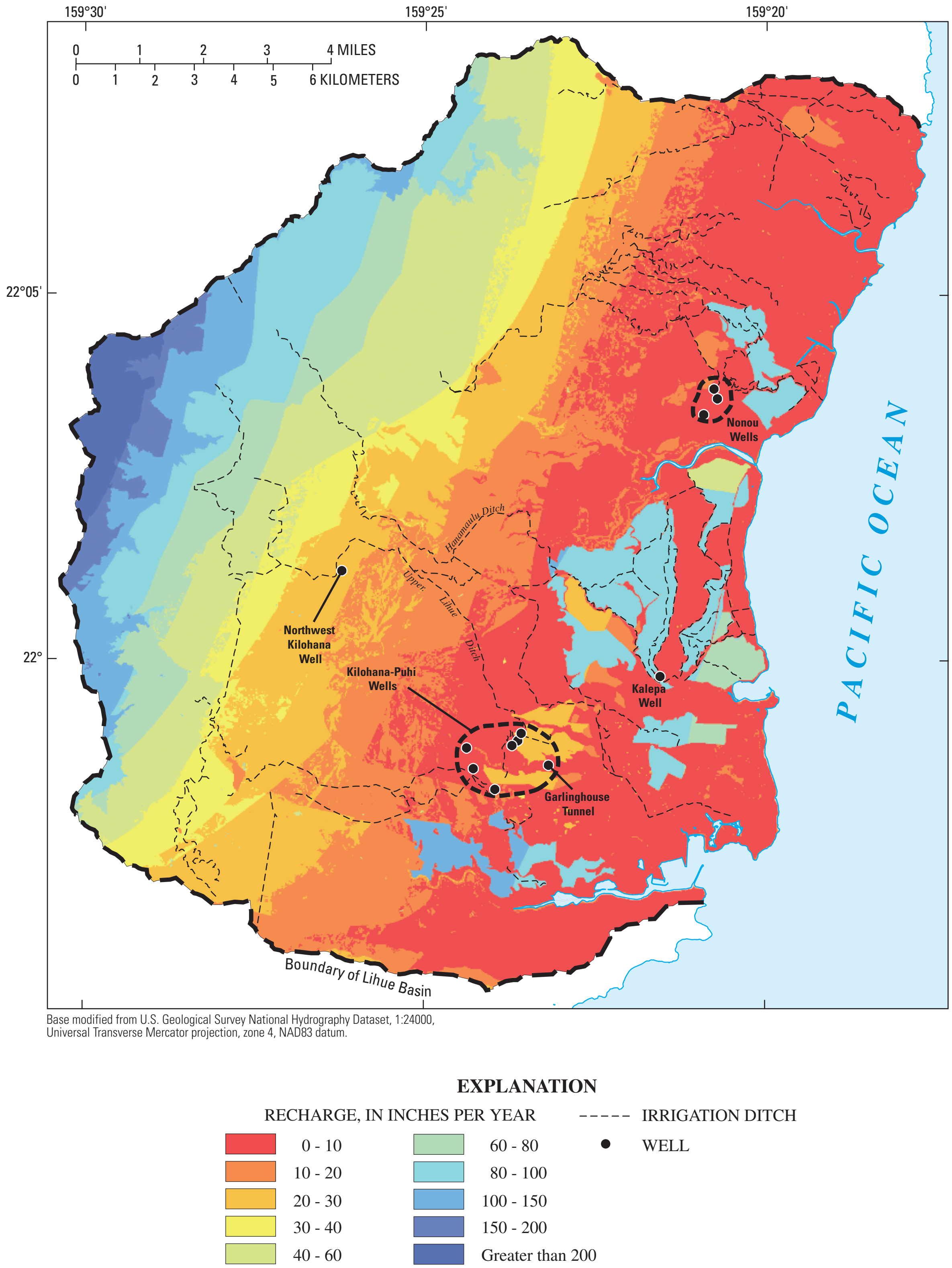
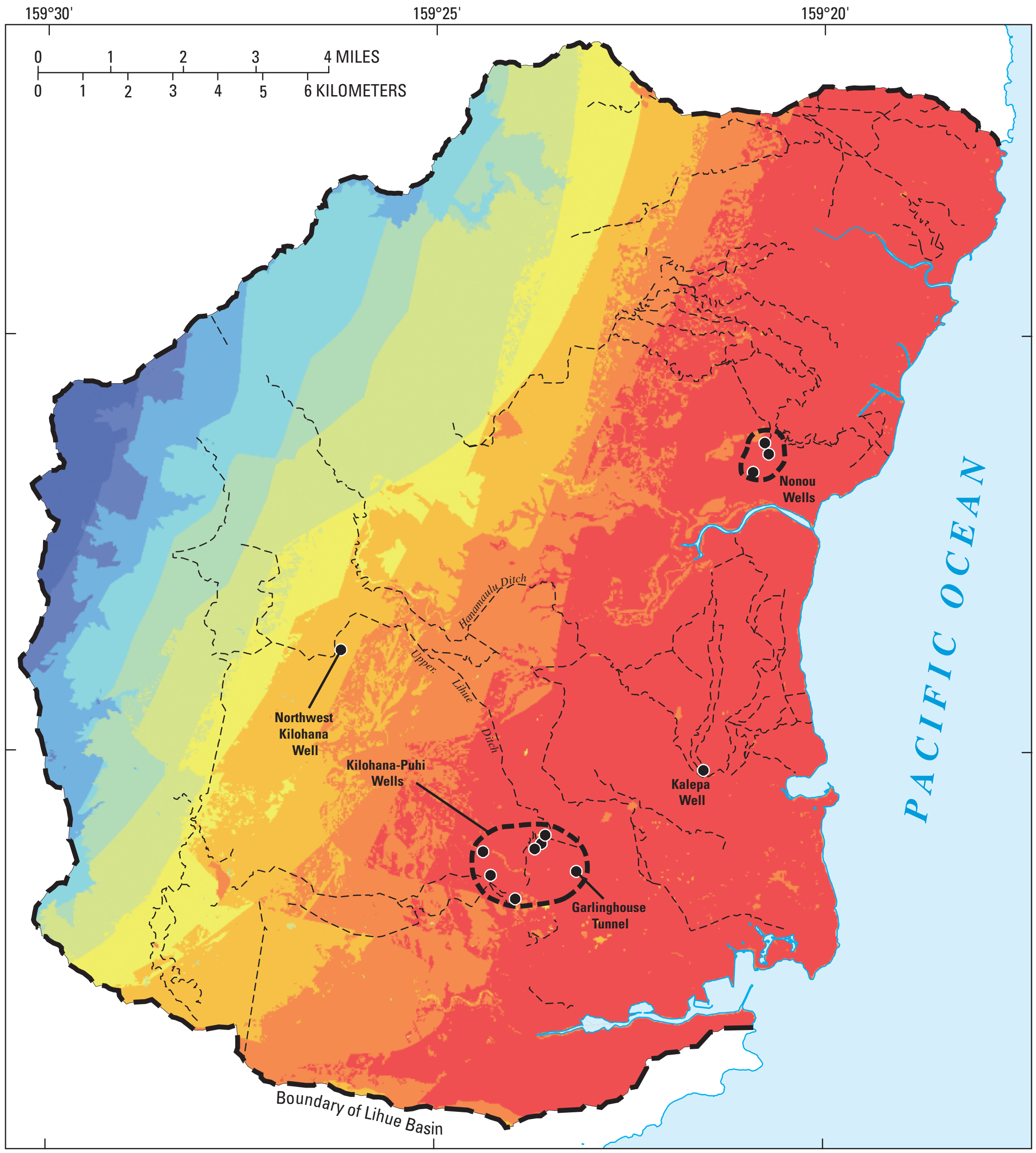


Figure 18. Distribution of estimated recharge for 1998 land-use conditions in the Lihue Basin, Kauai, Hawaii.



Base modified from U.S. Geological Survey National Hydrography Dataset, 1:24000, Universal Transverse Mercator projection, zone 4, NAD83 datum.

EXPLANATION

RECHARGE, IN INCHES PER YEAR

- 0 - 10
- 10 - 20
- 20 - 30
- 30 - 40
- 40 - 60
- 60 - 80
- 80 - 100
- 100 - 150
- 150 - 200
- Greater than 200

IRRIGATION DITCH

WELL

Figure 19. Distribution of estimated recharge if irrigation ceases in the Lihue Basin, Kauai, Hawaii.

