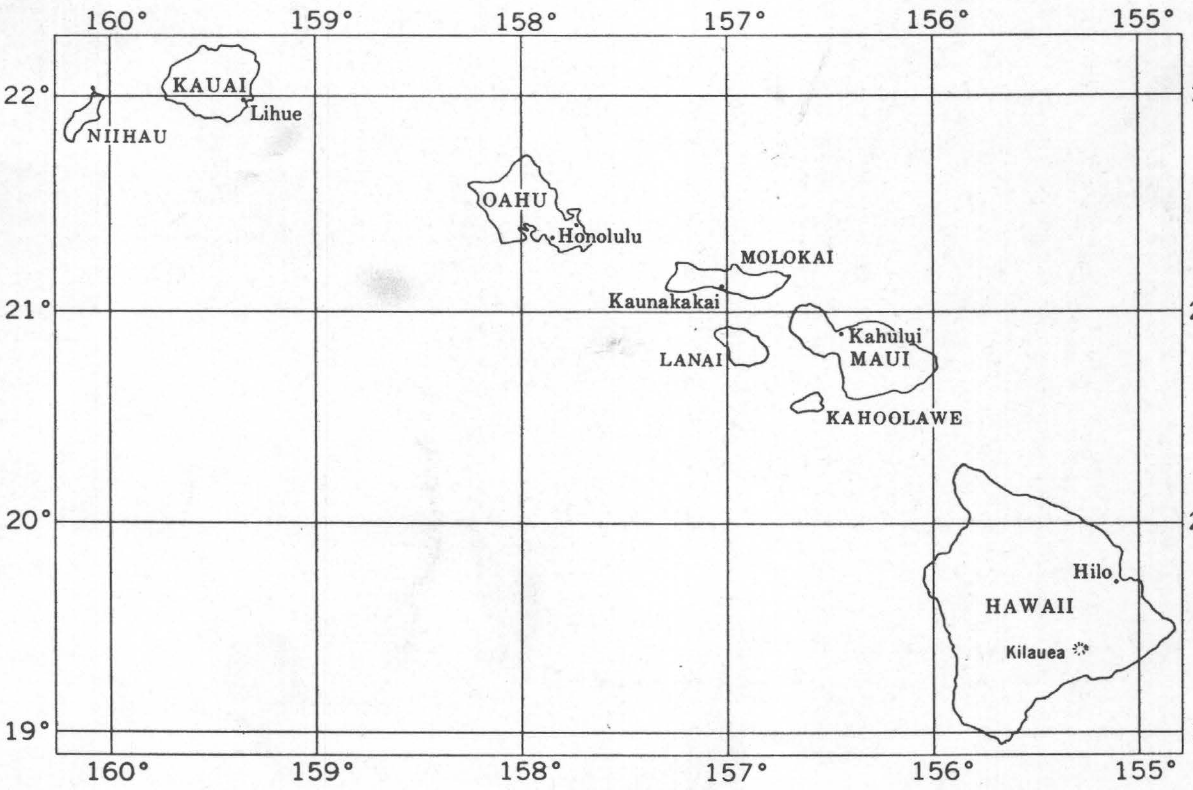
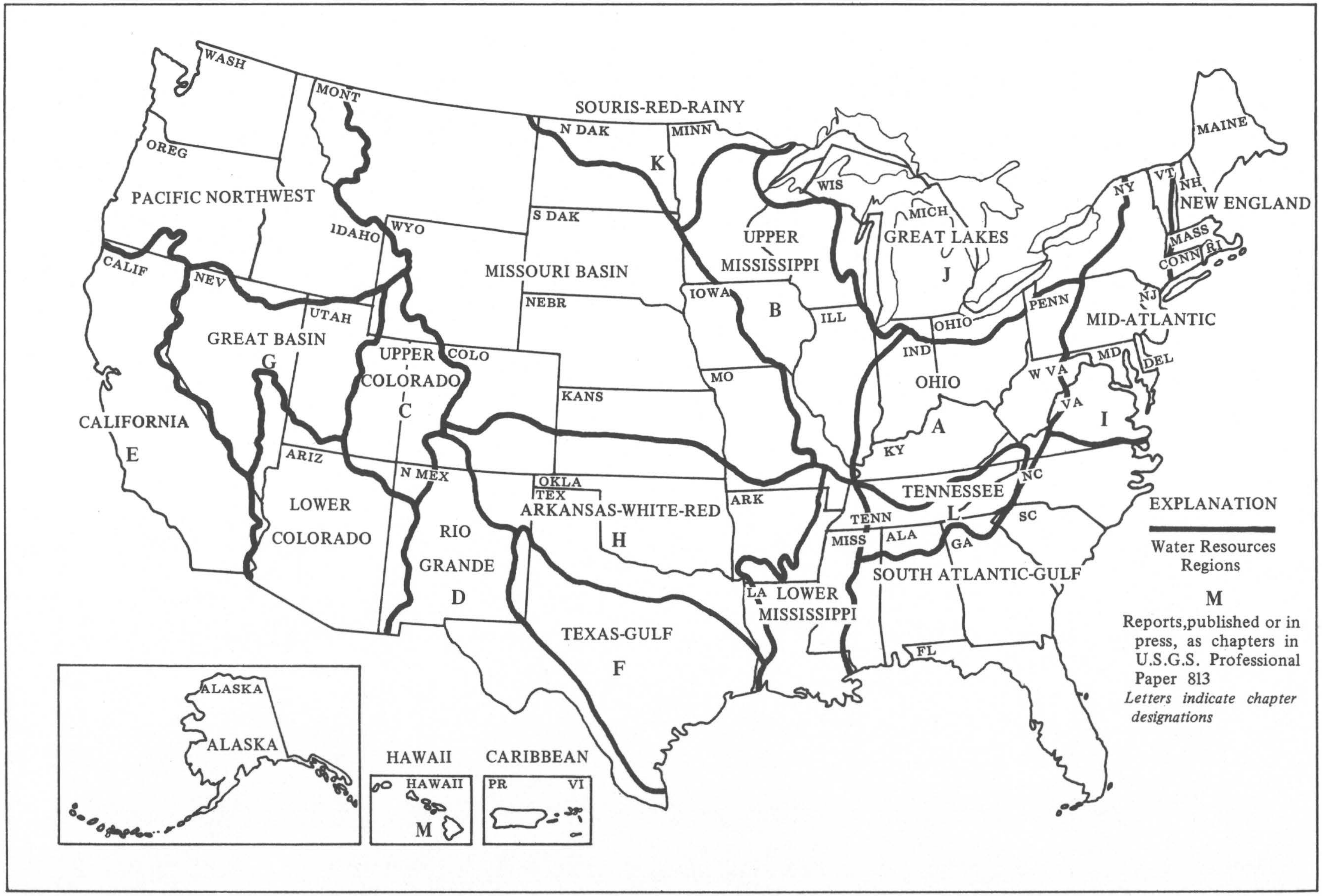
Summary Appraisals of the Nation's Ground-Water Resources— Hawaii Region

GEOLOGICAL SURVEY PROFESSIONAL PAPER 813-M





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Boundaries shown are those established by the United States Water-Resources Council for Water-Resources Regions in the United States.

Summary Appraisals of the Nation's Ground-Water Resources— Hawaii Region

By K. J. TAKASAKI

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Problems and opportunities related to the development and management of the ground-water resources in the region

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CONTENTS

ILLUSTRATIONS

TABLES

FACTORS FOR CONVERTING ENGLISH UNITS TO INTERNATIONAL SYSTEM (SI) UNITS

The following factors may be used to convert the English units given herein to the International System of Units (SI)

Multiply English units	By	To obtain SI units
acre	4047	square meter (m^2)
square foot (ft^2)	.0929	square meter (m^2)
square inch (in^2)	.0006452	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
foot (ft)	0.3048	meter (m)
inch (in.)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
yard (yd)	.9144	meter (m)
acre-foot (acre-ft)	1233	cubic meter (m^3)
cubic foot (ft^3)	.02832	cubic meter (m^3)
gallon (gal)	3.785	liter (L)
million gallons (10^6 gal or Mgal)	3785	cubic meters (m^3)
cubic foot per second-day [(ft^3/s)-d]	2447	cubic meter (m^3)
	.002447	cubic hectometer (hm^3)
cubic foot per second (ft^3/s)	.02832	cubic meter per second (m^3/s)
	28.32	liter per second (L/s)
gallon per minute (gal/min)	.06309	liter per second (L/s)
million gallons per day (10^6gal/d) or (Mgal/d)	.04381	cubic meter per second (m^3/s)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
cubic foot per second per square mile [(ft^3/s)/mi^2]	.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
foot per day (ft/d)	0.3048	meter per day (m/d)
gallon per minute per foot [(gal/min)/ft]	.207	liter per second per meter [(L/s)/m]
foot squared per day (ft^2/d)	.0929	meter squared per day (m^2/d)

SUMMARY APPRAISALS OF THE NATION'S GROUND-WATER RESOURCES— HAWAII REGION

By K. J. Takasaki

ABSTRACT

The water resources of the Hawaii Region, taken as a whole, are far greater than foreseeable future demands on them, but this is not so for the individual islands. Each and every island is independent with respect to water supply, and the occurrence and availability of water vary widely from island to island.

The ground-water resources offer better prospects for supplying additional water needs in the future than the surface-water resources. Most of the surface supplies that are easy to develop have been fully utilized where needed, and conduits and reservoirs necessary to develop new or additional supplies would generally require large and perhaps prohibitive outlays of capital. In 1975, ground water supplied 46 percent, and surface water 54 percent of the water needs but, in the years ahead, these percentages will likely be reversed as more ground-water development takes place. Total water use, in 1975, averaged about 1,775 million gallons per day, of which about 810 million gallons per day was ground water. The total water use is divided into public supply, 11 percent; self-supplied industrial use, 23 percent; and agricultural, 66 percent.

Rainfall is the principal source of ground-water recharge. Local mean annual rainfall ranges from less than 20 inches to more than 300 inches, with the annual average rainfall on the large islands exposed to the trade winds being slightly more than 73 inches and that on the small islands situated in the rain shadow of the larger islands being less than 26 inches. Ground-water recharge has been estimated at about 2,400 billion gallons per year (6.5 billion gallons per day) or roughly 30 percent of the rainfall.

Most fresh ground water in the region is stored below sea level in porous lava flows, much of it as basal-water lenses floating on saline ground water, as distinguished from dike-impounded water in the interior of the islands. The basal-water lens is maintained by recharge, which, if reduced, leads to thinning of the lens and subsequent encroachment of seawater. Seawater is the biggest pollutant of freshwater, and many of the ground-water problems are, in some way, associated with the encroachment of saline water induced by development.

The major problem areas include the entire island of Oahu, south Kohala-Kona coast on the island of Hawaii, Lahaina District in Maui, and the Koloa and Kekaha-Mana areas in Kauai.

INTRODUCTION

The purpose of this report is to provide pertinent ground-water information and to relate this information to the potential role of ground water in meeting future water needs in the Hawaii Region. The report also focuses on some problems related to the hydrology of ground water in overall water supply and management, and on some of the deficiencies in information and understanding that hinder the optimum development of the ground-water resources.

Ground water in the Hawaii Region is a large and valuable resource. Despite the large overall supply, ground water is not available in some areas, and much of it, especially that which is of suitable quality for domestic use, has to be imported by pipeline from distant areas. In 1975, only about 20 percent of the approximately 810 million gallons per day (Mgal/d) of ground water developed was used for public supplies. As a result of development, the quality of the ground water has deteriorated at some places, but water of less than potable quality can be tolerated in uses such as irrigation of sugarcane and cooling.

Most recharge to ground water occurs in the wet interior mountains, generally upgradient from lower-lying developed areas where wastes and subsequent waste disposals are more likely to occur. This favorable situation is gradually changing for the worse as land developments encroach into the principal recharge areas. Some deterioration of the ground water is to be expected, the degree of which will depend greatly on how much deterioration is allowed by policies and decisions related to land use, land development, and waste-disposal practices. In most cases, the prevention of pollution by eliminating the pollutant at the source would be a more effective course to follow than attempting detection and surveillance of the pollutant after it reaches the ground-water reservoir.

NOTEWORTHY GROUND-WATER DEVELOPMENT EVENTS

In the early years of development in the Hawaiian Islands, water supply was generally not a major problem, except in the Honolulu area. Land and surface water were abundant at places within each of the larger islands, and development was concentrated in these areas. The early Hawaiians settled near perennial streams and springs and diverted water for their highly developed agriculture. Later, sugarcane was grown in areas where rainfall was sufficient or where water could be easily diverted from perennial streams. In the water-scarce areas, the land remained largely undeveloped and unsettled.

Domestic water needed for these early developments was not, as a rule, developed separately but was taken from the available irrigation supply. The water, thus obtained, was generally of good quality or was considered so because most of it came from sources in the wet interior areas and was usually diverted from ditches and streams upgradient from the developed areas.

Some ground water, other than from springs, was developed by the early Hawaiians from shallow wells dug at or near the beach. Most of the water thus developed was brackish.

By the middle 1850's, the population of Honolulu had grown to nearly 12,000. Whaling in the Pacific had reached its peak in activity, and Honolulu had become a principal port of supply. Thus, the city of Honolulu, unlike the rest of the Region, was even then experiencing a water-supply problem. Water was piped from distant surface-water sources but the supply could barely meet the demands of the population and of the ships. The availability of freshwater had, in fact, become a severely limiting factor to the growth of Honolulu (Honolulu Board of Water Supply, 1963).

