# WATER BUDGET FOR THE ISLAND OF KAUAI, HAWAII

*By* Patricia J. Shade

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1995

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BRUCE BABBITT, Secretary

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## CONVERSION FACTORS

| Multiply | By | To obtain |
|---|---|---|
| acre | 4,047 | square meter |
| foot (ft) | 0.3048 | meter |
| million gallons per day (Mgal/d) | 0.04381 | cubic meter per second |
| inch (in.) | 25.4 | millimeter |
| inch per year (in/yr) | 2.54 | centimeter per year |
| mile (mi) | 1.609 | kilometer |
| square mile ($mi^2$) | 2.590 | square kilometer |

# Water Budget for the Island of Kauai, Hawaii

*By* Patricia J. Shade

## Abstract

A geographic information system model was created to calculate a monthly water budget for the island of Kauai. Ground-water recharge is the residual component of a monthly water budget calculated using long-term average rainfall, streamflow, and pan-evaporation data, applied irrigation-water estimates, and soil characteristics. The water-budget components are defined seasonally, through the use of the monthly water budget, and spatially by aquifer-system areas, through the use of the geographic information system model.

The mean annual islandwide water-budget totals are 2,720 Mgal/d for rainfall plus irrigation; 1,157 Mgal/d for direct runoff; 911 Mgal/d for actual evapotranspiration; and 652 Mgal/d for ground-water recharge. Direct runoff is 43 percent, actual evapotranspiration is 33 percent, and ground-water recharge is 24 percent of rainfall plus irrigation. Ground-water recharge in the natural land-use areas is spatially distributed in a pattern similar to the rainfall distribution.

Distinct seasonal variations in the water-budget components are apparent from the monthly water-budget calculations. Rainfall and ground-water recharge peak during the wet winter months with highs in January of 3,698 Mgal/d (million gallons per day) and 981 Mgal/d, respectively; a slight peak in July and August relative to June and September is caused by increased orographic rainfall. Recharge is lowest in June (454 Mgal/d) and November (461 Mgal/d).

## INTRODUCTION

Growth and change are occurring on the island of Kauai. Kauai is a relatively rural island where the resident population in 1990 was about 51,000 (State of Hawaii, 1991). The population is mostly distributed near the coast in centers including Kekaha, Lihue, Kapaa, and Wailua. Resort developments also are located near the coast and with the growth and development has come an increased demand for water. To meet the demand, the Kauai County Department of Water, in cooperation with the U.S. Geological Survey (USGS), is investigating ground-water availability on the island. The project includes water-use data compilation, water-budget calculation, ground-water modeling, and a program of test drilling for aquifer analysis. This report describes the water-budget analysis and calculation of ground-water recharge, a data requirement for ground-water modeling.

The water supply for the population of the island of Kauai is obtained primarily from ground-water sources. Almost 50 Mgal/d is pumped for the 51,000 residents as well as for commercial, industrial, and some agricultural water needs (Shade, 1995). These sources are recharged by the infiltration of rainfall and irrigation water. An estimate of ground-water recharge is needed for management of the resource.

### Purpose and Scope

The purpose of this report is to describe the calculation of a mean monthly water budget for the island of Kauai. Monthly calculations give a more realistic value of ground-water recharge as compared with calculations made on a mean annual basis, because actual evapotranspiration (AE) and water held in the soil root zone are accounted for. Monthly data are available to support calculations on this time scale. Calculations assume natural land-use conditions except for the areas of irrigated agriculture on plantations. The monthly spatial distribution of the water-budget components islandwide and by State of Hawaii aquifer-system areas is displayed and tabulated.

## Acknowledgments

The author acknowledges the cooperation and assistance of personnel from the Kauai County Department of Water and the Natural Resources Conservation Service (U.S. Department of Agriculture) for providing data and aiding in making estimates when no data were available. The field maps provided by the major plantations were much appreciated and helpful in the analysis.

## Description of the Study Area

The study area encompasses the entire island of Kauai, 553 $mi^2$ (fig. 1). Population centers and more than 33,000 acres of irrigated agricultural land are located near the coast from west of Kekaha to Anahola on the east coast of the island. The interior of the island is undeveloped and rugged in the areas of Waimea Canyon, the Alakai Swamp, and in the uplands on the north and east sides of the island, as well as from the headwaters to the shore along the Na Pali coast.

Rainfall variability over the island is extreme (fig. 2), from less than 30 in/yr along the leeward (western) coast near Kekaha to more than 400 in/yr at Mt. Waialeale (Giambelluca and others, 1986), one of the wettest places on earth, at an altitude of over 5,100 ft. This range represents a rainfall gradient of more than 25 in/mi. A striking variability in vegetation accompanies this rainfall regime from dryland, xerophytic plants in the Kekaha coastal areas to rain forests on the upper slopes of Mt. Waialeale and in the Alakai Swamp.

Dramatic landscapes have evolved because of the abundance of water on Kauai. The combined erosional forces of rainfall and runoff from the wet summit area have formed Waimea Canyon, and the spectacular scenery of the cliffs and valleys along the Na Pali Coast.

# GEOLOGY AND GROUND-WATER OCCURRENCE

The following description of the geology and ground water of Kauai is based on the comprehensive geologic mapping and description of Macdonald and others (1960), which includes discussion of the water-bearing properties of the rocks and the ground-water resources of the island. Updated geologic names are from Langenheim and Clague (1987).

The island of Kauai is essentially a broad volcanic dome formed by the eruption of many thin layers of lava rock sloping away from the summit which was located near Mt. Waialeale (fig. 3). The island comprises two volcanic formations: the Waimea Canyon Basalt and the younger Koloa Volcanics. The Pliocene and Miocene(?) Waimea Canyon Basalt built the broad volcanic dome and includes lavas of the Napali, Haupu, Olokele, and Makaweli Members. These are all thick accumulations of individual lava flows with alternating massive flow cores and rubbly or fragmented interflow zones. The Napali Member is mostly thin-bedded, whereas the others are thicker-bedded. The interflow zones of all members are highly permeable. Macdonald and others (1960) have characterized the Haupu, Olokele, and Makaweli Members as moderately to poorly permeable, and the Napali Member as mostly highly permeable.

Lavas of the Koloa Volcanics (Pleistocene and Pliocene) erupted after a long period of volcanic quiescence and erosion during which time large parts of the eastern slope of the volcanic dome collapsed. Lavas of the Koloa Volcanics are found mostly on the east side of the island. They fill large depressions in the lavas of the Waimea Canyon Basalt, which they overlie except where erosional remnants protrude. The lavas of the Koloa Volcanics are generally massive and heterogeneous. The layering evident in the lavas of the Waimea Basalt is typically not evident in the Koloa lavas and Macdonald and others (1960) have characterized the Koloa lavas as poorly to moderately permeable. High rainfall on the windward (eastern) side of the island has weathered the surface of the Koloa lavas to a clay-rich mantle over the less weathered rock at depth.

Sedimentary rocks occupy a small fraction of Kauai. They are of marine and terrigenous origin and occupy valley floors and coastal areas. MacDonald and others (1960) characterized the sedimentary rocks as generally poorly permeable.

Ground water on the island is either basal water or high-level water. Basal water is a large body of ground water floating on the underlying saltwater in approximate accordance with the Ghyben-Herzberg relation: for every foot that freshwater stands above sea level, about 40 ft of freshwater extend below sea level. Basal water moves generally from the mountain recharge areas to the near-shore discharge areas and is found in all the geologic units, but the Napali Member is considered the most easily developed as an aquifer.

