INTRODUCTION

The water supply for the population of the island of Oahu, Hawaii is obtained primarily from ground-water sources, recharged by the infiltration of rainfall and irrigation water. The importance and limited nature of these sources caused the island of Oahu to be selected, along with 27 other aquifer systems in the United States, as part of the U.S. Geological Survey's Regional Aquifer System Analysis (RASA) program. The primary purpose of this program is to investigate the effects that ground-water development has had or could have on the ground-water levels and the distribution of ground-water flow on a regional scale.

An important factor in the study of an aquifer system is the quantity of water recharging and flowing through the system. Ground-water recharge can be estimated from water-balance calculations, which subtract runoff and evapotranspiration from rainfall and irrigation. The quantification and distribution of recharge are necessary for ground-water flow simulation, an important element of the RASA project.

Purpose and Scope

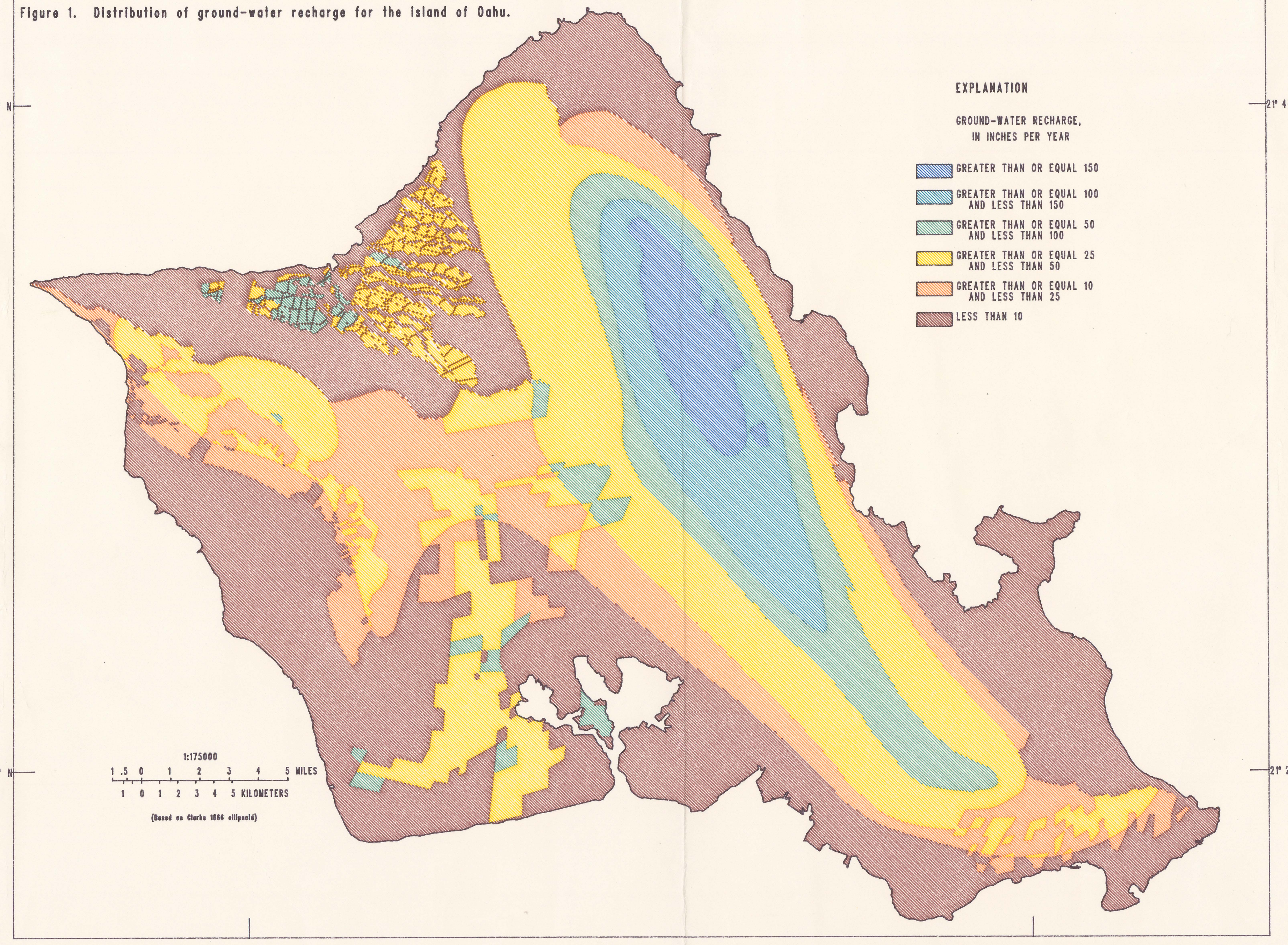
The purpose of this report is to show the spatial distribution of ground-water recharge over the island of Oahu, Hawaii (fig. 1). Various methods were used to calculate ground-water recharge, depending on the subsystem being analyzed and on the availability of prior information. These methods are discussed in the body of the report. The calculations of ground-water recharge, the display of the areally-distributed input data, and the resulting recharge distribution were aided by a geographic information system (GIS).