In 1879, a well tapping a basal ground-water aquifer under sufficient artesian head to flow freely was drilled in the arid land west of Pearl Harbor in Oahu. Many wells followed, first in Oahu and a little later in the other islands. The presence of a cheap and dependable ground-water supply in many of the dry leeward areas had immediate impact on the Region's development. By 1890, water from artesian wells provided a large share of the water needs for Honolulu, thereby removing the city's principal constraint to growth. By 1920, the cultivation of sugarcane had shifted from the generally wet windward areas to the drier leeward areas, and lands heretofore deemed useless became very much in demand. Sugarcane cultivation had become the principal economic base for the Region. By 1975, more than 1,000 wells had been drilled or dug, most of them to develop water for the irrigation of sugarcane.

Rapid and indiscriminate drilling of wells followed the first successful well and continued virtually unabated for nearly 50 years, especially in southern Oahu. During this time, water from wells near the coast in southern Oahu, once of domestic quality, became brackish. Artesian head, once as much as 43 feet above sea level, steadily declined to about 25 feet above sea level. Concern over this decline led to legislation and the establishment of an authority to curb waste and to manage the seemingly deteriorating artesian water supply in Honolulu.

Competition for the ground-water supply in Oahu did not become a serious problem until the Second World War, when the first significant transfer of sugarcane lands to other uses occurred. During the Second World War, large areas in the western part of Honolulu, abutting the Pearl Harbor area, were turned over to the military for their use. The military use necessitated the drilling of new wells to provide the domestic-quality water required. After the war urbanization increasingly replaced sugarcane lands, and the ensuing competition for water by the various users led to unplanned development in many areas. Problems related to water quality, rights, and management became apparent at this time and still persist.

The advent of statehood for Hawaii, in 1959, led to increased tourism and hastened the growth of the population of southern Oahu. More agricultural land was urbanized. Meanwhile, considerations of possible impact on the environment of further water and land development added to the complexity of problems.

Except for the intensive growth in sugarcane cultivation, the development and population growth in the other islands did not parallel that in Oahu in the years following the end of the Second World War. Sugarcane cultivation increased somewhat during this period, but owing to many technological advances, fewer workers were needed and the population on all the other islands declined. It was not until sometime after the coming of statehood and the growth of tourism in Oahu that resort areas and resort-residential complexes began to expand in the other islands. Tourism now is the fastest growing segment of the economy in all the islands. The ever-increasing demand for water, especially for domestic-quality ground water, in the heretofore undeveloped dry leeward areas that are favored for resort development, is a problem that needs to be solved if the tourist industry is to continue to grow.

REGIONAL SETTING

GEOLOGIC FRAMEWORK

The Hawaiian Archipelago, which makes up the Hawaii Region, is a group of shoals, reefs, and islands trending northwest to southeast more than 1,500 miles across the Pacific Ocean (fig. 1). The Hawaiian Islands, which lie at the southeastern end of the archipelago, constitute more than 99 percent of the region's total land area. Only these islands are considered in the appraisal of the region's ground-water resources.

The Hawaiian Islands are the tops of shield volcanoes rising from the ocean floor, the oldest is Kauai in the northwest part, and the youngest, the island of Hawaii in the southeast part. Each of the islands consists of one to five volcanic domes, the bulk of which is composed of thousands of basaltic lava flows. The lavas issued in repeated outpourings from narrow zones of

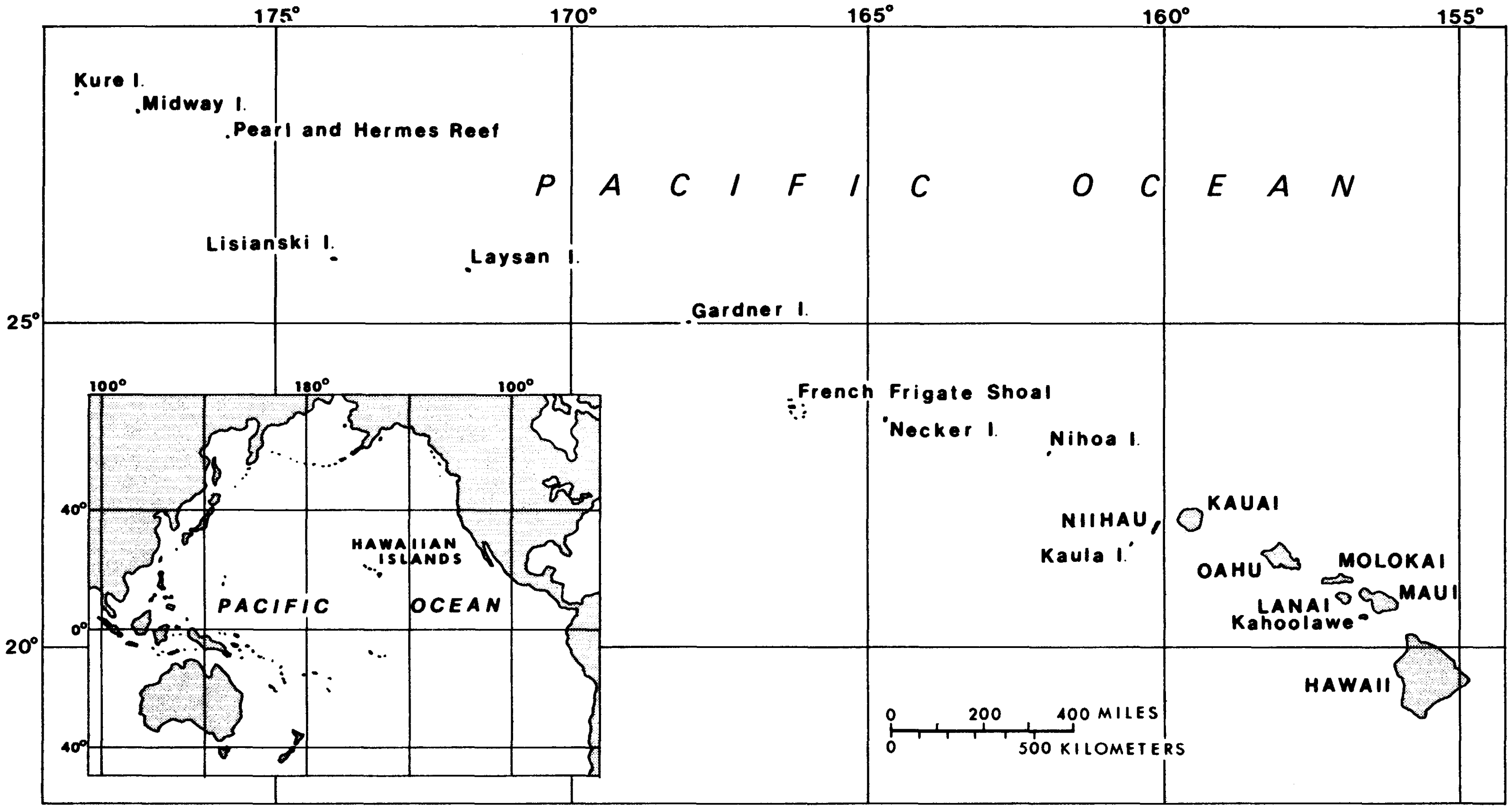


FIGURE 1.—The Hawaiian Archipelago. The small inset shows the location of the islands in the Pacific Ocean.

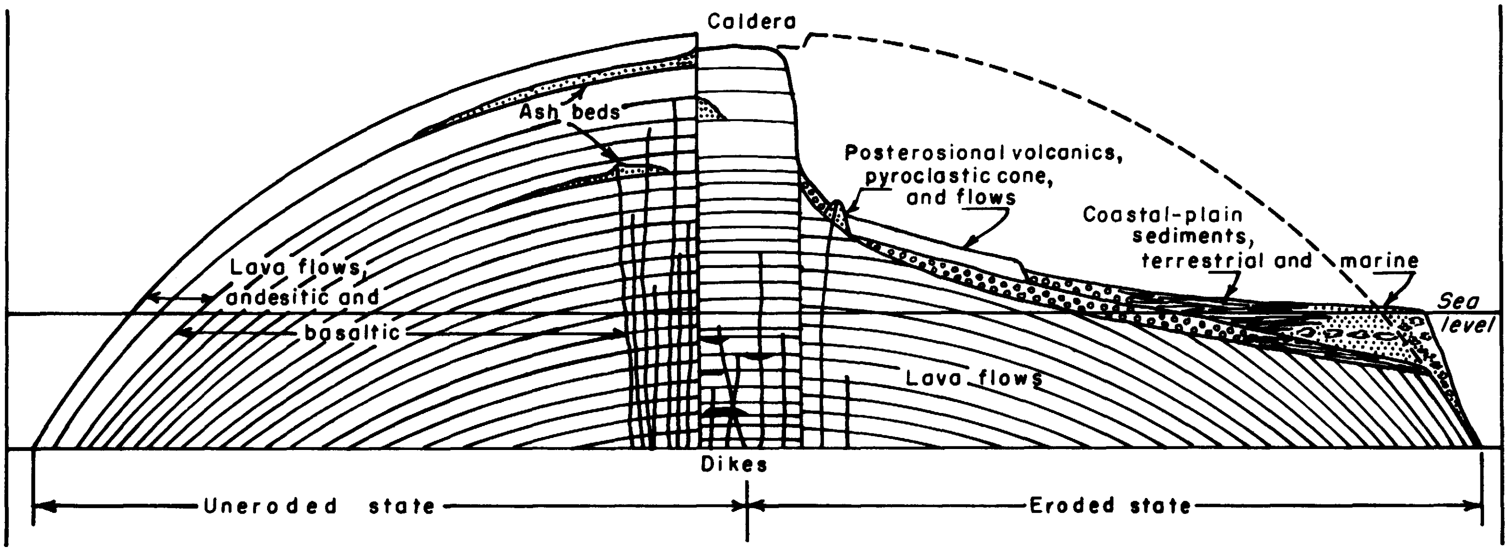


FIGURE 2.—Geologic structure of an idealized Hawaiian volcanic dome (from Cox, 1954).

fissures associated with each volcano, first below sea level, then above it, to form huge mountain masses. The basaltic lavas that were extruded above sea level are generally thin-bedded, highly clinkery, and highly permeable. In contrast, the lavas extruded in water were quickly chilled, are less clinkery, more massive, and are likely to be less permeable. All of the islands have sunk, to some extent, to adjust isostatically for their great weight on the earth's crust. Consequently, the highly permeable lava flows, which were originally extruded above sea level, now extend some distance below it. This rock assemblage of highly permeable basaltic lava flows, intruded in part by dikes in the zones of fissure and free of dikes outside of them, makes up the principal reservoirs for ground water in the Hawaiian Islands.

A diagrammatic cross section showing the geologic structure of a typical Hawaiian volcanic island in the form of an idealized volcanic dome is shown in figure 2. Rocks other than the basaltic flank flows, although widespread in places, generally do not comprise important reservoirs of ground water.

HYDROGRAPHIC AREAS

In order to facilitate a study of the water resources, the six larger islands were subdivided into hydrographic areas by the Hawaii Water Authority in 1959. The boundaries of the areas were based on topography and generally outline the major surface drainage basins (fig. 3). The boundaries of ground-water reservoirs could be better delineated and described if they were based on geology. In order to take advantage of the results of the previous studies, however, the hydrographic areas established in the 1959 study will be used in this appraisal.

RAINFALL

Rainfall is the principal source of recharge and its quantity and variability are significant in determining the extent and quality of ground water. Open-ocean rainfall near the Hawaiian Islands is about 25 inches per year compared with an average of about 70 inches on land. The islands, by their presence, thus increase the open-ocean rainfall by 45 inches per year or by 5,000 billion gallons (14 billion gallons per day). However, because most of the rainfall is orographic, that is, closely related to topography and exposure, the spatial variability of annual rainfall is extremely high.

Annual average rainfall for the islands ranges from less than 35 inches to more than 100 inches per year. Local mean annual rainfall within the larger islands, however, ranges from less than 20 inches to more than 300 inches per year. Variability of annual rainfall generally is greater where rainfall is low because rain types other than those due to trade wind, although small in total quantity, generally fall heavily during short and infrequent storms. These non-trade-wind rains make up most of the rainfall in the open-ocean and low-altitude areas, and their contribution to the recharge of ground water is generally small. The distribution of rainfall in the islands is shown in figure 4.

Owing to the large spatial variation in the trade-wind rainfall, there is a marked inverse relation between the areas of water supply and the areas of water demand. The orographic effects on rainfall are shown by cross-sectional sketches in figure 5.

The high volcanic domes referred to in figure 5 are Mauna Kea and Mauna Loa on the island of Hawaii and Haleakala on Maui. Examples of medium high domes are the Koolau dome on Oahu, the West Maui dome, and the island of Kauai. The low domes include the islands of Kahoolawe and Niihau.

EVAPOTRANSPIRATION

The amount of evapotranspiration approaches that of evaporation from a free-water surface wherever water is constantly available to plants or crops, owing either to the proximity of ground water or to high frequency of rainfall or irrigation. Research in Hawaii, mainly by the sugar and pineapple industries, shows that, although evapotranspiration differs widely from place to place, annual variations at any one place are small. The average pan evaporation in the larger islands ranges from less than 20 inches to more than 80 inches per year, and in the windy dry areas, to more than 90 inches per year. In Hawaii, where rainfall or an estimate of it is the only climatic datum generally available, the relation of rainfall to pan evaporation and to evapotranspiration recognized by Cox (Campbell and others, 1959) and Mink (1962b) is often the only tool available in studies involving the water budget of large drainage basins.

SURFACE RUNOFF AND INFILTRATION

Hawaiian streams, in general, are short and steep, and runoff depends largely on the intensity and duration of rainfall. Exceptions are streams in which runoff is made up largely of ground-water or swamp discharge. In areas where the infiltration capacity of the surface rocks is especially high, most rainfall is quickly absorbed, and there may be no runoff, except during intense storms. In some of these areas of high absorption rates overland runoff is so low that stream patterns have not yet been developed.

Where rainfall is plentiful and well distributed during the year, as in the wet interior mountains, streams are generally perennial and abundant. Where rainfall is light, as in the dry leeward areas, streams are ephemeral and flow only at infrequent intervals during heavy storms.