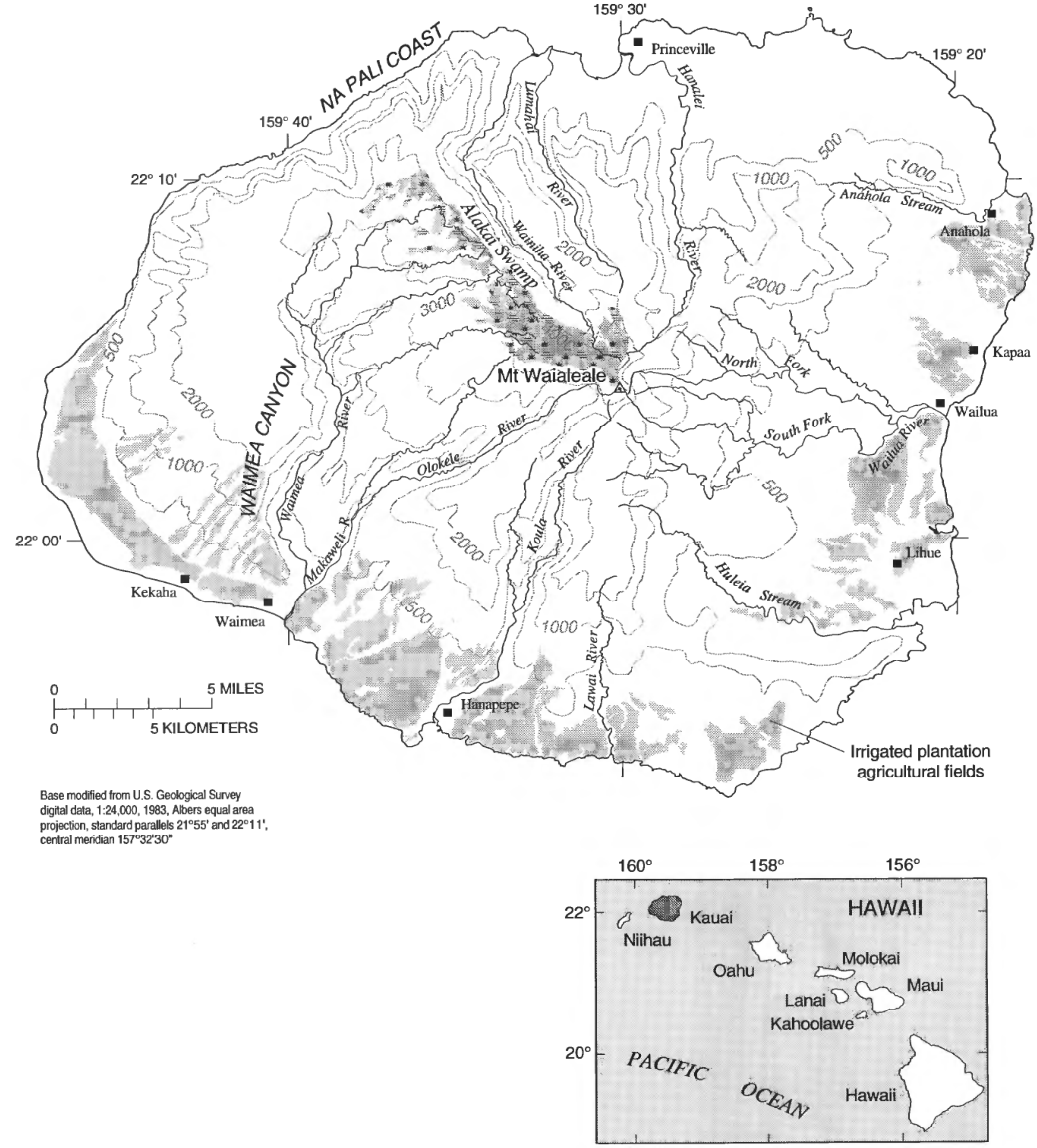



**Figure 1.** Hawaiian islands and island of Kauai.

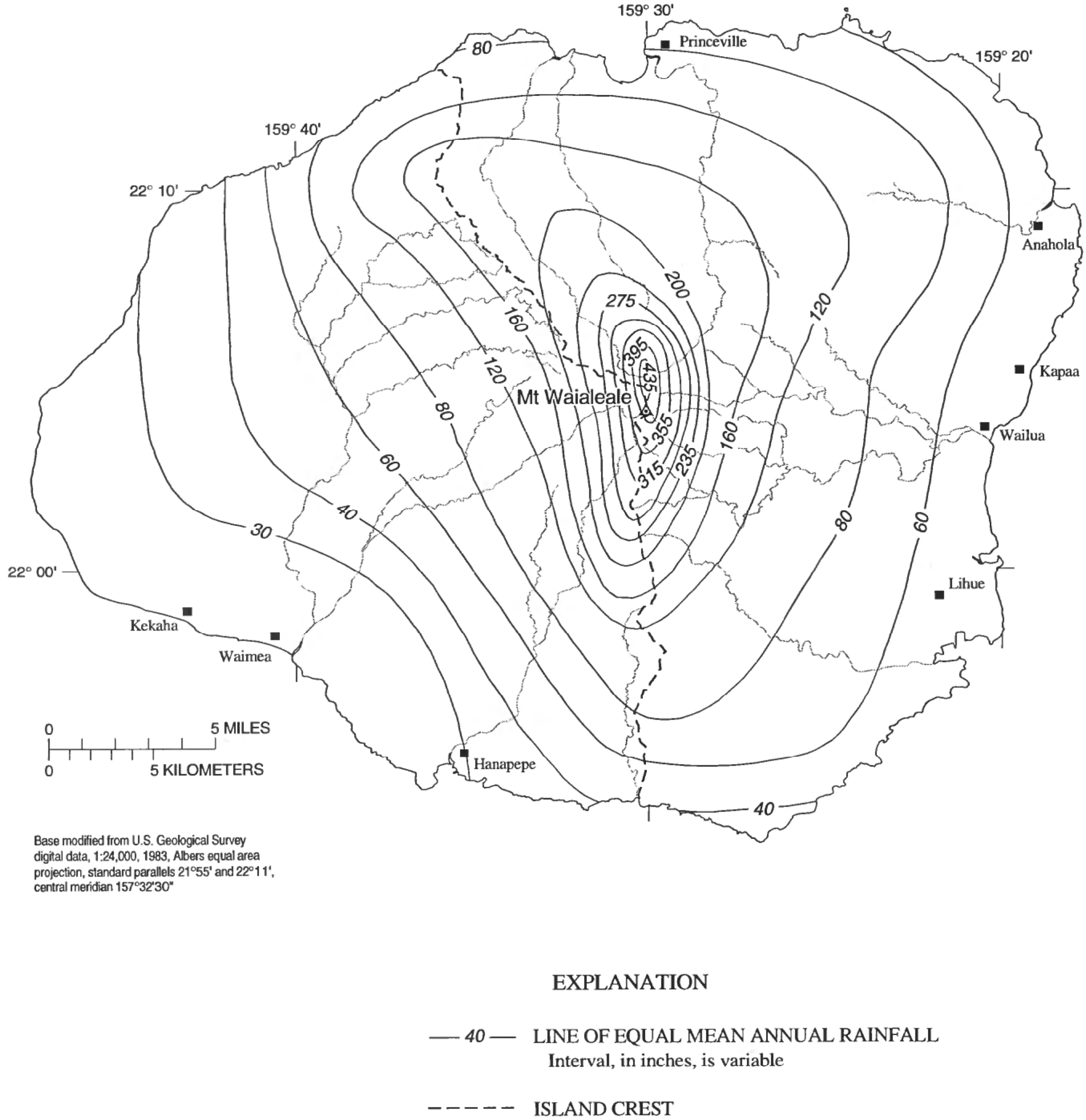



**Figure 2.** Mean annual rainfall, island of Kauai (modified from Giambelluca and others, 1986).

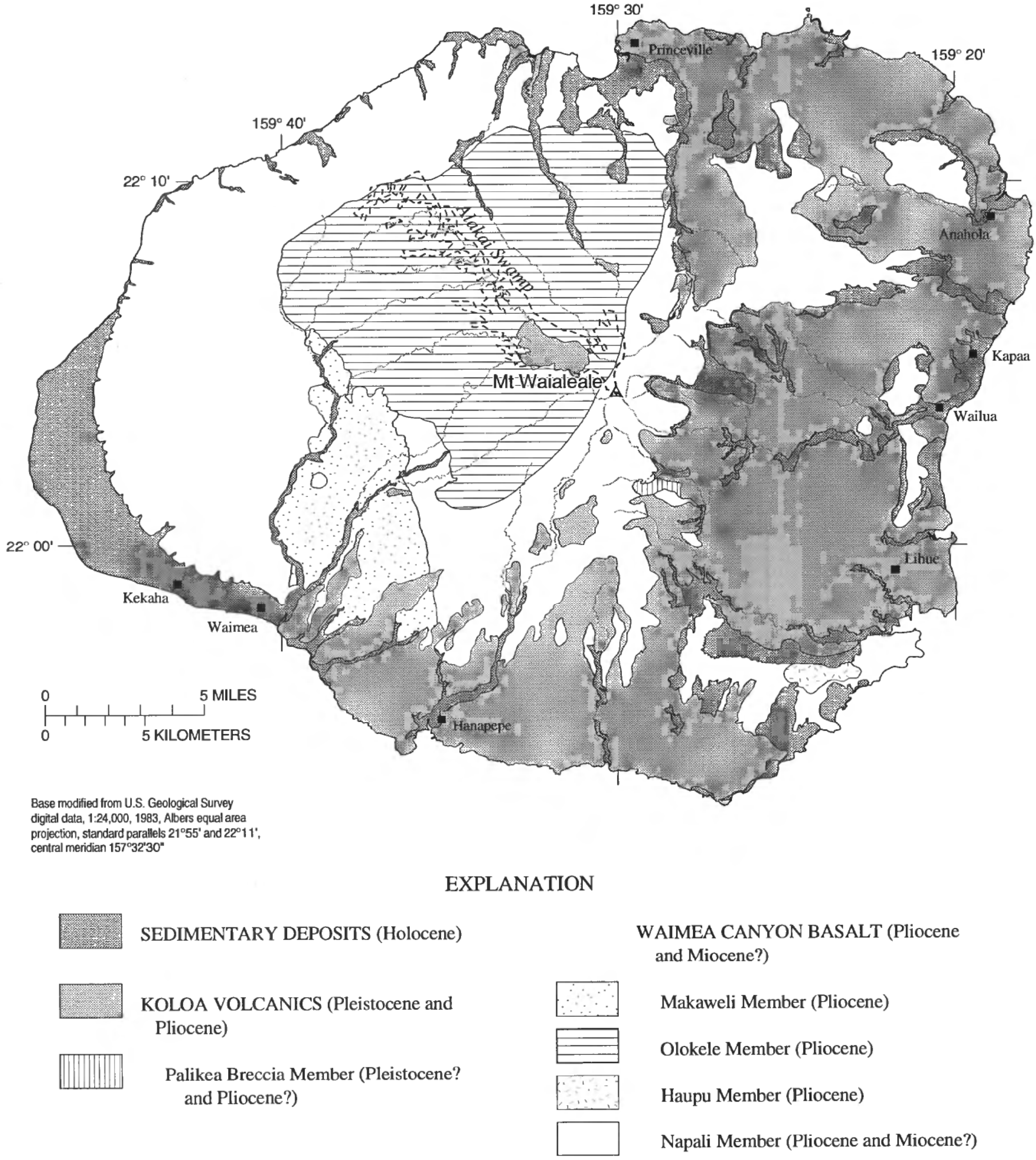



**Figure 3.** Geology of the island of Kauai (modified from Macdonald and others, 1960).

High-level water is impounded at altitudes above the basal-water level by relatively impermeable rock (Macdonald and others, 1960). In the absence of the relatively impermeable rock this water would descend to basal levels. High-level water is recharged by rainfall and discharges to springs and seeps scattered throughout the island and to streams as base runoff. The Alakai Swamp is in such an area where moderately to poorly permeable rock underlies an area that receives more than 200 in/yr of rainfall. The swamp covers more than 10 $mi^2$ and is underlain mostly by the Olokele Member (fig. 3). Toward Mt. Waialeale, a smaller area of the swamp is underlain by Koloa Volcanics (Macdonald and others, 1960). The major hydrologic characteristics of the swamp are discussed by van't Woudt and Nelson (1963) who concluded that:

1. more than half the swamp area is dissected by stream channels,
2. less than 30 percent of the area is flat to moderately sloping where permeability is low and peat has formed,
3. the area is constantly saturated and is essentially a collecting and overflow basin, and
4. about 33 Mgal/d (65 in/yr averaged over the GIS swamp area), derived from subsurface storage below the swamp, supplies the base-flow discharge in the Waimea and Makaweli Rivers.

## WATER-BUDGET MODEL

Ground-water recharge can be estimated by using a water-budget model. The method for calculating the water budget is similar to that developed by Thornthwaite (1948) and Thornthwaite and Mather (1955) and is a "bookkeeping" procedure for the plant-soil system that balances moisture inputs of rainfall, and moisture outputs of streamflow, evapotranspiration, and ground-water recharge. The relation is expressed by:

$$G = P + I - R - AE - \Delta SS \ , \qquad (1)$$

where: $G$ is ground-water recharge,
$P$ is rainfall,
$I$ is irrigation,
$R$ is direct runoff,
$AE$ is actual evapotranspiration, and
$\Delta SS$ is change in soil-moisture storage.

### Data Requirements

A geographic information system (GIS) model was created to calculate the monthly water budget by linking the spatial and quantitative characteristics of the variables in equation 1. The data requirements for the GIS water-budget model include rainfall, stream discharge (runoff) and associated drainage areas, pan evaporation, soil properties, and irrigated-agriculture land-use distribution.

Mean monthly rainfall data and spatial distributions were obtained by digitizing the monthly rainfall maps for the island of Kauai by Giambelluca and others (1986). The value assigned to the area between the lines of equal rainfall was the average value of the bounding lines.

Eight drainage basins around the island, digitized from USGS 1:24,000-scale topographic maps compiled in 1983, had USGS streamflow-gaging stations located near the shore. These basins were selected because they had long-term streamflow records averaging about 30 years, coincident with the period of record of the rainfall data.

The mean annual pan-evaporation data were obtained by digitizing the pan-evaporation map for the island of Kauai (Ekern and Chang, 1985). The average of the values of the bounding lines of equal pan evaporation was assigned to the area between the two lines.

Digital soil maps were provided by the [U.S.] Natural Resources Conservation Service (formerly, the Soil Conservation Service). Forty-nine soil types are delineated and representative values for the soil properties of rooting depth, available soil moisture (the difference between the amount of water held in the soil at field capacity and at wilting point), and maximum soil-moisture storage were obtained from Foote and others (1972). Maximum soil-moisture storage is the key soil property required by the model; thus a digital map of this soil-property distribution was created from the original soil maps to use in the GIS model.

Land-use information was obtained from the five large plantations on the island that, combined, irrigate more than 33,000 acres. The principal crop is sugarcane, with smaller areas planted in coffee and macadamia nuts. Maps of the fields were digitized and data regarding methods of irrigation and crop types were coded. The remainder of the island area was modeled as natural cover.

## Rainfall

Rainfall on Kauai is notable for its extremes (fig. 2). The island lies in the path of the persistent northeast tradewinds that gather substantial moisture as they pass over the Pacific Ocean. Rainfall along the windward (eastern) side of the island is orographically induced as the air is forced to rise over Mt. Waialeale, where the measured mean annual rainfall is 449 in/yr (Giambelluca and others, 1986). As the air descends on the leeward (western) side of the island, rainfall diminishes drastically near the town of Kekaha, where the mean annual rainfall is about 22 in. This range represents a rainfall gradient of more than 25 in/mi.

Twelve maps showing lines of equal mean monthly rainfall for the island of Kauai were compiled from data collected at a network of 12 base stations that had complete records for the base period from 1916 through 1983. Data from an additional 9 stations that had long periods of record were used in the statistical analyses (Giambelluca and others, 1986). These monthly maps were digitized and compose the rainfall data set for the GIS model. These data were used to calculate mean monthly rainfall values for the island that range from a low in June of about 1,550 Mgal/d to almost 3,500 Mgal/d in January.

The spatial distribution of rainfall varies from month to month, and most significantly from winter to summer months (figs. 4 and 5). In general, rainfall seasonality is more pronounced in dry leeward areas, such as near Kekaha, than in wet areas such as Mt. Waialeale. Figures 4 and 5 show that June rainfall near Kekaha is about 25 percent of January rainfall, but near Mt. Waialeale, June rainfall is about 80 percent of January rainfall.

## Runoff

Streamflow comprises direct runoff, the water that flows into stream channels promptly after rainfall, and base runoff, the part of streamflow that is sustained through periods of dry weather from discharge of ground water (Langbein and Iseri, 1960). Generally, hydrographs from measured perennial streams on Kauai have storm-generated peaks of short duration. Usually within a few days the flow decreases to the level sustained between storms by ground-water discharge. To avoid including the ground-water component of streamflow, monthly direct runoff was calculated as the difference between mean monthly streamflow and mean monthly base runoff. Base runoff was calculated in this study from monthly flow-duration analyses as the discharge maintained at least 90 percent of the time during the chosen month, a conservative estimate of the ground-water component.

