# WATER BUDGET FOR THE ISLAND OF MOLOKAI, HAWAII

*By* Patricia J. Shade

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BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director



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For additional information write to:

District Chief
U.S. Geological Survey
677 Ala Moana Blvd., Suite 415
Honolulu, HI 96813

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# Water Budget for the Island of Molokai, Hawaii

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## Abstract

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

The long-term average ground-water recharge for Molokai was estimated for natural land-use conditions. The island-wide mean recharge rate for natural conditions is 189 million gallons per day, which is 34 percent of rainfall. The island-wide rainfall, direct runoff, and actual evapotranspiration are 552, 89, and 274 millions gallons per day, respectively.

## INTRODUCTION

Ground-water development on Molokai is becoming increasingly important to meet present and projected municipal and agricultural demands. Although rainfall is abundant in the mountainous upland watersheds, development in this area is difficult. Ground-water development has been concentrated at a few specific areas at lower altitudes closer to the coast. In an effort to meet the present and future water demand and to increase knowledge of the ground-water system on Molokai, the State of Hawaii, Department of Hawaiian Home Lands entered into a cooperative agreement with the U.S. Geological Survey (USGS) to study ground-water availability on the island. The project includes a water-budget calculation described in this report and simulation 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 natural conditions on the island of Molokai. The island is sparsely populated and there is little urban development affecting the water-budget components. Recently, diversified agriculture has expanded after large-scale pineapple production was discontinued on the island. Island-wide, the effect of irrigated agriculture on the water budget is minimal because of the limited areas occupied by agriculture.

The availability of monthly mean rainfall distribution maps for the island was the determining factor for the time period used in the water-budget calculation. Because monthly calculations provide an estimate of actual evapotranspiration and water held in the soil root zone rather than assuming evapotranspiration occurs at the maximum rate, the resulting estimates of ground-water recharge are considered more realistic. Three water budgets are described that together present a range of actual evapotranspiration and ground-water recharge values useful for water-resource management. The spatial distribution of the water-budget components by water-management areas is tabulated, and the ground-water recharge distribution is displayed.

### Previous Investigations

Several reports address aspects of the water resources of the island of Molokai. Stearns and Macdonald (1947) described the geology and ground-water occurrence on the island. Numerous reports describe various surface- and ground-water development and transmission projects (Lindgren, 1903; Howell, 1938; Austin and Stearns, 1954; Hirashima, 1963; Parsons, Brinckerhoff, Hirota Assoc., 1969). A study containing water-budget estimates relevant to this investigation was prepared by the State of Hawaii (1990) for a water-resources protection plan.

### Description of the Study Area

The study area encompasses the entire island of Molokai, 260.5 mi$^2$ (fig. 1). Molokai is the fifth largest of the Hawaiian islands and is located about 25 mi southeast of Oahu and 8.5 mi northwest of Maui. The island is long and narrow, 38 miles by 10 miles, and was formed by volcanic activity at the East Molokai Volcano and the West Molokai Volcano.

***East Molokai.***--The peak of East Molokai is at an altitude of 4,961 ft at Kamakou (fig. 1). Originally, a large caldera, more than 4 mi across, existed near the summit of this volcano (Stearns and Macdonald, 1947) (fig. 2). Streams originate in this area of high rainfall, and most flow north and east, carving deep valleys into the north side of the extinct East Molokai Volcano. Streamflow in the uplands is perennial, fed by ground-water discharge at springs and by seepage from a high-level swamp (fig. 1). Some of this streamflow is diverted through a network of ditches and tunnels to reservoirs for municipal and agricultural supply. Forested conservation land dominates the uplands and the north part of East Molokai. East Molokai is undeveloped except for small communities located along the southern shore.

***Kalaupapa.***--The Kalaupapa Peninsula was formed from rejuvenated-stage lava at the base of a sea cliff on the north side of the East Molokai Volcano (fig. 2). This area is isolated from the rest of the island by the steep cliff and it is here that a settlement for Hansen's disease patients has been located since 1865. A well in the lower Waihanau Stream valley supplies water to the residents of the area.

***Hoolehua Plain.***--Lava flows of the East Molokai Volcano partially buried the eastern flanks of the older West Molokai Volcano (fig. 2) to form the Hoolehua Plain (fig. 1). No perennial streams exist in the area but a reservoir supplied by diverted water from East Molokai is located here. This reservoir and some limited ground-water development in East Molokai (fig. 3) supply water to meet the agricultural and municipal demands of the 6,600 residents that live in small communities in the area, in the central town of Kaunakakai, and along the southern shore of eastern Molokai. Much of the ground water is developed at wells near Kualapuu where the 1995 withdrawals totaled 2.49 Mgal/d. Agriculture is the predominant land use on the plain. Several thousand acres of pineapple were once cultivated near Kualapuu and in western Molokai beginning in the 1920's. Until 1985 pineapple production was a major source of employment on the island. Since then, smaller-scale diversified farms have been established cultivating coffee, watermelons, and other crops. Much of this fertile land was allocated to native Hawaiians as homestead lands by the Hawaiian Homes Commission Act of 1920.

***West Molokai.***--To the west of the Hoolehua Plain the island is much drier and there are no perennial streams. The peak of the West Molokai Volcano is at an altitude of 1,430 ft near Puu Nana (fig. 1). Ranching is the major land-use activity in this relatively barren area. A resort development along the western coast is sustained by water developed from East Molokai.

Most of the fresh ground water on the island is in East Molokai and moves from the mountain toward the ocean. Within the rift zone of the volcano, low-permeability basaltic dikes impede ground-water movement and impound ground water at high levels. The approximate location of this high-level water as well as other ground-water areas was described by Stearns and Macdonald (1947) (fig. 4). Freshwater floats on saltwater near sea level within the more permeable lava flows on the flank of the volcano. The aquifer is confined in places along the southern coast by low-permeability sedimentary deposits (fig. 2), locally known as caprock.

## WATER-BUDGET MODEL

Ground-water is replenished by recharge from rainfall that percolates through and beyond the root zone in the soil to the subsurface rock. Ground-water recharge can be estimated using a water-budget model. The method used in this study for calculating the water budget is similar to that developed by Thornthwaite (1948) and Thornthwaite and Mather (1955) and is an accounting procedure that balances moisture input of rainfall, and moisture outputs of direct runoff, evapo-

