WATER BUDGET FOR THE KOHALA AREA, ISLAND OF HAWAII

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 95-4114

Prepared in cooperation with the
DEPARTMENT OF WATER SUPPLY
COUNTY OF HAWAII

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By Patricia J. Shade

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Honolulu, Hawaii
1995

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Conversion Factors

Multiply	By	To obtain
foot (ft)	0.3048	meter
gallon (gal)	0.003785	cubic meter
gallon per day (gal/d)	0.06308	liter per day
million gallons (Mgal)	3,785	cubic meter
million gallons per day (Mgal/d)	0.04381	cubic meter per second
mile (mi)	1.609	kilometer
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 Kohala Area, Island of 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 and pan evaporation data, and soil and vegetation characteristics. The water-budget components are defined seasonally, through the use of the monthly water budget, 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 Kohala area, estimated by water-budget analysis for the topographic areas used in the analysis, is 162 Mgal/d in area A (south windward Kohala), 41 percent of average rainfall; 60 Mgal/d in area B (north windward Kohala), 33 percent of average rainfall; and 24 Mgal/d in area C (leeward Kohala), 13 percent of average rainfall.

INTRODUCTION

Resorts have been developed along the coast north of Kailua-Kona and just south of the study area because of the area's warm, dry climate. However, there is tremendous stress on the area's water resources to supply the thousands of hotel rooms and condominiums, and to turn barren lava rock into lush golf courses and hotel grounds. To meet the present and future water demand and to increase knowledge of ground water in the Kohala area, the Hawaii County Department of Water entered into a cooperative agreement with the U.S. Geological Survey (USGS) to study ground-water availability in the north Kohala area. The project includes a water-budget calculation, a test-drilling and aquifer-testing program, 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 Kohala area of the island of Hawaii, including an estimate of ground-water recharge, which is a data requirement for numerical simulation of the ground-water-flow system. Monthly calculations give a more realistic value of ground-water recharge, compared with calculations made on a mean annual basis, because actual evapotranspiration and water held in the soil root zone are accounted for. Calculations assume natural land-use conditions, which is a reasonable assumption given the rural, sparsely populated aspects of the area. The monthly spatial distribution of the water-budget components by topographic areas is tabulated, and the ground-water recharge distribution is displayed.

Description of the Study Area

The study area encompasses the entire north end of the island of Hawaii, 264.5 mi^2 (fig. 1). The extinct volcanic dome, Kohala Mountain, reaches an altitude of 5,600 ft and dominates the area. Three topographic areas are defined within the study area. The delineation of the rift zone subdivides the topographic areas. Area A, to the east (windward) of the mountain crest, between Waipio Valley and Pololu Valley, is severely eroded from landslides and streamflow resulting from the abundant rainfall generated from the orographic lifting of moisture-laden air in the predominant northeast tradewind flow. Mean annual rainfall (fig. 2) ranges from more than 160 in. near Waipio Valley to about 70 in. near Pololu Valley. Similarly, streamflow is abundant in this area from rainfall and because streams are perennial, fed by ground-water discharge in the deeply incised valleys. There is no urban development from Waipio Valley to Pololu Valley from the coast to the Kohala Mountain crest. During the early 1900's the

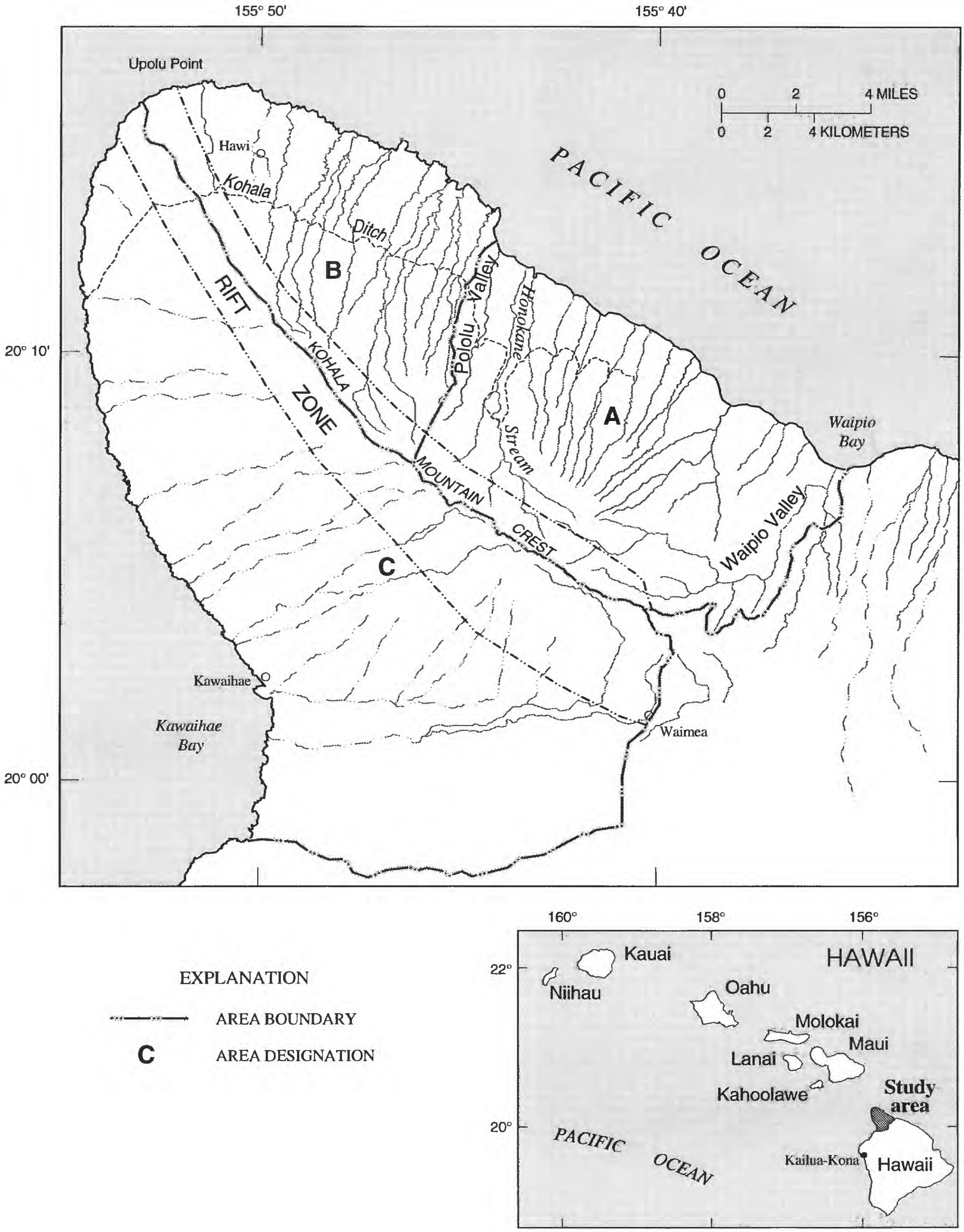
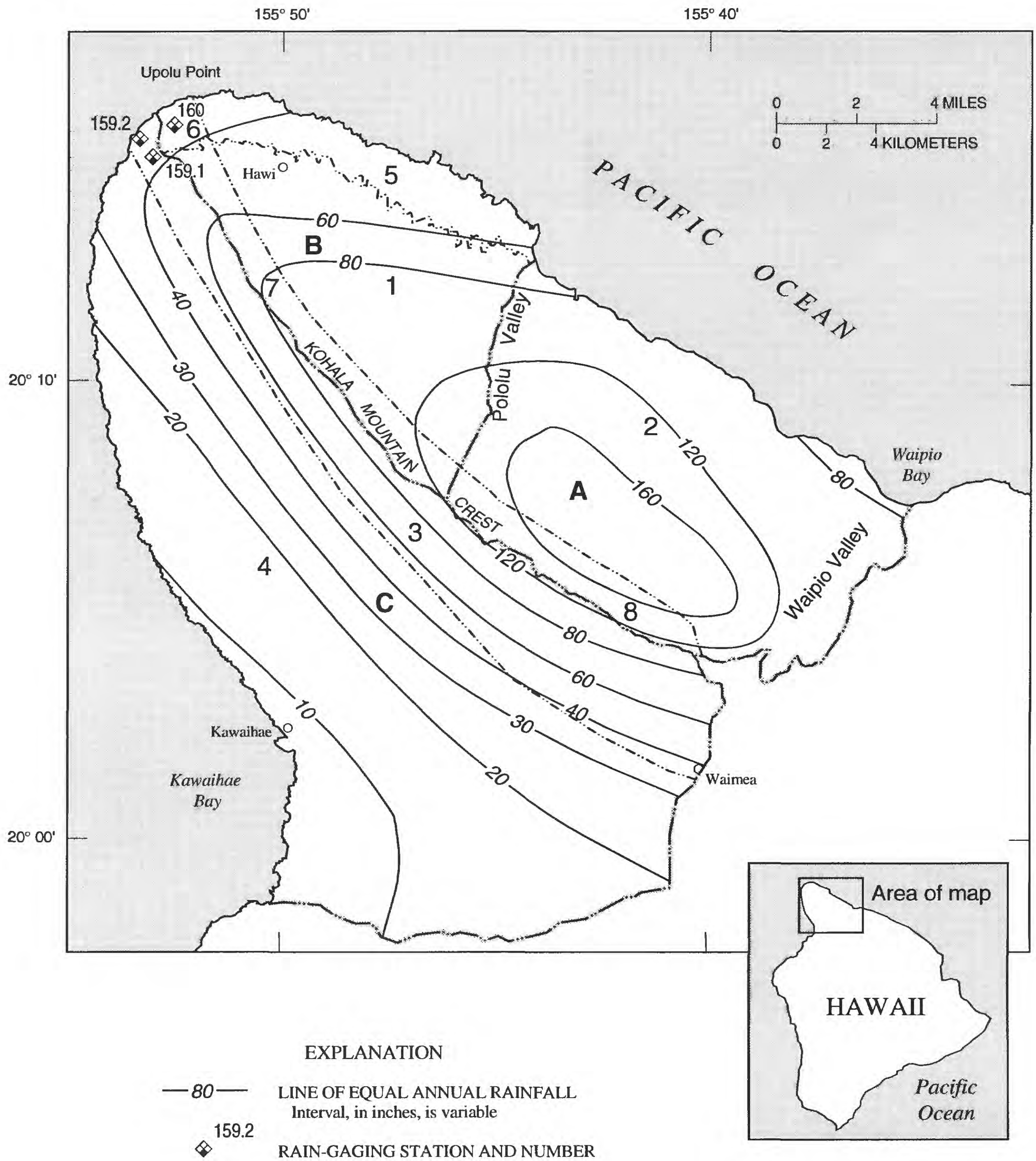