Direct runoff was calculated from data from eight streamflow-gaging stations located near the shore around the island (fig. 6). These sites were selected because they had long-term records averaging about 30 years, coincident with the period of record of the rainfall data. These gaged drainage basins, as with all the major drainage basins on the island, are characterized by large ranges of elevation and rainfall from the headwaters to the shore.

The gaged drainage basins were digitized and relations between average direct runoff, measured at the eight stations, and average rainfall over the drainage basins were calculated by overlaying rainfall data and drainage basins in the GIS model. These eight runoff to rainfall relations are considered representative of the relations at the lower ends of ungaged basins. Table 1 shows the mean monthly rainfall and runoff for each gaged drainage basin and groups these data by the location of the gage relative to a topographic divide that separates the windward and leeward sides of the island. The average of these runoff to rainfall ratios shows a distinct spatial distribution. Basins on the windward side of the topographic divide, at stations 0600, 0710, 0932, and 1030, have runoff to rainfall ratios about twice those of basins on the leeward side of the divide, stations 0310, 0360, 0490, and 0525. (Station numbers used in this report are abbreviated, complete numbers are preceded by 16 and end in 00.) The poorly permeable Koloa Volcanics that predominates on the windward side of the island (fig. 7), and the increased weathering and resulting decreased permeability of the rock induced by high rainfall, contribute to the high runoff to rainfall ratios in the windward basins.

In the water-budget model, direct runoff for gaged drainage basins was calculated by multiplying average monthly rainfall over the basin by the monthly runoff to rainfall ratio for that basin. On the basis of the data in table 1, direct runoff to rainfall ratios were regionalized for ungaged areas of the island by applying the average of the windward or leeward basins runoff to rainfall ratios (table 1) to the mean monthly rainfall in the area,

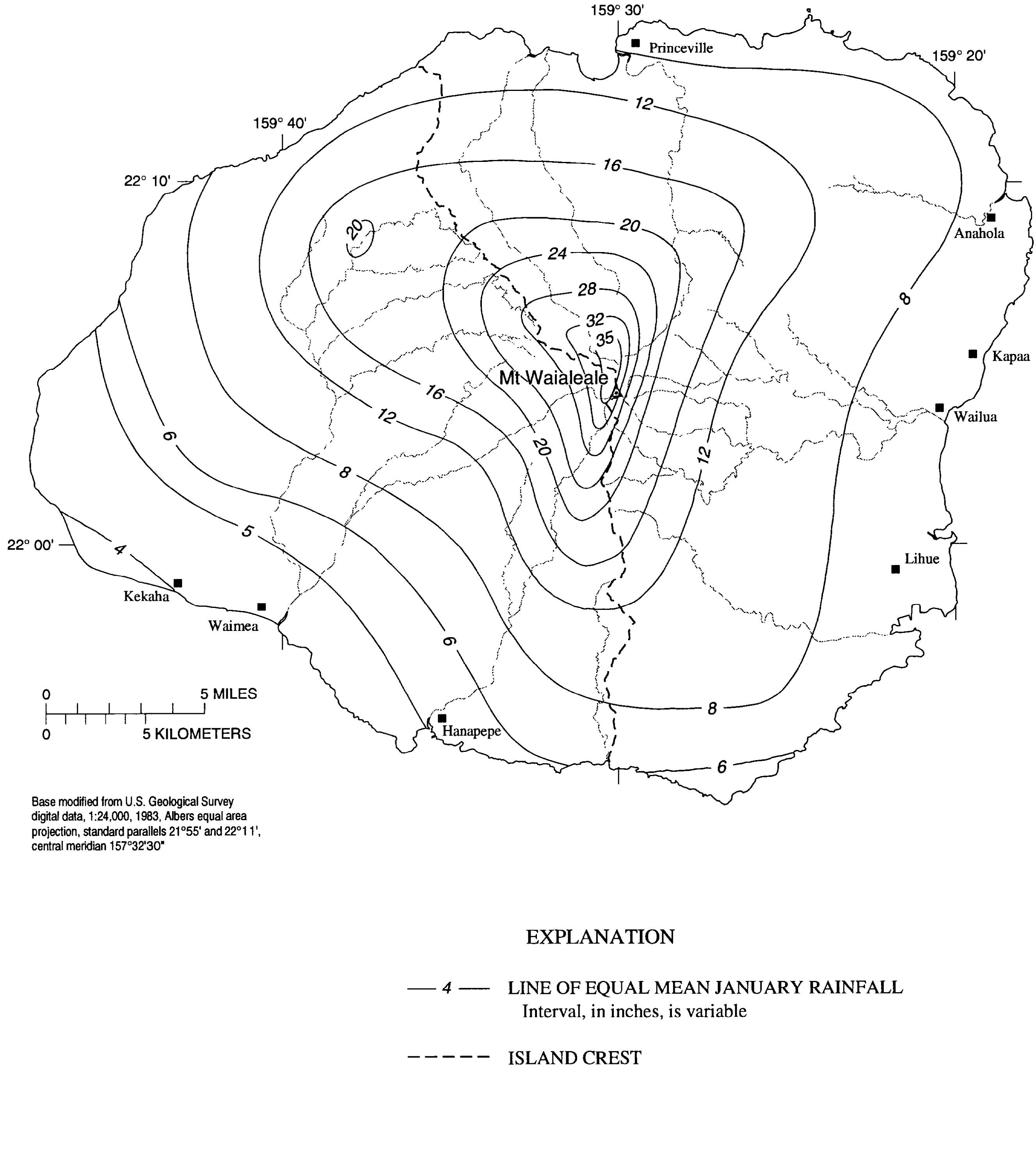
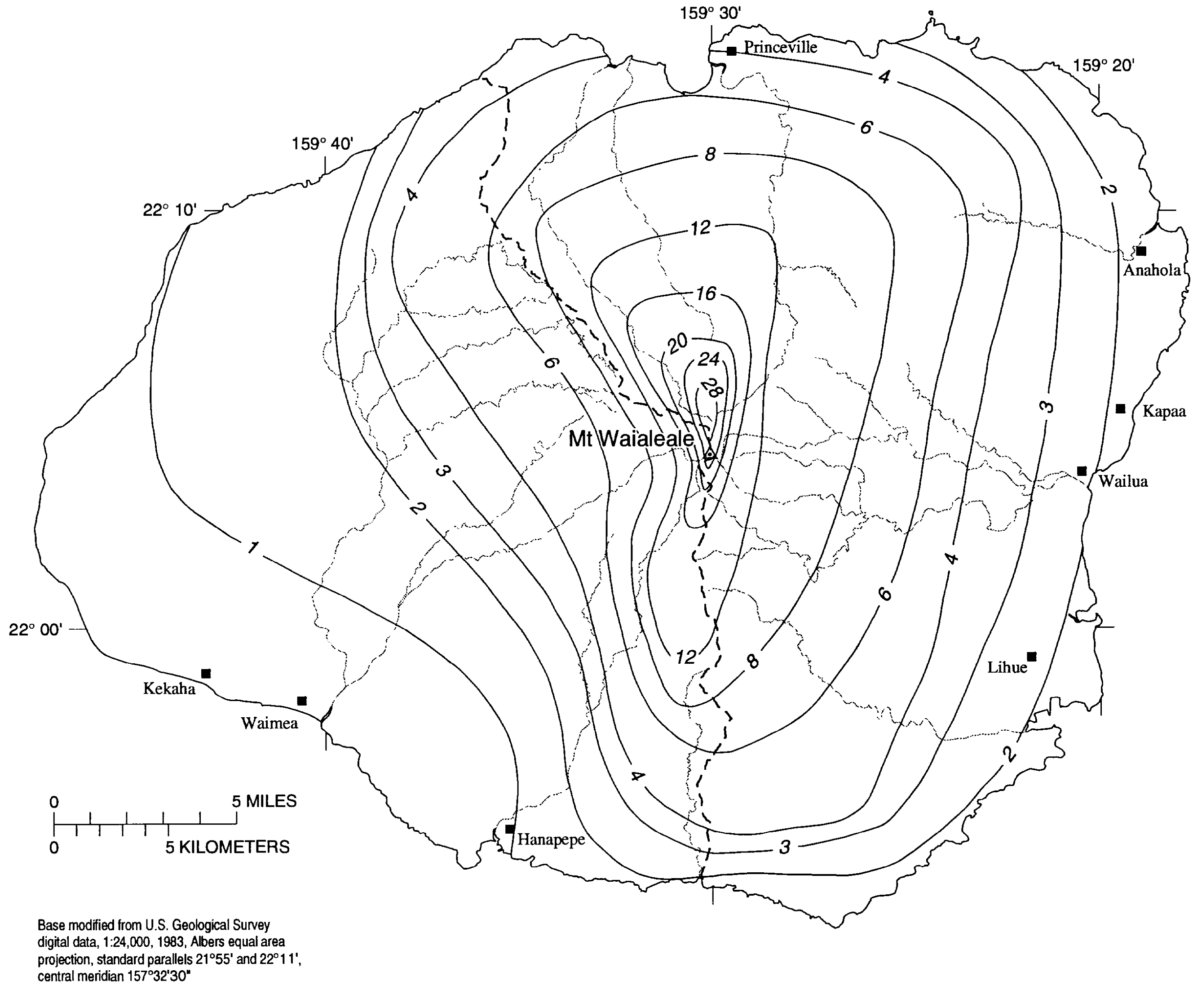



**Figure 4.** Mean rainfall for January, island of Kauai (modified from Giambelluca and others, 1986).

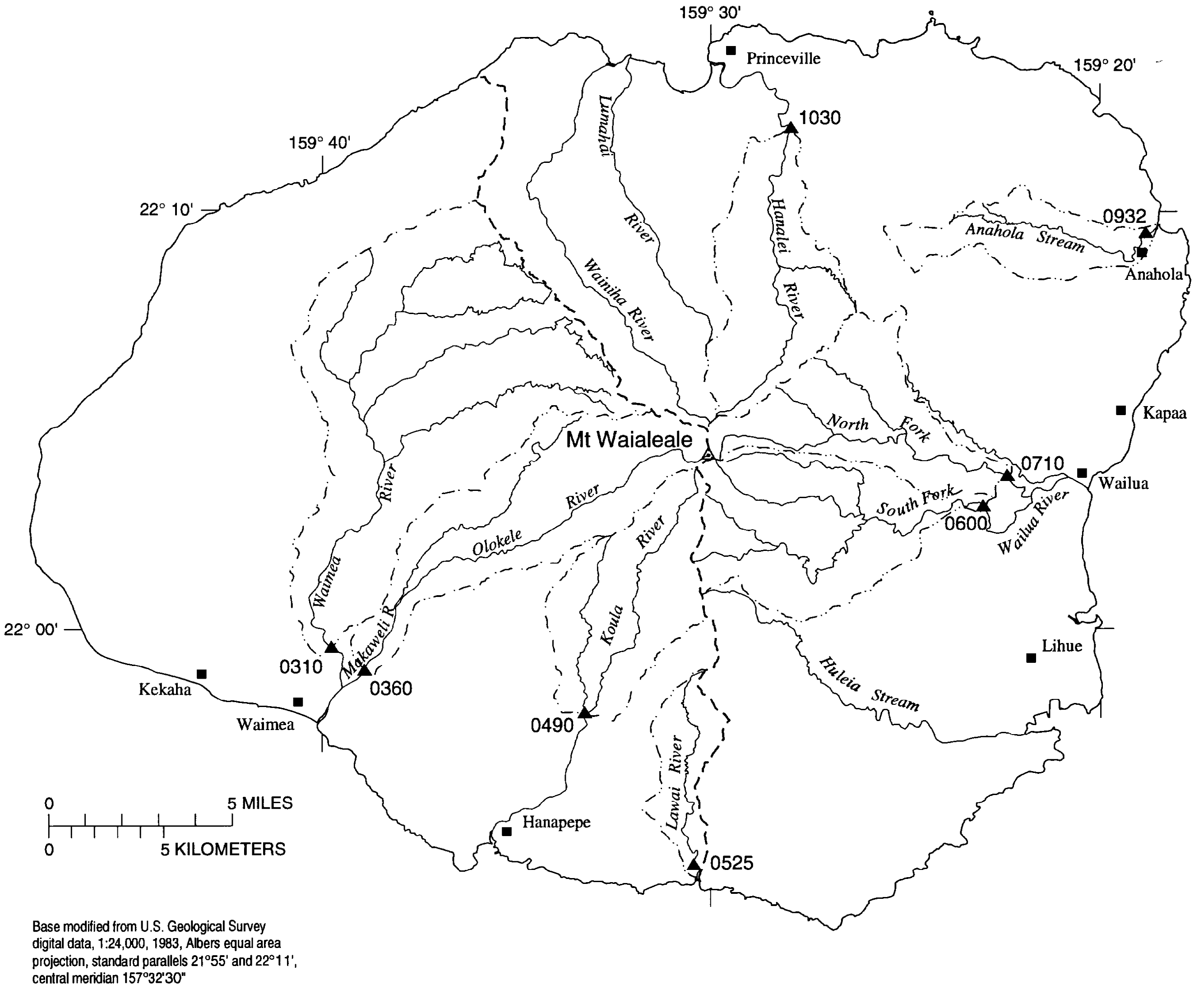



EXPLANATION

— 4 — LINE OF EQUAL MEAN JUNE RAINFALL
Interval, in inches, is variable

- - - - - ISLAND CREST

**Figure 5.** Mean rainfall for June, island of Kauai (modified from Giambelluca and others, 1986).




EXPLANATION

| | |
|---|---|
| ---·---·--- | DRAINAGE DIVIDE |
| – – – – – | ISLAND CREST AND DRAINAGE DIVIDE |
| ▲0525 | STREAMFLOW-GAGING STATION AND ABBREVIATED NUMBER--Complete number is preceeded by 16 and ends in 00. |