DISTRIBUTION OF GROUND-WATER RECHARGE

The island was divided into 5 subsystems shown in figures 2 through 6. Ground-water recharge was calculated using rainfall, streamflow, pan evaporation, land use, vegetation, and soils data. The narrative sections above figures 2 through 6 describe how the GIS recharge model was applied to each subsystem. Figure 7 and table 3 display the ground-water recharge distribution by ground-water area. Figure 8 and table 4 display the ground-water recharge distribution by geologic type.

For each of the 5 subsystems the data input for the GIS recharge model was determined by the availability of a previously calculated water balance. For 2 of the subsystems, water balances had been calculated previously. For these subsystems regression analyses yielded relations with high correlation among rainfall, land use/land cover, and recharge. These regression equations were then applied to the Waianae and north central subsystems. Because of the distinct hydrogeologic characteristics of the windward subsystem, the regression equations were not appropriate, and this area required a different approach. An annual water balance was calculated whereby streamflow and evaporation were subtracted from rainfall to determine recharge.

Figure 1. Distribution of ground-water recharge for the island of Oahu.

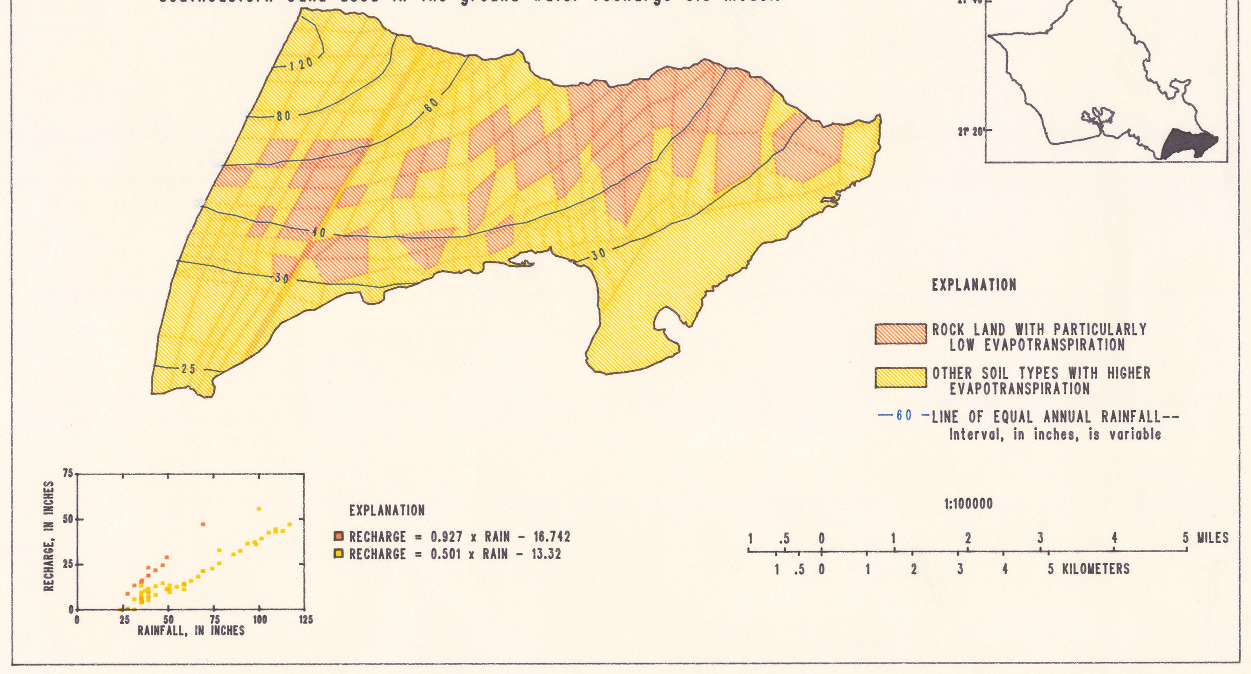


Southeastern Oahu

The distribution of ground-water recharge for southeastern Oahu was first calculated from a monthly water balance presented by Eyre and others (1986). Recharge and rainfall relations were developed from the earlier water balance for the GIS recharge model. In addition, these relations enable the GIS recharge model to be applied to a similar area, the Waianae area on the western part of the island (fig. 4), where a more rigorous water balance has not been calculated.