Figure 1. Hawaiian islands and Kohala area, island of Hawaii.



EXPLANATION

—80—	LINE OF EQUAL ANNUAL RAINFALL Interval, in inches, is variable
◈ 159.2	RAIN-GAGING STATION AND NUMBER
----	AREA BOUNDARY
C	AREA DESIGNATION
-·-·-	ZONE BOUNDARY
6	ZONE NUMBER

Figure 2. Mean annual rainfall, Kohala, island of Hawaii (from Giambelluca and others, 1986).

Kohala Ditch system (fig. 1) was constructed in this area to supply irrigation water to the sugarcane fields of the Kohala Sugar Company near Hawi. Since the company ceased operations in the 1970's, part of the ditch system has been abandoned. However, the remainder of the system from Honokane Stream to Hawi (fig. 1) presently delivers most of its water, 10 to 15 Mgal/d to a hydroelectric plant in Hawi. In Waipio Valley there is a small rural Hawaiian farming community where taro is the major crop.

North of Pololu Valley in area B, rainfall decreases to about 35 in/yr near Upolu Point as the altitude of the orographic barrier decreases. Streams in the area are mostly intermittent. Springs in the area are at altitudes from about 600 to 1,800 ft. The public water supply for the area is developed from three tunnel systems that tap spring discharge. The town of Hawi had a population of 924 in 1990 (State of Hawaii, 1991), and the surrounding area is mostly undeveloped or in small farms south and east to Pololu Valley.

The climate in area C on the west side (leeward) of the Kohala Mountain crest is usually hot and dry where rainfall decreases significantly downslope to the coast. The mean annual rainfall in this area ranges from about 120 in. along the southeast end of the mountain crest to about 8 in at Kawaihae. The area to the west of the mountain crest slopes more moderately to the coast than in area A, from a maximum altitude of 5,605 ft over a distance of about 6 mi. No perennial streams discharge at the shore in this area. Streams discharge at the coast only for short periods during significant heavy rainfall. Ranching is the predominant activity along the mountain crest where there is adequate rainfall. Some "gentleman estate" development occupies a narrow strip from the crest to the coast just north of Kawaihae Bay. The lower slopes are mostly barren lava rock. Because of the warm sunny climate, resort development in the area is expected to increase in the future. However, development is presently being limited by water availability.

WATER-BUDGET MODEL

Ground-water recharge can be estimated 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:

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

where: G = ground-water recharge,
P = precipitation,
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 water-budget model include rainfall, stream discharge (runoff) and associated drainage areas, pan evaporation, and soil and vegetation properties.

The study area was digitized from a 1:100,000-scale USGS topographic map prepared in 1980. The area was divided into topographic areas which were subdivided by the delineation of the rift zone and the 400 ft topographic contour in area B (fig. 3). These subdivisions were necessary for subsequent ground-water flow simulations. These spatial data allow the modeler to calculate and display data by individual area or any combination of areas.

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

Several drainage basins (fig. 4) were digitized from USGS 1:24,000-scale topographic maps compiled in 1983. Runoff/rainfall ratios were calculated for each of these basins. Monthly ratios were applied to the rainfall distributions to calculate the runoff component of the water budget.

Mean annual pan evaporation data were obtained by digitizing the adjusted annual pan evaporation map (fig. 5) for the island (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.

The soil data layer was created by digitizing soil maps from Sato and others (1973). Before digitizing,