**Figure 6.** Gaged drainage basins used in the water-budget analysis, island of Kauai.

**Table 1.** Mean monthly direct runoff and rainfall, and runoff to rainfall ratios, island of Kauai

[Years shown are period of record; Q, direct runoff, in inches; R, rainfall, in inches; %, runoff to rainfall ratio, in percent]

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Windward streamflow-gaging stations | | | | | | | | | | | | |
| *Station 0600 (1959-87)* | | | | | | | | | | | | |
| Q | 8.66 | 5.51 | 7.48 | 6.30 | 4.72 | 2.36 | 3.54 | 3.94 | 3.15 | 4.33 | 7.87 | 7.87 |
| R | 13.55 | 12.06 | 13.59 | 14.19 | 12.80 | 9.42 | 12.65 | 13.02 | 10.25 | 12.82 | 14.45 | 14.38 |
| % | 63.9 | 45.7 | 55.0 | 44.4 | 36.9 | 25.1 | 28.0 | 30.3 | 30.7 | 33.8 | 54.5 | 54.7 |
| *Station 0710 (1953–87)* | | | | | | | | | | | | |
| Q | 9.45 | 7.48 | 9.45 | 9.45 | 7.48 | 3.54 | 5.51 | 5.51 | 3.15 | 5.91 | 11.02 | 10.24 |
| R | 13.23 | 12.04 | 13.72 | 14.0 | 12.22 | 8.76 | 11.74 | 12.33 | 9.74 | 12.17 | 13.93 | 14.53 |
| % | 71.4 | 62.1 | 68.9 | 67.5 | 61.2 | 40.4 | 46.9 | 44.7 | 32.3 | 48.6 | 79.1 | 70.5 |
| *Station 0932 (1966–82)* | | | | | | | | | | | | |
| Q | 4.72 | 3.94 | 4.72 | 5.91 | 4.72 | 1.97 | 1.97 | 1.57 | 1.18 | 2.76 | 5.91 | 5.12 |
| R | 9.91 | 8.89 | 10.01 | 8.64 | 7.09 | 4.08 | 6.41 | 6.20 | 4.43 | 7.22 | 9.49 | 9.55 |
| % | 47.6 | 44.3 | 47.2 | 68.4 | 66.6 | 48.3 | 30.7 | 25.3 | 26.6 | 38.2 | 62.3 | 53.6 |
| *Station 1030 (1964–87)* | | | | | | | | | | | | |
| Q | 10.63 | 9.45 | 16.54 | 14.96 | 11.02 | 5.91 | 8.27 | 7.87 | 7.09 | 8.66 | 15.35 | 12.60 |
| R | 19.22 | 17.15 | 19.79 | 20.30 | 16.53 | 12.23 | 17.74 | 17.69 | 13.31 | 15.80 | 18.26 | 19.22 |
| % | 55.3 | 55.1 | 83.6 | 73.7 | 66.7 | 48.3 | 46.6 | 44.5 | 53.3 | 54.8 | 84.1 | 65.6 |
| ***Windward average monthly runoff to rainfall ratio, in percent:*** | | | | | | | | | | | | |
| | 59.5 | 51.8 | 63.8 | 63.5 | 58.0 | 40.3 | 38.3 | 36.0 | 35.8 | 44.0 | 69.8 | 61.3 |
| Leeward streamflow-gaging stations | | | | | | | | | | | | |
| *Station 0310 (1945–89)* | | | | | | | | | | | | |
| Q | 5.12 | 3.54 | 4.33 | 2.76 | 1.18 | 0.39 | 0.79 | 1.18 | 0.39 | 1.18 | 3.54 | 4.33 |
| R | 15.23 | 10.53 | 10.25 | 10.31 | 6.17 | 3.65 | 5.11 | 5.59 | 4.42 | 5.71 | 8.47 | 11.61 |
| % | 33.6 | 33.6 | 42.2 | 26.6 | 19.1 | 10.7 | 15.5 | 21.1 | 8.8 | 20.7 | 41.8 | 37.3 |
| *Station 0360 (1944–87)* | | | | | | | | | | | | |
| Q | 5.51 | 4.33 | 5.51 | 3.94 | 1.97 | 1.18 | 1.97 | 1.97 | 0.79 | 1.97 | 4.72 | 5.51 |
| R | 15.60 | 10.23 | 11.19 | 11.86 | 9.11 | 4.91 | 6.44 | 6.82 | 5.91 | 7.31 | 9.76 | 11.77 |
| % | 35.3 | 42.3 | 49.2 | 33.2 | 21.6 | 24.0 | 30.6 | 28.9 | 13.4 | 26.9 | 48.4 | 46.8 |
| *Station 0490 (1928–87)* | | | | | | | | | | | | |
| Q | 6.30 | 5.12 | 6.69 | 5.12 | 3.54 | 2.36 | 3.54 | 3.94 | 2.36 | 2.76 | 5.51 | 6.30 |
| R | 16.75 | 10.55 | 13.26 | 13.37 | 11.05 | 8.31 | 10.31 | 11.26 | 9.57 | 10.36 | 13.57 | 14.99 |
| % | 37.6 | 48.5 | 50.5 | 38.3 | 32.0 | 28.4 | 34.3 | 35.0 | 24.7 | 26.6 | 40.6 | 42.0 |
| *Station 0525 (1964–72)* | | | | | | | | | | | | |
| Q | 2.36 | 1.57 | 1.57 | 1.97 | 0.79 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 2.36 | 2.76 |
| R | 9.40 | 6.51 | 8.50 | 7.19 | 6.41 | 5.55 | 6.82 | 6.57 | 5.55 | 6.95 | 8.33 | 8.87 |
| % | 25.1 | 24.1 | 18.5 | 27.4 | 12.3 | 7.0 | 5.7 | 5.9 | 7.0 | 5.6 | 28.3 | 31.1 |
| ***Leeward average monthly runoff to rainfall ratio, in percent:*** | | | | | | | | | | | | |
| | 33.0 | 37.3 | 39.8 | 31.3 | 21.3 | 17.5 | 21.5 | 22.8 | 13.5 | 20.3 | 39.8 | 39.3 |

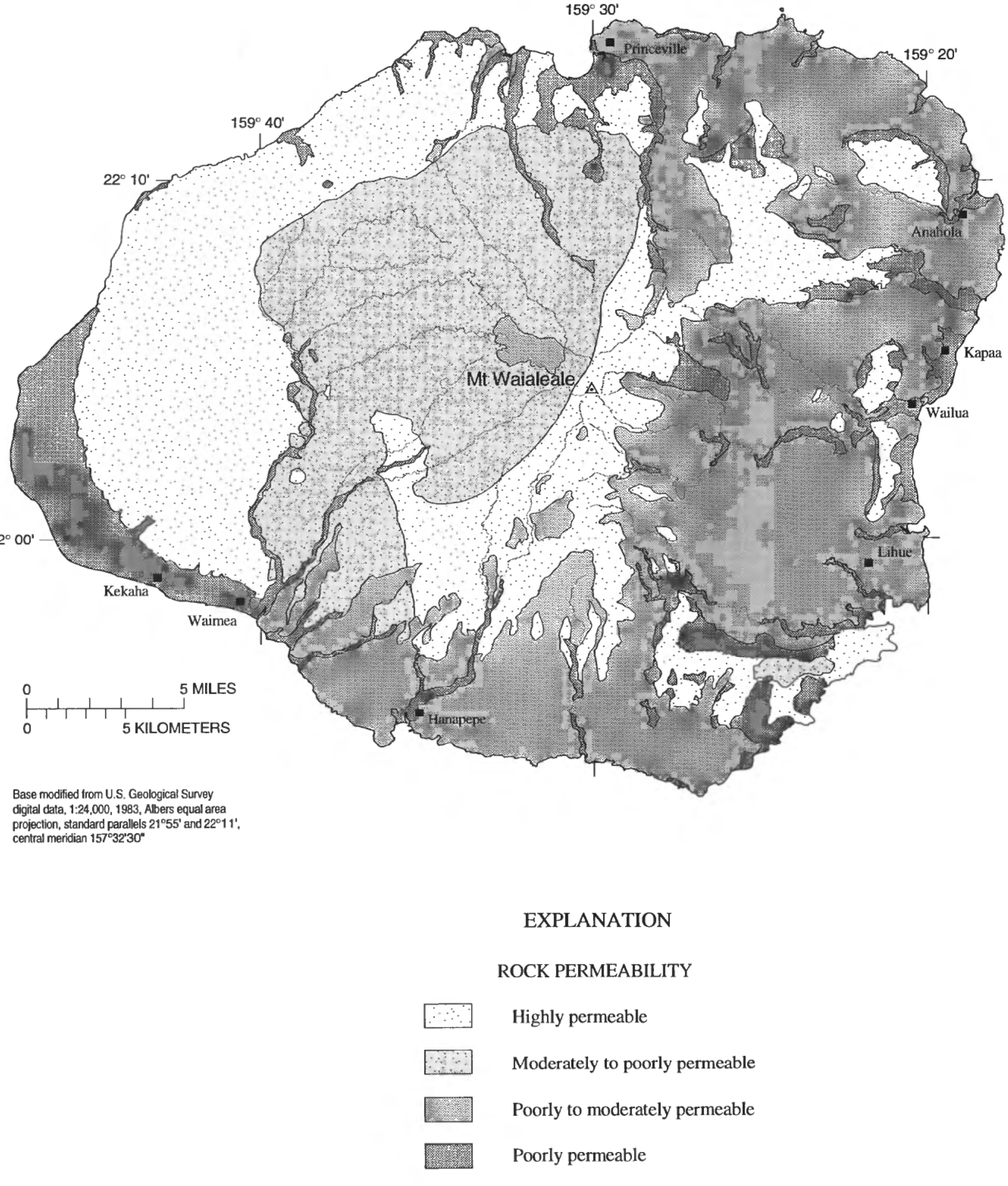



**Figure 7.** Rock permeability characteristics, island of Kauai (from Macdonald and others, 1960).

depending on the location of the area relative to the topographic divide.

Islandwide monthly direct runoff ranges from a low of about 500 Mgal/d in June and September to highs of about 1,700 Mgal/d in January, March, November, and December. The islandwide monthly runoff to rainfall ratios computed from the results of the water-budget model range from a low of 30 percent in September to a high of 60 percent in November.

## Actual Evapotranspiration and Soil-Moisture Accounting

Actual evapotranspiration (AE) is the quantity of water evaporated from water and soil surfaces and transpired by plants. Islandwide AE data from direct measurements from field experiments do not exist. It is possible to estimate AE, however, from pan-evaporation and soil data through the application of the water-budget model.