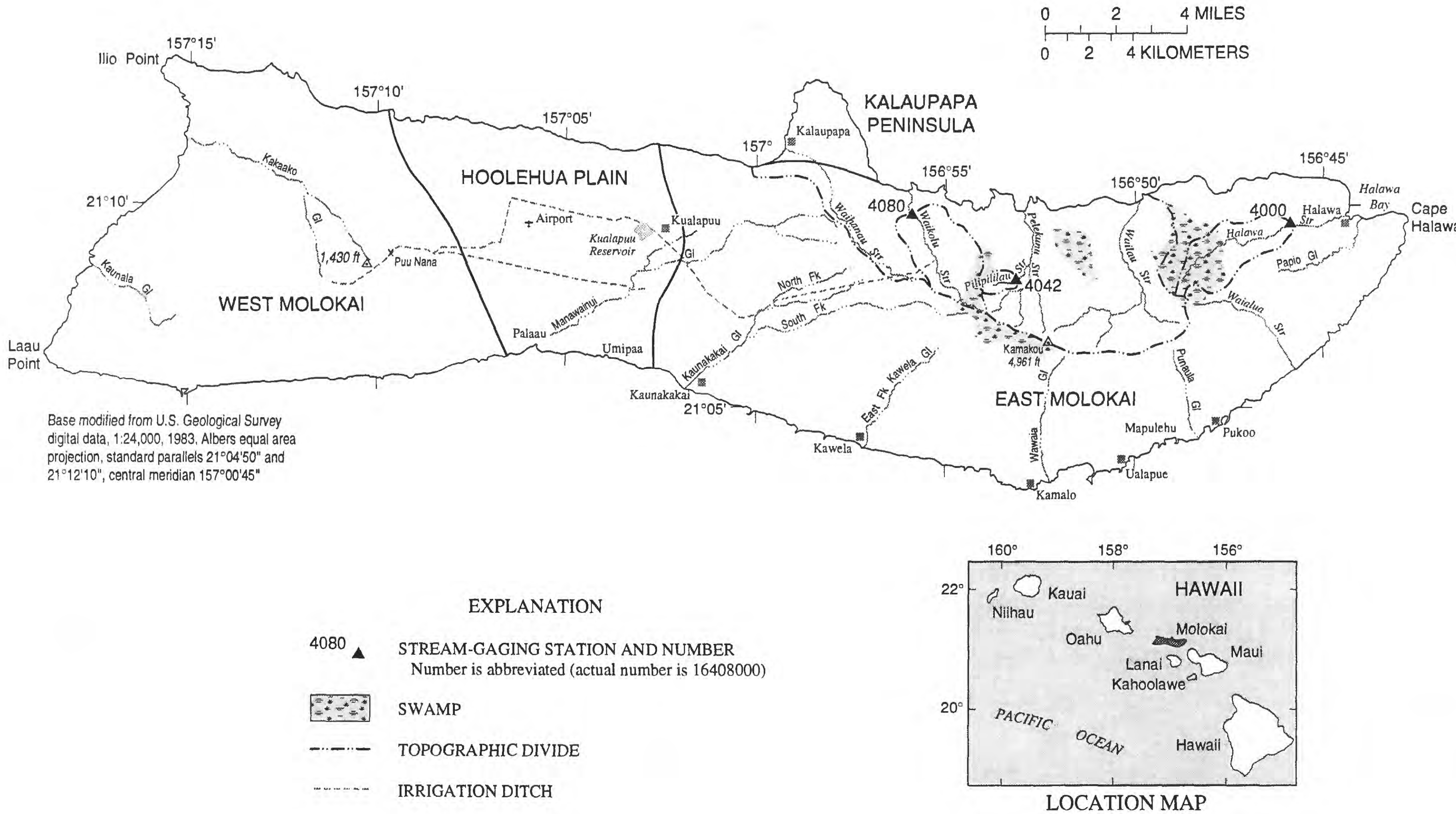


**Figure 1.** Geographic areas and selected stream-gaging stations, Molokai, Hawaii.

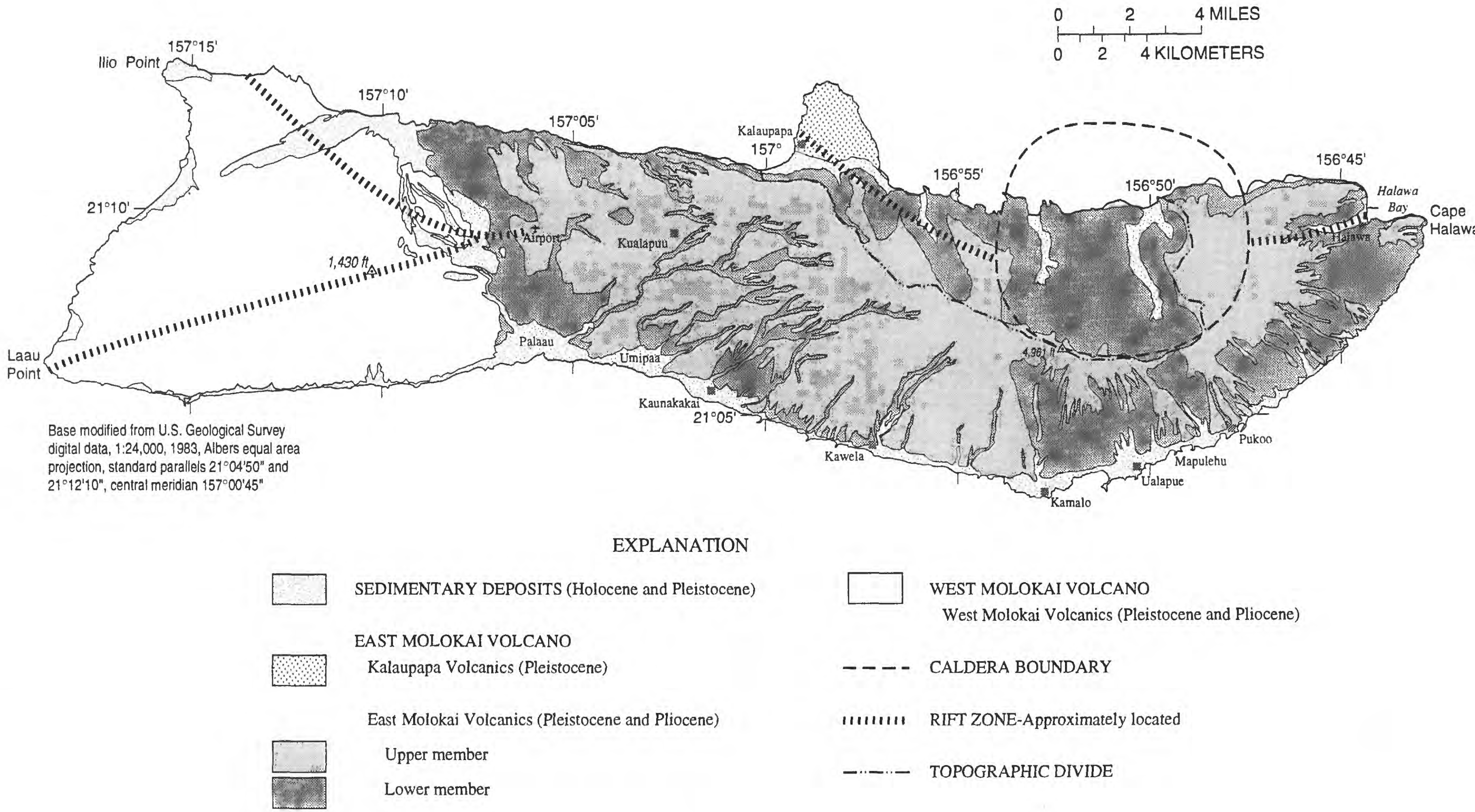


**Figure 2.** Generalized geology of Molokai, Hawaii (from Stearns and Macdonald, 1947; and Langenheim and Clague, 1987).

