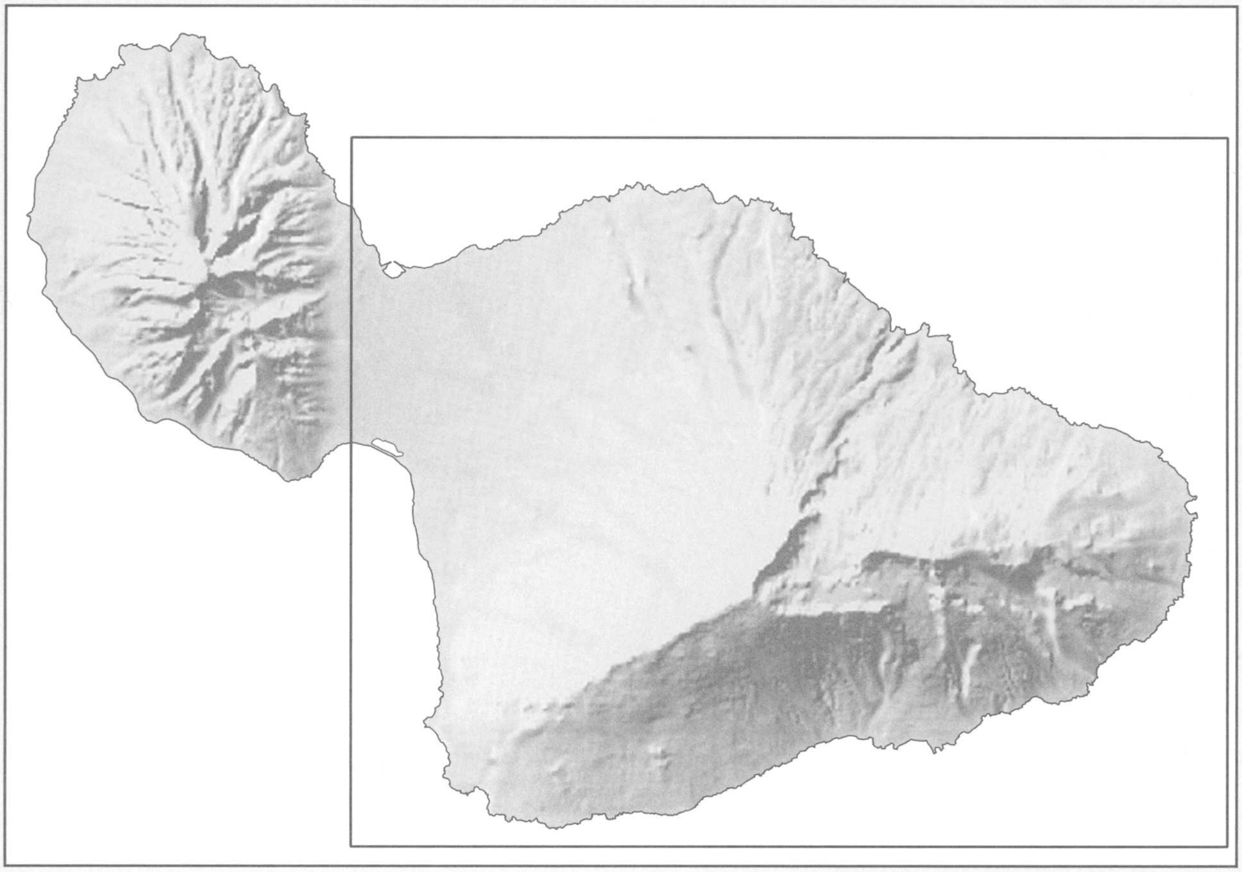
U.S. Department of the Interior

Water Budget of East Maui, Hawaii

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 98-4159



Prepared in cooperation with the
COUNTY OF MAUI DEPARTMENT OF WATER SUPPLY
STATE OF HAWAII COMMISSION ON WATER RESOURCE MANAGEMENT

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By Patricia J. Shade

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Honolulu, Hawaii

1999

U.S. DEPARTMENT OF THE INTERIOR
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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 day (in/d)	2.54	centimeter per day
inch per year (in/yr)	2.54	centimeter per year

Water Budget of East Maui, Hawaii

By Patricia J. Shade

Abstract

Ground-water recharge is estimated from six monthly water budgets calculated using long-term average rainfall and streamflow data, estimated pan-evaporation and fog-drip data, and soil characteristics. The water-budget components are defined seasonally, through the use of monthly data, and spatially by broad climatic and geohydrologic areas, through the use of a geographic information system model.

The long-term average water budget for east Maui was estimated for natural land-use conditions. The average rainfall, fog-drip, runoff, evapotranspiration, and ground-water recharge volumes for the east Maui study area are 2,246 Mgal/d, 323 Mgal/d, 771 Mgal/d, 735 Mgal/d, and 1,064 Mgal/d, respectively.

INTRODUCTION

Growth in resident population, tourism, and commercial development has increased the demand for freshwater on Maui. Presently, the main source for municipal supply is located on the western side of the island and is being stressed near its limit. A potential supplementary source of ground water is in the northeastern part of the east Maui study area (fig. 1). Substantial interaction between ground water and surface water is indicated by the large perennial discharge of many streams and springs in the northeast part of the study area. It is possible that ground-water development could reduce the perennial flow in these streams. Thus, in an effort to protect instream water uses and to increase knowledge of the interaction between the ground-water and surface-water flow systems on volcanic islands, the State of Hawaii Commission on Water Resource Management and the Maui County Department of Water entered into a cooperative agreement with the U.S. Geological Survey to quantify ground-water discharges to streams in the area, and to simulate the ground-water flow system. The project includes a water-budget calculation described in this report and subsequent description of the ground-water flow system using the ground-water recharge data provided by the water budget.

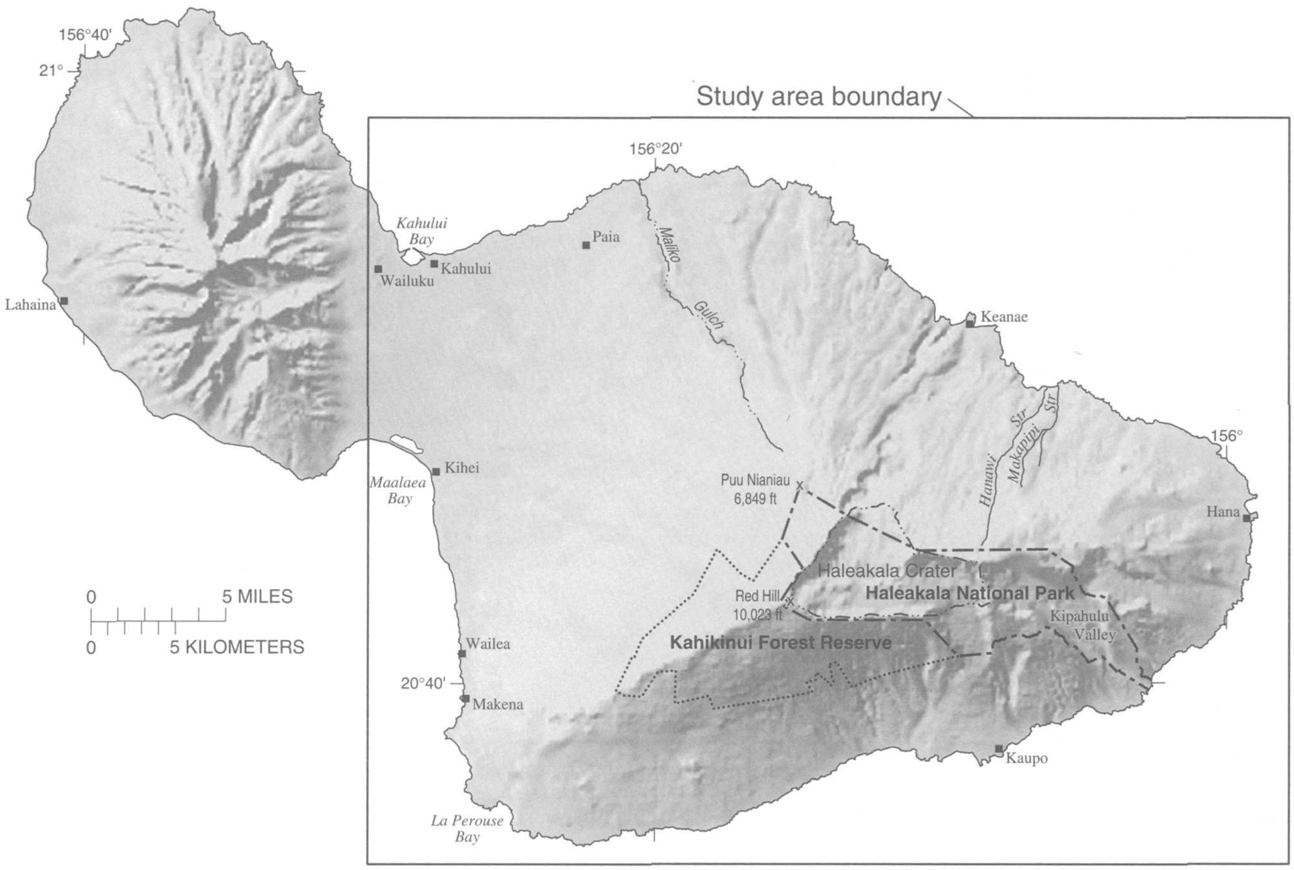
Purpose and Scope

The purpose of this report is to describe the calculation of a mean monthly water budget for east Maui. Extensive areas of east Maui are sparsely populated and are protected in the form of conservation areas, forest reserves, or State and national parks. Thus, only natural land use was modeled.

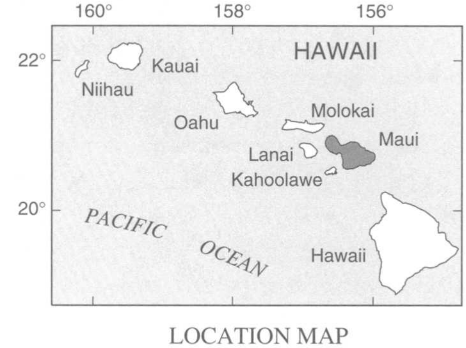
No new data were collected for this study. The availability of monthly mean rainfall distribution maps for east Maui was the determining factor for the monthly period used in the water-budget calculation. Six water budgets with variations in accounting sequences and fog-drip contribution are described. Together the budgets present a range of evapotranspiration and ground-water recharge values useful for water-resource management. A map of the average ground-water recharge is displayed and the water-budget components are tabulated by selected physiographic subareas and by water-management areas.

Surface-Water Gaging-Station Numbers

The surface-water gaging stations mentioned in this report are numbered according to the USGS numbering system. For this report, however, the complete 8-digit number is abbreviated to the middle 4 digits; for example, station 16508000 is referred to as 5080.



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 20°39'30" and 20°57'30", central meridian 156°20'15". Shaded relief from U.S. Geological Survey digital elevation models, 1:250,000



LOCATION MAP

Figure 1. Island of Maui and east Maui study area, Hawaii.

Previous Investigations

Water-budget estimates relevant to this investigation were included in State of Hawaii (1990). Stearns and Macdonald (1942) describe the geology and ground-water resources for the entire island of Maui. Takasaki and Yamanaga (1970) describe geologic structures and their water-bearing properties, as well as ground-water and surface-water interaction in the northeast part of Maui. Takasaki (1971) discusses the water-bearing properties of geologic structures and water resources of southeast Maui. Takasaki (1972) describes the water resources and geology of central Maui, which is included in the east Maui study area.

Description of the Study Area

The study area of 567.3 mi^2 encompasses the part of the island of Maui east of 156°30′00″ longitude (fig. 1). The area is dominated by the Haleakala Volcano, which rises to an altitude of 10,023 ft above mean sea level at Red Hill. A variety of climates have developed as a result of the interaction of this mountain mass with the predominant northeast tradewind flow pattern. For the purposes of this report the study area is divided into several physiographic zones, A through F (fig. 2). Zone A is characterized by low rainfall and abundant sunshine. There is irrigated agriculture on the isthmus between the urban centers of Kahului and Kihei where average rainfall is less than 25 in/yr (fig. 3). Further south along the coast at Wailea and Makena, where rainfall is about 15 in/yr, resort development has been considerable. Upslope of this area, rainfall increases with altitude to about 50 in/yr and temperatures are cooler along the mid-altitude slopes of Haleakala. Small residential communities are located in this area among farms that specialize in crops such as Maui onions, cabbage, and flowers such as carnations and proteas that thrive with cooler temperatures. Further upslope are ranches and forest reserves adjacent to the western boundary of Haleakala National Park, which lies between Puu Nianiau (6,849 ft) and Red Hill (fig. 1).

Zone B represents the crater of Haleakala, the floor of which is at an average altitude of about 7,000 ft. This area lies almost entirely within the boundaries of the national park where the major activities are hiking and camping. The effect of the temperature inversion on rainfall is apparent with annual means ranging from less than 25 to 75 in. for most of the area. Rainfall increases at the eastern edge of the area to more than 100 in/yr. Vegetation is sparse over much of the crater floor.

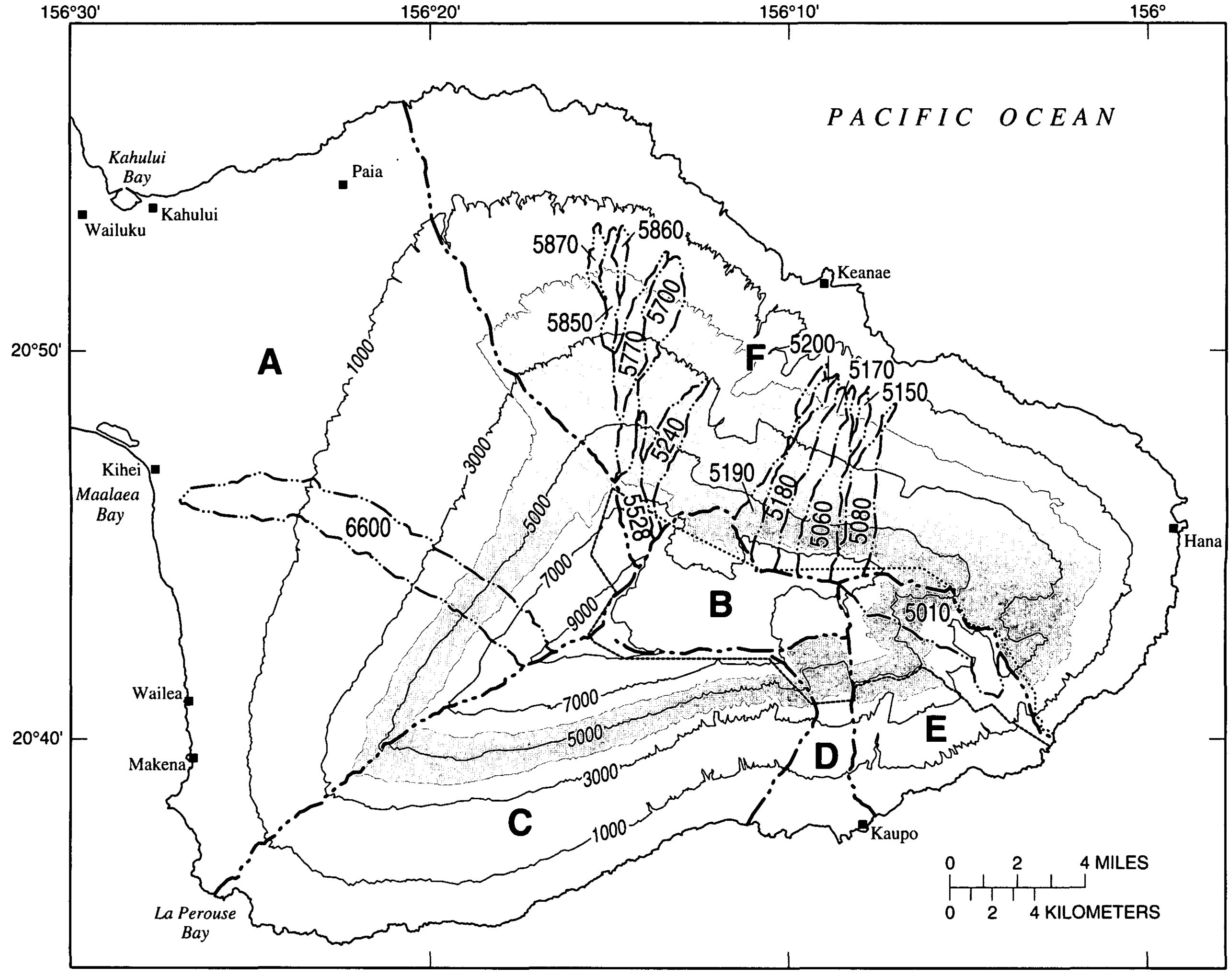
On the leeward (southern) side of Haleakala, (fig. 2, zone C) the climate is dry with average rainfall ranging from about 75 in/yr near the southern national park boundary to about 25 in/yr at the southern coast (figs. 1 to 3). This area is sparsely populated and covered by dry-land vegetation at lower altitudes. Between the park boundary and above about 4,000-ft altitude, the area is dominated by the Kahikinui forest reserve (fig. 1).