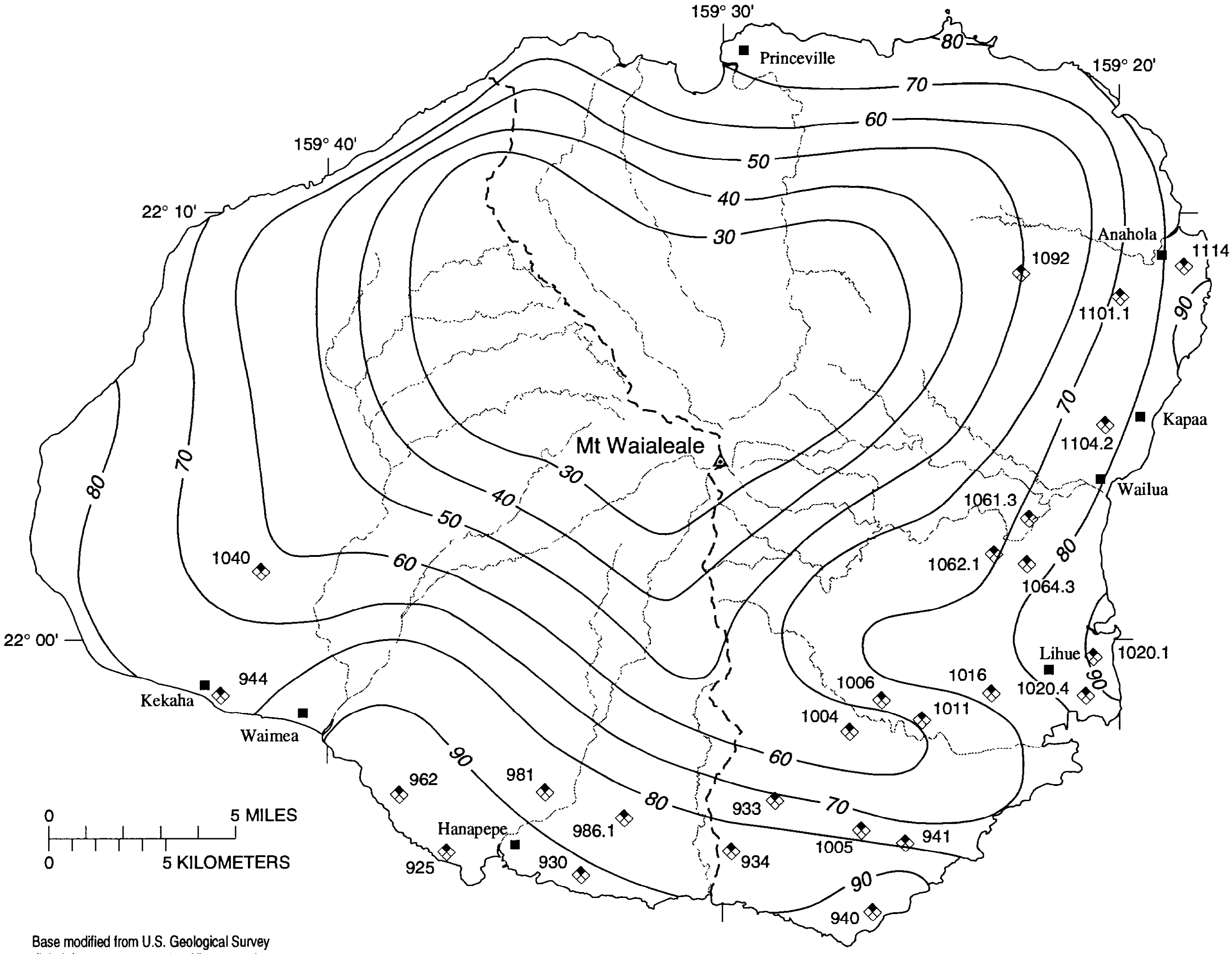
Pan-evaporation data from class A evaporating pans provide an estimate of the potential (maximum) evapotranspiration (PE) on the island. For this study pan evaporation is assumed to equal PE on the basis of the results of lysimeter studies in sugarcane fields (Chang, 1968; Campbell and others, 1959) where the average ratio between PE and pan evaporation was about 1.0. The map of mean annual pan evaporation for Kauai (Ekern and Chang, 1985) is shown in figure 8 and was digitized for the GIS water-budget model. Where sugarcane is grown, pan evaporation is well-defined by data from 25 stations with from 10 to almost 30 years of record (table 2). The mean annual pan evaporation in these areas ranges from about 50 in/yr at high altitudes where temperatures are low and rainfall and cloud cover are high to more than 90 in/yr in the hot dry leeward lowlands.

Other pan-evaporation stations with few data allow the contours to be extended inland in the central uplands to a value of 30 in/yr. Pan evaporation probably declines to 20 in/yr in the uplands near Mt. Waialeale because of decreasing temperatures and persistent cloud cover (Ekern and Chang, 1985). Ekern and Chang (1985) note that in this area, seasonal fluctuations in PE are insignificant because there is no seasonal advection of heat energy as there is at low altitudes near the leeward coast.

The islandwide mean monthly PE distributions were calculated by multiplying the annual pan-evaporation value (the average of the values of the bounding contours is assigned to the area between contour lines) shown in figure 8 by the monthly to annual pan-evaporation ratios shown in table 3. Data from 7 leeward stations and 18 windward stations were averaged separately, and variability in the ratios showed no spatial tendencies. Thus, the average of the ratios from all stations was applied in the areas where there are seasonal variations in PE, where the pan-evaporation value is more than or equal to 30 in/yr. Within the 30-in. contour, the monthly pan evaporation was calculated as one-twelfth of the annual value, simulating the lack of summer increases in pan-evaporation values.

If the PE demand in a particular month is not met by the amount of water in soil storage, then AE is less than PE. To estimate AE the maximum soil moisture-storage capacity was calculated for each of the soil series on Kauai. The soils and their characteristics have been mapped and tabulated by the Natural Resources Conservation Service (Foote and others, 1972) and were digitized by the Natural Resources Conservation Service. Estimates of the available water and rooting depth for each soil series on the island are from Foote and others (1972) and are shown in table 4. The available water value for each soil series in table 4 is the average of the range reported by Foote and others (1972). The rooting depth was assumed to be at the depth where the profile description changed from "abundant roots" to "few roots." For the few soil types where Foote and others (1972) did not provide values for available water or rooting depth, estimates were provided by the Natural Resources Conservation Service in Honolulu (C. Smith and S. Nakamura, oral commun., 1992). The maximum soil-moisture storage capacity of a particular soil series is the product of its available water and rooting depth. A map of maximum soil moisture-storage capacity was generated (fig. 9) and used with the monthly rainfall and pan-evaporation maps in the GIS model to calculate monthly values of AE and ground-water recharge.

The month-to-month bookkeeping procedure calculates changes in the amount of water (moisture) in soil storage. This volume changes month by month, and it is from this reservoir that actual evapotranspiration (AE) is withdrawn. In the water-budget model, the difference between the month's rainfall and direct runoff is the volume of water added to soil storage (eq. 2). If the new amount of water in soil storage exceeds the maxi-




Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 21°55' and 22°11', central meridian 157°32'30"

EXPLANATION

—— 60 —— LINE OF EQUAL MEAN ANNUAL PAN EVAPORATION--Interval 10 inches

– – – – – ISLAND CREST

981 ◈ PAN-EVAPORATION STATION AND NUMBER

**Figure 8.** Mean annual pan evaporation, island of Kauai (modified from Ekern and Chang, 1985).

**Table 2.** Mean monthly and annual pan-evaporation, island of Kauai (modified from Ekern and Chang, 1985)
[Station is pan evaporation station; values are in inches]

| Station no. | No. years[1] | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. | Mean annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 925 | 12 | 5.46 | 5.59 | 7.17 | 7.66 | 8.26 | 8.87 | 9.63 | 9.51 | 8.16 | 7.54 | 6.48 | 5.55 | 91.12 |
| 930 | 21 | 5.72 | 5.66 | 7.10 | 7.07 | 8.20 | 7.94 | 8.67 | 8.43 | 7.87 | 7.03 | 5.86 | 5.24 | 84.96 |
| 934 | 17 | 5.30 | 5.34 | 6.68 | 6.55 | 7.22 | 6.80 | 7.18 | 7.15 | 6.78 | 6.23 | 5.43 | 5.34 | 76.18 |
| 940 | 22 | 5.36 | 5.77 | 7.00 | 7.72 | 8.06 | 8.59 | 9.42 | 8.98 | 8.07 | 7.21 | 5.99 | 5.23 | 87.11 |
| 941 | 22 | 5.14 | 5.65 | 6.93 | 7.43 | 7.82 | 8.05 | 9.10 | 9.37 | 8.23 | 7.33 | 6.17 | 5.40 | 86.58 |
| 944 | 21 | 4.54 | 4.98 | 6.31 | 6.67 | 7.07 | 7.29 | 7.59 | 7.55 | 6.82 | 5.96 | 4.89 | 4.15 | 73.53 |
| 962 | 10 | 5.22 | 5.30 | 7.03 | 7.77 | 8.96 | 9.40 | 9.68 | 9.50 | 8.24 | 7.71 | 6.16 | 5.50 | 92.94 |
| 981 | 11 | 4.36 | 4.10 | 6.12 | 6.45 | 7.09 | 7.82 | 8.70 | 9.15 | 7.75 | 6.70 | 4.98 | 4.43 | 78.31 |
| 986.1 | 21 | 4.97 | 5.03 | 6.34 | 6.64 | 7.70 | 7.80 | 8.39 | 8.09 | 7.23 | 6.38 | 5.14 | 4.66 | 78.46 |
| 993 | 20 | 4.43 | 4.93 | 5.79 | 5.95 | 6.49 | 6.55 | 7.09 | 7.15 | 6.36 | 5.89 | 4.74 | 4.39 | 66.74 |
| 1004 | 20 | 3.63 | 4.03 | 4.37 | 4.78 | 5.43 | 5.84 | 6.15 | 5.72 | 5.07 | 4.55 | 3.75 | 3.29 | 57.84 |
| 1005 | 20 | 4.83 | 4.98 | 5.58 | 5.81 | 5.97 | 5.90 | 6.19 | 6.53 | 6.21 | 5.77 | 4.75 | 4.44 | 66.04 |
| 1006 | 19 | 3.57 | 3.66 | 4.23 | 4.90 | 5.56 | 5.85 | 6.18 | 6.21 | 5.30 | 4.69 | 3.71 | 3.32 | 55.49 |
| 1011 | 20 | 3.98 | 4.16 | 4.81 | 5.30 | 6.19 | 6.32 | 6.76 | 6.45 | 5.54 | 5.10 | 4.09 | 3.82 | 61.66 |
| 1016 | 19 | 4.25 | 4.63 | 5.39 | 5.97 | 6.71 | 6.79 | 7.27 | 6.73 | 6.14 | 5.62 | 4.50 | 3.99 | 66.83 |
| 1020.1 | 27 | 5.59 | 6.06 | 7.43 | 8.10 | 9.08 | 9.68 | 10.30 | 10.10 | 9.22 | 8.04 | 6.36 | 5.64 | 96.20 |
| 1020.4 | 17 | 5.36 | 5.66 | 6.46 | 7.19 | 7.76 | 8.09 | 8.72 | 8.56 | 7.52 | 6.83 | 5.56 | 5.12 | 83.31 |
| 1040 | 19 | 4.23 | 4.50 | 5.23 | 5.24 | 5.34 | 5.40 | 5.53 | 5.69 | 5.21 | 4.86 | 4.86 | 4.10 | 61.23 |
| 1061.3 | 16 | 4.39 | 4.07 | 4.24 | 4.27 | 5.00 | 5.30 | 6.07 | 5.93 | 5.61 | 4.80 | 3.90 | 3.74 | 58.16 |
| 1062.1 | 16 | 4.53 | 4.55 | 5.78 | 6.17 | 6.46 | 6.51 | 7.07 | 6.87 | 6.22 | 5.57 | 4.52 | 4.46 | 68.24 |
| 1064.3 | 12 | 4.86 | 5.04 | 6.30 | 6.63 | 7.28 | 7.48 | 8.27 | 8.10 | 7.47 | 6.72 | 5.16 | 5.06 | 78.64 |
| 1092 | 12 | 3.57 | 3.56 | 4.25 | 4.18 | 4.76 | 5.01 | 5.33 | 5.44 | 4.78 | 4.48 | 3.57 | 3.45 | 53.05 |
| 1101.1 | 12 | 4.86 | 4.85 | 6.10 | 6.61 | 7.24 | 6.89 | 7.28 | 7.55 | 6.72 | 6.14 | 5.02 | 5.05 | 74.17 |
| 1104.2 | 10 | 5.01 | 5.44 | 6.46 | 6.78 | 7.49 | 7.21 | 7.68 | 7.76 | 6.97 | 6.50 | 5.43 | 5.40 | 78.16 |
| 1114 | 13 | 4.81 | 5.06 | 6.08 | 6.70 | 7.78 | 7.76 | 7.72 | 7.82 | 7.03 | 6.29 | 5.04 | 4.91 | 77.50 |

[1] Number of years refers to the average number of years of monthly data. The mean annual value is not the sum of monthly means.