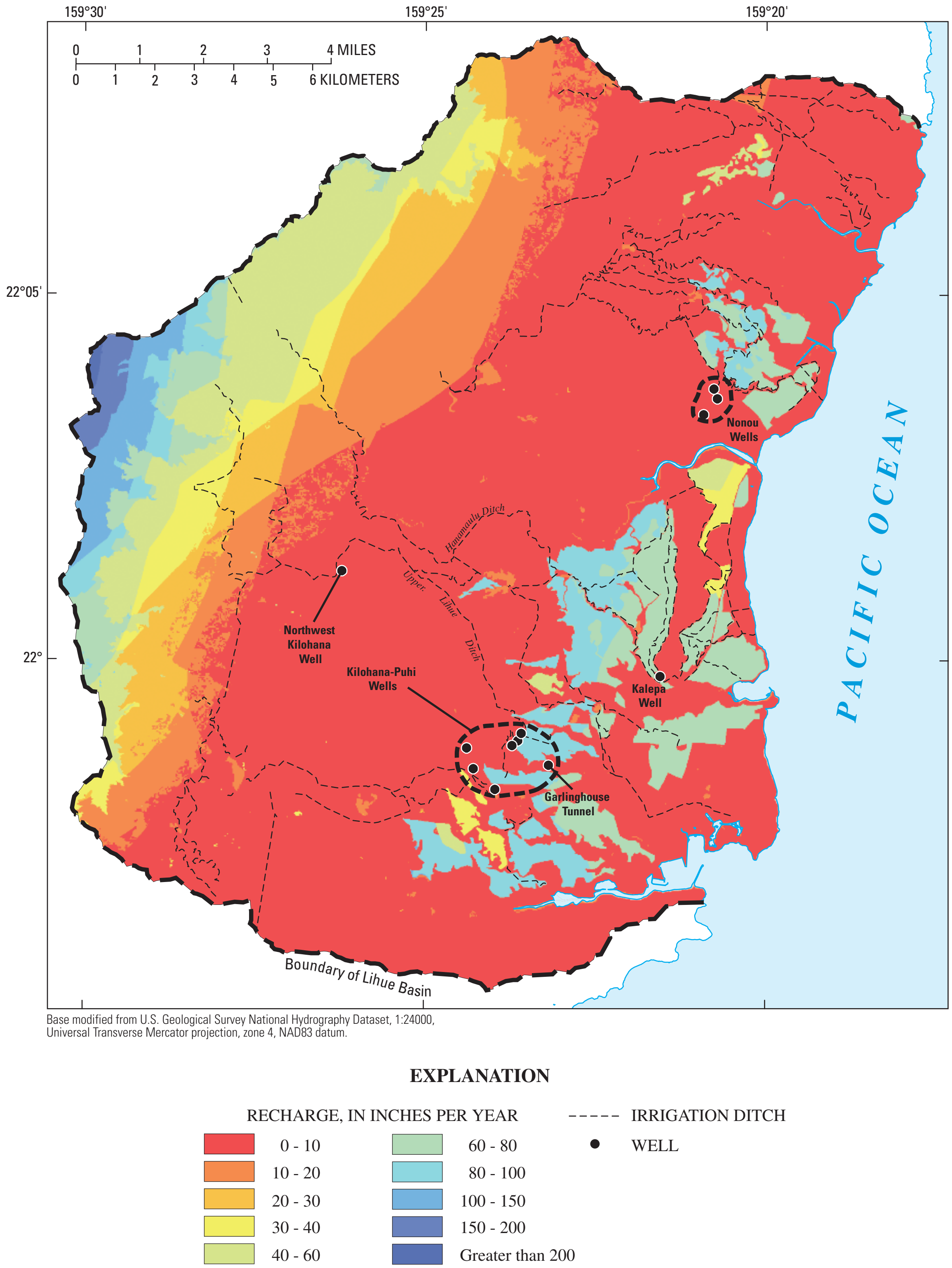


Figure 20. Distribution of estimated recharge for 1981 land-use conditions and moderately dry rainfall conditions in the Lihue Basin, Kauai, Hawaii.

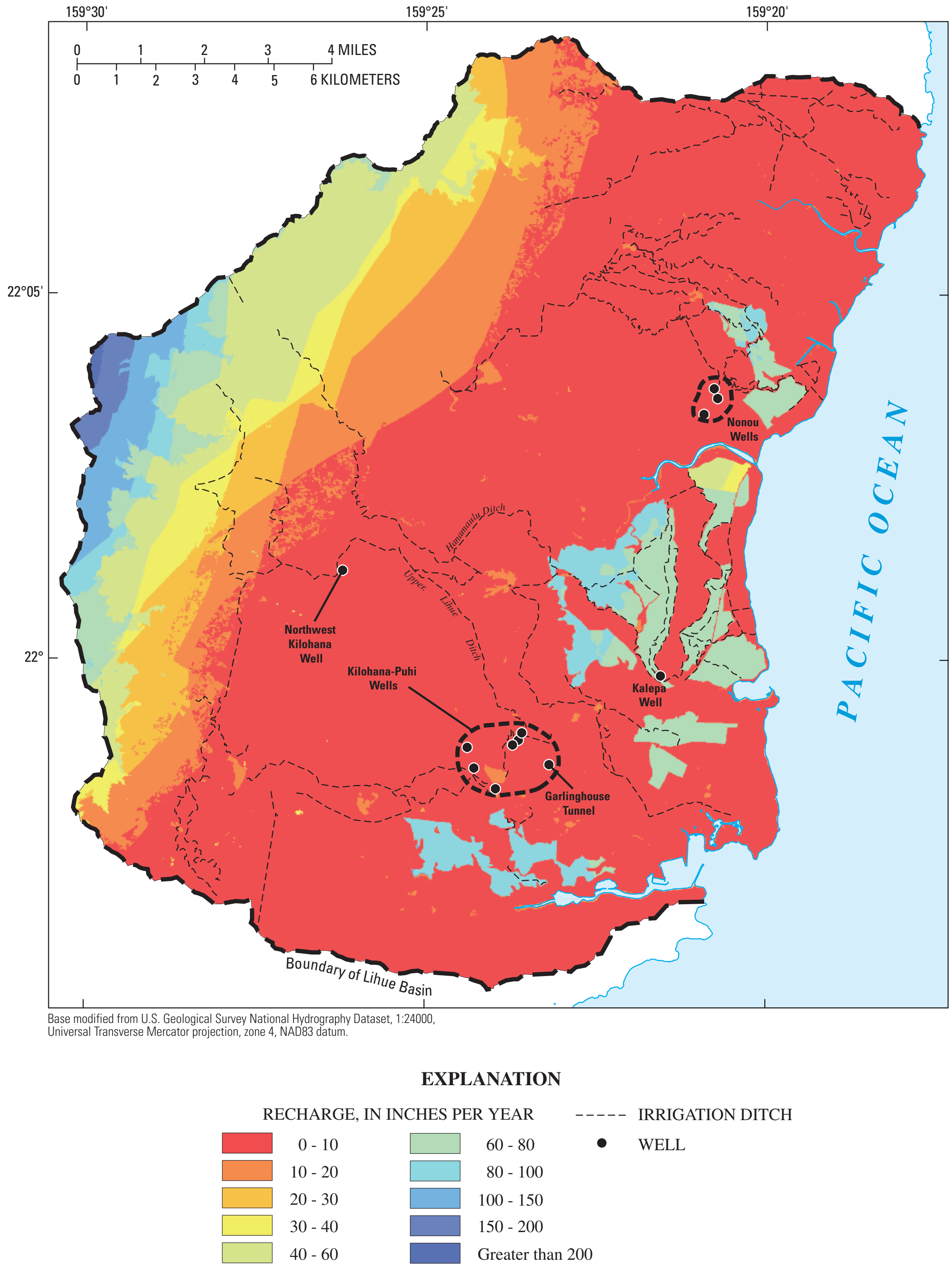


Figure 21. Distribution of estimated recharge for 1998 land-use conditions and moderately dry rainfall conditions in the Lihue Basin, Kauai, Hawaii.

Drought with no irrigation.—If drought conditions occur when there is no irrigation, the input of water to the water balance will be substantially decreased. The computed combined water-balance input assuming no irrigation and moderately dry, very dry, and extremely dry conditions was 428, 351, and 305 Mgal/d, respectively (table 8), which constitutes a 43 to 59 percent decrease in input relative to the 1981 base case and 41 to 58 percent decrease relative to the 1998 base case. Computed recharge ranged from 84 to 41 Mgal/d, which is 180 to 223 Mgal/d (68 to 84 percent) less than the recharge computed in the 1981 base case, and 162 to 205 Mgal/d (66 to 83 percent) less than the 1998 base case. The pattern of recharge distribution for moderately dry rainfall conditions when there is no irrigation shows that recharge in about two-thirds of the Lihue Basin would be 10 in/yr or less (fig. 22).

Comparison with previous recharge estimates.—The water balance of Kauai for land-use conditions that existed in 1990 was studied previously by Shade (1995a). Because the land-use conditions in 1990 were close to those of the 1998 base-case scenario of this study, an opportunity exists to compare the recharge computed by two different methods. Shade used a water-balance approach similar to the one used in this study, except that (1) the water balance was computed on a monthly basis rather than a daily basis, (2) fog drip was not considered, (3) runoff-to-rainfall ratios were computed using flow-duration analysis rather than hydrograph-separation analysis, and (4) evapotranspiration losses were subtracted from the soil water after recharge was computed. Shade also reported the results of her study by sectors that do not fit precisely the area of this study. Shade's Wailua and Hanamaulu sectors closely approximate the southern 80 percent of the Lihue Basin, but the remainder of the basin is encompassed in Shade's Anahola sector, about one-half of which extends beyond the northern boundary of the basin. For the purposes of this discussion, an adequate estimate of Shade's recharge for the Lihue Basin can be obtained by summing the recharge of the Wailua and Hanamaulu sectors, and 50 percent of the recharge for the Anahola sector.

