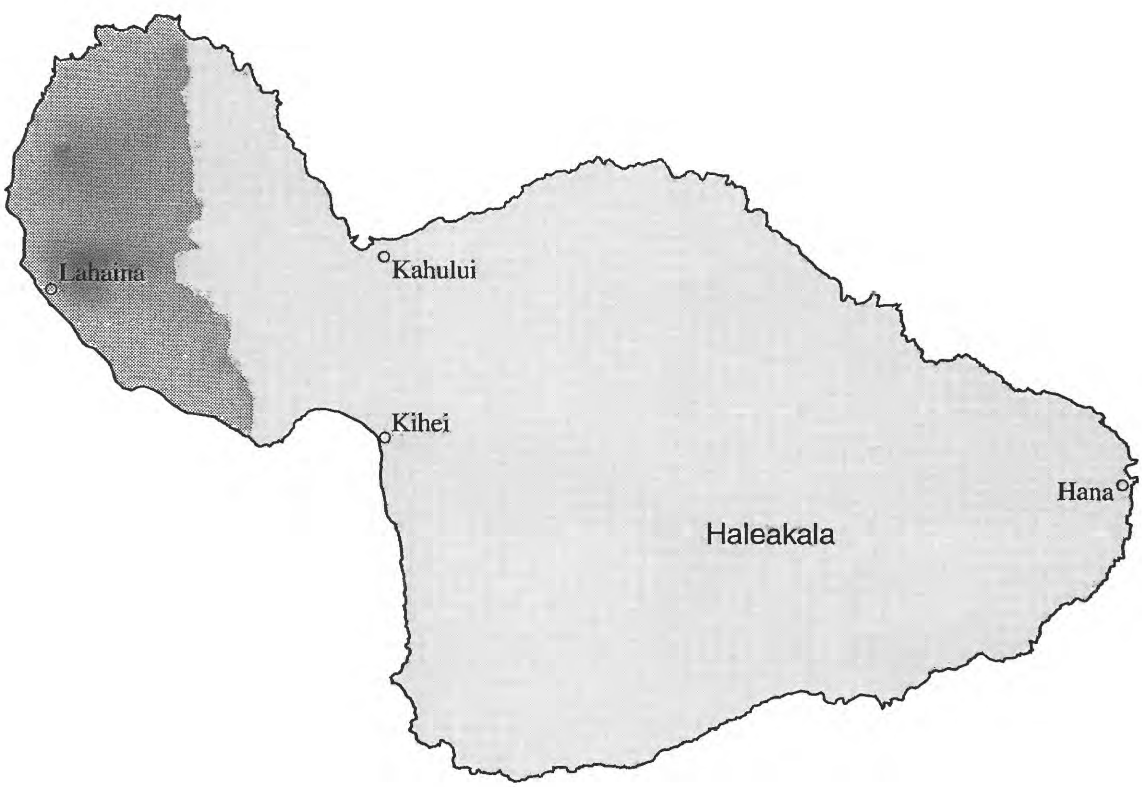
WATER BUDGET FOR THE LAHAINA DISTRICT, ISLAND OF MAUI, HAWAII

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 96-4238



Prepared in cooperation with the
STATE OF HAWAII COMMISSION ON WATER RESOURCE MANAGEMENT
DEPARTMENT OF LAND AND NATURAL RESOURCES

U.S. DEPARTMENT OF THE INTERIOR
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CONTENTS

FIGURES

TABLES

Conversion Factors

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

Water Budget for the Lahaina District, Island of Maui, Hawaii

By Patricia J. Shade

Abstract

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

The long-term average ground-water recharge for the Lahaina District was estimated for three scenarios using 1923–78 land-use and irrigation data, 1986–93 land-use and irrigation data, and natural conditions. The average annual ground-water recharge rate for 1923–78 conditions is 190 million gallons per day, which is 45 percent of the sum of rainfall and irrigation. The recharge rate for 1986–93 conditions is 163 million gallons per day, which is 42 percent of rainfall plus irrigation. The recharge rate for natural conditions is 145 million gallons per day, which is 44 percent of rainfall.

INTRODUCTION

Water development in the Lahaina District of Maui (fig. 1) began when Hawaiians first diverted stream discharge to irrigate taro fields. In the early 1900's, Pioneer Mill Co. constructed a large network of stream diversions and ditches and drilled several wells to develop irrigation water for thousands of acres of sugarcane. The town of Lahaina had developed into a bustling community as a major port for whaling ships and traders journeying between the islands, Asia, and the U.S. mainland.

Presently, Lahaina remains a busy port, but increasingly for recreational activities such as fishing, whale-watching, snorkeling, and sunset cruises. Extensive resort and condominium developments are located north of Lahaina along the coast from Kaanapali to Napili. The Lahaina District is one of the most popular tourist destinations in the State of Hawaii. Several small communities and plantation villages also are located in the district. Plantation agriculture remains a major land use in the area where thousands of acres of sugarcane and pineapple are irrigated from surface- and ground-water sources. Ground water is an important source to meet this demand as well as the demands of the extensive resort and residential developments. In an effort to meet the present and future water demand and to increase knowledge of ground water in the Lahaina District, the State Commission on Water Resource Management entered into a cooperative agreement with the U.S. Geological Survey (USGS) to study ground-water availability in the Lahaina District. The project includes a water-budget calculation and numerical simulation analysis of the ground-water flow system.

Purpose and Scope

The purpose of this report is to describe the calculation of a mean monthly water budget for the Lahaina District of the island of Maui. Included in the water budget is a calculation of ground-water recharge, which is a data requirement for numerical simulation of the ground-water flow system. Monthly calculations yield a more accurate value of ground-water recharge, compared with calculations made on a mean annual basis, because the method accounts for actual evapotranspira-

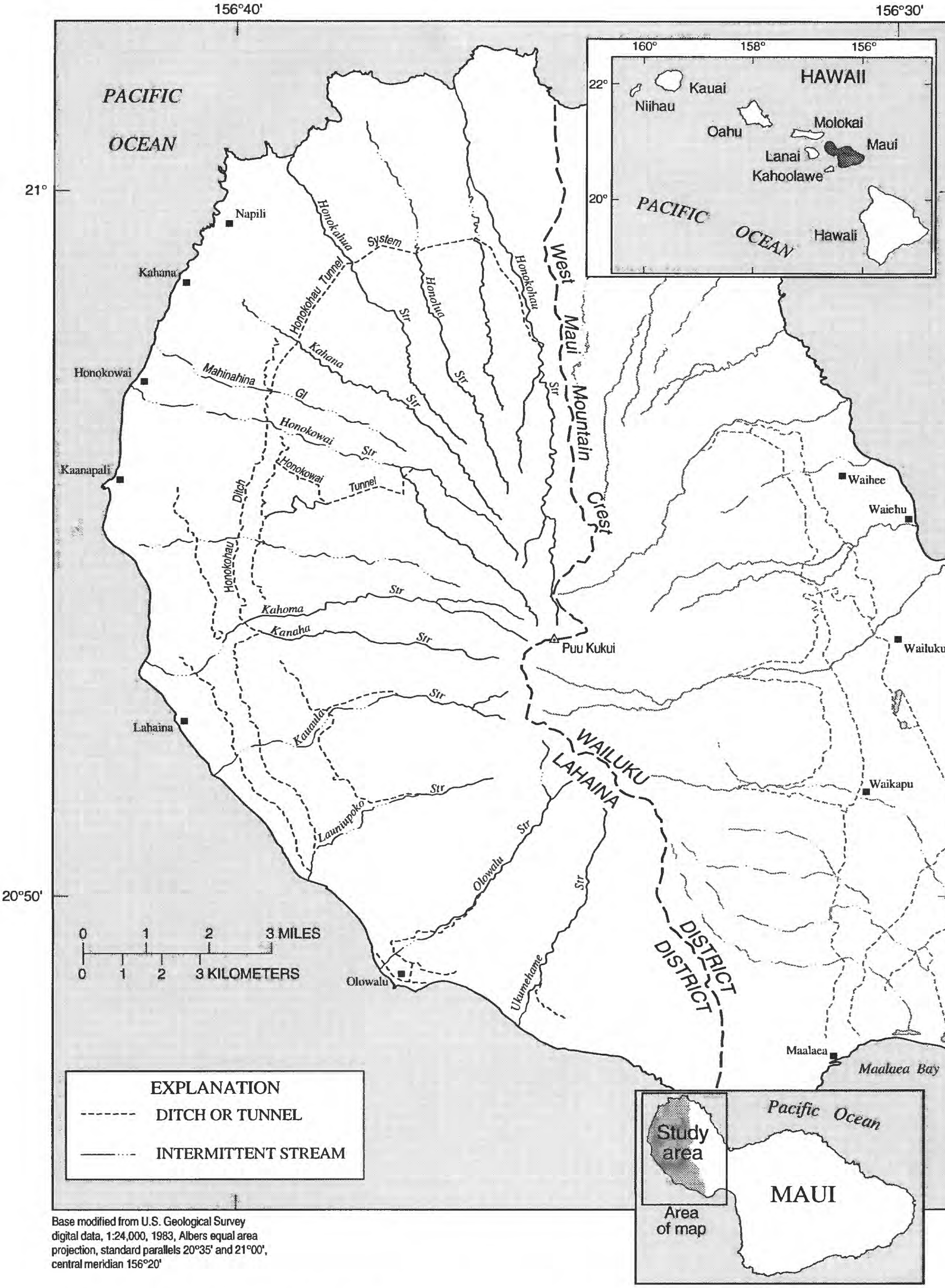


Figure 1. Lahaina District, Maui, Hawaii.

tion and water held in the soil root zone. Estimates of ground-water recharge were calculated for three land-use scenarios. The monthly spatial distribution of the water-budget components by topographic areas is tabulated, and the ground-water recharge distribution is displayed.

Previous Investigations

Several reports address various aspects of the water resources of the Lahaina District. The studies containing water-budget estimates relevant to this investigation include those by Yamanaga and Huxel (1969); Broadbent (1969); Belt, Collins and Associates (1969); Wilson, Okamoto and Associates (1977); Takasaki (1978); and Austin, Tsutsumi and Associates, Inc. (1991).

Description of the Study Area

The study area encompasses about 96 mi^2 from the northwest coast of Maui to the crest of the West Maui Mountain, an extinct volcano (fig. 1). Rainfall is abundant along the crest, which peaks at an altitude of 5,785 ft at Puu Kukui. Several streams originating in the area of high rainfall have carved deeply incised valleys into this extinct volcanic dome. Streamflow in the uplands is perennial, fed by ground-water discharge. Much of this stream discharge is diverted through a large network of ditches and tunnels for irrigation of sugarcane, pineapple, resort landscaping and golf courses, and for some domestic use. Plantation agriculture and conservation land use dominate the uplands. Small rural communities, agriculture and resort development occupy the gently sloping coastal plain.

Three aquifer-system areas (A, B, and C in fig. 2) were delineated within the study area by Mink and Lau (1990). These subdivisions of the study area were helpful in making comparisons of water-budget results from previous investigations. Area A is the northwest part of the island defined by the crest of the West Maui Mountain and the southern ridge of Kahana Valley. South of area A, area B occupies the central part of the Lahaina District, bounded by the mountain crest and on the south by the ridge between Launiupoko and Olowalu Streams. Area C is the southwest part of the district, just south of area B and bounded by the mountain crest.

Within the three aquifer-system areas, ground water moves from the West Maui Mountain toward the ocean. Within the rift zone of this volcano, a subsurface barrier of low-permeability basaltic dikes impedes ground-water movement and forces water levels in wells to several hundred feet above mean sea level. The approximate location of this ground-water flow barrier, described by Takasaki (1978), subdivides the aquifer-system areas into the high-level ground-water areas, as they are commonly referred to in Hawaii (areas 2, 4, and 5) and basal-water areas (areas 1, 3, and 6) (fig. 2). Basal water, also called the Ghyben-Herzberg lens, is a body of freshwater that floats on saltwater near sea level within the more permeable lava flows on the flank of the volcano.