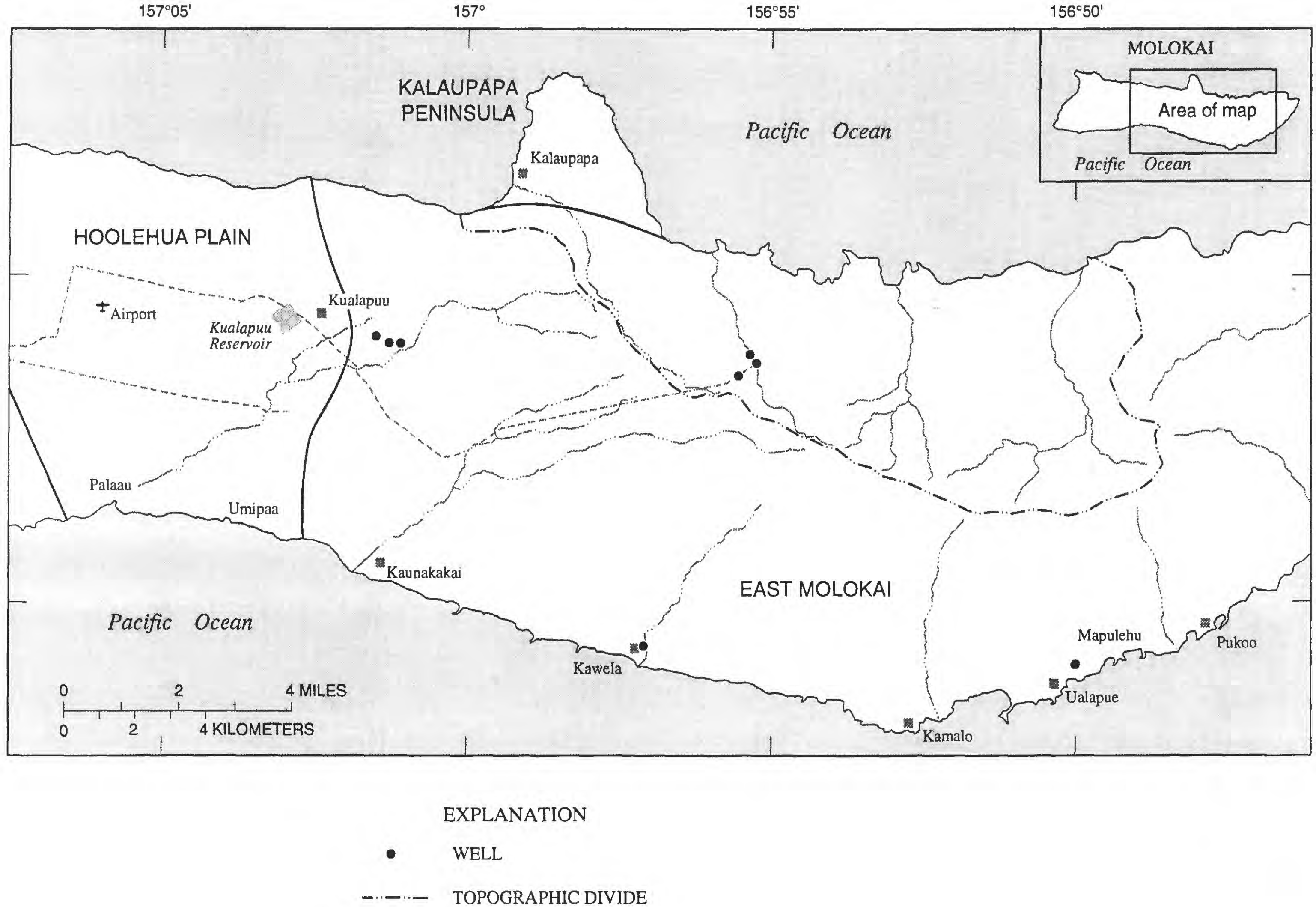


**Figure 3.** Selected wells in east-central Molokai, Hawaii, 1995.

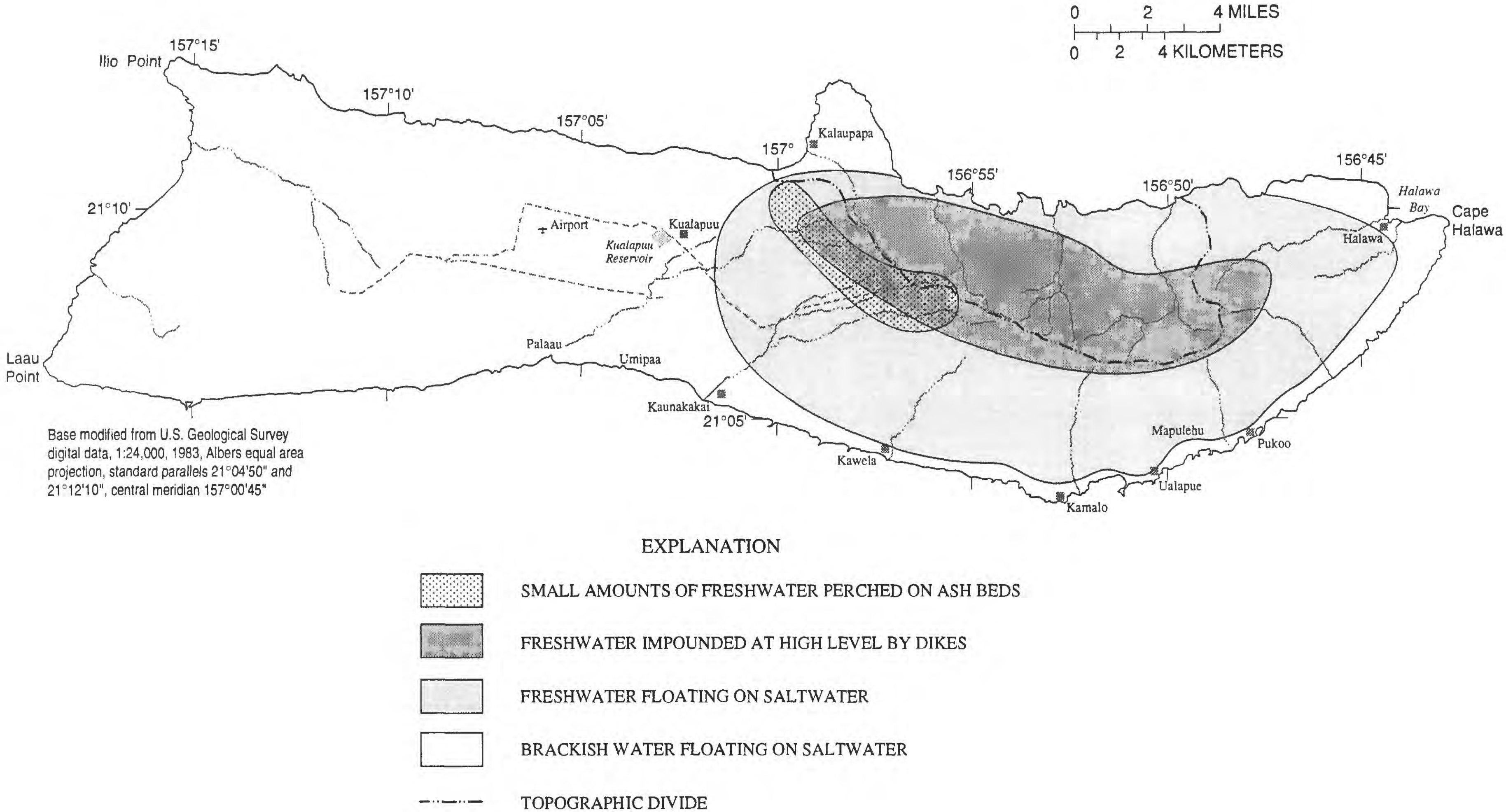


**Figure 4.** Estimated distribution of the principal modes of ground-water occurrence, Molokai, Hawaii (from Stearns and Macdonald, 1947).

transpiration, and ground-water recharge. This budgeting method is a coarse representation of the allocation of water to the continuous processes of soil-wetting and plant interception of rainfall, runoff in streams, the return of moisture to the atmosphere by way of evaporation from soil and water surfaces and evapotranspiration by plants, and percolation past the plant root zone to recharge ground water. The relation of the water-budget components is expressed by:

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

where: G = ground-water recharge,
P = precipitation rainfall,
R = direct runoff,
AE = actual evapotranspiration, and
ΔSS = change in soil-moisture storage.

In the water-budget model, direct runoff is calculated as a percentage of rainfall and thus the budgeting method solves for the remaining components of ground-water recharge, actual evapotranspiration, and the change in soil-moisture storage. All the specific conditions including the variety of rainfall intensities, the instances when evapotranspiration is suppressed because of rainy, cloudy conditions and 100 percent humidity, or when the soil is so dry there is no water for plant evapotranspiration, are not specifically simulated by the budget using monthly data. The monthly budget does provide, however, average values of the water-budget components appropriate for a general assessment of the magnitude of the resource.

## 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 spatial distributions of the rainfall, runoff (streamflow) and associated drainage area, soil properties, and pan-evaporation. The spatial data allow the water-budget components to be calculated and displayed by individual area or any combination of areas.

The digital map of the shoreline of the study area was prepared by the National Mapping Division of USGS from 1:24,000-scale USGS topographic maps prepared in 1983. The area was subsequently divided into water-management areas (called "aquifer-system" areas) defined by the State of Hawaii (1990). The digital representation of these areas was prepared by and obtained from the State of Hawaii Department of Health (fig. 5). These subdivisions allow comparisons with previous water-budget estimates for the island.

## Rainfall

The rainfall distribution in the study area is influenced by an orographic effect caused by the East Molokai Volcano. Rainfall is abundant along the crest of the East Molokai Volcano and on the windward (north) side of east Molokai as the prevailing northeast tradewinds are forced to rise and cool over the mountain mass. However, the rainfall maximum here is lower than that found at peaks of similar altitude on other Hawaiian islands, because the orientation of the crest is approximately parallel to the tradewind direction (Giambelluca and others, 1986). In some locations windward of the mountain crest, the mean annual values are more than 150 in. (Giambelluca and others, 1986) (fig. 6). Rainfall decreases dramatically towards the southern coast, where average rainfall is less than 15 in/yr near Kaunakakai.

Giambelluca and others (1986) prepared 12 maps showing lines of equal mean monthly rainfall for the island of Molokai. The maps were compiled from data collected at 84 stations including a network of five base stations that had complete records for the base period from 1931 through 1983. Records from an additional four stations with long periods of record were used in their statistical analyses (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. Yet some inconsistencies among nearby stations remained. Adjustments were made on the basis of the available data and on knowledge of the rainfall-producing mechanisms. Thus, there is an element of subjectivity incorporated into these maps (Giambelluca and others, 1986). These monthly maps were digitized and constitute the rainfall data set for the GIS model. The value assigned to the area between the lines of equal rainfall is the average value of the bounding lines.

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 899 Mgal/d (27,876 Mgal/mo) in January