Farther east on the leeward side, rainfall increases to a maximum of about 200 in/yr (fig. 3). Near Kaupo and the eastern side of zone E (figs. 1 and 2) there are small settlements and extensive conservation and forest reserve areas to protect native Hawaiian flora and fauna. Zone D is drier than zone E with a mean annual rainfall of less than 150 in. near the crater (zone B) and less than 50 in/yr west of Kaupo along the coast. In the northern part of zone E the mean annual rainfall is more than 200 in., and at the coast rainfall is more than 75 in/yr.

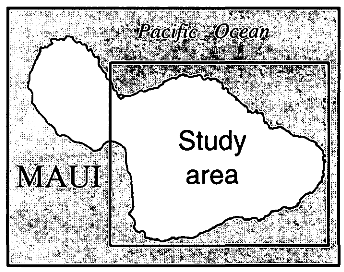
Around the eastern flank of the volcano towards the north (fig. 2, zone F), the climate changes to a wet, windward regime dominated by the orographic rainfall that is generated by the strong northeast tradewind flow of warm, moist air forced to rise and cool by the Haleakala Volcano. At low altitudes there are small farms and towns, and at intermediate altitudes, rain forests densely cover the slopes to about 7,000 ft. Because of a temperature inversion above about 6,560 to 8,200 ft (Giambelluca and Nullet, 1991 and Lavoie, 1967), rainfall decreases, and grasses and shrubs cover the upper slopes to the north wall of Haleakala Crater (zone B). Ground- and surface-water resources are significant in this area. Taro is grown near Keanae by capturing some flow from streams and springs in the area. Large water-development projects, constructed beginning in the late 1870's, include ditches and tunnels that capture and route large volumes of water for sugarcane cultivation on the isthmus in zone A.

WATER-BUDGET MODEL

Ground water is replenished by recharge from rainfall and fog drip that percolates through and beyond the root zone to the subsurface rock. Ground-water recharge can be estimated using a water-budget model. The method used in this study for estimating the water budget is similar to that developed by Thornthwaite



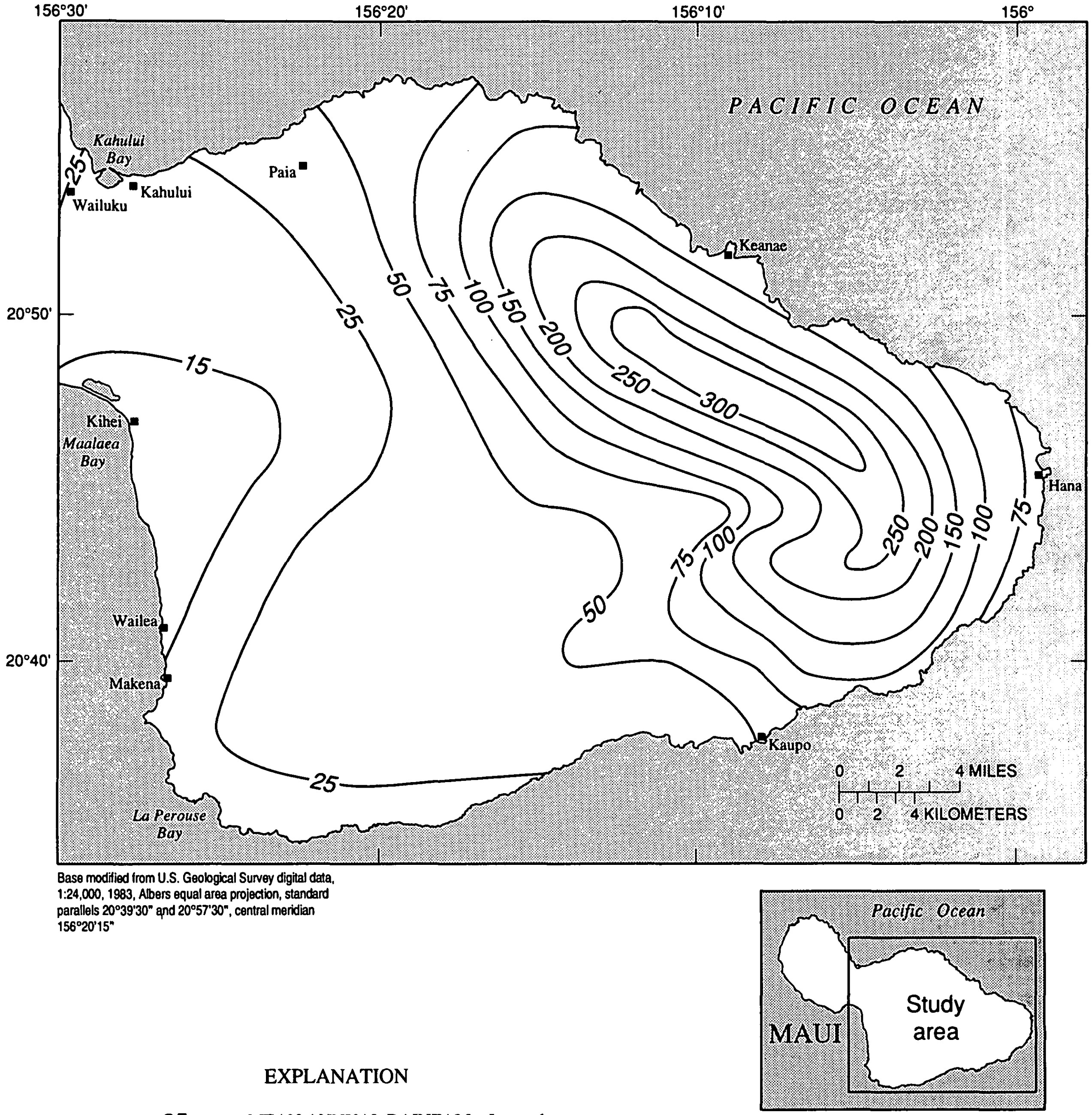
Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 20°39'30" and 20°57'30", central meridian 156°20'15"



EXPLANATION

- FOG AREA
- PHYSIOGRAPHIC ZONE DIVIDE
- **B** PHYSIOGRAPHIC ZONE
- DRAINAGE BASIN DIVIDE
- 5010 ABBREVIATED STREAM-GAGING STATION NUMBER (COMPLETE NUMBER IS 16501000)
- BOUNDARY OF HALEAKALA NATIONAL PARK
- —*1000*— TOPOGRAPHIC CONTOUR--Interval 1,000 and 2,000 feet

Figure 2. Selected drainage basins and fog area, east Maui, Hawaii.



EXPLANATION

—25— MEAN ANNUAL RAINFALL--Interval, in inches, is variable. Contours were determined by summing the monthly mean rainfall maps of Giambelluca and others (1986)

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

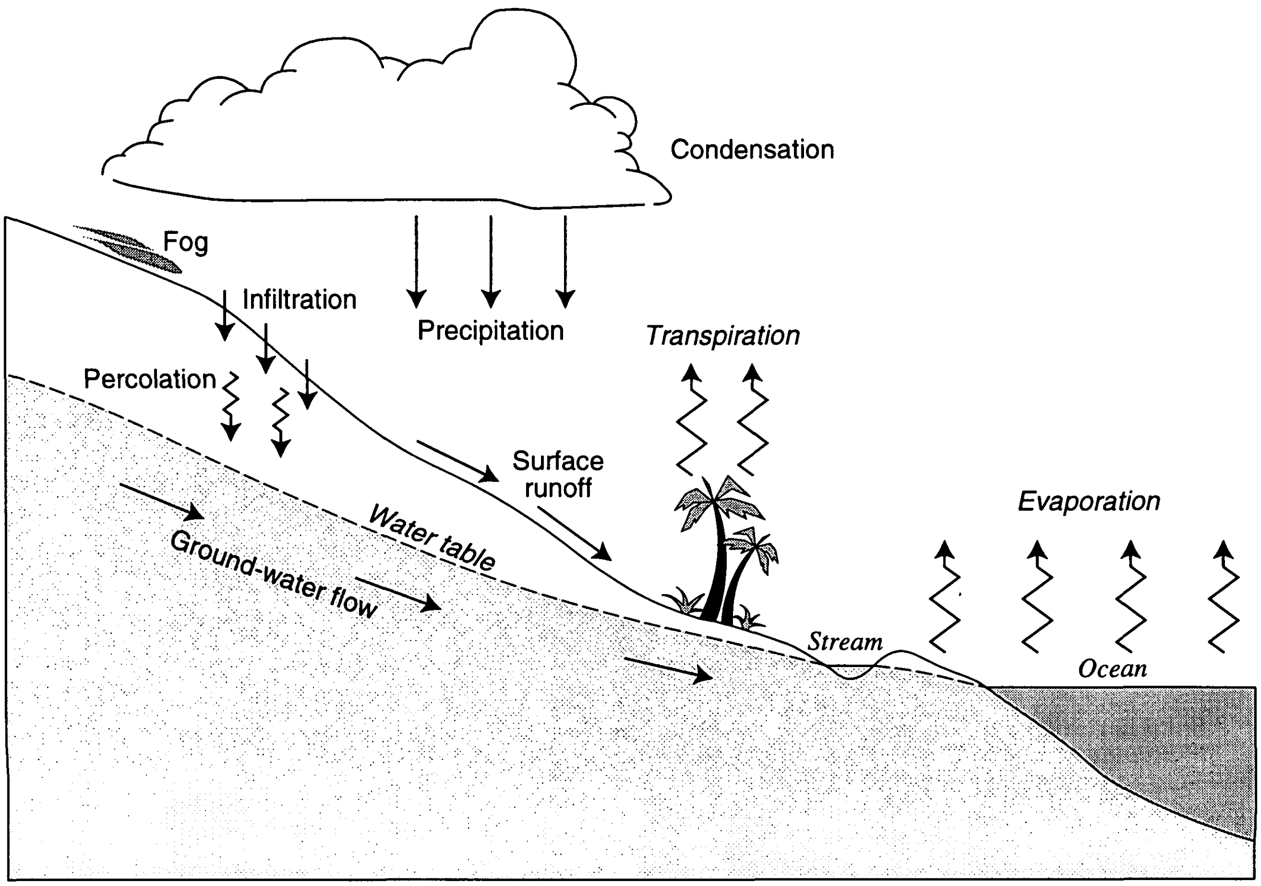


Figure 4. The hydrologic cycle.

(1948) and Thornthwaite and Mather (1955) and is an accounting procedure that balances moisture input of rainfall and fog drip (cloud-water interception); moisture output of runoff, evapotranspiration, and ground-water recharge; and the change in soil-moisture storage. (fig. 4). The relation of the water-budget components is expressed by:

$$G = P + F - R - ET - \Delta SS, \qquad (1)$$

where:
G = ground-water recharge,
P = rainfall,
F = fog drip,
R = runoff,
ET = evapotranspiration, and
ΔSS = change in soil-moisture storage.

In the water-budget model for most of the study area, runoff was calculated as a percentage of rainfall and thus the budgeting method solves for the remaining components of ground-water recharge, evapotranspiration, and change in soil-moisture storage. The monthly values of each water-budget component represent average long-term climatic conditions.

The accuracy of the water budget is predominantly determined by the available data for the time period for which the budget is calculated. Because measurements of rainfall, fog drip, runoff, evapotranspiration, and percolation rates made every minute would faithfully describe the movement of water through the hydrologic cycle, a budget calculated with such data would likely yield accurate volumes for all components at the measurement location. But, for large study areas such as east Maui, continuous measurements are usually made of just rainfall and streamflow and these measurements are not made uniformly throughout the area. At some locations only peak streamflow may be measured, and rainfall measuring instrumentation may consist of a container that measures only the total rain that falls between station visits providing only coarse temporal information. If the budget is calculated using mean data for time periods greater than a day, such as months or years, the resulting budget-component volumes become less accurate, and the level of inaccuracy can not be distinctly determined because of the lack of data. By using mean data, the budget does not explicitly describe the quantity of water that moved through each component of the hydrologic cycle at a specific site. However, the budget does provide average component volumes that are useful and appropriate for regional assessments of resource availability.

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, fog drip, runoff and associated drainage area, soil-type distribution and properties, and pan-evaporation distribution. The spatial data allow the water-budget components to be calculated and displayed by individual area or any combination of areas.

Rainfall

The rainfall distribution in east Maui is influenced by the orographic effect of Haleakala Volcano. Rainfall is abundant as the prevailing northeast tradewinds are forced to rise and cool over the mountain mass. At altitudes below the atmospheric temperature inversion (from about 6,560 to 8,200 ft), rainfall generally increases with increasing altitude. At altitudes above the inversion the environment is dry; the Haleakala summit area is one of Maui's two minimum rainfall areas (Giambelluca and others, 1986). Thus, on the windward (north) side of the volcano, moving from the shore upslope to the wall of Haleakala Crater, rainfall increases with increasing altitude to a maximum of about 350 in/yr, and then decreases with altitude above about 6,560 ft to less than about 39 in/yr at Haleakala summit (fig. 3) (Giambelluca and others, 1986). On the leeward (south) side of Haleakala, rainfall continues to decrease from the summit of Haleakala toward the shore to a minimum of less than 25 in/yr near La Perouse Bay. Rainfall is nearly continuous in the maximum areas, and occurs in all manners from light drizzle for several days, to extremely intense downpours with hourly totals of more than 1 in. occurring for several hours. In the dry areas, intense, infrequent rainfall is more the norm, and there are many days of no rainfall.

Giambelluca and others (1986) prepared twelve maps (January–December) showing lines of equal mean monthly rainfall for the island of Maui. The maps were compiled from data collected at more than 250 sites including a network of 18 base stations that had complete records for the base period from 1916 through 1983. Data from an additional 11 long-term stations were used in the statistical analyses. Data from short-term stations were extrapolated for the final analysis and map construction (Giambelluca and others, 1986, p. 6–12). In the analysis of mean annual rainfall, the most weight was given to stations with the longest record. However, there is an element of subjectivity in the interpretation and contouring of these data. 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 two bounding lines (fig. 5).

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 about 3,036 Mgal/d in December to a low of about 1,418 Mgal/d in June (table 1 and fig. 5). Winter rainfall ranges from about 2,502 to 3,036 Mgal/d from November through April, and summer rainfall ranges from about 1,418 to 1,865 Mgal/d from May through October. During the summer, rainfall increases in July and August relative to June and September because tradewinds are more persistent.

Fog Drip

Presently, long-term data for cloud-water interception, locally referred to as fog drip, are not available for east Maui. However, research regarding the contribution of fog drip to the hydrology of high mountain areas in Hawaii (Juvik and Nullet, 1995; Giambelluca and Nullet, 1991) allows this component of the water budget for east Maui to be estimated. The fog zone on the windward (north) side of Haleakala Volcano extends from the mean cloud base level, at about 1,970 ft, to the lower

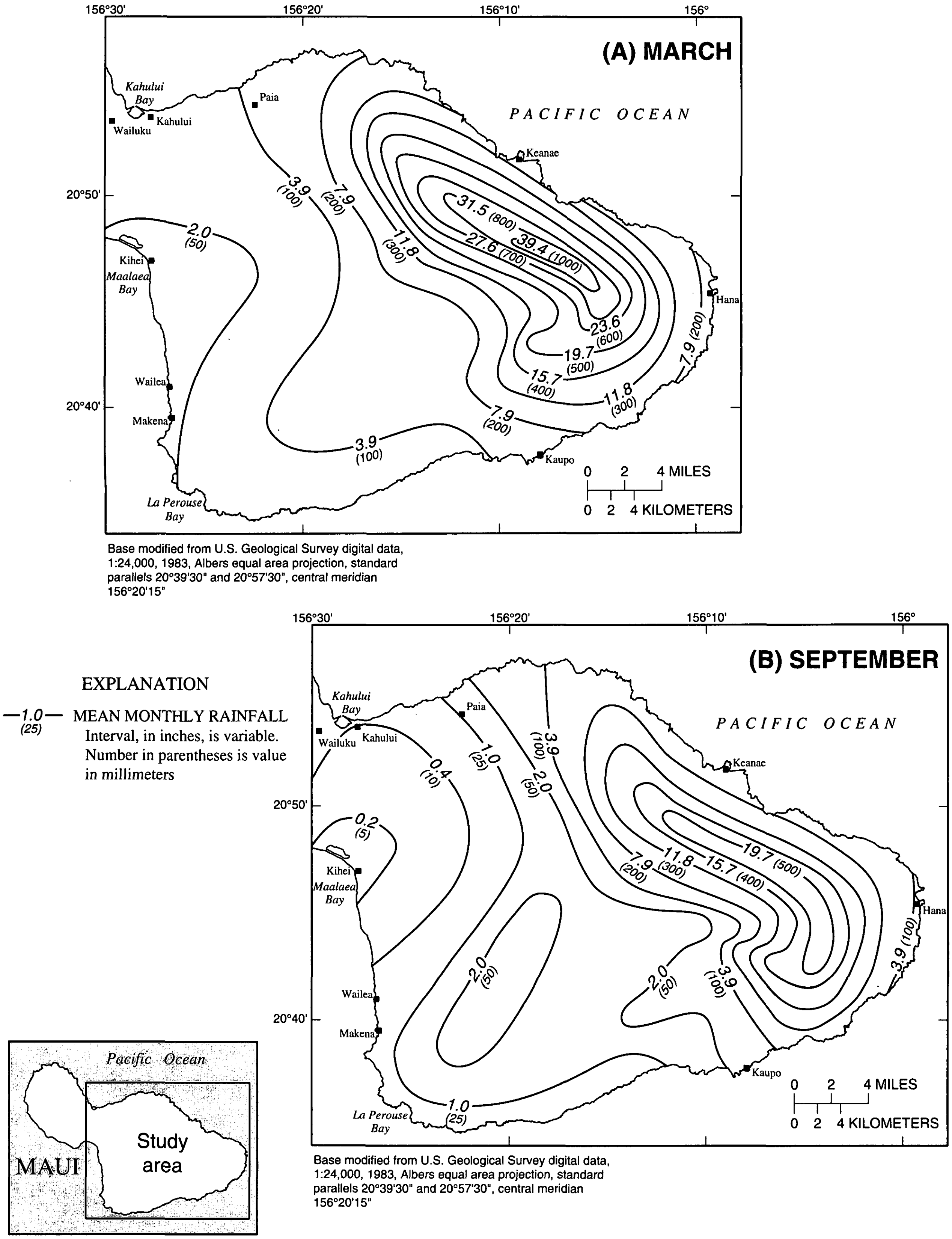


Figure 5. Mean monthly rainfall for (A) March (wet season) and (B) September (dry season), east Maui, Hawaii (modified from Giambelluca and others, 1986).