Two regression equations were used to calculate recharge for southeastern Oahu. One equation, Recharge = 0.927 x Rain - 16.742, with a correlation coefficient (R^2) = 0.85, was applicable for soil areas classified as rock land, rock outcrop, and stony steep land (Foote and others, 1972). These areas are characterized by permeable rock outcrops and a thin soil layer covered with grass; therefore, evapotranspiration is particularly low. The other equation: Recharge = 0.501 x Rain - 13.32, with an R^2 = 0.91 was applicable where soil cover and vegetation are greater, and to urban areas. Each of the 285 subareas corresponding with the ground-water flow model finite elements (Eyre and others, 1986) was assigned a land cover code. On the basis of this code, the appropriate regression equation was applied to the rainfall (Giambelluca and others, 1986) in that subarea. The mean annual ground-water recharge in the southeastern Oahu area totaled 18.7 million gallons per day (Mgal/d), and its distribution is shown in figure 1. This recharge value compares well with recharge calculated previously (Eyre and others, 1986) of 15.1 Mgal/d. The previous work estimated that there was no ground-water recharge in the elements that lie along the shoreline. The GIS model calculated 0.5 Mgal/d recharge in this area. Which of the estimates of recharge is more accurate cannot be determined because the difference between them, 3 Mgal/d (less than 20 percent), is well within the uncertainty of the calculations.

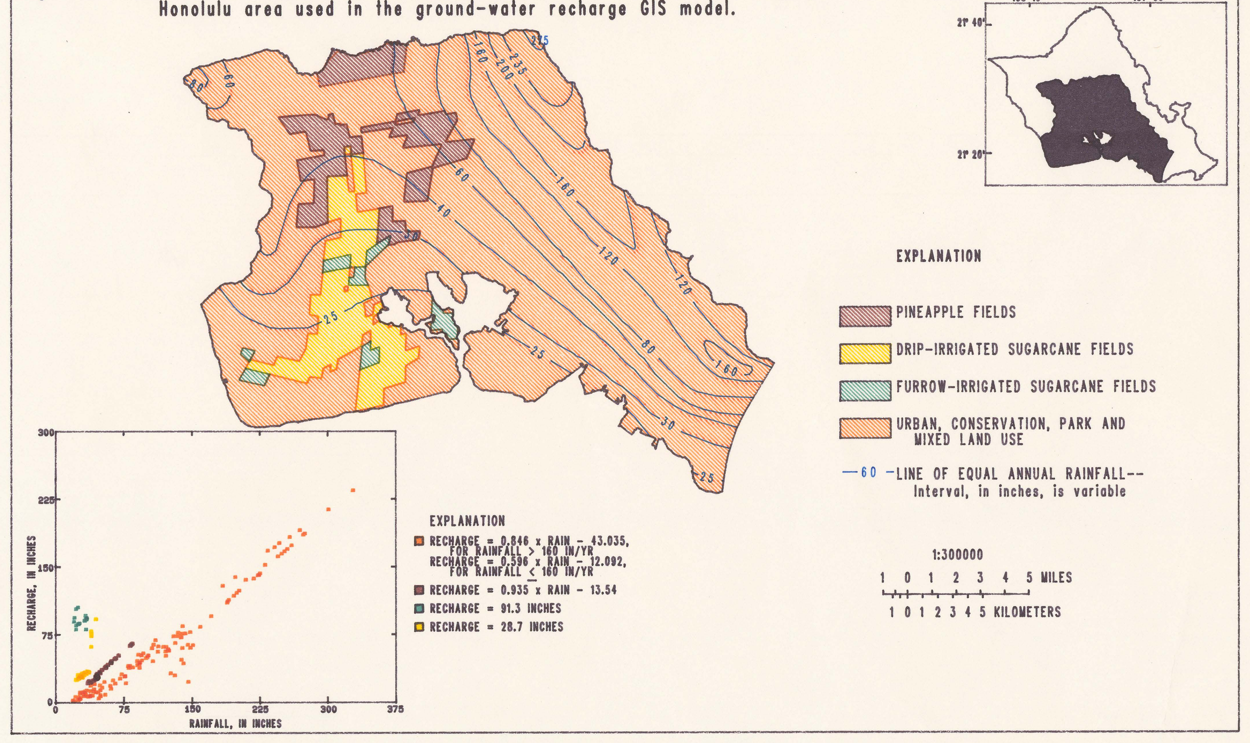
Figure 2. Geologic and soil characteristics and mean annual rainfall of southeastern Oahu used in the ground-water recharge GIS model.