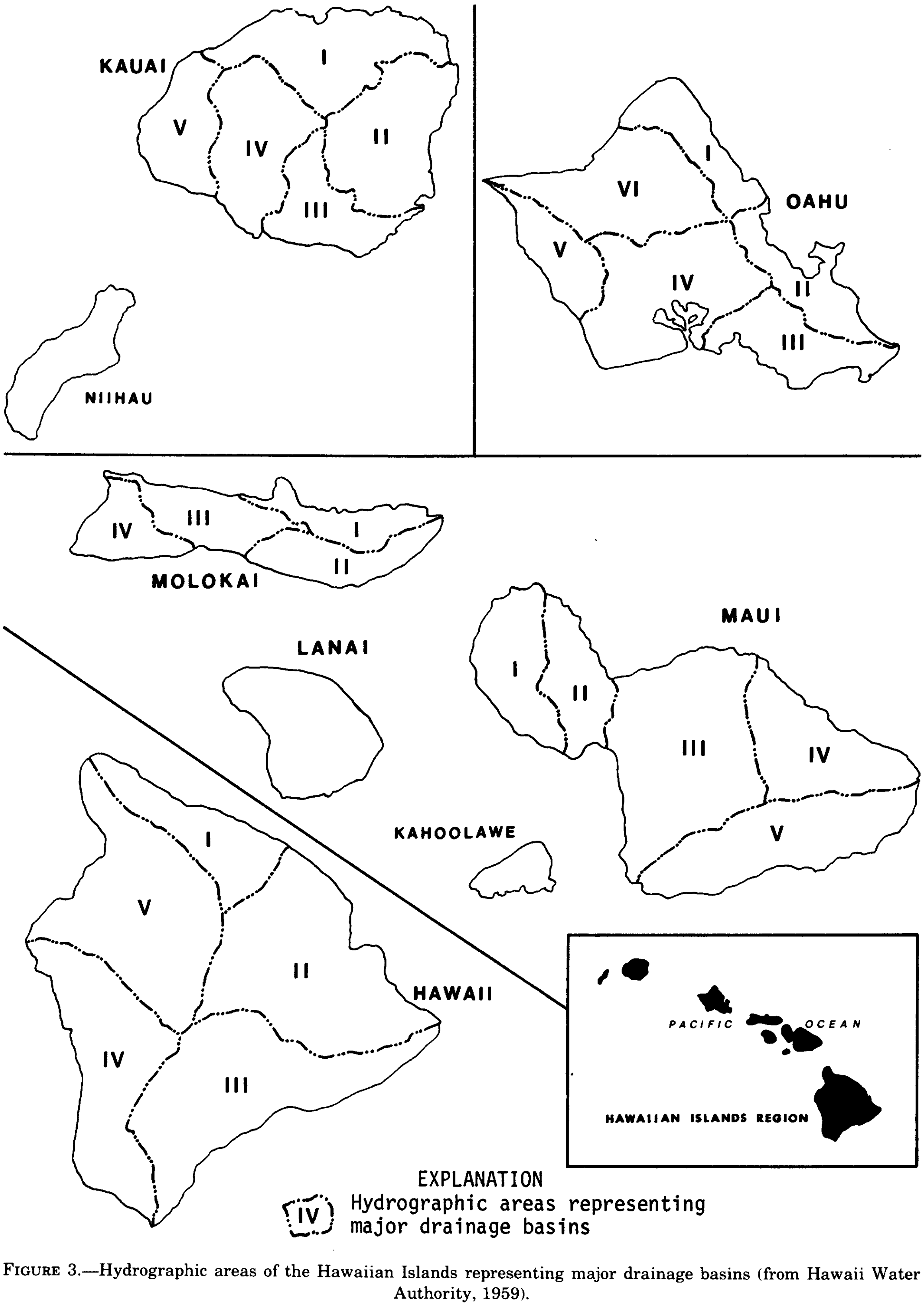
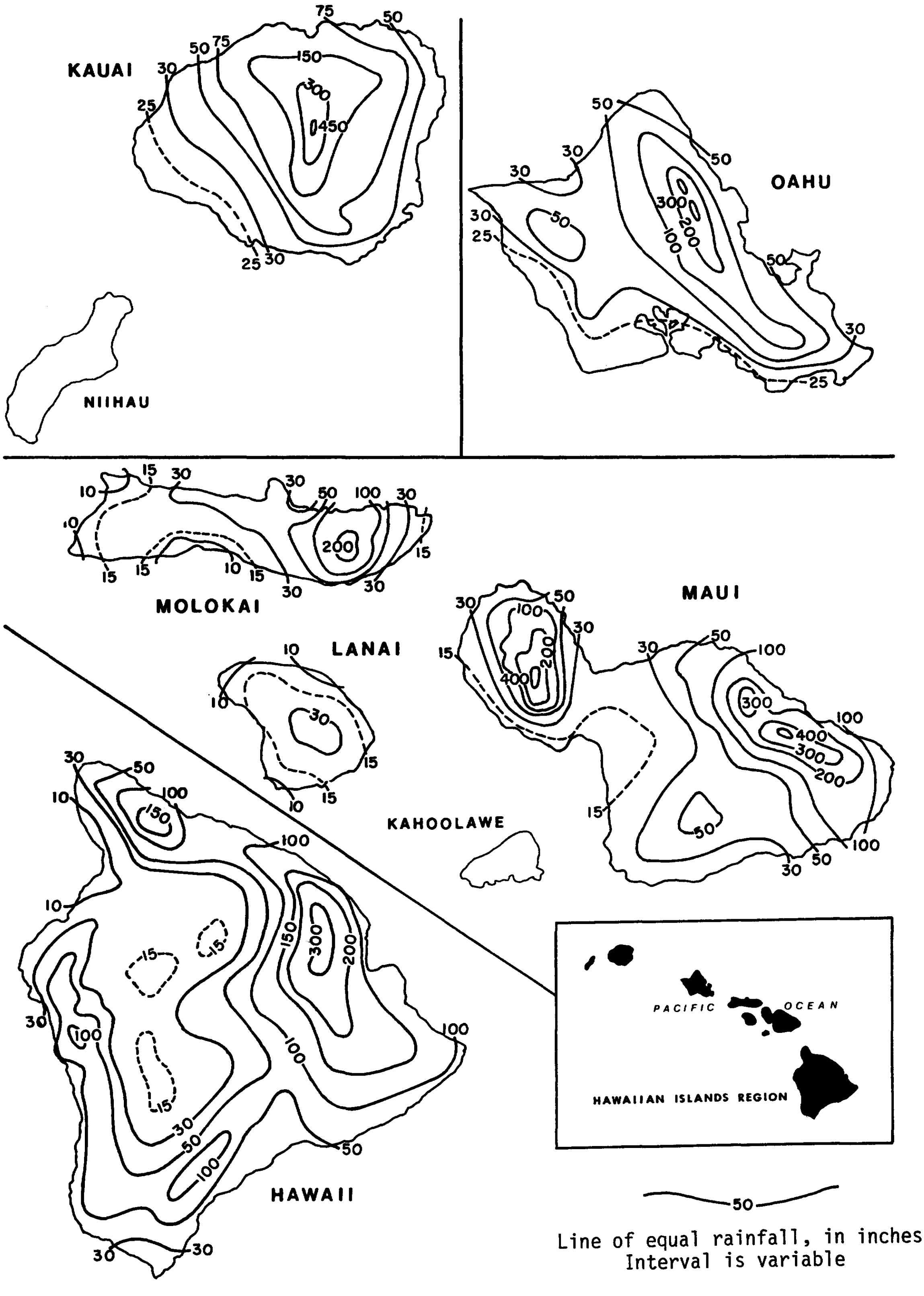


FIGURE 3.—Hydrographic areas of the Hawaiian Islands representing major drainage basins (from Hawaii Water Authority, 1959).



Data from Blumenstock, 1961

FIGURE 4.—Map of the Hawaiian Islands showing lines of equal annual average rainfall in inches.

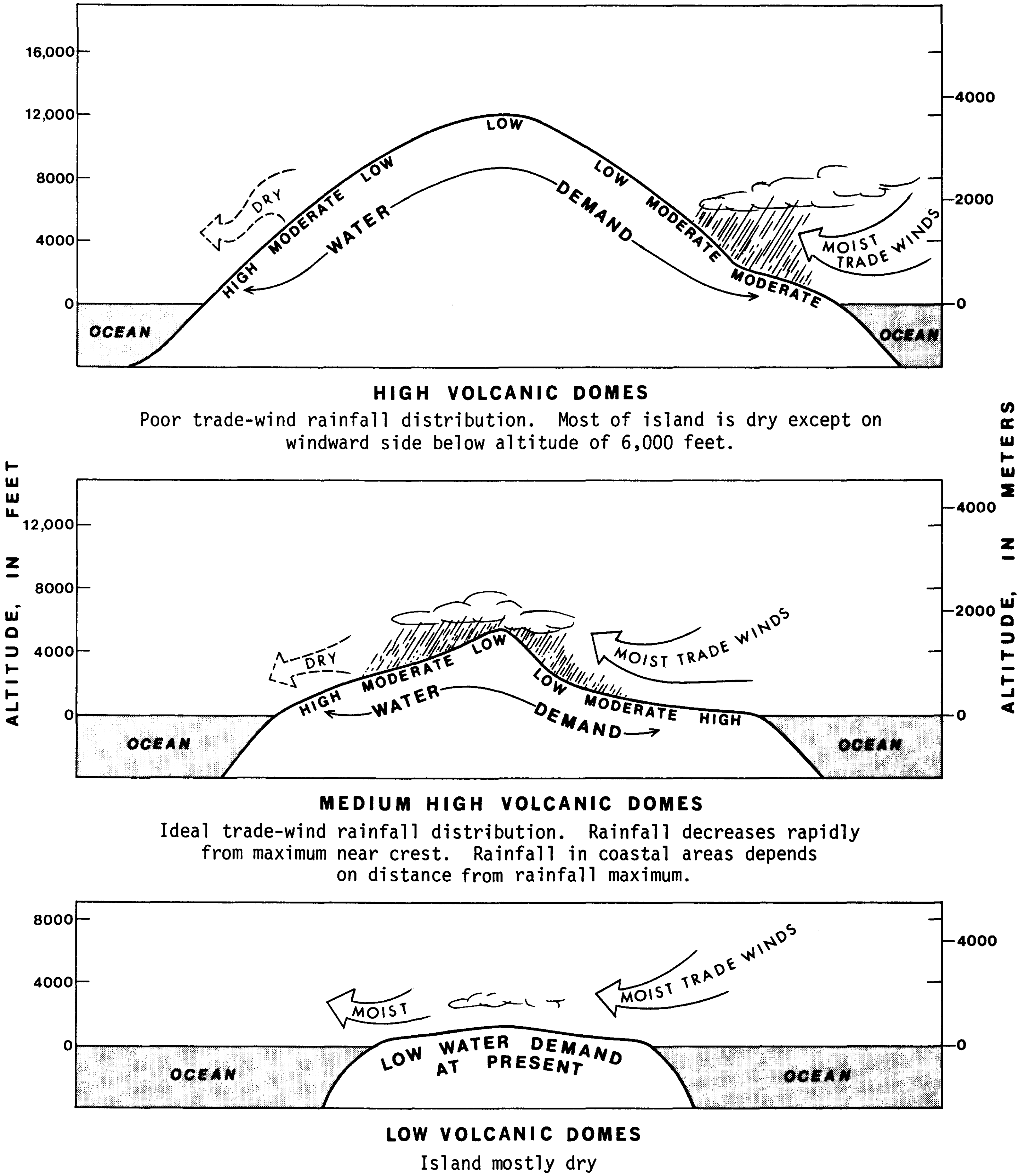


FIGURE 5.—Orographic effects on rainfall.

DISTRIBUTION OF RAINFALL

Rainfall is the principal source of freshwater. Some of it evaporates or is transpired by plants, some replenishes soil moisture, some runs off, and the remainder percolates to ground-water reservoirs. The distribution of the rainfall, however, is not the same everywhere and depends largely on the quantity and variability, and the absorption ability of the land surface. The distribution of rainfall by islands is shown in figure 6.

An example of the change in the distribution of rainfall with change in rainfall is shown in figure 7. The area considered in figure 7 consists roughly of the eastern two-thirds of hydrographic area IV on Oahu. The surface rocks are mostly highly permeable flank flows of the Koolau Volcanic Series. The data used to construct the figure were taken from Hirashima (1971) and Dale and Takasaki (1976).

Table 1 gives a rough estimation of the distribution of rainfall in the hydrographic areas of the region. This table was adapted from a study element report on the surface-water and ground-water resources prepared for the Hawaii Water Resources Regional Study (1975). At best, the figures on distribution of rainfall listed in table 1 are gross estimates and should be regarded as such. They do, however, reflect production possibilities of surface water and ground water in the hydrographic areas, based on known or inferred conditions of rainfall, surface geology, and the geologic framework of the subsurface.

Ground-water pumpage and the quantity of water transported by pipelines and ditches from and into the various hydrographic areas are also listed in table 1.

WATER USE

WATER USE IN 1975

Water use in the Hawaii Region in 1975 averaged about 1,775 Mgal/d, of which about 810 Mgal/d, or 46 percent, was derived from ground-water sources. Table 2 shows the breakdown in use and sources by islands.

Public-supply water use includes general domestic, commercial and limited industrial use.

Self-supplied industrial water use is limited to water systems that are privately owned and operated by industry. The bulk of this use consists of process water used by the sugar industry and of cooling water for the electrical power industry. Industrial water supplied by municipal systems is not included. Brackish ground water used for cooling purposes is included.

The largest use of water in the Region is for irrigation (1,175 Mgal/d) and, of this amount, as much as 90 percent is used for irrigation of sugarcane in dry sunny areas. Sugar yields are highest where sugarcane is irrigated and water use may be as much as 12 acre feet per acre per year. In many places, the irrigation water is imported from distant wet areas. Upwards of 500 Mgal/d of irrigation water is diverted from wet to dry areas, 360 Mgal/d of this quantity from one hydrographic area to another.