Table 1. Water-budget components, east Maui, Hawaii

[Values in million gallons per day; PE, potential evapotranspiration; ET, evapotranspiration; I, recharge first; II, ET first; a, fog; b, no fog; avg, average of methods I and II; EndSS, end of month soil-moisture storage; ΔSS, the change in soil-moisture storage; mean, sum of monthly values divided by 12; --, not applicable. The sum of rainfall plus fog drip minus direct runoff, ET, and recharge may not equal zero because of rounding. Any other imbalance is owing to an unequal number of days in the months]

Water-budget component	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
Rainfall	2,854	2,713	2,964	2,748	1,835	1,418	1,716	1,865	1,506	1,797	2,502	3,036	2,246
Fog drip	137	141	162	320	232	186	551	584	470	311	433	343	323
Runoff	934	940	1,104	1,169	678	338	516	630	393	555	922	1,067	771
PE	792	1,068	888	1,143	1,952	4,068	3,185	2,295	2,785	1,761	1,210	845	1,833
ET I,a	599	722	610	683	665	539	533	561	598	625	649	584	614
ET I,b	599	722	609	682	660	531	516	543	580	610	640	583	607
ET II,a	789	1,023	836	956	1,064	789	705	764	816	842	885	796	855
ET II,b	789	1,023	836	955	1,056	766	674	726	778	820	872	795	841
ET avg,a	694	873	723	820	865	664	619	663	708	734	768	690	735
ET avg,b	694	872	723	818	858	648	595	634	679	715	757	689	723
Recharge I,a	1,411	1,263	1,382	1,297	860	764	1,185	1,248	1,027	909	1,283	1,588	1,185
Recharge I,b	1,273	1,123	1,220	978	633	585	653	683	573	614	858	1,246	870
Recharge II,a	1,129	927	1,211	1,046	600	566	1,021	1,042	795	686	1,010	1,285	944
Recharge II,b	985	790	1,046	732	386	393	507	498	361	398	585	944	635
Recharge avg,a	1,269	1,095	1,296	1,171	730	665	1,104	1,145	911	798	1,146	1,437	1,064
Recharge avg,b	1,130	958	1,133	854	509	489	580	591	468	506	721	1,095	752
EndSS I,a	325	285	290	219	75	42	73	82	42	62	144	279	--
EndSS I,b	325	285	289	219	76	42	71	81	43	60	143	279	--
EndSS II,a	830	873	770	692	395	319	333	346	331	346	476	693	--
EndSS II,b	829	869	769	688	381	315	325	336	320	334	468	684	--
EndSS avg,a	578	579	530	455	235	182	203	214	187	204	310	486	--
EndSS avg,b	577	577	529	453	228	179	199	209	182	198	306	482	--
ΔSS I,a	+46	-40	+5	-71	-144	-35	+31	+9	-40	+20	+82	+135	--
ΔSS I,b	+46	-40	+4	-70	-143	-34	+29	+10	-38	+17	+83	+136	--
ΔSS II,a	+137	+43	-103	-78	-297	-76	+14	+13	-15	+15	+130	+217	--
ΔSS II,b	+145	+40	-100	-81	-307	-66	+10	+11	-16	+14	+134	+216	--
ΔSS avg,a	+92	+1	-49	-75	-220	-53	+21	+11	-27	+17	+106	+176	--
ΔSS avg,b	+95	0	-48	-76	-225	-49	+20	+10	-27	+16	+108	+176	--

limit of the most frequent temperature inversion base height at about 6,560 ft (Giambelluca and Nullet, 1991). Therefore, the 2,000-ft and 6,560-ft contours were digitized from a 1:62,500 scale map to represent the fog zone in the water-budget model (fig. 2). Juvik and Nullet (1995, fig. 2, p. 168) presented an illustration that generalizes the fog contribution, relative to rainfall, on the windward slopes of Mauna Loa on the island of Hawaii. Fog-drip/rainfall ratios (table 2) estimated from this illustration were multiplied by the monthly rainfall values in east Maui within the fog area (fig. 2) to calculate the fog-drip contribution to the water budget. The high July to September ratio is the result of a well-developed atmospheric temperature inversion and strong tradewinds. As the moist air is forced upslope, cloud height is restricted by the inversion, thus favoring fog rather than rain-drop formation (Juvik and Nullet, 1995, p. 169). Fog-drip estimates range from about 137 to 320 Mgal/d from January through June and from about 311 to 584 Mgal/d from July through December (table 1). Figure 6 shows the relative proportions of rainfall and fog drip in the windward east Maui area.

Table 2. Fog-drip/rainfall ratios for windward slopes of Mauna Loa, island of Hawaii

[Values in percent; estimated from Giambelluca and Nullet, 1991, fig. 2]

January–March	13
April–June	27
July–September	67
October–November	40
December	27

Recently, fog-drip measurements were made at three sites within zone C (Juvik and Hughes, 1997). Although only a single site had a complete record for the year between May 1996 and June 1997, the sparse data generally agree with the ratios shown in table 2, except for the months of August through October. During these months, their conservative fog-drip/rainfall ratios ranged from 1.5 to 3.3 (Juvik and Hughes, 1997, p. 19) compared with the 0.4 to 0.67 ratios shown in table 2. Therefore, for these months it is possible that fog drip has been underestimated in the present water-budget model. Because the fog-drip component is poorly known, the water budget was calculated with and without fog drip.

Runoff

In the water-budget model, runoff is calculated as a percentage of rainfall in most areas. Streamflow consists of runoff (R in equation 1), the water that flows into stream channels promptly after rainfall, and base flow, 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, mean monthly runoff was calculated as the difference between mean monthly streamflow and mean monthly base flow in perennial streams.

In zone A, data are available for one drainage basin measured at stream-gaging station 6600 (fig. 2) on a stream that is not perennial. Monthly runoff-rainfall ratios for the basin were developed by comparing the mean basin rainfall for each month with the related mean monthly streamflow measured at station 6600. There are no perennial streams in this area, and thus the mean monthly streamflow-rainfall ratios at station 6600 (table 3) were applied to the rainfall over this basin as well as over all of zone A to calculate monthly runoff values.

There are no defined stream channels or streamflow data for Haleakala Crater (zone B). Similarly, there are no long-term continuous streamflow data for leeward zones C and D (fig. 2). Although these areas are considerably different in terms of geologic age, and thus, shape and height of the volcanic mountain, the range of mean annual rainfall values, the soil permeability rates, and the general leeward rainfall regime of these areas is similar to those of the leeward southern Oahu area (table 4). Shade and Nichols (1996) derived a mean annual runoff-rainfall regression equation (eq. 2) from a detailed monthly water budget of the leeward southern Oahu area (Giambelluca, 1983).

$$\text{For annual rainfall} \leq 175 \text{ in.: mean annual runoff} = 0.013 \times \text{mean annual rainfall}^{1.536}. \qquad (2)$$

The equation was used with mean annual rainfall values (sum of mean monthly rainfall) to calculate mean annual runoff for any location within the three leeward Maui zones B, C, and D (fig. 2). The mean annual runoff values were apportioned to mean monthly runoff by the respective monthly-rainfall/annual-rainfall ratios calculated for any location in these zones.

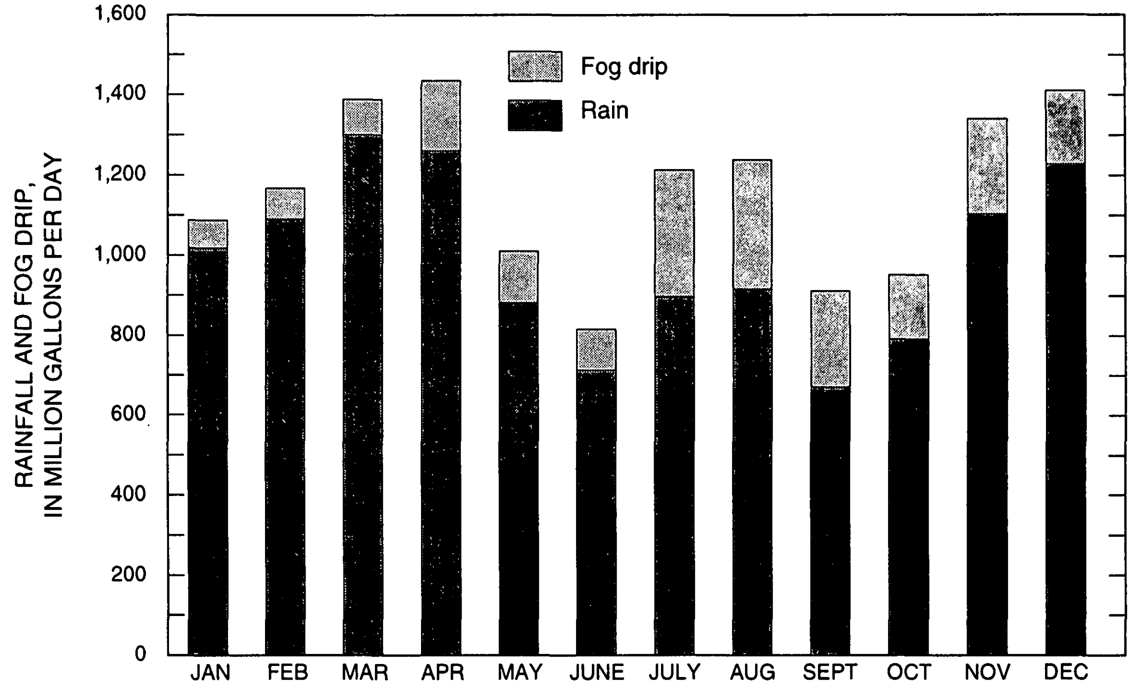


Figure 6. Relative proportion of rainfall and fog drip in the windward east Maui area, Hawaii.

Table 3. Base-flow values and runoff/rainfall ratios, selected drainage basins, east Maui, Hawaii

[Mean values in percent except for base flow; Mean, sum of monthly base-flow values divided by 12; Mgal/d, million gallons per day; --, not applicable; <, less than; complete station number is preceded by 16 and ends in 00]

Drainage basin gaging station number	Gaging station location	Mean base flow (Mgal/d)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
5010	Palikea Stream	1.07	67	82	77	58	54	36	47	47	30	47	58	62
5080	Hanawi Stream	3.76	50	48	49	49	30	16	26	26	20	30	40	37
5150	Waiohue Gulch	3.57	67	85	66	66	46	29	34	41	31	37	57	71
5160	Kopiliula Stream	4.29	53	45	45	57	45	23	32	37	30	35	43	53
5170	East Wailuaiki Stream	4.80	64	56	53	65	51	26	34	39	32	39	48	61
5180	West Wailuaiki Stream	4.70	65	67	72	80	48	26	40	42	37	49	64	58
5190	West Wailuanui Stream	2.30	54	49	48	54	51	25	32	39	34	37	42	54
5200	East Wailuanui Stream	1.68	64	72	63	65	60	41	43	49	44	43	60	72
5240	Honomanu Stream	0.79	52	34	46	39	29	21	20	21	27	34	57	31
5528	Waikamoi Stream	0.05	13	29	6	12	10	6	9	15	4	10	17	20
5700	Nailiilihaele Stream	7.27	49	55	50	57	57	33	46	46	38	44	58	57
5770	Kailua Stream	4.32	70	70	73	71	59	41	52	59	39	52	59	87
5850	Hoolawanui Stream	2.70	44	52	40	52	46	22	27	38	26	29	48	51
5860	Hoolawaliilii Stream	2.33	63	50	50	62	57	24	34	49	32	33	56	59
5870	Honopou Stream	1.21	45	38	40	46	36	21	24	33	23	27	42	39
6600	Kulanihakoi Gulch	--	1	1	5	<1	<1	0	<1	0	<1	0	2	<1

Table 4. Annual rainfall and permeability of soils in southern Oahu and east Maui zones B, C, and D
[>, greater than; from Foote and others, 1972; Saku Nakamura, oral commun., 1998; and Giambelluca and others, 1986]

Oahu soil series	Oahu annual rainfall (inches)	Permeability (inches per hour)	East Maui soil series	East Maui annual rainfall (inches)	Permeability (inches per hour)
Rock outcrop	93–170	0	Rock outcrop	50–180	0
Rock land	20–328	0.06–2.0	Rock land	38–88	0.06–2.0
Rough mountain land	80–328	0.2–6.0	Rough mountain land	93	0.2–6.0
Lahaina	25–82	0.63–2.0	Waiakoa	24–30	0.63–2.0
Stony steep land	23–39	2.0–6.0	Stony alluvial land	30–39	2.0–6.0
Helemano	24–148	2.0–6.3	Io	24–31	2.0–6.3
			Kaupo	40–60	2.0–6.3
			Oanapuka	20	2.0–6.3
			Puu Pa	44–55	2.0–6.3
Jaucas	19–27	6.3–20	Cinder land	21–70	6–20
			Very stony land	29–120	6–20
			Aa lava flow	22–68	20
			Uma	31–48	>20

In zone E, a transitional area between windward and leeward rainfall regimes (fig. 2), data are available for only one perennial stream. Flow in this stream is measured at station 5010. Runoff is calculated as the difference between total streamflow and base flow in perennial streams. Base flow was calculated using an automated base-flow hydrograph separation program developed by Wahl and Wahl (1995). The daily streamflow data at station 5010 was divided into non-overlapping N-day periods for which the base-flow separation model computes a minimum flow. The appropriate N-value for this basin was estimated by the point of slope change on a graph of the ratio of base flow to total flow compared with the number of days (N) in the period. As proposed by the Institute of Hydrology (Wahl and Wahl, 1995, p. 80) the value for f, the turning-point test factor, was set at 0.9, which indicates that if the minimum flow within a given N-day period is less than 90 percent of the adjacent minimums, then the central minimum is a turning point on the base-flow hydrograph. The base-flow hydrograph is defined on semilogarithmic paper by straight lines connecting all turning points. The area beneath the hydrograph represents the volume of base flow for the period of record. The daily base flow was summed for each month and monthly average base-flow values were calculated for the period of record. The mean base flow at this station is listed in table 3 and monthly runoff/rainfall ratios (table 3) determined for the gaged area were applied to the rainfall over all of zone E to calculate runoff for the zone.

In zone F, 14 gaged drainage basins were digitized (figs. 2 and 7). The topographic boundaries of these basins do not necessarily coincide with ground-water divides, although the results of the base-flow and water-budget analyses can indicate where some discrepancies occur. Streamflow is perennial at all of the gages. The same method used to calculate the monthly base-flow separation and runoff/rainfall ratio for transitional area zone E, was followed for zone F.