WATER-BUDGET MODEL

Aquifers are replenished by ground-water recharge from rainfall and irrigation water that percolates through and beyond the root zone in the soil to the subsurface rock. Ground-water recharge can be estimated using a water-budget model. The method used in this study 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 precipitation (rainfall) and applied irrigation water, and moisture outputs of runoff (streamflow), evapotranspiration, and ground-water recharge. The relation is expressed by:

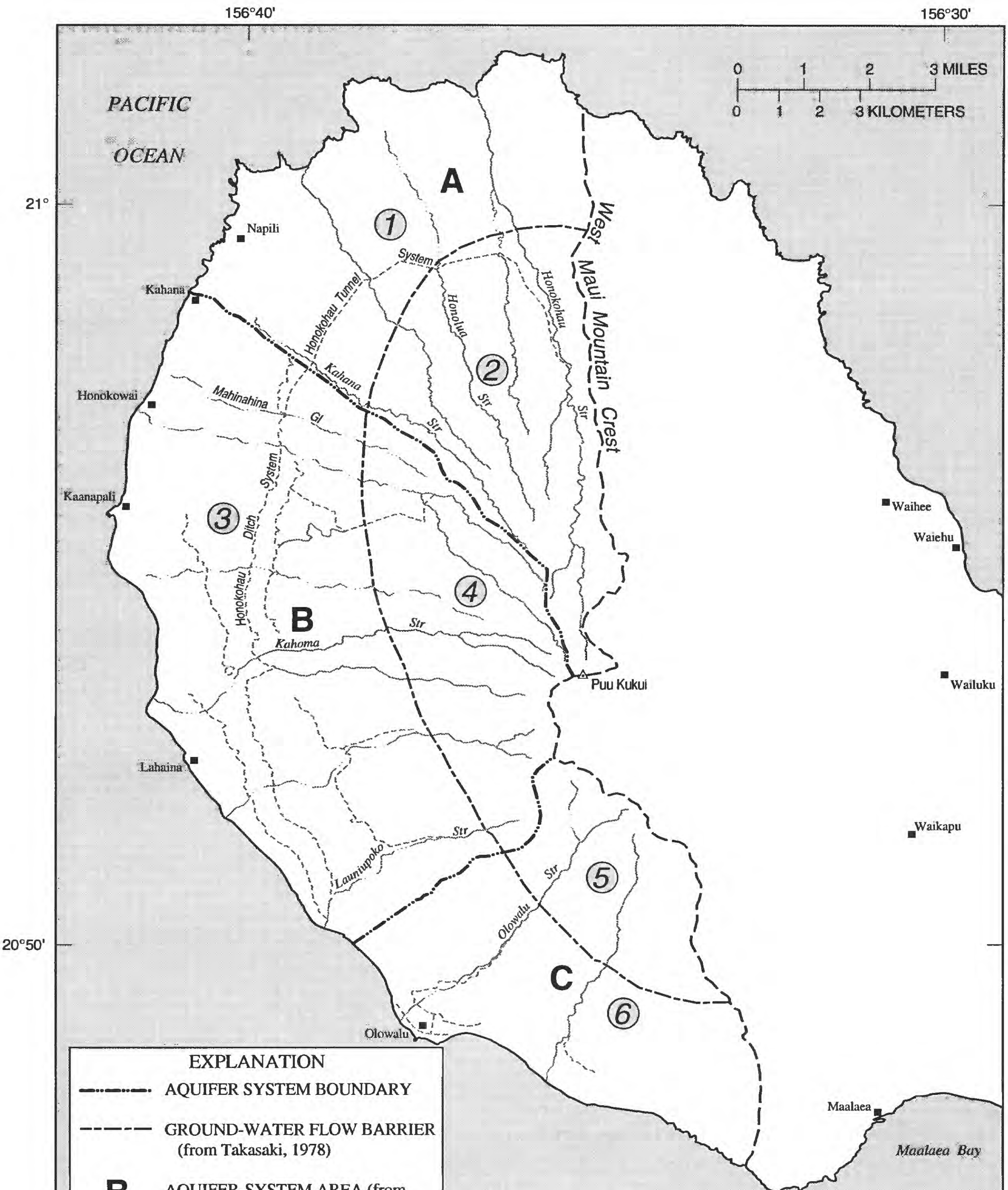
$$G = P + I - R - AE - \Delta SS, \quad (1)$$

where:

G = ground-water recharge,
P = precipitation (rainfall),
I = applied irrigation,
R = direct runoff,
AE = actual evapotranspiration, and
ΔSS = change in soil 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



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 20°35' and 21°00', central meridian 156°20'

Figure 2. Aquifer-system and ground-water areas in the Lahaina District, Maui, Hawaii.

water-budget model include rainfall, agricultural irrigation and land-use distribution, runoff (streamflow) and associated drainage areas, pan-evaporation distribution, and soil-type distribution and properties. The spatial data allow the water-budget components to be calculated and displayed by individual area or any combination of areas.

The study area was digitized from 1:24,000-scale USGS topographic maps prepared in 1983. The area was divided into three aquifer-system areas which were subdivided by the delineation of the approximate location of a subsurface ground-water flow barrier (fig. 2). These subdivisions were necessary for subsequent ground-water flow simulations.

In basal ground-water areas 1, 3, and 6, no streamflow data are available that are representative of the runoff generated from within these drainage-area boundaries. Therefore, a procedure to calculate direct runoff/rainfall ratios on the basis of soil type and rainfall was developed.

Rainfall

The rainfall distribution in the study area is influenced by the orographic effect of the West Maui Mountain. Because the mountain is cone-shaped, orographic rainfall can be generated by winds from any direction, not only the prevailing northeast tradewinds. The orographic lifting also is enhanced by the deeply incised valleys that funnel air toward the summit (Giambelluca and others, 1986). Thus, lines showing equal annual rainfall have an elliptical shape (fig. 3) radiating from the mountain peak where the mean annual rainfall exceeds 355 in., the second highest recorded rainfall in the State (Giambelluca and others, 1986). Rainfall is abundant along the mountain crest in the study area where mean annual values range from about 60 to 355 in. Rainfall decreases dramatically towards the coast, in the rain shadow (toward the southwest) of the mountain, where the average rainfall is about 15 in/yr along the southern shore of the study area north to Lahaina. Rainfall gradually increases north of Lahaina along the shore to about 40 in/yr near Napili.

Giambelluca and others (1986) prepared twelve maps showing lines of equal mean monthly rainfall for the island of Maui. The maps were compiled from data collected at a network of 18 base stations that had complete records for the base period from 1916 through 1983. Records from an additional 11 stations were used in their statistical analyses. In the analysis of mean annual rainfall the most weight was given to stations with the longest record. Yet some inconsistencies among nearby stations remained. Adjustments were made on the basis of the available data and on knowledge of the rainfall-producing mechanisms. Thus, there is an element of subjectivity incorporated into these maps (Giambelluca and others, 1986). These monthly maps were digitized and constitute the rainfall data set for the GIS model. The value assigned to the area between the lines of equal rainfall is the average value of the bounding lines. Figures 4 and 5 are representative of the wet and dry seasons distribution, respectively. In March rainfall at Lahaina averages 2 in. and in June rainfall averages less than 0.25 in. Although Puu Kukui is always wet, a similar variability occurs, with 32 in. of rainfall in March decreasing to 20 in. in June.

The spatial distribution of rainfall varies from month to month, and most significantly from winter to summer months. These data were used in the study area to calculate mean monthly rainfall volumes that range from a high of 452 Mgal/d in March to a low of 186 Mgal/d in June. Rainfall ranges from about 380 to 452 Mgal/d from November through April and from about 186 to 272 Mgal/d from May through October.

Irrigation

Irrigation water was distributed in the GIS model by the use of a digital land-use map of the pineapple and sugarcane fields produced by the USGS in 1976 at a 1:100,000 scale and updated by a 1982 field map provided by Pioneer Mill Co. on a USGS 1:24,000-scale base. Average values of applied water for various time periods were compiled from Pioneer Mill Co. irrigation data.

Substantial volumes of water are used for plantation agricultural irrigation in the Lahaina District. Perennial flow in the upper reaches of Honokohau and Honolua Streams, in area A, is diverted in the Honokohau Tunnel System to Mahinahina Gulch in area B where the Honokohau Ditch System continues to Kahoma Stream (fig. 2). The average diverted water for 1983–93 to Mahinahina Gulch is 21.93 Mgal/d. Several other tunnel and ditch systems divert perennial flow from other streams in areas B and C to the fields throughout these areas. Ground water developed at

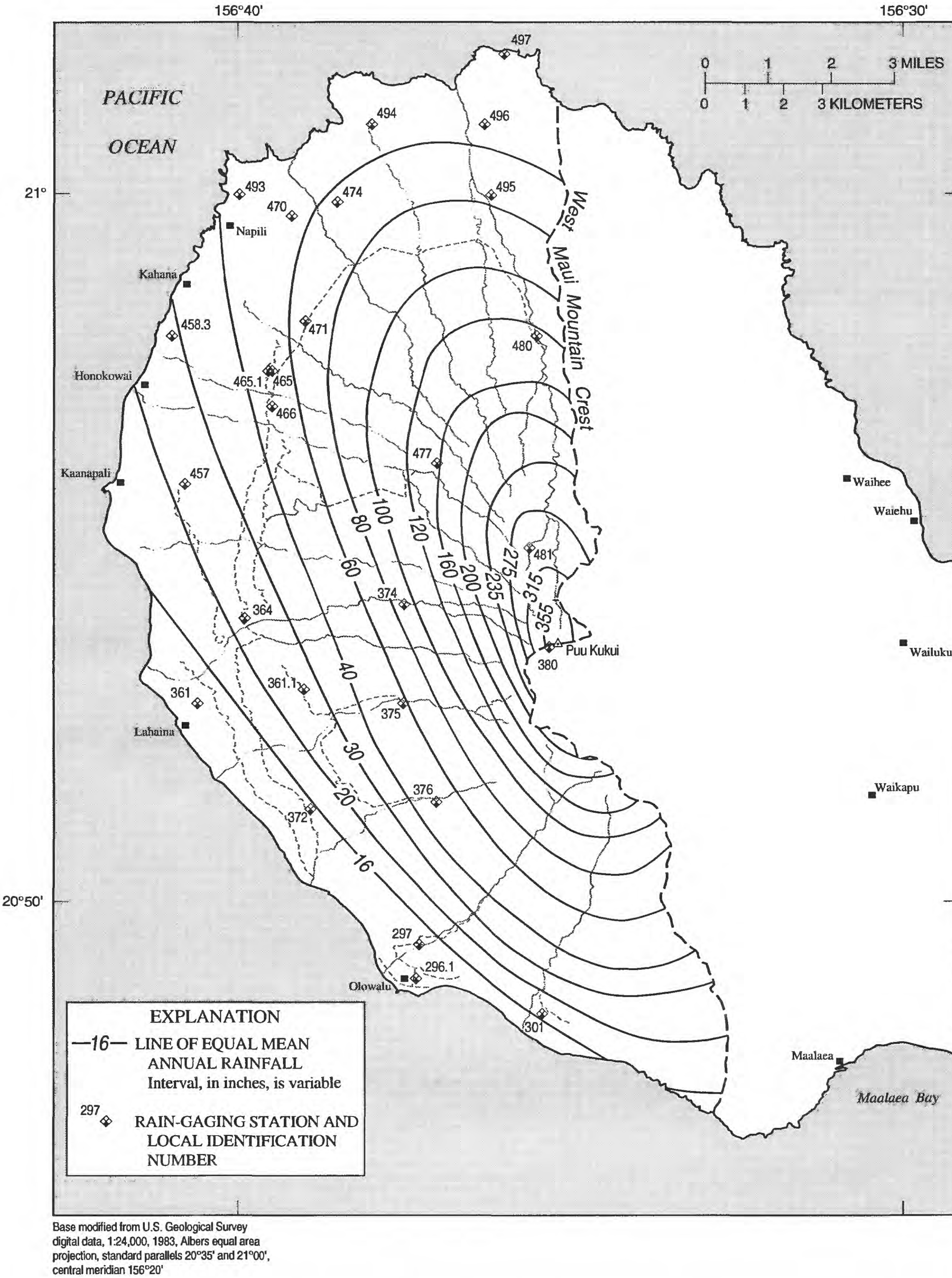
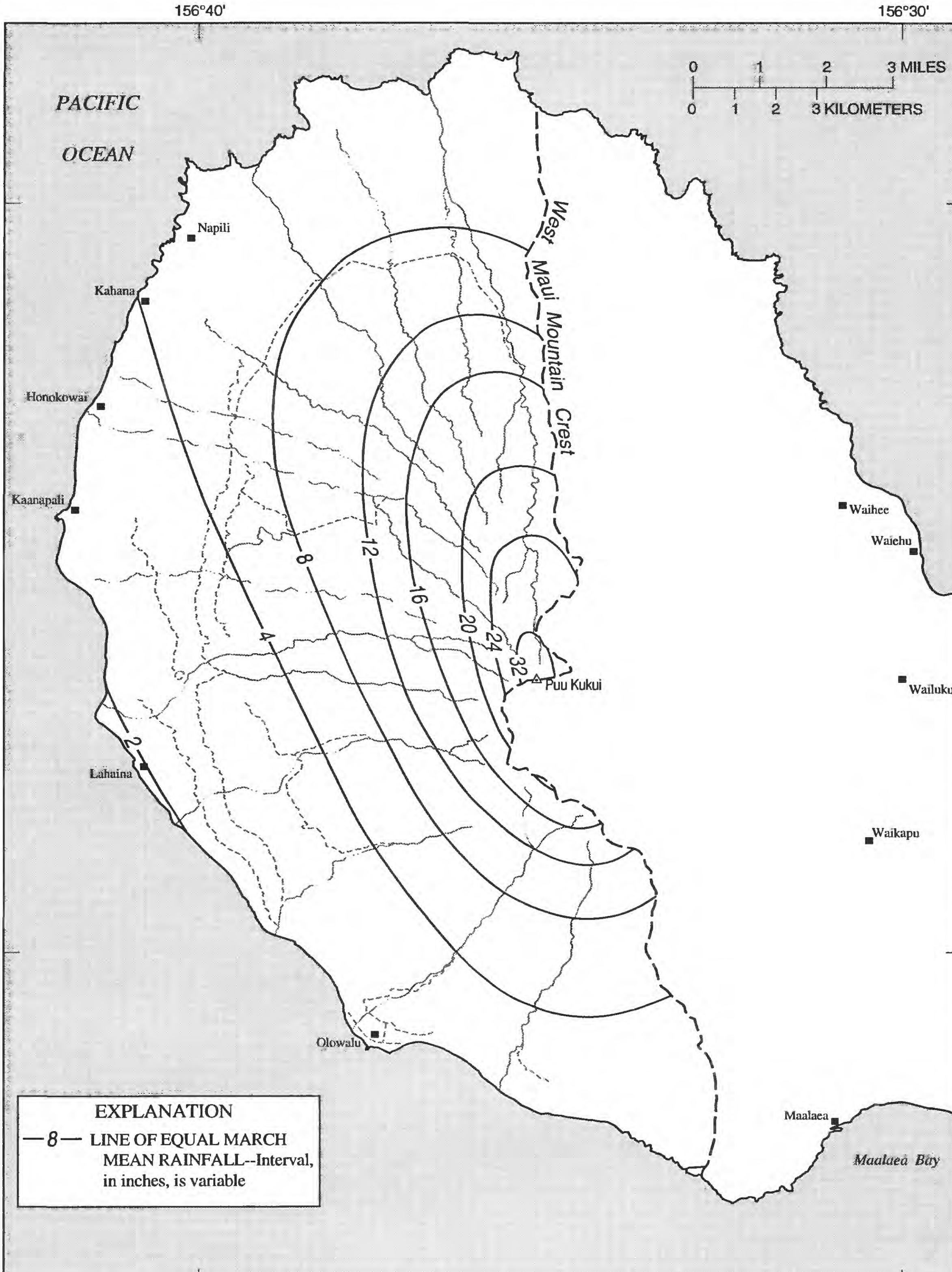