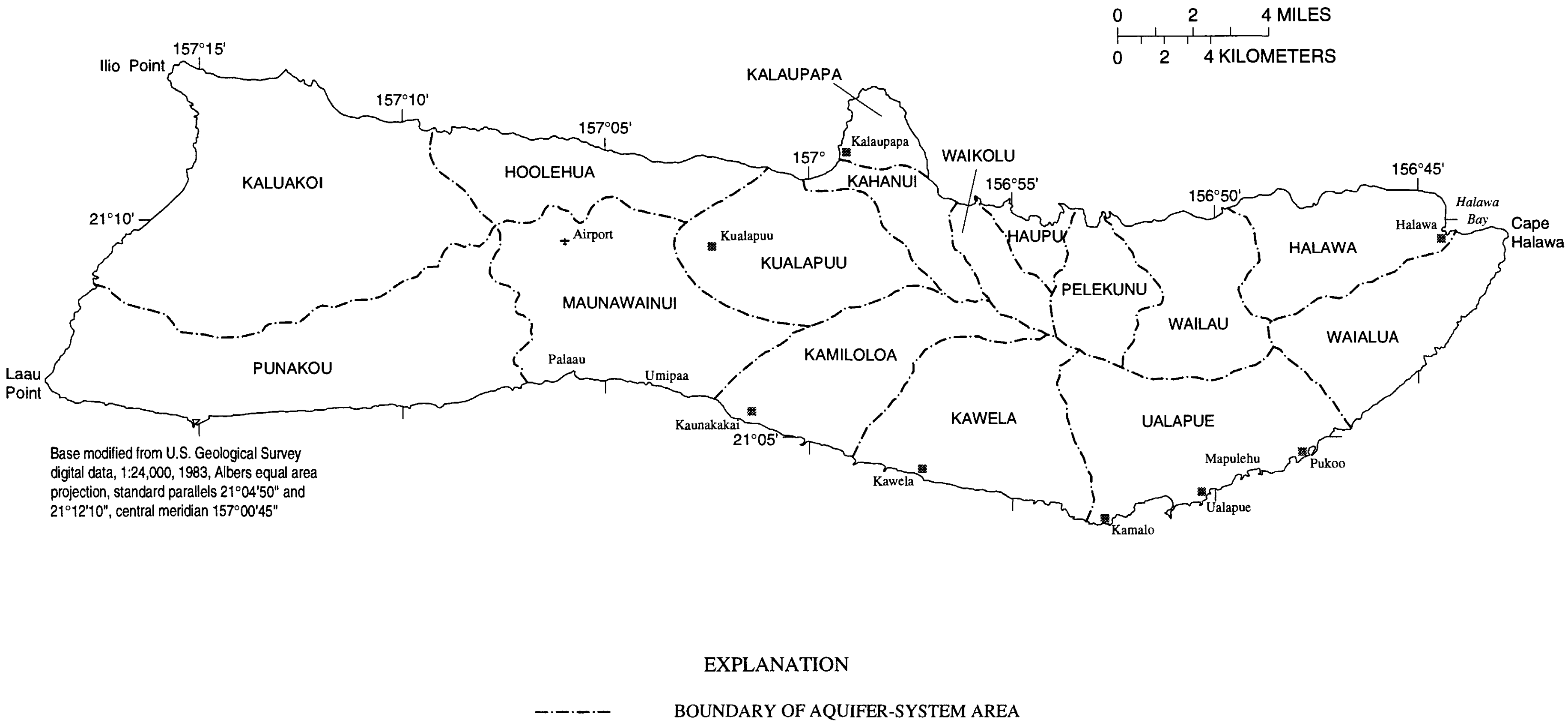


**Figure 5.** Aquifer-system areas, Molokai, Hawaii (from Mink and Lau, 1992).

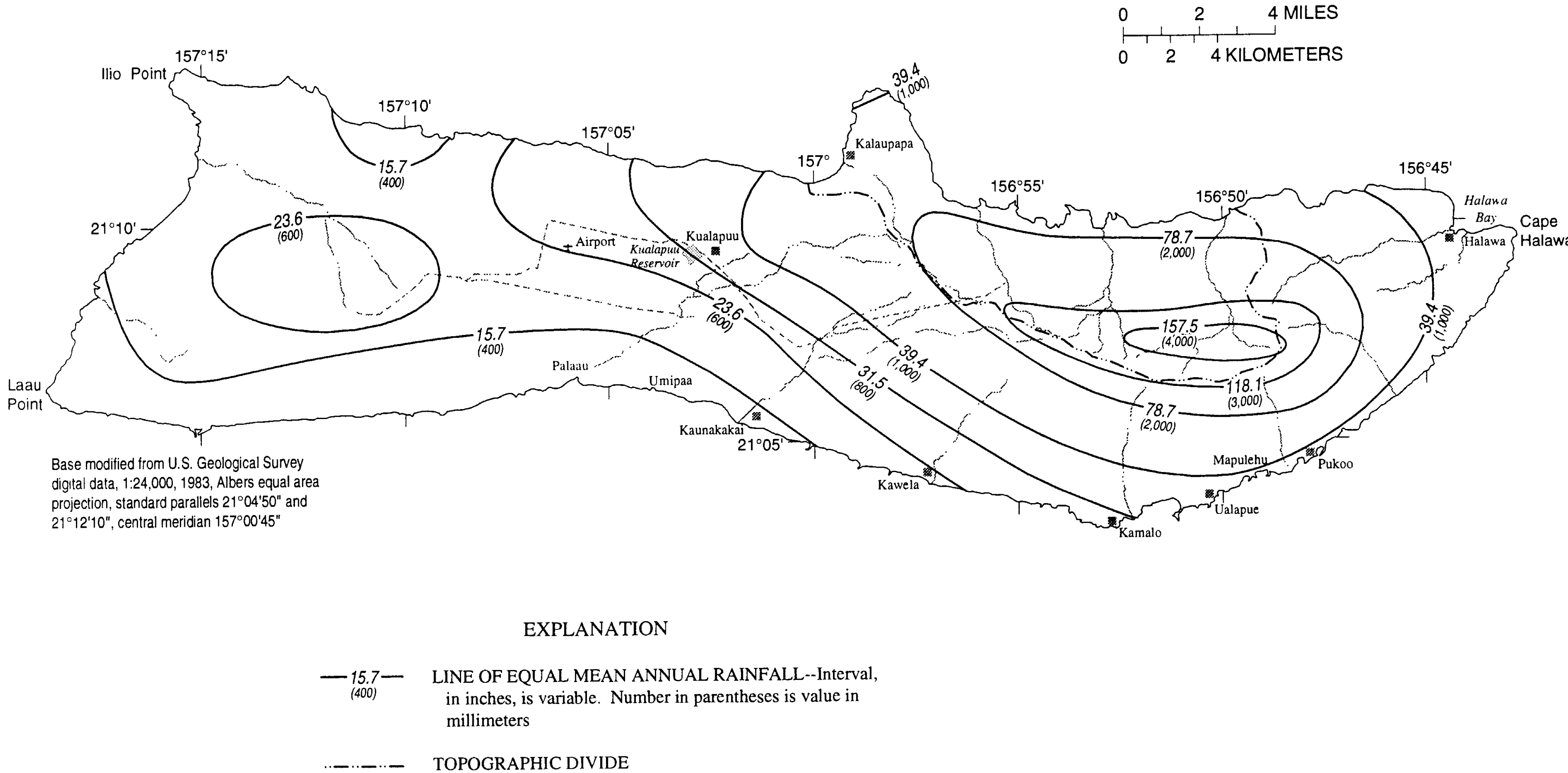


**Figure 6.** Mean annual rainfall, Molokai, Hawaii (modified from Giambelluca and others, 1986).

to a low of 215 Mgal/d (6,456 Mgal/mo) in June. Winter rainfall ranges from about 703 to 929 Mgal/d (21,093 to 27,876 Mgal/mo) from November through April and in the summer from about to 215 to 451 Mgal/d (6,456 to 13,988 Mgal/mo) from May through October.

## Runoff

Streamflow consists of direct runoff, the water that flows into stream channels promptly after rainfall, and base runoff, the part of streamflow that is sustained through dry weather from discharge of ground water (Langbein and Iseri, 1960). To avoid the inclusion of the ground-water component of streamflow, monthly direct runoff was calculated as the difference between mean monthly streamflow and mean monthly base runoff. Daily base runoff was calculated in this study using an automated base-flow hydrograph separation program (BFI) developed by Wahl and Wahl (1995). The daily streamflow record at each station is divided into N-day periods for which the BFI model computes a minimum flow. The appropriate N-value, 3, for each basin was determined by the point of slope change on graphs of the BFI index compared with the number of days in the period. The value for f, the turning point test factor, was set at 0.9 which indicates that if the minimum flow within a given 3-day period is less than 90 percent of the adjacent minimums, then the central minimum is a turning point on the base runoff hydrograph. The base runoff hydrograph is defined on semilogarithmic paper by straight lines connecting all turning points. The area beneath the hydrograph represents the volume of base runoff for the period of record. These daily values were summed for each month and monthly average base runoff values were calculated for the period of record.

The drainage basins for Halawa, Pilipililau, and Waikolu Streams upstream of stream-gaging stations 16400000, 16404200, and 16408000 (fig. 1), respectively, were digitized from USGS 1:24,000-scale topographic maps (fig. 1). Mean monthly rainfall volumes for these basins were calculated by overlaying each basin area with each month's rainfall distribution in the GIS model. Monthly direct runoff-rainfall ratios (table 1) were calculated for each of the three basins and these monthly ratios were multiplied by the mean monthly rainfall amounts over the respective drainage basin to compute the monthly direct runoff component of the water budget for the basins.

For non-perennial stream drainage basins and for areas where there are no, or only limited, streamflow data, a second procedure was followed to calculate direct runoff-rainfall ratios on the basis of soil type and rainfall. Rainfall in these areas varies greatly, from more than 150 in/yr at high altitudes in windward areas to less than 15 in/yr at many locations along the coast. The runoff-rainfall ratios were developed for three ranges of annual rainfall (greater than or equal to 100 in., greater than or equal to 50 in. and less than 100 in., and less than 50 in.) and for three generalized soil runoff ratings (rapid, medium, and slow).

Runoff ratings of soils on the island are described by Foote and others (1972). On the basis of soil texture, permeability, and slope, soil types have a broad runoff rating of slow, medium, or rapid. From results of a water balance computed for the Pearl Harbor area of Oahu (Giambelluca, 1983), comparable areas on Oahu

**Table 1.** Direct runoff-rainfall ratios for drainage areas of selected streams, Molokai, Hawaii
[values in percent; see figure 1 for areas]

| Stream | Station | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Halawa | 16400000 | 60 | 50 | 73 | 77 | 100 | 100 | 100 | 98 | 1,007 | 100 | 73 | 79 |
| Pilipililau | 16404200 | 22 | 12 | 13 | 16 | 12 | 4 | 5 | 4 | 3 | 7 | 15 | 12 |
| Waikolu | 16408000 | 29 | 25 | 26 | 28 | 28 | 17 | 18 | 24 | 18 | 23 | 23 | 33 |

| Direct runoff-rainfall ratios for areas outside of above drainage areas | | | |
|---|---|---|---|
| Soil Runoff | Rain ≥ 100 in/yr | 50 in/yr ≤ Rain < 100 in/yr | Rain < 50 in/yr |
| Rapid | 21 | 13 | 11 |
| Medium | 17 | 13 | 11 |
| Slow | not applicable | 11 | 11 |

were chosen with similar mean annual rainfall and soil properties as those of Molokai. The Oahu data provided average annual runoff-rainfall ratios for each soil runoff rating within each rainfall range (table 1). The ratios were multiplied by the monthly rainfall values to estimate monthly direct runoff values.

## Study Area Soils

The soil types have been mapped and digitized and their characteristics tabulated by the Natural Resources Conservation Service (Foote and others, 1972) (table 2). Values for the soil characteristics of permeability, available water capacity (a measure of the quantity of water held in the soil available to plants between field capacity and wilting point), and the root depth presented by Foote and others (1972) were entered into attribute data tables associated with the digital soil distribution.

Data that were not available from Foote and others (1972) were provided by the Natural Resources Conservation Service (Saku Nakamura, written commun., 1997). The available-water value for each soil series in table 2 is the central value of the range reported by Foote and others (1972). The root depth was assumed to

**Table 2.** Average soil characteristics, Molokai, Hawaii

[Data from Foote and others, 1972; and Saku Nakamura, Natural Resources Conservation Service, written commun., 1997]

| Soil series | Available-water capacity (inch per inch of soil) | Root depth (inches) | Maximum soil-moisture storage (inches) | Permeability (inches per hour) |
|---|---|---|---|---|
| Alaeloa | 0.13 | 29.0 | 3.77 | 2.0–6.0 |
| Amalu | 0.35 | 8.0 | 2.48 | 0.06–20.0 |
| Beaches | 0.04 | 6.0 | 0.24 | 6.0–20.0 |
| Colluvial land | 0.12 | 10.0 | 1.15 | 0.6–2.0 |
| Gullied land | 0.01 | 2.0 | 0.02 | 0.2–6.0 |
| Halawa | 0.13 | 44.0 | 5.72 | 2.0–6.0 |
| Haleiwa | 0.14 | 48.0 | 6.72 | 0.6–2.0 |
| Holomua | 0.13 | 26.0 | 3.38 | 0.6–2.0 |
| Hoolehua | 0.07 | 15.0 | 2.25 | 0.6–2.0 |
| Jaucas | 0.06 | 13.0 | 0.78 | 6.0–20.0 |
| Kahanui | 0.11 | 18.0 | 1.98 | 2.0–6.0 |
| Kalaupapa | 0.20 | 14.0 | 2.8 | 0.6–2.0 |
| Kapuhikani | 0.12 | 20.0 | 2.40 | 0.06–0.2 |
| Kealia | 0.10 | 19.0 | 1.90 | 2.0–6.0 |
| Koele | 0.14 | 18.0 | 2.52 | 2.0–6.0 |
| Kalae | 0.13 | 9.0 | 1.17 | 2.0–6.0 |
| Kawaihapai | 0.13 | 54.0 | 7.02 | 0.6–6.0 |
| Lahaina | 0.11 | 31.0 | 3.41 | 0.6–2.0 |
| Lualualei | 0.12 | 30.0 | 3.60 | 0.06–0.2 |
| Mala | 0.12 | 40.0 | 4.80 | 0.6–20.0 |
| Marsh | 0.27 | 10.0 | 2.70 | 2.0–6.0 |
| Molokai | 0.12 | 15.0 | 1.80 | 0.6–2.0 |
| Naiwa | 0.10 | 52.0 | 5.20 | 0.2–6.0 |
| Niulii | 0.13 | 11.0 | 1.43 | 2.0–6.0 |
| Olelo | 0.11 | 19.0 | 2.09 | 2.0–6.0 |
| Oli | 0.13 | 21.0 | 2.73 | 2.0–6.0 |
| Olokui | 0.19 | 15.0 | 2.85 | 0.01–20.0 |
| Pamoa | 0.08 | 62.0 | 4.96 | 0.06–2.0 |
| Pulehu | 0.135 | 33.0 | 4.46 | 0.6–2.0 |
| Rock land | 0.14 | 4.0 | 0.56 | 0.6–2.0 |
| Rock outcrop | 0.04 | 0.60 | 0.02 | not applicable |
| Rough broken land | 0.15 | 30.0 | 4.50 | 0.6–2.0 |
| Rough mountain land | 0.14 | 25.0 | 3.38 | 0.2–6.0 |
| Stony alluvial | 0.06 | 50.0 | 3.00 | 2.0–6.0 |
| Stony colluvial | 0.10 | 10.0 | 1.00 | 0.6–2.0 |
| Tropaquods | 0.22 | 5.0 | 1.10 | 0.01–20.0 |
| Very stony land | 0.09 | 5.0 | 0.45 | 0.06–2.0 |
| Waihuna | 0.10 | 18.0 | 1.80 | .06–0.6 |
| Waikapu | 0.10 | 12.0 | 1.20 | 0.6–2.0 |