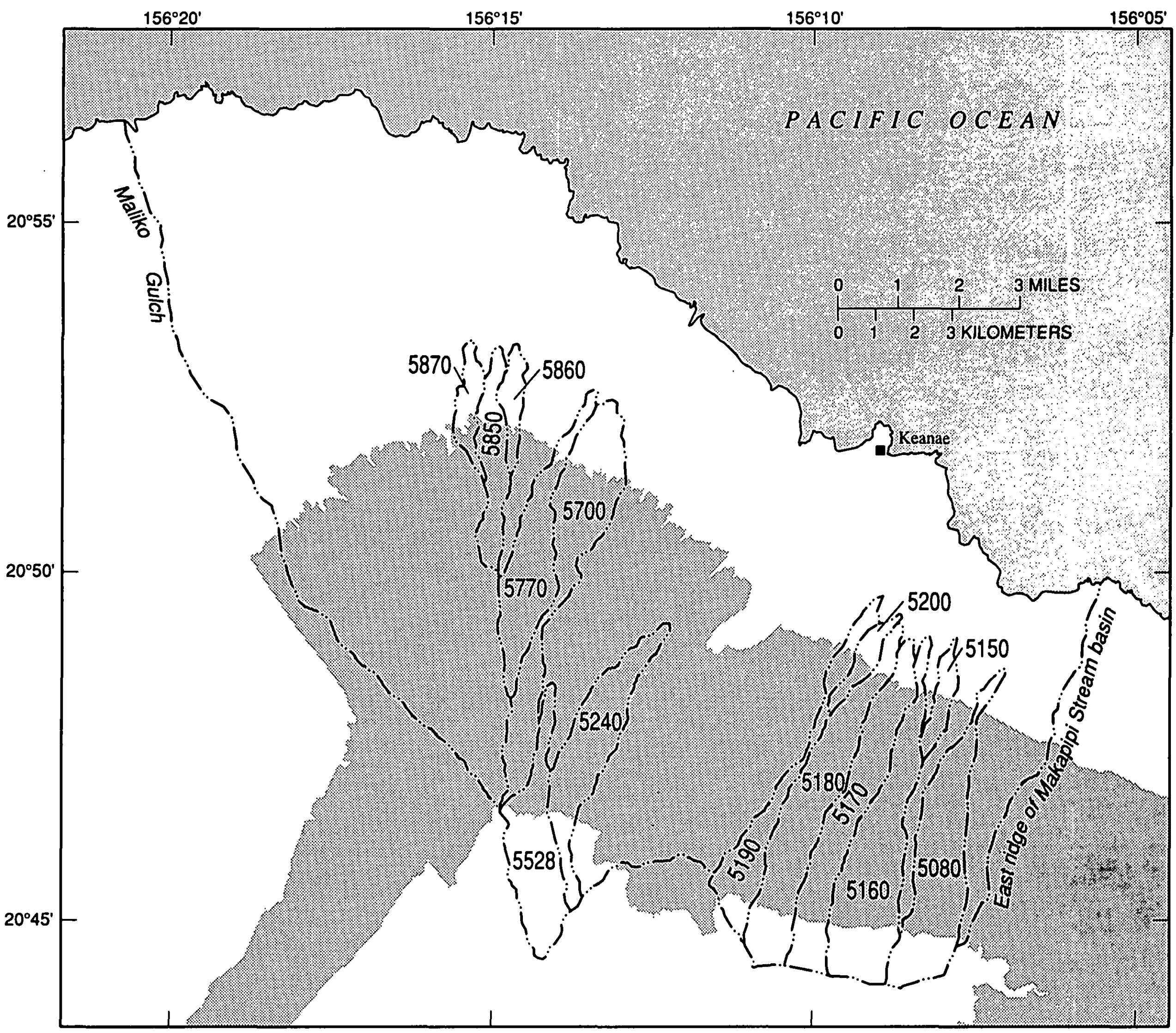
The mean monthly runoff at each gage in zone F was divided by the mean monthly rainfall over the respective drainage basin to calculate a monthly runoff/rainfall ratio for each basin (table 3). Each drainage-basin runoff/rainfall ratio was multiplied by the mean monthly rainfall within the respective drainage basin or subarea of the basin to calculate a mean monthly runoff for that basin or subarea.

These 14 drainage basins are located in the windward part of east Maui in zone F (figs. 2 and 7) between Maliko Gulch on the west to Makapipi Stream basin on the east (fig. 1). Monthly regression equations were developed in the form of:

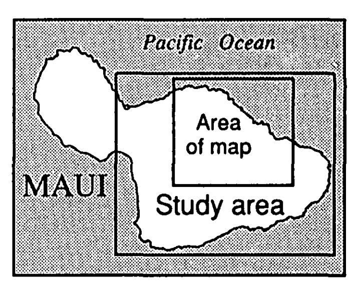
$$\text{runoff} = a\,(\text{rainfall}) + b, \qquad (3)$$

where:

runoff is the mean monthly runoff, in inches,
a is the slope of the regression line,
rainfall is the mean monthly rainfall, in inches, and
b is the regression line intercept at the y-axis.



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 20°39'30" and 20°57'30", central meridian 156°20'15"



EXPLANATION

FOG AREA

DRAINAGE BASIN DIVIDE

5850 ABBREVIATED STREAM-GAGING STATION NUMBER (COMPLETE NUMBER IS 16585000)

Figure 7. Selected drainage basins and fog area for windward east Maui, Hawaii.

The regression equations use the mean monthly drainage basin rainfall and mean monthly runoff data from these 14 drainage basins. Table 5 lists the monthly regression equation coefficients. These equations were used to calculate monthly runoff from rainfall for the remaining part of the windward area (zone F, fig. 2) outside of the 14 drainage basins.

Table 5. Regression equation coefficients for the calculation of mean monthly runoff for areas of zone F outside of the 14 gaged drainage basins, using equation 3
[*a*, slope of regression line; *b*, regression line intercept at y-axis; r^2, coefficient of determination]

Month	*a*	*b*	r^2
January	1.08	-8.75	0.94
February	1.21	-10.91	0.91
March	0.88	-7.76	0.91
April	0.82	-4.71	0.93
May	0.64	-2.57	0.92
June	0.43	-1.84	0.89
July	0.49	-2.18	0.89
August	0.55	-2.14	0.92
September	0.46	-1.58	0.91
October	0.47	-1.25	0.92
November	0.73	-3.92	0.92
December	1.02	-9.50	0.86

Evapotranspiration

Evapotranspiration (ET) is the quantity of water evaporated from soil and water surfaces and from plant transpiration, which is the vaporization of water through the plant's stomata (Brutsaert, 1982). Estimates of evapotranspiration rates can best be made using several methods including the use of evaporimeters or lysimeters in field studies, or mathematically by the use of various climatic data and, for some areas, from crop information. These types of data are usually available only for local areas where data has been collected intensively. For this regional water budget, these data are not available, however, so evapotranspiration was estimated using soil and pan-evaporation data.

Soil Characteristics

Soils of east Maui have been mapped and digitized and their characteristics tabulated by the Natural Resources Conservation Service (Foote and others, 1972) (table 6). An attribute data table including values of permeability, available water capacity (a measure of the quantity of water held by the soil available to plants between field capacity and wilting point), and the root depth (Foote and others, 1972) was associated with the soil-type spatial distribution in the GIS model. Data that were not available from Foote and others (1972) were provided by the Natural Resources Conservation Service (Nicole Vollrath, NRCS, written commun., 1996).

The available-water capacity for each soil series in table 6 is the average of the range reported by Foote and others (1972). The root 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." The maximum soil-moisture storage (SS_{max}) is the product of the root depth and the available water capacity for the soil type (table 6). A distribution map (fig. 8) of maximum soil-moisture storage was created for use in the GIS model.

Pan Evaporation and Potential Evapotranspiration

Pan evaporation data from class-A evaporating pans are used to provide an estimate of the potential (maximum) evapotranspiration (PE). Potential evapotranspiration is an estimate of the maximum evapotranspiration from an extensive area of well-watered, actively growing vegetation. Thus, although influenced by other factors, potential evapotranspiration is primarily a function of solar radiation energy (Chang, 1968, p. 131; Mather, 1978, p. 8). In dry, sunny areas, evapotranspiration rarely occurs at the estimated *potential* rate without irrigation, because there is a lack of water to satisfy the maximum demand described by the potential evapotranspiration value. For this study, pan evaporation is assumed to equal potential evapotranspiration on the basis of the results of lysimeter studies in sugarcane fields in Hawaii (Chang, 1968; Campbell and others, 1959) where the average ratio between potential evapotranspiration and pan evaporation was about 1.0. This 1.0 ratio may underestimate potential evapotranspiration in wet, forested areas. Giambelluca (1983) lists ratios of 1.0 for forests in dry and moderately wet areas, and 1.3 for wet, forested areas.

Mean annual pan evaporation data are available for only the western part of east Maui (Ekern and Chang, 1985) (fig. 9). For the remainder of the study area, a relation between potential evapotranspiration and rainfall was established from the method used by Takasaki and others (1969) for windward Oahu. Values of annual pan evaporation and mean annual rainfall were estimated from intersections of contour lines on a transect extending from the coast north of Hilo to the summit of Mauna Kea on the island of Hawaii (Ekern and Chang, 1985; Giambelluca and others, 1986) (fig. 10). As in

Table 6. Average soil characteristics, east Maui, Hawaii
[<, less than; from Foote and others, 1972 and Nicole Vollrath, Natural Resources Conservation Service, written commun., 1996)

Soil series	Permeability (inches per hour)	Available-water capacity (inch per inch of soil)	Root depth (inches)	Maximum soil-moisture storage (inches)
Aa lava flow	20.0	0.005	10.0	0.05
Alae	6.0–20.0	0.090	7.0	0.63
Amalu	0.63–2.0	0.350	8.0	2.80
Beaches	0.63–.0	0.040	6.0	0.24
Cinder land	6.0–20.0	0.030	36.0	1.08
Dune land	20.0	0.035	6.0	0.21
Ewa	6.0–20.0	0.110	60.0	6.60
Fill land	0.63–2.0	0.150	30.0	4.50
Haiku	0.63–.0	0.120	14.0	1.68
Haliimaile	6.0–20.0	0.090	15.0	1.35
Hamakuapoko	0.63–2.0	0.130	16.0	2.08
Hana	0.63–.0	0.130	34.0	4.42
Honolua	6.0–20.0	0.130	36.0	4.68
Honomanu-Amalu	0.63–2.0	0.190	25.0	4.75
Hydrandept-Tropaquods	0.63–.0	0.170	26.0	4.42
Iao	6.0–20.0	0.140	25.0	3.50
Io	0.63–2.0	0.160	30.0	4.80
Jaucas	0.63–.0	0.045	13.0	0.59
Kailua	6.0–20.0	0.130	9.0	1.17
Kaimu	>20.0	0.020	20.0	0.40
Kaipoioi	2.0–6.3	0.140	30.0	4.20
Kamaole	0.63–2.0	0.060	8.0	0.48
Kanepuu	0.63–2.0	0.120	11.0	1.32
Kaupo	2.0–6.3	0.110	27.0	2.97
Keahua	0.63–2.0	0.080	15.0	1.20
Kealia	2.0–6.3	0.100	27.0	2.70
Keawakapu	0.63–2.0	0.110	9.0	0.99
Kula	2.0–6.3	0.150	54.0	8.10
Laumaia	0.06–6.3	0.120	42.0	5.04
Makaalae	0.63–2.0	0.090	40.0	3.60
Makawao	2.0–6.3	0.100	9.0	0.90
Makena	2.0–6.3	0.160	44.0	7.04
Malama	<20.0	0.020	28.0	0.56
Molokai	0.63–2.0	0.120	15.0	1.80
Oanapuka	2.0–6.3	0.120	43.0	5.16
Olinda	2.0–6.3	0.140	28.0	3.92
Paia	0.63–2.0	0.140	30.0	4.20
Pane	2.0–6.3	0.150	39.0	5.85
Pauwela	2.0–6.3	0.110	12.0	1.32
Pulehu	0.63–2.0	0.135	33.0	4.46
Puuone	<0.06–20.0	0.070	20.0	1.40
Puu Pa	2.0–6.3	0.130	31.0	4.03
Rock land	0.06–2.0	0.140	4.0	0.56
Rock outcrop	0	0.040	0.6	0.02
Rough broken land	0.6–2.0	0.150	30.0	4.50
Rough mountain land	0.2–6.0	0.135	25.0	3.38
Rough stony land	0.6–2.0	0.11	18.0	1.98
Stony alluvial land	2.0–6.0	0.060	50.0	3.00
Tropaquepts	0.2–6.0	0.150	18.0	2.70
Ulupalakua	2.0–6.3	0.180	33.0	5.94
Uma	>20.0	0.060	6.0	0.36
Very stony land	6.0–20.0	0.150	10.0	1.50
Waiakoa	0.63–2.0	0.110	33.0	3.63
Wailuku	0.63–.0	0.140	12.0	1.68

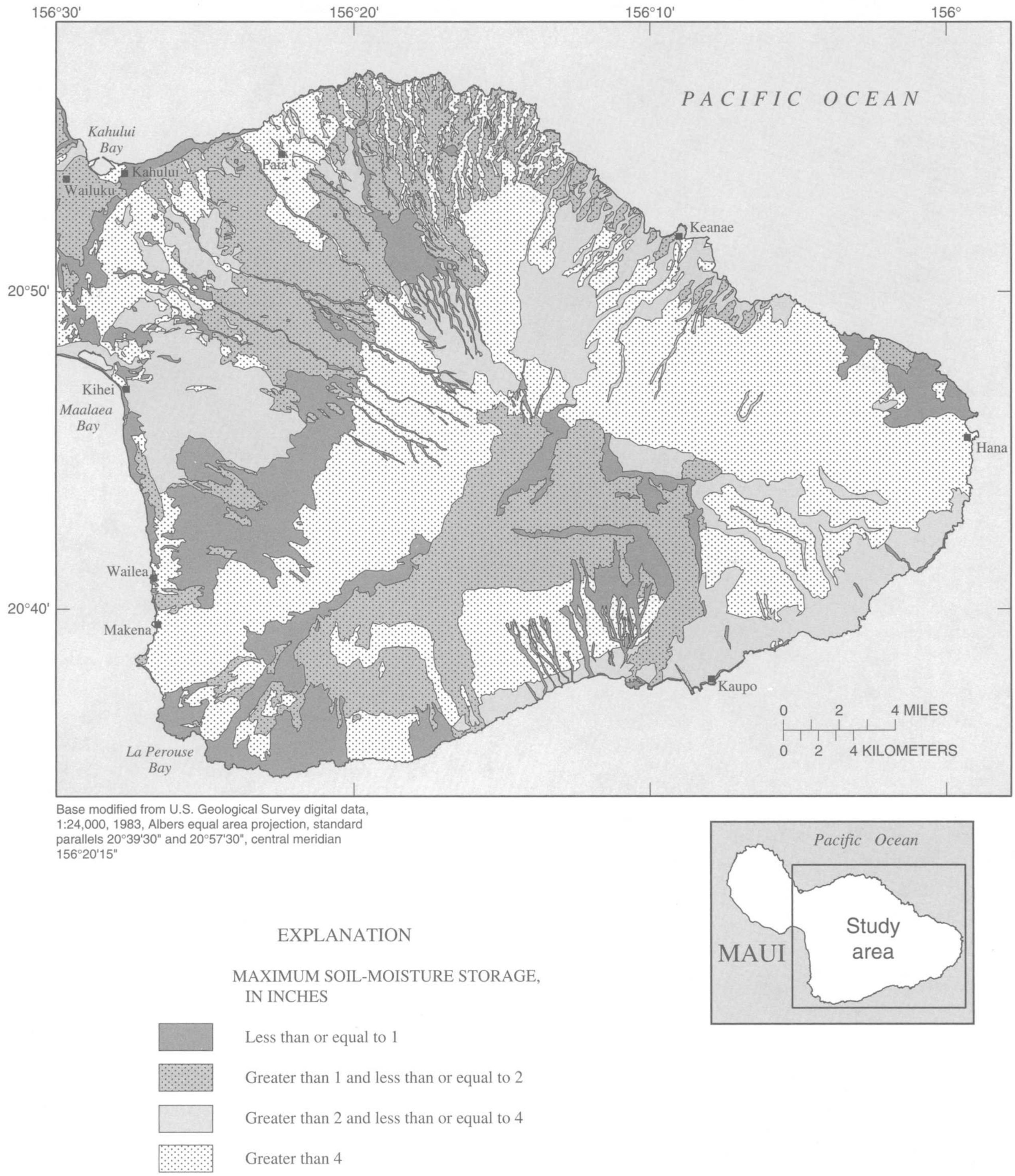


Figure 8. Estimated maximum soil-moisture storage, east Maui, Hawaii.