Figure 3. Mean annual rainfall, Lahaina District, Maui, Hawaii (modified from Giambelluca and others, 1986).



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 20°35' and 21°00', central meridian 156°20'

Figure 4. Mean rainfall in March, Lahaina District, Maui, Hawaii (modified from Giambelluca and others, 1986).

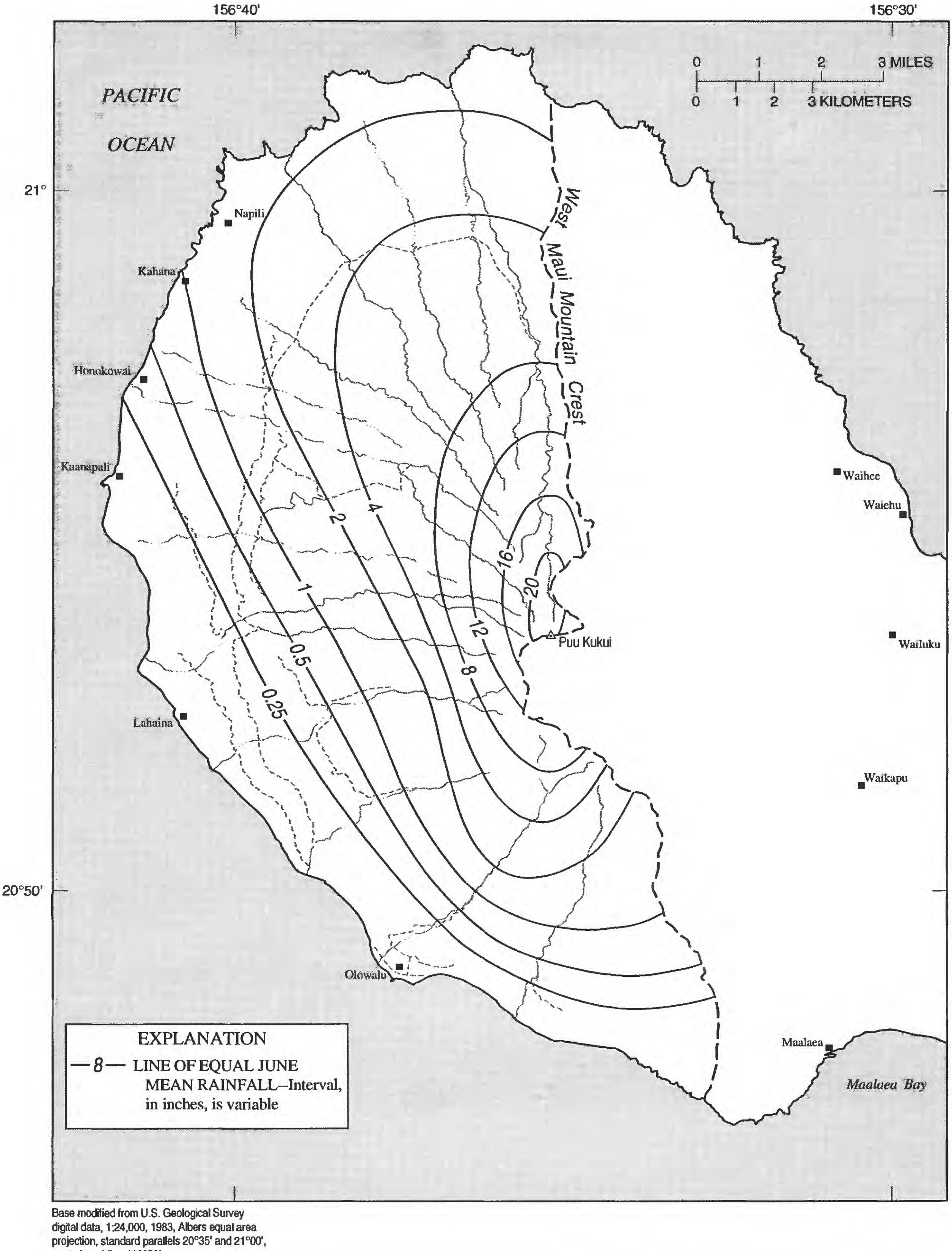


Figure 5. Mean rainfall in June, Lahaina District, Maui, Hawaii (modified from Giambelluca and others, 1986).

wells in areas B and C is used to irrigate fields in those areas. The movement and distribution of large volumes of irrigation water between and within areas have significant effects on the components of evapotranspiration and ground-water recharge in the water budget.

Three scenarios of irrigation patterns were modeled. Scenario I represents the agricultural field distribution and a representative value of applied water, 138 in/yr, for the period from 1923 through 1978 (fig. 6). During this period pineapple was not irrigated and sugarcane acreage was not constant. Hawaii Sugar Planters' Association data indicate total sugarcane acreage, which includes fallow, irrigated, and unirrigated land, of 10,307 acres in 1940 decreasing to 8,599 acres in 1980. The area calculated in the GIS model of 8,779 acres is a representative average irrigated area. The mean annual applied water was calculated as the sum of the mean annual ground-water pumpage for the period and the average surface-water withdrawals for the 1986–93 period, because surface-water withdrawal data for 1923–78 were not available. This sum was distributed monthly on the basis of the 1986–93 period monthly ground-water pumpage distribution (table 1). The estimated mean annual irrigation during 1923–78 is 90 Mgal/d, which distributed over this acreage equals about 138 in/yr of applied water. During this period the plantation used only furrow-irrigation techniques, where large amounts of water are applied so that plants at the end of the rows are irrigated. The estimated applied water, 138 in/yr, is not unusual given the peak water-use rates of mature sugarcane of about 124 in/yr documented by lysimeter studies in central Maui (Campbell and others, 1959).

For scenario II, 1986–93, the area of sugarcane cultivation was decreased to about 7,493 acres in the GIS model (fig. 7). During this time some of the sugarcane fields were converted to pineapple and the sugarcane irrigation method changed from furrow to drip which requires smaller volumes of water applied directly at the base of the plants. About 57 Mgal/d (102 in/yr) was applied to the sugarcane area. Pineapple acreage, about 6,250 acres, was also irrigated in this scenario, however with substantially less water than sugarcane because of the physiology of the plant. Less than 1 Mgal/d (287 Mgal/yr) was applied to the pineapple area, which equates to less than 2 in/yr over the area.

In the natural scenario, scenario III, no irrigation water is applied. This scenario can be used to model the pre-development water budget for natural land-use conditions.

Runoff

Streamflow consists of direct runoff, the water that flows into stream channels promptly after rainfall, and base runoff, the part of streamflow that is sustained through dry weather from discharge of ground water (Langbein and Iseri, 1960). To avoid the inclusion of 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 quantity that occurs at least 95 percent of the time during the chosen month. This procedure yields a lower estimate than standard hydrograph separation analyses of base runoff.

Monthly direct runoff was calculated as a percentage of monthly rainfall on the basis of rainfall and streamflow data representative of each of the upland areas 2, 4, and 5 (fig. 8). One drainage basin within each of the areas was digitized from USGS 1:24,000-scale topographic maps compiled in 1983. Runoff-rainfall ratios were calculated for each of these basins. These monthly ratios were applied to the rainfall distributions over the respective high-level ground-water areas, 2, 4, and 5, to calculate the runoff component of the water budget.