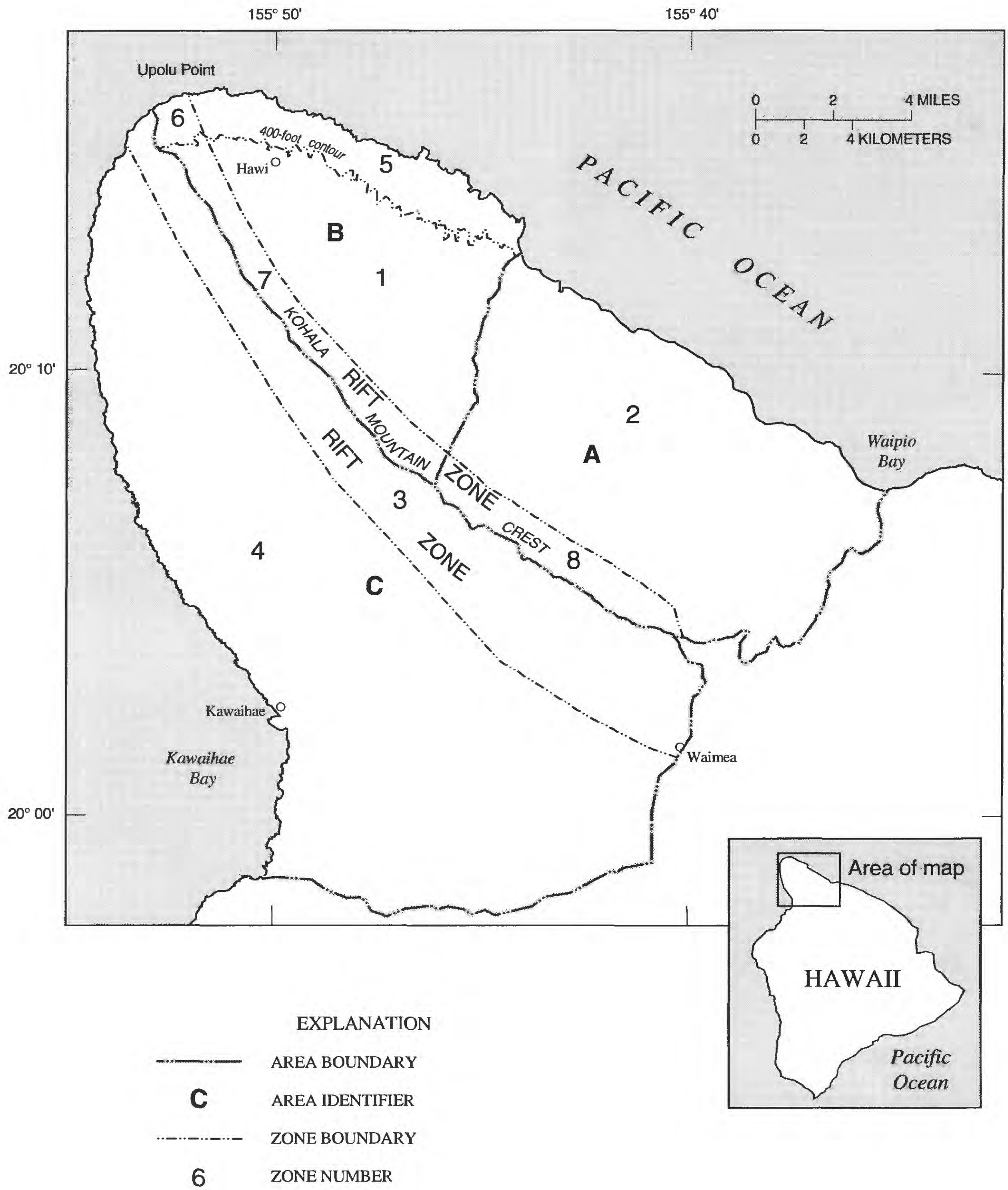


Figure 3. Areas and zones used in the water-budget analysis, Kohala, island of Hawaii.

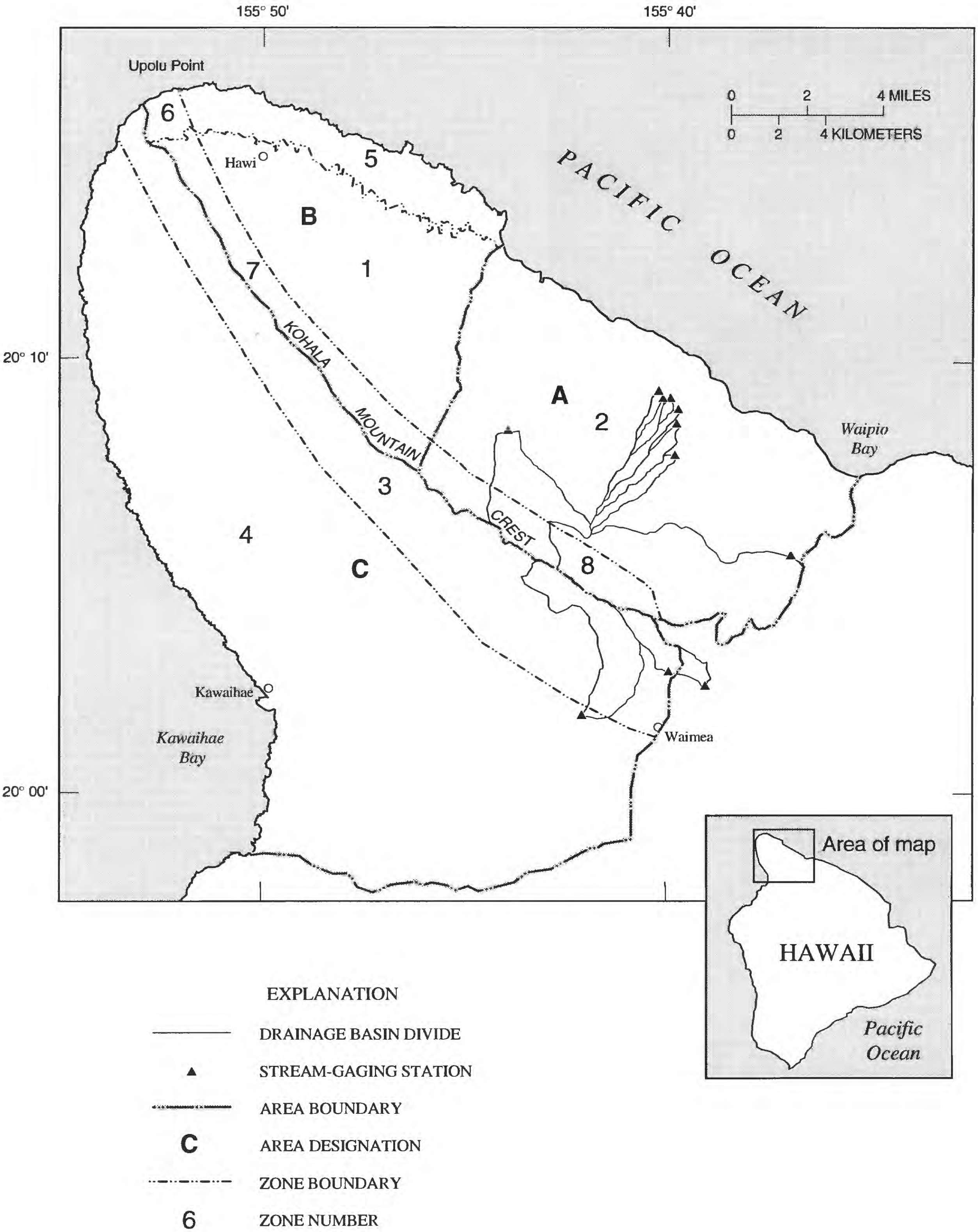


Figure 4. Gaged drainage basins used to calculate the runoff component of the water budget, Kohala, island of Hawaii.