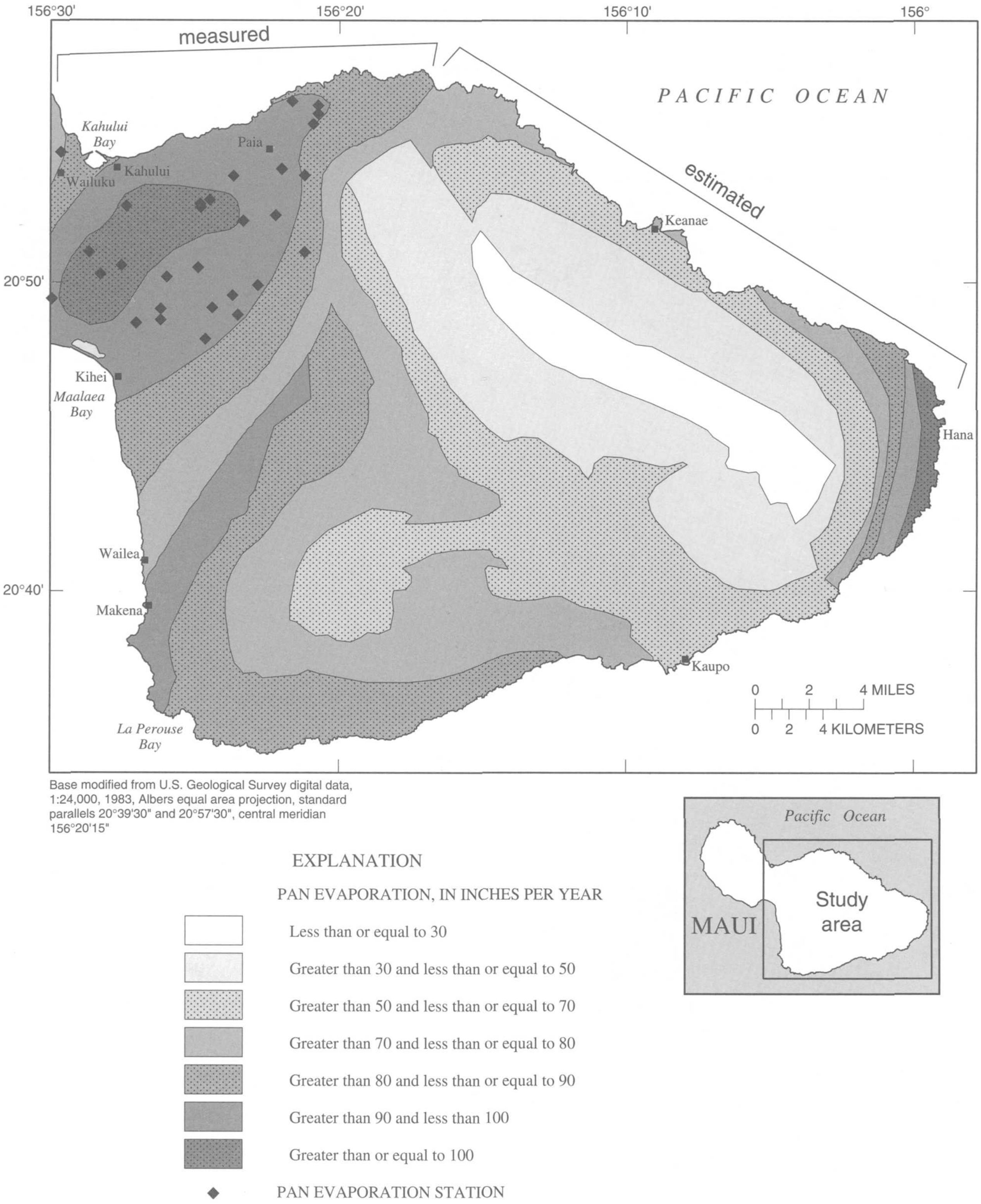
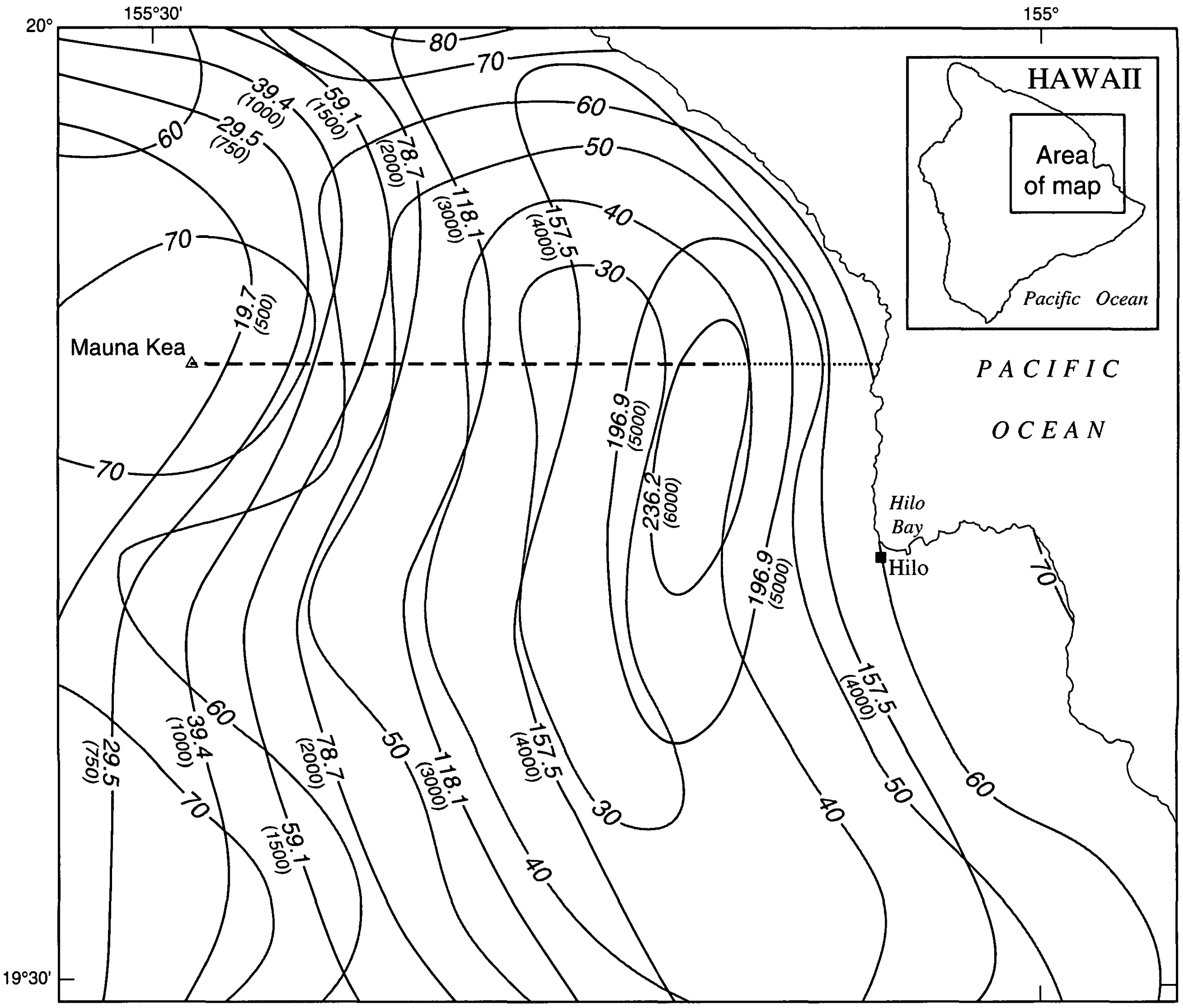


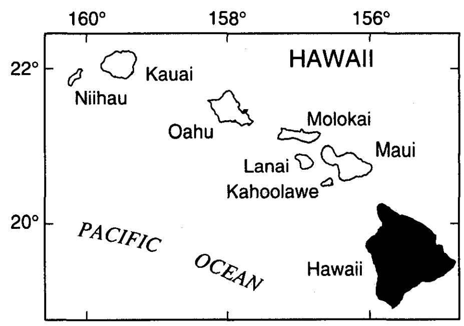
Figure 9. Adjusted annual pan evaporation for east Maui, Hawaii (from Ekern and Chang, 1985).



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 19°08'30" and 20°02'30", central meridian 155°26'30"

0 2 4 MILES

0 2 4 KILOMETERS



LOCATION MAP

EXPLANATION

—19.7— (500)	MEAN ANNUAL RAINFALL--Interval, in inches, is variable. Number in parentheses is value in millimeters (modified from Giambelluca and others, 1986)
—30—	ANNUAL PAN EVAPORATION--Interval, in inches, is variable (from Ekern and Chang, 1985)
....	BELOW INVERSION LINE (EQUATION 4)
— — — — ·	ABOVE INVERSION LINE (EQUATION 5)

Figure 10. Mean annual rainfall and pan evaporation transects, island of Hawaii.

east Maui, the distribution of rainfall along the windward slopes of Mauna Kea is strongly influenced by two processes. The orographic process on the windward side of the mountain induces rainfall to generally increase with increasing altitude. However, for peaks higher than 6,500 ft, the upslope flow of air is capped by the tradewind temperature inversion at about 6,560 ft (Giambelluca and Nullet, 1991) to about 8,200 ft (Lavoie, 1967), where air tends to move around rather than over these high peaks (Leopold, 1949). The frequency and strength of the temperature inversion also is important in controlling variations in solar and net radiation and air temperature (Giambelluca and Nullet, 1991). As a result, the distribution of rainfall amounts and the main factors controlling potential evapotranspiration (solar radiation, humidity, wind speed) are roughly the same areally.

Two equations for predicting potential evapotranspiration as a function of rainfall were developed; below the inversion (eq. 4) rainfall generally increases with increasing altitude, and above the inversion (eq. 5) rainfall decreases with increasing altitude.

$$\text{Annual } PE = 2{,}209.19 \times \text{annual rainfall}^{-0.73} \text{ and } r^2 = 0.72, \quad (4)$$

$$\text{Annual } PE = 295.96 \times \text{annual rainfall}^{-0.44} \text{ and } r^2 = 0.83. \quad (5)$$

The annual potential evapotranspiration (PE) was apportioned monthly on the basis of a set of monthly factors that describe the relations between the monthly and annual rainfall values (eq. 6).

$$PE_m = \frac{\text{annual } PE\,(x/P_m)}{y}, \quad (6)$$

where:

PE_m = monthly potential evapotranspiration,

P_m = monthly rainfall,

x = annual rainfall/12 and,

$$y = \sum_{m=1}^{12} \frac{x}{P_m}.$$

In the study area, the estimated monthly potential evapotranspiration (PE_m) values decrease in the wet winter months to a low in January of 792 Mgal/d, and increase in the dry summer months to a high of 4,068 Mgal/d in June (table 1). Similarly, a comparison of figures 3 and 9 indicates that in areas of high rainfall (hence low solar radiation), greater than 200 in/yr, estimated potential evapotranspiration is low, less than 30 in/yr.

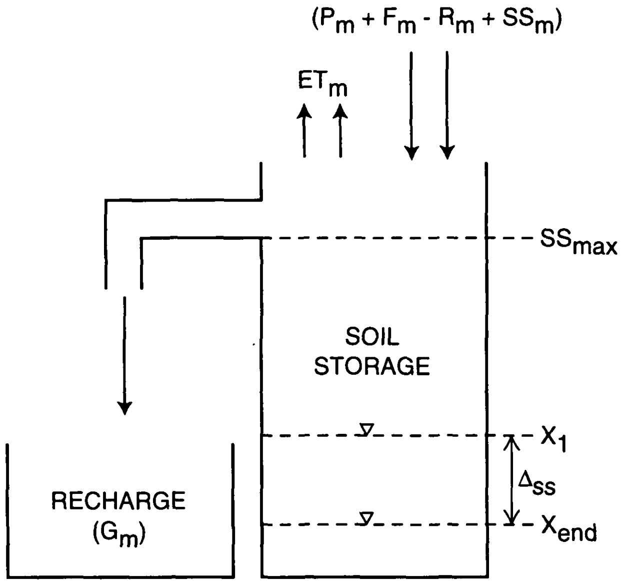
Evapotranspiration Calculation and Soil-Moisture Accounting

The water-budget model calculates evapotranspiration every month on the basis of potential evapotranspiration values, the current status of soil-moisture storage, and the maximum soil-moisture storage (SS_{max}) values. In any month, the amount of water in soil-moisture storage may never exceed the maximum soil-moisture storage values that were calculated for each soil series (table 6). Similarly, in any month, evapotranspiration is limited by the quantity of water available in soil-moisture storage during that month and by the potential evapotranspiration values. For any month, the potential evapotranspiration values may be greater than the quantity of water currently available in soil-moisture storage. In such a situation, there is not enough water in soil storage to meet the potential evapotranspiration demand, and therefore evapotranspiration would be less than the potential evapotranspiration value. There can also be months and locations where the potential evapotranspiration value exceeds the maximum soil-moisture storage value. In this situation, even if soil-moisture storage is full, it is clear that evapotranspiration could not occur at the potential evapotranspiration rate. Thus, the maximum soil-moisture storage value is a determining factor in the calculation of evapotranspiration.

The volume of water in soil-moisture storage changes from month to month. To estimate an appropriate initial soil-moisture storage value for the water-budget model, the model was executed three times using three different soil-moisture storage values for the month of January: maximum soil-moisture storage (SS_{max}), half of SS_{max}, and zero. The resulting values of soil-moisture storage at the end of December were identical for each simulation. Therefore each simulation was run twice and the December values of soil-moisture storage from the first simulation were used as initial soil-moisture storage in January for the second simulation.

Water-Budget Accounting Methods

Two accounting sequences were used in the GIS model. Method I allocates excess soil moisture to



EXPLANATION

P_m	RAINFALL FOR THE MONTH
F_m	FOG DRIP FOR THE MONTH
ET_m	EVAPOTRANSPIRATION FOR THE MONTH
R_m	RUNOFF FOR THE MONTH
SS_m	BEGINNING SOIL-MOISTURE FOR THE MONTH
SS_{max}	MAXIMUM SOIL-MOISTURE STORAGE
G_m	GROUND-WATER RECHARGE FOR THE MONTH
Δ_{ss}	CHANGE IN SOIL-MOISTURE STORAGE
X_1	FIRST INTERIM SOIL-MOISTURE STORAGE
X_{end}	SOIL-MOISTURE STORAGE AT THE END OF THE MONTH

Figure 11. Soil-moisture storage diagram.

ground-water recharge before evapotranspiration, and method II allocates excess soil moisture to evapotranspiration before ground-water recharge. The results of the two water-budget accounting procedures were averaged to present a reasonable, although not overly conservative, estimate of ground-water recharge.

Water-Budget Accounting Method I

This accounting sequence maximizes ground-water recharge. First, the runoff for the month is subtracted from the rainfall and this volume plus the fog drip is added to the month's initial soil moisture. This volume is the first interim soil-moisture storage value. If this volume exceeds SS_{max}, the excess recharges ground water, and a second interim soil-moisture storage value is calculated. Evapotranspiration is subtracted from the second interim soil-moisture storage at either the potential evapotranspiration volume or the interim soil-moisture storage volume, whichever is less. Any water remaining in soil-moisture storage is carried over to the next month. This accounting procedure is shown in equations 7 through 9 and in figure 11.

$$X_1 = P_m - R_m + F_m + SS_m \qquad (7)$$

where:

X_1 = first interim soil-moisture storage,
P_m = rainfall for the month,
R_m = runoff for the month,
F_m = fog drip for the month, and
SS_m = beginning soil-moisture storage for the month.

$$\text{If } X_1 > SS_{max}, \text{ then } X_1 - SS_{max} = G_m \text{ and } X_2 = SS_{max}, \quad \textbf{OR} \quad \text{If } X_1 \le SS_{max}, \text{ then } G_m = 0 \text{ and } X_2 = X_1, \qquad (8)$$

where:

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

$$\text{If } X_2 \ge PE_m, \text{ then } ET_m = PE_m \text{ and } X_{end} = X_2 - PE_m, \quad \textbf{OR} \quad \text{If } X_2 < PE_m, \text{ then } ET_m = X_2 \text{ and } X_{end} = 0, \qquad (9)$$

where:

ET_m = evapotranspiration for the month,
PE_m = potential (maximum) evapotranspiration for the month, and
X_{end} = soil-moisture storage at the end of the month which becomes the beginning soil-moisture storage for the next month.

Water-Budget Accounting Method II

This accounting method maximizes evapotranspiration. First, the runoff for the month is subtracted from the rainfall and this volume plus the fog drip is added to the month's initial soil-moisture. This volume is the first interim value of soil-moisture storage. If this volume exceeds potential evapotranspiration, then evapotranspiration occurs at the potential evapotranspiration rate, and a second interim soil-moisture storage value is calculated by subtracting the potential evapotranspiration volume from the first interim soil-moisture storage value. If the second interim soil-moisture storage exceeds SS_{max}, then the excess recharges ground water. Any water remaining in soil-moisture storage is carried over to the next month. This accounting procedure is shown in the following equations:

$$X_1 = P_m - R_m + F_m + SS_m, \qquad (10)$$

If $X_1 \geq PE_m$, then $ET_m = PE_m$ and $X_2 = X_1 - PE_m$.	**OR**	If $X_1 < PE_m$ then $ET_m = X_1$ and $X_2 = 0$. (11)
If $X_2 \geq SS_{max}$, then $G_m = X_2 - SS_{max}$ and $X_{end} = SS_{max}$.	**OR**	If $X_2 < SS_{max}$, $G_m = 0$ and $X_{end} = X_2$. (12)

WATER-BUDGET RESULTS

From the GIS model, the water-budget results can be analyzed and tabulated for the complete study area as well as for various subareas of interest. Because the climate is distinctly different from place to place within the study area, the relations among the water-budget components likewise vary dramatically from place to place. Thus, the water-budget results are presented for the entire study area; for the wet, windward subarea; for an individual windward drainage basin; and for a dry, leeward subarea.

East Maui Study Area

The average ground-water recharge for east Maui is 1,064 Mgal/d, which represents 41 percent of the sum of rainfall and fog drip (2,569 Mgal/d) (table 1). The calculated ground-water recharge varies significantly through the months and by water-budget accounting method. The mean ground-water recharge for method I (favoring ground-water recharge) is 1,185 Mgal/d, the recharge ranges from a low of 764 Mgal/d in June to a high of 1,588 Mgal/d in December. The mean ground-water recharge for method II (favoring evapotranspiration) is about 20 percent less (944 Mgal/d). The mean ground-water recharge from the average of the two methods not considering a fog-drip contribution is 752 Mgal/d. The relative proportion of the water-budget components is shown in figure 12. The ground-water recharge distribution (fig. 13) from the average of the two accounting methods including fog drip is similar to the rainfall pattern (fig. 3). Because of rounding and an unequal number of days in the months, slight imbalances can appear in the budget when the values are listed in units of Mgal/d.

For east Maui, the mean runoff (771 Mgal/d) is 34 percent of the mean rainfall (2,246 Mgal/d) (table 1). The mean evapotranspiration from the average of methods I and II (735 Mgal/mo) is 29 percent of the sum of the mean rainfall and fog drip (2,569 Mgal/d). The mean potential evapotranspiration is 1,833 Mgal/d for the area. The averaged mean evapotranspiration (735 Mgal/d) represents evapotranspiration occurring at 40 percent of the maximum rate for the entire study area. However, this water-budget result cannot be appropriately evaluated at the study-area scale owing to the extreme climatic variability within the area.