In area 2, the mean monthly streamflow was calculated from 77 to 79 years of data available at stream-gaging station 6200 on Honokohau Stream. Fifteen years of data available at station 6360 on Kanaha Stream were used to calculate mean monthly streamflow from the drainage basin above the station, most of which is within area 4. The base runoff calculated from monthly flow-duration analyses was subtracted from the mean monthly streamflow yielding a direct runoff

Table 1. Monthly applied irrigation water as a percentage of annual withdrawals from ground-water and surface-water sources for sugarcane and pineapple fields, Lahaina District, Maui, Hawaii, 1986–93

Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
.0446	.082	.0717	.0735	.0712	.0971	.101	.1022	.116	.1394	.0703	.031

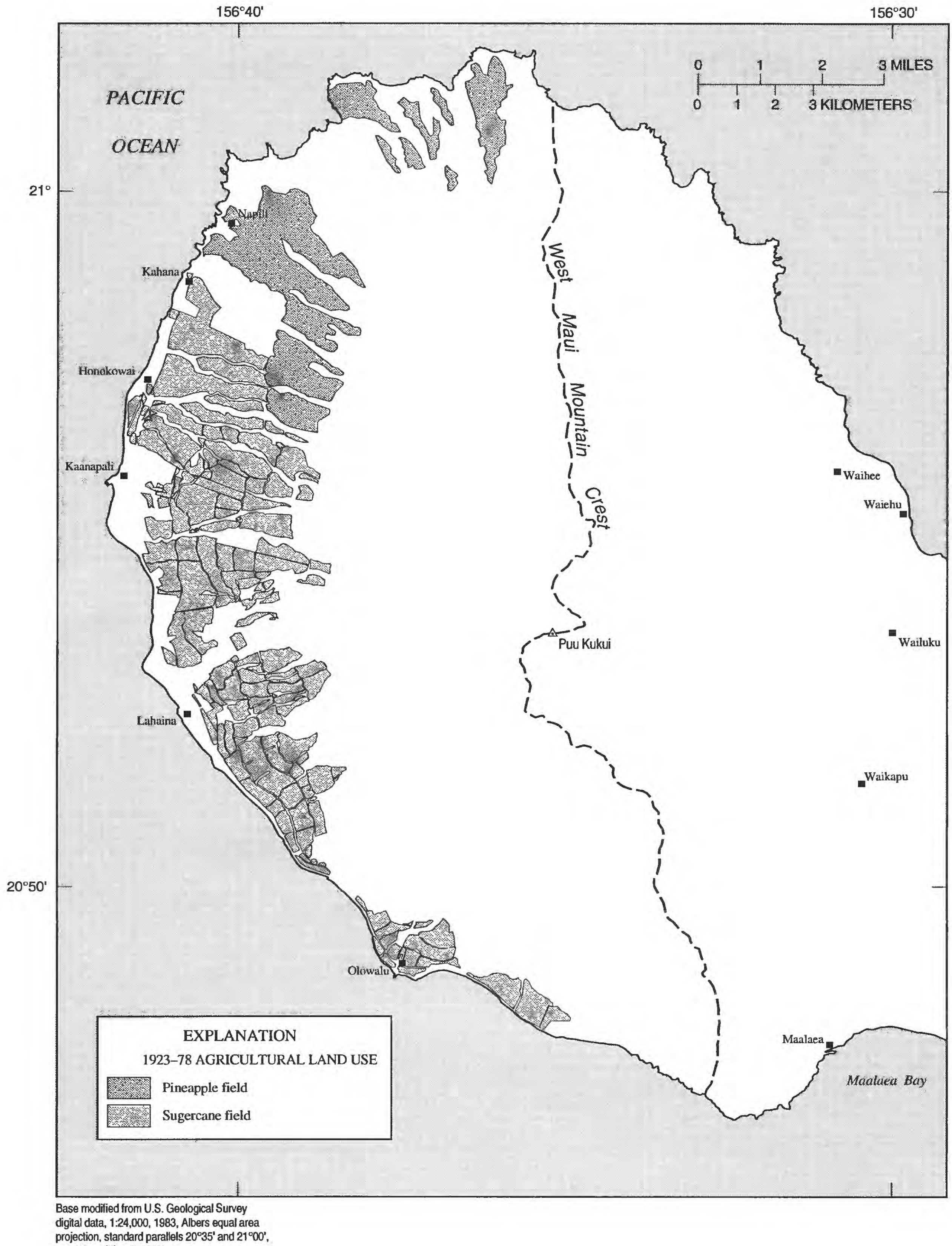


Figure 6. Agricultural land use, 1923–78, Lahaina District, Maui, Hawaii.

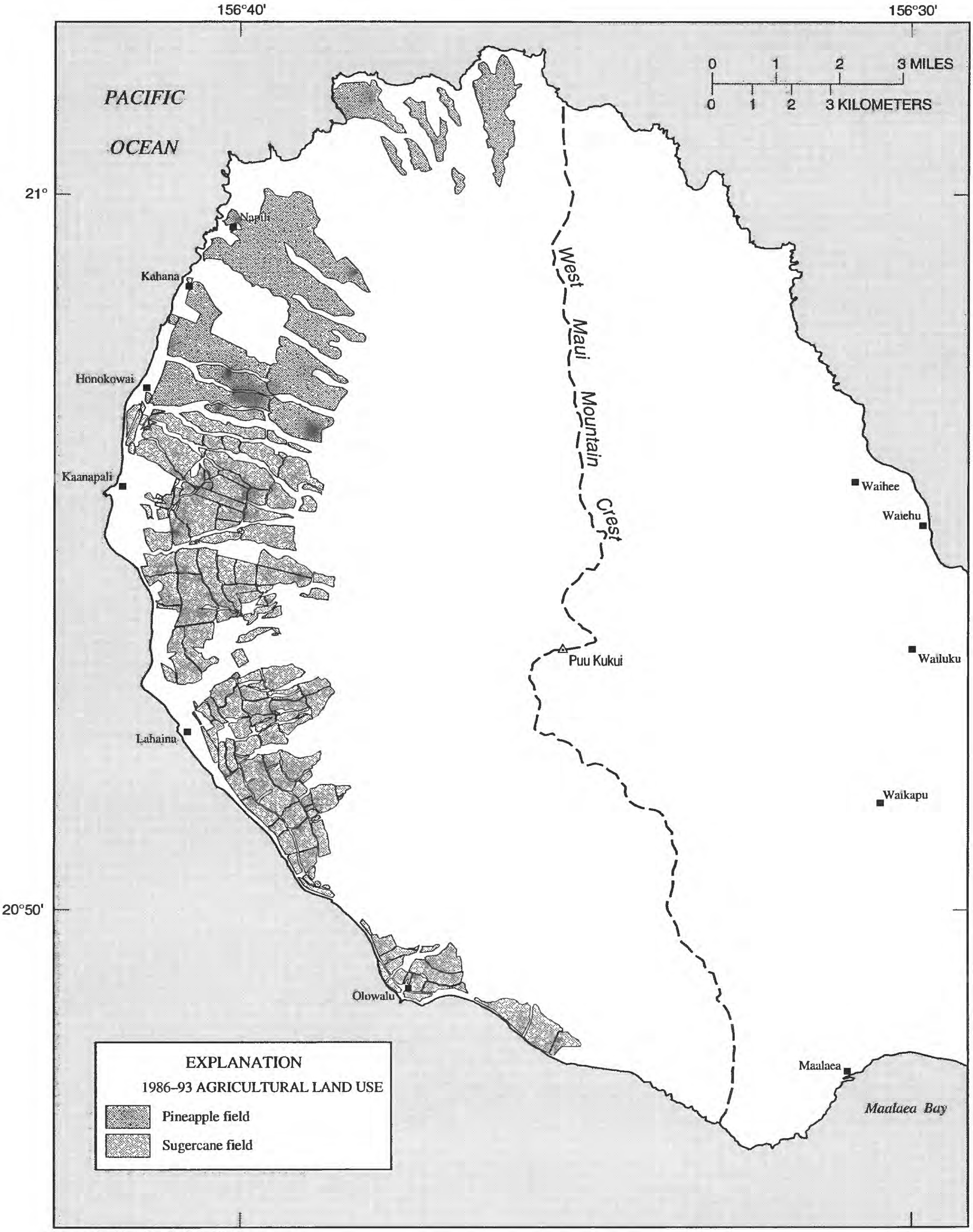


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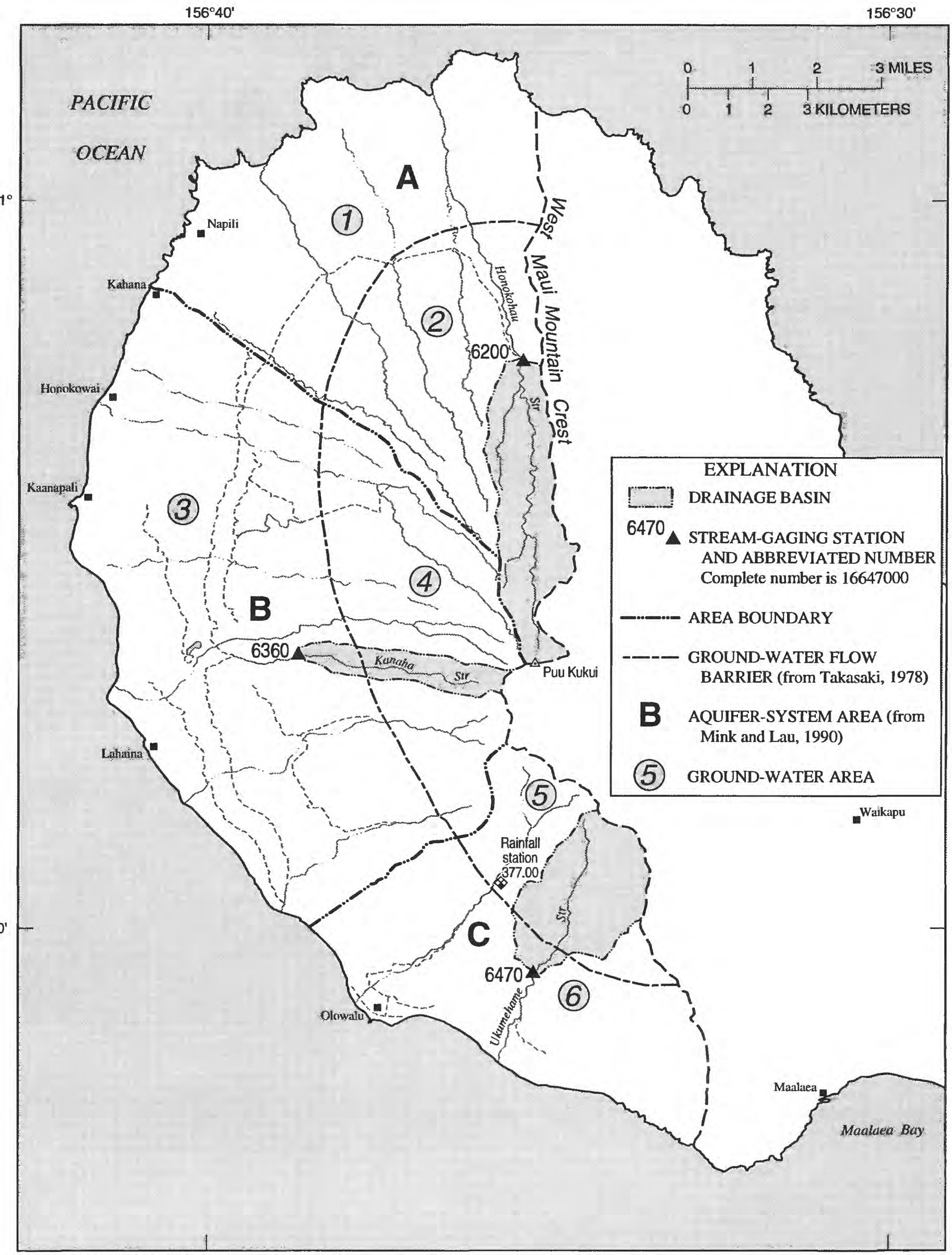
Figure 7. Agricultural land use, 1986–93, Lahaina District, Maui, Hawaii.



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 20°35' and 21°00', central meridian 156°20'

Figure 8. Drainage basins and stream-gaging stations used in the water-budget model, Lahaina District, Maui, Hawaii.

value for each month. The Honokohau and Kanaha Stream basins were digitized and mean monthly rainfall volumes for the basins were calculated using the GIS model. Monthly direct runoff-rainfall ratios for the basins could then be calculated, and these ratios (table 2) were applied to the mean monthly rainfall distribution in the respective areas to compute the monthly runoff component of the water budget.

Because of a limited length of record (7 years) available at stream-gaging station 6470 on Ukumehame Stream, a slight modification of the above procedure was made to calculate direct runoff-rainfall ratios for this drainage basin. Because most of this basin is within area 5, the direct runoff-rainfall ratios are representative of this area. Instead of comparing short-term runoff means with long-term rainfall means, rainfall data at station 377.00 (fig. 8) for the corresponding years of streamflow data were used to calculate the direct runoff-rainfall ratios. The ratios (table 2) were applied to the mean monthly rainfall distribution in area 5 to compute the area's direct runoff.

For areas 1, 3, and 6 there are no streamflow data available representative of the runoff generated from within these boundaries. Therefore, a second procedure was followed to calculate direct runoff/rainfall ratios on the basis of soil type and rainfall.

Rainfall in these areas decreases from about 93 in/yr at the higher altitudes to about 15 in/yr at some locations along the coast. The runoff/rainfall ratios were developed for three ranges of annual rainfall: from less than 94 to 70 in/yr, from less than 70 to 40 in/yr, and for less than 40 in/yr.