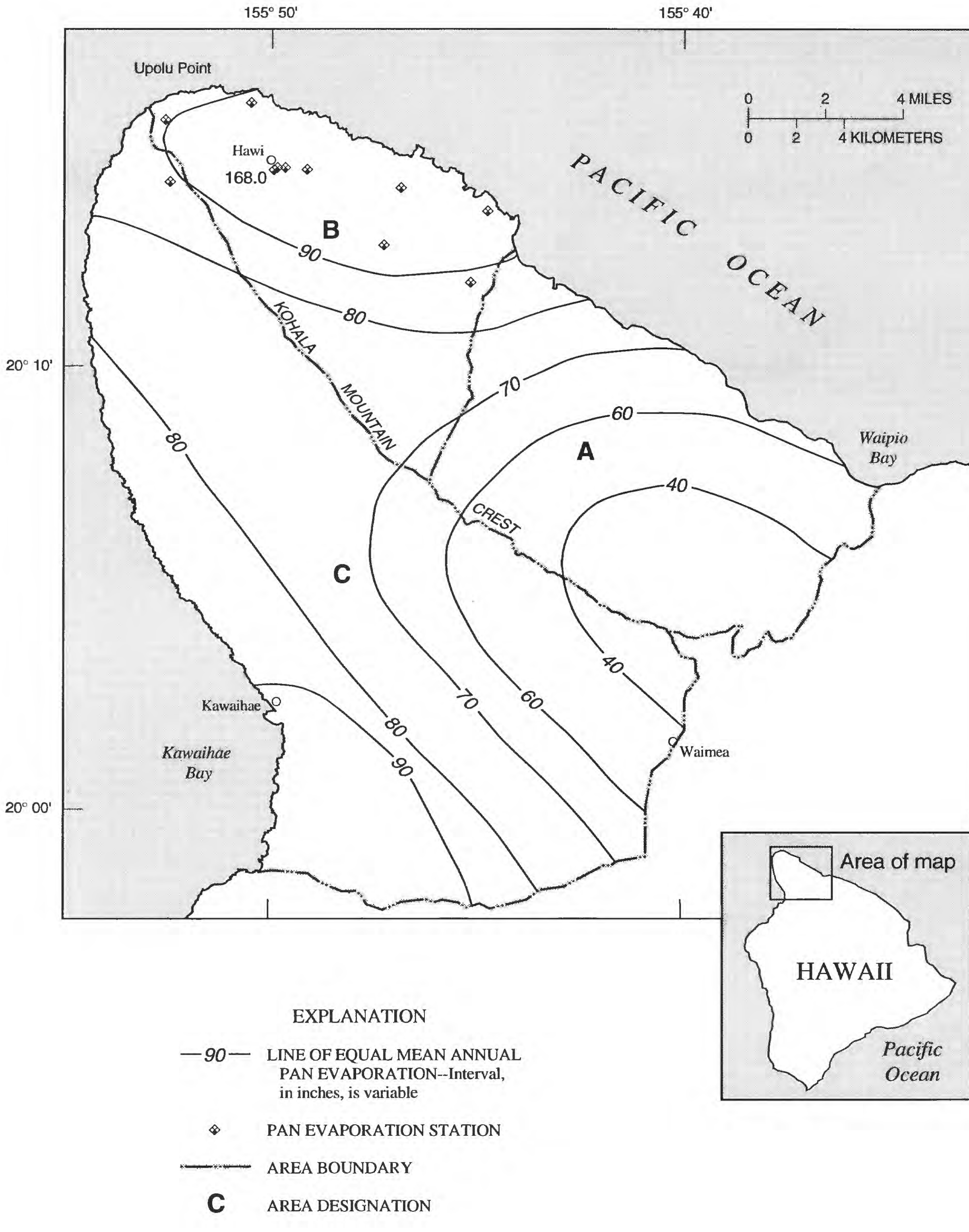


Figure 5. Mean annual pan evaporation, Kohala, island of Hawaii (from Ekern and Chang, 1985).

the soil types were generalized by grouping soils that had similar available water capacities, rooting depths, permeabilities, and textures based on values from Sato and others (1973). Boundary lines of these soil groups were transferred to 1:24,000 scale USGS topographic maps for digitizing.

The vegetation data layer was created by digitizing generalized vegetation areas from a 1:250,000 scale map (U.S. Army, 1951). Vegetation rooting depths for these broad categories were provided by the State of Hawaii Division of Forestry and Wildlife (Michael Buck, oral commun., 1989). These data were combined with the soil data to establish a more comprehensive estimate of rooting depth. In the combined data there were many areas that had the same values for rooting depth obtained from the vegetation map and soil map. For the areas where the two rooting depths differed, the average of the two values was assigned to the area. Maximum soil-moisture storage values were calculated from these combined soil and vegetation data, and a digital map (fig. 6) of the distribution of this soil characteristic was created to use in the GIS model.

Rainfall

The rainfall distribution in the study area is influenced by the orographic effect of the Kohala Mountain on the prevailing northeast tradewinds (fig. 2). Rainfall is abundant in area A (maximum is more than 160 in/yr) where the warm moist air is cooled and forced to rise over the mountains. In the rain shadow of the Kohala Mountain on the leeward (west) side of the mountain crest in area C, rainfall decreases dramatically towards the coast where the average rainfall is less than 10 in/yr at Kawaihae, the driest area in the State (Giambelluca and others, 1986). Rainfall in area B is more moderate than in area A. As the mountain crest decreases in altitude toward the north shore, air is not forced to ascend and cool, and therefore rainfall decreases.

Twelve maps (Giambelluca and others, 1986) showing lines of equal mean monthly rainfall for the island of Hawaii were compiled from data collected at a network of 31 base stations that had complete records for the base period from 1916 through 1983. Records from an additional 13 stations were used in the statistical analyses. These monthly maps were digitized and constitute the rainfall data set for the GIS model. These data were used to calculate mean monthly rainfall values for the study area that range from a low of 476 Mgal/d in September to a high of 1,021 Mgal/d in April.

The spatial distribution of rainfall varies from month to month, and most significantly from winter to summer months (figs. 7 and 8). In general, rainfall seasonality in the study area appears to be slightly more pronounced in the dry leeward areas along the coast near Kawaihae, than in the wet areas along the Kohala Mountain crest. Figures 7 and 8 show that June rainfall near Kawaihae is about 40 percent of the December rainfall in the area, and near the mountain crest, the June rainfall is about 50 percent of the December rainfall.

Runoff

Streamflow is formed by 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 stream discharge, monthly direct runoff was calculated as the difference between mean monthly discharge 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 90 percent of the time during the chosen month. This procedure is consistent with hydrograph separation analyses of these streams.

Monthly direct runoff was calculated as a percentage of monthly rainfall based on streamflow records representative of each area. In area A, data from eight continuous stream-gaging stations (fig. 4) were used to calculate direct runoff from each basin by subtracting baseflow from the mean monthly flow. For each month, the resulting total direct-runoff volume from these eight drainage basins was divided by the total rainfall volume over the eight basins to determine the monthly direct runoff-rainfall ratios to be applied to the monthly rainfall over area A (table 1).

In area B and in area C zone 4, there are no continuous stream-gaging stations. 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 and soil properties as those of area B and area C zone 4. The Oahu data provided monthly runoff-rainfall ratios that were adjusted for area B and area C zone 4 on the basis of a comparison of the monthly rainfall with annual rainfall