The most striking difference between the results of the two studies is that Shade's (1995a) water balance for the Lihue Basin shows significantly lower recharge and higher runoff than the basin-wide water balance computed in this study (table 10). This difference primarily is due to the differences in the method used to compute rainfall-runoff ratios. To distinguish between base flow and direct runoff in the records of streamflow-gaging stations, Shade used a discharge corresponding to the 90th percentile on a flow-duration curve. This common practice presumes that flow that is equaled or exceeded 90 percent of the time represents the mean base flow of the stream. The 90th percentile is arbitrary, however, and does not consider that the relation between ground water and surface water in each stream basin is unique. For stream basins in which ground-water discharge constitutes a large portion of total flow, such as the streams in the Lihue Basin, base flow may be more frequent than indicated by the 90th percentile. In these cases, the 90th-percentile flow underestimates actual base flow, and in turn overestimates direct runoff. In contrast, the hydrograph-separation technique used in this study is less arbitrary because it analyzes the shape of the stream hydrograph to determine base flow, and the shape of the hydrograph reflects the unique base-flow characteristics of each stream. Other differences between Shade's approach and the approach used in this study resulted in smaller differences in recharge. Shade's resultant actual evapotranspiration is lower because evapotranspiration was subtracted after recharge was computed, which tends to overestimate recharge and underestimate evapotranspiration. Pan coefficients, root depths, and the method of computing evapotranspiration also differed between the two studies. Total input in Shade's water balance is lower because fog drip was not considered.

Table 10. Comparison of recharge estimates from this study with previous estimates.

[**Percent of total input:** Total input for 1998 base case is the sum of rainfall, fog, and irrigation; total input for Shade (1995a) is the sum of rainfall and irrigation]

	Percent of total input		
	Runoff	Actual evapotranspiration	Recharge
1998 base case	30	36	34
Shade (1995a)	48	34	19

Sensitivity Analysis

Several of the input parameters required for the water-balance computation have significant uncertainty. Values used in the computations above were considered to be the most reasonable, but for some parameters, other values or ranges of values also could be considered reasonable. In the sensitivity tests discussed below, parameters were varied individually within reasonable ranges to assess how much of a difference this would make in the recharge estimates. The parameters tested include the (1) rainfall, (2) available water capacity in soil, (3) fog-to-rain ratio, (4) ratio of drip-irrigation efficiency to furrow-irrigation efficiency, (5) runoff-to-rainfall ratio, (6) root depth, (7) pan coefficient, and (8) rainfall weights used to represent droughts (table 11). For all tests except irrigation efficiency, 1981 land-use conditions were used. For the test of the ratio of drip-to-furrow irrigation efficiency, the 1998 land-use condition was used because the conversion from furrow to drip irrigation probably had reached its maximum by this time.

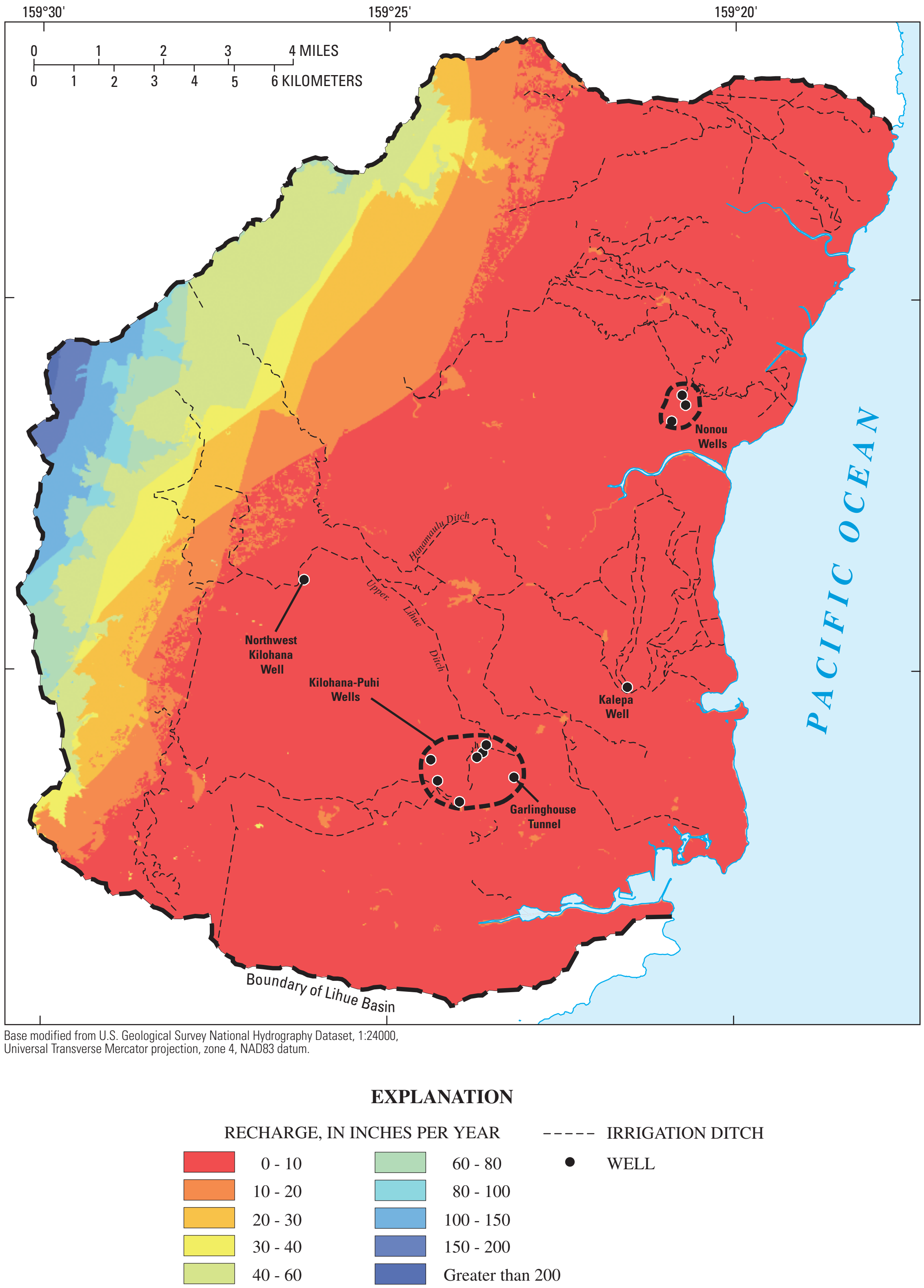


Figure 22. Distribution of estimated recharge if irrigation ceases under moderately dry conditions in the Lihue Basin, Kauai, Hawaii.

Table 11. Results of sensitivity testing for parameters used in the water-balance computation of recharge in the Lihue Basin, Kauai, Hawaii.

Parameter	Test	Water-balance components (million gallons per day)						Percent difference in recharge relative to 1981 base case except where noted
		Rain	Fog	Irrigation	Runoff	Actual evapotrans-piration	Recharge	
Rainfall	1.1 times base case	732	17	70	220	276	323	22
Available water capacity[1]	High reported value	665	15	70	220	267	263	0
	Low reported value	665	15	70	220	264	266	1
Fog-to-rain ratio	0.0	665	0	70	220	265	249	-6
	0.1	665	8	70	220	265	258	-2
	0.2	665	17	70	220	266	266	1
	0.3	665	25	70	220	266	274	4
Ratio of drip efficiency to furrow efficiency	2.0	665	15	48	220	260	247	[2]0
	1.5	665	15	49	220	260	249	[2]1
	1.0	665	15	52	220	260	252	[2]2
Runoff-to-rainfall ratio	1.5 times base cases	665	15	70	339	231	181	-31
	0.5 times base cases	665	15	70	110	280	360	36
	From gage 16068000	665	15	70	232	265	254	-4
Root depth	2.0 times base cases	665	15	70	220	275	255	-3
	0.5 times base cases	665	15	70	220	248	282	7
Pan coefficient	0.8 times base cases	665	15	70	220	229	300	14
	1.2 times base cases	665	15	70	220	294	236	-11
Rainfall weights for drought	0.84	549	12	70	182	256	194	[3]48
	0.74	483	11	70	160	244	161	[3]23

[1] High and low values reported in Foote and others (1972).

[2] Relative to 1998 base case.

[3] Relative to 1981 land use with moderately dry rainfall.