Pearl Harbor/Honolulu Area

The distribution of ground-water recharge in the Pearl Harbor/Honolulu area is the result of a detailed monthly water balance calculated by Giambelluca (1986). Rainfall-recharge-land cover relations were developed from Giambelluca's work; accordingly, the GIS recharge model could be applied to the area, and could be extended to areas with similar physical and climatological characteristics. The relations are shown in figure 3. For most of the area, in urban, conservation, park, and mixed land use, two regression equations were used. For areas with greater than 160 inches of rainfall annually, Recharge = 0.846 x Rain - 43.035 inches, with an R^2 = 0.95. For areas with less than or equal 160 inches of rainfall, Recharge = 0.596 x Rain - 12.092, with an R^2 = 0.89. The regression equation applied to areas planted in pineapple is Recharge = 0.935 x Rain - 13.54, with an R^2 = 0.98. Pineapple is a bromeliad, which reduces the natural rate of evapotranspiration by closing its stomata during the day. Therefore, recharge in areas planted in pineapple is greater than in areas of natural land cover. Recharge from sugarcane fields is not a function of rainfall, because the fields are irrigated to maintain a relatively constant soil moisture for the plant. Wet areas receive little irrigation and dry areas receive abundant irrigation. Sugarcane fields irrigated by the furrow method produce an average of 91.3 inches of ground-water recharge per year. Fields irrigated by the more efficient drip method produce an average of 28.7 inches of ground-water recharge per year. With these formulas, the GIS recharge model for the Pearl Harbor/Honolulu area operates as a function of the mean annual rainfall and the simplified landuse distribution. By this method the mean annual ground-water recharge in this area equals 428.3 Mgal/d, which is within 10 percent of the 393.5 Mgal/d recharge reported by Thomas Giambelluca (University of Hawaii, written communication, 1989). The recharge distribution for this area is shown on figure 1.

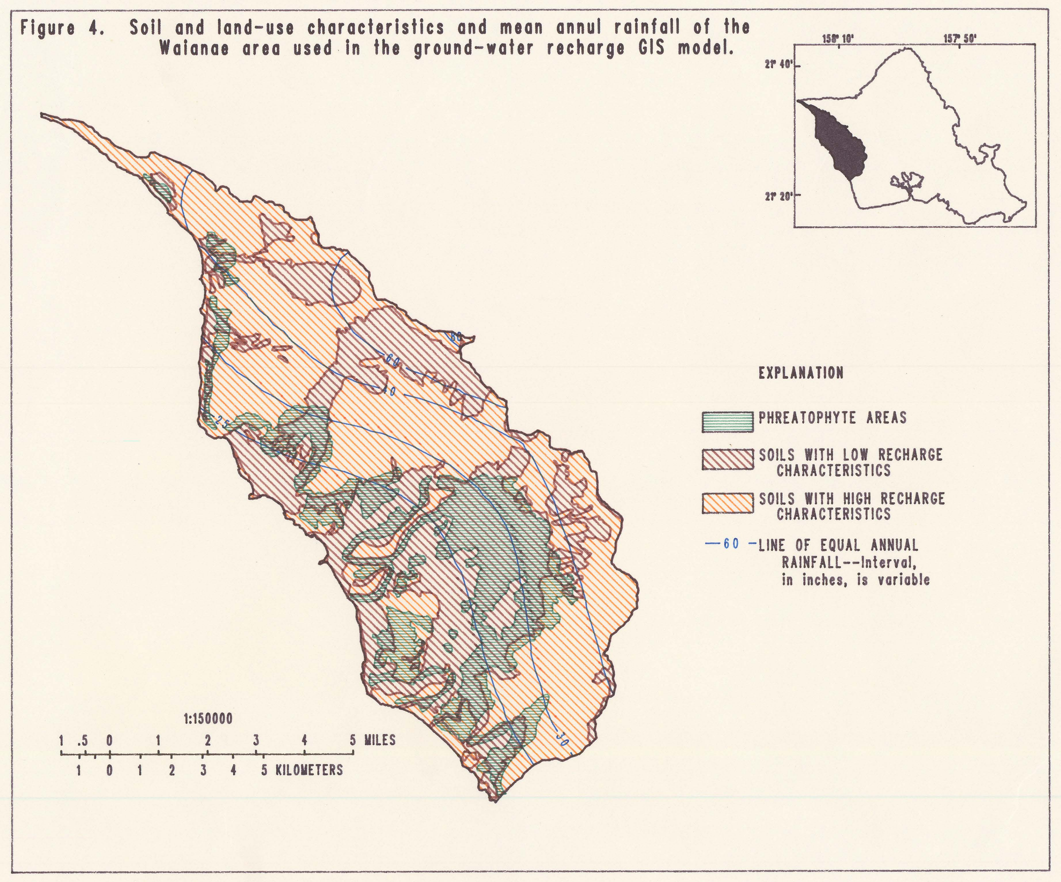
Figure 3. Land-use characteristics and mean annual rainfall of the Pearl Harbor/Honolulu area used in the ground-water recharge GIS model.