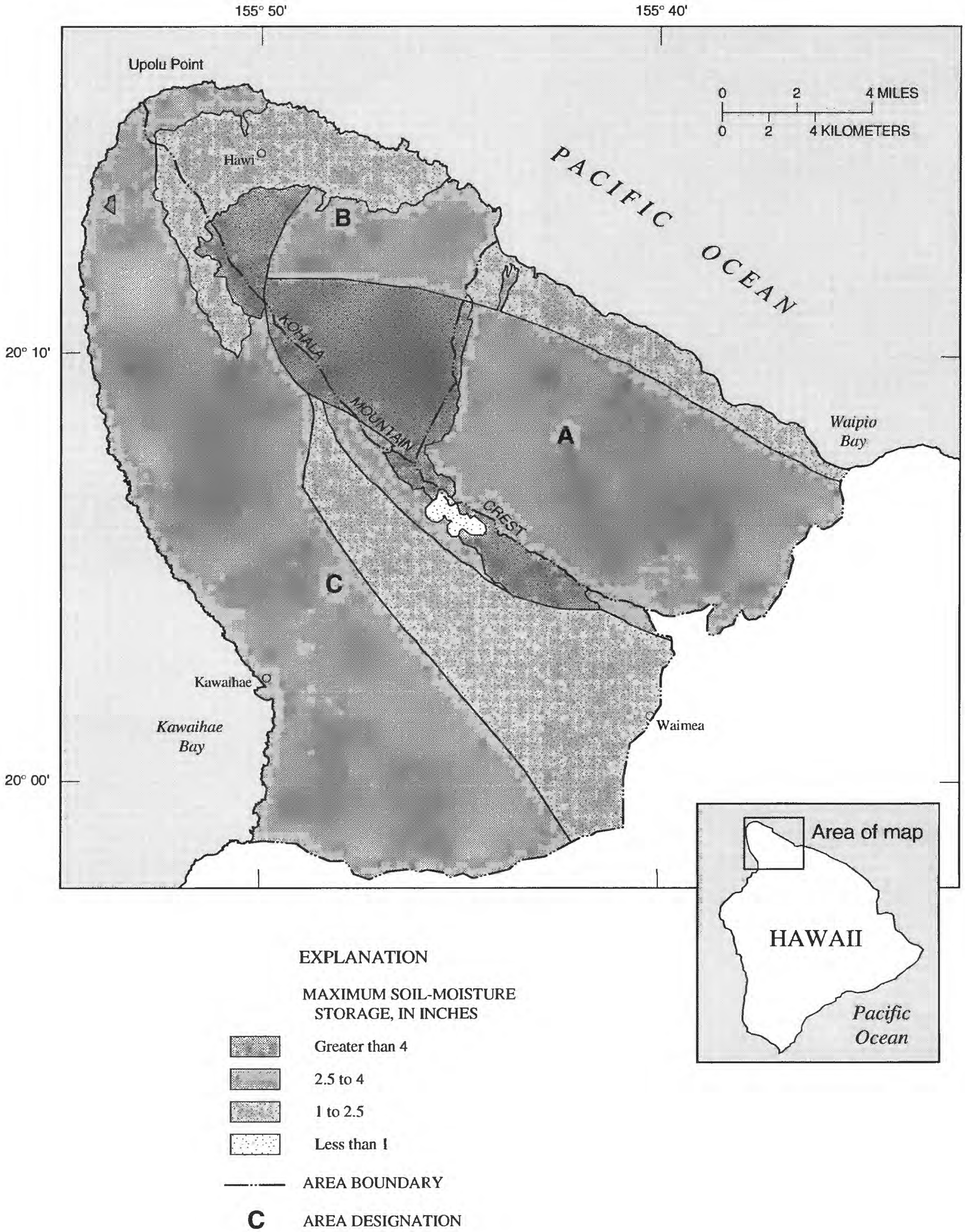


Figure 6. Maximum soil-moisture storage, Kohala, island of Hawaii.

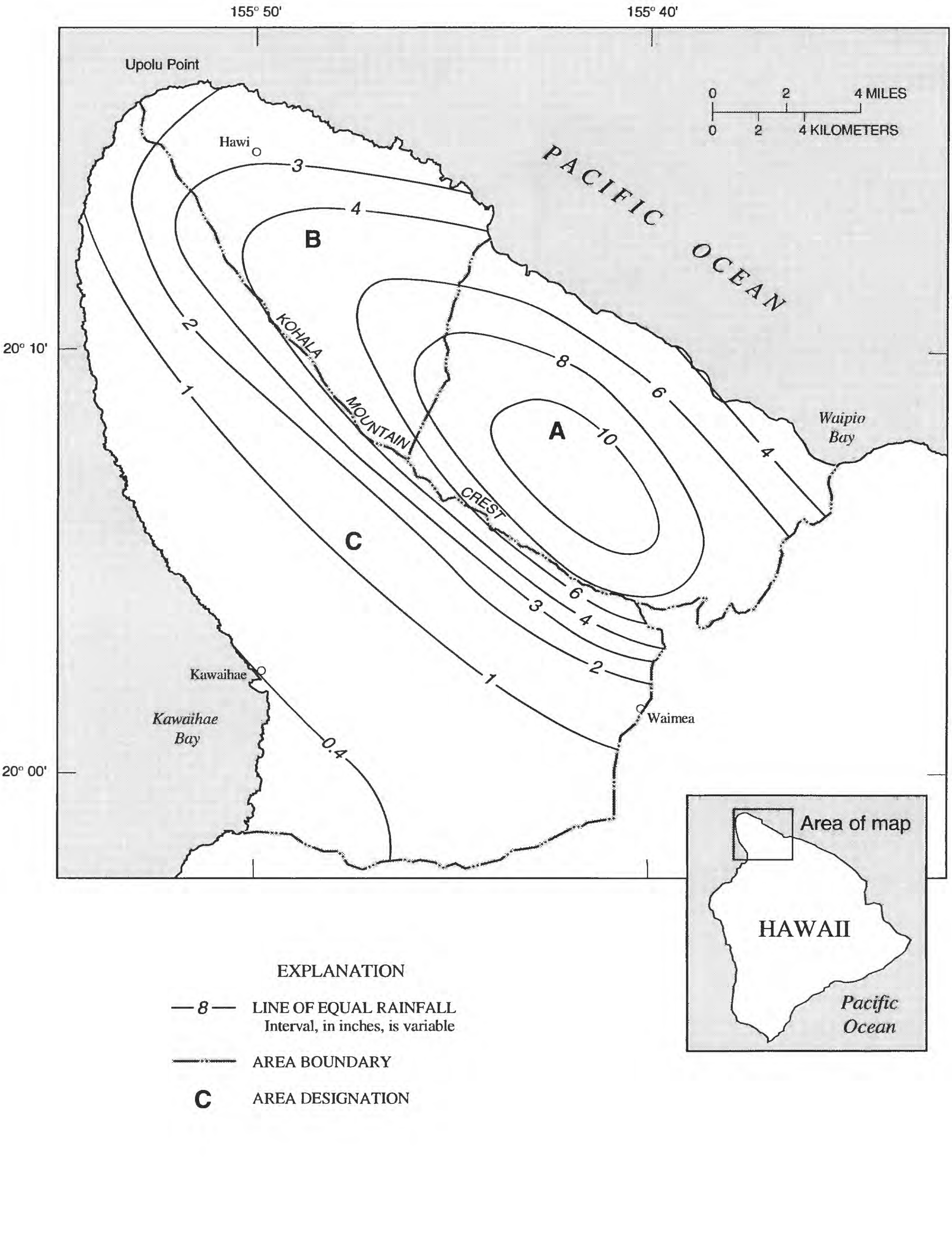


Figure 7. June rainfall, Kohala, island of Hawaii.