The impact on the ground-water resources in the wet areas, resulting from the exportation of water, is usually not pronounced because much of the water exported represents natural ground-water discharge. The impact, however, on ground water in the dry areas to which the water is delivered for irrigation, is pronounced. When used for irrigation between furrows, as much as 60 percent of the irrigated water applied filters into the ground and recharges the underlying ground-water reservoir. In many dry areas, this return of irrigation water represents the principal source of recharge to ground water, the effect of which is to maintain a usable ground-water resource where none may have existed previously.

FUTURE WATER-USE PATTERNS

Most of the current demands for water are in the dry sunny areas where sugarcane yields are highest and where most of the population resides. No change is foreseen in this pattern for the future, except that the demand will increase significantly, owing to the development of larger tourist-oriented and residential complexes in presently little-developed coastal areas. In some areas, the demand is already larger than the supply and must be met by importing water. This is likely to be the situation for other areas of high growth in the future. Some of these problems could be avoided by locating new industries in the areas of plentiful water supply. Predictions of future water-use patterns and demands based on projections of past trends may be unreliable, however, owing to rapid changes in the principal economic base, shifts in population, and changes in life styles.

MUNICIPAL

Per-capita water-use figures based on current population samplings are generally not reliable for future projections. The higher proportion of use by the tourist and related industries, changes in life styles, and more widespread use of luxury home appliances are the reasons for possible discrepancies in projecting water use.

AGRICULTURAL

Many factors other than crop type affect the use pattern of irrigation water. Water use for sugarcane, for instance, is dependent on the type, slope, and profile

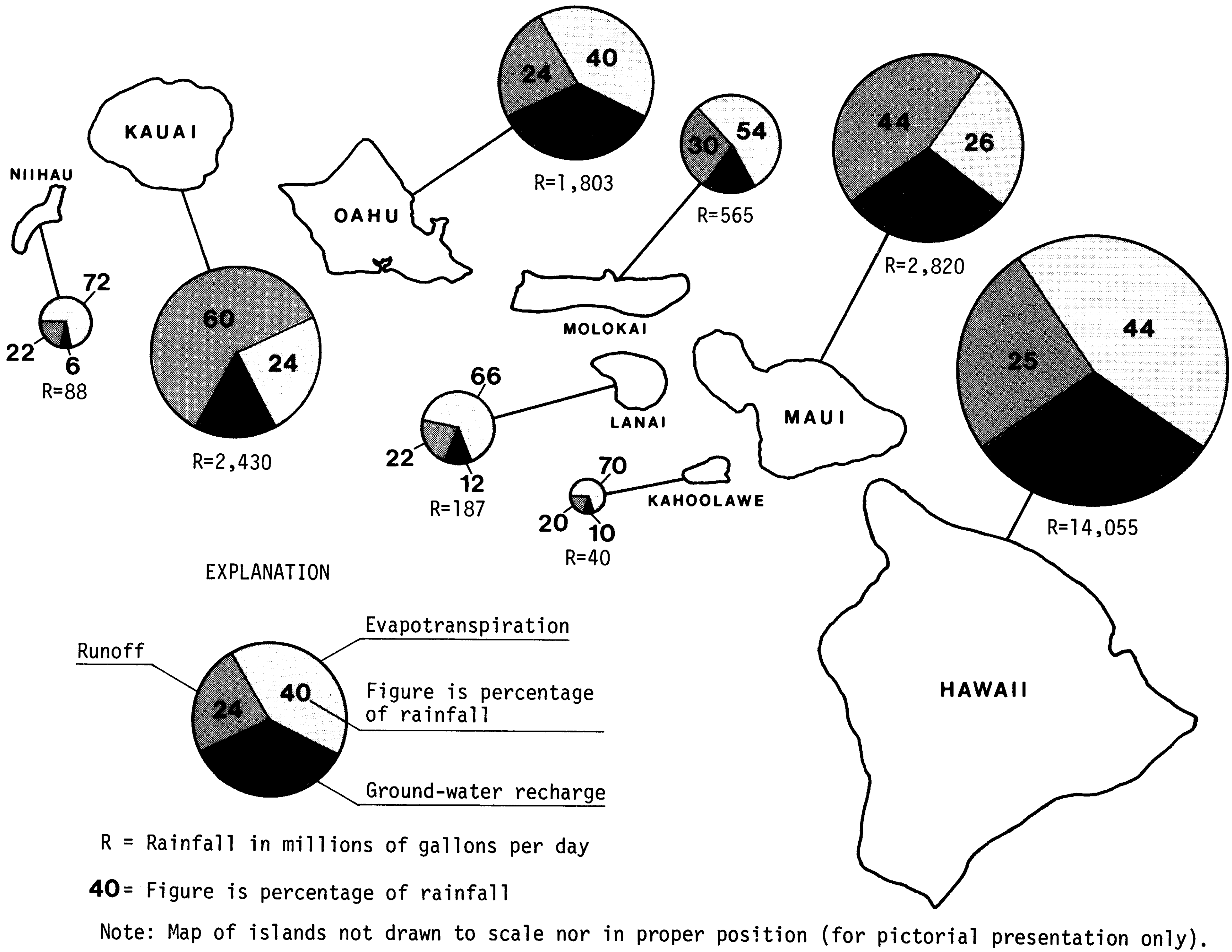


FIGURE 6.—Distribution of rainfall by islands.

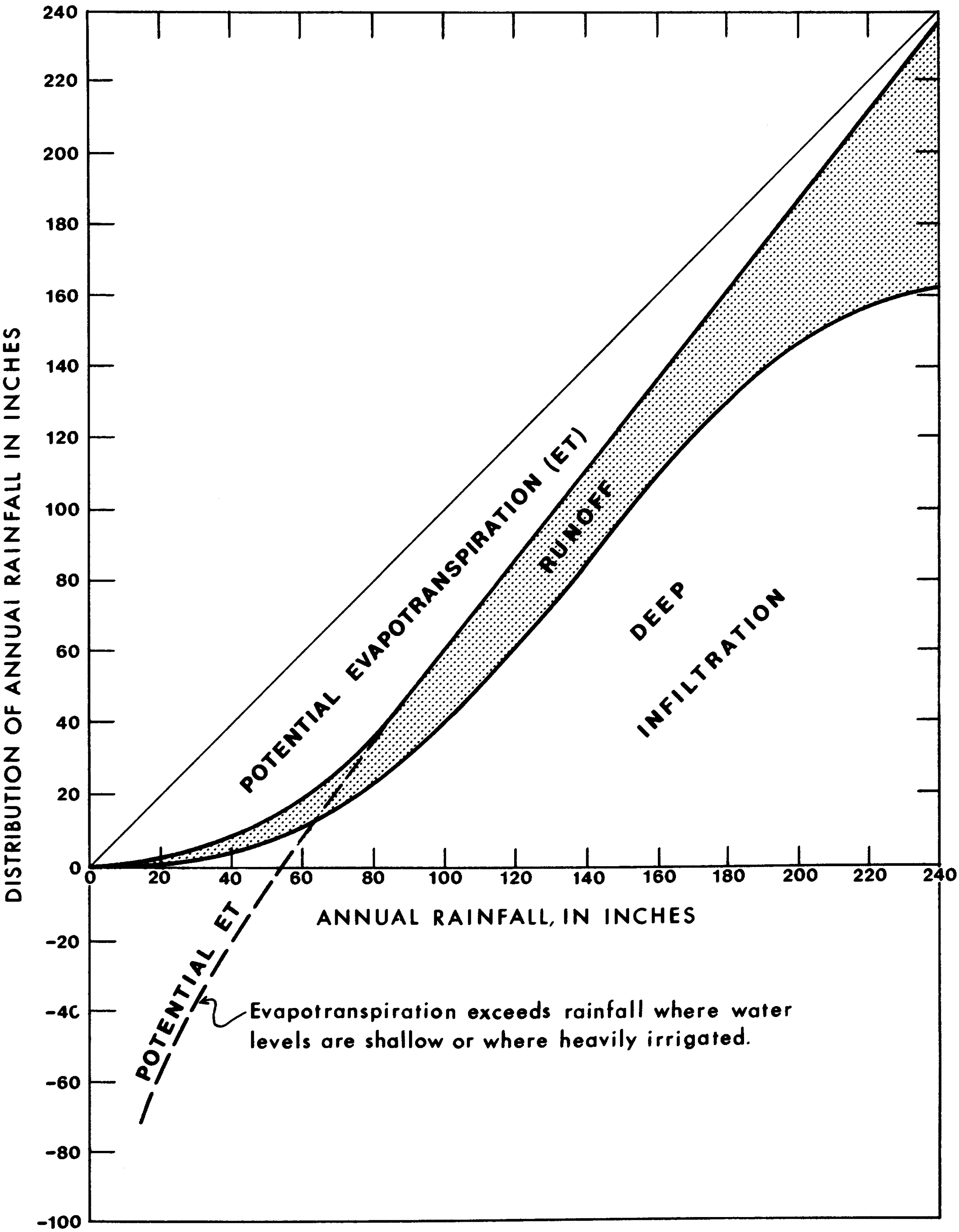


FIGURE 7.—Distribution of rainfall as related to rainfall range in leeward Koolau Range.

TABLE 1.—*Distribution of rainfall, in million gallons per day, to evapotranspiration, runoff, and ground-water recharge*

Island	Hydrographic area representing major drainage basin	Total rainfall	Distribution of rainfall						1975 ground-water quantities (approximate)		
			Evapotranspiration	Percentage of rainfall	Runoff	Percentage of rainfall	Ground-water recharge	Percentage of rainfall	Exported	Imported	Withdrawn from wells
Large islands exposed to trade winds											
Hawaii	I	1,430	695	49	430	30	305	21	5	1	5
	II	7,335	1,730	24	2,510	34	3,095	42	0	0	18
	III	2,340	[1]1,705	73	235	10	400	17	0	0	8
	IV	1,790	[1]1,265	71	180	10	345	19	0	0	3
	V	1,160	[1]745	64	180	16	235	20	1	5	1
	Totals (rounded)	14,100	6,200	44	3,500	25	4,300	31	6	6	35
Maui	I	340	125	37	145	41	70	21	0	0	60
	II	370	130	35	175	47	65	18	20	0	26
	III	685	215	31	325	47	145	21	0	180	170
	IV	925	145	16	310	34	470	51	160	0	7
	V	500	145	29	270	54	85	17	0	0	1
	Totals	2,820	760	27	1,225	43	835	30	180	180	264
Molokai	I	230	30	13	150	65	50	22	5	0	<1
	II	175	125	71	15	9	35	20	1	1	<1
	[2]III, IV	160	150	94	5	3	5	3	0	5	<1
	Totals	565	305	54	170	30	90	16	6	6	1
Oahu	I	270	90	33	85	31	95	35	3	1	8
	II	255	115	45	100	39	40	16	25	3	42
	III	235	120	51	30	13	85	36	0	22	56
	IV	425	105	25	70	16	250	59	24	25	260
	V	98	77	79	15	15	6	6	0	2	6
	VI	520	210	40	130	25	180	35	1	0	48
	Totals (rounded)	1,800	715	40	430	24	655	36	53	53	420
Kauai	I	910	160	18	[3]705	77	[4]45	5	18	0	2
	II	710	219	31	[3]455	64	[4]36	5	11	18	2
	III	280	75	27	[3]195	70	[4]10	4	25	11	12
	IV	414	89	21	[3]300	72	[4]25	6	55	25	2
	V	116	50	43	58	50	8	7	0	55	32
	Totals (rounded)	2,430	595	24	[3]1,715	70	120	5	109	109	50
Kauai	Adjusted totals	2,430	595	24	[5]1,455	60	380	16	109	109	
Large islands	Totals (rounded)	21,700	8,520	39	6,820	31	6,340	30	354	354	770
Small islands in rain-shadow of large islands											
Kahoolawe	Total	40	28	70	8	20	4	10	0	0	0
Lanai	Total	187	124	66	40	22	23	12	0	0	2
Niihau	Total	88	63	72	20	23	5	5	0	0	0
Small islands	Totals (rounded)	315	215	68	70	22	30	10	0	0	2
Region	Grand totals (rounded)	22,000	8,730	40	6,800	31	6,460	29	357	357	772

[1]Probably too high owing to infrequency of storms which provide much of rainfall total.
[2]Hydrographic areas combined owing to low rainfall density in each area.
[3]Includes large quantity of ground-water inflow, see footnote 5.
[4]Too low; ground water included with runoff.
[5]Reduced by 15 percent and added to ground water.

TABLE 2.—*Water use in Hawaii Region, in million gallons per day*
[From water-supply study-element report, Hawaii Water Resources Regional Study (1975)]

	Water use				Source	
Island	Public supplies	Self-supplied industrial	Agri-cultural	Total	Surface water	Ground water
Hawaii	15	117	31	163	134	29
Maui	13	85	467	565	305	260
Molokai	0.4	0	2	2.4	2	1
Oahu	161	130	321	612	152	460
Kauai	7	72	352	431	371	60
Lanai	0.3	0	2.2	2.5	0	2
Kahoolawe	0	0	0	0	0	0
Niihau	0	0	0	0	0	0
	197	404	1,175	1,776	964	812

of the soil, climatic parameters (rainfall, etc.), the length of fallow period, and the availability and quality of water. Available information is generally not adequate for planning future irrigation needs owing to large-scale shifts from furrow to drip irrigation.

INDUSTRIAL

At present most self-supplied industrial water is used as cooling water for air-conditioning and for electric power generation. Potential industries that may require large quantities of water include the mining of manganese or other ores from the sea floor, the extraction of minerals from seawater, or the utilization of geothermal energy resources.