Waianae Area

In the dry western Waianae area, soil types, land cover, and climate are similar to those of southeastern Oahu (figure 2). The same recharge regression equations developed for southeastern Oahu --(1) Recharge = 0.927 x Rain - 16.742 or (2) Recharge = 0.501 x Rain - 13.32-- were applied in Waianae. Equation 1 was applied where soils are thin or permeable. Equation 2 was applied where soils are thick or less permeable. Soil characteristics were obtained from Foote and others (1972), and the spatial distribution of soil types is shown in figure 4. Only natural land use is considered in the Waianae area, as there is little urban development. The location of phreatophytes is a significant element in the land cover distribution. Phreatophytes transpire water by way of roots that reach the water table. For areas of phreatophyte growth, any water that infiltrated into the soil was assumed to be transpired by these plants, and therefore, ground-water recharge in these areas was set at zero. The distribution of mean annual ground-water recharge is shown in figure 1, and the total for the Waianae area equals 31.4 Mgal/d.

Figure 4. Soil and land-use characteristics and mean annul rainfall of the Waianae area used in the ground-water recharge GIS model.



North Central Oahu

North central Oahu was modeled as an extension of the Pearl Harbor/Honolulu area, because both areas have similar climate, topography, and soils, and large agricultural areas (fig. 5). Hence, ground-water recharge for the area was calculated in the GIS recharge model by applying recharge-rainfall-land use relations (table 1) developed from Giambelluca's (1986) water balance calculations for the Pearl Harbor/Honolulu area. The distributions of rainfall and land use (fig. 5) were considered in choosing the appropriate rainfall-recharge ratio for a given area. The mean annual recharge distribution is shown in figure 1 and the total for the north central area is 218.4 Mgal/d.

Figure 5. Land-use characteristics and mean annual rainfall of north central Oahu used in the ground-water recharge GIS model.