**Table 3.** Mean monthly to annual pan-evaporation ratios, island of Kauai
[Stations are pan-evaporation stations; values are in percent]

| Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Leeward stations (7 stations)* | | | | | | | | | | | |
| 6.29 | 6.29 | 8.29 | 8.29 | 9.57 | 9.71 | 10.29 | 10.14 | 9.14 | 8.14 | 7.00 | 6.14 |
| *Windward stations (18 stations)* | | | | | | | | | | | |
| 6.44 | 6.94 | 8.06 | 8.67 | 9.39 | 9.67 | 10.39 | 10.11 | 9.28 | 8.17 | 6.94 | 6.39 |
| ***Applied ratio*** | | | | | | | | | | | |
| 6.40 | 6.76 | 8.12 | 8.56 | 9.44 | 9.68 | 10.36 | 10.12 | 9.24 | 8.16 | 6.96 | 6.32 |

mum storage capacity, the excess recharges ground-water (eq. 3). Evapotranspiration is subtracted from soil-moisture storage at either the maximum potential rate or some lesser actual rate, depending on the amount of water in storage available to meet the demand (eq. 4). Any water remaining in soil storage is carried over to the next month.

$$SS_{Jan} + P_{Jan} - R_{Jan} = X_1 \qquad (2)$$

where:

$SS_{Jan}$ = beginning January soil-moisture storage,
$P_{Jan}$ = January rainfall,
$R_{Jan}$ = January runoff, and
$X_1$ = first interim soil-moisture storage.

If $X_1 > SS_{max}$, then $X_1 - SS_{max} = G$ and $X_1 - G = X_2$. **OR** If $X_1 \le SS_{max}$, then $G = 0$ and $X_1 = X_2$. (3)

where:

$X_1$ = first interim soil storage in the month,
$SS_{max}$ = maximum soil storage,
$G$ = ground-water recharge, and
$X_2$ = second interim soil storage in the month.

If $X_2 \ge PE$, then $AE = PE$ and $X_2 - PE = X_{end}$. **OR** If $X_2 < PE$, then $AE = X_2$ and $X_{end} = 0$. (4)

where:

$AE$ = actual evapotranspiration,
$PE$ = potential (maximum) evapotranspiration, and
$X_{end}$ = soil-moisture storage at the end of the month.

The water-budget model accounts for soil-moisture storage through the months by calculating a beginning soil storage and ending soil storage for each month where the ending value becomes the beginning value for the next month. The beginning soil-moisture for January was determined to be 92 percent of capacity by modeling three scenarios with initial soil-moisture at 100 percent, 50 percent, and 0 percent of capacity. Ending soil-moisture in December was identical for the three scenarios, and therefore, these values were input for January initial soil moisture.

**Table 4.** Soil characteristics, island of Kauai

| Soil series | Available water (inch per inch of soil) | Rooting depth (inch) | Maximum soil-moisture storage (inch) |
|---|---|---|---|
| Alakai | 0.20 | 32 | 6.40 |
| Halii | 0.11 | 15 | 1.65 |
| Hanalei | 0.17 | 13 | 2.21 |
| Hanamaulu | 0.14 | 36 | 5.04 |
| Hihimanu | 0.12 | 45 | 5.40 |
| Hulua | 0.13 | 16 | 2.08 |
| Ioleau | 0.13 | 15 | 1.95 |
| Jaucas | 0.06 | 13 | 0.78 |
| Kaena | 0.12 | 37 | 4.44 |
| Kalapa | 0.13 | 20 | 2.60 |
| Kalihi | 0.13 | 46 | 5.98 |
| Kaloko | 0.13 | 20 | 2.60 |
| Kapaa | 0.14 | 14 | 1.96 |
| Kekaha | 0.16 | 21 | 3.36 |
| Kokee | 0.16 | 32 | 5.12 |
| Koloa | 0.11 | 20 | 2.20 |
| Kolokolo | 0.13 | 28 | 3.64 |
| Koolau | 0.13 | 7 | 0.91 |
| Kunuweia | 0.08 | 12 | 0.96 |
| Lawai | 0.15 | 26 | 3.90 |
| Lihue | 0.14 | 27 | 3.78 |
| Lualualei | 0.12 | 30 | 3.60 |
| Mahana | 0.12 | 20 | 2.40 |
| Makapili | 0.13 | 28 | 3.64 |
| Makaweli | 0.15 | 36 | 5.40 |
| Mamala | 0.17 | 19 | 3.23 |
| Mokuleia | 0.10 | 22 | 2.20 |
| Niu | 0.12 | 36 | 4.32 |
| Nohili | 0.13 | 120 | 15.60 |
| Nonopahu | 0.11 | 31 | 3.41 |
| Oli | 0.13 | 21 | 2.73 |
| Paaiki | 0.18 | 9 | 1.62 |
| Pakala | 0.11 | 27 | 2.97 |
| Pamoa | 0.10 | 62 | 6.20 |
| Pohakupu | 0.13 | 38 | 4.94 |
| Pooku | 0.10 | 43 | 4.30 |
| Puhi | 0.11 | 33 | 3.63 |
| Puu Opae | 0.13 | 29 | 3.77 |
| Waialeale | 0.21 | 4 | 0.84 |
| Waiawa | 0.16 | 14 | 2.24 |
| Waikomo | 0.10 | 20 | 2.00 |
| Badland (BL) | [1]0.07 | [1]30 | 2.10 |
| Badland (BM) | [1]0.09 | [1]40 | 3.60 |
| Beaches | [1]0.05 | [1]0 | 0 |
| Dune land | [1]0.05 | [1]0 | 0 |
| Fill | [1]0.15 | [1]17 | 2.55 |
| Marshes | [1]0.27 | [1]60 | 16.20 |
| Riverwash | [1]0.03 | [1]0 | 0 |
| Rough broken land | [1]0.12 | [1]30 | 3.60 |

[1]Value provided by [U.S.] Natural Resources Conservation Service, Honolulu

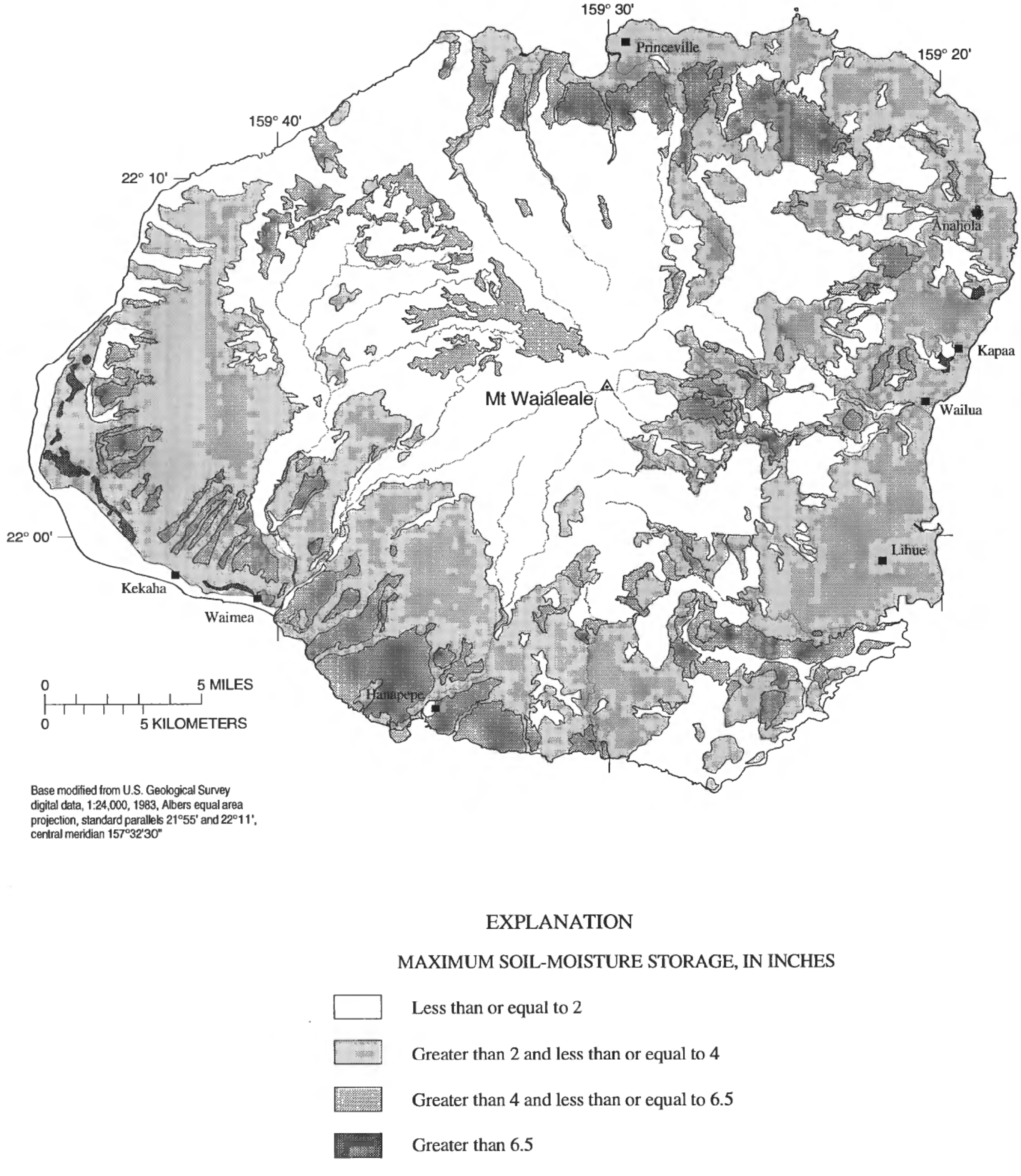



**Figure 9.** Maximum soil-moisture storage, island of Kauai.

## Irrigation

In irrigated agricultural areas, significant AE (actual evapotranspiration) and ground-water recharge result from applied irrigation water. In 1990 more than 33,000 acres were planted principally in drip-irrigated sugarcane, with additional acreage in coffee and macadamia nuts. To simulate the effects of irrigation on the water budget, a sub-routine was added to the GIS model. The agricultural fields were digitized from the plantation's field maps, and furrow- or drip-irrigation and crop type were coded. Irrigation water was estimated from 1990 data supplied by the major plantations on the island and discussed by Shade (1995). For each plantation in the GIS model, the irrigation water was applied homogeneously over the fields and equally for each month.

Crop AE demand was calculated as a factor of pan evaporation (table 5). Irrigation recharge was calculated as the difference between applied irrigation water and crop AE requirements. The irrigation recharge was superposed on the ground-water recharge calculated from rainfall in these areas. Islandwide, applied irrigation water was about 218 Mgal/d and AE was 187 Mgal/d, 86 percent of the applied water. Ground-water recharge from the infiltration of agricultural irrigation water was 31 Mgal/d, which is 14 percent of the applied irrigation water. Fourteen percent is about one-third the irrigation recharge rate from sugarcane fields calculated by Dale (1967). However, Dale's (1967) agricultural field data were from 1931 through 1965, when all fields were furrow-irrigated indicating that application rates were a factor of pan evaporation equal to 1.6.

## Ground-Water Recharge and Water-Budget Results

Ground-water is recharged during months when soil-moisture storage exceeds the maximum soil-storage capacity. In an average year on an islandwide basis, ground-water is recharged every month, although more recharge occurs in the wet months, and none occurs in the dry months in the driest areas. Average monthly values for the components of the water budget for Kauai are shown in table 6. January is the wettest month with almost 3,700 Mgal/d of rainfall and irrigation, and more than 980 Mgal/d of recharge. Recharge increases during

**Table 5.** Irrigated plantation crops, island of Kauai

| Crop | Acres | Irrigation method | Crop actual evapotranspiration (factor of pan evaporation) |
|---|---|---|---|
| Sugarcane | 18,600 | drip | 1.0 |
| Sugarcane | 9,400 | furrow | 1.0 |
| Coffee | 225 | drip | 0.5 |
| Macadamia nuts | 5,000 | drip | 0.6 |

Note: Plantation estimates the evaporative demand of macadamia nut trees to be 50 inches per year. This value, on average, converts to 0.6 × pan evaporation in the area of irrigated macadamia nut fields.