Runoff characteristics of soils in this area are described by Foote and others (1972). On the basis of soil texture, permeability, and slope, soil types have a runoff rating of slow, medium, or rapid. From results of a water balance computed for the Pearl Harbor area of Oahu (Giambelluca, 1983), comparable areas on Oahu were chosen with similar mean annual rainfall, land use, and soil properties as those of areas 1, 3, and 6. The Oahu data provided average annual runoff-rainfall ratios for each soil runoff rating within each rainfall range (table 2). The ratios were applied to the sum of the monthly rainfall values in the Lahaina area, thus providing annual runoff values. These annual runoff values were distributed monthly on the basis of the monthly rainfall to annual rainfall ratios.

Actual Evapotranspiration and Soil-Moisture Accounting

Actual evapotranspiration (AE) is the quantity of water evaporated from water and soil surfaces and transpired by plants. Actual evapotranspiration data from direct field measurements do not exist for the Lahaina District; however, it is possible to estimate actual evapotranspiration from pan evaporation and soil data.

Pan evaporation data from class-A evaporating pans provide an estimate of the potential (maximum) evapotranspiration (PE). For this study, pan evaporation is assumed to equal potential evapotranspiration on the basis of the results of lysimeter studies in sugarcane fields (Chang, 1968; Campbell and others, 1959) where the average ratio between potential evapotranspiration

Table 2. Direct runoff-rainfall ratios for monthly and annual rainfall, Lahaina District, Maui, and Pearl Harbor, Oahu, Hawaii
[Values in percent; in/yr, inches per year; see figure 2 for areas]

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Monthly direct runoff/rainfall ratios for Lahaina area 2											
33	36	31	39	44	39	39	41	33	37	39	37
Monthly direct runoff/rainfall ratios for Lahaina area 4											
33	31	33	41	30	40	44	45	34	27	36	43
Monthly direct runoff/rainfall ratios for Lahaina area 5											
52	50	35	41	37	33	51	64	49	56	23	35

Annual direct runoff / annual rainfall ratios (in percent) for Lahaina areas 1, 3, and 6			
Soil Runoff	**Rain > 70 < 94 in/yr**	**Rain > 40 < 70 in/yr**	**Rain < 40 in/yr**
Rapid	17	13	11
Medium	12	12	11
Slow	12	12	7

and pan evaporation was about 1.0. The map of mean annual pan evaporation for Maui (Ekern and Chang, 1985) is shown in figure 9 and was digitized for the GIS water-budget model of the study area. The average of the values of the bounding lines of equal pan evaporation was assigned to the area between the two lines. For the closed area the value within the area was set equal to the value of the bounding line (90 in.). Data were not available for the area towards the mountain crest above the 70-in. line. Although it is presumed pan evaporation decreases to lower values with increased rainfall at the mountain crest, pan values were set at 70 in. for the area.

Since the early 1900's, 13 pan evaporation stations have been established by sugarcane growers in the study area (fig. 9), although some have since been discontinued. There is a distinct range in the mean annual pan evaporation moving inland and upslope from the coast. Values are about 90 in/yr at the coast and decrease in the mountains to less than 70 in/yr because of increased cloud cover and rainfall and lower temperatures. Setting the value in this area to 70 in/yr likely overestimates pan evaporation in this area. Other pan evaporation stations outside of the study area aid in estimating the location of lines of equal pan evaporation in the study area where no stations are located.

The monthly potential evapotranspiration distributions in the study area were calculated by multiplying the annual pan evaporation value shown in figure 9 by the monthly to annual pan evaporation ratios shown in table 3. These ratios were estimated from 7 to 9 years of monthly data at station 363.10 (Ekern and Chang, 1985). The ratios agree with the inverse relation between pan evaporation and rainfall, decreasing in the wet winter months and increasing in the dry summer months.

The potential evapotranspiration demand in a particular month can not always be met by the amount of water in soil storage. In such cases actual evapotranspiration is less than potential evapotranspiration. To estimate actual evapotranspiration, the maximum soil-moisture storage capacity was calculated for each of the generalized soil groups in the study area. The soils have been mapped and digitized and their characteristics tabulated by the Natural Resources Conservation Service (Foote and others, 1972) (table 4). Values for the soil characteristics of available water capacity, a measure of the quantity of water held by the soil available to plants between field capacity and wilting point, the rooting depth, and general runoff characteristics presented by Foote and others (1972) were entered into attribute data tables associated with the digital soil data. Maximum soil-moisture storage (SS_{max}) values were calculated as the product of available water capacity and rooting depth. A digital map (fig. 10) of the distribution of maximum soil-moisture storage was created to use in the GIS model.

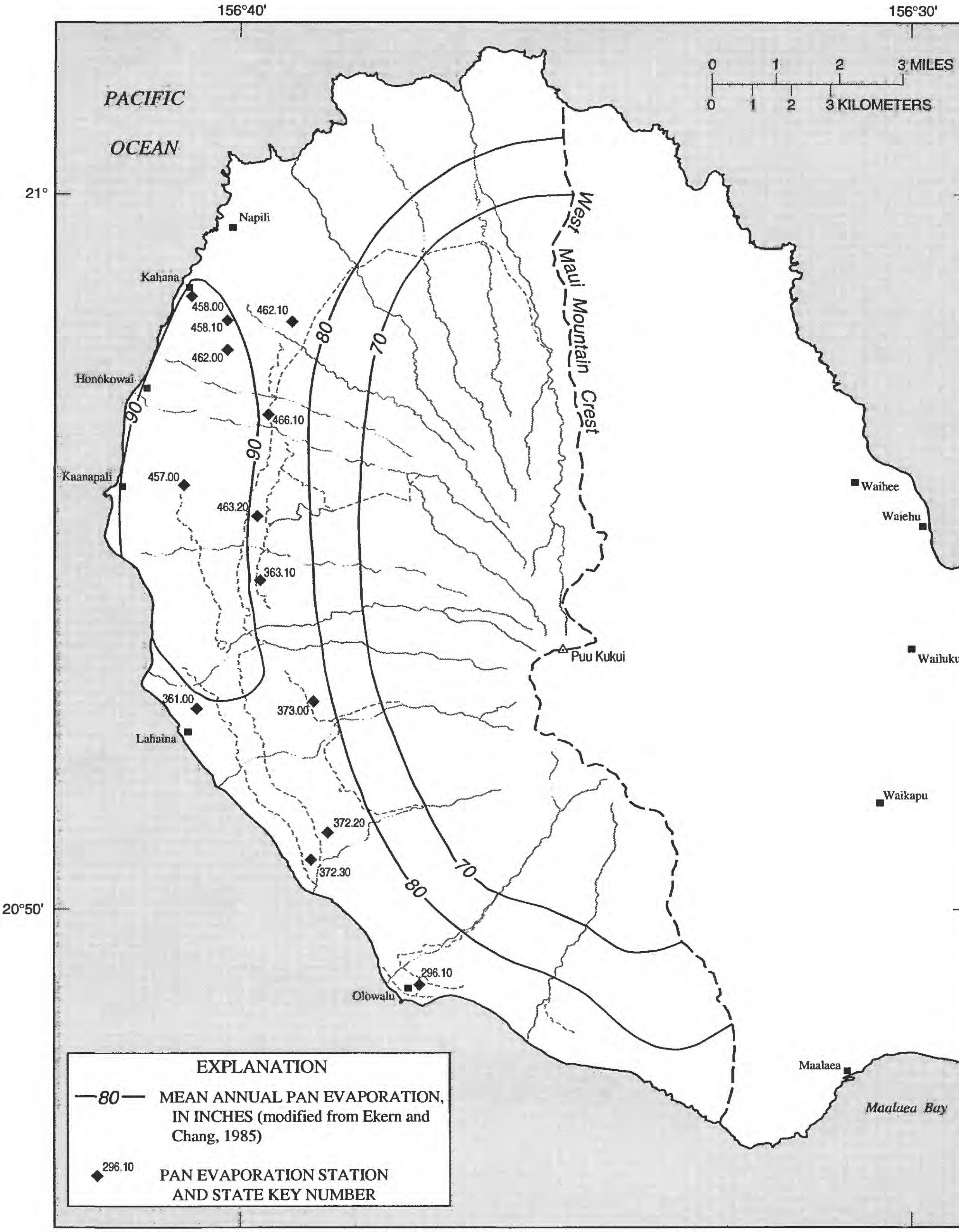
Data that were not available from Foote and others (1972) were provided by the Natural Resources Conservation Service (Saku Nakamura, oral commun., 1995). The available-water value for each soil group in table 4 is the average of the range reported by Foote and others (1972). The rooting depth was assumed to be at the depth where the soil-profile description changed from "abundant roots" or "common roots" to "few roots" or "no roots."

SS_{max} is the product of the rooting depth and the available water capacity for the soil type (fig. 10 and table 4). The SS_{max} value is important in the water budget because it is the limit above which ground-water recharge occurs and is a determining factor in the calculation of the evapotranspiration rate. A modification was made to the GIS model in sugarcane areas only. To simulate more accurately the high evapotranspiration demand of sugarcane and the continuous soil wetting from irrigation, SS_{max} was set equal to the monthly pan evaporation value. This change in the model creates the ability for evapotranspiration to occur at the maximum (pan) rate if water is available.

The amount of water held in the soil changes from month to month calculated by a bookkeeping procedure. The water-budget model is initialized by beginning the month of January with three soil-moisture storage values: SS_{max}, half of SS_{max}, and zero. The resulting soil-moisture storage values at the end of

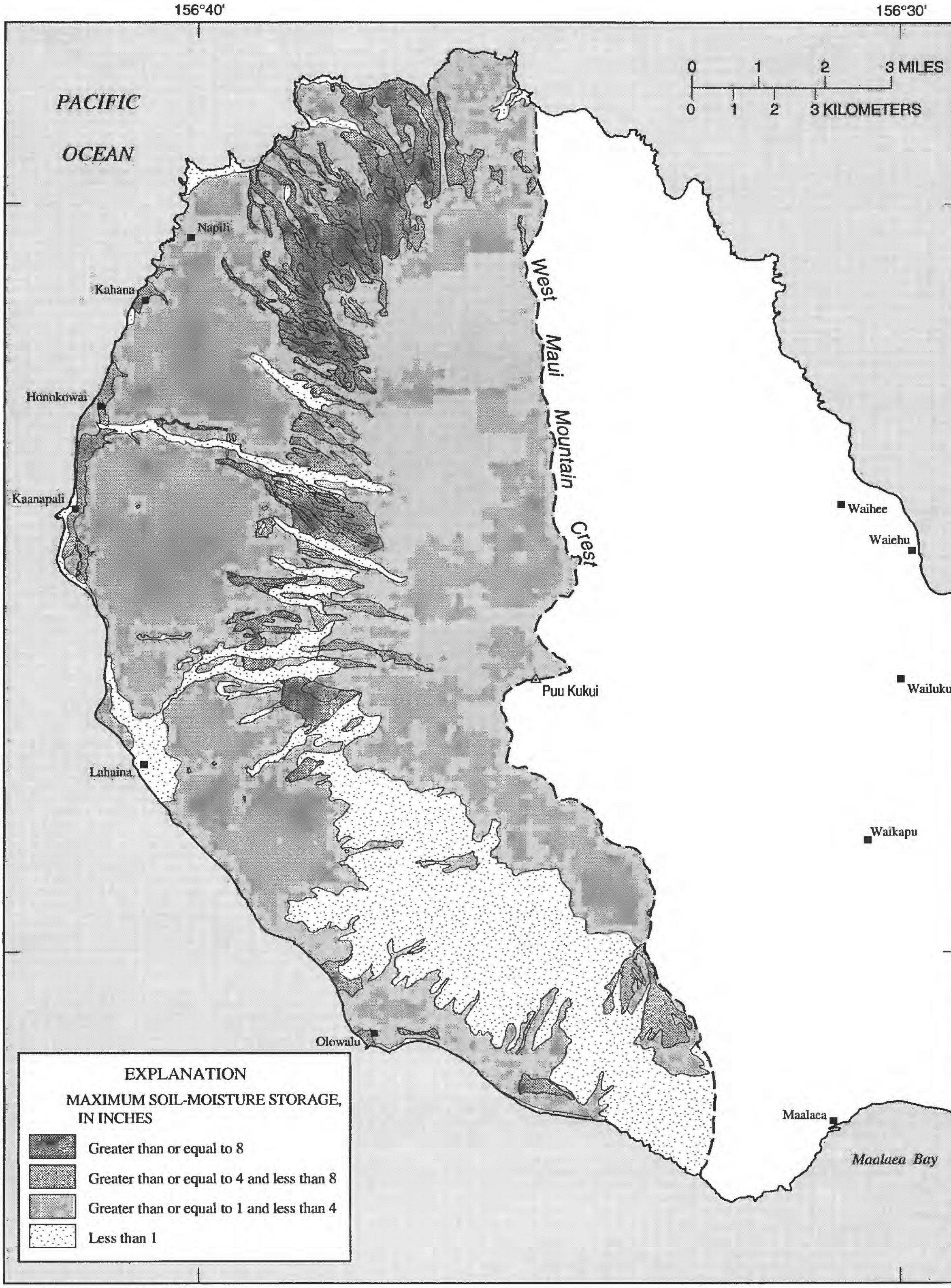
Table 3. Monthly to annual pan evaporation ratios, in percent, from station 363.10 (from Ekern and Chang, 1985), Lahaina District, Maui, Hawaii

Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
.07	.07	.08	.08	.1	.094	.1	.1	.09	.08	.073	.063



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 20°35' and 21°00', central meridian 156°20'

Figure 9. Mean annual pan evaporation, Lahaina District, Maui, Hawaii.