Windward East Maui

Table 7 shows the water-budget components for part of zone F of east Maui between Maliko Gulch on the west to Makapipi Stream on the east, from the shore to the north rim of Haleakala Crater (figs. 1 and 7). Rainfall is abundant in this area (fig. 3) with a mean of 989 Mgal/d or about 160 in/yr over the 129 mi^2 area. The mean fog drip is 176 Mgal/d. Mean runoff (416 Mgal/d) is 42 percent of the mean rainfall. Average evapotranspiration (220 Mgal/d) and average ground-water recharge (529 Mgal/d) are 19 and 45 percent of the sum of rainfall plus fog drip (1,164 Mgal/d), respectively. The relative proportions of the water-budget components in this area are shown in figure 14.

A somewhat qualitative assessment of the calculated evapotranspiration values can be made by comparing estimated actual evapotranspiration with potential evapotranspiration. In wet areas and during the wet

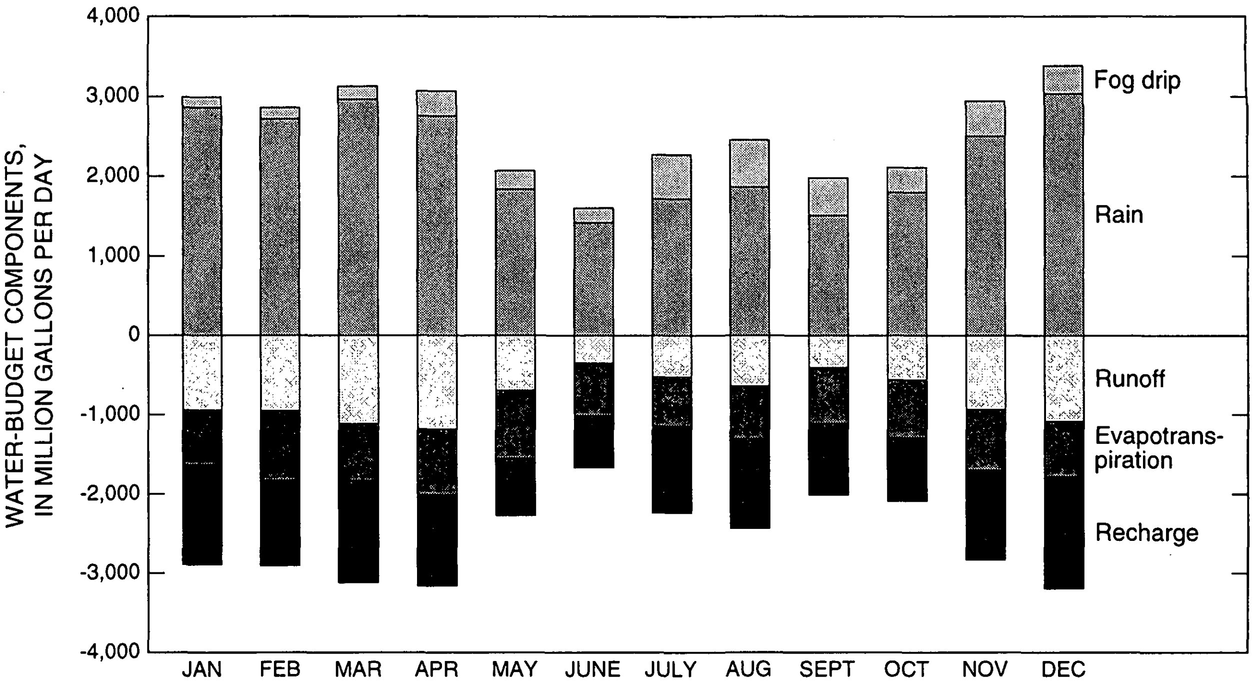


Figure 12. Relative proportion of water-budget components in east Maui, Hawaii.

months, evapotranspiration is expected to occur at nearly the potential evapotranspiration rate, because generally, there would be enough water available from rainfall and fog drip to meet the potential evapotranspiration demand. Using the average values from methods I and II, evapotranspiration, 220 Mgal/d, occurs at 77 percent of the mean potential evapotranspiration value, 284 Mgal/d. During the wet months from November through April, the average evapotranspiration/potential-evapotranspiration ratio increases to 85 to 88 percent, indicating evapotranspiration is occurring at nearly the maximum rate during a time when evapotranspiration is generally not limited by water availability. These ratios are generally double the ratio reported for the entire study area, a finding that is appropriate given the wet climate of this subarea.

The evapotranspiration/potential-evapotranspiration ratio can also be used in an assessment of the calculated ground-water recharge values. In the water-budget equation, assuming rainfall, fog-drip, runoff, and potential-evapotranspiration volumes are reasonably estimated, and because the change in soil-storage volume is relatively small (table 7) compared with other budget components, the validity of the evapotranspiration/potential-evapotranspiration ratios (77 to 88 percent) indicates evapotranspiration and thus, the remaining budget component, ground-water recharge, are reasonably estimated.

The variability in the average evapotranspiration is 61 percent, between the lowest winter value (169 Mgal/d) and the highest summer value (276 Mgal/d). The average ground-water recharge varies slightly more significantly with the lowest monthly value in June (394 Mgal/d) representing 58 percent of the highest value (678 Mgal/d) in July. The increase in summer rainfall and fog, and subsequently, recharge in July and August is generated from strong tradewinds and a well-developed temperature inversion during these months. Because fog generally occurs in wet areas where the evapotranspiration-rainfall ratio is low because of incessant cloud cover, most of the fog is apportioned to recharge in the budget.

The average water budgets for 14 of the gaged drainage basins in the windward east Maui area are shown in table 8. A comparison of tables 3 and 8 shows a discrepancy between the mean volume of base flow (2.33 Mgal/d) and ground-water recharge (1.82 Mgal/d) for the Hoolawaliilii Stream basin. Because the base flow at station 5860 exceeds the computed ground-water recharge for the basin, it is likely that the

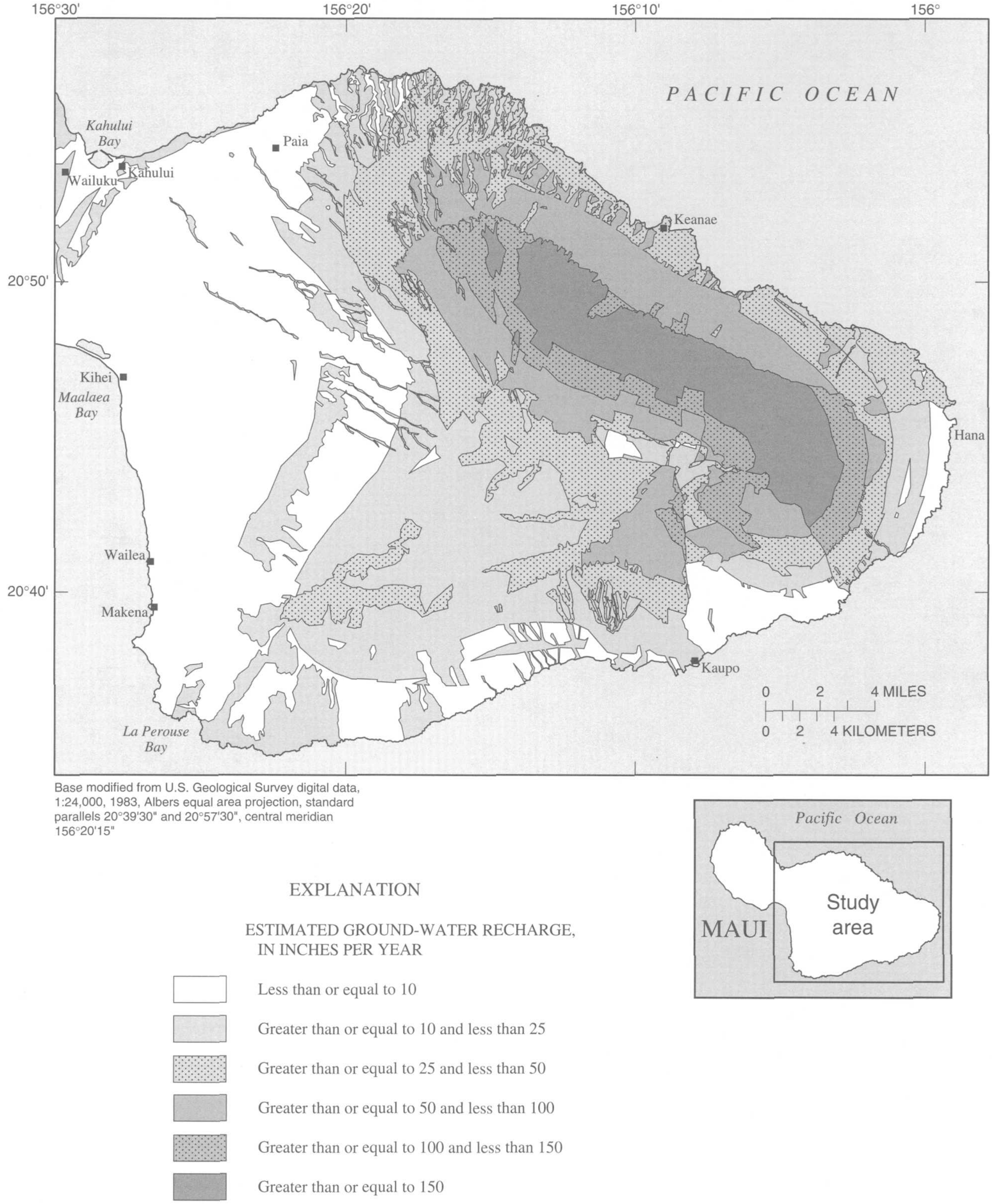


Figure 13. Estimated ground-water recharge, east Maui, Hawaii.

Table 7. Water-budget components, windward east Maui, Hawaii

[Values in million gallons per day; PE, potential evapotranspiration; ET, evapotranspiration, I, recharge first; II, ET first; a, fog; b, no fog; avg, average of methods I and II; EndSS, end of month soil-moisture storage; ΔSS, the change in soil-moisture storage; mean, sum of monthly values divided by 12; --, not applicable. The sum of rainfall plus fog drip minus runoff, ET, and recharge may not equal zero because of rounding. Any other imbalance is owing to an unequal number of days in the months]

Water-budget component	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
Rainfall	1,018	1,090	1,300	1,261	881	713	897	917	671	792	1,104	1,228	989
Fog drip	70	77	89	174	129	103	316	322	241	161	237	183	176
Runoff	475	493	598	684	378	175	286	346	193	285	509	569	416
PE	235	272	191	211	306	415	297	298	426	319	239	203	284
ET I,a	172	190	146	160	190	215	189	186	222	202	172	152	183
ET I,b	172	190	146	160	190	213	187	185	219	200	172	152	182
ET II,a	234	270	191	210	286	328	270	257	329	273	235	202	257
ET II,b	234	270	191	210	286	324	264	254	322	271	235	202	255
ET avg,a	203	230	169	185	239	272	230	222	276	238	204	177	220
ET avg,b	203	230	169	185	238	269	225	219	270	236	204	177	219
Recharge I,a	460	485	617	600	479	450	713	703	529	453	620	675	566
Recharge I,b	390	409	528	426	350	348	400	383	290	294	383	492	391
Recharge II,a	374	405	598	542	376	338	642	631	412	380	572	627	492
Recharge II,b	305	328	509	368	250	238	335	314	179	222	327	443	318
Recharge avg,a	417	445	608	571	428	394	678	667	471	417	596	651	529
Recharge avg,b	348	369	519	397	300	293	368	349	235	258	355	468	354
EndSS I,a	70	75	95	89	49	27	50	53	22	36	76	89	--
EndSS I,b	70	75	95	89	49	27	49	52	22	35	76	89	--
EndSS II,a	237	259	237	243	206	188	196	201	186	195	227	233	--
EndSS II,b	237	259	237	243	203	185	192	195	178	186	225	233	--
EndSS avg,a	154	167	166	166	128	108	123	127	104	116	152	161	--
EndSS avg,b	154	167	166	166	126	106	121	124	100	111	151	161	--
ΔSS I,a	-19	+5	+20	-6	-40	-22	+23	+3	-31	+14	+40	+13	--
ΔSS I,b	-19	+5	+20	-6	-40	-22	+22	+3	-30	+13	+41	+13	--
ΔSS II,a	+4	+22	-22	+6	-37	-18	+8	+5	-15	+9	+32	+6	--
ΔSS II,b	+4	+22	-22	+6	-40	-18	+7	+3	-17	+9	+41	+8	--
ΔSS avg,a	-7	+13	-1	0	-38	-20	+15	+4	-23	+12	+36	+9	--
ΔSS avg,b	-7	+13	-1	0	-40	-20	+15	+3	-24	+11	+40	+10	--

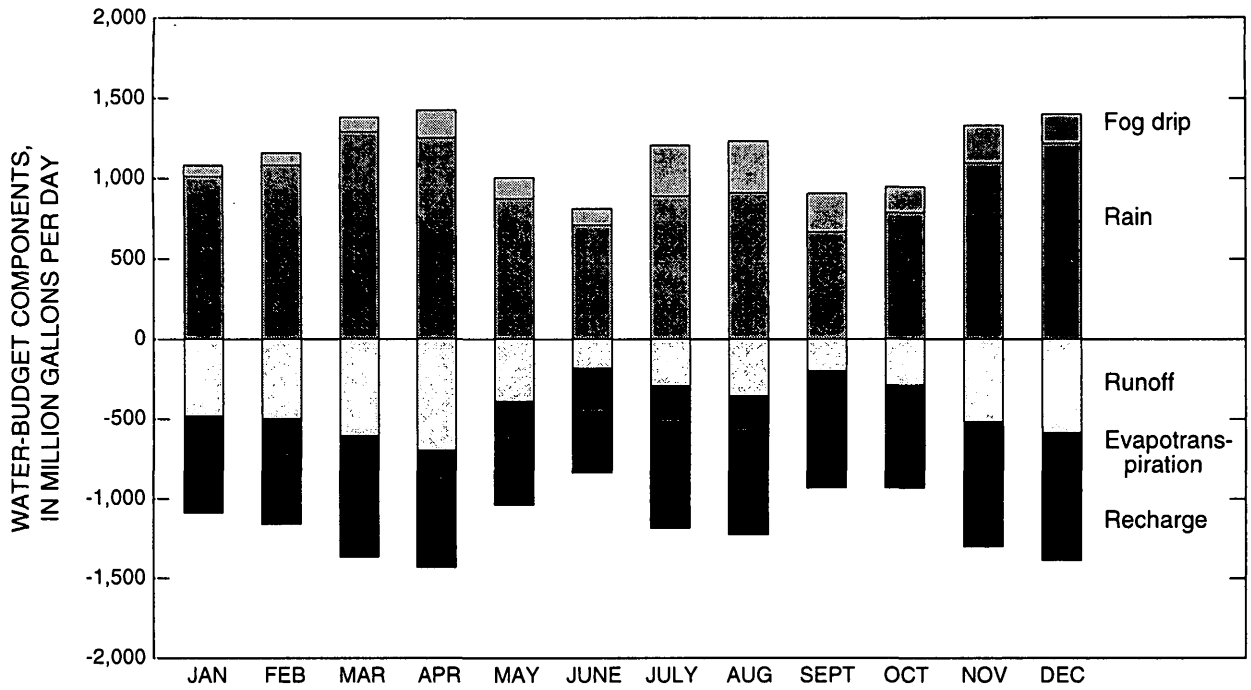


Figure 14. Relative proportion of water-budget components in windward east Maui, Hawaii.

Table 8. Water-budget components for gaged drainage basins, windward east Maui, Hawaii

[mi^2, square miles; Mgal/d, million gallons per day. The difference of the quantity of rainfall plus fog drip minus runoff, evapotranspiration, and recharge may not equal zero because of rounding. Drainage basins shown in figure 2. The values for evapotranspiration and recharge are the average values from the two accounting methods; complete station numbers are preceded by 16 and end in 00]

Gaging station	Gaging station location	Area (mi^2)	Rainfall (Mgal/d)	Fog drip (Mgal/d)	Runoff (Mgal/d)	Evapotranspiration (Mgal/d)	Recharge (Mgal/d)
5080	Hanawi Stream	3.46	32.3	8.91	12.0	4.63	24.6
5150	Waiohue Gulch	0.52	7.25	1.49	3.91	0.87	3.96
5160	Kopiliula Stream	3.91	32.0	8.69	13.9	5.50	21.3
5170	East Wailuaiki Stream	3.11	30.2	8.46	14.9	4.33	19.4
5180	West Wailuaiki Stream	3.67	33.1	9.28	18.8	5.05	18.6
5190	West Wailuanui Stream	1.92	16.2	4.18	7.27	2.93	10.2
5200	East Wailuanui Stream	0.51	7.10	1.29	4.07	0.85	3.47
5240	Honomanu Stream	2.55	19.6	6.05	7.05	3.65	15.0
5528	Waikamoi Stream	2.46	9.19	1.18	1.29	3.22	5.87
5700	Nailiilihaele Stream	3.61	34.8	8.81	17.5	6.30	19.8
5770	Kailua Stream	2.39	23.9	7.22	15.2	3.62	12.4
5850	Hoolawanui Stream	1.34	12.5	3.12	5.13	2.39	8.09
5860	Hoolawaliilii Stream	0.57	5.18	0.45	2.52	1.29	1.82
5870	Honopou Stream	0.65	5.36	0.58	1.93	1.30	2.72

topographic boundaries of this basin do not coincide with the ground-water contributing area to this basin. Further analysis of the water-budget results in an individual windward drainage basin can indicate if appropriate ratios between water-budget components exist in an even smaller part of the study area.