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 2). A digital map (fig. 7) of maximum soil-moisture storage was created for use in the GIS model. The $SS_{max}$ value is important in the water budget because it is the maximum limit for evapotranspiration and the limit above which ground-water recharge occurs.

## Pan Evaporation and Potential Evapotranspiration

Pan evaporation data from class-A evaporating pans provide an estimate of the potential (maximum) evapotranspiration. Potential evapotranspiration (PE) is an estimate of the amount of water that could be evapotranspired from a given area, assuming a continuous water supply. Thus, PE, although influenced by other factors, is primarily a function of solar radiation energy (Chang, 1968, p. 131 and Mather, 1978, p. 8). Therefore in dry, sunny areas, actual evapotranspiration can rarely occur at the estimated potential rate without irrigation, because there is a lack of water to satisfy the maximum demand described by the PE value. For this study, pan evaporation is assumed to equal potential evapotranspiration on the basis of the results of lysimeter studies in sugarcane fields (Chang, 1968; Campbell and others, 1959) where the average ratio between potential evapotranspiration and pan evaporation was about 1.0.

Pan evaporation data are available at three sites on Molokai (Ekern and Chang, 1985), one in west Molokai and two on the Hoolehua Plain. Two of these sites have a period of record of less than 4 years, but one had 14 years of data. These data indicate high pan evaporation rates on the uplands of the Hoolehua Plain where it is dry and windy. Ekern and Chang (1985) found that the annual pan evaporation rates in this area are 30 to 40 percent greater than that for the open ocean adjacent to Hawaii, which is 79 in/yr. Thus in the GIS model, annual pan evaporation was calculated to be 135 percent of 79 in., between the altitudes of 500 and 800 ft on the Hoolehua Plain. Annual values for the remainder of the island were estimated on the basis of a rainfall-pan evaporation relation (eq. 2) established from data available near the southern part of the island of Hawaii (Giambelluca and others, 1983; and Ekern and Chang, 1985) for an area with equally varying climatic patterns of dry windy conditions in the lowlands and similar rapidly increasing rainfall and cloud cover and lower temperatures with increasing altitude:

$$\textit{Annual Pan Evaporation} = 235.16 \times \textit{Annual Rain}^{-0.32} \quad (2)$$

The annual pan evaporation was distributed monthly on the basis of a set of monthly factors that describe the relation between the monthly and annual rainfall values:

$$Pan_m = \frac{\textit{annual pan } (x/Rain_m)}{y}, \quad (3)$$

where $x = \textit{annual rain}/12$ and

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

The monthly pan evaporation values are inversely related to rainfall, decreasing in the wet winter months and increasing in the dry summer months.

## Actual Evapotranspiration and Soil-Moisture Accounting

Actual evapotranspiration is the quantity of water evaporated from water, plant, and soil surfaces and transpired by plants. Actual evapotranspiration data from direct field measurements are not available for Molokai; however, it is possible to estimate actual evapotranspiration from estimates of pan evaporation and soil data.

The potential evapotranspiration (pan evaporation) demand in a particular month can not always be met by the amount of water in soil storage. In such situations actual evapotranspiration is less than the potential evapotranspiration. The maximum soil-moisture storage capacity, $SS_{max}$, 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 evapotranspiration. Two water-budget accounting sequences were used; one that favors recharge and one that favors evapotranspiration.

The amount of water held in the soil changes from month to month. To determine an initial soil-moisture storage value for the water-budget model, three model runs were made using different soil-moisture storage values for the month of January: $SS_{max}$, half of $SS_{max}$, and zero. The resulting soil-moisture storage values at

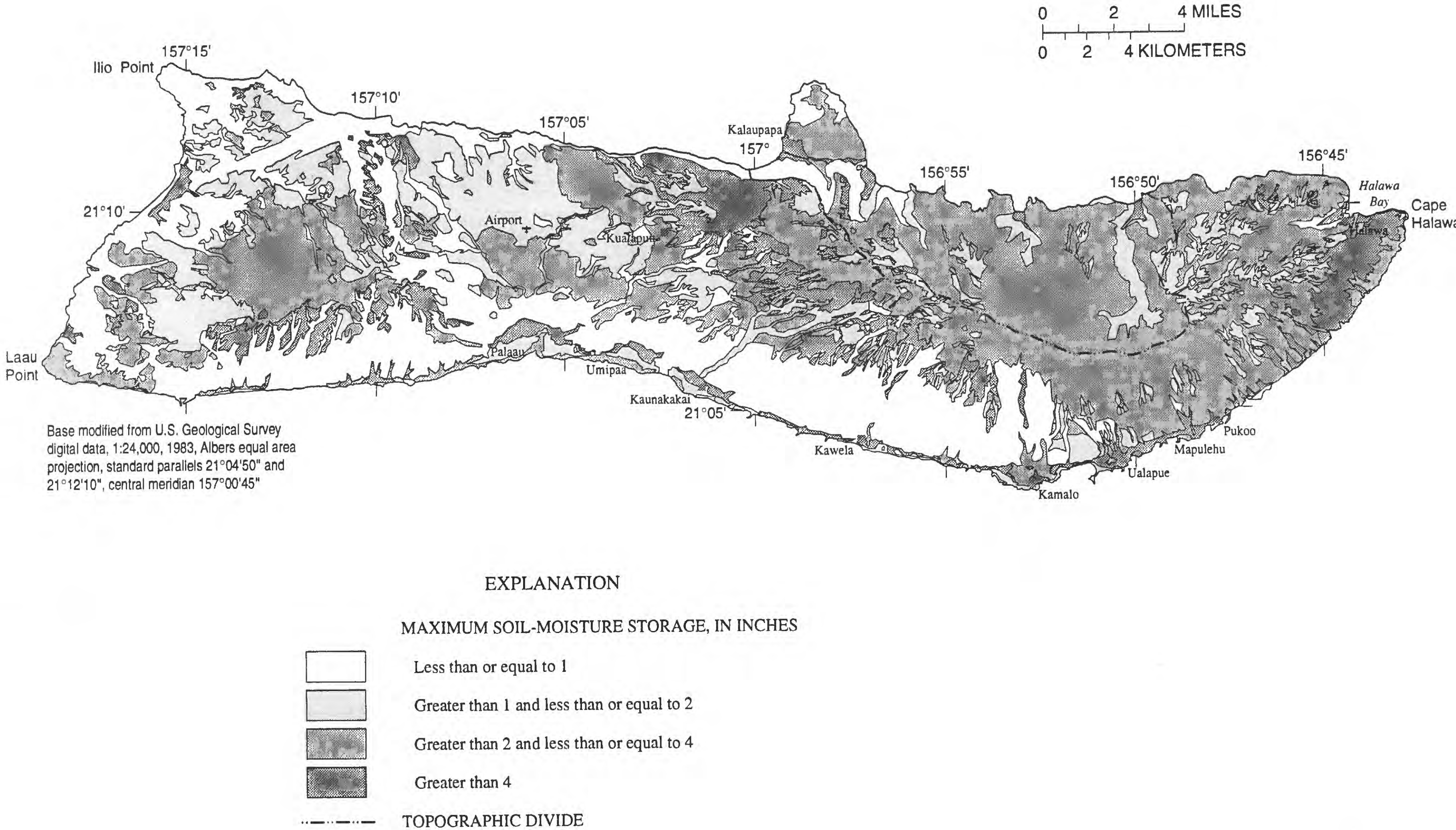


**Figure 7.** Maximum soil-moisture storage, Molokai, Hawaii.

the end of December were identical for these three model runs. Thus, the December values were input for the initial soil-moisture storage in January for the final water-budget calculation. The first accounting sequence, method I, creates the opportunity for excess soil-moisture to be allocated to ground-water recharge first, and the second accounting sequence, method II, allocates excess soil-moisture to evapotranspiration. The results of the two water-budget accounting procedures were averaged to present a reasonable, although not overly-conservative estimate of ground-water recharge.

The following accounting sequence, method I, favors ground-water recharge. The runoff for the month is subtracted from the sum of the month's initial soil-moisture and rainfall. The remainder is the first interim soil-moisture storage value ($X_1$), and if this quantity exceeds $SS_{max}$, the excess recharges ground water. Evapotranspiration is subtracted from the second interim soil-moisture storage ($X_2$) at either the potential (maximum) evapotranspiration value or at some lesser actual evapotranspiration value depending on the quantity of water in soil-moisture storage available to meet the demand. Any water remaining in soil-moisture storage ($X_{end}$) is carried over to the next month. This accounting procedure is shown in the following equations.

$$X_1 = SS_m + P_m - R_m, \tag{4}$$

where:

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

If $X_1 > SS_{max}$, then $G_m = X_1 - SS_{max}$ and $X_2 = SS_{max}$. **OR** If $X_1 \leq SS_{max}$, then $G_m = 0$ and $X_2 = X_1$. (5)

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.