Parameters having minor effects on recharge estimates.—Varying available water capacity, fog-to-rain ratio, ratio of drip-to-furrow irrigation efficiency, and root depth within ranges that encompassed the uncertainty associated with these parameters resulted in relatively minor effects (difference of 7 percent or less relative to the base cases) on estimated recharge (table 11). To test the effect of uncertainty in available water capacity for each soil type, the maximum and minimum values reported by the U.S. Department of Agriculture (2001) were tested. The actual available water capacity is likely to be between these maximum and minimum values. Fog-to-rain ratios were tested within a range from 0.0, which represents no fog input, to 0.3, which is slightly higher than the value reported by Juvik and Ekern (1978) for the Kulani Camp Station. The Kulani Camp Station has a windward orographic climate regime and elevation comparable to the highest elevation in the Lihue Basin. Fog contribution probably decreases with elevation, thus the average fog-to-rain ratio below the highest point in the basin down to 2,000 ft probably is between 0.0 and 0.3.

As discussed previously, estimates for drip-irrigation efficiency for sugar plantations in Hawaii range from 80 to 95 percent whereas estimates for furrow-irrigation efficiency range from 30 to 70 percent. These values indicate that the ratio of drip to furrow irrigation efficiency is 1.1 to 3.2. The ratio used in the computation of the recharge presented previously was already near the maximum of this range; therefore, in the sensitivity analysis, the ratio of furrow to drip efficiency was tested over the range of 1.0 to 2.0. Root depths were tested in a range from 0.5 to 2.0 times the root depths used in the 1981 base case.

Rainfall.—Most rain gages are not completely efficient in capturing rainfall, therefore rain-gage records commonly under represent actual rainfall (Brakensiek and others, 1979). The efficiency of a rain gage depends on many factors, including design of the rain gage and the environmental conditions at the site. Giambelluca (1986) acknowledged that the data used in his report were not adjusted to account for rain-gage efficiency. The possibility therefore exists that the rainfall shown in Giambelluca's monthly rainfall maps is lower than actual rainfall. To examine how this uncertainty may affect recharge, rainfall was increased by 10 percent over the 1981 base-case scenario for the entire study area. Rainfall-runoff ratios also were adjusted to be consistent with the 10-percent higher rainfall. The resulting basin-wide recharge was 22 percent higher than the base-case scenario (table 11). Inasmuch as most rain gages collect less rain than actually falls, the base-case recharge estimate can be considered conservative.

Runoff-to-rainfall ratio.—Tests using runoff-to-rainfall ratios that were 0.5 to 1.5 times the values used in the 1981 base-case scenario showed that recharge estimates are sensitive to this parameter (table 11). However, the hydrograph-separation method used to compute direct runoff in this study is the best available method to determine runoff-to-rainfall ratios given the scope of this study because it is less arbitrary than previously used methods. Even so, potential inaccuracy may be associated with using the hydrograph-separation program on the composite of the hydrographs from the gaging stations of streams and their upstream diversions. To assess this potential, the hydrograph-separation program was used to determine the runoff-to-rainfall ratio from the record of a streamflow-gaging station on the East Branch North Fork Wailua River (16096000), which has a small drainage area but no upstream diversions (fig.15). The resulting mean monthly runoff-to-rainfall ratios are similar to those of the larger drainage basins used in this study (table 4), which supports the premise that the ratios used in this study are representative of the basin as a whole. The runoff-to-rainfall ratios for the East Branch North Fork Wailua River also were tested in the water-balance computation, and the resulting basin-wide recharge estimate differs from the base case by only 4 percent (table 11).

Pan coefficients.—As discussed previously, the pan coefficient for fully grown sugarcane, the predominant crop grown in the Lihue Basin for over a century, is about 1.0 to 1.2. The coefficient for wet forested areas could be as high as 1.3 times that of sugarcane (Giambelluca, 1983). Significant areas in the Lihue Basin would not likely have vegetation that has a pan coefficient as low as 0.5 because such coefficients are associated with low-water-demand crops such as pineapple and coffee that were not grown in the Lihue Basin. In the sensitivity tests, pan coefficients were varied by multiplying the coefficients used in the base case by factors of 0.8 to 1.2. Inasmuch as it is difficult to narrow the range of uncertainty of pan-coefficient estimates, the uncertainty translates directly to an uncertainty in the recharge estimates. The estimated basin-wide recharge resulting from the sensitivity tests differed from the 1981 base case by –11 percent when the base-case pan coefficients were multiplied by a factor of 1.2, and by +14 percent when the coefficients were multiplied by a factor of 0.8 (table 11). This uncertainty pertains primarily to the absolute estimated recharge values, but has little significance to the relative changes in recharge caused by droughts and irrigation changes.

Rainfall weighting factors for droughts.—In the water-balance computation, the difference in rainfall between drought periods and normal-rainfall periods was based entirely on the rainfall record of the Lihue Airport rain gage because it has one of the most complete records for the Lihue Basin and is one of the rain gages for which the NWS continuously updates the SPI. However, the apparent severity of a given drought may differ from one location to the next. For example, during the period 1998 to 2002, average annual rainfall at the Lihue Airport was 27 in., which is in the moderately dry SPI classification (table 9). This value is 65 percent of the average annual rainfall (41.4 in.) based on the period 1950 to 2001. In comparison, average annual rainfall for the 1998–2002 dry period at the USGS rain gage on Mt. Waialeale was 363 in., which is 84 percent of the average annual rainfall (431 in.) based on the period of record (1912 to 2002) for this rain gage. This indicates that during the drought of 1998-2002, conditions appear to have been less severe in wet areas than in dry areas. Inasmuch as Mt. Waialeale and the Lihue Airport probably represent the wettest and driest climate extremes in the Lihue Basin (figs. 1, 2), conditions throughout most of the Lihue Basin are probably intermediate between the conditions at Mt. Waialeale and the Lihue Airport. To examine the effect of the uncertainty in using the Lihue Airport rain gage in the drought analysis, two alternative drought-rainfall weighting factors were tested in the sensitivity analysis: (1) 0.84, representing the 1998–2002 dry-period data for Mt. Waialeale; and (2) 0.74, which is the average between the 0.84 from Mt. Waialeale and 0.64, the value used to represent moderately dry conditions in the drought scenarios. Tests using these weighting factors indicates that drought effects may be smaller than indicated in the previous discussions of drought scenarios (table 11), but the drought effects, relative to the 1981 base case, are still substantial.

Discussion

The recharge estimates resulting from the water-balance computations indicate that over a short term and on a basin-wide basis, the effect of changes in irrigation are small compared to effects of droughts (fig. 23). The decreases in irrigation between 1981 and 1998 constituted a change of only 3 percent in the total water input to the Lihue Basin and a 7-percent decline in basin-wide recharge (table 8). Even the complete cessation of irrigation constituted a decrease of 6 to 9 percent of total water input and resulted in a 14- to 20-percent decrease in recharge. In comparison, a drought of only moderate magnitude could reduce the short-term basin-wide water input by 34 to 37 percent, and cause recharge to decrease to less than half of recharge under normal rainfall conditions. A drought of this magnitude occurred in the period 1998 to 2002, when rainfall at the airport averaged 27 in/yr. This dry period coincides with part of the period of observed declining ground-water levels. Thus, for the period during the observed decline in ground-water levels, the water-balance simulations indicate that the effect of the recent drought was greater than the effect of reduced irrigation.

Because droughts are defined on the basis of statistical aberrations from normal or mean rainfall, however, droughts are temporary conditions that will be mitigated eventually by wet periods. Changes in irrigation, on the other hand, can be of long duration or even permanent. In the Lihue Basin, irrigation at the rates formerly provided by the sugarcane industry will probably not return in the foreseeable future. In this context, the cumulative effects of prolonged irrigation loss on recharge may have a greater effect on long-term trends in ground-water levels.

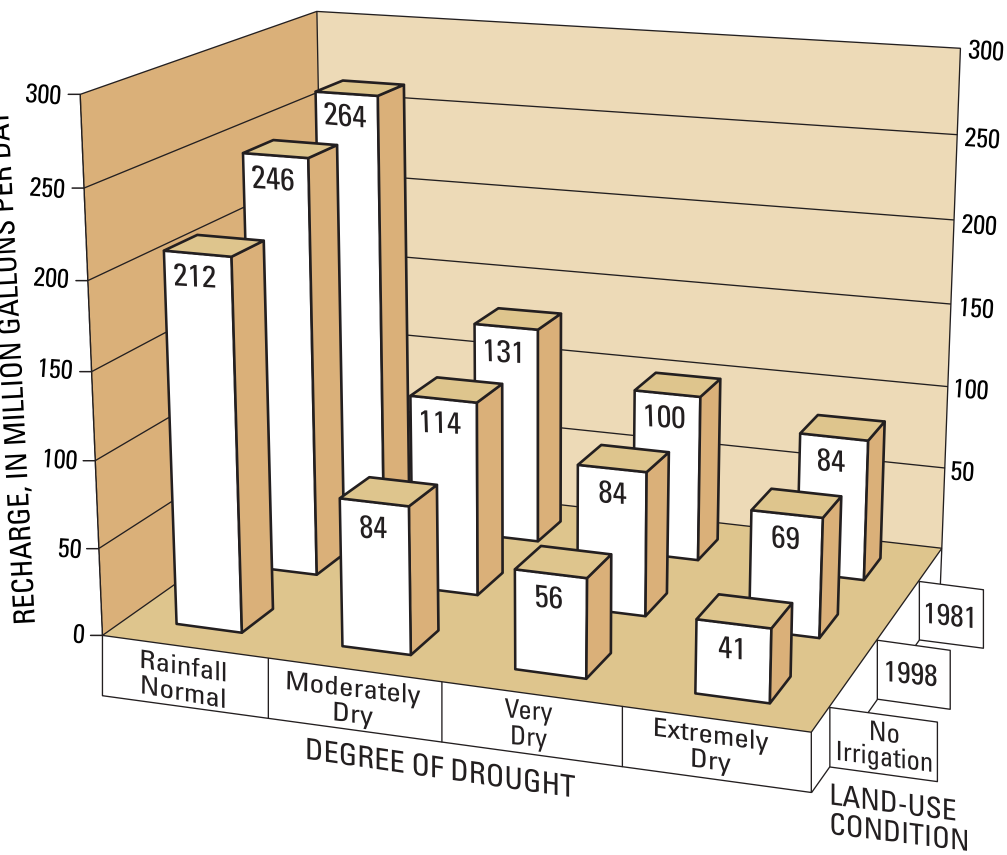


Figure 23. Summary of estimated recharge for various land-use and rainfall conditions in the Lihue Basin, Kauai, Hawaii.
Numbers on bars are recharge values, in million gallons per day.