Hanawi Drainage Basin

The Hanawi drainage basin (fig. 15) is within the windward east Maui area. Because of the large stream and spring discharges, this basin is of particular interest. Streamflow data from 1914 to the present are available for gaging station 5080 located just above the Koolau irrigation ditch (fig. 15) that was constructed in the early 1900's to convey water from the windward east Maui area to central Maui for cultivation of sugarcane. Test drilling was done in the Hanawi basin during the 1930's and 1940's to explore the source of Big Spring, which is located below the ditch and above gaging station 5090. Surface- and ground-water interaction within the basin is currently the subject of another part of this study.

Table 9 summarizes the water-budget components for the 3.46 mi^2 area of Hanawi drainage basin above gaging station 5080 (area 5080; figs. 7 and 15). Figure 16 shows the relative proportion of the water-budget components in the area. Mean rainfall and fog drip are 32 Mgal/d and 9 Mgal/d, respectively. The evapotranspiration/potential-evapotranspiration ratio is 80 percent for method I, which favors ground-water recharge, and is 100 percent for method II, which favors evapotranspiration. These ratios represent evapotranspiration occurring at nearly the maximum rate, which is reasonable for an area that rarely lacks water to satisfy the maximum evaporative demand. The average value from methods I and II for ground-water recharge for this subbasin, 24 Mgal/d (table 9), and the mean recharge from each method, are all 59 percent of the sum of rainfall plus fog drip (41 Mgal/d). The addition of about 9 Mgal/d of fog drip in the budget increases ground-water recharge by more than 1.6 times over that calculated without fog drip.

Rainfall and fog drip are estimated to be 48 and 13 Mgal/d, respectively, for the entire (4.72 mi^2) area above the Koolau ditch (fig. 15 and table 10). The larger area above the Koolau ditch compared with the drainage area for station 5080 does not yield a proportional increase in the values of the water-budget components, because the area above the ditch has a greater proportion that receives 250 in/yr of rainfall, more than the area of drainage basin 5080. The average ground-water recharge for this area above the Koolau ditch is 36 Mgal/d with fog drip and 23 Mgal/d without fog drip. Evapotranspiration is 6.5 Mgal/d with and without fog drip.

Fog drip is estimated to be zero in the sub-basin of 0.29 mi^2 below the Koolau ditch and above the lower station 5090. Rainfall and runoff are about 2.7 and 0.98 Mgal/d, respectively, in this area. Evapotranspiration and ground-water recharge are 0.56 and 1.1 Mgal/d, respectively.

Within the sub-area of 0.20 mi^2 below station 5090, rainfall and runoff are 1.5 and 0.57 Mgal/d, respectively. Evapotranspiration and recharge are 0.37 and 0.60 Mgal/d, respectively, for this area. For the entire (5.21 mi^2) Hanawi drainage basin, rainfall, fog drip, runoff, and evapotranspiration are about 52, 13, 19, and 7.5 Mgal/d, respectively. The average evapotranspiration is about 7.5 Mgal/d with and without fog drip. The average ground-water recharge is about 38 Mgal/d with fog drip and 25 Mgal/d without fog drip.

Leeward East Maui

An analysis of a dry sub-area of interest indicates distinctly different ratios among the water-budget components as compared with those of the wet windward area. The leeward sub-area (zone C, fig. 2) is in a dry part of east Maui on the south side of Haleakala and includes most of the Kahikinui Forest Reserve (fig. 1). Rainfall in this area ranges from about 75 to less than 25 in/yr near the coast (fig. 3) and averages 170 Mgal/d (table 11). The mean fog drip is estimated to average 10 Mgal/d. Mean runoff is 17 Mgal/d, which is 10 percent of rainfall.

The average value of evapotranspiration from methods I and II, 88 Mgal/d, is 49 percent of the sum of rainfall plus fog drip, 180 Mgal/d (table 11), and is 27 percent of the mean potential evapotranspiration, which indicates that there is a lack of water in this area to meet the maximum evapotranspiration demand. The ratio of evapotranspiration to rainfall plus fog drip, 0.49, is much higher than in the windward area where the ratio is 0.19. Conversely, the ratio of runoff to rainfall, 0.10, is much lower than for windward areas where it is 0.43. These differences are consistent with the much lower rainfall and fog drip totals in zone C. The average

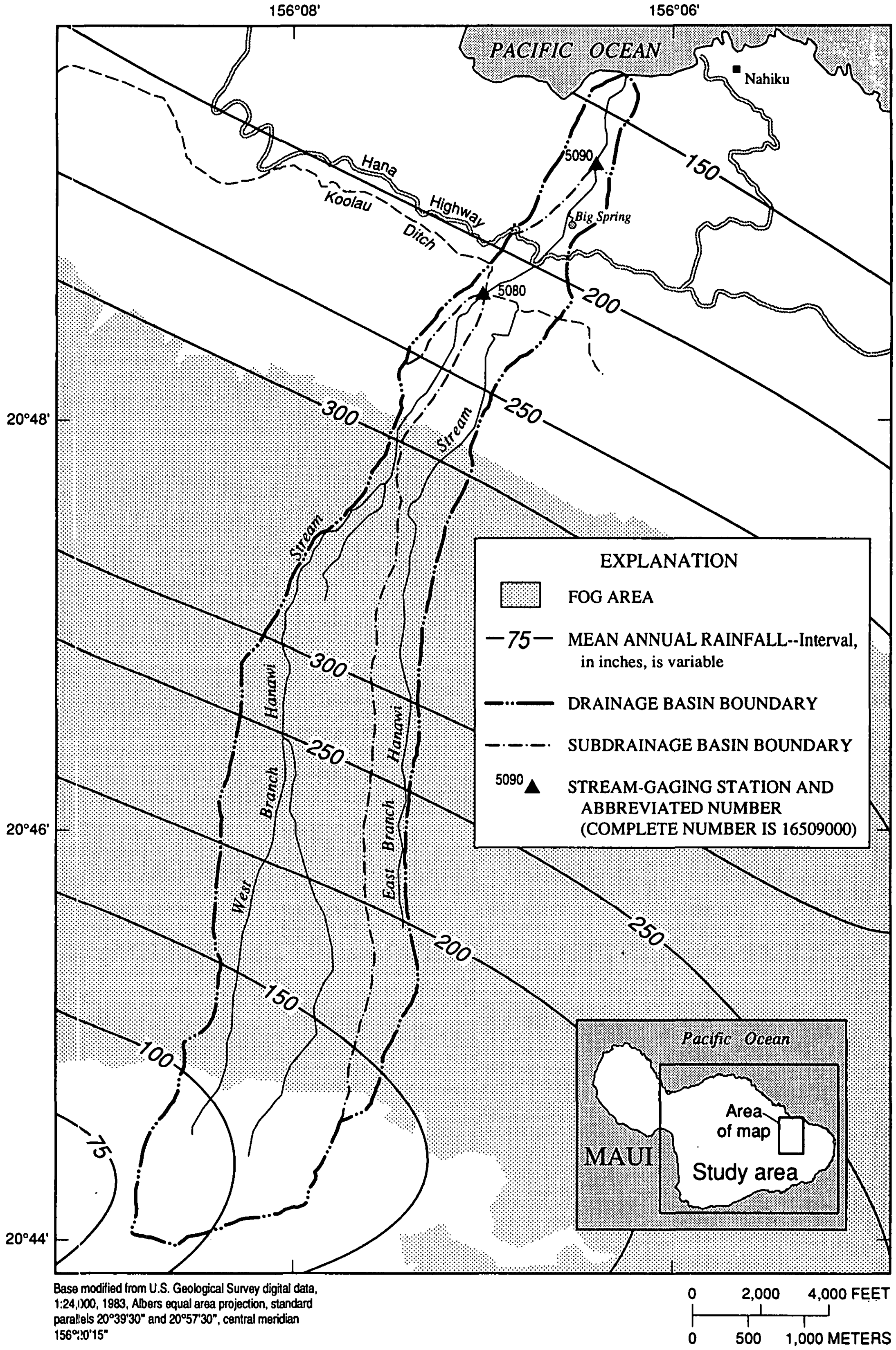


Figure 15. Stream-gaging stations in the Hanawi Stream drainage area, east Maui, Hawaii.

Table 9. Water-budget components at stream-gaging station 16508000, Hanawi drainage basin, east Maui, Hawaii

[Values in million gallons per day; PE, potential evapotranspiration; ET, evapotranspiration; I, recharge first; II, ET first; a, fog; b, no fog; avg, average of methods I and II; EndSS, end of month soil-moisture storage; ΔSS, the change in soil-moisture storage; mean, sum of monthly values divided by 12; --, not applicable. The sum of rainfall plus fog drip minus runoff, ET, and recharge may not equal zero because of rounding. Other imbalance is owing to an unequal number of days in the months]

Water-budget component	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
Rainfall	33	35	46	38	30	24	25	28	22	23	39	45	32
Fog drip	3	4	5	8	7	6	15	16	13	8	13	10	9
Runoff	16	17	22	19	9	4	7	7	4	7	16	17	12
PE	4	5	3	4	5	7	7	6	7	8	4	3	5
ET I,a	4	4	3	4	4	6	5	5	6	5	3	3	4
ET I,b	4	4	3	4	4	6	5	4	6	5	3	3	4
ET II,a	4	5	3	4	5	7	6	5	7	6	4	3	5
ET II,b	4	5	3	4	5	7	6	5	7	6	4	3	5
ET avg,a	4	5	3	4	5	7	6	5	7	6	4	3	5
ET avg,b	4	5	3	4	5	7	6	5	7	6	4	3	5
Recharge I,a	17	18	24	25	24	21	28	32	26	18	31	35	25
Recharge I,b	13	14	19	16	17	15	13	16	13	10	18	25	15
Recharge II,a	15	17	25	24	22	19	28	31	24	18	32	35	24
Recharge II,b	12	13	20	16	15	14	13	15	11	10	19	25	15
Recharge avg,a	16	18	25	24	23	20	28	32	25	18	31	35	24
Recharge avg,b	13	13	19	16	16	15	13	16	12	10	19	25	15
EndSS I,a	3	4	4	4	3	2	2	3	2	2	4	4	--
EndSS I,b	3	4	4	4	3	2	2	3	2	2	4	4	--
EndSS II,a	7	8	7	8	7	7	7	7	7	7	8	7	--
EndSS II,b	7	8	7	8	7	7	7	7	7	7	8	7	--
EndSS avg,a	5	6	6	6	5	5	4	5	4	4	6	6	--
EndSS avg,b	5	6	6	6	5	4	4	5	4	5	6	6	--
ΔSS I,a	-1	+1	0	0	-1	-1	0	+1	-1	0	+2	0	--
ΔSS I,b	-1	+1	0	0	-1	-1	0	+1	-1	0	+2	0	--
ΔSS II,a	0	+1	-1	+1	-1	0	0	0	0	0	+1	-1	--
ΔSS II,b	0	+1	-1	+1	-1	0	0	0	0	0	+1	-1	--
ΔSS avg,a	-1	+1	0	0	-1	0	-1	+1	-1	0	+2	0	--
ΔSS avg,b	-1	+1	0	0	-1	-1	0	+1	-1	+1	+1	0	--

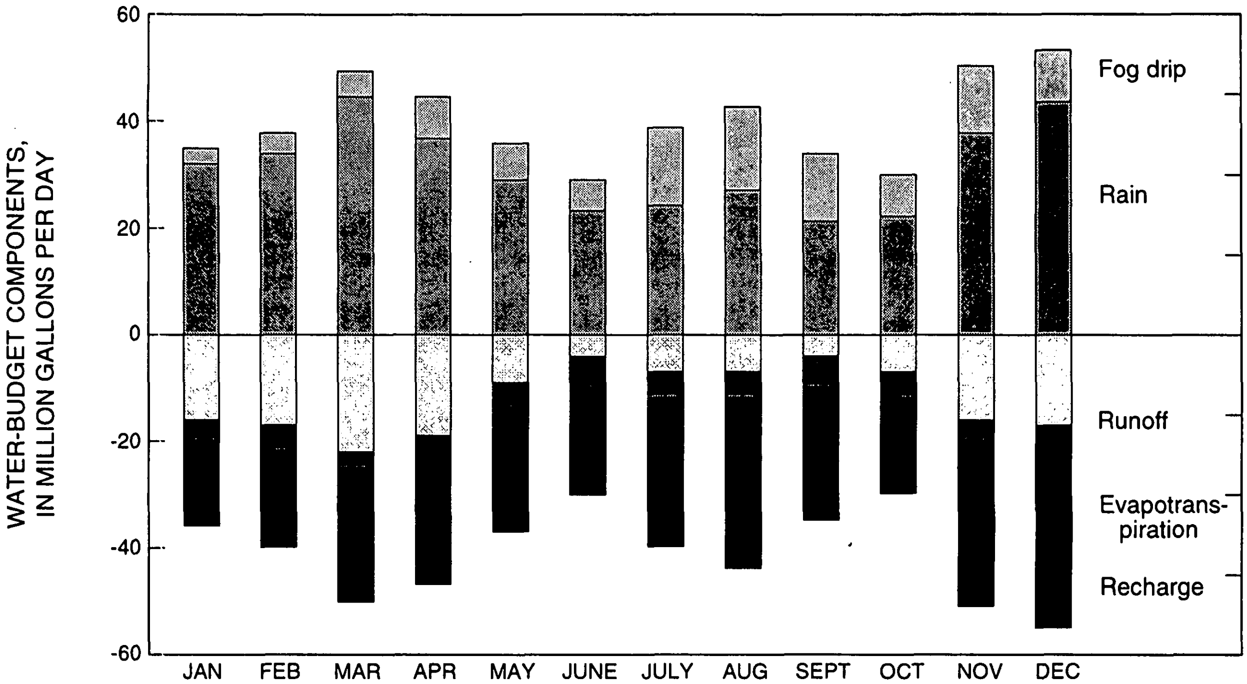


Figure 16. Relative proportion of water-budget components in Hanawi drainage basin at station 1650800, east Maui, Hawaii.

Table 10. Water-budget components for Hanawi sub-basins, windward east Maui, Hawaii

[mi^2, square miles, Mgal/d, million gallons per day. The sum of rainfall plus fog drip minus runoff, evapotranspiration, and recharge may not equal zero because of rounding. Drainage sub-basins shown in figure 12. The values for evapotranspiration and recharge are the average values from the two accounting methods; complete station numbers are preceded by 16 and end in 00]

Sub-basin	Area (mi^2)	Rainfall (Mgal/d)	Fog drip (Mgal/d)	Runoff (Mgal/d)	Evapotran-spiration (Mgal/d)	No fog evapotran-spiration (Mgal/d)	Recharge (Mgal/d)	No fog recharge (Mgal/d)
Area above station 5080	3.46	32	8.9	12	4.6	4.6	25	16
Area above Koolau ditch	4.72	48	13	18	6.5	6.5	36	23
Area below ditch to station 5090	0.29	2.7	0	0.98	0.56	0.56	1.1	1.1
Area below station 5090 to coast	0.20	1.5	0	0.57	0.37	0.37	0.60	0.60
Entire Hanawi basin	5.21	52	13	19	7.5	7.5	38	25

Table 11. Water-budget components, leeward east Maui, Hawaii

[Values in million gallons per day; PE, potential evapotranspiration; ET, evapotranspiration; I, recharge first; II, ET first; a, fog; b, no fog; avg, average of methods I and II; EndSS, end of month soil-moisture storage; ΔSS, the change in soil-moisture storage; mean, sum of monthly values divided by 12; --, not applicable. The sum of rainfall plus fog drip minus runoff, ET, and recharge may not equal zero because of rounding. Any other imbalance is owing to an unequal number of days in the months]

Water-budget component	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
Rainfall	336	268	247	205	107	49	49	82	80	146	192	282	170
Fog drip	8	7	7	12	6	3	7	12	11	12	16	15	10
Runoff	32	26	24	20	10	5	5	8	8	14	19	27	17
PE	94	149	138	191	333	731	802	469	449	234	205	120	326
ET I,a	62	83	77	90	73	36	39	49	56	75	75	69	65
ET I,b	62	83	77	90	72	34	36	46	53	72	74	69	64
ET II,a	94	142	131	148	157	59	52	86	84	126	127	114	110
ET II,b	94	142	131	148	152	55	44	74	73	119	123	114	106
ET avg,a	78	113	104	119	115	47	46	68	70	100	101	91	88
ET avg,b	78	113	104	119	112	45	40	60	63	95	98	91	85
Recharge I,a	233	181	156	124	42	12	12	36	27	68	103	184	98
Recharge I,b	225	174	149	112	37	10	8	28	20	58	87	169	90
Recharge II,a	197	111	105	71	4	0	0	0	0	13	37	106	54
Recharge II,b	188	104	98	60	3	0	0	0	0	7	26	91	48
Recharge avg,a	215	146	130	97	23	6	6	18	14	40	70	145	76
Recharge avg,b	206	139	123	86	20	5	4	14	10	33	57	130	69
EndSS I,a	47	37	30	14	0	0	0	0	0	1	13	29	--
EndSS I,b	47	37	30	14	0	0	0	0	0	1	13	29	--
EndSS II,a	101	106	91	73	12	0	0	0	0	5	30	79	--
EndSS II,b	101	106	91	71	10	0	0	0	0	5	29	78	--
EndSS avg,a	74	72	61	43	6	0	0	0	0	3	21	54	--
EndSS avg,b	74	72	61	43	5	0	0	0	0	3	21	54	--
ΔSS I,a	+18	-10	-7	-16	-14	0	0	0	0	+1	+11	+17	--
ΔSS I,b	+18	-10	-7	-16	-14	0	0	0	0	+1	+11	+17	--
ΔSS II,a	+21	+6	-15	-19	-61	-12	0	0	0	+5	+25	+49	--
ΔSS II,b	+22	+6	-15	-20	-61	-10	0	0	0	+5	+24	+49	--
ΔSS avg,a	+19	-2	-11	-17	-37	-6	0	0	0	+3	+18	+33	--
ΔSS avg,b	+20	-2	-11	-18	-37	-5	0	0	0	+3	+18	+33	--