**Table 6.** Water-budget results, island of Kauai
[Values are in million gallons per day]

| Month | Rainfall and Irrigation | Runoff | Actual evapotranspiration | Recharge | Change in soil-moisture storage |
|---|---|---|---|---|---|
| January | 3,698 | 1,689 | 1,024 | 981 | +4 |
| February | 3,081 | 1,323 | 1,009 | 756 | –7 |
| March | 3,220 | 1,716 | 928 | 594 | –18 |
| April | 3,123 | 1,507 | 905 | 718 | –7 |
| May | 2,425 | 1,019 | 832 | 583 | –9 |
| June | 1,764 | 517 | 790 | 461 | –4 |
| July | 2,246 | 700 | 857 | 690 | –1 |
| August | 2,302 | 697 | 877 | 727 | +1 |
| September | 1,914 | 502 | 870 | 541 | +1 |
| October | 2,401 | 807 | 973 | 610 | +11 |
| November | 3,079 | 1,727 | 894 | 454 | +4 |
| December | 3,386 | 1,683 | 969 | 710 | +24 |
| Mean annual | 2,720 | 1,157 | 911 | 652 | –1 |

Note: Annual average values are the average of the monthly values.

the summer months of July and August, to 690 Mgal/d and 727 Mgal/d, respectively, relative to June (461 Mgal/d) and September (541 Mgal/d). This slight peak in recharge is a direct result of increased orographic rainfall from the more persistent trade winds in July and August (Giambelluca and others, 1986). Annual average recharge is 652 Mgal/d for the island.

Annual recharge distribution and monthly recharge distribution over the island for a wet (January) and a dry (June) month are shown in figures 10, 11, and 12. The annual distribution of ground-water recharge (fig. 10) is similar to annual rainfall distribution (fig. 2). Departure from this pattern is due primarily to the effect of ground-water recharge from irrigation, noticeable particularly in the low rainfall areas along the southwest coast near Kekaha and Waimea, and near Kapaa and Anahola on the northeast coast. By comparing figures 9 and 10 the effect on recharge of differences in the soil characteristic of maximum soil-moisture storage capacity can also be seen. Ground-water recharge is highest at the highest altitudes at the center of the island and occurs over the largest area in the rainy winter months (fig. 11) when the soil moisture is high and AE is low, and decreases significantly at these altitudes in drier months (fig. 12).

Islandwide rainfall is highest during the winter months but increases slightly in mid-summer, relative to the other dry months, because of increased orographic rainfall generated from strong northeast trade winds. The runoff component has a similar monthly distribution showing a slight peak in the summer months of July and August. The magnitude of AE variability is less through the months, ranging from 790 Mgal/d to 1,024 Mgal/d on an islandwide basis. AE values decrease as moisture becomes more limited during the drier summer months. Because ground-water recharge is the result of the interaction of the other water-budget components there is no direct correlation between recharge variability and the other components through the year. Soil-moisture storage begins to decrease from February through July as shown by the negative change in soil storage values, and increases in August, continuing through January. The mass balance result of -1 Mgal/d is the result of round-off error in the calculations. The monthly results totaled and divided by 12 indicate the annual average obtained from the monthly calculations. Expressed as a percentage of rainfall, runoff is 43 percent, AE is 33 percent, and recharge is 24 percent on an islandwide basis.

## APPLICATION OF WATER-BUDGET RESULTS TO WATER-MANAGEMENT AREAS

Water-budget results can be applied to the areas used by water managers for resource management. Aquifer-system areas on Kauai, as defined by the State of Hawaii for regulatory purposes (George A.L. Yuen and Associates, Inc., 1990), are shown in figure 13. The system boundaries generally coincide with topographic drainage divides. Water-budget results for each of the areas are shown in table 7. Ground-water pumpage from each of these areas in 1990 is also included (Shade, 1995). Two systems have relatively high ground-water withdrawal to ground-water recharge ratios, as compared with the other systems. In the Kekaha system, where several thousand acres of sugarcane are irrigated, water-budget results indicate a ground-water recharge rate of 12 Mgal/d, yet water-use data indicate a ground-water withdrawal rate of almost 23 Mgal/d. Ground-water from outside the Kekaha system is flowing into the system from the upgradient Waimea system. Another noteworthy area is the Koloa system where substantial agricultural and resort developments are located. This system shows ground-water withdrawals of about one-third the ground-water recharge rate. In all other systems ground-water recharge rates substantially surpass ground-water pumping rates.

Another point to note is the high proportion of AE in comparison with rainfall and applied irrigation water in the systems that have large agricultural areas. These ratios are 53 percent, 45 percent, 42 percent, 72 percent, and 47 percent in the Koloa, Hanamaulu, Anahola, Kekaha, and Makaweli systems, respectively. Because these agricultural areas are presently dominated by sugarcane, which has a high water demand, the continuing diversification of agricultural crops to lower-water-demand crops and development of agricultural land for housing and resorts will distinctly shift the balance of the water-budget components. The AE proportion of the balance in these areas will decrease as will ground-water recharge from a decrease in applied irrigation water.

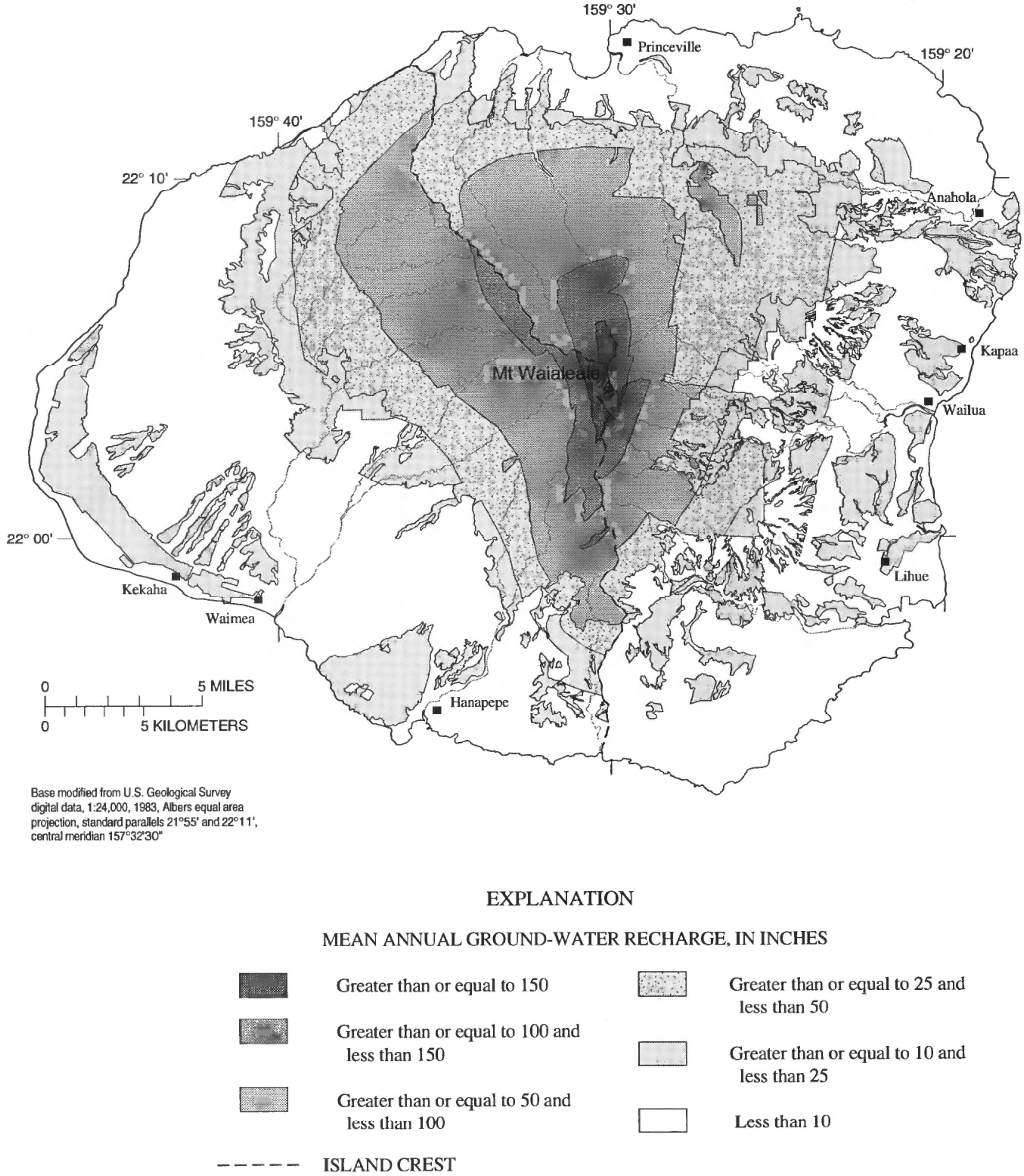
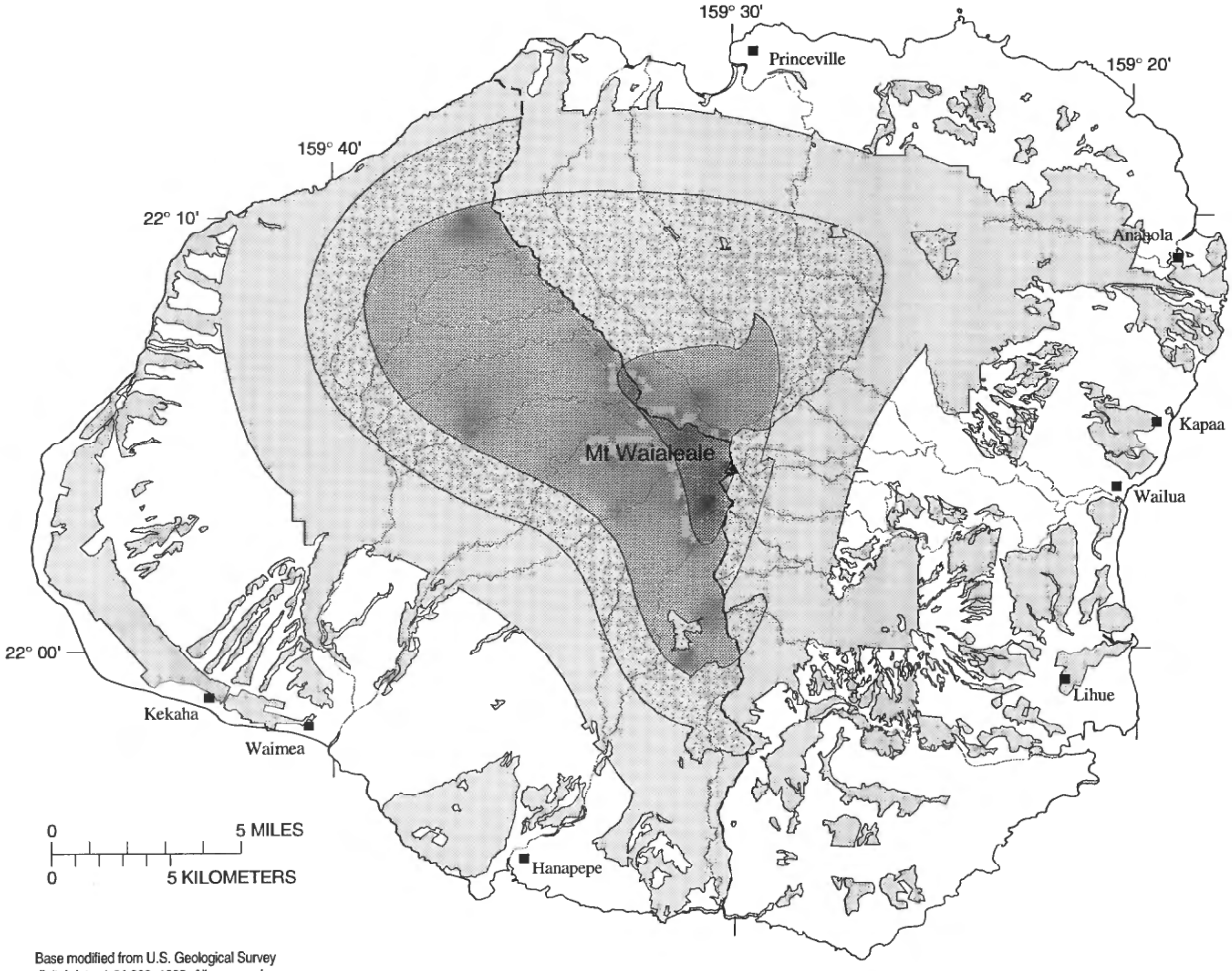