SURFACE WATER VERSUS GROUND WATER

The major source of usable surface water is the fair-weather or base flow of streams. Much of this water is transported from wet to dry areas in extensive ditch systems which were constructed early in this century. More such water could be developed but only at high cost because new ditches or enlargements of the present ditches would be needed. Other constraints that could restrict future development and transfer of water include existing water rights, environmental considerations, and State and Federal statutory regulations.

Generally, there are few constraints other than cost in the onsite development of ground water, except where land development is extensive such as in Oahu and possibly in the Lahaina area in Maui. Areas of high water demand in coastal areas generally coincide with areas underlain by poor-quality basal ground water. In many areas, availability of good-quality ground water would necessitate development 3 to 4 miles farther inland to an altitude of 1,000 feet or higher. A well at these altitudes would have to be drilled to below sea level and the water pumped up from near sea level to the land surface.

In areas where ground-water and surface-water sources are closely integrated and where the withdrawal of ground water is quickly reflected in reduced surface-water flow, the need to maintain streamflow may restrict ground-water development. Knowledge of the hydraulic characteristics of the aquifers and the nature of the stream-aquifer interconnection are needed in order to estimate safe limits for development in these areas.

Compliance with the Federal Safe Drinking Water Act (PL 93-529, 1974) will have pronounced effect on managerial and planning decisions, especially in areas where both ground-water and surface-water sources are being considered as municipal supplies. The high costs of treating surface-water supplies must be weighed against the cost of developing new ground-water supplies.

GROUND-WATER RESERVOIRS

Most fresh ground water is stored near and below sea level to depths ranging to 1,000 feet or more below sea level. The principal fresh ground-water reservoirs consist of thin-bedded basaltic lava flows. These reservoirs contain interconnected water bodies that are impounded by dikes in the interior of the islands or are in dynamic equilibrium with the underlying saline ground water in the outer rims of the islands. Ground water in these settings is referred to, respectively, as dike-impounded water and basal water. Other water bodies, small in comparison, are perched above and isolated from these interconnected water bodies and are called perched water. The term high-level water is often used to describe both dike-impounded and perched water, or a combination of them when they occur at high altitudes.

A diagrammatic cross section showing occurrence and development of ground water in an idealized Hawaiian volcanic dome is shown in figure 8. The principal ground-water reservoirs in each of the Hawaiian Islands are outlined in figures 9 to 15. Estimates of ground-water recharge and ground-water draft in each of the hydrographic areas are also shown in figures 9 to 15 and table 1. A brief description of the principal reservoirs and their potential for additional development is given by hydrographic areas in table 3.

Ground-water development is generally most favorable in areas directly downslope from mountain areas of high rainfall and becomes less favorable with increasing distance away from these downslope areas.

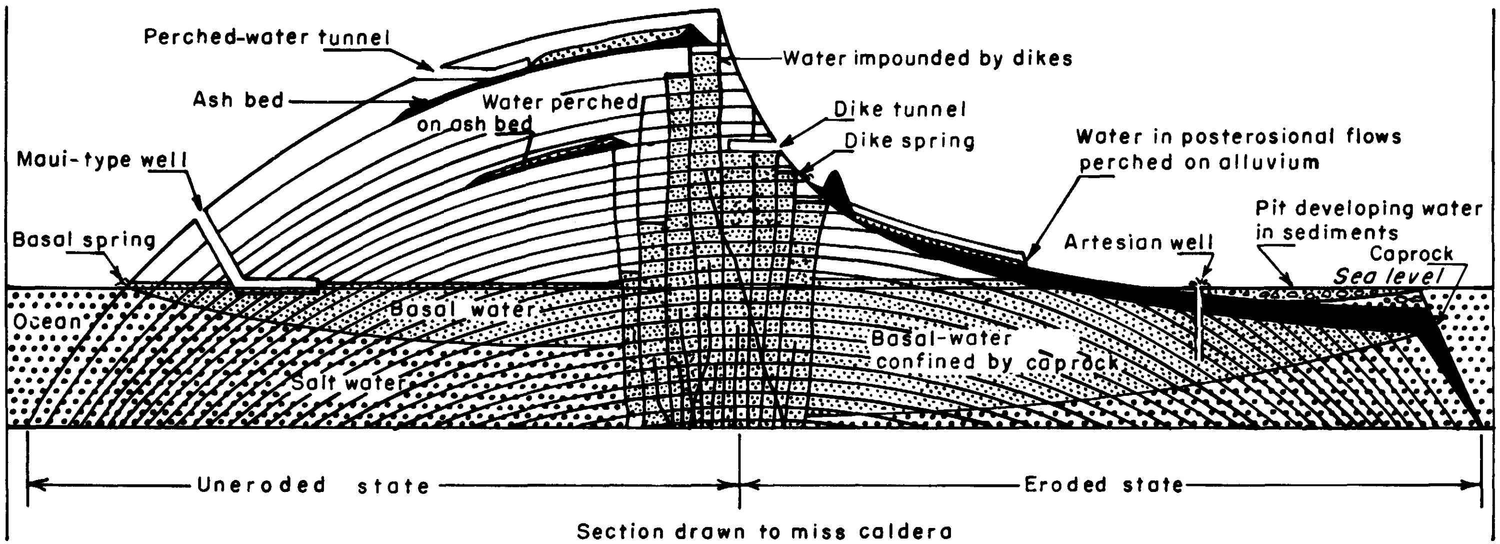


FIGURE 8.—Occurrence and development of ground water in an idealized Hawaiian volcanic dome (from Cox, 1954).

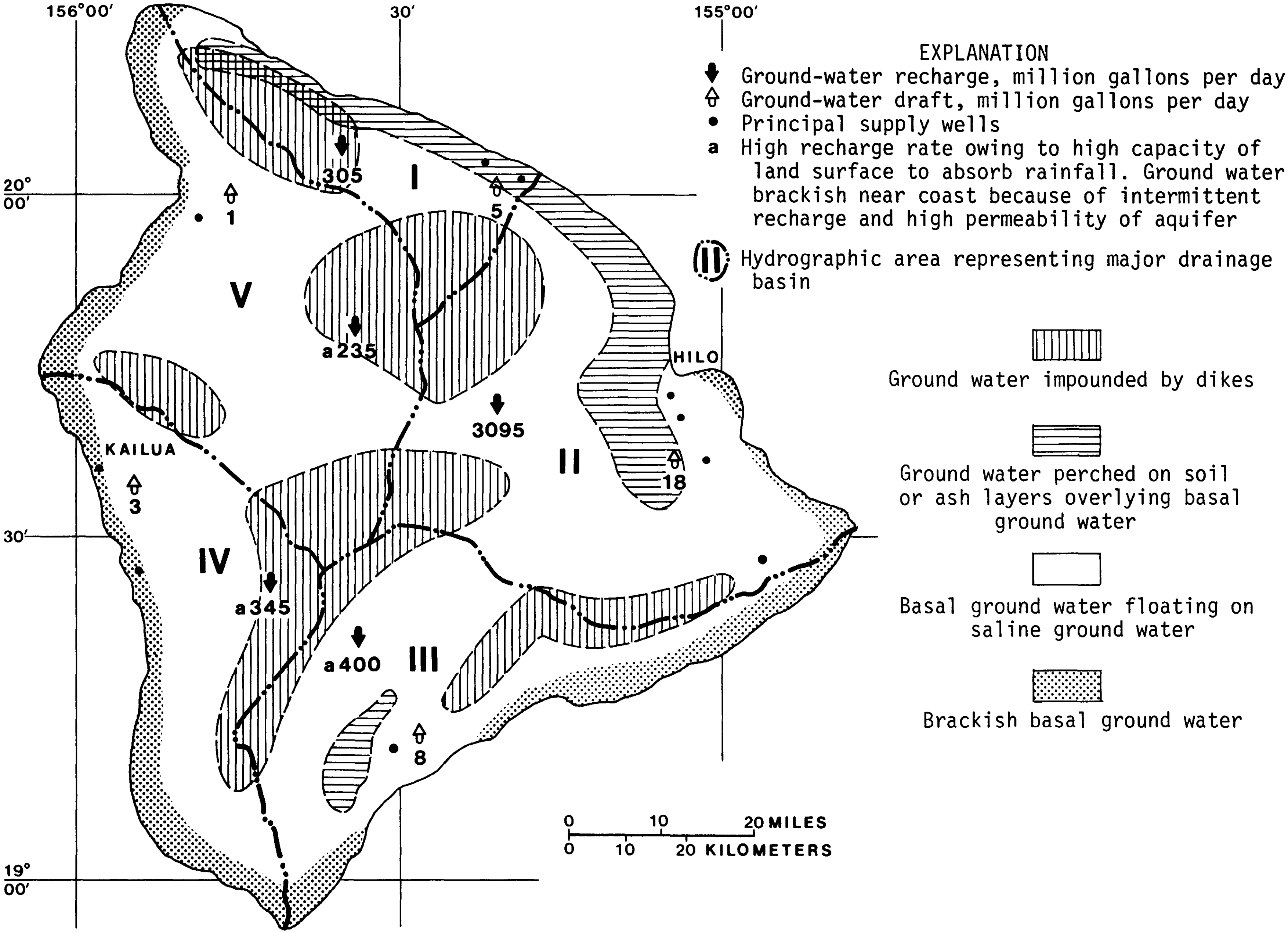


FIGURE 9.—Map of island of Hawaii showing approximate outline of ground-water reservoirs, recharge, 1975 draft, and principal supply wells by hydrographic areas representing major drainage basins. (Modified from Davis and Yamanaga, 1973.)

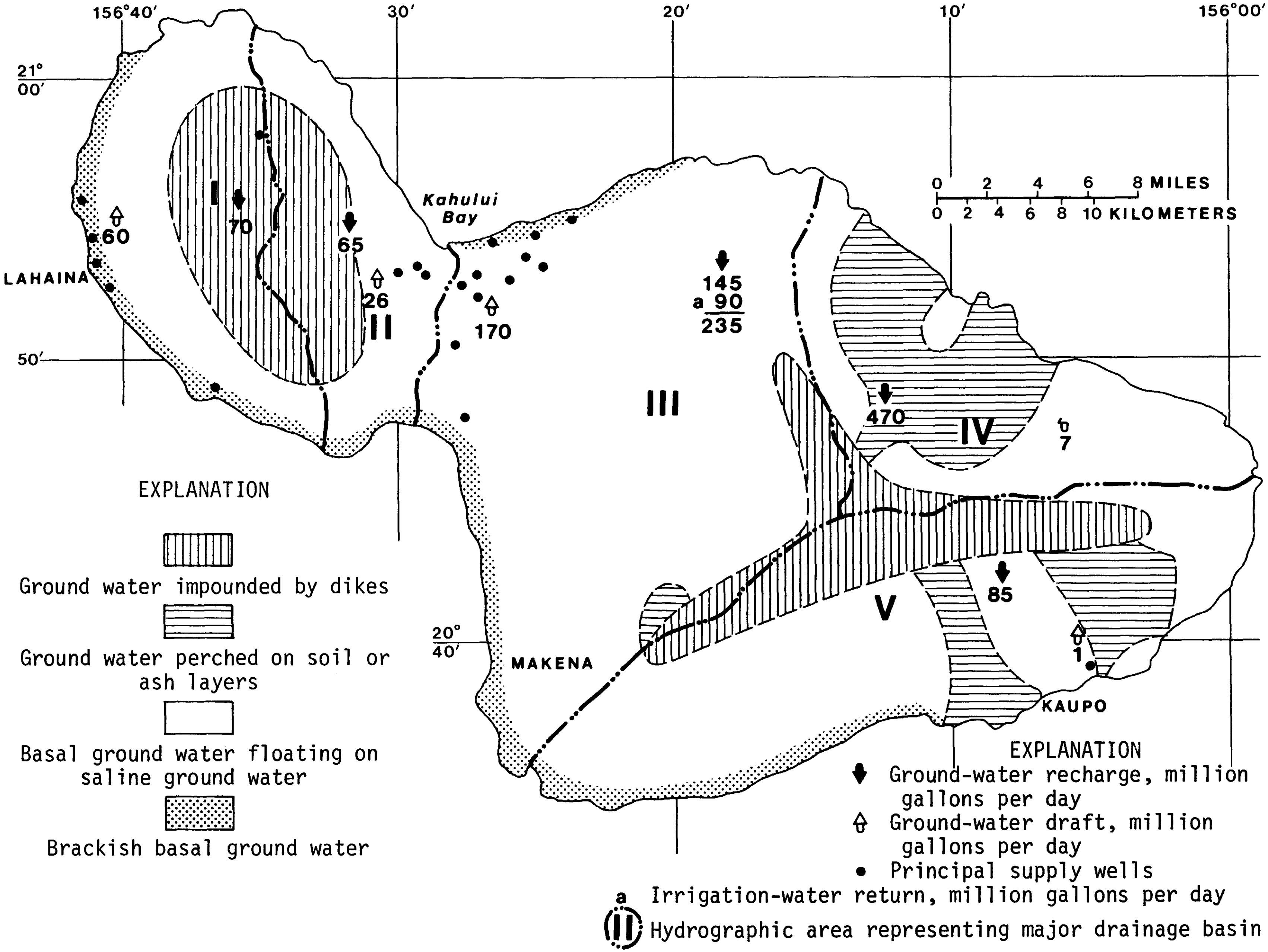


FIGURE 10.—Map of island of Maui showing approximate outline of ground-water reservoirs, recharge, 1975 draft, and principal supply wells by hydrographic areas representing major drainage basins. (Modified from Stearns and Macdonald, 1942.)