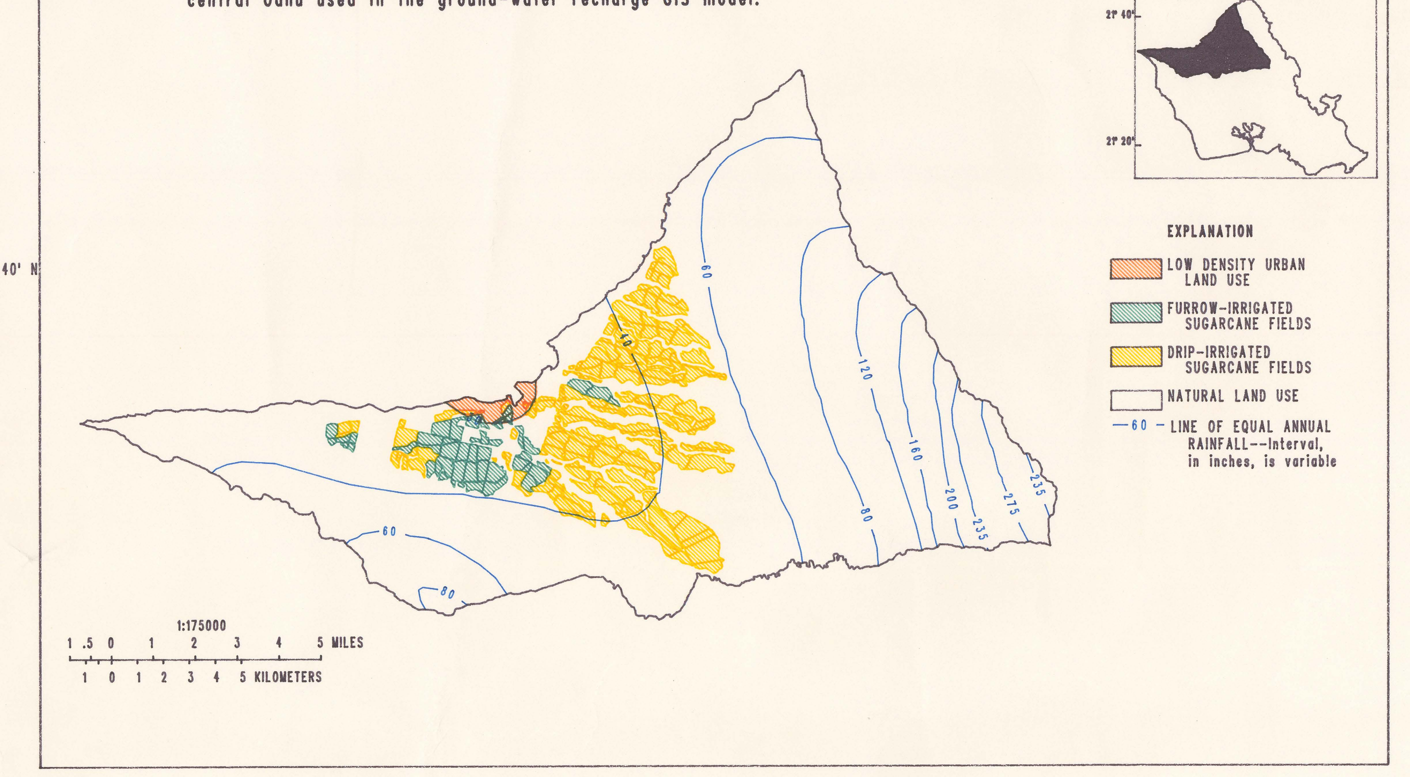


Table 1. North central Oahu ground-water recharge/rainfall ratios.

[For irrigated sugarcane the ratio is ground-water recharge/rainfall + irrigation.]

Rainfall (inches)	Ground-water recharge (percentage of rainfall)	Land use
255	69	Natural
215	64	Natural
180	60	Natural
140	52	Natural
100	50	Natural
80	49	Natural
70	38	Natural
50	19	Natural
50	65	Furrow sugar
50	45	Drip sugar
35	18	Natural
35	63	Furrow sugar
35	37	Drip sugar
30	13	Low density urban
30	62	Furrow sugar
30	34	Drip sugar

Windward Oahu

Ground-water recharge in windward Oahu is calculated from an annual water balance applied by drainage area. The annual water balance equation is: Rainfall - Direct Runoff - Potential Evapotranspiration = Recharge. Mean annual rainfall bands presented by Giambelluca and others (1986), and lines of equal pan evaporation by Ekern and Chang (1985), are the two data sets used to estimate recharge in eleven drainage areas (fig. 6). Most of the pan stations are equipped with U.S. Weather Bureau Class A evaporation pans. Because of the numerous types of vegetation in the study area, and various stages of growth, the pan coefficient fluctuates above and below 1.0. For this water balance of mean annual conditions, the pan coefficient is assumed to equal 1.0, and pan evaporation equals potential evapotranspiration. Direct runoff is calculated as the difference between mean basin discharge and baseflow, and is expressed as a fraction of rainfall in the GIS recharge model. Much of the streamflow information was obtained from Takasaki, Hirashima, and Lubke (1969) and from Takasaki and Valenciano (1969). Table 2 indicates the runoff/rainfall ratios that were applied to the mean annual rainfall over each drainage area. The mean annual ground-water recharge for the windward Oahu area equals 198 Mgal/d and the distribution is shown in figure 1.

Figure 6. Mean annual rainfall and pan evaporation of windward Oahu used in the ground-water recharge GIS model.