The importance of irrigation changes on the observed decline in ground-water levels may also be obscured by the voluminous recharge of the entire basin. How irrigation changes relate to declining ground-water levels depends partly on the proximity of the irrigation to the wells. The entire 18-Mgal/d difference in recharge between the 1981 and 1998 scenarios took place in the sugarcane fields. During this time, one of the fields near the Nonou wells was taken out of sugarcane production, and much of the area near the Kilohana wells was converted from furrow to drip irrigation (fig. 10). Similarly, the 34 to 52 Mgal/d decrease in recharge between the 1981 and 1998 base-case scenarios on one hand, and the no-irrigation scenario on the other, took place entirely within the area of the sugarcane fields. Significantly, the Kilohana-Puhi wells, Garlinghouse Tunnel, and Nonou wells are all near areas that without irrigation would receive less than 10 in/yr of recharge, but with irrigation receive more than 80 in/yr of recharge (figs. 17 to 22). Irrigation changes may therefore have a larger connection to the observed decline in localized areas than the basin-wide statistics imply.

If the irrigation formerly provided by the sugarcane industry is completely stopped and a drought occurs, a substantial reduction in total water input to the basin and in basin-wide recharge would result. The water-balance computations indicate that a lack of irrigation combined with moderately dry conditions could cause recharge to decline to only a third of what it was under 1981 and 1998 irrigation levels and normal rainfall; very dry and extremely dry conditions would reduce recharge even more (fig. 23). Rainfall statistics indicate that droughts will return at some frequency, with moderately dry conditions occurring more frequently than very dry or extremely dry conditions. On the other hand, the future of irrigation in the Lihue Basin is generally unknown and is currently in a state of change. Diversified agriculture has replaced some of the sugarcane fields, but the overall extent of agriculture in the basin is much less than during the peak of sugarcane production. If the future of irrigation in the Lihue Basin can be better predicted, the water balance can be recomputed to better assess the future of ground-water recharge.

Results of the water-balance analysis indicate that recent variations in precipitation and irrigation in the Lihue Basin have caused large reductions in ground-water recharge, and that plausible scenarios of future land-use changes and drought could result in even greater reductions in ground-water recharge. Periods of low rainfall caused short-term reductions in basin-wide recharge, and irrigation changes caused local reductions in recharge. In combination these reductions in recharge could be significant to ground-water levels, particularly in areas that include important production wells surrounded by former sugarcane fields.

This study shows that significant reductions in ground-water recharge have resulted from recent dry weather and changes in irrigation, but does not specifically address how the reduced recharge translates to lowering of ground-water levels. Historical increases in ground-water withdrawal still remain a possible (perhaps even greater) cause of the observed decline in ground-water levels.

Conditions affecting recharge prior to the start of sugarcane irrigation are unknown, but the no-irrigation base-case scenario can provide a close approximation of recharge at that time. The main difference between the conditions simulated in the no-irrigation base-case scenario and the conditions that probably existed prior to the onset of sugarcane irrigation is the presence of the sugarcane itself. The no-irrigation base-case scenario assumed that sugarcane still existed in the fields and that its water consumption varied on a cyclical basis corresponding to crop growth stages. Under pre-irrigation conditions, the sugarcane fields would presumably have been covered with natural vegetation that did not undergo cycles similar to crops. Despite the differences, if the basin-wide recharge of 212 Mgal/d from the no-irrigation base-case scenario is considered an approximation of pre-development recharge, then comparison with the recharge computed for the 1981 base-case scenario indicates that the sugarcane industry had, at its peak, artificially increased recharge by 25 percent over natural conditions.

Although records of ground-water withdrawal are incomplete, previous studies and the data that do exist indicate that average ground-water withdrawal from the Lihue Basin over the last decade is a small fraction of the ground-water recharge computed in this study. Shade (1995) estimated that in 1990, ground-water withdrawals from the Hanamaulu and Wailua aquifer sectors (which lie entirely within the Lihue Basin), and the Anahola aquifer sector (which lies partly within the Lihue Basin) were 5.24, 0.75, and 2.73 Mgal/d, respectively. Summing the withdrawals for the Hanamaulu and Wailua sectors and adding one half of the withdrawal of the Anahola sector indicates a total 1990 ground-water withdrawal of about 7.4 Mgal/d for the Lihue Basin. Data at CWRM for the period January 25, 2003 to about April 28, 2004 (the actual period varies for specific wells) for wells in the Lihue Basin indicate total average ground-water withdrawal of 4.56 Mgal/d (K. Gooding, CWRM, written commun., 2004), but this number may be incomplete. Assuming that the reporting is about 75 percent complete (Izuka and Gingerich, 1998), the estimated ground-water withdrawal for the Lihue Basin would be 6.5 Mgal/d. A ground-water withdrawal rate of 7 Mgal/d constitutes only 3 percent of the basin-wide recharge for all the base-case scenarios, including the scenario in which all irrigation ceases. In the hypothetical severe-drought simulation in which irrigation ceases and conditions are extremely dry, a ground-water withdrawal of 7 Mgal/d would constitute 17 percent of the recharge, but such a condition is rare and would likely be brief.

Assessing how the reduced recharge translates to lowering of ground-water levels requires coupling the recharge estimates with the ground-water system. Incorporating the results of this study into a comprehensive analytical tool (such as a numerical ground-water model) could address specific questions such as (1) whether the timing and location of the decline in recharge is consistent with the observed decline in water levels, considering the rate of aquifer response to pumping and recharge stresses; and (2) whether ground-water withdrawals were more, less, or equally responsible as recharge decreases for the observed declining ground-water levels. A numerical model could also be used to address whether a century of irrigation in the Lihue Basin had significantly altered the ground-water levels from preexisting natural conditions. Answers to these questions can help in formulating management strategies to mitigate the problem of declining water levels in the Lihue Basin.

Summary and Conclusions

Trends in ground-water development, irrigation changes, and variations in rainfall indicate that these factors may be related to the recent decline in ground-water levels observed in the Lihue Basin. Water-balance computations indicate that periods of decreased precipitation and irrigation, concurrent with the observed ground-water-level decline, caused substantial reductions in ground-water recharge relative to periods of normal rainfall and full irrigation.

Comparison of water-balance simulations in which irrigation was completely withheld versus simulations in which irrigation was at its peak indicates that the sugarcane industry had artificially increased recharge by as much as 25 percent over natural conditions. Simulations of the decreases in irrigation between 1981 and 1998 resulted in a decrease in basin-wide recharge of 7 percent, whereas the complete cessation of irrigation resulted in a decrease in recharge of 14 to 20 percent.

Simulation of a drought of moderate magnitude, such as the dry period from 1998 to 2002, resulted in a decrease in recharge of 50 to 54 percent. Simulations of complete cessation of irrigation combined with a moderate drought decreased recharge by 68 percent relative to the 1981 base case and 66 percent relative to the 1998 base case. Complete cessation of irrigation combined with more severe droughts decreased recharge by as much as 84 percent relative to the 1981 base case and 83 percent relative to the 1998 base case. For the period during the observed decline in ground-water levels, the water-balance simulations indicate that the effect of the recent drought was greater than the effect of recent reductions in irrigation.

The cumulative effects of prolonged irrigation loss may, however, be larger than the relatively brief effects of droughts. The effects of droughts are temporary conditions that will eventually be mitigated by wet periods, whereas loss of irrigation in the Lihue Basin may be permanent. Irrigation changes may have a larger connection to the observed ground-water-level decline than the basin-wide statistics imply. Effects of reduced irrigation may be small when compared to basin-wide recharge, but the effects would have been concentrated within the area of former sugarcane fields, some of which are near wells showing declining water levels.