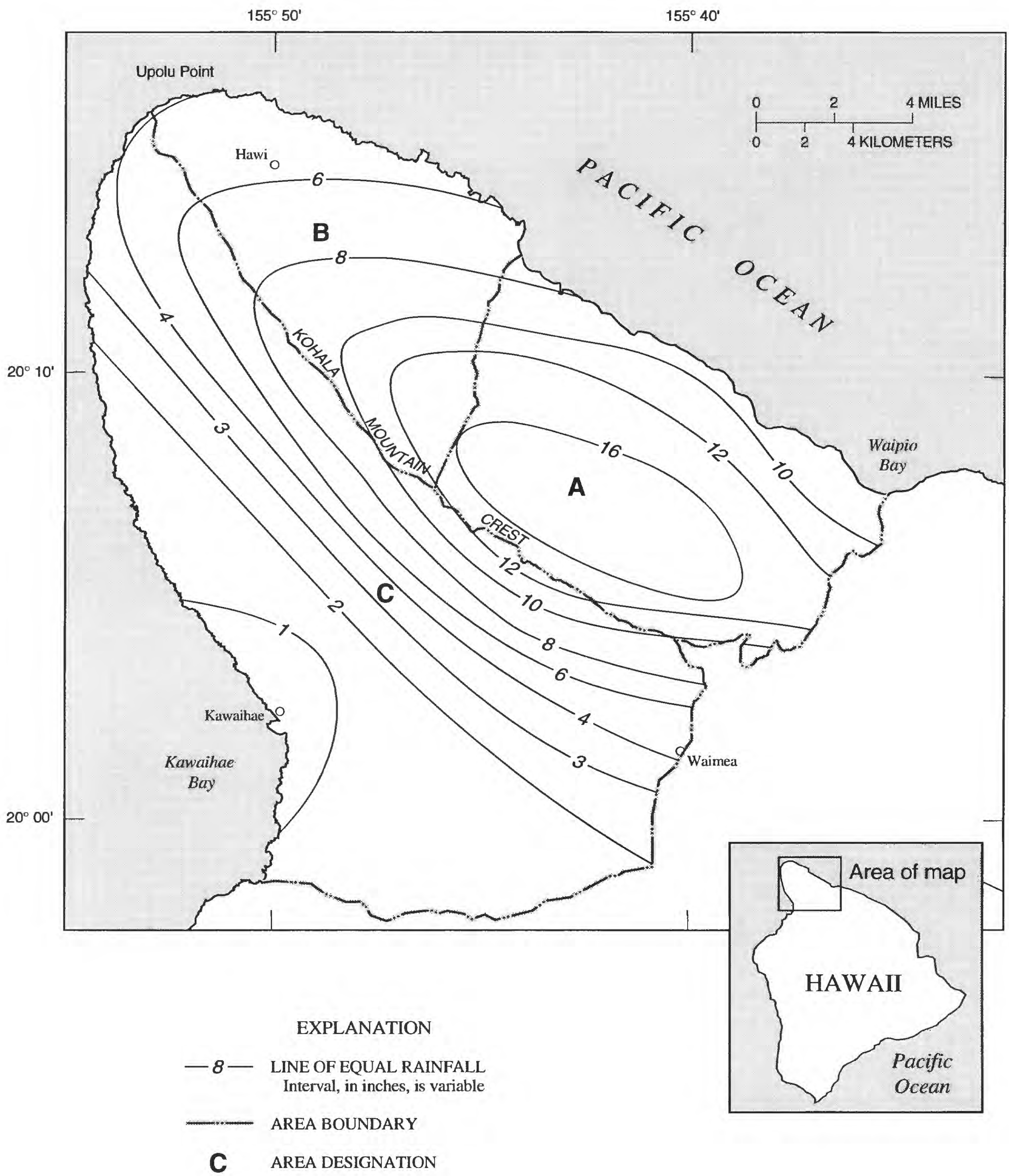


Figure 8. December rainfall, Kohala, island of Hawaii.

distribution determined from rain gages in area B and area C zone 4 (table 1).

The monthly direct runoff-rainfall ratios applied in area C zone 3 were estimated following the same procedure as for the perennial stream basins in area A. Three basins were digitized and the ratio of the sum of the basin's direct runoff to the sum of the basin's rainfall was calculated for each month. For the months of April and July, however, the runoff-rainfall ratios were inordinately high, perhaps because of comparing short-term streamflow records containing large flood events, with long-term rainfall data. A linear regression was computed for the remaining 10 months of runoff and rainfall data, in units of inches:

$$\text{Runoff} = -141.34 + 0.66\ (\text{Rain}). \qquad R^2 = 0.83 \quad (2)$$

This relation was applied to calculate a runoff-rainfall ratio for April and July. Table 1 shows the monthly runoff-rainfall ratios for area C zone 3.

Tables 1. Direct runoff/rainfall ratios and monthly to annual rainfall, Kohala, island of Hawaii and Pearl Harbor, island of Oahu
[values in percent; in/yr, inches per year; see figure 3 map for areas and zones; rain stations shown in figure 2]

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Monthly direct runoff-rainfall ratios for Kohala area A												
	27	26	40	39	34	32	41	30	25	32	35	33
Pearl Harbor, Oahu monthly to annual rainfall ratios for areas with 34 to 35 in/yr of rainfall (from Giambelluca, 1983)												
	20	11	12	8	4	3	3	3	5	7	13	13
Kohala area B monthly to annual rainfall ratios for areas with 31 to 35 in/yr of rainfall[a,b]												
Rain station 159.1	14	10	12	12	6	6	9	10	4	6	11	13
Rain station 159.2	12	9	10	9	6	6	8	7	4	6	9	10
Rain station 160.0	14	9	10	10	6	6	8	7	4	7	10	11
average	13	9	11	10	6	6	8	8	4	6	10	11
Oahu direct runoff-rainfall ratios for the part of the Pearl Harbor area with 34 to 35 in/yr of rainfall (from Giambelluca, 1983)												
	14	7	10	6	3	1	1	1	2	4	10	9
Kohala area B (zone 6) direct runoff-rainfall ratios for areas with 34 to 35 in/yr of rainfall[c]												
	13	7	10	6	3	1	1	1	2	4	10	9
Kohala area B direct runoff-rainfall ratios												
Zones 1 and 7	18	17	18	18	7	7	8	8	6	7	17	18
Zone 5	11	7	12	12	6	1	7	9	1	6	11	11
Kohala area C (zone 4) direct runoff-rainfall ratios												
	13	7	10	6	2	1	1	2	1	3	11	8
Kohala area C (zone 3) direct runoff-rainfall ratios												
Rain less than or equal to 50 inches	14	9	10	9	6	1	3	3	1	6	6	12
Rain greater than 50 inches	44	45	45	47	54	41	38	49	21	23	43	56

[a] Monthly and annual data from Giambelluca, 1986 (appendix table A.1)

[b] Total of monthly percentage values slightly greater than 100 due to rounding

[c] Because of the difference between Oahu and Kohala area B January monthly to annual rainfall ratios, the January runoff-rainfall ratio for Kohala area B was decreased slightly from the Oahu January ratio.

Actual Evapotranspiration and Soil-Moisture Accounting

Actual evapotranspiration (AE) is the quantity of water evaporated from water and soil surfaces and transpired by plants. Island-wide AE data from direct field measurements do not exist. It is possible to estimate AE however, 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 PE based on 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 Hawaii (Ekern and Chang, 1985) is shown in figure 5 and was digitized for the GIS water-budget model of the study area.

Where sugarcane had been grown in the northeastern part of the study area, pan evaporation is defined by data from stations (fig. 5) with periods of record from 2 to 12 years. There is little variability in the mean annual pan evaporation in the northeastern area: about 80 to more than 90 in/yr. The effect of the Kohala Mountain is most apparent in areas A and C. In area A pan evaporation ranges from about 70 in/yr at the coast to less than 40 in/yr near the mountain summit where temperatures are lower and there is increased rainfall and cloud cover. On the leeward side of the mountains in area C, pan evaporation increases to a high of more than 90 in/yr near Kawaihae. 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 study area monthly PE distributions were calculated by multiplying the annual pan evaporation value (the average value of the bounding lines is assigned to the area between the lines) shown in figure 5 by the monthly to annual pan evaporation ratios shown in table 2. These ratios were estimated from 12 years of data at Hawi station 168.0 (Ekern and Chang, 1985).