If $X_2 \geq PE_m$, then $AE_m = PE_m$ and $X_{end} = X_2 - PE_m$. **OR** If $X_2 < PE_m$, then $AE_m = X_2$ and $X_{end} = 0$. (6)

where:

$AE_m$ = actual 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 ($SS_{m+1}$).

Method II also begins by subtracting the month's runoff from the sum of the month's initial soil-moisture and rainfall. The remainder is the first interim soil-moisture storage. Evapotranspiration is subtracted from this soil-moisture storage at either the potential evapotranspiration value or at some lesser actual evapotranspiration value depending on the quantity of water in soil-moisture storage available to meet the demand. After evapotranspiration is subtracted from storage, if the remaining water in storage, second interim soil-moisture storage, exceeds $SS_{max}$, 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:

$$X_1 = SS_m + P_m - R_m, \tag{7}$$

where:

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

If $X_1 \geq PE_m$, then $AE_m = PE_m$ and $X_2 = X_1 - PE_m$. **OR** If $X_1 < PE_m$, then $AE_m = X_1$ and $X_2 = 0$. (8)

where:

$PE_m$ = potential (maximum) evapotranspiration for the month,
$AE_m$ = actual evapotranspiration for the month, and
$X_2$ = second interim soil-moisture storage for the month.

If $X_2 \geq SS_{max}$, **OR** If $X_2 < SS_{max}$, (9)

then $G_m = X_2 - SS_{max}$ then $G_m = 0$

and $X_{end} = SS_{max}$. and $X_{end} = X_2$.

where:

$SS_{max}$ = maximum soil-moisture storage,

$G_m$ = ground-water recharge 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 ($SS_{m+1}$).

## Ground-Water Recharge

The average recharge for Molokai is calculated to be 5,739 Mgal/month or 189 Mgal/d for natural conditions. The distribution of ground-water recharge (fig. 8) is somewhat similar to the distribution of annual rainfall (fig. 6). Ground-water recharge ranges from less than 1 in/yr at many locations in western Molokai and at some locations along the southern and eastern shore to 100 in/yr near the eastern Molokai mountain crest. Recharge during the winter months is considerably more than during the summer months (table 3). From November through April, average recharge ranges from 218 Mgal/d (6,547 Mgal/mo) in November to a high of 427 Mgal/d (13,241 Mgal/mo) in January. During the summer months average recharge ranges from a low of 17 Mgal/d (513 Mgal/mo) in June to a high of 70 Mgal/d (2,157 Mgal/mo) in October. The low recharge values in June and September are directly related to the distinct low rainfall values for the same months.

# WATER-BUDGET RESULTS

The relations between the water-budget components for natural conditions for Molokai are summarized in table 3. The water budget shows distinct variations in rainfall, runoff, evapotranspiration, and ground-water recharge through the months. The winter rainfall is generally three times the summer rainfall with a similar seasonal pattern for runoff. The average monthly evapotranspiration values do not vary as dramatically through the months because actual evapotranspiration is limited in the winter by a decrease in evaporative energy and in the summer by a lack of water to meet the evaporative demand. Seasonality in ground-water recharge is similar to that of rainfall, although the difference in the average values is more extreme, with the highest winter (January) recharge volume being more than 20 times the lowest summer (June) volume.

**Table 3.** Monthly water budget, Molokai, Hawaii

[Values in million gallons per month; AE, actual evapotranspiration; SS, soil-moisture storage; I, method I; II, method II]

| Water-budget component | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. | Mean[1] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rainfall | 27,876 | 23,563 | 26,181 | 20,647 | 11,169 | 6,456 | 9,080 | 9,415 | 7,258 | 13,988 | 21,093 | 24,892 | 16,801 |
| Direct runoff | 4,246 | 3,578 | 4,203 | 3,453 | 1,921 | 1,113 | 1,579 | 1,678 | 1,212 | 2,272 | 3,385 | 3,987 | 2,719 |
| Pan evaporation | 9,898 | 12,392 | 11,455 | 15,921 | 30,095 | 70,649 | 56,479 | 51,555 | 49,055 | 23,052 | 14,569 | 11,656 | 29,731 |
| AE I | 7,530 | 8,392 | 7,757 | 8,317 | 6,971 | 4,360 | 5,277 | 5,421 | 4,955 | 7,562 | 8,062 | 7,820 | 6,869 |
| AE II | 9,889 | 12,045 | 10,864 | 12,107 | 11,970 | 7,490 | 7,153 | 7,399 | 6,548 | 10,696 | 10,856 | 10,804 | 9,818 |
| AE average | 8,709 | 10,218 | 9,311 | 10,211 | 9,471 | 5,924 | 6,215 | 6,410 | 5,752 | 9,129 | 9,459 | 9,312 | 8,343 |
| Recharge I | 15,245 | 12,388 | 13,713 | 10,037 | 3,274 | 1,025 | 2,224 | 2,317 | 1,092 | 4,144 | 8,928 | 12,185 | 7,214 |
| Recharge II | 11,236 | 8,608 | 10,993 | 7,182 | 583 | 0 | 88 | 213 | 0 | 171 | 4,164 | 7,936 | 4,264 |
| Recharge average | 13,241 | 10,497 | 12,353 | 8,610 | 1,929 | 513 | 1,156 | 1,264 | 547 | 2,157 | 6,547 | 10,059 | 5,739 |
| EndSS I | 2,484 | 1,690 | 2,198 | 1,038 | 40 | 0 | 1 | 1 | 0 | 10 | 727 | 1,628 | 818 |
| EndSS II | 8,332 | 7,664 | 7,787 | 5,691 | 2,386 | 239 | 501 | 627 | 138 | 975 | 3,661 | 5,828 | 3,652 |
| EndSS average | 5,408 | 4,678 | 4,992 | 3,364 | 1,212 | 119 | 249 | 312 | 69 | 491 | 2,192 | 3,725 | 2,234 |
| ΔSS I | +856 | -794 | +508 | -1,160 | -998 | -40 | +1 | 0 | -1 | +10 | +717 | +901 | 0 |
| ΔSS II | +2,504 | -668 | +123 | -2,096 | -3,305 | -2,147 | +262 | +126 | -489 | +837 | +2686 | +2,167 | 0 |
| ΔSS average | +1,683 | -730 | +314 | -1,628 | -2,152 | -1,093 | +130 | +63 | -244 | +423 | +1701 | +1,533 | 0 |

[1] Sum of January through December values divided by 12; for ΔSS mean is sum of January through December values which should equal 0, any imbalance in budget is due to rounding

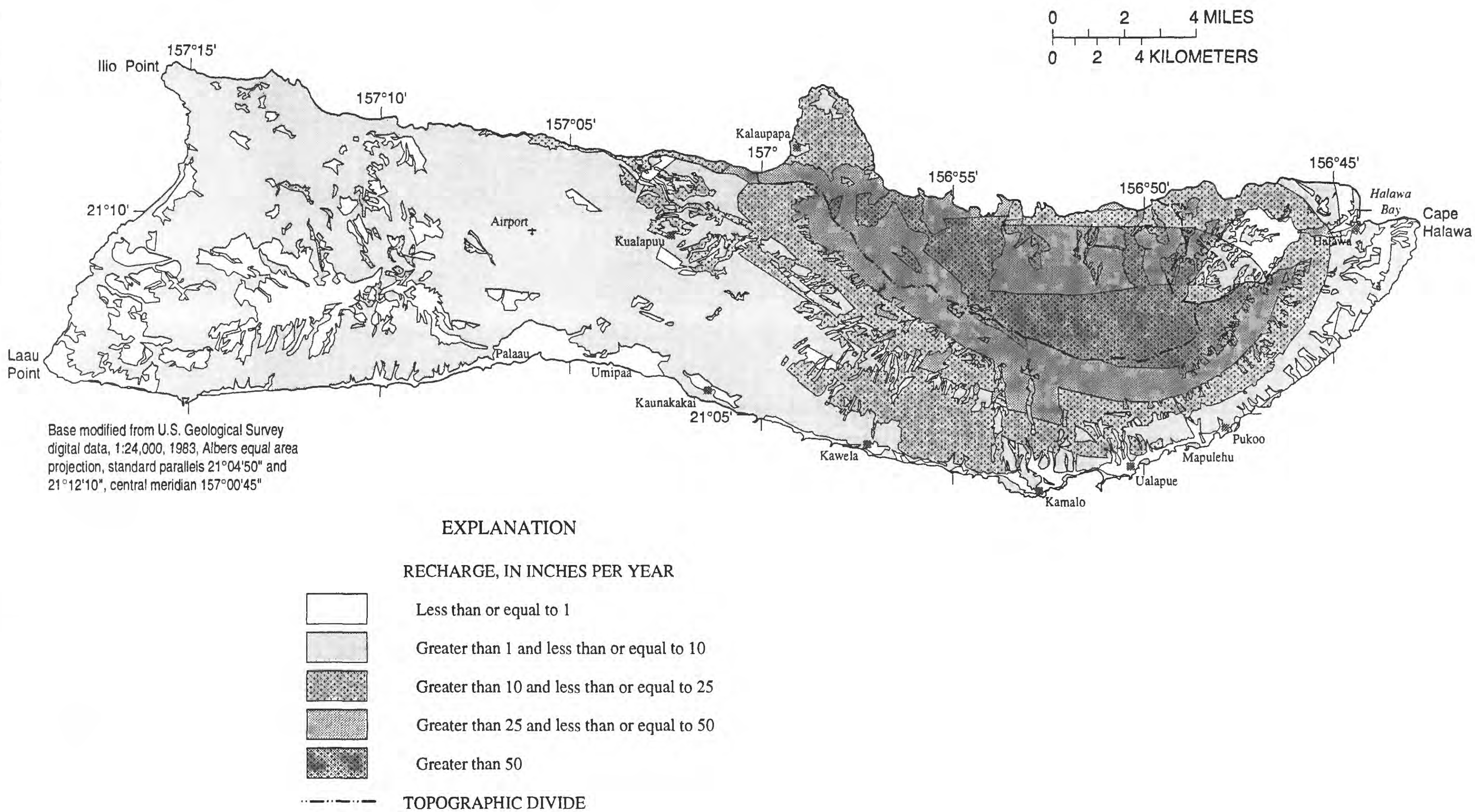


**Figure 8.** Estimated ground-water recharge, Molokai, Hawaii.

The effect of the accounting sequence in the budget is indicated by a comparison of the actual evapotranspiration and recharge values from method I which favors ground-water recharge and method II which favors actual evapotranspiration. The mean ground-water recharge value for method I (7,214 Mgal/mo), is about 69 percent greater than for method II (4,264 Mgal/mo). The monthly actual evapotranspiration values for method II are greater than the actual evapotranspiration values for method I by an average of about 43 percent for the mean.