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 20°35' and 21°00', central meridian 156°20'

Figure 10. Maximum soil-moisture storage, Lahaina District, Maui, Hawaii.

December were identical for these three model runs. Thus the December values were input for the initial soil-moisture storage in January for the final water-budget calculation. January runoff is subtracted from the sum of the initial January soil-moisture storage and January rainfall. The remainder is added to soil-moisture storage, and if this quantity exceeds SS_{max}, the excess recharges ground-water. Evapotranspiration is subtracted from soil-moisture storage at either the potential (maximum) evapotranspiration rate or at some lesser actual evapotranspiration rate depending on the quantity of water in soil-moisture storage available to meet the demand. Any water remaining in soil-moisture storage is carried over to the next month. This bookkeeping procedure is shown in the following equations.

$$SS_{Jan} + P_{Jan} - R_{Jan} = X_1 \tag{2}$$

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 $X_1 \leq SS_{max}$, then $G = 0$ and $X_1 = X_2$. (3)

where:

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

If $X_2 \geq PE$, 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 which becomes the beginning February soil-moisture storage.

The bookkeeping process provides a running account of month-to-month moisture stored in the soil

Table 4. Average soil characteristics, Lahaina District, Maui, Hawaii (from Foote and others, 1972; Saku Nakamura, Natural Resources Conservation Service, oral commun., 1995)

Soil series	Available-water capacity (inch per inch of soil)	Root depth (inches)	Maximum soil-moisture storage (inches)
Alaeloa	0.13	29	3.77
Beaches and dune land	0.035	6	0.21
Cinder land	0.03	36	1.08
Ewa	0.11	60	6.60
Honolua	0.13	36	4.68
Hydrandepts-Tropaquods	0.17	10	1.70
Jaucas	0.06	13	0.78
Kahana	0.11	22	2.42
Kealia	0.10	27	2.70
Lahaina	0.11	31	3.41
Molokai	0.12	15	1.80
Naiwa	0.10	52	5.20
Olelo	0.11	37	4.07
Oli	0.13	30	3.90
Pulehu	0.14	33	4.62
Rock land	0.14	4	0.56
Rock outcrop	0.04	0.60	0.02
Rough broken land	0.15	54	8.10
Rough stony land	0.15	18	2.70
Stony alluvial land	0.06	50	3.00
Wahikuli	0.13	27	3.51
Wainee	0.06	36	2.16

root area from which evapotranspiration occurs. By identifying the soil's moisture-holding capacity, and applying the water-budget bookkeeping procedure, water surplus and water deficit can be calculated. In this report, water surplus is equated to ground-water recharge; hence, recharge occurs when maximum soil-moisture storage is exceeded. A water deficit occurs when soil-moisture storage is less than full and insufficient to meet the potential (maximum) evapotranspiration demand.

Ground-Water Recharge

The mean annual distribution of ground-water recharge for 1986–93 conditions, scenario II, (fig. 11) in the Lahaina District is somewhat similar to the distribution of rainfall (fig. 3). Ground-water recharge ranges from less than 1 in/yr at some locations along the coast and increases towards the West Maui Mountain crest to more than 185 in/yr near Puu Kukui. The distinct effect of irrigation on ground-water recharge is apparent where irrigated areas have recharge as much as 5 to 10 times more than that of nearby areas. Recharge during the winter months is about twice that during the summer months (table 5). From November through April, recharge ranges from 191 Mgal/d in February to a high of 259 Mgal/d in March. During the summer months recharge ranges from a low of 82 Mgal/d in June to a high of 117 Mgal/d in October. The mean recharge for the Lahaina District for 1986–93 conditions is 163 Mgal/d.

During 1923–78 (scenario I, table 5 and fig. 12), the estimated applied irrigation was about 30 Mgal/d more than in the 1986–93 conditions scenario. Most of this additional 30 Mgal/d appears as an increase in recharge, shown by the mean of 190 Mgal/d. Recharge increased substantially compared with 1986–93 conditions inland from Lahaina to north of Kaanapali near the coast (fig. 12).

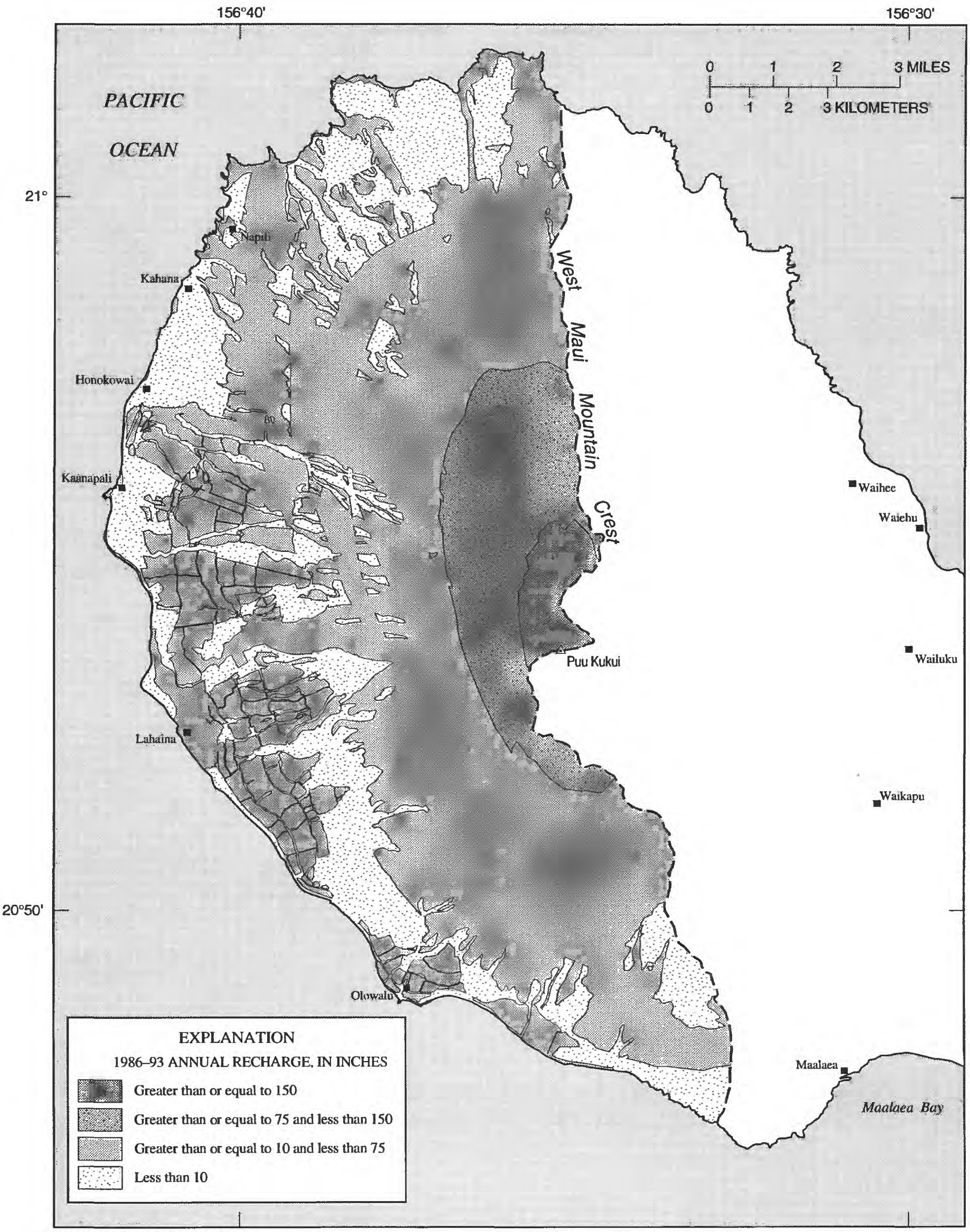
For natural conditions scenario III, applied irrigation was eliminated and the mean ground-water recharge decreased to 145 Mgal/d (table 5). The recharge distribution in areas that were never irrigated is identical for the three scenarios (fig. 13). However, a comparison of the recharge distributions in areas that previously were irrigated shows recharge decreasing in some places inland of Kaanapali, Honokawai, and Kahana to less than 10 in/yr (fig. 13) where once it had been more than 75 in/yr (fig. 12).

In the high-level ground-water area there is no difference in the water-budget component values for the three scenarios (table 6) because there was no applied irrigation water during the 1923–78 scenario and the

Table 5. Mean monthly water budget for three land-use scenarios in the Lahaina District, Maui, Hawaii

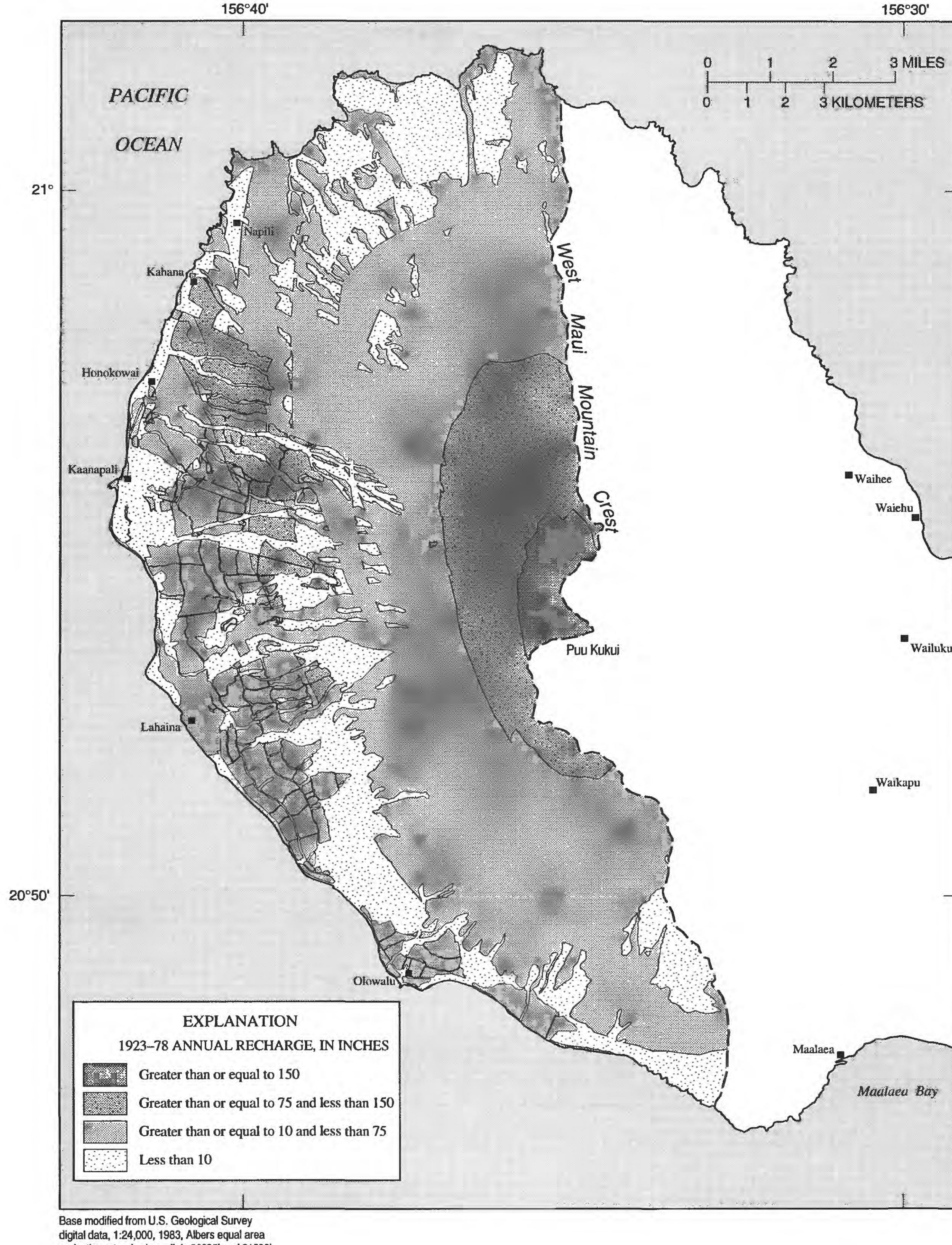
[Values in million gallons per day; I, 1923–78 scenario; II, 1986–93 scenario; III, natural scenario. The sum of rainfall and irrigation minus direct runoff, actual evapotranspiration, and recharge may not equal zero because of rounding. The mean is calculated as the sum of monthly values divided by 12.]