The PE demand in a particular month can not always be met by the amount of water in soil storage. In such cases AE is less than PE. To estimate AE, the maximum soil storage capacity was calculated for each of the generalized soil groups in the study area. The soils have been mapped and their characteristics have been tabulated by the Natural Resources Conservation Service (Sato and others, 1973) (table 3). Data that were not available in Sato and others (1973) were provided by R.E. Green and Haruyoshi Ikawa (Dept. of Agronomy and Soil Science, University of Hawaii, oral commun., 1989). The available water value for each soil group in table 3 is the average of the range reported in Sato and others (1973). Available water is a measure of the quantity of water the soil can hold between field capacity and wilting point; the quantity available to plants. The rooting depth was assumed to be at the depth where

Table 2. Monthly to annual pan evaporation ratios, in percent, from station 168.0, Kohala, island of Hawaii

Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
.065	.068	.077	.079	.094	.098	.100	.105	.095	.084	.066	.069

Table 3. Average soil characteristics, Kohala, island of Hawaii

Soil series	Available water (inch per inch of soil)	Root depth (inches)	Maximum soil storage (inches)
Amalu,Tropaquepts, mixed alluvial land, rough broken land	0.12	25	3.0
Niulii	0.18	30	5.4
Kahua	0.17	36	6.12
Kehena, Niulii, Ainakea	0.18	30	5.4
Kohala	0.14	14	1.96
Hawi	0.14	48	6.72
Kawaihae, Mahukona	0.0	24	0
Manahaa, Maile, Palapalai, Kikoni, PuuPa, Waimea	0.15	40	6.0
Cinder land	0.04	6	0.24

the soil profile description changed from "abundant roots" or "common roots" to "few roots" or "no roots."

The estimate of rooting depth was refined by combining the soil information with a vegetation map of the area. The vegetation types in the study area included areas sparsely covered by kiawe and grasses, areas more densely covered by koa haole, guava and grasses, and areas covered with mature large trees such as koa with an understory of grasses and shrubs. Table 4 shows the broad vegetation groups, typical plants in each group and an estimated rooting depth provided by the State of Hawaii Division of Forestry and Wildlife (Michael Buck, oral commun., 1989). By overlaying the soil and vegetation maps, many areas had the same rooting depth values from the vegetation and soil data. For areas where the soil and vegetation rooting depths differed, the average of the two values was assigned to the area.

Maximum soil-moisture storage capacity is the product of the rooting depth and the available water capacity for the soil type (fig. 6). The maximum soil-moisture storage 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.

Soil-moisture storage changes each month and is calculated using a month-to-month bookkeeping procedure. The water-budget model was initialized by beginning the month of January with three soil-moisture storage values: the maximum soil capacity value, half the maximum value, and zero. The soil-storage values at the end of December were equal for these three scenarios and these values were input for the initial soil storage in January for the final water-budget calculation. January runoff is subtracted from the sum of the initial January soil storage and January rainfall. The remainder is added to soil storage, and if this quantity exceeds the maximum storage capacity, the excess recharges ground-water. Evapotranspiration is subtracted from soil storage at either the maximum PE rate or at some lesser AE rate depending on the quantity of water in soil storage available to meet the demand. Any water remaining in soil storage is carried over to the next month. This bookkeeping procedure is shown in the following equations.

$$SS_{Jan} + P_{Jan} - R_{Jan} = X_1 \qquad (3)$$

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 $X_1 = X_2$. (4)

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 $X_2 \geq PE$,
then $AE = PE$
and $X_2 - PE = X_{end}$.

OR

If $X_2 < PE$,
then $AE = X_2$
and $X_{end} = 0$. (5)

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

The bookkeeping process provides a running account of month-to-month moisture stored in the soil root area from which evapotranspiration occurs. By identifying the soil's moisture-holding capacity, and applying the water-balance bookkeeping procedure, water surplus and water deficit can be calculated. For this project, water surplus is equated to ground-water recharge; hence, recharge occurs when soil-moisture storage is exceeded. A water deficit occurs when soil-moisture storage is less than full and insufficient to meet the maximum potential evapotranspiration demand.

Ground-Water Recharge

The distribution of ground-water recharge (fig. 9) in the Kohala area is similar to the distribution of rainfall (fig. 2). Ground-water recharge ranges from less than 1 in/yr near Kawaihae and increases towards the Kohala Mountain crest to more than 40 in/yr in wet area A. Recharge similarly varies through the months from highs of about 235 Mgal/d in April and December, to lows of about 90 Mgal/d in June, September, and October in area A (table 5). The mean recharge for area A is 162 Mgal/d.

In area B recharge ranges from 1 to 10 in/yr near Upolu Point to greater than 40 in/yr near the boundary with area A. The monthly recharge varies from a low of 8 Mgal/d in September to a high of 99 Mgal/d in April. The mean ground-water recharge for area B is 60 Mgal/d.

Ground-water recharge in area C ranges from less than 1 in/yr along the coast at Kawaihae to about 10 in/yr along the Kohala Mountain crest. Pockets of higher recharge are in areas where the calculated maximum soil-moisture storage is distinctly lower than surrounding areas (fig. 6), and/or where the runoff-rainfall ratio is different from that of surrounding areas. Recharge ranges from a low of 4 Mgal/d in June to a high of 58 Mgal/d in January. The mean ground-water recharge for area C is 24 Mgal/d.

Table 4. Average vegetation characteristics, Kohala, island of Hawaii

Cover	Typical plants	Root depth (inches)
Xerophytic shrub with coastal fringe of trees	kiawe and koa haole	30
Xerophytic shrub with some trees	koa haole and lantana	21
Mixed open forest and shrubs	koa haole, guava, lantana	24
Mixed open forest	plantain	12
Shrub and closed forest	guava	18
Closed forest	ohia lehua and tree fern	30
Open forest	koa	24

Table 5. Mean monthly and annual water budget, Kohala, island of Hawaii
[values in million gallons per day; ET, evapotranspiration; see figure 4 for areas. The sum of runoff, ET, and recharge may not equal zero due to rounding]

Component	Area	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
Rainfall	A	402	411	448	564	367	290	415	416	268	286	428	496	399
	B	213	206	229	243	164	131	169	172	99	126	202	228	182
	C	310	226	258	214	165	113	135	177	109	127	183	253	189
Runoff	A	108	107	179	220	125	93	156	125	67	91	150	164	132
	B	36	32	39	41	11	8	11	14	5	9	32	38	23
	C	71	48	61	48	33	19	23	43	9	14	43	69	40
Actual ET	A	99	110	104	108	107	110	107	107	109	106	102	100	106
	B	98	108	100	103	99	98	99	100	86	95	101	100	99
	C	181	145	147	139	124	91	100	111	92	102	119	147	125
Recharge	A	193	196	169	237	138	87	153	184	92	88	168	234	162
	B	78	68	90	99	54	25	59	58	8	23	67	91	60
	C	58	33	51	28	9	4	13	24	7	10	18	37	24