The water-balance analysis demonstrates that recent variations in precipitation and irrigation in the Lihue Basin have caused large reductions in ground-water recharge, and that plausible future scenarios could result in even greater reductions in ground-water recharge. Coupling the recharge estimates from this study with the characteristics of the ground-water system by use of a comprehensive tool such as a numerical ground-water model could allow better assessment of how the reduced recharge translates to lowering of ground-water levels and whether it is more, less, or equally responsible as ground-water withdrawal for causing the observed declining ground-water levels in the Lihue Basin.

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Appendix A

Water-Balance

Background

The daily water-balance method used in this study of recharge in the Lihue Basin, Kauai, Hawaii is a variant of the Thornthwaite and Mather (1955) mass-balance procedure that accounts for water entering, leaving, and being stored within the plant-soil system. Water entering the plant-soil system includes rainfall, irrigation, and fog drip. Water leaving the plant-soil system includes direct runoff, evapotranspiration, and recharge. Water storage (soil-moisture storage) within the plant root zone is dependent on the depth of the root zone and the available water capacity of the soil. The water-balance method can be used to compute recharge if values for the other components are known or can be reasonably estimated. Recharge to the aquifer occurs when, during a specified period of time, more water infiltrates than can be held in the soil given its water-storing capacity, antecedent water content, and losses due to evapotranspiration. The excess infiltrated water is then passed as recharge to the aquifer underlying the soil.

In nature, the timing of input, output and storage of water is irregular. In this study, the water-balance was computed on a daily basis. The water balance was computed by stepping through consecutive days, using the ending soil moisture for one day as the antecedent soil moisture for the next day. The analysis required an assumed starting soil moisture for the first day, but by computing the water balance for thousands of consecutive days (50 years in this study) the water balance converged on a long-term average recharge value.

Water-Balance Computations

Daily ground-water recharge for the Lihue Basin was computed using the daily water-balance method and input data that quantify the spatial and temporal distribution of rainfall, fog drip, pan evaporation, runoff, soil, irrigation, land use, and land cover. The water balance computed daily recharge for areas of homogeneous climatological, hydrological, soil, land-use, and land-cover properties. The areas of homogeneous properties were determined by combining separate GIS coverages that characterize the spatial and temporal distribution of rainfall, fog drip, pan evaporation, runoff, soil, irrigation, land use, and land cover. In the water balance, all volumes of water are expressed as an equivalent depth of water over an area by dividing the volumes by the total area.

The mass-balance computation begins with determining daily interim soil moisture, which is the amount of water that enters the soil-water system each day (i.e., infiltration) plus the amount of water already in the soil from the previous day. For an area having homogeneous properties the interim soil moisture is given by the equation

$$X_i = P_i + I_i + F_i + W_i - R_i + S_{i-1}\,, \qquad (1)$$

where

X_i is interim soil-moisture storage for current day [L],
S_{i-1} is ending soil moisture storage from previous day (i–1) [L],
P_i is rainfall for current day [L],
I_i is irrigation for current day [L],
F_i is fog drip for current day [L],
W_i is excess rainfall from the impervious fraction of an urban area [L],
R_i is runoff for current day [L], and
i is a subscript designating current day.

Most of the Lihue Basin is not urban, but because some areas are urbanized, the interim soil-moisture equation includes the factor W_i which pertains to the fraction of urban areas that are virtually impervious. In non-urban areas where there is no impervious fraction, W_i is zero, and X_i is the result of subtracting daily runoff from daily water input (rainfall plus irrigation plus fog drip) and adding the ending soil-moisture storage for the previous day.

Urban areas are a mix of pervious areas, such as lawns and parks, and impervious areas where pavement or buildings prevent precipitation from infiltrating the underlying soil. Recharge is limited to the pervious areas, but these areas also receive some of the water that runs off from nearby impervious areas. In the water balance, the pervious and impervious surfaces are not distinguished as separate areas, but are lumped into areas classified as urbanized. The urbanized areas are assigned a percentage (z) that is impervious depending on whether the intensity of the urbanization is low (z = 20 percent) or high (z = 50 percent). This percentage is used to separate, from the total water that falls in an urbanized area, a fraction that is treated computationally as though it fell on an impervious surface. From this impervious fraction of the water, some water is subtracted to account for direct evaporation; the remainder of the water (W_i) is added to the water balance of the pervious fraction. Thus, for the pervious fraction of an urban area, the total daily water input includes an excess of water from the impervious fraction.

For the impervious fraction of an urbanized area with homogeneous properties, excess rainfall, W_i, and moisture storage were determined using the following conditions:

$$X1_i = P_i - R_i + T_{i-1}\,, \tag{2}$$

$$\begin{aligned} &\text{for } X1_i \le N, \quad && W_i = 0, \text{ and} \\ & && X2_i = X1_i, \\ &\text{for } X1_i > N, \quad && W_i = (X1_i - N)(1-z)/z, \text{ and} \\ & && X2_i = N\,, \end{aligned} \tag{3}$$

where

- $X1_i$ is interim moisture storage for impervious area for current day [L],
- $X2_i$ is second interim moisture storage for impervious area for current day [L],
- T_{i-1} is ending moisture storage for impervious area from previous day (i–1) [L],
- N is rainfall interception capacity (maximum amount of water that can be retained on the surface) of impervious area [L], and
- z is fraction of area that is impervious.

The ending moisture storage on the impervious area for the current day, T_i, is determined from the equation:

$$\begin{aligned} &\text{for } X2_i > V_i, \quad && T_i = X2_i - V_i, \text{ and} \\ &\text{for } X2_i \le V_i, \quad && T_i = 0\,, \end{aligned} \tag{4}$$

where

- V_i is pan evaporation for current day [L],

The next step in the water-balance computation is to determine the actual amount of water that will be removed from the soil by evapotranspiration. Actual evapotranspiration is a function of potential evapotranspiration and interim soil moisture (X_i). A vegetated surface loses water to the atmosphere at the potential-evapotranspiration rate if sufficient water is available. Although Penman (1956) defined potential transpiration as "the amount of water transpired in unit time by a short green crop, completely shading the ground, of uniform height and never short of water," in this study the potential-evapotranspiration concept was applied to all vegetated surfaces and was not restricted to a reference short green crop.

At all sites, the potential evapotranspiration was assumed to be equal to pan evaporation multiplied by an appropriate vegetation factor. For soil-moisture contents greater than or equal to a threshold value, C_i, the rate of evapotranspiration was assumed to be equal to the potential-evapotranspiration rate. For soil-moisture contents less than C_i, the rate of evapotranspiration was assumed to occur at a reduced rate that declines linearly with soil moisture content:

$$\begin{aligned} &\text{for } S \ge C_i, \quad && E = PE_i, \text{ and} \\ &\text{for } S < C_i, \quad && E = S \times PE_i\,/\,C_i\,, \end{aligned} \tag{5}$$

where

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

The threshold soil moisture, C_i, was estimated using the model of Allen and others (1998). In this method, a depletion fraction, p, which ranges from 0 to 1, is defined as the fraction of maximum soil-moisture storage that can be depleted from the root zone before moisture stress (reduction in evapotranspiration) occurs. The threshold soil moisture, C_i, is estimated from p by the equation:

$$C_i = (1-p) \times S_m\,, \tag{6}$$

where

- S_m is maximum soil-moisture storage [L],

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

$$S_m = D \times \phi\,, \tag{7}$$

where

- D is plant root depth [L],
- ϕ is $\theta_{fc} - \theta_{wp}$ [L^3/L^3],
- θ_{fc} is volumetric field-capacity moisture content [L^3/L^3], and
- θ_{wp} is volumetric wilting-point moisture content [L^3/L^3].

Values for p depend on vegetation type and can be adjusted to reflect different potential-evapotranspiration rates. In this study, a p value of 0.65 was used for sugarcane and 0.50 for all other types of vegetation based on data in Allen and others (1998).

In the water balance, the evapotranspiration rate may be (1) equal to the potential-evapotranspiration rate for part of the day and less than the potential-evapotranspiration rate for the remainder of the day, (2) equal to the potential-evapotranspiration rate for the entire day, or (3) less than the potential-evapotranspiration rate for the entire day. The total evapotranspiration during a day is a function of the potential-evapotranspiration rate, interim soil-moisture storage, and threshold soil-moisture content. By recognizing that $E = -\mathrm{d}S/\mathrm{d}t$, the total depth of water removed by evapotranspiration during a day, E_i, was determined as follows:

$$\text{for } X_i > C_i,\ t_i < 1, \text{and } C_i > 0,$$
$$E_i = PE_i t_i + C_i\{1 - \exp[-PE_i(1-t_i)/C_i]\},$$

$$\text{for } X_i > C_i,\ t_i < 1, \text{and } C_i = 0,$$
$$E_i = PE_i t_i,$$

$$\text{for } X_i > C_i \text{ and } t_i = 1,$$
$$E_i = PE_i$$

$$\text{for } X_i \le C_i \text{ and } C_i > 0,$$
$$E_i = X_i\{1 - \exp[-PE_i / C_i]\},$$

$$\text{for } X_i \le C_i \text{ and } C_i = 0,$$
$$E_i = 0\ , \qquad (8)$$

and

$$\text{for } (X_i - C_i) < PE_i, \quad t_i = (X_i - C_i)/PE_i,$$
$$\text{for } (X_i - C_i) \ge PE_i, \quad t_i = 1\ , \qquad (9)$$

where

t_i is time during which soil-moisture storage is above C_i [T].