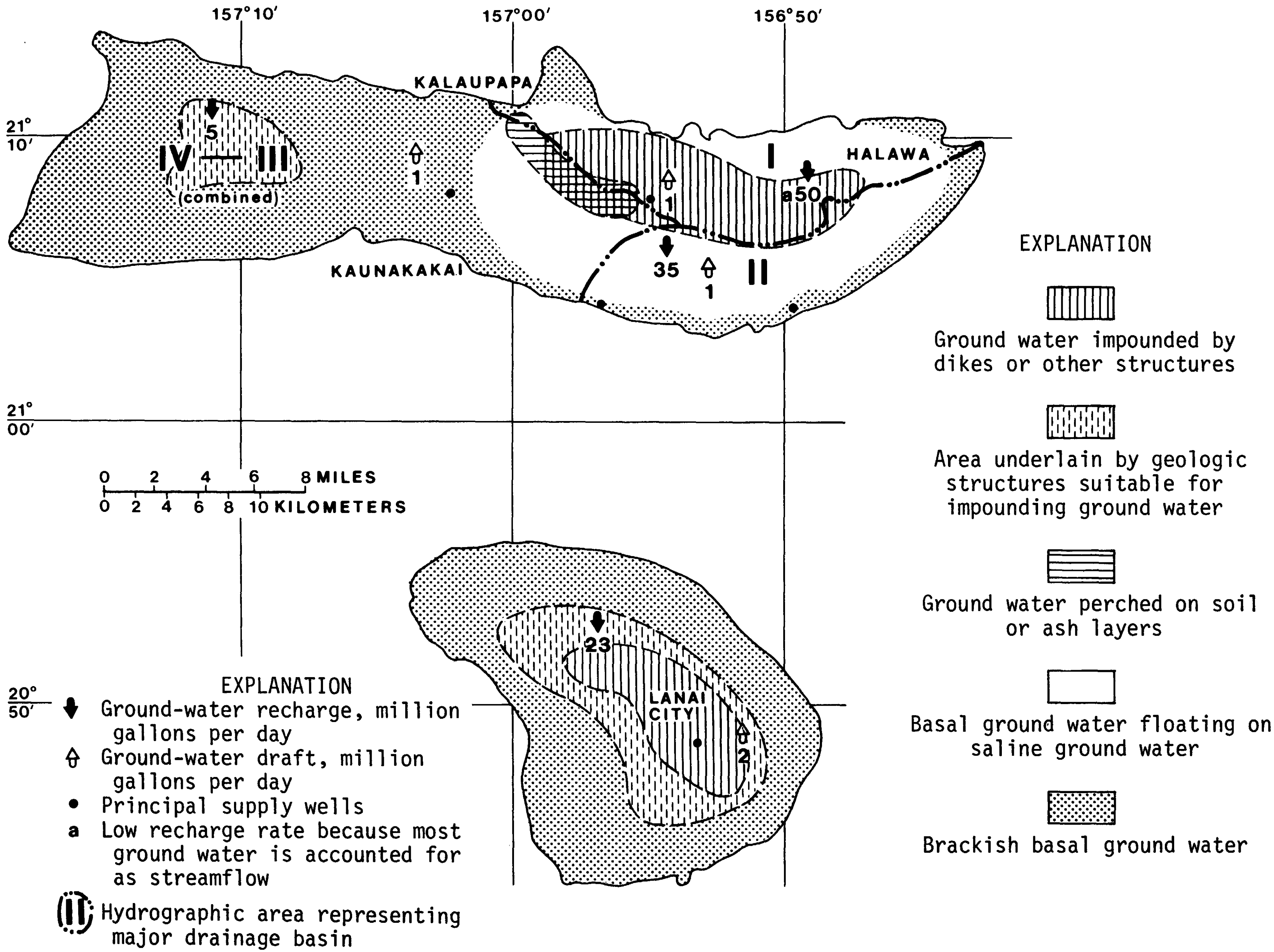


FIGURE 11.—Map of islands of Molokai and Lanai showing ground-water reservoirs, recharge, 1975 draft, and principal supply wells by hydrographic areas representing major drainage basins. (Molokai: modified from Stearns and Macdonald, 1947; Lanai: from S.P. Bowles, unpublished data, in 1973.)

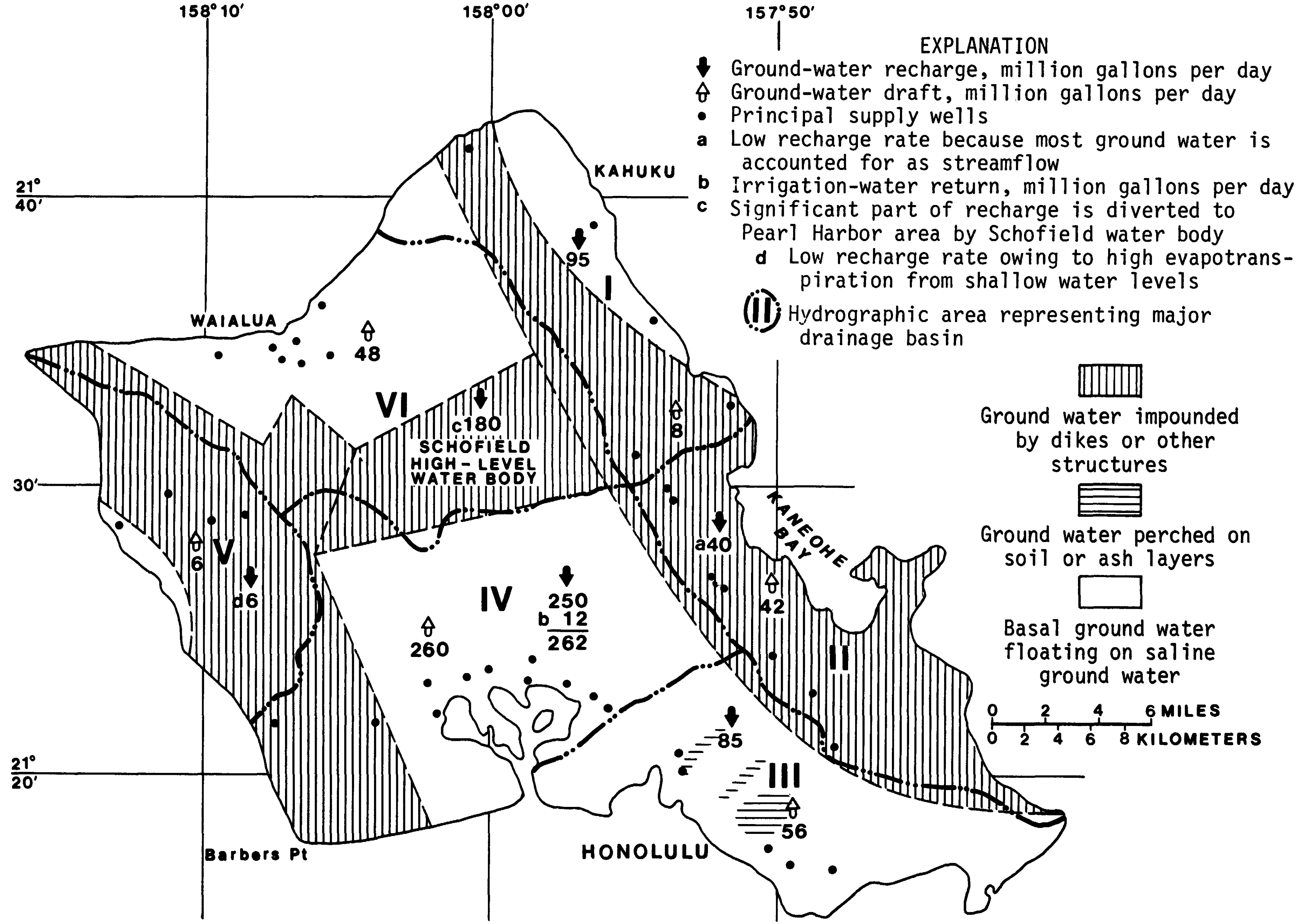


FIGURE 12.—Map of island of Oahu showing approximate outline of ground-water reservoirs, recharge, 1975 draft, and principal supply wells by hydrographic areas representing major drainage basins.

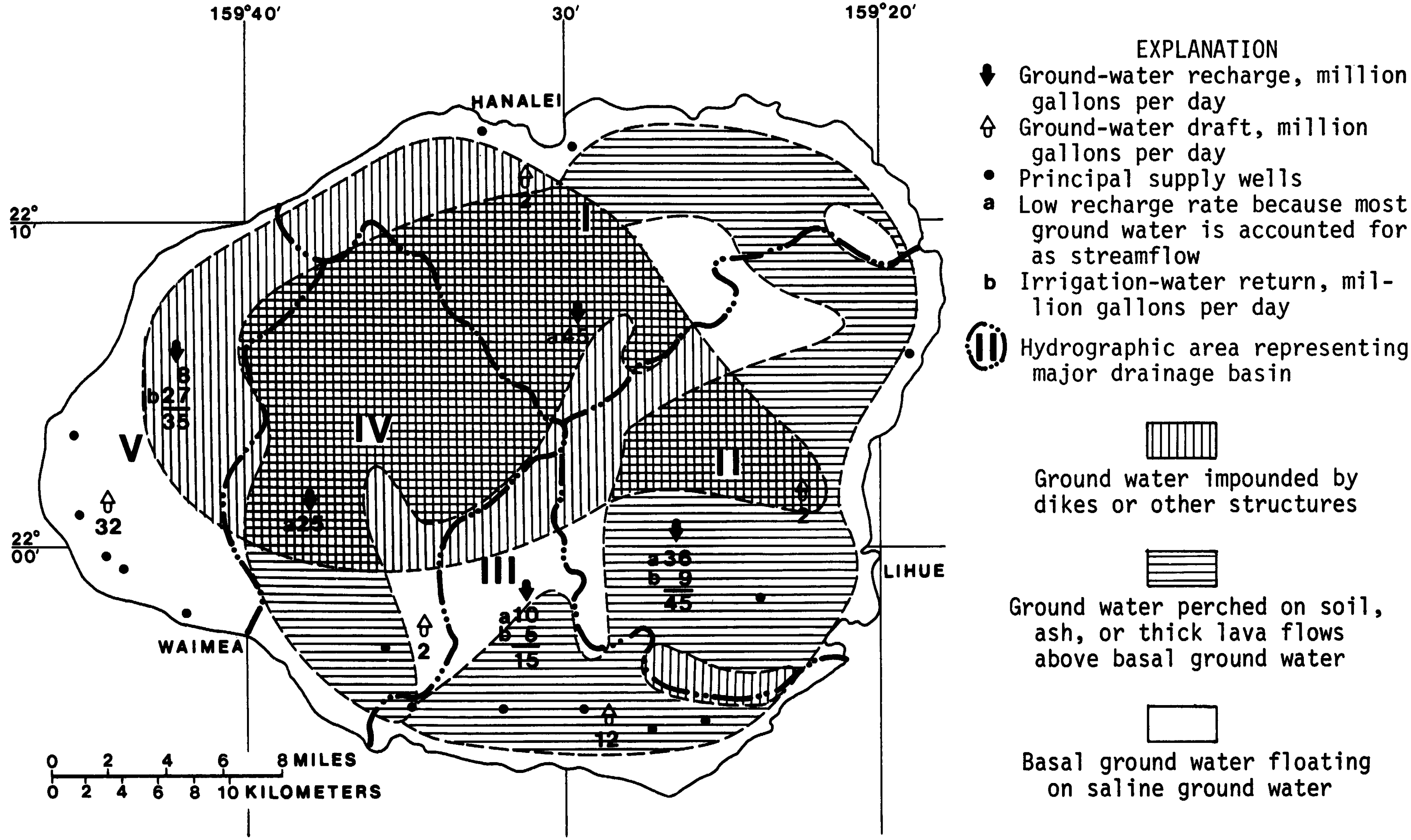


FIGURE 13.—Map of island of Kauai showing approximate outline of ground-water reservoirs, recharge, 1975 draft, and principal supply wells by hydrographic areas representing major drainage basins.

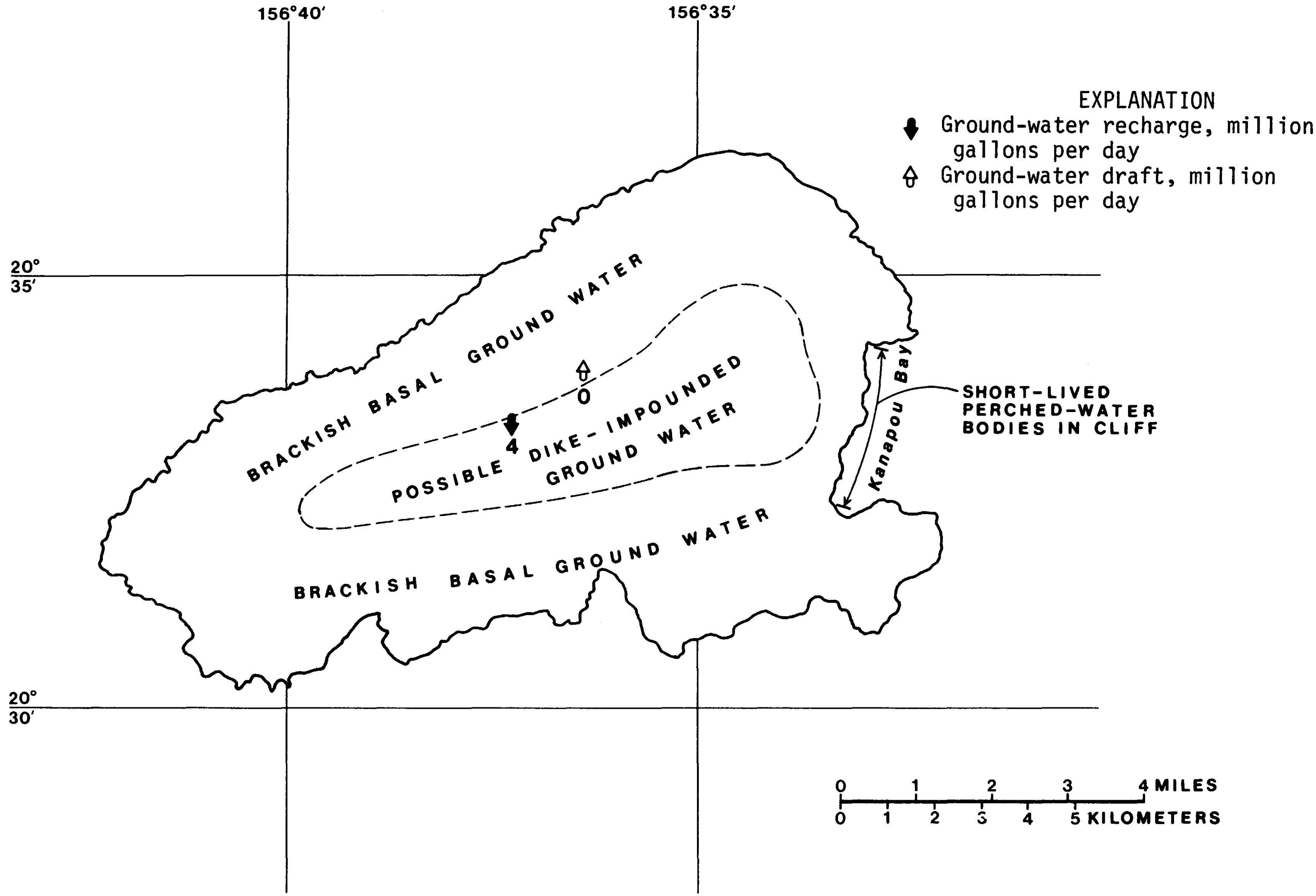


FIGURE 14.—Map of island of Kahoolawe showing approximate outline of ground-water reservoirs, recharge, and 1975 draft.