**Figure 10.** Mean annual ground-water recharge, island of Kauai.



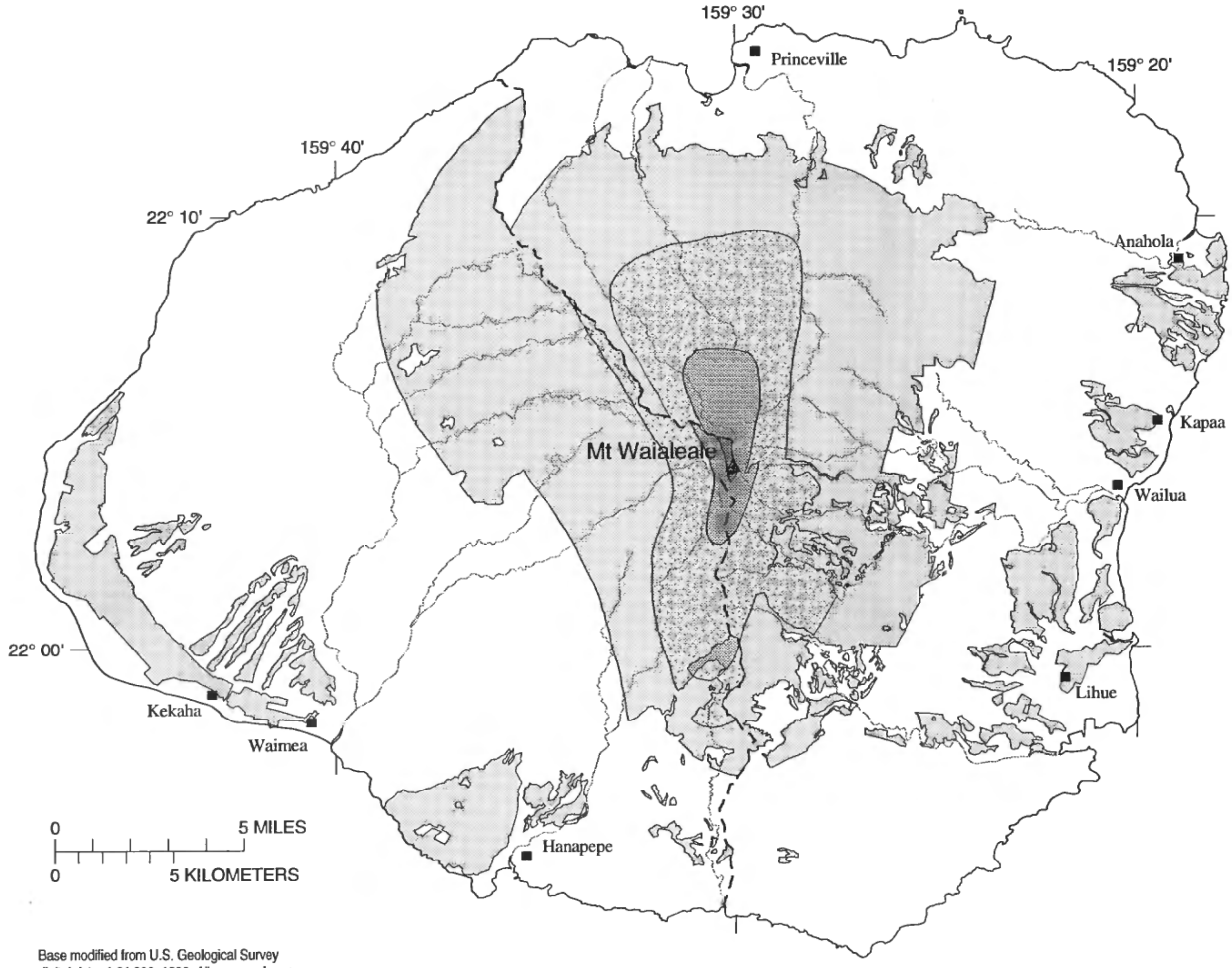

Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 21°55' and 22°11', central meridian 157°32'30"

EXPLANATION

MEAN JANUARY GROUND-WATER RECHARGE, IN INCHES

- Greater than or equal to 15
- Greater than or equal to 10 and less than 15
- Greater than or equal to 5 and less than 10
- Greater than or equal to 1 and less than 5
- Less than 1
- ISLAND CREST

**Figure 11.** Mean ground-water recharge for January, island of Kauai.




Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 21°55' and 22°11', central meridian 157°32'30"

EXPLANATION

MEAN JANUARY GROUND-WATER RECHARGE, IN INCHES

- Greater than or equal to 15
- Greater than or equal to 10 and less than 15
- Greater than or equal to 5 and less than 10
- Greater than or equal to 1 and less than 5
- Less than 1
- ----- ISLAND CREST

**Figure 12.** Mean ground-water recharge for June, island of Kauai.

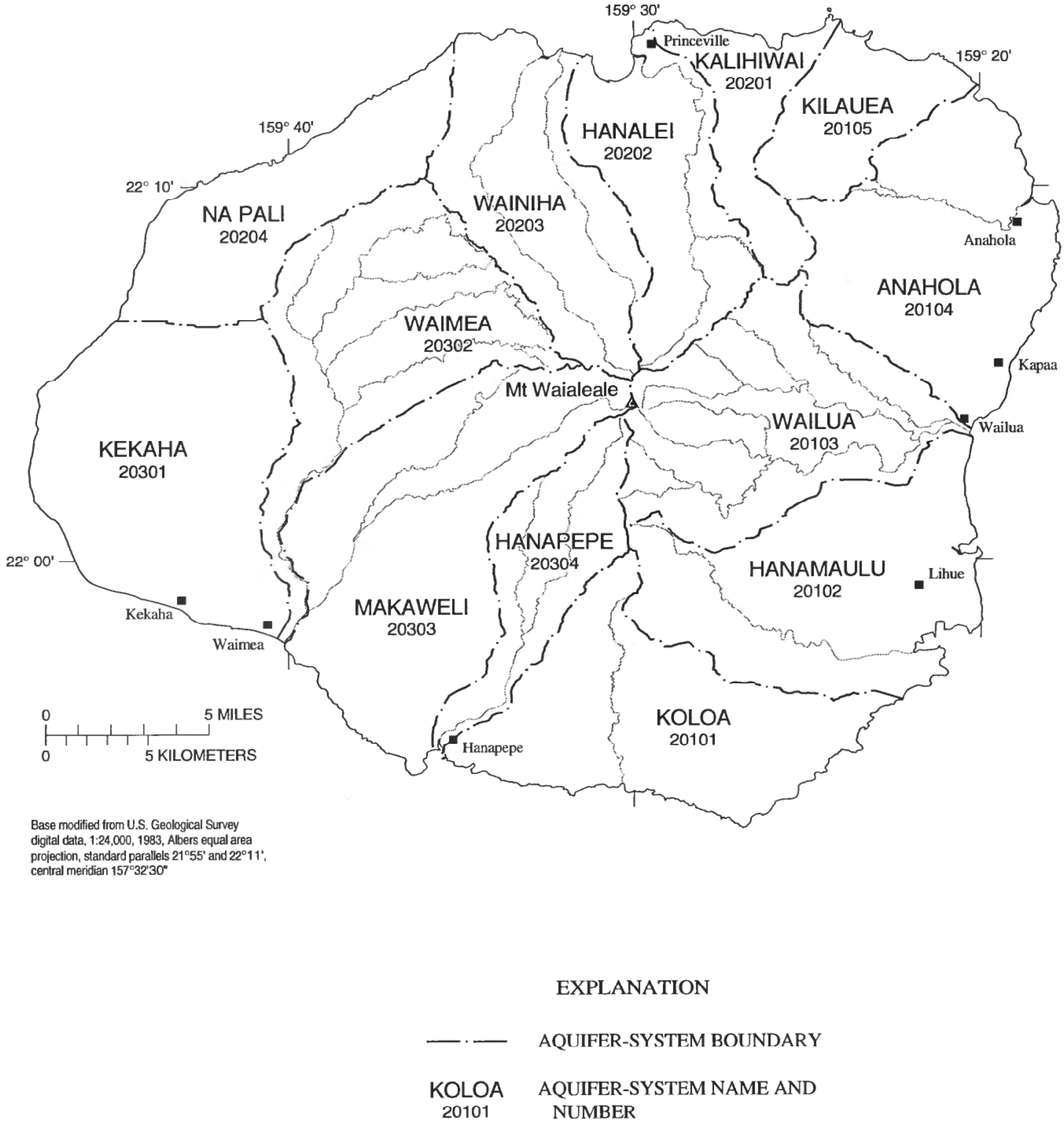



**Figure 13.** Aquifer-system areas, island of Kauai (from George A. L. Yuen and Assoc., 1990).

**Table 7.** Water-budget results by aquifer system, island of Kauai
[Aquifer-system names and numbers are from George A.L. Yuen and Associates, Inc., 1990; values are in million gallons per day]

| Aquifer-system name | Aquifer-system number | Rainfall and irrigation | Runoff | Actual evapo-trans-piration | Recharge | Pumpage |
|---|---|---|---|---|---|---|
| Koloa | 20101 | 198 | 66 | 104 | 28 | 9.64 |
| Hanamaulu | 20102 | 249 | 112 | 111 | 26 | 5.24 |
| Wailua | 20103 | 338 | 169 | 78 | 91 | 0.74 |
| Anahola | 20104 | 217 | 101 | 91 | 25 | 2.97 |
| Kilauea | 20105 | 83 | 45 | 30 | 8 | 0.42 |
| Kalihiwai | 20201 | 96 | 52 | 27 | 17 | 1.22 |
| Hanalei | 20202 | 274 | 162 | 49 | 63 | 0.12 |
| Wainiha | 20203 | 352 | 190 | 51 | 111 | 0.10 |
| Na Pali | 20204 | 102 | 33 | 41 | 28 | 0.00 |
| Kekaha | 20301 | 149 | 29 | 108 | 12 | 22.68 |
| Waimea | 20302 | 248 | 73 | 60 | 115 | 0.82 |
| Makaweli | 20303 | 273 | 75 | 127 | 71 | 2.16 |
| Hanapepe | 20304 | 141 | 50 | 34 | 57 | 0.17 |
| TOTAL........................ | | 2,720 | 1,157 | 911 | 652 | 46.28 |

## SUMMARY AND CONCLUSIONS

Ground water is the main source of public water supply for the island of Kauai. Aquifers on the 553 square mile island are replenished by ground-water recharge from rainfall and agricultural irrigation water that percolates through and beyond the root zone in the soil to the subsurface rock. Rainfall ranges from less than 20 inches per year near sea level along the southwest coast to more than 400 inches annually at the summit of the island at an altitude of over 5,100 feet. Most of the agricultural irrigation water used on the five large plantations is diverted from streams, and almost 220 Mgal/d (million gallons per day) is applied to the fields.

Ground-water recharge is the residual component of a monthly water budget calculated using long-term average rainfall, streamflow, and pan-evaporation data, and applied irrigation-water estimates and soil characteristics. The water-budget components are defined seasonally, through the use of the monthly water budget, and spatially by aquifer-system areas, through the use of a geographic information system model.

Islandwide rainfall is highest during the winter months, November through April, with a slight increase in July and August owing to increased orographic rainfall generated from persistent summer trade winds. Monthly direct runoff has a similar distribution through the year. The least monthly variability is in the actual evapotranspiration, which ranges from 790 to 1,024 Mgal/d islandwide. Monthly ground-water recharge ranges from a low of 461 Mgal/d in June and 454 Mgal/d in November to a high of 981 Mgal/d in January. The annual average ground-water recharge for Kauai is 652 Mgal/d, 24 percent of the total of the annual average rainfall and applied irrigation water. The ground-water recharge in the natural land-use areas is spatially distributed in a pattern similar to the rainfall distribution. Islandwide average annual direct runoff and evapotranspiration are 1,157 Mgal/d and 911 Mgal/d, 43 and 33 percent of the total average rainfall and irrigation water, respectively.

The water-budget components are also tabulated for the 13 aquifer systems used by the State of Hawaii for water management. In all but one of the aquifer systems, ground-water pumpage is less than ground-water recharge. In the Kekaha system, pumpage exceeds recharge by almost 11 Mgal/d indicating that ground water likely flows into this system from an adjacent upgradient aquifer system.

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