After accounting for runoff (equation 1), evapotranspiration for a given day was subtracted from the interim soil-moisture storage, and any soil moisture remaining above the maximum soil-moisture storage was assumed to be recharge. Recharge and soil-moisture storage at the end of a given day were assigned according to the following conditions:

$$\text{for } X_i - E_i \le S_m, \quad Q_i = 0, \text{ and}$$
$$S_i = X_i - E_i, \text{ and}$$
$$\text{for } X_i - E_i > S_m, \quad Q_i = X_i - E_i - S_m, \text{ and}$$
$$S_i = S_m\ , \qquad (10)$$

where

E_i is evapotranspiration during the day [L],
Q_i is ground-water recharge during the day [L], and
S_i is soil-moisture [L] at the end of the current day, i.

Ending soil-moisture storage for the current day, expressed as a depth of water, is equal to the root depth multiplied by the difference between the ending volumetric soil moisture content within the root zone for the current day, and the volumetric wilting-point moisture content.

$$S_i = D \times \left(\theta_i - \theta_{wp}\right), \qquad (11)$$

where

θ_i is ending volumetric soil-moisture content for the current day i, [L^3/L^3], and
θ_{wp} is volumetric wilting-point moisture content [L^3/L^3].

Input Requirements

The water-balance model for this study uses spatial information from GIS coverages and user-defined parameter values that may be linked to the spatial information. Two random selection procedures are implemented in the water balance: (1) selection of rainfall-fragment sets for each month, and (2) selection of sugarcane fields assumed to be in either of two different initial crop-growth stages. The random selection procedures use random numbers, ranging from 0 to 1, which are generated from a uniform distribution given an initial seed value for the random-number generator. The water balance can be computed multiple times to determine the effect of the random-selection procedures on the computed evapotranspiration and recharge values. The water balance requires information separated into types that are briefly described below.

Spatially and Temporally Invariant Data

Some of the input data required by the program do not vary spatially or temporally. These include:

1. Number of times the water balance should be computed (whole number greater than or equal to 1). By computing the water balance multiple times, the effects of the random selection procedures on the resulting evapotranspiration and recharge estimates can be determined. In this study, water balances were computed multiple times only for the 1981 and 1998 base-case scenarios. These computations showed that running the water balance only once versus running the water balance 25 times resulted in a difference in recharge of less than one tenth of one percent. Therefore, for each of the remaining scenarios and sensitivity tests, the water balance was computed only once.

2. Number of years in each water-balance simulation (whole number greater than or equal to 1). For the water balance, all years are assumed to have 365 days. Long simulations reduce effects of arbitrary initial conditions and random selection procedures. In this study, each water-balance simulation was run for a 50-year period.

3. Seed value for the random number generator (arbitrary whole number).

4. Initial soil-moisture storage over the study area, expressed as a fraction of the maximum soil-moisture storage (0 to 1). This value can be varied to determine the effect of the initial soil-moisture storage on the evapotranspiration and recharge estimates.
5. Soil depth, in inches, from which evaporation can take place in all bare soil areas, including fallow sugarcane fields.
6. Initial tolerance (allowable fractional error) for selecting 50 percent of the sugarcane-field area to be in initial growing-schedule 1. Because sugarcane has a 2-year growth cycle, fields were planted so that half the fields could be harvested in alternating years. To simulate this harvesting and planting schedule, fields were categorized by irrigation type and then randomly placed into one of two growing schedules: growing-schedule 1, which began on the first day of the 50-year simulation, or growing-schedule 2, which began on the 365th day of the 50-year simulation. The selection procedure was successfully terminated when the cumulative area for each growing schedule equaled half (plus or minus the initial tolerance) of the sugarcane area for that irrigation type. If the cumulative area exceeded half (plus the initial tolerance) of the sugarcane area for that irrigation type, the random selection procedure was repeated a maximum of 100 times until it successfully terminated. If the selection procedure was not successfully terminated after 100 attempts, then the initial tolerance was doubled and the random-selection procedure repeated.
7. Length of period that sugarcane crop is irrigated, in days.
8. Length of period that sugarcane crop is not irrigated, in days.
9. Length of period that sugarcane field is fallow, in days.
10. Initial day of sugarcane planting for fields in initial growing-schedule 1. The value ranges from 1 day to the total number of days in a sugarcane crop cycle (number of days of irrigated period + number of days of non-irrigated period + number of fallow days).
11. Initial day of sugarcane planting for fields in initial growing-schedule 2. The value ranges from 1 day to the total number of days in a sugarcane crop cycle (number of days of irrigated period + number of days of non-irrigated period + number of fallow days).
12. The number of irrigation application days per month for drip-irrigated sugarcane fields. If the specified number of irrigation application days per month is equal to 28, then every day of every month is assumed to receive irrigation water.
13. List of days in each month that receive irrigation applications for drip-irrigated sugarcane fields. For example, if drip-irrigated sugarcane fields receive irrigation on the first and fifteenth days of the month, the list would include days 1 and 15.
14. The number of irrigation application days per month for furrow-irrigated sugarcane fields. If the specified number of irrigation application days per month is equal to 28, then every day of every month is assumed to receive irrigation water.
15. List of days in each month that receive irrigation applications for furrow-irrigated sugarcane fields. For example, if furrow-irrigated sugarcane fields receive irrigation on the first and fifteenth days of the month, the list would include days 1 and 15.
16. Rainfall-interception capacity of impervious surfaces in urban areas, in inches.
17. Constant recharge rate from beneath water reservoirs, in inches per year.

Spatial Information

The spatial information required for the water balance is derived from a GIS coverage formed by merging individual coverages of mean monthly rainfall (1 coverage for each of 12 months), monthly fragment zones (1 coverage for each of 12 months), land-use codes, sugarcane-field codes, runoff-zone codes, soil-type codes, annual pan evaporation, and fog-zone code. By overlaying the individual coverages to form a single coverage, the study area is divided into smaller areas (polygons) with homogeneous properties. The required spatial information for each polygon with homogeneous properties is described in this subsection.

1. Twelve mean monthly rainfall values. Lines of equal mean monthly rainfall (Giambelluca and others, 1986) are used to define areas of equal mean monthly rainfall. Areas between adjacent lines of equal mean monthly rainfall are assigned the average value of the two adjacent lines. In the water-balance computation, the monthly rainfall values are linked to a file of rainfall weights that are used to adjust the mean monthly values to simulate annual variations in rainfall or drought rainfall conditions. The rainfall weights are ratios of annual rainfall to mean annual rainfall for a reference rain-gaging station with annual rainfall characteristics that are assumed to be representative of the study area.
2. Monthly fragment zones. The monthly fragment zones represent zones within which the statistical distribution of ratios of daily rainfall to monthly rainfall (rainfall fragments) for a given month are assumed to be similar. Monthly fragment zones are defined by selected lines

of equal mean monthly rainfall. The fragment zones are linked to a rainfall-fragment file that contains monthly sets of rainfall fragments (ratios of daily to monthly rainfall).

3. Land-use code. Each land use within the study area is assigned a unique numeric code. Land use is defined on the basis of information from plantation maps and digital spatial data from 2000 (National Oceanic and Atmospheric Administration, 2000).

4. Sugarcane-field code. Each sugarcane field in the study area is assigned a numeric code based on the irrigation method (drip, furrow, unirrigated, or any combination thereof). For fields with multiple irrigation methods (either because multiple irrigation methods were used or the irrigation method could not be narrowed down to a single type), the irrigation method in the water balance is alternated with each crop cycle. The order for fields with multiple irrigation methods is assumed to be as follows: drip preceded both furrow or unirrigated methods, and furrow preceded the unirrigated method.

5. Runoff-zone code. Basins with equal monthly runoff-rainfall ratios are assigned a unique numeric code. Monthly runoff-to-rainfall ratios assigned to each code can be changed as needed for each simulation.

6. Soil-type code. Areas with common soil type are assigned unique numeric codes. Soil types are defined by soil map units (U.S. Department of Agriculture, 2001). Available water capacity values were assigned to each code and could be varied as needed in the water-balance simulations. Each soil-type code (soil map unit) in the study area may have associated with it up to two soil components, and each soil component may have associated with it up to four soil layers (U.S. Department of Agriculture, 2001). Information on the fraction of area occupied by each soil component within a soil map unit, available-water capacity of each soil layer, and plant root depth was used to compute an area-weighted and depth-integrated maximum soil-moisture storage for each soil map unit and land use. For each soil-type code, the number of soil components must be specified, and for each component, the following must be specified:

   A. Fraction (0–1) of soil-map-unit area occupied by the soil component.

   B. Number of soil layers. Each soil component in the study area had 1 to 4 soil layers. For each soil layer, the depth of the top and bottom of the layer, in inches below the ground surface, were specified.