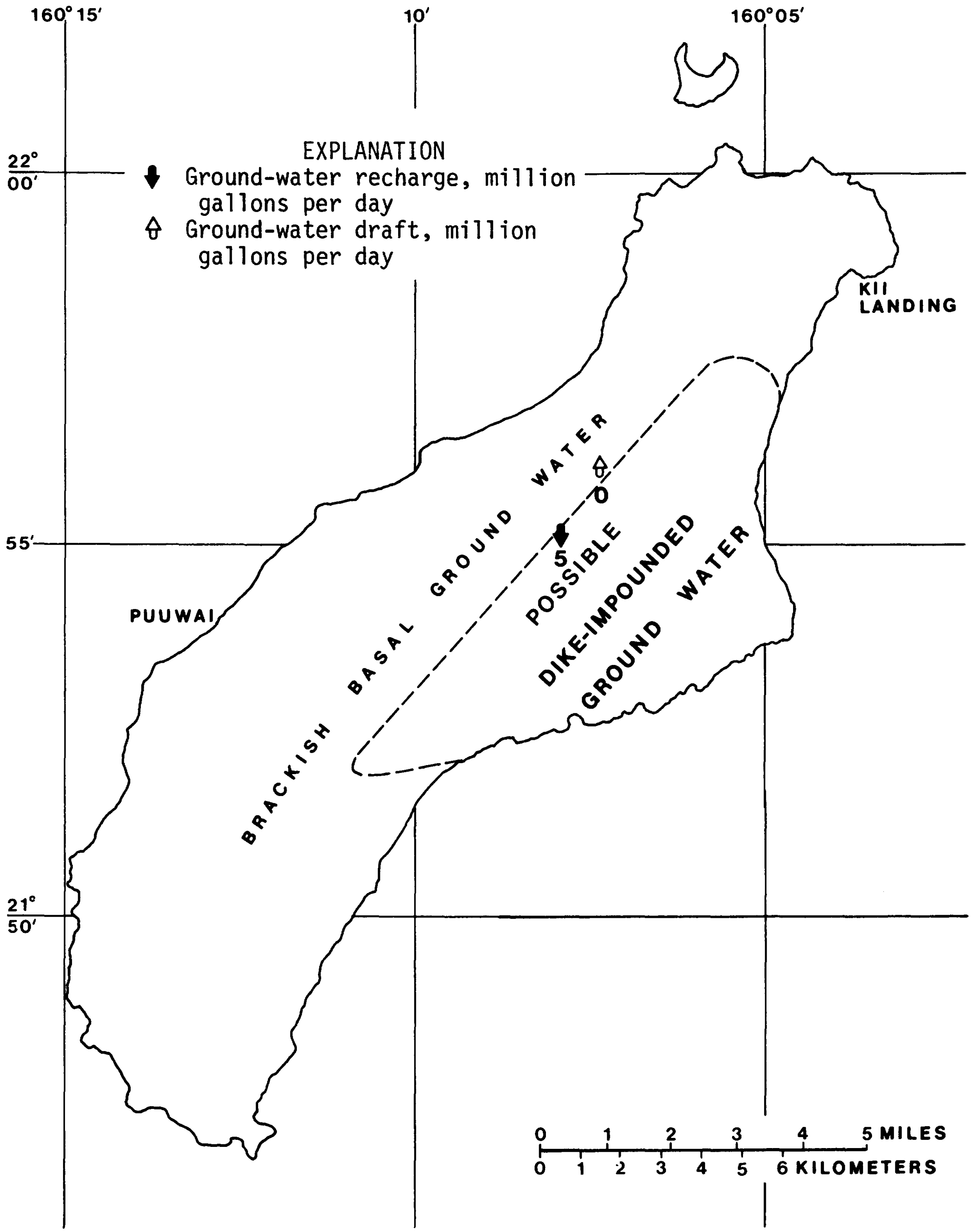


FIGURE 15.—Map of island of Niihau showing approximate outline of ground-water reservoirs, recharge, and 1975 draft.

This downslope direction generally coincides with the downslope flow direction of the lavas and the favorable direction of ground-water flow from the mountains and the sea. Owing to this generally favorable direction of ground-water flow, ground-water development is seriously limited in leeward areas where rainfall is heavy only on the windward side. The south Kohala-Kona coast on the island of Hawaii and the Kihei-Makena

TABLE 3.—*Principal ground-water reservoirs*

Hydrographic area representing major drainage basin	Principal ground-water reservoirs		Remarks	Potential for additional development
	Occurrence	Aquifer rock		
Hawaii I	Basal	Kohala Mt. lavas	Large, untapped source.	Good
	Dike impounded	do	Excellent domestic quality.	Good
	Basal	Mauna Kea lavas	Flow increases toward south.	Fair to good
Hawaii II	do	do	Large, little-tapped source.	Good
	do	Mauna Loa lavas	Very large, little-tapped source.	Good
Hawaii III	High level	do	Large impounded supply.	Good
	Basal	do	Large supply in eastern part.	Poor to good
Hawaii IV	do	do	Brackish near coast.	Poor to fair
	do	Hualalai Volcanic Series	do	Poor to fair
Hawaii V	do	do	do	Poor
	do	Mauna Loa lavas	do	Poor
	do	Mauna Kea lavas	do	Poor to fair
Maui I	Dike impounded	West Maui lavas	Excellent domestic quality.	Fair
	Basal	do	Poor quality near coast.	Poor
Maui II	Dike impounded	do	Excellent domestic quality.	Fair
	Basal	do	Excellent quality water.	Fair to good
Maui III	do	Haleakala lavas	Large recharge from return irrigation water, quality improves to the east.	Fair
Maui IV	Perched	Posterosional Haleakala lavas	Excellent quality water.	Good
	Basal	do	Fair to good quality in thin basal-water bodies.	Fair to good
Maui V	do	Haleakala lavas	Good quality in east part and poor in west part.	Poor to fair
Molokai I	Dike impounded	East Molokai Volcanic Series	Excellent quality water.	Good
Molokai II	Basal	do	Quality and flow improve toward east.	Fair
Molokai III, IV	do	East and West Molokai Volcanic Series	do	Poor to fair
Oahu I	Dike impounded	Koolau Volcanic Series	Development will reduce streamflow.	Fair
	Basal	do	Separated into two parts by dike zone.	Fair to good.
Oahu II	Dike impounded	do	Development will reduce streamflow.	Fair
Oahu III	Basal	do	Heavily tapped in coastal plain areas.	Poor
Oahu IV	High level	do	Schofield water body; development at expense of reduced flow to Pearl Harbor and Waialua areas.	Good
	Basal	do	Thick lens, heavily tapped.	Poor
	do	Waianae Volcanic Series	Heavily pumped for irrigation, poor general quality.	Poor
	do	Coralline	Heavily pumped for irrigation and recharged by return irrigation water.	Poor to fair
Oahu V	Dike impounded	Waianae Volcanic Series	Excellent quality in limited supply.	Poor to fair
	Basal	do	Brackish near coast.	Poor
Oahu VI	High level	Koolau Volcanic Series	Schofield water body, development at expense of reduced flow to Pearl Harbor and Waialua areas.	Fair to good
	Basal	do	Deep valleys restrict lateral flow.	Fair
	do	Waianae Volcanic Series	Thick lens.	Fair
Kauai I	do	Napali Formation	Large, little-tapped source, excellent quality.	Good
	Perched	Koloa Volcanic Series	Large, untapped source, yield poorly to wells.	Poor to fair
Kauai II	Basal	Napali Formation	Thick basal reservoirs, excellent quality.	Fair
	do	Koloa Volcanic Series	Large, little-tapped source, yield generally low to wells.	Poor to fair
	Perched	do	Mostly in small reservoirs, excellent quality.	Fair
Kauai III	Basal	Napali Formation	High water levels owing to impoundment by Koloa Volcanic Series.	Fair to good Poor to fair
	do	Koloa Volcanic Series	Brackish near coast.	
	Perched	do	Little-tapped source in eastern part.	Fair
Kauai IV	Basal	Makaweli Formation	High water levels.	Fair
Kauai V	do	Napali Formation	Significant recharge by return irrigation water.	Poor
Kahoolawe	do		Mostly brackish.	Poor
Lanai	Dike or fault impounded	Lanai Volcanic Series	Large storage, can be utilized for peaking.	Fair
Niihau	Basal		Mostly brackish.	Poor

area in Maui are such areas. In the high volcanic dome of Haleakala on Maui, for instance, more than two-thirds of the rain falls on the windward side. About 160 Mgal/d of water developed in this area is conveyed by ditches to irrigate sugarcane in the lower eastern slopes, but much more goes unused to the sea owing to the lack of adequate conduits.

Water for domestic use in east Maui is currently transported from limited ground-water sources in west Maui and plans are to increase the amount of water transported for this purpose. From the standpoint of long-term optimum use of the ground-water resource in west Maui, development of the large but unused water resources available in the windward slopes of east Maui should be considered for use in east Maui.

OPTIMIZING GROUND-WATER DEVELOPMENT

The ground-water resources of the region, taken as a whole, are far greater than foreseeable future demands of the region, but this is not true for single basins and single islands. Each island is a separate entity and stands alone with respect to utilization of its ground-water resources. Within each island, ground water may be obtained from the three types of reservoirs described in the preceding section. Optimal development will occur, however, only by taking into account the relationships of discharge and recharge that may exist locally among the various ground-water bodies.

BASAL GROUND WATER

It is commonly not recognized that basal ground water is a highly fugitive, as well as renewable, resource, and that the ocean, to which it escapes, represents a sink of no recovery and no return. Many existing well fields utilize ground water inefficiently by concentrating the wells in small areas, thus causing large local drawdowns while permitting large amounts of ground water to escape unused to the sea in the intervening areas. The wells are concentrated spatially, partly for efficiency of distribution, but in part this has been done because of mistaken belief that they tap an underground river. Pumping may also be unnecessarily intermittent rather than steady in the belief that the longer the hiatus in pumping, the greater the buildup in storage.

Ideally, optimum development of basal ground water would occur by constantly pumping a line of wells normal to the flow paths, which are generally perpendicular to the coastline. Assuming that reliable estimates of ground-water recharge and hydraulic conductivity were obtained, the well spacing and pumping rates could be optimized. An optimum development plan is generally a compromise based on a theoretical scheme for maximum development, aquifer-test results, and economics. Land ownership and availability, however, may be the most important considerations in areas of high land cost and development.

Problems in implementing an optimum plan are few if the existing ground-water draft is small. The problems, however, increase manyfold where the draft is large and the existing development is inefficient as the result of poorly constructed wells, improperly spaced wells, and sustained localized overdraft. The remedy for existing problem areas may involve high costs in the abandonment of old wells and the drilling of new wells, in land acquisition for new well sites, and in the curtailment of ground-water withdrawals at some places. These costs must be weighed against the long-term benefits of optimum development.

At places where basal water is confined by sedimentary caprock and is under artesian pressure, optimum development may require reduction of the artesian heads and pumping at constant rates in order to minimize leakage through the caprock. This operating plan will result in permanent reduction of storage in the basal freshwater lens and possible intrusion of saline water into some existing wells. The costs of these consequences must be carefully considered.

In order that reliable estimates of the consequences can be made and the alternatives properly considered, there is a need for development of hydrologic models of the aquifers. These models can be used to predict results of implementation or nonimplementation of certain operation plans. The degree of success derived from the use of such models would depend entirely, however, on the amount and reliability of the hydrologic data used in constructing the models.

DIKE-IMPOUNDED WATER

A dike-impounded reservoir accumulates rainfall, stores it temporarily, and steadily leaks it to abutting basal reservoirs or to streams cutting into the reservoir. Development of dike-impounded reservoirs is attractive because hydraulic heads are high and the reservoirs are isolated from saline water. One major consequence, not fully understood or acknowledged, is that withdrawal of water from such a reservoir reduces its leakage to abutting basal reservoirs by the quantity developed. The most perplexing consequence, however, is the loss of hydraulic head in the reservoir and the tremendous waste of water from storage during construction of water-development tunnels below the top of the reservoir. During the tunneling period, which lasts for many months, all of the storage above the invert of the tunnel is depleted and flow from the tunnel is reduced to some steady rate. The reduction of storage caused by construction of eight tunnels in Oahu has been estimated at 25,800 Mgal (Takasaki and others, 1969), equivalent to the total ground-water withdrawal in Oahu for about 60 days. The combined steady-state flow of these eight tunnels is about 28 Mgal/d, which implies that it would require at least 920 days for natural recharge to restore the depleted storage.