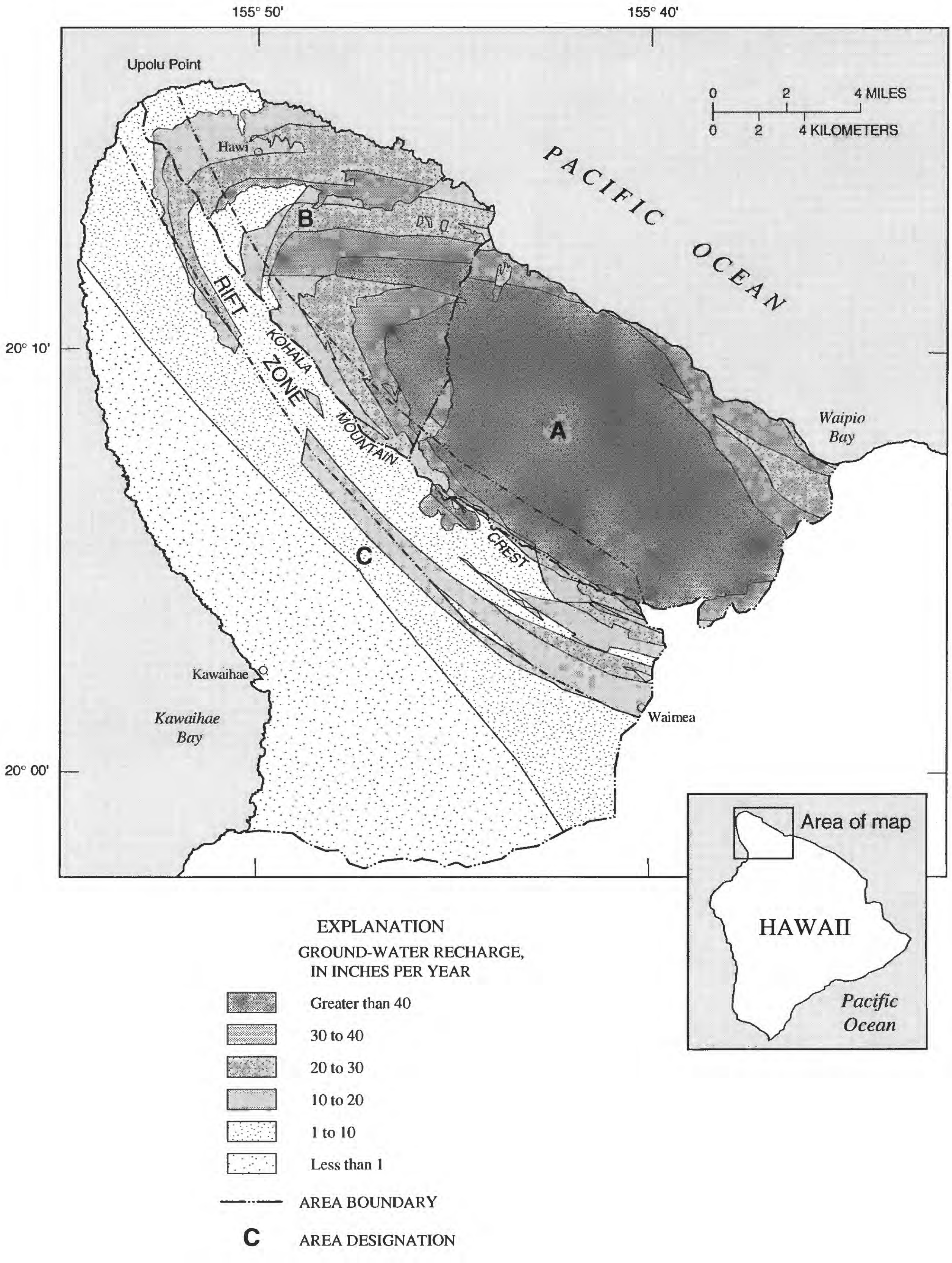


Figure 9. Annual ground-water recharge, Kohala, island of Hawaii.

WATER-BUDGET RESULTS

The water budget for the Kohala area shows distinct variations in rainfall, runoff, evapotranspiration and ground-water recharge through the months and for areas A, B, and C (table 5). Tables 6 and 7 indicate the ratios of runoff, actual evapotranspiration, and ground-water recharge to rainfall on an annual and monthly basis for each area. These ratios, obtained from the water budget, can be used to estimate the water-budget components in the different areas for given rainfall values. The ratios summarize the extreme climatic differences between the areas. Note the high percentage of rainfall used by evapotranspiration and low percentages for ground-water recharge and direct runoff in the dry area C compared with the ratios in area A. As in area C, evapotranspiration is more than 50 percent of rainfall in area B, but only 27 percent of annual rainfall in the wet area A. With a lower runoff/rainfall ratio, the recharge/rainfall ratio attains 33 percent in area B, compared with only 13 percent in area C.

To better understand seasonal ground-water recharge fluctuations, the months were grouped into winter (December, January, February), spring (March, April, May), summer (June, July, August), and fall (September, October, and November) (table 8). In area B the average seasonal ground-water recharge is 79 Mgal/d in winter, 81 Mgal/d in spring, 47 Mgal/d in summer, and 33 Mgal/d in fall. Varied pumping scenarios might be applied in this area considering this seasonal variation in ground-water recharge.

Figure 9 shows the mean annual distribution of ground-water recharge computed by the monthly water-budget model. Generally, the distribution of recharge is similar to the distribution of rainfall: high rainfall areas have high recharge, and low rainfall areas have low recharge values. In some places recharge varies drastically over short distances. This is a result of a difference in the soil-moisture storage values and/or a difference in runoff-rainfall ratios. High soil-moisture storage values effectively decrease the calculated ground-water recharge.

Table 6. Annual water-budget ratios, Kohala, island of Hawaii

[Values in percent; see figure 4 map for areas; values were calculated by summing the monthly volumes of runoff, for example, and dividing by the sum of the monthly rainfall volumes]

Area	Runoff/rainfall	Actual evapotranspiration/rainfall	Recharge/rainfall
A	33	27	41
B	13	54	33
C	21	66	13

Table 7. Monthly water-budget ratios, Kohala, island of Hawaii

[values in percent; AE, actual evapotranspiration; see figure 4 map for areas]

Ratio	Area	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Runoff/rain	A	27	26	40	39	34	32	38	30	25	32	35	33
	B	17	16	17	17	7	6	7	8	5	7	16	17
	C	23	21	24	22	20	17	17	24	8	11	23	27
AE/rain	A	25	27	23	19	29	38	26	26	41	37	24	20
	B	46	52	44	42	60	75	59	58	87	75	50	44
	C	58	64	57	65	75	81	74	63	84	80	65	58
Recharge/rain	A	48	48	38	42	38	30	37	44	34	31	39	47
	B	37	33	39	41	33	19	35	34	8	18	33	40
	C	19	15	20	13	5	4	10	14	6	8	10	15

Table 8. Seasonal water budget, Kohala, island of Hawaii
[values in million gallons per day; see figure 4 map for areas]

Water-budget component	Area	Winter (Dec.-Feb.)	Spring (Mar.-May)	Summer (June-Aug.)	Fall (Sept.-Nov.)
Rainfall	A	436	460	374	327
	B	216	212	157	142
	C	263	212	142	140
Runoff	A	126	175	125	103
	B	35	30	11	15
	C	63	47	28	22
Actual evapotranspiration	A	103	106	108	106
	B	102	101	99	94
	C	158	137	101	104
Recharge	A	208	181	141	116
	B	79	81	47	33
	C	43	29	14	12

Figure 9 and table 5 display the results of the GIS water-budget model as distinct values associated with defined areas. Yet, in reality the vegetation areas, soil areas, and study area boundaries have gradational limits; sharp increases or decreases in associated values are sometimes unrealistic. Similarly, available water capacity and rooting depth values that determine the maximum soil-moisture storage, are average values and there is a certain amount of error associated with that average. The maximum soil-moisture storage component in the water budget has a substantial effect on the calculation of evapotranspiration and ground-water recharge. Therefore, because of the error in the maximum soil-moisture storage value, there is error in the resulting ground-water recharge. Thus, the ground-water recharge distribution depicted in figure 9 needs to be viewed as an estimate.

SUMMARY AND CONCLUSIONS

Ground water is the preferred source for the public water supply on the island of Hawaii because of its quality and dependability. The development of several resorts along the dry and sunny Kohala coast north of Kailua-Kona requires additional water resources to meet future demand.

Rainfall over the Kohala study area ranges from less than 10 inches per year along the coast near Kawaihae to more than 160 inches annually windward of the crest of Kohala Mountain. Aquifers in the 264.5 square mile Kohala area are replenished by ground-water recharge from rainfall 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 and pan evaporation data, and soil and vegetation characteristics. The water-budget components are defined seasonally, through the use of the monthly water budget, and spatially by topographic and geologic areas, through the use of a geographic information system (GIS) model.

The long-term average ground-water recharge for the entire Kohala area, estimated by water-budget analysis, is about 246 Mgal/d, 32 percent of average rainfall. Average direct runoff and evapotranspiration are 195 Mgal/d and 330 Mgal/d, 25 and 43 percent of average rainfall, respectively. The long-term average ground-water recharge for areas A, B, and C are 162, 60, and 24 Mgal/d, respectively.

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