7. Annual pan evaporation. Lines of equal mean annual pan evaporation (Ekern and Chang, 1985) are used to define areas of equal mean annual pan evaporation. Areas between adjacent lines of equal mean annual pan evaporation are assigned the average value of the two adjacent lines. The annual pan-evaporation is linked to a file of monthly-to-annual pan evaporation ratios that are assumed to be representative of the study area. This allows the simulation of monthly variations in pan evaporation.

8. Fog-zone code. Areas that receive fog-drip are assigned a code of 1. Areas that do not receive fog drip are assigned a code of 0. Daily fog drip in the fog zone was estimated using a linear relation between daily fog drip (inches) and daily rainfall (inches) of the form:

$$\text{Daily fog} = a \times (\text{daily rainfall}) + b\,. \tag{12}$$

   For each of the 12 months of the year, the slope, a, and intercept, b, of the linear relation were specified.

9. Land-use information. For each land-use code, the following information was provided:

   A. Plant root depth, in inches.

   B. Fraction of the total area that is pervious (0-1).—For non-urban areas, this fraction generally is assigned a value of 1.

   C. Depletion fraction, p, for a potential evapotranspiration rate of 5 millimeters per day (Allen and others, 1998).

   D. Pan coefficients 1 through 4 (values greater than or equal to zero). The four pan coefficients allow potential evapotranspiration in agricultural areas to be varied as the crop passes through five growth stages (initial, developmental, middle, late, and fallow). Throughout stage 1 (initial-growth stage), pan coefficient 1 is used. During stage 2 (developmental-growth stage), the pan coefficient varies linearly with time between pan coefficient 1 and pan coefficient 2. Throughout stage 3 (middle-growth stage), pan coefficient 2 is used. During stage 4 (late-growth stage), the pan coefficient varies linearly with time between pan coefficient 2 and pan coefficient 3. Throughout stage 5 (fallow stage), pan coefficient 4 is used.

   E. The number of days associated with the initial-growth, developmental-growth, middle-growth, late-growth, and the fallow stages in the sugarcane-growing cycle.

   F. Monthly irrigation (in inches) for fields using drip irrigation and fields using furrow irrigation.

GIS Coverages Used in the Water-Balance for the Lihue Basin

Areas of homogeneous precipitation, sugarcane cultivation and irrigation, runoff, and evapotranspiration were defined by merging GIS coverages created or obtained from multiple sources. This section describes the source of each GIS coverage used and any modifications that were done in preparation for the water-balance analysis. For the purposes of this study, GIS coverages can be envisioned as one of two types: (1) line coverages, such as maps showing lines of equal rainfall, elevation, etc., and (2) polygon coverages, in which the area circumscribed by the polygon has uniform characteristics for the parameters in the coverage. The merged GIS coverage used in the water-balance analysis is of the polygon type, thus, any of its components that were line coverages had to be converted to polygon coverages.

Rainfall

Images of monthly mean rainfall distribution for Kauai were scanned from the Rainfall Atlas of Hawaii (Giambelluca and others, 1986). Control points created by extending latitude and longitude tic marks on the margins of the maps were added to the scanned images. The control points were used to register the image in GIS to a geographic coordinate system. The original maps of Giambelluca and others (1986) lacked coordinate information such as projection and datum, therefore the images were registered in an unprojected geographic coordinate system. The datum of the maps was assumed to be the North American Datum for 1927 (NAD27). Lines of equal rainfall and the coastline were then digitized from the scanned images, projected to Albers projection, and converted to the North American Datum for 1983 (NAD83).

In each of the monthly rainfall maps, the coastline digitized from the maps of Giambelluca and others (1986) was replaced with the more detailed National Hydrography Dataset (NHD) (U.S. Geological Survey, 1999). This was accomplished using a process known as “rubber sheeting” in which the entire digitized coverage (both coastline and rainfall lines) was modified until the original coastline matched the NHD coastline as closely as possible. The digitized coastline was then deleted and replaced by the NHD coastline.

The monthly rainfall coverages were converted from line to polygon coverages. Boundaries of the polygons were defined by the rainfall lines and coastline. Rainfall values were assigned to each polygon based on the value of the bounding rainfall lines. In most cases, polygons located between two sequential rainfall lines received the arithmetic average of the two rainfall lines. Polygons bounded by only one rainfall line, such as those along the coast or at the peak of the mountains, were assigned the average of the rainfall data (listed in Giambelluca and others, 1986) for rain gages within the polygon. The coastal portion of the polygons might be truncated from the inland portion for separate calculation. If no rain gages were within the polygon, the polygon was assigned the average of the value of the existing rainfall line and the value of the line that would logically have been next in the sequence of existing lines on the map of Giambelluca and others (1986).

Pan Evaporation

Maps showing the distribution of annual pan evaporation for Kauai were scanned from Ekern and Chang (1985). The same procedures used to create the rainfall polygon coverage from the monthly rainfall map were used to create a pan-evaporation coverage from the single annual pan-evaporation map.

Fog Zone

The fog zone coverage has two categories of polygons representing (1) areas in the fog zone, which in this study is defined as all areas above 2000 ft elevation, and (2) areas outside the fog zone, which includes all areas below 2000 ft. The fog-zone coverage was based on elevations from the USGS 10-meter resolution Digital Elevation Model (DEM).

Drainage Basins for Computing Runoff-to-Rainfall Ratios

Adequate streamflow data for determining runoff-to-rainfall ratios were available for gaging stations on Huleia Stream (station 16055000), South Fork Wailua River (station 16060000), North Fork Wailua River (station 16071000), and the East Branch North Fork Wailua River (station 16068000). The drainage areas for these gaging stations were determined by GIS Weasel, a set of tools developed by the USGS (http://wwwbrr.cr.usgs.gov/weasel/) for hydrological modeling. River features from the NHD were added to the drainage-basin polygon coverage and used as a guide to delineate ungaged areas that would be assigned runoff-to-rainfall ratios of the nearest gaged basins.

Land Cover

A land-cover image of Kauai produced by the National Oceanic and Atmospheric Administration (NOAA, 2000) was converted to a GIS polygon coverage. Adjacent polygons with the same land cover codes were merged so that the total number of polygons could be reduced. This formed the basis of the land-cover dataset used in the water-balance analysis. The NOAA map classification sometimes did not agree with air photographs, plantation maps, and ground-based knowledge of the area. In particular, areas of known active sugarcane cultivation in 2000 were in some cases classified as "grassland" and in other cases as "cultivated land," presumably on the basis of how the land appeared at the time of the satellite imaging (from above, recently plowed or planted fields have the appearance of actively cultivated land, whereas mature sugarcane has the appearance of grass). In areas where there were discrepancies, the areas of known active sugarcane cultivation, as indicated by plantation maps and records, took precedence over the NOAA classification.

An existing GIS coverage, NISUGAR (State of Hawaii, 1991), contains polygons of sugarcane plantation of the Lihue area, Kauai. Some of the polygons in this coverage were not consistent with the boundaries of sugarcane fields shown in the paper copies of plantation maps provided by the Lihue Plantation Company. These polygons were redigitized using the plantation maps as a visual guide and spatial references from (1) USGS digital line graphics of roads, streams, and coastlines, and (2) shaded-relief images created from USGS 10-meter resolution digital elevation models. Using information on irrigation methods supplied by the Lihue Plantation Company, the fields were categorized as (1) furrow irrigated; (2) drip irrigated; (3) unirrigated; (4) mixed furrow and drip irrigated; (5) mixed furrow irrigated and unirrigated; (6) mixed drip irrigated and unirrigated; or (7) mixed drip irrigated, furrow irrigated, and unirrigated.

Soil Type and Available Water Capacity

A GIS coverage of soil types in the Lihue Basin was obtained from datasets in the Soil Survey Geographic Database (SSURGO) (U.S. Department of Agriculture, 2001). SSURGO also contains detailed attribute tables containing information on each component of each soil type, including maximum and minimum available water capacity (AWC) for soil layers of different depths. Three separate files, one each for maximum AWC, minimum AWC, and median AWC, were generated for input into the water-balance computation in this study. This allowed AWC to be changed between simulations by simply changing the AWC file.

Merged Coverages for the Water-Balance Computation

The separate GIS coverages of (1) mean monthly rainfall (12 coverages total, one per month), (2) pan-evaporation, (3) fog zone, (4) rainfall-to-runoff-ratio basins, (5) land cover, and (6) soil type were merged into a large coverage before input to the water-balance computation. Each polygon in the merged coverage was formed by the intersection of the polygons in the component coverages, and all areas within a given polygon would have a single value for each parameter in the water-balance computation. For this study, two merged GIS coverages were created, representing (1) 1981 land-use conditions and (2) 1998 land-use conditions. Polygons in the mean monthly rainfall and pan-evaporation coverages were assigned fixed values before merging. Polygons in the fog zone, rainfall-to-runoff basin, and soil and land-cover coverages were assigned codes rather than fixed values so that the values could be changed without having to use GIS to reconstruct component coverages and the large merged coverage.

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