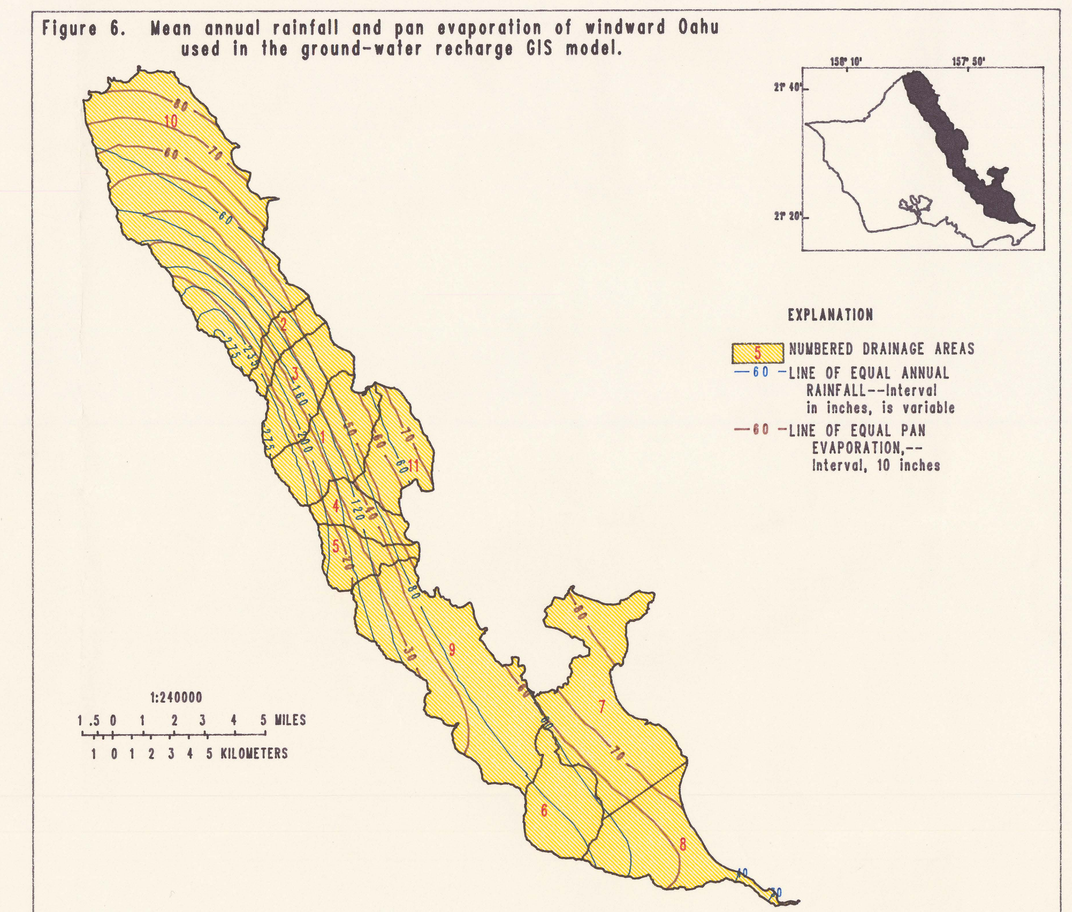


Table 2. Runoff/rainfall ratios for windward Oahu.

Drainage area	Runoff/rainfall ratio (percent)
1. Kahana	26
2. Kaluanui	23
3. Punaluu	16
4. Waikane	17
5. Waiahole	24
6. Maunawili	21
7. Kailua	11
8. Waimanalo	11
9. Kaneohe	17
10. Kahuku	20
11. Kaaawa/Hakipuu	9

A composite of the hydrogeologic boundaries that affect ground-water flow on Oahu is shown in figure 7. These boundaries were defined by Dale (1978), Dale and Takasaki (1976), Takasaki (1985), Takasaki, Hirashima and Lubke (1969), Takasaki and Valenciano (1969), and Visher and Mink (1964). The physical features that coincide with these boundaries include topographic divides, erosional unconformities, and rift zones. It is important to quantify ground-water recharge in these areas (table 3) for ground-water flow modeling. For several areas on Oahu, particularly the areas numbered 9, 13, 15, and 20, there has been considerable discussion regarding how much of this water may be flowing from these areas into either the Pearl Harbor/Honolulu area (fig. 3) or the north central area (fig. 5). Ground-water recharge to the basalt and volcanic parts of the ground-water areas (figs. 7 and 8) has been calculated and is shown on table 3.

Figure 7. Ground-water areas of Oahu.

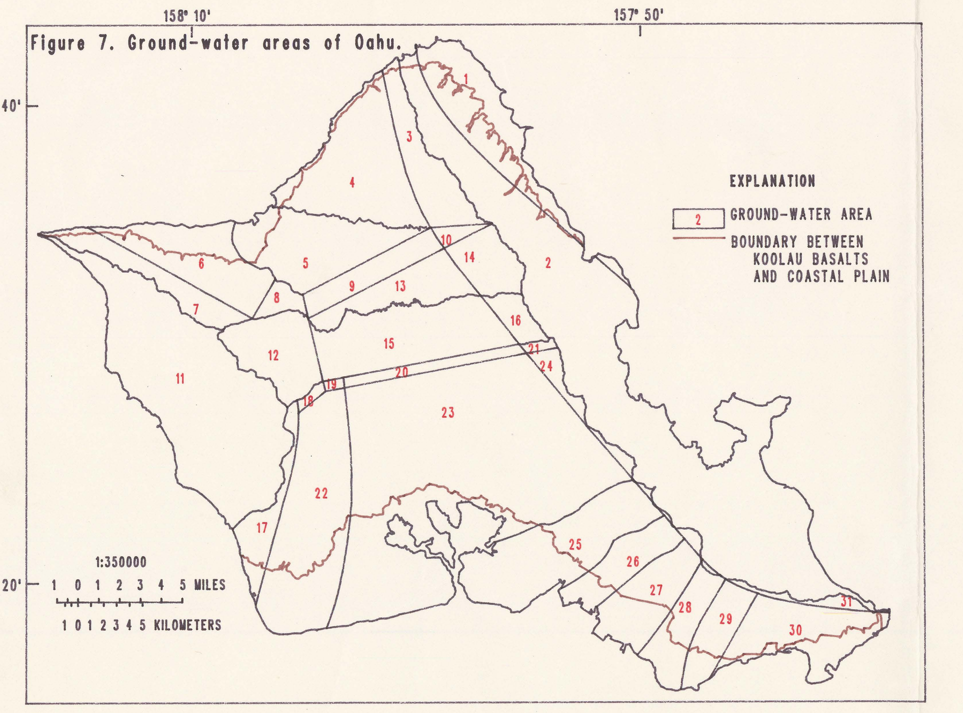


Table 3. Ground-water recharge by ground-water area.
[Mgal/d, million gallons per day. The total ground-water recharge for the island of Oahu is 895 Mgal/d.]