A comparison of the method II actual evapotranspiration and pan evaporation values indicates the degree to which evapotranspiration can be overestimated in a water budget that uses an estimate of maximum evapotranspiration, such as pan evaporation, rather than calculating some actual evapotranspiration value. The method II accounting sequence favors ET rather than ground-water recharge. From December through March, the AE and pan values are similar. However, as rainfall decreases from April through October, there is not enough water to meet the evaporative demand. Thus, pan values consistently exceed AE values by as much as 9 times in June.

The seasonality in evapotranspiration and recharge can also be described in proportion to rainfall (table 4). The direct runoff-rainfall ratio average is 16 percent. The slight variability throughout the year, is a consequence of the lack of data and of the runoff estimation method. Actual evapotranspiration varies from about 31 to 49 percent of rainfall from November through April (winter) and increases to 65 to 92 percent during the summer months from May through October. The converse relation for recharge shows recharge occurring at 31 to 47 percent of rainfall in the winter and at about 8 to 17 percent of rainfall from May through October.

Because the values in table 3 are a compilation of the water budgets calculated for any location on the island, the water budget for a smaller area (table 5) shows the variations that can occur and are masked at the island scale. A large part of the island's ground-water development is from the Kualapuu aquifer-system area (figs. 3 and 5). The area is 18 mi$^2$ and receives an average amount of rainfall for the island (fig. 6) with a mean of 1,181 Mgal/mo (39 Mgal/d). The direct runoff is 11.5 percent of rainfall at 136 Mgal/mo (about 4.5 Mgal/d). The calculated mean actual evapotranspiration, 696 Mgal/mo, is 59 percent of rainfall and mean ground-water recharge, 349 Mgal/mo, is about 30 percent of rainfall. Compared with the island-wide ratios (table 4), these ratios describe a relatively dry area where ground-water recharge is significant during the wet winter months and negligible during the summer. The magnitude of the effect of the two accounting methods is indicated where the method II actual evapotranspiration exceeds rainfall in May and June drawing down the volume in soil storage to zero throughout the summer months, and causing zero ground-water recharge in these same months. The ground-water recharge values calculated by the two methods provide a range of data with which to test conceptual models of the ground-water flow system in the area.

***Comparison with results of previous study.***--Water-budget results from this study and a previous investigation are presented by aquifer-system areas (fig. 5) in tables 6 and 7. The presentation highlights the comparative magnitude of the effects of assumptions made in the water-budget calculations on the water-budget results. The water budget by the State of Hawaii (1990) is somewhat similar to the results of the water-budget accounting method II in this report in that it calculates a significant proportion of evapotranspiration in all areas of the island. The State budget assumes evapotranspiration occurs at a maximum, potential rate which emphasizes evapotranspiration and reduces ground-water recharge. The effect of assuming potential evapotranspiration rather than calculating an actual evapotranspiration volume is most apparent in Kawela where the State evapotranspiration estimate, 32 Mgal/d, is about twice that estimated by the average value in the present study, 20 Mgal/d. Similarly, the

**Table 4.** Monthly water-budget ratios for natural conditions, Molokai, Hawaii

[Values using average of methods I and II in percent; AE, actual evapotranspiration; sum of monthly ratios may not equal 100 due to rounding and amount of water in soil storage]

| Ratio | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Direct runoff/rain | 15 | 15 | 16 | 17 | 17 | 17 | 17 | 18 | 17 | 16 | 16 | 16 | 16 |
| AE/rain | 31 | 43 | 36 | 49 | 85 | 92 | 68 | 68 | 79 | 65 | 45 | 37 | 50 |
| Recharge/rain | 47 | 45 | 47 | 42 | 17 | 8 | 13 | 13 | 8 | 15 | 31 | 40 | 34 |

estimate of recharge from the State study is about one-third to half of the average recharge values estimated in the present study in several of the areas, including Kahanui, Haupu, Waikolu and Wailau.

Although the same rainfall data were used for these two studies, the present study used a monthly rainfall distribution and the previous study used the annual distribution. It is not clear how area rainfall values were determined in the State of Hawaii report (1990). A comparison of the monthly and annual rainfall distributions in the GIS showed some discrepancies particularly in the windward aquifer-system areas of Pelekunu, Wailau, and Halawa. The sum of the monthly rainfall values were significantly greater than the mean annual values, apparently owing to a registration error in the monthly rainfall GIS data causing the rainfall lines to be

**Table 5.** Monthly water budget for Kualapuu aquifer-system area, Molokai, Hawaii
[Values in million gallons per month; I, method I; II, method II]

| Water-budget component | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. | Mean[1] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rainfall | 1,996 | 1,657 | 1,805 | 1,503 | 869 | 441 | 531 | 544 | 407 | 1,006 | 1,428 | 1,982 | 1,181 |
| Direct runoff | 229 | 190 | 208 | 173 | 100 | 51 | 61 | 63 | 47 | 116 | 165 | 227 | 136 |
| Pan evaporation | 743 | 899 | 841 | 1,056 | 1,802 | 3,919 | 3,193 | 3,148 | 3,928 | 1,524 | 1,065 | 754 | 1,906 |
| AE I | 633 | 736 | 697 | 259 | 816 | 381 | 427 | 439 | 340 | 706 | 769 | 638 | 570 |
| AE II | 743 | 899 | 840 | 987 | 1,309 | 718 | 469 | 481 | 360 | 880 | 935 | 751 | 781 |
| AE average | 688 | 818 | 768 | 873 | 1,063 | 549 | 448 | 460 | 350 | 793 | 852 | 694 | 696 |
| Recharge I | 1,120 | 828 | 863 | 653 | 161 | 24 | 42 | 42 | 20 | 181 | 399 | 864 | 433 |
| Recharge II | 866 | 553 | 754 | 446 | 2 | 0 | 0 | 0 | 0 | 0 | 45 | 501 | 264 |
| Recharge average | 993 | 691 | 808 | 550 | 82 | 12 | 21 | 21 | 10 | 91 | 222 | 682 | 349 |
| EndSS I | 367 | 268 | 306 | 223 | 15 | 0 | 0 | 0 | 0 | 4 | 100 | 353 | 136 |
| EndSS II | 957 | 972 | 975 | 871 | 328 | 0 | 0 | 0 | 0 | 11 | 295 | 798 | 434 |
| EndSS average | 662 | 620 | 640 | 547 | 172 | 0 | 0 | 0 | 0 | 7 | 197 | 575 | 285 |
| ΔSS I | +14 | -99 | +38 | -83 | -208 | -15 | 0 | 0 | 0 | +4 | +96 | +253 | 0 |
| ΔSS II | +159 | +15 | +3 | -104 | -543 | -328 | 0 | 0 | 0 | +11 | +284 | +503 | 0 |
| ΔSS average | +86 | -42 | +20 | -93 | -375 | -172 | 0 | 0 | 0 | +7 | +190 | +378 | 0 |

[1] Mean is sum of January through December values divided by 12; for ΔSS, mean is sum of January through December values which should equal 0.

**Table 6.** Water budgets from this study for aquifer-system areas, Molokai, Hawaii
[Mgal/d, million gallons per day; AE, actual evapotranspiration. The difference of rainfall minus runoff, average AE, and average recharge may not equal zero due to rounding, areas shown in figure 9]

| Aquifer-system area | Area ($mi^2$) | Rainfall (Mgal/d) | Runoff (Mgal/d) | Runoff/ Rainfall (percent) | Method I AE (Mgal/d) | Average AE (Mgal/d) | Method II AE (Mgal/d) | Average AE/ rainfall (percent) | Method I recharge (Mgal/d) | Average recharge (Mgal/d) | Method II recharge (Mgal/d) | Average recharge/ rainfall (percent) | Pan evaporation (Mgal/d) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kaluakoi | 44.4 | 43 | 5 | 12 | 24 | 31 | 38 | 72 | 12 | 7 | 1 | 16 | 191 |
| Punakou | 34.7 | 25 | 3 | 12 | 14 | 18 | 21 | 72 | 8 | 5 | 1 | 20 | 164 |
| Hoolehua | 13.6 | 18 | 2 | 11 | 10 | 13 | 15 | 72 | 6 | 4 | 1 | 22 | 53 |
| Manawainui | 25.4 | 22 | 2 | 9 | 14 | 16 | 18 | 73 | 6 | 4 | 2 | 18 | 121 |
| Kualapuu | 18.0 | 39 | 4 | 10 | 20 | 23 | 26 | 59 | 14 | 11 | 9 | 28 | 63 |
| Kamiloloa | 16.7 | 27 | 3 | 11 | 13 | 15 | 18 | 56 | 11 | 9 | 7 | 33 | 64 |
| Kawela | 19.8 | 37 | 4 | 11 | 14 | 20 | 26 | 54 | 19 | 13 | 7 | 35 | 71 |
| Ualapue | 21.7 | 69 | 10 | 14 | 29 | 35 | 42 | 51 | 31 | 24 | 17 | 35 | 66 |
| Waialua | 15.0 | 43 | 6 | 14 | 22 | 24 | 27 | 56 | 16 | 13 | 11 | 30 | 47 |
| Kalaupapa | 3.5 | 8 | 1 | 13 | 4 | 4 | 5 | 50 | 4 | 3 | 2 | 38 | 11 |
| Kahanui | 6.4 | 24 | 3 | 13 | 6 | 9 | 11 | 38 | 14 | 12 | 9 | 50 | 18 |
| Waikolu | 4.5 | 25 | 6 | 24 | 6 | 8 | 9 | 32 | 13 | 11 | 9 | 44 | 11 |
| Haupu | 2.6 | 15 | 3 | 20 | 4 | 5 | 5 | 33 | 8 | 8 | 7 | 53 | 6 |
| Pelekunu | 7.4 | 39 | 6 | 15 | 12 | 14 | 16 | 36 | 21 | 19 | 17 | 49 | 19 |
| Wailau | 13.6 | 75 | 13 | 17 | 19 | 24 | 28 | 32 | 42 | 38 | 33 | 51 | 34 |
| Halawa | 13.2 | 43 | 17 | 40 | 14 | 16 | 18 | 37 | 12 | 10 | 7 | 23 | 39 |
| *Total* | 260.5 | 552 | 88 | | 225 | 275 | 323 | | 237 | 191 | 140 | | 978 |

shifted slightly to the north in this area. The monthly rainfall values were adjusted so that the sum of the monthly values equals the mean annual rainfall in these three areas.