The Honolulu Board of Water Supply recently drilled an inclined well to tap dike-impounded water in Oahu.

This technique permitted the development of dike-impounded water without the large initial and uncontrollable waste of stored water common to development by tunneling.

A significant part of the reduction in storage by tunneling could be restored by constructing bulkheads at the controlling dikes. Bulkheads have been installed in several tunnels, but only the one in a tunnel in Waihee Valley is effective in restoring water to its pretunnel level. Bulkheads in other tunnels in Oahu were not constructed at dikes that originally stored the most water; hence, they are only partly effective in the restoration of storage. The locations of dikes that control the most water can best be determined at the time of tunneling. If tunneling information is not available and storage is depleted, gain in flow between dikes, determined by measurements, should indicate the best sites for bulkheads. Bulkheads are most effective where single dikes control large quantities of water and where the contrast in permeability between lava flows and dikes is great. In a dike complex, the permeability contrast is too small or the dikes are too numerous for bulkheads to be very effective.

The storage above the tunnel in Waihee Valley has been estimated at 2,200 Mgal and capability of manipulating this amount of storage is of tremendous value in water-supply management. The remaining tunnels are operating at steady-state flow and storage is virtually nil. The restoration of significant amounts of storage above these tunnels would be invaluable. Optimum use of these tunnels would be to store water during the wet winter months for use during the dry summer months at rates much larger than the perennial steady-state flow of 28 Mgal/d. This scheme would eliminate excessive pumping of basal-water wells during the high-demand summer months, thus allowing pumping to be held at some constant rate throughout the year. The reverse is the current practice, involving near-constant withdrawal from dike-impounded reservoirs and manipulated light-winter to heavy-summer withdrawal from basal reservoirs.

SURFACE ACTIVITIES TO MAXIMIZE RECHARGE OF GROUND WATER

Owing to the general lack of surface-reservoir sites, surface activities designed to induce the recharge of ground water must be such that large surface storage is not essential. Possibilities are:

1. Construction of multipurpose flood control structures designed to maximize or to induce recharge.
2. Lowering near-surface ground-water levels by development to reduce evapotranspiration and induce recharge.
3. Agricultural and forest-management practices conducive to recharge and the enhancement of water quality.
4. Fog-drip inducement by artificial means for the purposes of recharge.
5. Artificial recharge of excess surface and irrigation water or sewage effluent by ponding and deep injection.
6. Land development conducive to preservation of water quality and increased recharge.
7. Maximum use and storage of water at high altitudes instead of dropping the water quickly to lower altitudes as is commonly practiced where abutting property owners discharge water individually.
8. Use of inexpensive or excess power generated by burning bagasse at sugar mills for pumping unused irrigation water for storage in reservoirs or for subsurface injection at high levels.

GROUND-WATER PROBLEMS

Water-supply and other water-assessment problems are rarely regional problems, but are, for the most part, single-island problems. Problems related to technology, water rights, use, pollution, and management of ground water, however, are generally regional in scope.

The ground-water problems common to the Region can be considered in three interrelated groups: (1) problems of inadequate information, (2) technological problems, and (3) institutional problems.

PROBLEMS ARISING FROM INADEQUATE INFORMATION

Inadequate information of the geologic framework, meterology, and streamflow often presents serious problems in interpretation of ground-water regimes. Inadequate geologic information leads to difficulty in describing the ground-water reservoirs, the flow within them, and the outflow from them. Inadequate meteorological and streamflow information leads to problems in determining quantitatively the recharge to and the discharge from the ground-water reservoirs.

Major ground-water problems arise from lack of information on the following aspects of the geologic framework:

1. The water-bearing properties of lava flows below sea level. Most of the Region's basal ground water, and the saline ground water that underlies it, occur in these rocks. Lava flows extruded below sea level are generally of low permeability; however, the aquifers that now occur below sea level in the Region are often highly permeable subaerial flows which were subsequently submerged. The extent of the submergence is not known nor is the thickness of the permeable lava flows below sea

level. This leads to difficulty in evaluating amounts of storage and the deep circulation pattern of the fresh and saline ground water.

2. The extent of water-bearing properties of near-shore sedimentary and volcanic rocks. The ensuing problems are those related to the discharge of polluted ground water at or near the shore resulting from the injection of wastes into these rocks.
3. The structure, extent, and density of occurrence of dikes in the dike-intruded zones. The occurrence and movement of dike-impounded waters could be better described if this information were available, and related problems pertaining to water rights and priorities and to environmental impacts that would result from development could be handled more intelligently.
4. The geology and hydrology of rift-zone areas of active or recently active volcanoes. Rift zones occur on the flanks of volcanoes in places where magma is extruded from long fissures. The rift zones become areas of dike intrusion as the magmas cool in the fissures. Hot waters of possible interest for geothermal development occur in these areas. A major concern is the determination of the sustained water yield and the potential energy yield as a basis for evaluating the economic potential of the geothermal waters.

Problems in evaluating ground-water recharge and discharge arise from inadequacies in the following meteorological and streamflow information:

1. The rainfall distribution in the wet interior areas where most recharge occurs.
2. The relation between actual and potential evapotranspiration in the moderately dry to moderately wet areas, especially where the potential evapotranspiration has been estimated as being equal to pan evaporation.
3. The contribution of fog drip to ground-water recharge. Preliminary studies in the region suggest that the contribution of fog drip to recharge may be significant either as direct infiltration or as a replacement for water lost by evaporation and transpiration.
4. The relation between basin rainfall and basin runoff in the wet interior areas where drainage basins are small and where the ground-water divide often differs significantly from the topographic divide.

TECHNOLOGICAL PROBLEMS

The major technical problems related to ground-water hydrology in the Region are those pertaining to basal ground water. Some of the more important are as follows:

1. The relation of basal ground-water levels and their natural and induced fluctuations to the storage, recharge, discharge, and development of the basal lens. More importantly, how to evaluate anticipated changes in rates of natural recharge and discharge at places where water levels are declining.
2. The general inadequacy of equations available for analyzing pumping-test data from partially penetrating wells, and also the application of the concept of transmissivity, which includes aquifer thickness, for determining hydraulic conductivity. The inadequacy is compounded for aquifers consisting of thin lenses, where pumping, even at moderate rates, causes rapid upconing of the saltwater interface.
3. The determination of the relation between horizontal and vertical hydraulic conductivities in basaltic lava-flow aquifers. This relation often determines the yield and, consequently, the optimum mode of development, especially from thin basal lenses where upconing of the underlying saline ground water is always a threat.
4. The evaluation, in space and time, of recharge to and discharge from storage in the part of the basal lens below sea level with change in water level above sea level.
5. The evaluation of tidal responses in basal lenses, especially in thin lenses, and the application of this information to the understanding of the mechanics of flow and the mixing process in the lenses, and in determining hydraulic conductivity. This may be the only applicable hydrologic analytical method in many areas in the Region where the major stress on the basal aquifer is not caused by pumping but by tidal fluctuations.
6. The analysis, in water-budget studies, of the large intermittent amounts of recharge to thin basal lenses as potentially recoverable increments of stored ground water. Intermittent recharge due to intense storm precipitation usually disperses quickly in thin basal lenses, particularly where these lenses occur in highly permeable recent lava flows.
7. Many of the problems mentioned earlier are related to the potential for degradation of water quality which, although not restricted to basal ground-water bodies, is most evident in these water bodies because of their widespread occurrence. Water quality is a critical factor which often limits the use and development of ground water. Over-development results in saltwater upconing or encroachment, and man's activities may produce other contaminants which may degrade present

supplies. There is a need to identify areas where overdevelopment has occurred, where the activities of man may endanger present and future supplies, and where geologic and hydrologic conditions might permit the surface or subsurface disposal of wastes without undesirable environmental consequences.

INSTITUTIONAL PROBLEMS

Owing to recent interest in the quality of the environment and the need to comply with government regulations on water quality and waste disposal, the roles of government, business, and the public in ground-water management have been significantly altered. Government's managerial role includes research, control, conservation, development, monitoring, and planning. The relations of these public functions at various levels of the Federal, State, and County governments warrant review because of these recent changes. The jurisdictional lines between different levels of government and between agencies at the same level remain extremely complex.

Problems in water management related to priority and exchange or transfer of water may require government intervention and assistance for resolution so that water development can be better integrated and coordinated with land-use plans and comprehensive planning in general.

The allocation and management of water has been left largely to private agreements through user associations, which generally include land estates, agricultural interests, municipal suppliers, and the military. Problems are beginning to arise as water supplies locally become more scarce and as land developments affect recharge rates and quality of the water. To cope with these problems, the State, through the Ground Water Use Statutes (Chapter 177, Hawaii Revised Statutes, as amended, was reenacted by Act 122, of the 1961 Session Laws of Hawaii), is authorized to designate ground-water areas for regulation, protection, and control if conditions are found to exist that will endanger the quality or quantity of ground water in such areas. Technical problems will likely arise, however, in trying to establish that such conditions do exist.

Management problems are likely to arise because of changes in the hydrology caused by:

1. Intensive development of ground water, which would significantly reduce perennial flow in nearby streams.
2. Massive shifts to drip irrigation from furrow irrigation.
3. Extensive changes in land use and irrigation practice that would occur in the "Hanapepe" State Supreme Court decision (1973, McBryde Sugar Co., Ltd. v. Almer F. Robinson, et al.) is upheld and the transfer of surface water from one watershed to another is curtailed. The Hanapepe decision establishes that all surface-water rights belong to the State; appurtenant rights, as use rights, remain in existence; all other rights to the use of water are based on the riparian doctrine; and water rights are not transferable from one watershed to another. Clarification is still needed as to whether or not the state can transfer water from one watershed to another.
4. The 1973 State Supreme Court decision which declared the State owner of surplus water in Hawaii's rivers and streams (Hanapepe decision) was overturned as unconstitutional on October 26, 1977 by the Federal District Court in Honolulu (1977, Selwyn A. Robinson, et al. v. George K. Ariyoshi, et al.). The State may appeal the recent Federal Court ruling to the U.S. Supreme Court. The State did not seek title to the water rights in the initial suit.

The State government has developed a carrying-capacity concept for use as a growth management tool and framework for decisionmaking (1976). The carrying capacity of a region can be defined as the capacity of the region's environmental and resource systems to support a given or planned level of economic activity. The methodology has been formalized and integrated for a prototype study of the water supply of Oahu. Safe yields representing reasonable developable supplies, assuming present technology and economics, need to be translated into carrying capacities which can be extrapolated into the future. A major problem in the effective implementation of such a concept lies in the general lack of information needed to adequately evaluate the water resources.

CONCLUSIONS

The ground-water resources of the Hawaii Region offer the best prospects for meeting future water needs. In comparison to the surface-water resources, they appear to be less costly to develop and more dependable when developed. Development of ground water may also be more compatible with environmental quality considerations, existing water rights, and statutory regulations.

About 810 Mgal/d is currently withdrawn from the ground-water resources. This quantity represents about 4 percent of the estimated rainfall. In spite of this small percentage, many problems in the quantity and quality of the ground-water supply exist. Under natural conditions, these problems exist owing to the extremely uneven distribution of rainfall, size and shape of the islands, and the varying ability of the rocks to absorb and transport the water. The heavy local development needed to meet increasing demands and the deterioration of the ground-water supply owing to withdrawal, land development, and waste disposal contribute most to the existing problems.

Owing to the large spatial variation in the predominant trade-wind rainfall and the subsequent marked inverse relation in water availability between the areas of supply and areas of demand, most water-supply problems have been solved by the transport of water. With a significant increase in the number of conduits for water transport, many of the future supply problems can probably be best resolved in this way. The import of water from the wet to the dry areas, especially for irrigation, is a most desirable solution because it has the effect of widening the rainfall recharge area.

In many water-deficient areas, where water is unavailable for import or is too costly, supply problems would have to be resolved by measures that would reduce demand or enable the use of treated sewage effluent or brackish water for some purposes. For example, in coastal areas where additional development of good-quality ground water is not feasible, brackish ground water might be substituted in irrigation and industrial uses for the domestic-quality water now being used for these purposes. Water-supply problems that now exist in areas where sugarcane is heavily irrigated, such as in the Lahaina District in Maui and the Kekaha-Mana and Koloa areas in Kauai, could be relieved somewhat by similar types of water-exchange practices.

For the island of Oahu, where the demand for domestic-quality water has a high priority and where most easily obtainable water has already been developed, actions needed to resolve supply problems are more restrictive and specific.

There has been a tendency for large users of water to ignore the development of small sources of water, the primary reason being the difficulty or infeasibility of assimilating small scattered supplies in the existing distribution systems. However, in view of the pressing need, many excellent small sources available in windward Oahu, the Waianae area, and the southeastern end of the island should be seriously considered for development.

There is a general lack of manmade storage to meet summer peaking needs, and the prospects of significantly increasing the storage are nil. Lacking adequate storage, summer peaking needs are now met by increased pumping. This method is undesirable in that extreme pumping stresses are imposed in the basal-water bodies which are the principal sources of supply. Some of the summer peaking needs could be met by restoring dike-impounded storage in the Koolau Mountains which was lost by development. This additional storage and the use of water currently stored at high levels in the Schofield water body could be utilized principally for high-demand summer periods. This scheme would make it possible to reduce some of the extremely heavy summer pumping from the basal aquifers.

Some increase in the domestic water supply could be accomplished on Oahu by the exchange of poor quality water, such as brackish water or treated sewage effluent for domestic-quality water now used for irrigation. Large amounts of nonpotable water are available from treated sewage or from water in coastal sediments.

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