Area	Mean annual ground-water recharge (Mgal/d)	Mean annual ground-water recharge to volcanic part of the area (Mgal/d)	Area	Mean annual ground-water recharge (Mgal/d)	Mean annual ground-water recharge to volcanic part of the area (Mgal/d)
1	3.77	3.43	16	31.65	31.65
2	193.80	155.30	17	2.11	2.05
3	36.78	36.65	18	0.62	0.61
4	34.00	32.94	19	0.71	0.19
5	25.35	19.86	20	11.64	11.64
6	16.73	6.39	21	5.86	5.86
7	7.74	7.55	22	23.20	8.57
8	1.18	1.13	23	181.09	152.45
9	9.89	9.88	24	22.03	22.03
10	7.55	7.55	25	29.95	22.70
11	31.43	12.92	26	18.23	10.64
12	13.35	6.28	27	23.25	13.25
13	17.59	17.59	28	12.17	7.68
14	61.62	61.62	29	7.25	6.65
15	52.45	50.39	30	9.06	7.26
			31	2.42	2.34

Figure 8. Generalized geologic map of Oahu (modified from Stearns and Vaksvik, 1935).

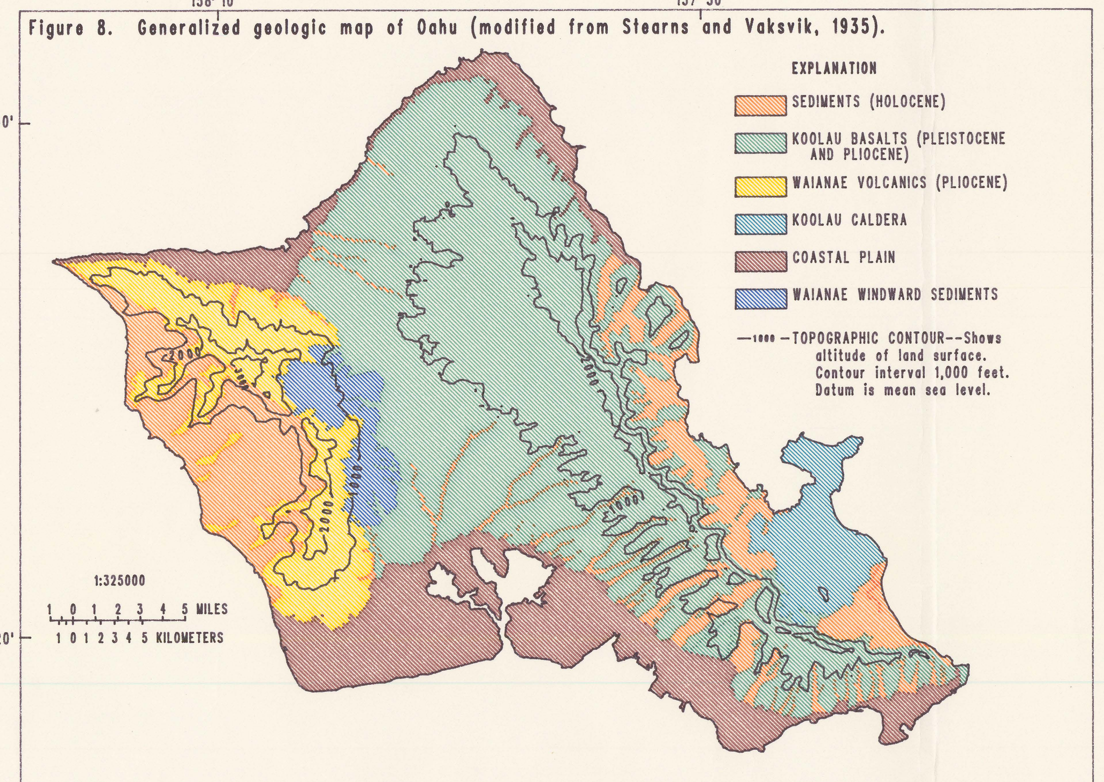


Table 4. Ground-water recharge by geologic type.
[Mgal/d, million gallons per day]

Type	Ground-water recharge (Mgal/d)
Sediments	84.24
Koolau Basalts	693.69
Waianae Volcanics	41.29
Koolau caldera	3.81
Coastal plain	55.10
Waianae windward sediments	16.28

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DISTRIBUTION OF GROUND-WATER RECHARGE, OAHU, HAWAII

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