Water-budget component	Scenario	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
Rainfall	I	435	381	452	406	253	186	270	272	224	248	387	447	330
	II	435	381	452	406	253	186	270	272	224	248	387	447	330
	III	435	381	452	406	253	186	270	272	224	248	387	447	330
Irrigation	I	70	88	84	85	86	106	96	98	100	111	88	68	90
	II	53	53	57	56	59	68	58	59	54	58	60	56	58
	III	0	0	0	0	0	0	0	0	0	0	0	0	0
Direct runoff	I	112	101	111	124	79	60	94	101	66	70	102	123	95
	II	112	101	111	124	79	60	94	101	66	70	102	123	95
	III	112	101	111	124	79	60	94	101	66	70	102	123	95
Actual evapotranspiration	I	139	146	145	143	135	120	133	136	126	125	140	133	135
	II	135	143	140	138	127	112	125	127	119	120	136	130	129
	III	112	115	111	102	73	59	71	74	69	81	106	111	90
Recharge	I	255	222	282	224	128	112	139	134	131	165	231	257	190
	II	241	191	259	200	109	82	109	103	93	117	207	248	163
	III	212	166	232	180	103	68	106	98	89	98	177	211	145



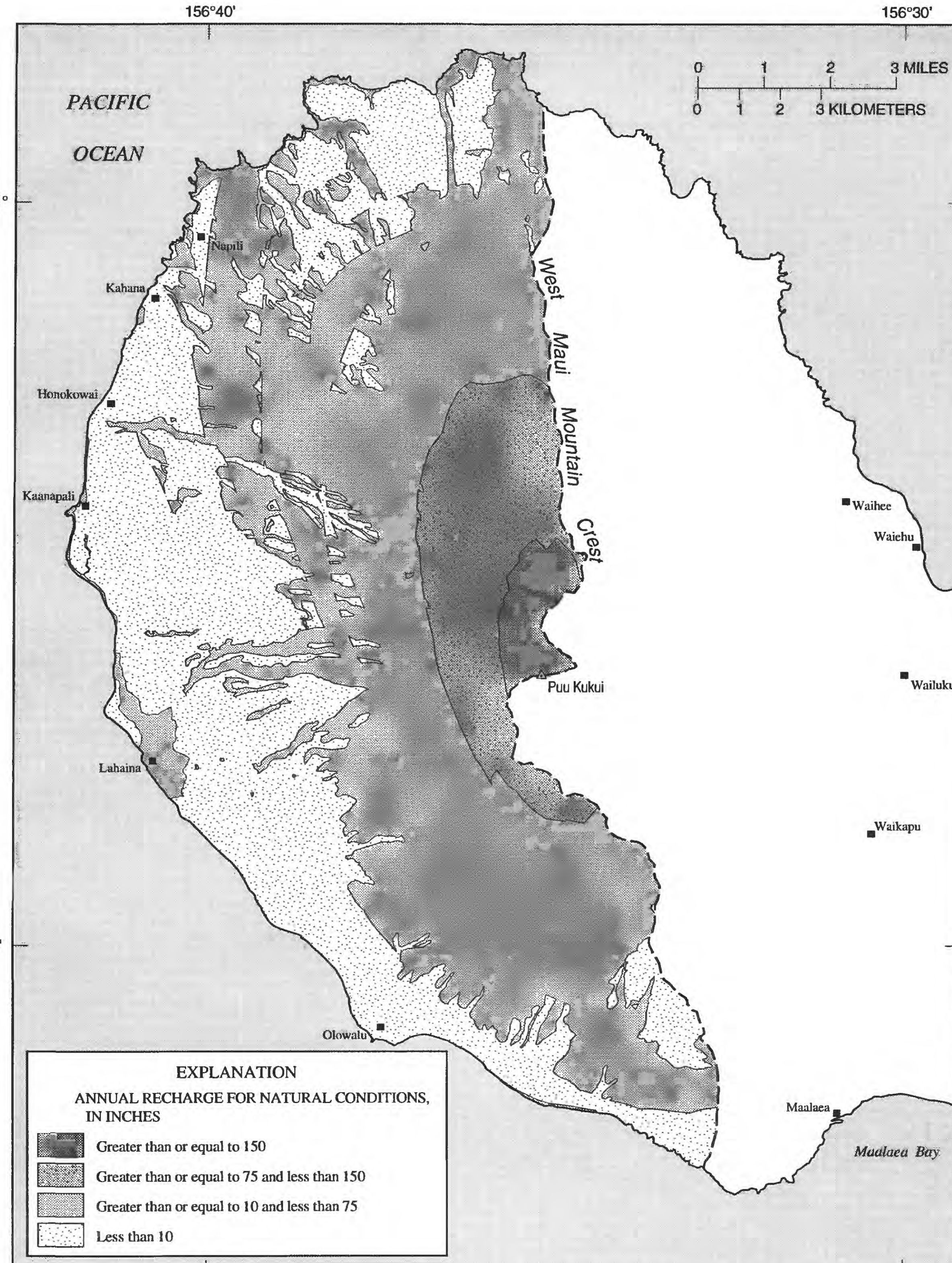
Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 20°35' and 21°00', central meridian 156°20'

Figure 11. Annual ground-water recharge, 1986–93, Lahaina District, Maui, Hawaii.



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 20°35' and 21°00', central meridian 156°20'

Figure 12. Annual ground-water recharge, 1923–78, Lahaina District, Maui, Hawaii.



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 20°35' and 21°00', central meridian 156°20'

Figure 13. Annual ground-water recharge for natural conditions, Lahaina District, Maui, Hawaii.

natural scenario, and very little during the 1986–93 conditions scenario. The seasonal distribution of ground-water recharge in this area is similar to the distribution for the entire Lahaina District. During the summer months recharge is about half of the winter recharge with a low of 59 Mgal/d in June to a high of 88 Mgal/d in May and July. Ground-water recharge increases substantially during the winter months from a low of 117 Mgal/d in February to a high of 166 Mgal/d in March. The mean recharge for the high-level ground-water area is 106 Mgal/d.

WATER-BUDGET RESULTS

The water budgets for the three scenarios for the Lahaina District and its sub-areas show distinct variations in rainfall, runoff, evapotranspiration, and ground-water recharge through the months and among the scenarios and areas (tables 7 through 12). The effect of irrigation was most significant in area B. During 1923–78 when irrigation was at the maximum, annual evapotranspiration and ground-water recharge values were about twice what they are estimated to be in the natural scenario with no irrigation (tables 8 and 9). Similarly, the strongest seasonality in evapotranspiration and recharge is in the most heavily irrigated areas B and C during 1986–93 conditions (table 10). In area B, the percentage of water (rainfall and irrigation) in the system that is distributed as evapotranspiration reaches a high of 54 percent in June and a low of 30 percent in December. In area C, the evapotranspiration to applied water (rainfall and irrigation) ratio reaches a high of 38 percent in June and a low of 17 percent in January. The related converse distribution of recharge shows the highest ratios in the winter months of January at 50 percent in area B and in November at 64 percent in area C. The lowest recharge ratio, 26 percent, occurs during the summer, in August for both areas B and C. In area A where there was much less irrigation for pineapple, seasonality in the water-budget components is similar, but less striking.

Table 11 summarizes the relations between the water-budget components for the entire Lahaina District. District-wide, the effect of irrigation appears slight with a 6 point increase in the runoff ratio, a 5 point decrease in the actual evapotranspiration ratio and a 1 point decrease in the recharge ratio between the high-

Table 6. Mean monthly water budget for all land-use scenarios in the high-level ground-water areas of the Lahaina District, Maui, Hawaii

[Values in million gallons per day; see figure 2 for areas. The difference of rainfall minus direct runoff, actual evapotranspiration, and recharge may not equal zero because of rounding. The mean is calculated as the sum of monthly values divided by 12.]

Water-budget component	Aquifer-system area	Ground-water area	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
Rainfall	A	2	112	109	146	141	95	75	97	99	77	84	117	126	107
	B	4	90	88	104	91	68	51	78	71	63	60	83	97	79
	C	5	46	35	38	37	23	14	26	30	25	23	41	38	31
Direct runoff	A	2	37	39	45	55	42	29	38	41	25	31	46	47	40
	B	4	30	27	34	37	20	20	34	32	21	16	30	42	29
	C	5	24	18	13	15	9	5	13	19	12	13	10	13	14
Actual evapotranspiration	A	2	13	14	13	14	13	13	13	13	13	13	13	13	13
	B	4	12	13	12	12	11	10	11	11	12	11	12	12	12
	C	5	4	4	4	4	3	3	3	3	3	3	4	4	4
Recharge	A	2	62	55	88	73	40	33	47	46	38	40	58	66	54
	B	4	49	48	58	42	36	20	33	28	30	32	41	44	38
	C	5	18	14	21	18	11	7	9	8	9	7	28	21	14
Total for high-level ground-water areas															
Rainfall			249	232	288	270	186	140	201	200	165	167	241	261	217
Direct runoff			91	84	93	108	71	54	85	92	59	60	85	102	82
Actual evapotranspiration			29	31	29	30	28	27	27	27	28	28	30	29	28
Recharge			130	117	166	132	88	59	88	81	77	79	126	131	106

Table 7. Mean monthly water budget for 1986–93 conditions (scenario II) in the three aquifer- system areas of the Lahaina District, Maui, Hawaii

[Values in million gallons per day; see figure 2 for areas. The sum of rainfall and irrigation minus direct runoff, actual evapotranspiration, and recharge may not equal zero because of rounding. The mean is calculated as the sum of monthly values divided by 12.]

Water-budget component	Aquifer-system area	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
Rainfall	A	174	166	208	206	131	102	138	141	108	124	180	193	156
	B	179	158	180	146	92	66	101	97	86	92	144	187	127
	C	82	57	65	54	29	18	30	35	30	32	62	68	47
Irrigation	A	.26	.29	.30	.54	.71	.61	.78	.52	.73	.78	.58	.30	.53
	B	46	46	50	49	52	59	50	51	47	50	53	49	50
	C	6	6	7	7	7	8	7	7	6	7	7	7	7
Direct runoff	A	45	46	53	63	46	33	43	46	29	36	54	55	46
	B	39	35	42	43	23	22	37	35	24	20	36	51	34
	C	28	20	16	17	9	5	14	20	13	14	12	16	15
Actual evapo-transpiration	A	46	49	47	48	41	34	41	42	38	41	48	46	43
	B	75	79	78	76	74	68	73	74	70	67	74	71	73
	C	15	15	15	14	12	10	11	11	11	11	14	14	13
Recharge	A	84	71	109	94	46	36	54	53	42	48	77	91	67
	B	112	91	110	76	47	35	42	39	39	56	86	113	71
	C	45	29	40	30	15	11	13	11	12	13	44	44	26

Table 8. Mean monthly water budget for 1923–78 conditions (scenario I) in the three aquifer-system areas of the Lahaina District, Maui, Hawaii

[Values in million gallons per day; see figure 2 for areas. The sum of rainfall and irrigation minus direct runoff, actual evapotranspiration, and recharge may not equal zero because of rounding. The mean is calculated as the sum of monthly values divided by 12.]