Although the aquifer-system areas in figure 5 are identical in the two studies, it is not known how the areas were computed in the previous study. The area discrepancy is about 4 mi$^2$ for both Kawela and Ualapue systems; however, island-wide, the total area differs by less than 1 percent.

***Limitations of the model.***--The GIS water-budget 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 the island, the runoff calculations are regionalized by applying average relations, determined from soil characteristics and data from another study, over large areas. The available-water capacity and the calculated maximum soil-moisture storage of the soil types on Molokai are important components in the water-budget model, because they limit ground-water recharge and evapotranspiration. The data used to calculate these components come from individual soil profiles that are regionalized for the soil series. All rainfall, direct runoff, pan evaporation, and soil data are averages that eliminate the extremes that occur in nature. The error associated with these average data is likely compounded by the budget accounting with a monthly time interval. Although monthly water-budget calculations estimate evapotranspiration more accurately than assuming the maximum evapotranspiration rate as is done in annual water-budget calculations, in reality, the components of the water budget are interacting on the order of minutes and hours within small areas. Averaging the results of the two methods of monthly calculations presented in this study attempts to mitigate possible errors associated with each method. Although daily, watershed-scale, temporal data could more accurately determine evapotranspiration and ground-water recharge, these data are not available, and a monthly budget for the island is the time period the available data warrant.

## SUMMARY AND CONCLUSIONS

A preliminary step in understanding the ground-water system on the island of Molokai is the calculation of a water budget. A mean monthly water budget was developed to estimate ground-water recharge. These recharge estimates are integral to the understanding of the ground-water system over time and to the ground-water availability assessment for Molokai.

The water-budget components are defined seasonally, through the use of the monthly water budget, and spatially by geohydrologic areas, through the use of a

**Table 7.** Water budgets from State of Hawaii (1990) for aquifer-system areas, Molokai, Hawaii

[Mgal/d, million gallons per day; ET, evapotranspiration. The difference of rainfall minus runoff, ET, and recharge may not equal zero due to rounding, areas shown in figure 9]

| Aquifer-system area | Area (mi$^2$) | Rainfall (Mgal/d) | Runoff (Mgal/d) | Runoff/ Rainfall (percent) | ET (Mgal/d) | ET/ Rainfall (percent) | Recharge (Mgal/d) | Recharge/ Rainfall (percent) |
|---|---|---|---|---|---|---|---|---|
| Kaluakoi | 44.6 | 43 | 2 | 5 | 34 | 79 | 7 | 16 |
| Punakou | 35.2 | 28 | 2 | 6 | 20 | 71 | 6 | 21 |
| Hoolehua | 13.8 | 19 | 1 | 3 | 14 | 72 | 4 | 21 |
| Manawainui | 24.6 | 21 | 1 | 6 | 15 | 72 | 5 | 24 |
| Kualapuu | 18.2 | 34 | 2 | 5 | 25 | 74 | 9 | 27 |
| Kamiloloa | 17.2 | 29 | 2 | 6 | 21 | 74 | 7 | 24 |
| Kawela | 23.7 | 54 | 3 | 6 | 39 | 73 | 11 | 20 |
| Ualapue | 17.7 | 58 | 6 | 10 | 34 | 58 | 18 | 31 |
| Waialua | 14.9 | 53 | 6 | 12 | 28 | 53 | 19 | 36 |
| Kalaupapa | 4.5 | 10 | 1 | 7 | 7 | 73 | 3 | 31 |
| Kahanui | 5.5 | 16 | 1 | 8 | 10 | 67 | 4 | 25 |
| Waikolu | 4.5 | 18 | 4 | 21 | 9 | 47 | 6 | 33 |
| Haupu | 2.6 | 10 | 2 | 20 | 5 | 48 | 3 | 29 |
| Pelekunu | 7.4 | 35 | 10 | 27 | 14 | 40 | 12 | 34 |
| Wailau | 13.3 | 62 | 16 | 27 | 25 | 41 | 20 | 32 |
| Halawa | 13.9 | 44 | 7 | 15 | 26 | 61 | 10 | 23 |
| *Total* | 261.6 | 534 | 66 | | 326 | | 144 | |

geographic information system (GIS) model. Rainfall distribution over the island ranges from less than 15 in/yr along the central southern coast to greater than 150 in/yr windward of the East Molokai Volcano crest. Ground water is replenished by recharge from rainfall that percolates through and beyond the root zone in the soil to the subsurface rock. Average monthly ground-water recharge was estimated from two accounting methods; one that favors actual evapotranspiration, and the other favors ground-water recharge.

The average ground-water recharge for the island, estimated by the water-budget analysis, is 189 Mgal/d (5,739 Mgal/mo). The average rainfall, direct runoff, and evapotranspiration are 552 Mgal/d, 89 Mgal/d, and 274 Mgal/d, respectively.

## REFERENCES CITED


Austin, H.A.R., and Stearns, H.T., 1954, Methods for development and delivery of water for irrigation of Hawaiian Homes Commission Lands at Hoolehua Island of Molokai: Report to the Hawaii Irrigation Authority, Territory of Hawaii, 57 p.

Campbell, R.B., Chang, J.H., and Cox, D.C., 1959, Evapotranspiration of sugar cane in Hawaii as measured by infield lysimeters in relation to climate: Proceeding of the 10th congress of the International Society of Sugarcane Technologists, p. 637–649.

Chang, J.H., 1968, Climate and agriculture: Chicago, Ill., Aldine Publishing Company, 304 p.

Ekern, P.C., and Chang, J.H., 1985, Pan evaporation: State of Hawaii, 1894–1983: State of Hawaii, Department of Land and Natural Resources, Division of Water and Land Development, Report R74, 171 p.

Foote, D.E., Hill, E.L., Nakamura, Sakuichi, and Stephens, Floyd, 1972, Soil survey of the islands of Kauai, Oahu, Maui, Molokai, and Lanai, State of Hawaii: U.S. Department of Agriculture, Soil Conservation Service, 232 p.

Giambelluca, T.W., 1983, Water balance of the Pearl Harbor-Honolulu basin, Hawaii, 1946–1975: University of Hawaii Water Resources Research Center Technical Report 151, 151 p.

Giambelluca, T.W., Nullet, M.A., and Schroeder, T.A., 1986, Rainfall atlas of Hawaii: State of Hawaii, Department of Land and Natural Resources, Division of Water and Land Development, Report R76, 267 p.

Hirashima, G.T., 1963, Aspects of ground-water storage and depletion along the Molokai Irrigation Tunnel, Molokai, Hawaii: Division of Water and Land Development, Department of Land and Natural Resources, State of Hawaii, Circular C20, 21 p.

Howell, H., 1938, Final report on water supply studies, Hawaii, F.P. No. 45, Island of Molokai; Description of project objectives, estimate of cost: U.S. Bureau of Reclamation, 111 p.

Langbein, W.B., and Iseri, K.T., 1960, General introductions and hydrologic definitions, U.S. Geological Survey Water-Supply Paper 1541-A, 29 p.

Langenheim, V.A.M., and Clague, D.A., 1987, The Hawaiian-Emperor volcanic chain, Part II: Stratigraphic framework of volcanic rocks of the Hawaiian Islands: chap. 1 *of* U.S. Geological Survey Professional Paper 1350, v. 1, p. 55–84.

Lindgren, Waldemar, 1903, The water resources of Molokai, Hawaiian Islands: U.S. Geological Survey, Water-Supply and Irrigation Paper No. 77, 62 p.

Mink, J.F., and Lau, L.S., 1992, Aquifer identification and classification for Molokai: groundwater protection strategy for Hawaii: University of Hawaii, Water Resources Research Center, Technical Report no. 187, 31 p.

Parsons, Brinckerhoff, Hirota Associates, 1969, Island of Molokai, Waikolu and Pelekunu valleys, Water resources feasibility study: Department of Land and Natural Resources, State of Hawaii.

State of Hawaii, 1990, Water resources protection plan, volumes I and II, Hawaii Water Plan: State of Hawaii, Commission on Water Resource Management.

Stearns, H.T. and Macdonald, G.A., 1947, Geology and ground-water resources of the island of Molokai, Hawaii: Bulletin 11, Division of Hydrography, Territory of Hawaii, 113 p.

Thornthwaite, C.W., 1948, An approach toward a rational classification of climate: Geographical Review, v. 38, no. 1, p. 55–94.

Thornthwaite, C.W., and Mather, J.R., 1955, The water balance: Publications in Climatology, v. 8, no. 1, p. 1–104.

Wahl, K.L., and Wahl, T.L., 1995, Determining the flow of Comal Springs at New Braunfels, Texas: Proceedings of Texas Water '95, A Component Conference of the First International Conference on Water Resources Engineering, American Society of Civil Engineers, August 16–17, 1995, San Antonio, Tex., p. 77–86.