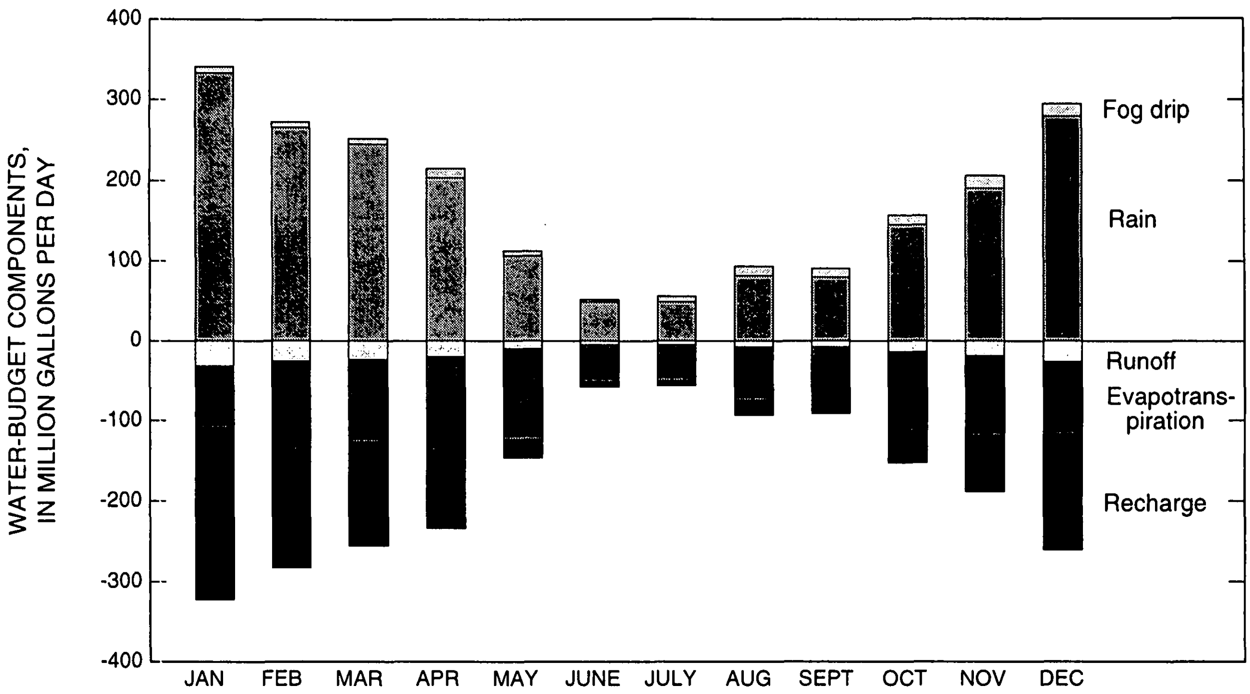


Figure 17. Relative proportion of water-budget components in leeward east Maui, Hawaii.

ground-water recharge, 76 Mgal/d, is 42 percent of the sum of rainfall plus fog drip. Assuming that all the above budget components and soil-moisture storage are reasonably estimated, the resulting ground-water recharge volume is reasonable. Because of the lack of field measurements in this area, the water-budget component volumes are best considered as rough estimates. The relative proportion of the water-budget components in this area are shown in figure 17.

Comparison With Results of Previous Study

A water budget from a previous investigation (State of Hawaii, 1990) (table 12) and the average water budget without fog drip (table 13) are presented by aquifer-system areas (fig. 18) for comparison. The presentation highlights the difficulty in comparing water budgets. A comparison of rainfall values for the areas shows considerable differences, particularly in the Kawaipapa aquifer-system area where the difference in rainfall is 39 Mgal/d. Both studies used the maps by Giambelluca and others (1986). The monthly maps were used for the present study and the annual map was used for the previous study, and different methods were used to distribute rainfall over the areas. The State of Hawaii report (1990) mentions using a weighted-average annual rainfall, but no calculation details are provided. In the GIS model, all spatial calculations of the water-budget components including rainfall can be reproduced. GIS also allows the method of calculation to be altered. For example, in this study, the average of the bounding lines of equal rainfall values was applied over the area between the lines. An alternative reproducible interpolation scheme also could have been applied to distribute the rainfall between the lines. The differences in rainfall calculations between the two studies confounds comparison of the remaining budget components.

Comparisons of the water-budget components from the two studies can be made by comparing the percentage of rainfall each component represents. The lack of runoff and evapotranspiration data required that a variety of estimation methods be used for large parts of the study area. This variety resulted in discrepancies between the two studies. Most runoff data are from drainage basins within the Waikamoi and Keanae aquifer-system areas (fig. 18). The runoff/rainfall ratios in these areas are fairly similar between the two studies.

Table 12. Water budgets for aquifer-system areas, east Maui, Hawaii (State of Hawaii, 1990)

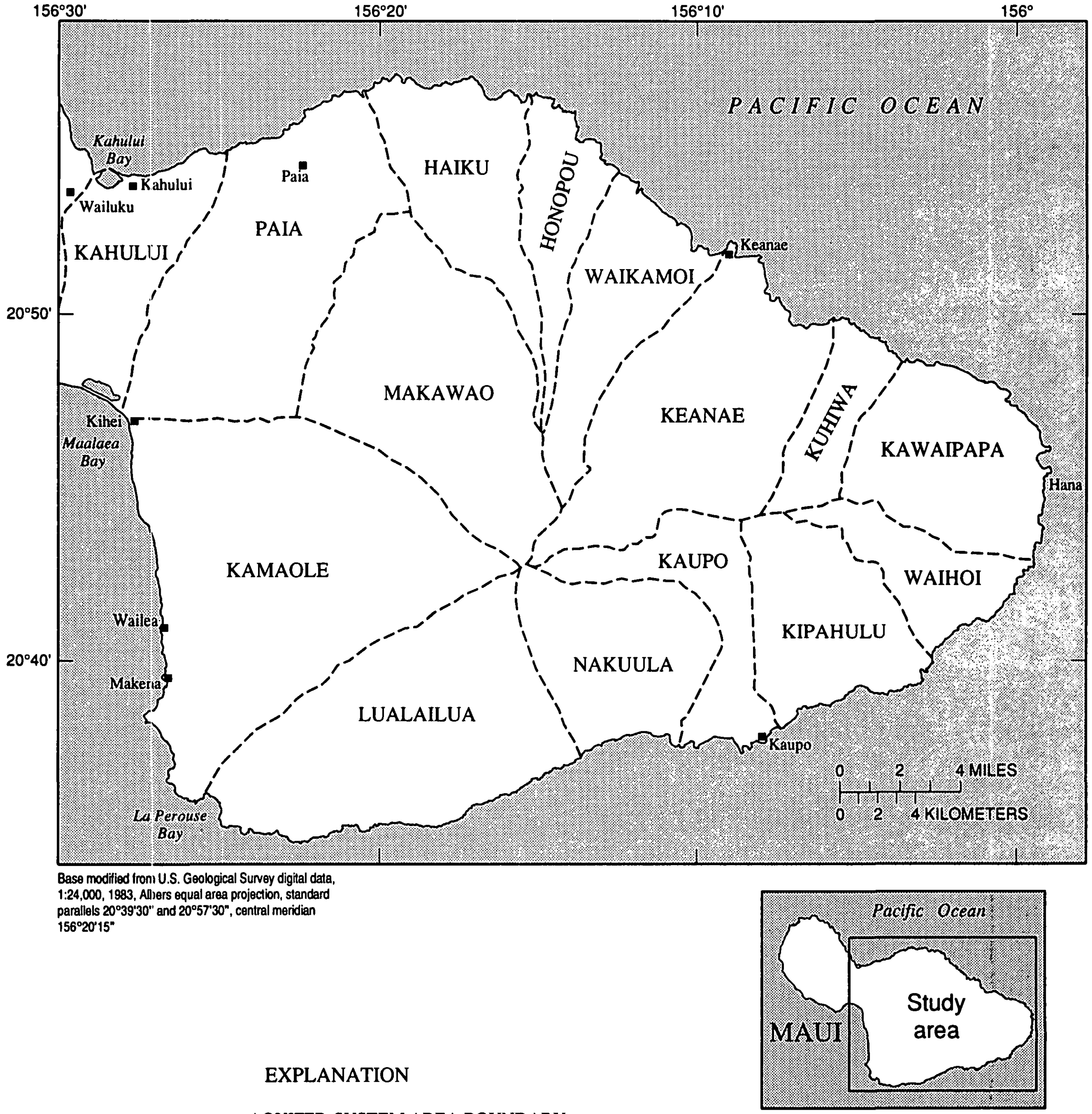
[Mgal/d, million gallons per day; ET, evapotranspiration; mi^2, square miles. The difference of rainfall minus runoff, ET, and recharge may not equal zero due to rounding, areas shown in figure 13]

Aquifer-system area	Area (mi^2)	Rainfall (Mgal/d)	Runoff (Mgal/d)	Runoff/ rainfall (percent)	Evapotranspiration (Mgal/d)	Evapotranspiration/ rainfall (percent)	Recharge (Mgal/d)	Recharge/ rainfall (percent)
Paia	60.73	78	3	4	55	71	17	22
Makawao	52.93	96	8	8	71	74	15	16
Kamaole	89.22	119	8	7	85	71	25	21
Haiku	35.71	163	34	21	68	42	61	37
Honopou	17.81	122	31	25	34	28	58	48
Waikamoi	26.08	223	83	37	50	22	91	41
Keanae	55.56	489	196	40	106	22	188	38
Kuhiwa	13.14	161	104	65	25	16	31	19
Kawaipapa	32.60	264	93	35	62	23	109	41
Waihoi	15.18	114	37	32	29	25	48	42
Kipahulu	30.22	213	59	28	58	27	96	45
Kaupo	20.73	88	13	15	39	44	36	41
Nakuula	30.94	69	3	4	50	72	16	23
Lualailua	68.11	123	6	5	91	74	26	21
Totals	548.96	2,322	678		823		817	

Table 13. Water budgets from this study without fog drip, for aquifer-system areas, east Maui, Hawaii

[Mgal/d, million gallons per day; ET, evapotranspiration; mi^2, square miles. The difference of rainfall minus runoff, ET, and recharge may not equal zero due to rounding, areas shown in figure 13. The water-budget without fog drip is used because the State of Hawaii (1990) study did not consider a fog-drip component]

Aquifer-system area	Area (mi^2)	Rainfall (Mgal/d)	Runoff (Mgal/d)	Runoff/ rainfall (percent)	Potential evapotranspiration (Mgal/d)	Evapotranspiration (Mgal/d)	Evapotranspiration/ rainfall (percent)	Recharge (Mgal/d)	Recharge/ rainfall (percent)
Paia	58.62	74	1	1	257	52	70	21	28
Makawao	58.55	134	10	7	183	68	51	57	43
Kamaole	91.45	110	1	1	354	85	77	24	22
Haiku	29.21	143	37	26	82	53	37	54	38
Honopou	16.35	120	50	42	42	34	28	36	30
Waikamoi	26.62	240	110	46	54	45	19	85	35
Keanae	53.69	461	212	46	102	78	17	171	37
Kuhiwa	12.85	132	65	49	25	23	17	44	33
Kawaipapa	32.49	225	85	38	102	71	32	70	31
Waihoi	15.60	124	51	41	41	32	26	40	32
Kipahulu	28.78	209	120	57	66	55	26	35	17
Kaupo	21.18	73	11	15	62	23	32	39	53
Nakuula	30.21	72	8	11	98	29	40	35	49
Lualailua	62.76	101	9	9	232	57	56	35	35
Total	538.36	2,219	770		1,700	705		746	



EXPLANATION

---- AQUIFER-SYSTEM AREA BOUNDARY

PAIA AQUIFER-SYSTEM AREA NAME

Figure 18. Aquifer-system areas, east Maui, Hawaii (from Mink and Lau, 1990).

For areas with less data, a comparison of these ratios shows an equal or similar percentage of rainfall apportioned to runoff in some aquifer-system areas, as in Kaupo, Makawao, and Kawaipapa, as well as large differences in these ratios, as in Honopou, Kuhiwa, and Kipahulu. Part of the differences in these areas is a result of differing methods of estimating runoff. In the previous study, runoff was assumed to equal total streamflow, and in this study runoff was assumed to equal total streamflow minus base flow in perennial streams. Since most of the perennial streams are located within the Waikamoi and Keanae areas, the runoff/rainfall ratios may be expected to be lower in this study than in the previous study; yet the opposite is true (tables 12 and 13). There is no complete or precise explanation for these results. However, the previous report does acknowledge poor correlations between rainfall and runoff from the estimation method (State of Hawaii, 1990, p. B-2).

The diverse methods used in the two studies to estimate evapotranspiration produced remarkably similar results in several of the areas. In the previous study, evapotranspiration is estimated as 40 in/yr in areas that have rainfall greater than or equal to 55 in/yr. Evapotranspiration is calculated as 73 percent of rainfall where the annual rainfall is less than 55 inches. In this study, evapotranspiration is calculated on the basis of soil-moisture storage, rainfall, estimates of potential evapotranspiration, and two water-budget accounting methods. The evapotranspiration/rainfall ratios are similar in the Paia, Kamaole, Haiku, Honopou, Waikamoi, Kuhiwa, Waihoi, and Kipahulu aquifer-system areas, and substantially different in the the Kaupo, Nakuula, and Lualailua areas. Assuming that the potential evapotranspiration estimates made in this study are reasonable, the evapotranspiration estimates for Keanae and Kuhiwa in the previous study are most likely excessive, because they equal or exceed the maximum. Overall, the similarity of the evapotranspiration results should be viewed as more coincidental than as an indication of mutual verification of accurate evapotranspiration estimates. The recharge-rainfall ratios for the two studies are only similar in the Paia, Kamaole, Haiku, and Keanae aquifer-system areas.

Model Limitations

The GIS water-budget model has several limitations, including the regional nature of the model, the average characteristic of all input data, and the monthly time-step of the calculations. For most of east Maui, the runoff calculations are regionalized by applying average relations over large areas, as in the windward part of the study area, or by applying relations from a single basin over the surrounding area, as in parts of the leeward area. The available-water capacity and the root depth are average values from individual soil profiles that are regionalized for the soil series, and thus the calculated maximum soil-moisture storage of the soil is regionalized as well. The soil-moisture storage is an important component in the water-budget model, because it affects the calculation of both ground-water recharge and evapotranspiration.

All rainfall, fog-drip, runoff, potential-evapotranspiration, and soil data are averages that eliminate extremes that occur in nature. Therefore, this water budget, using average monthly data, will not accurately simulate the budget of an intense 3-day storm in a localized area, nor an anomalous extended dry period of several weeks during December and January in an area that normally receives more than 300 in/yr of rainfall. However, these monthly average results are appropriate for broad-scale resource planning purposes.

The error associated with using average data is likely to be compounded by the budget accounting method that uses a monthly time interval. Although monthly water-budget calculations estimate evapotranspiration more accurately than methods that assume that evapotranspiration occurs at the maximum evapotranspiration rate, as is done in annual water-budget calculations, the components of the water budget are, in reality, interacting on the order of minutes and hours. Therefore, the monthly water-budget will not necessarily accurately represent daily occurrences. For example, monthly averages moderate the events when more than the average month's rainfall occurs in 2 days, resulting in a slug of runoff and ground-water recharge. Although daily, watershed-scale, temporal data could more accurately estimate evapotranspiration and ground-water recharge, these data are not available, and a monthly budget for the study area is the time period the available data warrant.

SUMMARY AND CONCLUSIONS

A preliminary step in understanding the ground-water system in the east Maui area is the calculation of a water budget. A variety of monthly water budgets for east Maui were calculated that present a range of reasonable values of evapotranspiration and ground-water recharge useful for resource assessments.

Rainfall over the east Maui study area ranges from less than 15 to greater than 300 inches per year. Ground water is replenished by recharge from rainfall and fog drip that percolates through and beyond the root zone. Average monthly ground-water recharge was estimated from two accounting methods; one that favors evapotranspiration, and one that favors ground-water recharge. The water-budget components are defined seasonally, through the use of the monthly water budget, and spatially by various sub-areas, through the use of a geographic information system (GIS) model.

Analyses of evapotranspiration/potential-evapotranspiration ratios by sub-areas indicate that the average budget adequately apportions water to evapotranspiration. Assuming that all other budget components are likewise appropriately estimated, the resulting ground-water recharge in both dry and wet locations within the study area is similarly reasonably estimated. The average rainfall, fog-drip, runoff, evapotranspiration, and ground-water recharge volumes for east Maui are 2,246 Mgal/d, 323 Mgal/d, 771 Mgal/d, 735 Mgal/d, and 1,064 Mgal/d, respectively.

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