Water-budget component	Aquifer-system area	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
Rainfall	A	174	166	208	206	131	102	138	141	108	124	180	193	156
	B	179	158	180	146	92	66	101	97	86	92	144	187	127
	C	82	57	65	54	29	18	30	35	30	32	62	68	47
Irrigation	A	0	0	0	0	0	0	0	0	0	0	0	0	0
	B	62	79	76	76	77	95	86	88	89	100	79	61	81
	C	7	9	9	9	9	11	10	10	10	11	9	7	9
Direct runoff	A	45	46	53	63	46	33	43	46	29	36	54	55	46
	B	39	35	42	43	23	22	37	35	24	20	36	51	34
	C	28	20	16	17	9	5	14	20	13	14	12	16	15
Actual evapo-transpiration	A	46	49	47	48	40	34	41	42	37	41	48	46	43
	B	78	82	83	81	83	76	81	83	78	73	79	73	79
	C	15	15	15	14	12	10	11	11	11	11	14	14	13
Recharge	A	84	71	109	94	46	36	54	53	42	47	77	91	67
	B	125	120	131	98	65	63	69	67	73	99	108	122	95
	C	46	32	42	32	17	14	16	14	16	18	45	44	28

Table 9. Mean monthly water budget for natural conditions (scenario III) in the three aquifer-system areas of the Lahaina District, Maui, Hawaii

[Values in million gallons per day; see figure 2 for areas. The difference of rainfall minus direct runoff, actual evapotranspiration, and recharge may not equal zero because of rounding. The mean is calculated as the sum of monthly values divided by 12.]

Water-budget component	Aquifer-system area	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
Rainfall	A	174	166	208	206	131	102	138	141	108	124	180	193	156
	B	179	158	180	146	92	66	101	97	86	92	144	187	127
	C	82	57	65	54	29	18	30	35	30	32	62	68	47
Direct runoff	A	45	46	53	63	46	33	43	46	29	36	54	55	46
	B	39	35	42	43	23	22	37	35	24	20	36	51	34
	C	28	20	16	17	9	5	14	20	13	14	12	16	15
Actual evapo-transpiration	A	46	49	47	48	40	34	41	42	37	41	48	46	43
	B	54	54	52	44	28	21	25	28	27	34	49	53	39
	C	13	11	12	9	5	4	4	5	5	6	10	12	8
Recharge	A	84	71	109	94	46	36	54	53	42	47	77	91	67
	B	86	69	86	59	42	23	39	34	35	39	59	81	54
	C	42	26	37	28	15	9	13	10	12	11	40	39	24

Table 10. Monthly water-budget ratios for 1986–93 conditions, Lahaina District, Maui, Hawaii

[Values in percent; see figure 2 for areas; ratios were calculated, from data in table 7, by dividing the mean values of runoff, for example, by the sum of the mean rainfall and mean irrigation; sum of monthly ratios may not equal 100 because of rounding.]

Ratio	Aquifer-system area	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Direct runoff/ rainfall + irrigation	A	26	28	25	31	35	32	31	33	27	29	30	28
	B	17	17	18	22	16	18	25	24	18	14	18	22
	C	32	32	22	28	25	19	38	48	36	36	17	21
Actual evapo-transpiration/ rainfall + irrigation	A	26	29	23	23	31	33	30	30	35	33	27	24
	B	33	39	34	39	51	54	48	50	53	47	38	30
	C	17	24	21	23	33	38	30	26	31	28	20	19
Recharge/ rainfall + irrigation	A	48	43	52	46	35	35	37	37	39	38	43	47
	B	50	45	48	39	33	28	28	26	29	39	44	48
	C	51	46	56	49	42	42	35	26	33	33	64	59

Table 11. Annual water-budget ratios for three scenarios, Lahaina District, Maui, Hawaii

[Values in percent; I, 1923–78 scenario; II, 1986–93 scenario; III, natural scenario; values were calculated by dividing the mean values, found in table 5, of direct runoff, for example, by the sum of the mean rainfall and mean irrigation. There is no irrigation for scenario III.]

Scenario	Direct runoff/ rainfall + irrigation	Actual evapotranspiration/ rainfall + irrigation	Recharge/ rainfall + irrigation
I	23	32	45
II	24	33	42
III	29	27	44

irrigation scenario I and scenario III in which there is no irrigation. In general terms, during irrigation scenarios I and II, the water-budget components for the entire district are distributed at about 25 percent runoff, about 30 percent evapotranspiration, and about 45 percent recharge. During periods of no irrigation, the distribution of water-budget components shifts slightly to favor higher runoff at about 30 percent and decreased evapotranspiration at about 25 percent and recharge remaining about the same at about 45 percent.

Table 12 summarizes the water-budget ratios by aquifer-system areas. In area B where most of the irrigation was applied, the ratios are more distinct between areas and scenarios than they are district-wide. The runoff ratio in area B for scenario I is about half what it is in areas A and C for the same scenario. Between scenarios I and III there is an 11 point increase in the runoff ratio in area B but no change in the runoff ratio in area A and only a 5 point increase in the runoff ratio in area C. The actual evapotranspiration ratios in areas B and C fluctuate about the same amount between scenarios I and III, but the magnitude of the ratio in area B is almost twice that of the ratio in area C.

Water-budget results are shown in table 13 with water budgets from previous investigations. Most notable are the differences in rainfall and evapotranspiration. The difference in rainfall is 10 Mgal/d more district-wide in Takasaki (1978), and in areas A and B combined, almost 20 Mgal/d less in Wilson, Okamoto and Associates (1977) than in this study. The rainfall maps used in the present water-budget rainfall calculations were not available when these previous reports were prepared.

In all the previous studies evapotranspiration was higher than in this study except in the basal part of area B because actual evapotranspiration with soil-moisture storage accounting was not estimated. Evapotranspiration was estimated as potential (maximum) evapotranspiration which overestimates evapotranspiration and, in turn, minimizes the estimate of ground-water recharge. Thus, recharge was less for each of the previous studies and was calculated as zero in the basal ground-water parts of areas A and B.

The district-wide direct runoff-rainfall ratio from Takasaki (1978), 43 percent, seems excessive and is perhaps more representative of the mean streamflow in the wet headwaters of the district. In that study, the coarse nature of the estimates was determined by the purpose and scope of the study, which was to provide a mean annual water budget for all the islands in the State of Hawaii.

The GIS water-budget results indicate limitations of the water-budget model. Three aspects to note are the regional nature of the model, the average characteristic of all input data, and the monthly time-step of the calculations. For part of the Lahaina district, the runoff calculations are regionalized by applying average relationships, determined from individual basins, over large areas. The available-water capacity and the calculated maximum soil-moisture storage of the soil types in the Lahaina District are important components in the water-budget model, because they limit ground-water recharge and evapotranspiration. The data used to cal-

Table 12. Annual water-budget ratios for three areas, Lahaina District, Maui, Hawaii

[Values in percent; I, 1923–78 scenario; II, 1986–93 scenario; III, natural scenario; see figure 2 for areas; values were calculated by dividing the mean values found in tables 7, 8, and 9 of direct runoff, for example, by the sum of the mean rainfall and mean irrigation. There is no irrigation for scenario III and only slight irrigation in area A scenario II.]

Aquifer-system area	Scenario	Direct runoff/ rainfall + irrigation	Actual evapotranspiration/ rainfall + irrigation	Recharge/ rainfall + irrigation
A	I	29	28	43
A	II	29	27	43
A	III	29	28	43
B	I	16	38	46
B	II	19	41	40
B	III	27	31	43
C	I	27	23	50
C	II	28	24	48
C	III	32	17	51

culate these components come from individual soil core profiles that are regionalized for the soil series. Similarly for irrigated areas, irrigation water was applied homogeneously over the area with no adjustments for high and low rainfall areas. All rainfall, direct runoff, pan evaporation, and soil data are averages that eliminate the extremes that occur in nature. These average data are meshed in the monthly time step of the calculations. Although monthly water-budget calculations estimate evapotranspiration more accurately than assuming the maximum evapotranspiration rate as is done in annual water-budget calculations, in reality, the components of the water-budget are interacting on the order of minutes and hours within small areas. The monthly time-step eliminates the ability to simulate gravity drainage from unsaturated soil conditions or additional losses to evapotranspiration through capillary action in the root/soil interface. Thus, ground-water recharge in this monthly budget is likely underestimated if compared with recharge computed on a daily or hourly basis. Unfortunately, these watershed-scale, detailed temporal data are not available, and a monthly budget for the Lahaina District is the time period the available data warrant. Considering particularly the length of record of the rainfall data and the distribution capabilities of the GIS model, as well as the modification to the model's evapotranspiration calculation in irrigated sugarcane areas, the water budget results are applicable for water availability assessments.

SUMMARY AND CONCLUSIONS

Land use has changed substantially during the past 100 years in the Lahaina District of Maui. Extensive agricultural development has occurred from the time of Hawaiians diverting streamflow to irrigate their taro patches to heavily irrigated sugarcane and pineapple

Table 13. Water-budget estimates from previous investigations, Lahaina District, Maui, Hawaii

[Mgal/d, million gallons per day; The difference of rainfall minus direct runoff, actual evapotranspiration, and recharge may not equal zero because of rounding; areas shown in figure 2.]

Area	Rainfall (Mgal/d)	Direct runoff (Mgal/d)	Direct runoff/rainfall (percent)	Evapotranspiration (Mgal/d)	Evapotranspiration/rainfall (percent)	Recharge (Mgal/d)	Recharge/ rainfall (percent)
A and B[1]	265	53	20	119	45	93	35
A and B[4]	283	80	28	82	29	121	43
District[2]	340	145	43	125	37	70	21
District[4]	330	95	29	90	27	145	44
High-level ground-water areas							
A[3]	80	40	50	16	20	24	30
A[4]	107	40	37	13	12	54	50
B[3]	104	42	40	30	29	32	31
B[4]	79	29	37	12	15	38	48
Basal ground-water areas							
A[3]	53	5	9	48	91	0	0
A[4]	49	6	12	30	61	13	27
B[3]	28	3	11	25	89	0	0
B[4]	49	5	10	27	55	16	33

[1] Wilson, Okamoto and Associates (1977)

[2] Takasaki (1978)

[3] Austin, Tsutsumi, and Associates, Inc. (1991)

[4] This study (for natural conditions, scenario III)

cultivation over thousands of acres. Resort and condominium developments now dominate large coastal areas. A preliminary step in understanding the ground-water system that has been tapped for water supply in the District is the calculation of a water budget. A mean monthly water budget was developed to estimate ground-water recharge for three scenarios: agricultural conditions during 1923–78, agricultural conditions during 1986–93, and natural conditions. These recharge estimates are an integral part of the ground-water availability assessment in the Lahaina District.

Rainfall distribution is dramatic in the Lahaina District, ranging from about 15 in/yr along the coast near Lahaina to more than 350 in/yr at the peak of the West Maui Mountain. For 1986–93 agricultural conditions, applied irrigation, predominantly for sugarcane, was estimated at 57 Mgal/d: about 102 in/yr over the sugarcane acreage and about 2 in/yr over the pineapple acreage.

Aquifers in the district are replenished by ground-water recharge from rainfall and irrigation water that percolates through and beyond the root zone in the soil to the subsurface rock. Ground-water recharge is estimated as the residual component of a monthly water budget calculated using long-term average rainfall, streamflow, irrigation and pan evaporation data, and soil characteristics. The water-budget components are defined seasonally, through the use of the monthly water budget, and spatially by topographic areas, through the use of a geographic information system (GIS) model.

The average ground-water recharge for the Lahaina District for 1986–93 conditions, estimated by the water-budget analysis, is about 163 Mgal/d. The average rainfall, irrigation, direct runoff, and evapotranspiration are 330 Mgal/d, 58 Mgal/d, 95 Mgal/d, and 129 Mgal/d, respectively. The average ground-water recharge was 190 Mgal/d during 1923–78 when irrigation averaged 90 Mgal/d. Recharge decreases to 145 Mgal/d in the natural scenario in which there is no agricultural irrigation.

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